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PRECIPITATION WHIPLASH EVENTS ACROSS THE SOUTHERN GREAT PLAINS OF THE UNITED STATES

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PRECIPITATION WHIPLASH EVENTS ACROSS THE SOUTHERN GREAT PLAINS OF THE UNITED STATES

A THESIS APPROVED FOR THE
SCHOOL OF METEOROLOGY

BY THE COMMITTEE CONSISTING OF

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Abstract

The Southern Great Plains is a region that is prone to precipitation extremes and transitions between them which have direct impacts on agriculture, infrastructure, water quality and water quantity. However, current understanding of transitions between precipitation extremes, including seasonal and annual characteristics as well as spatial and temporal patterns across the Southern Great Plains (SGP) is lacking. Most previous research has focused primarily on the characteristics and impacts of transitions on the annual scale, and those that have investigated shorted timescales have not completed an analysis across the Southern Great Plains. In this study, the characteristics and climatology of transitions between precipitation extremes on the subseasonal-to-seasonal (S2S) scale across the Southern Great Plains between 1981 and 2018 were examined. Transitions between precipitation extremes were defined using a percentile method where S2S precipitation totals at individual grid points are ordered. A transition from the low (high) percentile threshold to the high (low) percentile threshold from one period to the next were defined to be a drought-pluvial (pluvial-drought) transition. At least one transition event was found to occur somewhere within the Southern Great Plains every year between 1981 and 2018, with the Fall season being the time of year when these events are most likely to occur. The months of September and October are the most common months to be drought and pluvial months suggesting that the secondary peak in annual precipitation that is observed during the Fall is important in driving transitions in precipitation extremes across the SGP. One such example of a precipitation whiplash event occurred across the SGP in 2017. Above average precipitation totals throughout the year fell below average during the Fall period and the region transitioned from pluvial to drought conditions during the months of September to October. The insight this study gives into the climatology of transitions in precipitation extremes on the subseasonal scale will greatly enhance the

understanding of these events allowing for better predictability and preparedness into the future.

Chapter 1

Introduction

A transition occurring from extreme dry (drought) conditions to extreme wet (pluvial) conditions, or vice versa, can lead to cascading impacts across a region. The green-up of vegetation during periods of excessive rainfall can pose a considerable fire risk during a transition into drought conditions as desiccation of the land surface can yield fuel available for wildfires (Scasta et al., 2016). Texas experienced several major wildfire outbreaks during the drought of 2011, including the Bastrop Fire that destroyed over than 1,500 homes and killed 2 people (Huffman, Holly, 2011). Increasing wildfire risk is projected by model simulations across the Southern Great Plains (SGP) of the United States, as temperatures are predicted to rise and the duration of the fire season increases (An et al., 2015). Furthermore, if a drought occurs during the peak growing season, the agricultural production can suffer and results in lost yields (Basara et al., 2013).

On the other side, transitions from drought conditions to excessive rainfall are critical for the recovery of water resources and such features have been documented and shown to be increasing with time across the SGP (Christian et al., 2015). However, they can also pose a significant flood risk. As climate conditions continue to change, rare events such as 100-year floods are likely to become more common (Easterling et al., 2017; Wehner et al., 2017). During a transition from drought to pluvial conditions, vegetation which acts as a barrier protecting the topsoil withers and dies, increasing erosion during excessive precipitation (Hillel, 1998). In addition, the "baking" of the soil from strong surface heating can create a dense surface crust which partially seals the soil profile resulting in increased surface run-off and flooding.

The SGP is vulnerable to periods of droughts; most notably throughout the 1930s and 1950s and recently from 2010 to 2015, as well as periods of excessive precipitation, such as the 1940s and the 1980s (Hoerling et al., 2014). The SGP is also a region that is prone to transitions between these two extremes that produce precipitation whiplashes with direct impacts to agriculture, infrastructure, water quality and water quantity (Christian et al., 2015; Dong et al., 2011). A precipitation whiplash event hereby refers to when one precipitation extreme immediately follows the opposite extreme with no break in the middle (Swain et al., 2018). One such example occurred in 2017 and 2018 across the Oklahoma and Texas panhandle; a 6 month period of drought was preceded by an anomalous wet period throughout the growing season of 2017 and resulted in hundreds of wildfires during the Spring of 2018. April 2018 saw 123 fires burn 367,457.5 acres (Oklahoma Forestry Services, 2019).

Another example occurred during 2015 when an excessive rainfall event led to the abrupt end of the 2010 to 2015 drought across the region. Precipitation totals for a 4 month period during the spring of 2015 in south-central Oklahoma were greater than 40 inches, which is approximately equal to the average rainfall amount many locations would normally receive in one year (McManus, G, 2015; NOAA NCEI, 2018). Flooding in Oklahoma and Texas in 2015 caused an estimated $2.6 billion in damages (NOAA NCEI, 2018) with $1 million in emergency relief funds provided by the U.S. Department of Transportation's Federal Highway Administration to assist in the repair of damaged roads (Oklahoma Department of Transportation, 2015).

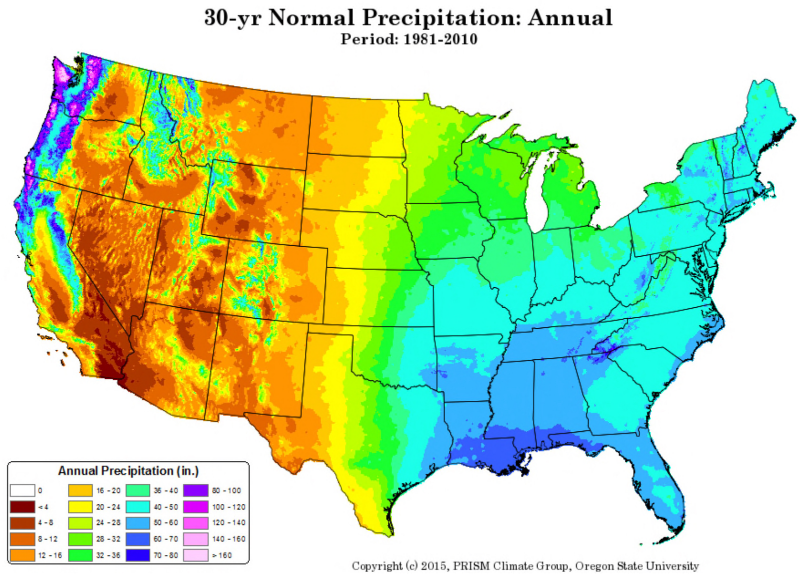


Figure 1.1: The 30-year mean annual precipitation from 1981 to 2010 across the United States. PRISM Climate Group, Oregon State University (2004)

It has been well documented that there is a well-defined transition zone between the arid western and humid eastern regions of the North American continent climatologically, approximately located along the 100th meridian (Fig. 1.1). This divide can fluctuate on a subseasonal to seasonal (S2S) to interannual basis (Powell, 1890; Webb, 1931; Seager et al., 2018). Although, our current overall understanding of precipitation whiplash events, including the seasonal and annual characteristics as well as spatial and temporal patterns across the SGP is lacking.

Recent research has shown that the transitions between extremes have largely increased in speed across the continental United States and in particular, across the Southern Great Plains (Basara et al., 2019; Christian et al., 2015; Ford et al., 2021). Droughts are following pluvials with decreasing transition time between the two precipitation extremes. Through decreasing the amount of time it takes to transition from one extreme to another it can exacerbate the impacts of the drought (Otkin et al., 2015). Drought and pluvial events also occur more frequently in the central portions of the United States with increasing impacts due to changes in population growth and the farming of marginal lands (Kangas and Brown, 2007).

Projected changes in climate model simulations show an increase in precipitation variability on the daily and monthly to interannual and decadal timescales into the middle and late twenty-first century (Pendergrass et al., 2017; Swain et al., 2018). An increase in precipitation variability will contribute to further vulnerability across the SGP, however the magnitude and timing of these events is still uncertain (Easterling et al., 2017). Regional droughts, in particular flash droughts, are expected to increase in number and in intensity (Otkin et al., 2016). However, when precipitation does occur it is expected to be more intense with a 10–15% increase in maximum 1-day precipitation across the SGP by 2065 (Shafter et al., 2014). As precipitation totals trend to the extremes of the distribution, impacts will be observed in the demand on food and energy systems across the SGP also (Kloesel et al., 2018).

Multiple methods have been developed to define precipitation extremes and the transitions between them (Dong et al., 2011; Christian et al., 2015; Francis et al.; Casson et al., 2019; He and Sheffield, 2020; Ford et al., 2021). Christian et al. (2015) used a standard deviation method to analyse whiplash events *annually*, whereas Ford et al. (2021) and He and Sheffield (2020) characterised whiplashes by computing the 1-month, 3-month and/or 12 month Standardised Precipitation Index. However, none of these studies have created a climatology of both drought-pluvial *and* pluvial-drought transitions on the *S2S scale* across the SGP.

Many extreme events have strong S2S forcing with climate modes such as the Madden Julian Oscillation and the El Ni*n*o Southern Oscillation playing a large role in precipitation predictability across the United States as well as elsewhere in the world. However, forecast skill at this timescale is extremely poor especially compared to 10 day weather forecasts and even our longer term seasonal forecasts (Fig. 1.2). Therefore, focusing on what drives precipitation whiplash events at the S2S scale and their climatological patterns is of extreme importance.

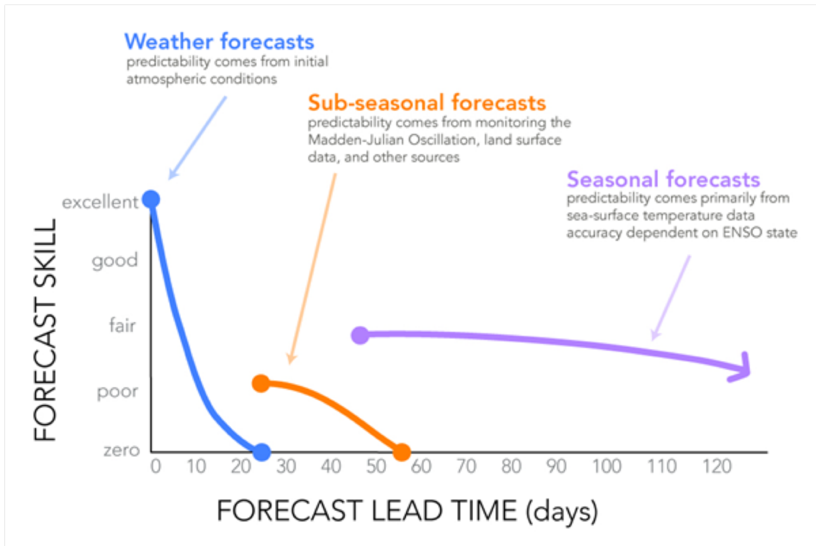


Figure 1.2: Qualitative estimate of forecast skill based on forecast range from short-range weather forecasts to long-range seasonal predictions, including potential sources of predictability. Relative skill is based on differing forecast averaging periods. (White et al., 2017)

The overarching goal of this project is to examine the characteristics and climatology of precipitation whiplashes on the S2S across the SGP between 1981 and 2018. To examine precipitation whiplashes on this scale this project has three smaller individual goals, which are:

- Develop a definition of precipitation whiplashes on the S2S scale. **Goal 1a**
- Create a database of precipitation whiplashes on the S2S scale. **Goal 1b**
- Analyse trends, spatial and temporal patterns, and changes within the data across varying timescales. **Goal 2**

- Examine observed trends and patterns with a focus on terrestrial conditions and relevant societal impacts (i.e. wildfires; infrastructure; health) via the analysis of a case study. **Goal 3**

Chapter 2

Data and Methods

2.1 Data

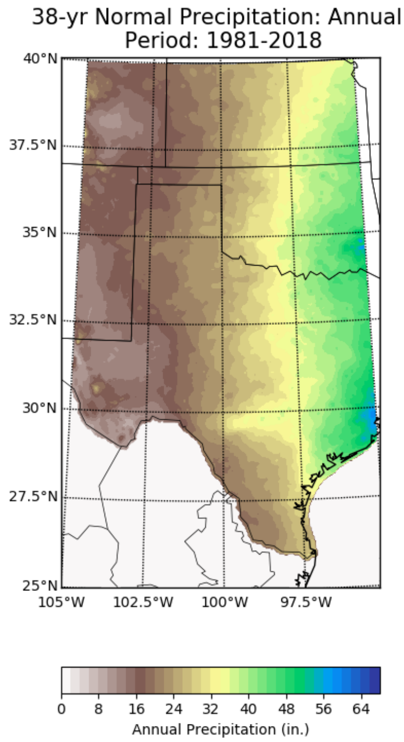
Daily precipitation from 1981-2018 from the Parameter-Elevation Regressions on Independent Slopes Model (PRISM) AN81d dataset (PRISM Climate Group, Oregon State University, 2004), was utilised in this study. PRISM is constructed from 13,000 rain gauges across multiple sources which are then interpolated onto a 4 km grid using a weighted regression scheme (Daly et al., 2008). This weighted regression scheme accounts for complex climate regimes such as orography and rain shadows. In addition, east of the Rockies AN81 PRISM data incorporates Next-Generation Radar (NEXRAD) analysis since 2002.

PRISM has a dry mean bias in precipitation estimates across the SGP which must be noted (Behnke et al., 2016). Therefore, daily precipitation from the Livneh dataset (Livneh et al., 2013) was also utilised for comparison throughout this study. The Livneh (0.0625° resolution, from 1915-2011) precipitation dataset is generated using the Variable Infiltration Capacity hydrological model representing approximately 20,000 National Climatic Data Center stations across the continental United States. Livneh exhibited the smallest mean biases in precipitation estimates across the SGP compared to 7 other datasets examined by Behnke et al. (2016), however the Livneh dataset only includes daily precipitation through 2011 whereas PRISM spans to present. Further, resolution differences exist whereby Livneh has a spatial resolution of 0.0625° (approximately 6 km) whereas PRISM is on a 4 km grid.

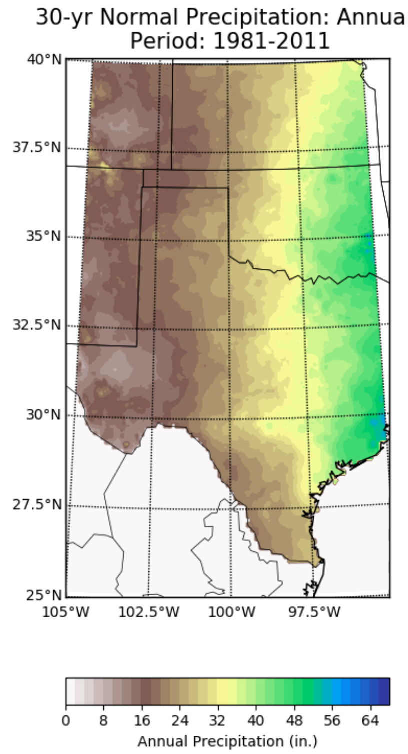
To address the 3 primary goals of this project, the following components were completed: (1) a definition of precipitation whiplash events on the S2S scale, (2) a climatological analysis of precipitation whiplash events across the SGP, and (3) an analysis of a specific precipitation whiplash event that occurred in 2017/2018. Precipitation whiplash events were defined using a percentile method discussed in Chapter 3.

2.2 Southern Great Plains

The SGP is characterised by a large east-west orientated precipitation gradient (Borchert, 1950) and as such, this study defined the SGP to span 105-95°W and 25-40°N incorporating the states of Texas, Oklahoma, Kansas, southeast Colorado and western New Mexico (Fig 2.1).



(a) PRISM



(b) Livneh

Figure 2.1: Mean annual precipitation across the Southern Great Plains in the PRISM dataset (left) and Livneh dataset (right).

2.3 Statistical Analysis

Long-term changes in transition frequency and magnitude were assessed using simple linear regression. To quantify the statistical significance of these linear trends with time a Monte-Carlo approach was used. The 38-year time series was shuffled, transitions were identified and the "true" trend was compared to 5000 iterations. Due to computing power to assess the statistical significance of trends in Fig. 4.11 the process was only repeated 1,000 times at each grid point. A trend is considered statistically significant if it either exceeds the 97.5th percentile or is less than the 2.5th percentile.

Chapter 3

Goal 1: Precipitation Whiplash Definition

3.1 The Definition

Due to the non-normality of precipitation data a percentile method was chosen to define precipitation whiplash events on a S2S scale by ordering S2S precipitation totals from the lowest to highest value. Precipitation totals on the S2S scale can be defined in multiple ways with this study having considered two alternative ways of calculating these totals.

Figure 3.1: A schematic showing the individual steps in the precipitation whiplash definition utilised by this study.

3.1.1 Defining S2S Precipitation: 30-day Rolling Sum vs Calendar Months

This study used two methods to define precipitation totals on a S2S scale; set calendar months and a 30-day rolling sum. The first method using set calendar months calculates precipitation totals that are bounded by the months of the year. Using this definition, a September precipitation whiplash occurs when the month of September is in the preceding conditions and the month of October is in the latter conditions.

However, when characterising climate extremes and transitions, the data temporal resolution can affect the magnitude and frequency of the extreme. This is especially important when dry or wet extremes occur near the middle of the calendar month and persist into the next calendar month. In this case, the set calendar month method will likely underestimate the overall magnitude of the extreme and may even miss events entirely. Therefore, a second method has been applied using a 30-day rolling sum of precipitation totals throughout the entire period.

Throughout the precipitation timeseries 30-day rolling sums of precipitation totals were calculated rather than monthly totals using the set calendar months. This gives 365 days a year of 30-day rolling sum precipitation totals until the very last year (2018) in our timeseries where the totals end on December 1st. The definition below was then applied over a 30-day period where if Day 1 was in drought conditions and Day 31 was in pluvial conditions this was be considered a drought-pluvial transition (Fig. 3.2). However, due to these being 30-day rolling sums of precipitation totals Day 2 - Day 32, Day 3 - Day 33, Day 4 - Day 34... etc can all be considered drought-pluvial transitions also.

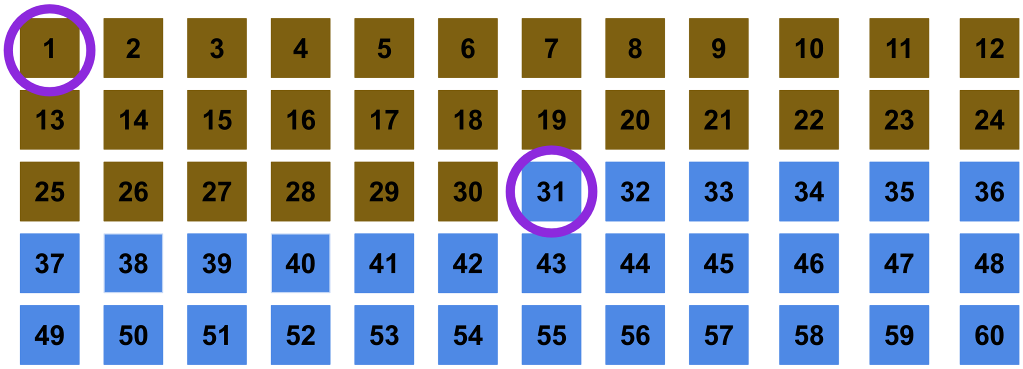


Figure 3.2: An example definition precipitation whiplash events using 30-day rolling sums of precipitation totals.

Therefore, a limitation of this time series is that is does not contain independent samples; as each individual precipitation whiplash event cannot be considered independent from each other and some events may be counted multiple times. For this reason certain conditions must be met in order for a transition to retained:

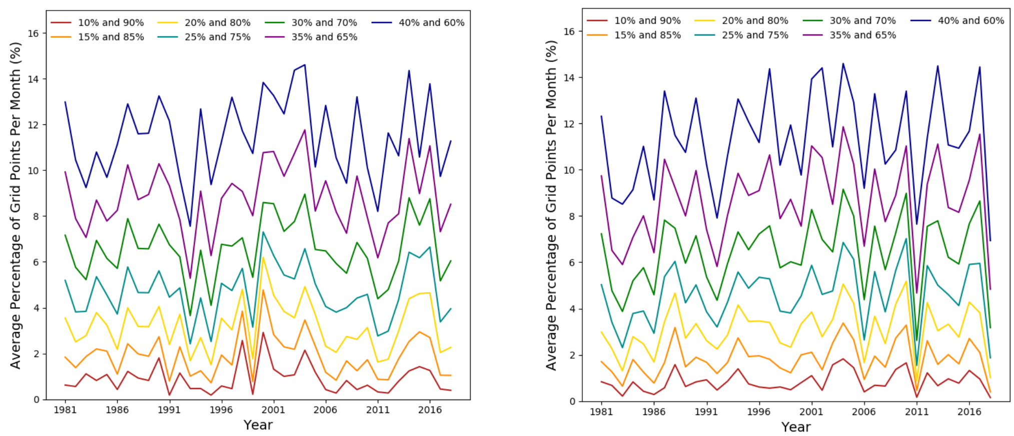
1. At least 10 days prior to the transition occurring must be in the extreme conditions i.e. 10 days prior to a drought to pluvial transition must be in drought conditions.

2. There must not be a precipitation whiplash event that immediately follows said event i.e. the precipitation whiplash event that is kept in the database is the last one in the series of events.

In Fig. 3.2 the transition from Day 30 - Day 60 would be the transition retained for analysis.

3.1.2 Defining Percentile Thresholds

Once precipitation totals at the S2S scale had been calculated they were then ordered at each grid point from the lowest to the highest value to determine a low percentile threshold and a high percentile threshold for extreme events. A sensitivity test on the choice of lower and upper thresholds to define extreme events was completed (Fig. 3.3); the more extreme the thresholds were, the smaller the percentage of grid points that showed a transition. Using 40% and 60% to define the lower and upper thresholds the average percentage of grid points per month in 1991 were approximately 13% compared to 4% when using 20% and 80% as the thresholds. However, the temporal and spatial patterns observed were the same, with a decrease observed between 1991 and 1993 in all cases. Therefore, this study used 25% as the lower threshold and 75% as the upper threshold.



(a) Drought to Pluvial (b) Pluvial to Drought

Figure 3.3: Decadal cycle of precipitation whiplash events where different upper and lower thresholds have been used to define extreme events.

3.1.3 Defining Transitions

Finally, drought-pluvial and pluvial-drought transitions were defined. A transition from the low percentile threshold to the high percentile threshold from one 30-day/monthly period to the next was defined to be a drought-pluvial transition; a transition from the high percentile threshold to the low percentile threshold was considered a pluvial-drought transition; and finally any difference transition from average to extreme conditions or vice versa was not the focus of this study. As an example, using 25% as the lower threshold and 75% as the upper threshold, if September was in the 12th percentile and the following October was in the 80th percentile, this would be considered a drought-pluvial transition using our calendar month method.

There are limitations to this definition however, such as no spatial component was applied. Currently, there is no check to see if any of the surrounding grid points were also showing a transition at that time iteration, or whether the grid point was a rogue grid point. To assess the impact this limitation may have on this study, the spatial distribution of precipitation whiplash events during the years (Table 3.1) with the two smallest and two largest average percentage of grid points for a typical month in those years were examined for each transition type (Figs. 3.4 and 3.5).

	Lowest Years	Highest Years
Drought-Pluvial	1993/1995	2000/2016
Pluvial-Drought	2011/2018	2010/2004

Table 3.1: The years between 1981 and 2018 with the lowest and highest average percentage of grid points per month experiencing a precipitation whiplash event.

In the drought to pluvial cases (Fig. 3.4), 1993 and 1995 which have the smallest average percentage of grid points per month at 2.5% and 2.6% respectively have less spatial coverage, as expected. However, this coverage is still largely spatially coherent, with large areas having experienced a drought to pluvial whiplash such as southeast Kansas and along the Kansas/Colorado border in 1993 and along the Texas/Mexico border in 1995. In the pluvial to drought case (Fig. 3.5), a similar pattern is observed, however the grid points are less spatially coherent in 2011 and 2018 which is likely explained by a smaller percentage of average grid points per month (<2% covered; Fig 4.9). In both cases, the years with the largest average percentage of grid points per month show the greatest spatial coherence with large areas having experienced a precipitation whiplash.

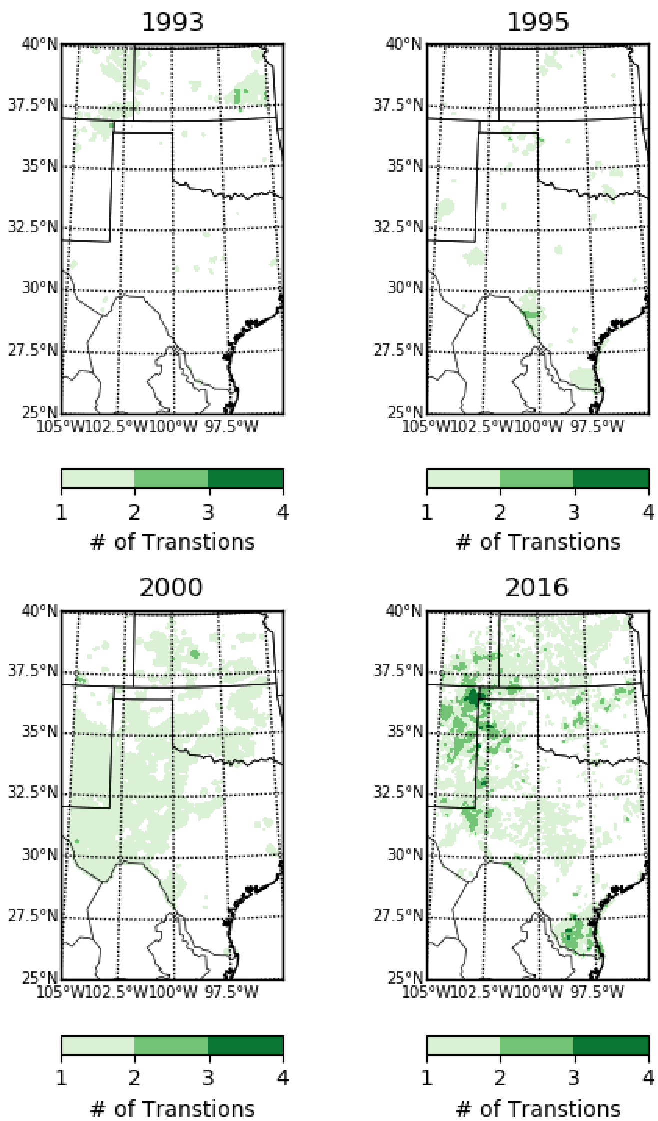


Figure 3.4: The spatial distribution of grid points which experienced a drought to pluvial transition in the two lowest years (1993 and 1995) and two highest years (2000 and 2016) in our time period as defined by Fig. 4.9a.

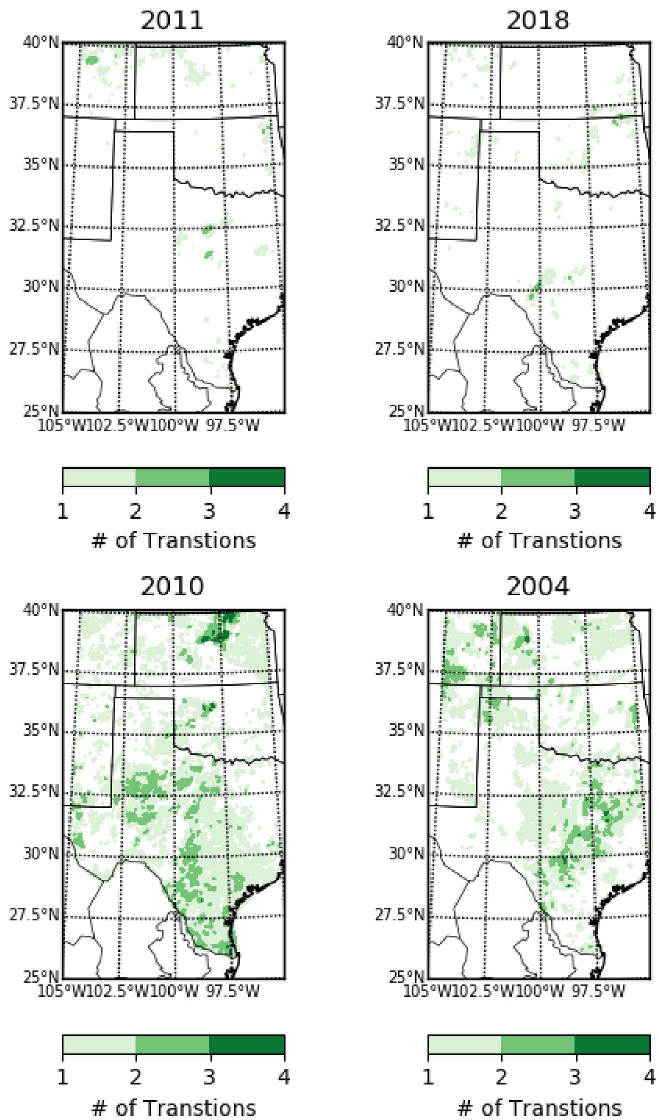


Figure 3.5: The spatial distribution of grid points which experienced a pluvial to drought transition in the two lowest years (2011 and 2018) and two highest years (2010 and 2004) in our time period as defined by Fig. 4.9b.

Chapter 4

Goal 2: Trends, Patterns and Changes Across Varying Timescales

A climatology of precipitation whiplash events across the SGP was created utilising the definition developed in Chapter 3, spatial and temporal trends and patterns were analysed seasonally and inter-annually.

4.1 Southern Great Plains Whiplashes

The spatial distribution of precipitation whiplash events across the SGP shows considerable variability with more precipitation events in the northwest and less events in the southeast. Between 1981 and 2018, approximately 35 or more precipitation whiplash events occurred in the northwest compared to less than 20 events in regions in the southeast (Fig 4.1). The same spatial distribution can be seen in the Livneh data over a similar period (1981-2011; Fig 4.2).

The east-west divide in precipitation whiplash events observed in Figs 4.1 and 4.2 falls approximately along the 100th meridian which is discussed in Chapter 1. The 100th meridian separates the arid west from the humid east with more precipitation whiplash events having occurred west of this divide where it is climatologically arid compared to east of this divide where it is humid.

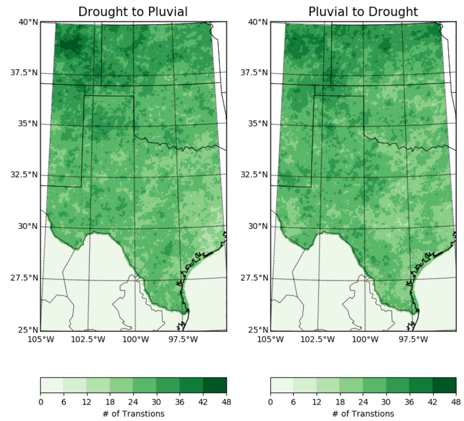


Figure 4.1: Spatial distribution of precipitation whiplash events between 1981 and 2018 using the PRISM data and set calendar month method to calculate S2S precipitation.

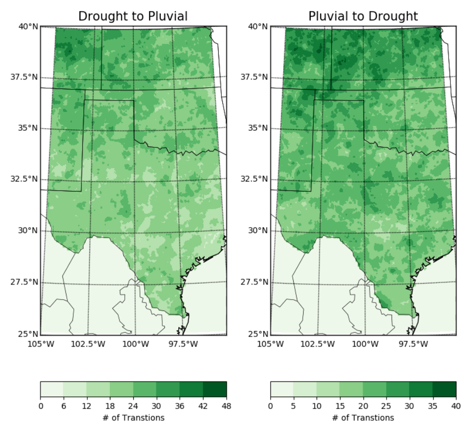


Figure 4.2: Spatial distribution of precipitation whiplash events between 1981 and 2011 using the Livneh data and set calendar month method to calculate S2S precipitation.

The 30-day rolling sum method of calculating S2S precipitation totals resulted in almost double the number of transitions with up to 90 events in the northwest throughout the period 1981-2018 (Fig 4.3). However, the overall spatial pattern with more precipitation whiplash events in the northwest and less in the southeast is still apparent.

Using set calendar months to define S2S precipitation totals results in drought-pluvial and pluvial-drought transitions looking very similar across the region (Figs. 4.1 and 4.2) however, in the 30-day rolling sum case there are clear differences between the two methods (Fig. 4.3). For example, in the 30-day rolling sum spatial maps more pluvial-drought transitions are seen across west-central Texas than drought-pluvial transitions. More pluvial-drought transitions are also seen across eastern Oklahoma using the 30-day rolling sum method however, using the set calendar months method more drought-pluvial transitions are observed across eastern Oklahoma. This suggests that the set calendar month method is missing pluvial-drought precipitation whiplash events as these events are more likely to start and end near the middle of the calendar month.

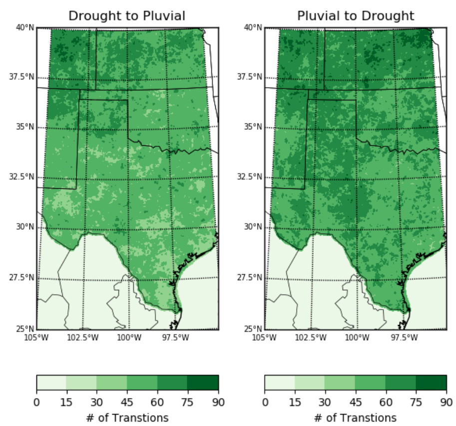


Figure 4.3: Spatial distribution of precipitation whiplash events between 1981 and 2018 using the PRISM data and 30-day rolling sum method to calculate S2S precipitation

4.2 Annual Cycle of Precipitation Whiplash Events

As the timing of precipitation is important for numerous sectors, we sought to determine if precipitation whiplash events occur more frequently at certain times of the year. The histograms in PRISM and Livneh show the annual cycle of precipitation whiplash events averaged over all 38 and 30 years respectively (Figs. 4.4 and 4.5). In general, there is a clear seasonal cycle in the precipitation whiplash events that follows the seasonal cycle in rainfall. This is indicative of less rapid transitions in precipitation extremes, less than 2% of grid points on average per year during NDJ, when the average expected rainfall across the region is less compared to >6% of grid points on average per year during JJA.

In both the PRISM and the Livneh datasets, September appears as the month with the highest average percentage of grid points per year, with approximately 9% of grid points having experienced a transition across the four distributions (Figs 4.4 and 4.5. Due to the way a September precipitation whiplash event is defined, both September and October are the months which are most likely to experience drought and pluvial conditions as well as the rapid transition between the two.

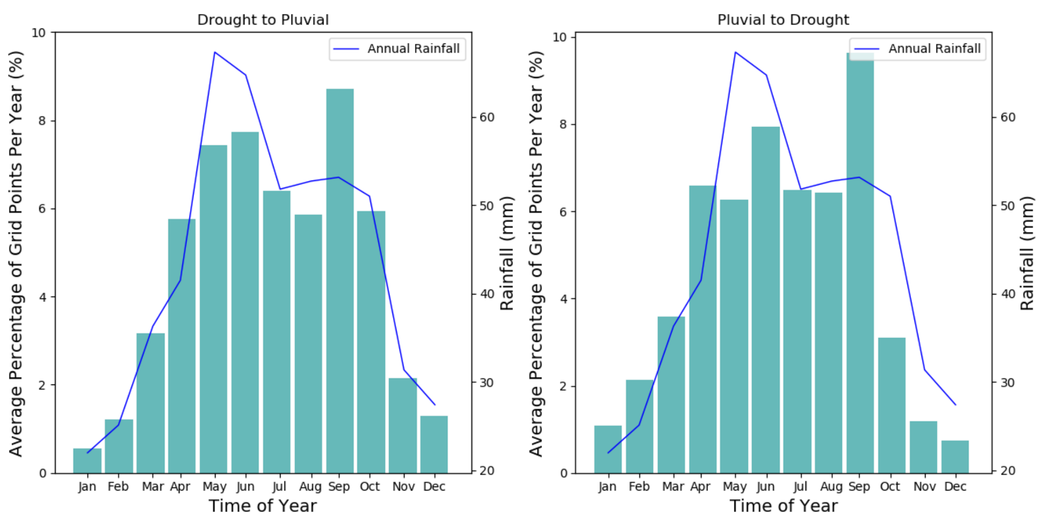


Figure 4.4: Annual cycle of precipitation whiplash events using the PRISM data and set calendar month method to calculate S2S precipitation. Overlayed is the mean annual rainfall for the SGP.

These findings also match with what is seen in the annual cycle of precipitation whiplash events produced using 30-day rolling sums for S2S precipitation. Fig. 4.6 shows a peak in the distribution during the months of September and October in the pluvial-drought distribution. A peak is also seen during the Fall in the drought-pluvial

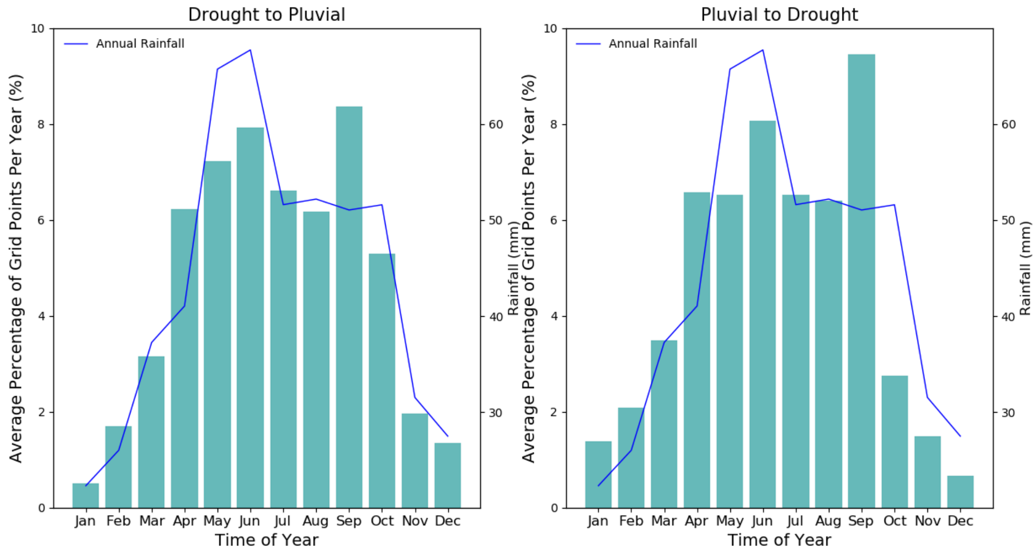


Figure 4.5: Annual cycle of precipitation whiplash events using the Livneh data 1981 through 2011 and set calendar month method to calculate S2S precipitation. Overlayed is the mean annual rainfall for the SGP.

distribution however, this distribution is bimodal with a second peak in the spring. The appearance of the Fall season, the months of September and October, as the most likely time to experience both a drought-pluvial and pluvial-drought transition, suggests that the secondary peak in the annual rainfall could be important for precipitation whiplash events across the SGP.

All of the seasonal distributions also show a rapid drop in precipitation whiplash events into the winter season. In the drought-pluvial distributions the drop in events occurs simultaneously with the drop in annual rainfall however, in the pluvial-drought distributions the event drop is slightly before. This more apparent in Fig. 4.6. The timing of the precipitation whiplash event drop off could be biased late in the 30-day rolling sum distributions by choosing the last event in a series of events to keep in the database. However, as all precipitation whiplash events have this bias it can be concluded that the drop in drought-pluvial events occurs after the drop in pluvial-drought events.

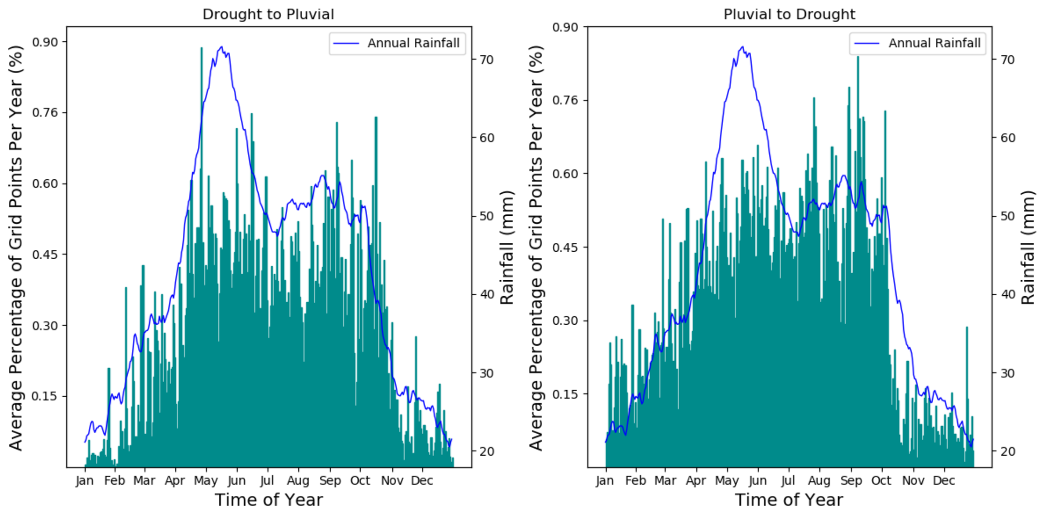


Figure 4.6: Annual cycle of precipitation whiplash events using the 30-day rolling sum method to calculate S2S precipitation. Overlay-ed is the mean annual rainfall for the SGP.

As the patterns observed through using set calendar months and a 30-day rolling sum to define precipitation totals on a S2S scale are similar, from here on in all results discussed used the set calendar months to define precipitation totals. A clear north-south east-west trend in precipitation whiplash events across the SGP is seen in Fig. 2.1. Therefore, the SGP has been divided into 4 regions along 32.5°N and 100°W to assess whether any differences exist in the annual cycle of precipitation whiplash events across the SGP.

As in the spatial maps more precipitation whiplash events are observed in the northern regions than in the southern regions especially during the middle of the year. Approximately 12% of grid points on average experience a drought-pluvial transition in the northwest during June compared to 4% in the southwest (Fig. 4.7). The average percentage of grid points experiencing a transition throughout the year remains fairly constant in the southeast and southwest with a difference of approximately 4% between the highest and lowest month (Fig 4.8). However, in the northern regions this difference is much larger, with just more than 14% of grid points experiencing a pluvial-drought transition and just less than 14% of grid points experiencing a drought-pluvial transition in September in the northwest, and almost zero grid grid points experiencing either precipitation whiplash event in December.

All four regions show the month of September as the month with the highest average percentage of grid points for drought-pluvial transitions and pluvial-drought transitions as in Fig. 4.9. This further highlights the importance of the secondary peak in annual rainfall that occurs during the Fall as being an important driver for precipitation whiplash events. Even when the SGP is divided into separate regions September still shows up as the as the most common month for a precipitation whiplash to occur indicating that this fall window of precipitation is important for all regions of the SGP.

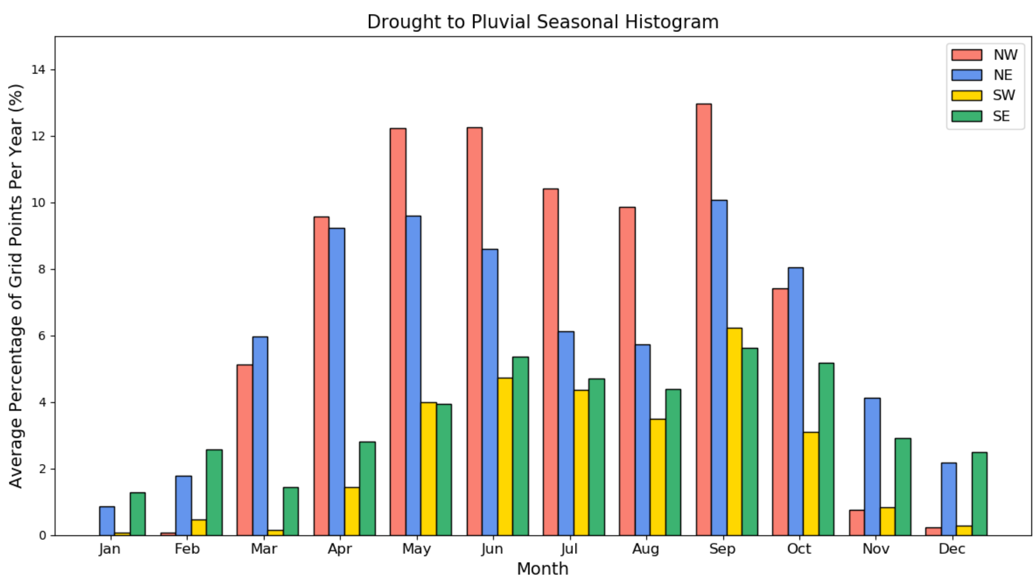


Figure 4.7: Annual cycle of drought-pluvial transitions across the SGP, where the SGP has been divided along 32.5°N and 100°W separating the SGP into 4 regions, using the set calendar month method to calculate S2S precipitation.

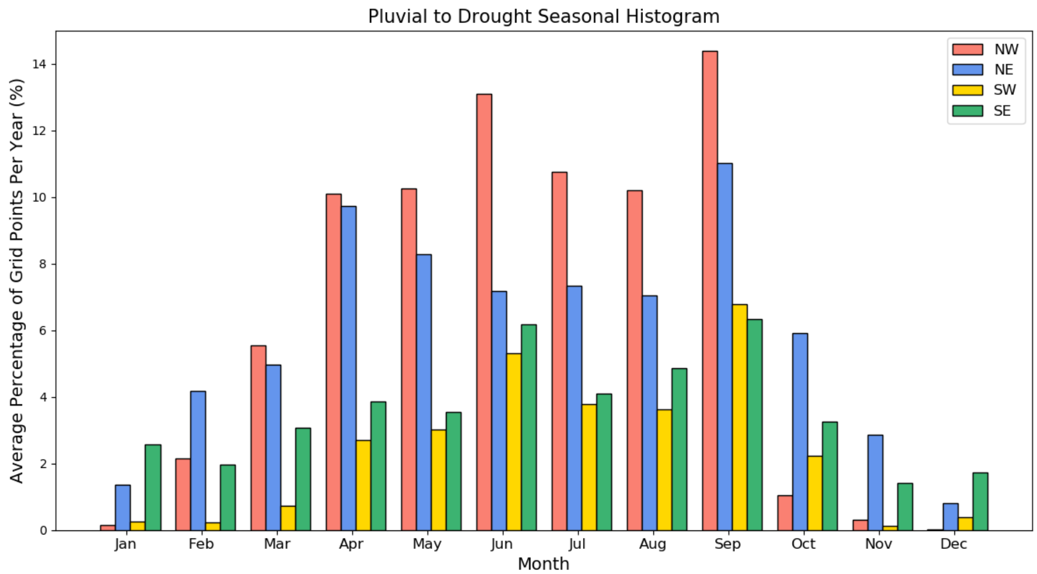


Figure 4.8: Annual cycle of pluvial-drought transitions across the SGP, where the SGP has been divided along 32.5°N and 100°W separating the SGP into 4 regions, using the set calendar month method to calculate S2S precipitation.

4.3 Inter-annual Variability

Along with examining precipitation whiplash events within the calendar year, precipitation whiplash events were examined inter-annually. The inter-annual variability of precipitation whiplashes was examined throughout the 38-year (1981-2018) time period in the PRISM dataset and the 96-year time period in the Livneh dataset (1915-2011). Variability was determined by calculating the percentage of grid points that experienced a precipitation whiplash each month for an individual year and taking an average. This was completed for all years throughout the time period. A transition was defined to occur within a designated calendar year, i.e. the months January to December are in the preceding conditions with the next month in the following conditions; therefore a December-January transition would be counted in Decembers year. Trends throughout time were also calculated to assess long-term change in transition frequency and magnitude.

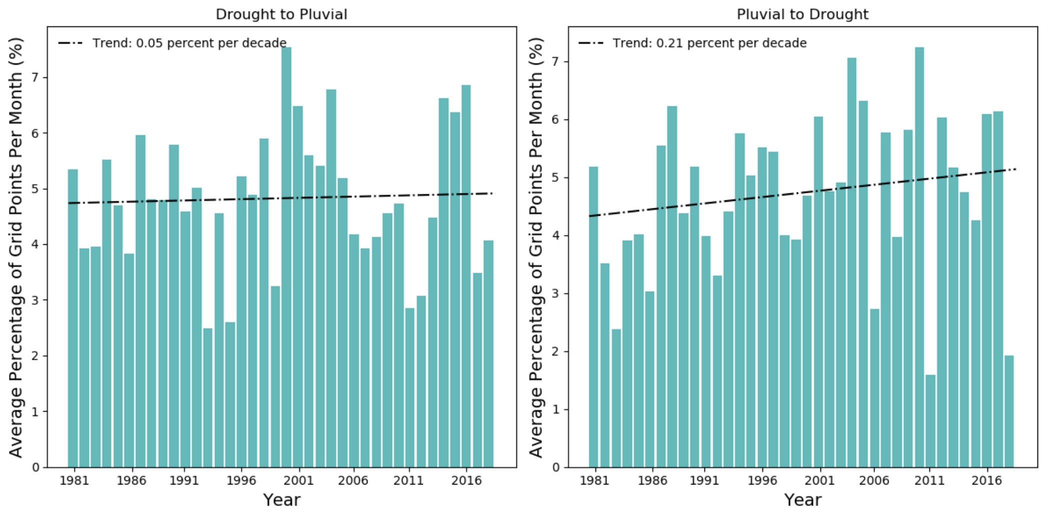


Figure 4.9: Annual distribution of precipitation whiplash events in the PRISM dataset (1981-2018) using the set calendar month method to calculate S2S precipitation. Overlayed is the trend per decade.

Both drought-pluvial and pluvial-drought transitions occur every year somewhere within the SGP (Fig. 4.9). Certain years stand out as experiencing more transitions with a large number of grid points in an average month that year having experienced a drought to pluvial transition such as the years 2000 and 2016 with 7.5% and 6.6% respectively. For pluvial to drought transitions 2010 and 2004 are high years 7.2% and 7% respectively. Similarly, there are years that stand out as having a reduced number of transitions; 2011 and 2018 for pluvial to drought transitions and 1993 and 1995 for drought to pluvial transitions. 3 out of the 4 years that stand out as being particularly high were La Niña with 2010 being a especially strong La Niña year. However, out of the four years that were particularly low no pattern is observed with 2 moderate La Niña years, one weak El Niño year and one neutral year (Table. 4.1).

Using the Livneh dataset the annual distribution of precipitation whiplash events can be expanded back to 1915. Over this 96-year period we still see both drought-pluvial and pluvial-drought transitions occurring every year somewhere within the SGP (Fig. 4.10). One year that stands out as being extremely low for drought-pluvial

	Precipitation Whiplash Event	ENSO Phase
1993	Low drought-pluvial	Neutral
1995	Low drought-pluvial	Moderate La Niña
2000	High drought-pluvial	Weak La Niña
2004	High pluvial-drought	Weak El Niño
2010	High pluvial-drought	Strong La Niña
2011	Low pluvial-drought	Moderate La Niña
2016	High drought-pluvial	Weak La Niña
2018	Low pluvial-drought	Weak El Niño

Table 4.1: The years between 1981 and 2018 with the lowest and highest average percentage of grid points per month experiencing a precipitation whiplash event and associated phase of the El Niño Southern Oscillation (ENSO).

transitions is 1955 with just less than 2% of grid points having experienced a transition on average each month that year. Throughout the 1950's the SGP is known for having been in severe drought with low month-to-month variability in moisture conditions (Heim Jr, 2017).

The drought occurred from July 1949 to September 1957 and these years show a moderate percentage of grid points per month having experienced a transition. In the drought-pluvial case they are not the lowest nor highest years if the year 1955 is removed, ranging from approximately 3% to just over 5% of grid points. In the pluvial-drought case the years 1950 and 1951 are in the top 15 highest years to have experienced a transition with 6% and 6.8% respectively. The second wettest year on record behind 2015 is 1957 which is also the lowest year throughout the time period, with approximately 1.5% of grid points having experienced a pluvial-drought transition on average each month. There were unlikely to be pluvial-drought transitions on the S2S scale during 1957 when the daily precipitation totals were extremely high. All other years throughout the drought period show a moderate percentage of grid points ranging from 3.5-4.5%.

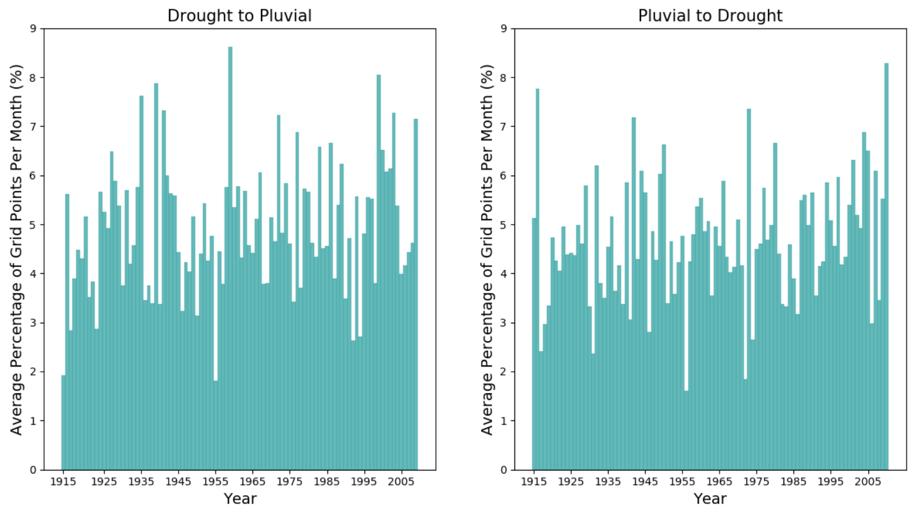


Figure 4.10: Annual distribution of precipitation whiplash events in the Livneh dataset (1915-2011) using the set calendar month method to calculate S2S precipitation.

To understand recent changes in precipitation whiplash events trends in magnitude in the PRISM dataset throughout time were calculated. Averaged across the entire SGP both drought-pluvial and pluvial-drought transitions show increasing trends with time of 0.05% and 0.21% of grid points on average in a typical month. Neither of these trends are significant at the 95% significance level. Maps of the trend in precipitation whiplash event frequency indicate significant increases across southeast Kansas and central Texas. Pluvial-drought transitions also show significant increases along the Gulf of Mexico, however this is a region of significant decreasing frequency in drought-pluvial transitions. Northwest Kansas is also an area in drought-pluvial transitions exhibiting a significant decreasing trend. The areas of Oklahoma and the Texas panhandle, which are important for our case study analysis in Chapter 5 show minimal areas of significance.

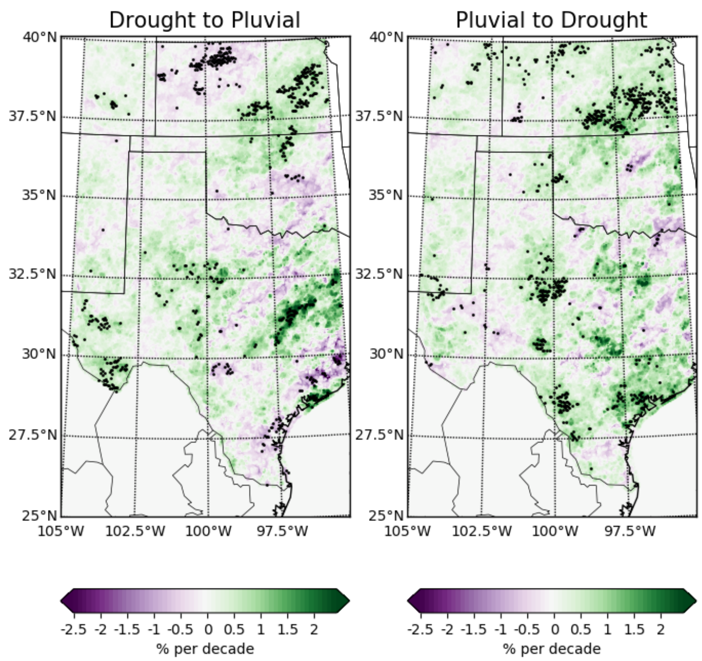


Figure 4.11: Spatial distribution of the trend with time at each individual grid point between 1981 and 2018. Regions of 95% significance are shown by black stippling calculated using the Monte-Carlo test.

Chapter 5

Goal 3: Terrestrial Conditions and Relevant Societal Impacts via Case Study Analysis

5.1 2017-2018 Precipitation Whiplash

The SGP has experienced a number of precipitation whiplash events over the past 40 years as shown in this study (Chapter 4). Most notable in recent years (Fig. 4.9) occurred at the end of 2017 where a 6 month period of drought was preceded by an anomalous wet period throughout the growing season that had severe societal impacts in the spring of 2018. Precipitation anomalies transitioned from 3 standard deviations above average to 1.7 standard deviations below average over a period of a couple days at the beginning of October (Fig. 5.1). To investigate how this event evolved in time and space leading to the large societal impacts that were observed in the spring of 2018, observations from surface precipitation data have been analysed.

The U.S. Drought Monitor analysis valid for 17 April 2018 shows large portions of western Oklahoma and the Texas panhandle in D3 Extreme Drought and smaller portions in D4 Exceptional Drought (Fig. 5.2). According to the U.S. Drought Monitor's report from that week, extreme and exceptional drought expanded to cover 8.2% of the contiguous United States which was up from 8.1% in the previous week (U.S. Drought Monitor, 2018). This week (April 12-18th) also corresponded with the most active week for fires across the SGP, with an estimated 67 fires burning 606,856 acres resulting in 2

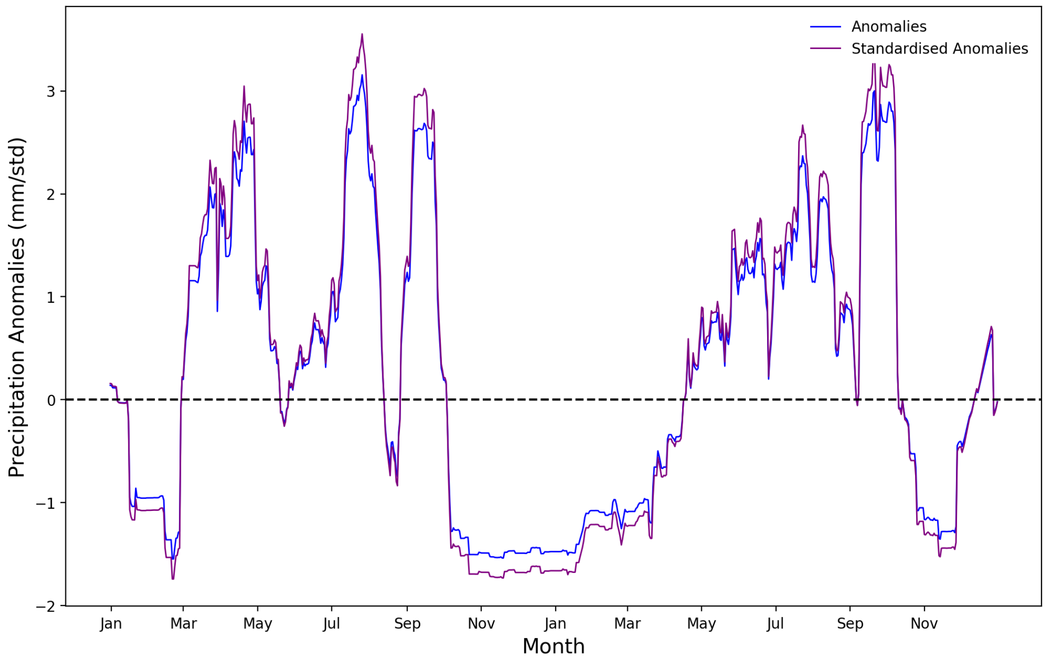


Figure 5.1: A 30 day running mean of precipitation anomalies in mm (blue) and standardised precipitation anomalies in std (purple) from January 1st 2017 to December 31st 2018. Same area as 5.4

fatalities; 81 structures destroyed; and 1,100 cattle deaths (Fuchs, Brian and Lindley, Todd, 2018). Using the Drought Monitor analysis the region of interest was defined to be 105-97°W and 34-39°N for the case study analysis. Precipitation anomalies and standardised anomalies were calculated based on the 1981-2010 climatological mean and standard deviation.

Using the definition developed in Chapter 3 the grid points in our region of interest which experienced a pluvial-drought transition in September of 2017 can be found (Fig. 5.3). Using 25% as the lower threshold for drought conditions during the month of September and 75% as the upper threshold for pluvial conditions during the month of October it can be seen that a large region west of 100°W experienced a transition. Most of this region encompasses southeast Colorado and northeast New Mexico. However, there are also regions of the Oklahoma and Texas panhandle which experienced a transition which matches with the areas that received less than 3 cm of cumulative precipitation between October 7th, 2017 and April 21st, 2018.

The map of cumulative precipitation totals between October 7th, 2017 and April 21st, 2018 indicates a clear boundary along the 98th meridian between high, greater than 15 cm, and extremely low, less than 9 cm, totals (Fig. 5.4). The lowest cumulative precipitation totals were observed across the Oklahoma and Texas panhandle with areas receiving less than 3 cm of rainfall during the 6 month period. This area that received the least amount of rainfall during the dry period matches almost perfectly with the areas in D4 Exceptional Drought on April 17th, 2018 (Fig. 5.2). However, there are regions that received similar precipitation totals that were not in Exceptional (D4) but in Extreme (D3) Drought on April 17th according to the U.S. Drought Monitor. This suggests that there were factors other than precipitation; such as high surface wind speed and high surface temperature that were contributing to the drought.

Despite the 6 month period of drought between October, 2017 and April, 2018 and the transition from pluvial to drought conditions, both 2017 and 2018 were above normal in terms of annual accumulated precipitation (Table. 5.1). During 2017, cumulative precipitation totals were above average throughout the growing season until precipitation totals fell below average and the region transitioned into drought conditions in October (Fig. 5.5). However during 2018, cumulative precipitation totals started below average, as the year began in drought conditions, until a heavy precipitation event on the S2S scale ($\tilde{1}00$ mm) in October led to a drought-pluvial transition and 2018 finished 10.3% above average.

Christian et al. (2015) analysed drought-pluvial dipole events on the annual scale, whereas in this study the 2017 precipitation whiplash event has been analysed on the S2S scale. If this pluvial-drought precipitation whiplash event was observed on the

	Annual Rainfall Total (mm)	Percentage Above Average
2017	702.7	22.5%
2018	632.6	10.3%

Table 5.1: 2017 and 2018 annual rainfall amounts.

annual scale, no precipitation whiplash would be picked up as both 2017 and 2018 were above average in terms of accumulated precipitation totals. However, this precipitation whiplash event, despite occurring on the S2S scale, had substantial impacts on the community. This case study analysis highlights the need to study these events both on an annual and S2S scale.

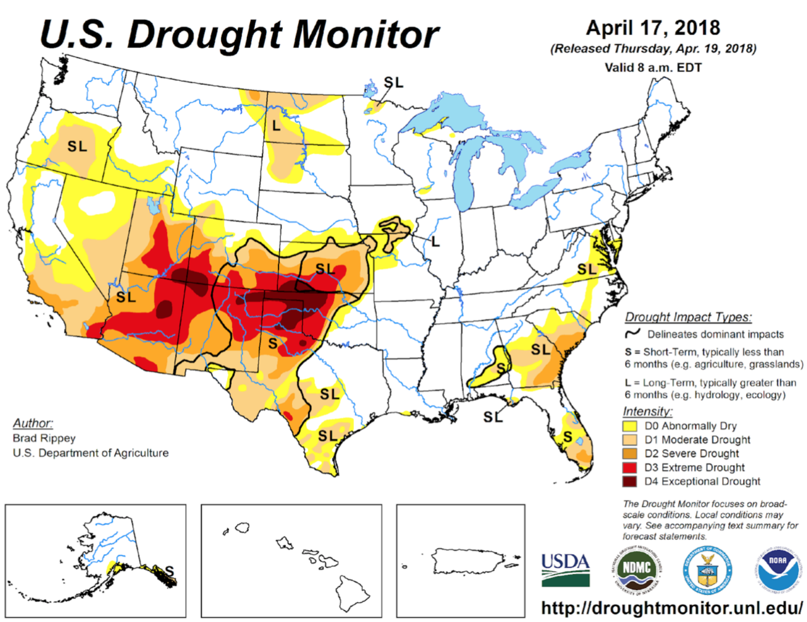


Figure 5.2: The U.S. Drought Monitor from April 17th 2018 which was released on April 19th 2018.

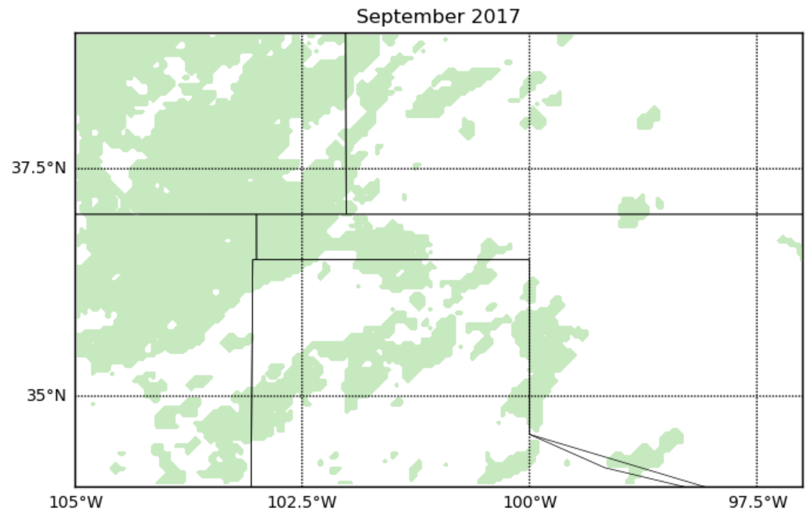


Figure 5.3: Regions experiencing a pluvial-drought transition in September 2017 utilising the definition in Chapter 3. Using this definition if a grid point shows a pluvial-drought transition, September 2017 was in pluvial conditions and October 2017 was in drought conditions at the 25% and 75% thresholds.

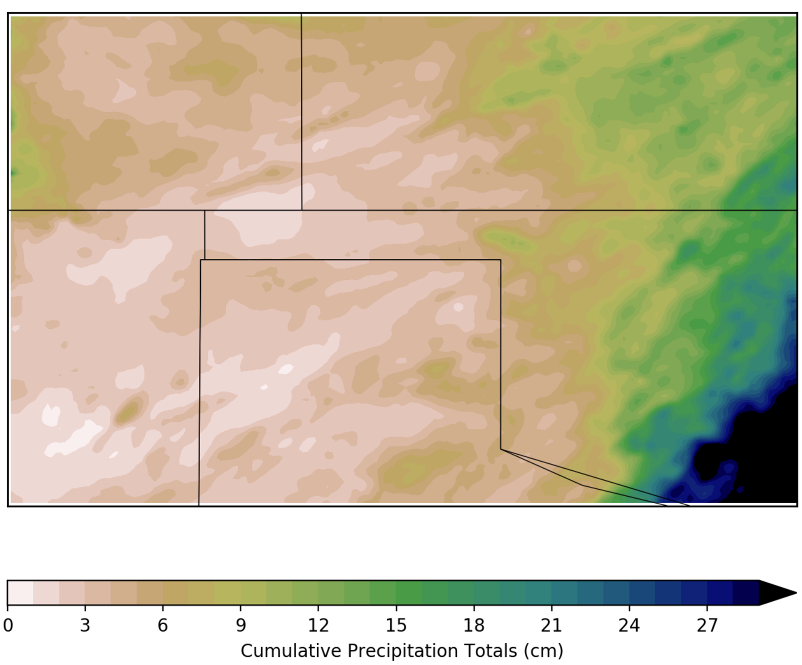


Figure 5.4: A spatial map of cumulative precipitation totals in cm from October 7th 2017 to April 21st 2018 for the region 105-97°W and 34-39°N.

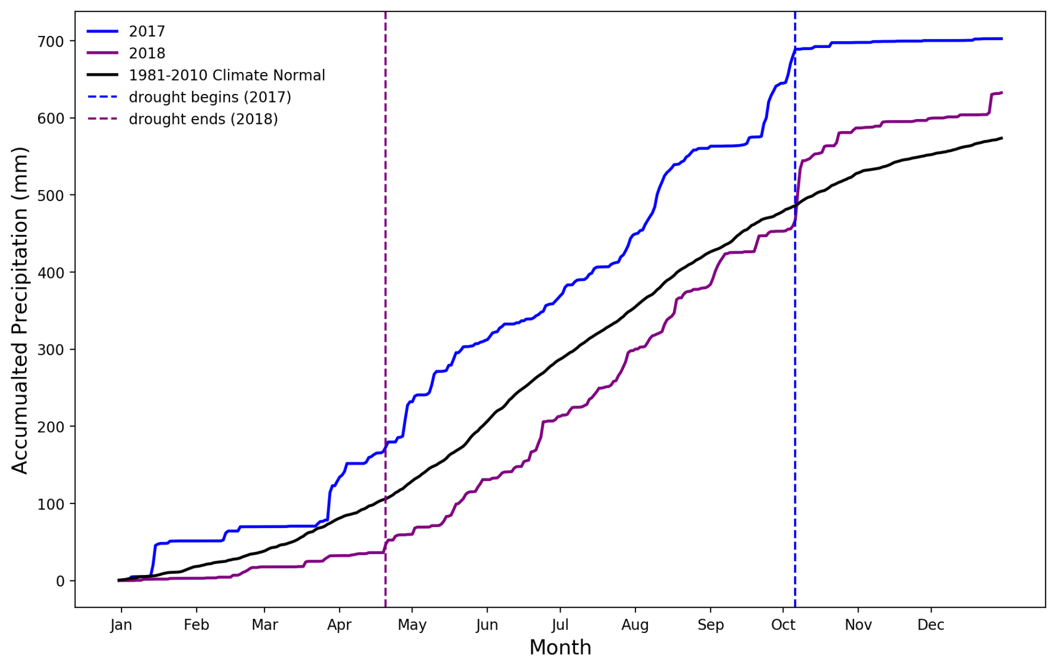


Figure 5.5: The cumulative precipitation totals for the years of 2017 (blue) and 2018 (purple) compared to the climatological (1981-2010) cumulative precipitation totals (black). The onset of the drought is shown by the blue dashed line and the ending of the drought is shown by the purple dashed line. Same area as 5.4

Chapter 6

Discussion

The SGP is characterised by a large east-west precipitation gradient with large annual precipitation values and the humid states of Missouri, Arkansas, and Louisiana to the east and small annual precipitation values and the desert southwest states of New Mexico and Colorado to the west. 30-year average annual precipitation values from 1981-2010 range from 20 inches and below at the far western boundary and over 40 inches at the eastern boundary declining uniformly as you move across the SGP (Fig. 1.1). This in turn leads to a large east-west contrast in surface water availability with many reservoirs in the east and few in the west creating different degrees of vulnerability to precipitation extremes, in particular drought. When analysing the 2017-2018 precipitation whiplash a sharp gradient in cumulative precipitation totals was observed along the 98th meridian. The U.S. Drought Monitor from April 17th, 2018 also showed a sharp boundary between D3 Extreme Drought in the western half of Oklahoma and no drought across the eastern half.

This climatological divide between the arid west and humid east has been discussed by many other studies where Seager et al. (2018) preferred the 100th meridian and Webb (1931) preferred the 98th meridian as the arid-humid divide. However, this study hypothesises that this arid-humid divide contributes to the increasing vulnerability of populations to precipitation whiplash events across the SGP as seen in the case study analysis. The east-west contrast in surface water availability enhances the development of drought across the west while helping to mitigate drought across the east. Especially following a precipitation whiplash event where the excess water in the west is likely to fall on hard top soil and become surface run-off whereas in the east the excess water is likely to fall more permeable ground becoming ground water storage or numerous reservoirs.

Over the past 50 years, significant pluvial years have followed a significant drought year approximately 25% of the time with the SGP when compared against the early part of the 20th century (Christian et al., 2015). Kangas and Brown (2007) also showed that drought and pluvial events occur most frequently within the central United States which this study's results corroborates as precipitation whiplash events at shorter timescales were found to occur every single year somewhere within the SGP. Ford et al. (2021) did not find the same thing to be occurring in the Midwest with many places not experiencing a transition every single year, and transitions were actually shown to be clustered in time. We hypothesise precipitation whiplash events are occurring more often in the SGP due to the climatological conditions of this fluctuating east-west boundary. As the SGP lies right on this boundary compared to the Midwest which has a more spatially consistent precipitation gradient the SGP is more prone and vulnerable to these rapid transitions in precipitation extremes making them more likely to occur at least once a year.

Annual precipitation across the United States has increased by approximately 5% since the 1900s with important regional and seasonal differences (Walsh et al., 2014). Across the SGP annual precipitation has increased by 8% relative to the 1901-1960 average with the largest increases observed during the fall season. Analysis by Bajgain et al. (2020) also revealed that the fall window in precipitation was critical for controlling the gross primary productivity of managed pastures across the SGP. In addition, both our study and the study conducted by Christian et al. (2015) demonstrate that the climatological period of autumn through early winter is critical for precipitation whiplash events; with October appearing 70% of the time as a pluvial month in Christian et al. (2015)'s study and September occurring most often as a drought and pluvial month in ours. We hypothesise that the with precipitation increasing during the fall season but not during the winter season; pluvial events are more likely to occur during the fall in addition to there being little chance of ending an ongoing drought event with a precipitation whiplash event during the winter months due to a lack of sufficient precipitation (Karl et al., 1987).

Changes in precipitation frequency, magnitude, duration and whiplash events will directly impact the infrastructure across the SGP and place more stress on water resources. Texas, Oklahoma and Kansas alone account for 25% of all U.S. energy production and the vast nature of the region's infrastructure makes maintenance difficult (U. S. Energy Information Administration, 2018). Infrastructure across the SGP is ranked one of the worst in the country and is designed to withstand historical climatic extremes (ASCE, 2018, 2021a,b). Therefore, as we are seeing a significant increasing trend across many regions of the SGP in these rapid transitions between precipitation extremes, we hypothesise that unless significant improvement is made to the SGP infrastructure the impacts that we see from these events are likely to get more adverse and more costly.

Chapter 7

Summary and Conclusions

Precipitation whiplash events across the SGP were studied between 1981 and 2018 with the overarching goal to examine the characteristics and climatology of these events on the S2S scale. This study had 3 individual goals to achieve this:

Goal 1: Develop a definition and create a database of precipitation whiplashes on the S2S scale.

Precipitation whiplash events were defined using a percentile method on the S2S scale where the definition was shown to not be sensitive to the choice of lower and upper threshold to define extreme events. By applying a 30-day rolling sum to calculate precipitation totals instead of using the set calendar months, almost double the number of precipitation whiplash events are observed across the SGP. This suggests using set calendar months is underestimating the magnitude of the extreme or missing events entirely. However, the analysis completed in Chapter 4 and the concluding results showed consistency when either the PRISM or Livneh dataset were used.

Goal 2: Analyse trends, spatial and temporal patterns and changes within the data across varying timescales

All years between 1981 and 2018 experienced a precipitation whiplash event somewhere within the SGP with the Fall season being the time of year when these events are most likely to occur. Highlighting the importance of these events as well as this secondary peak in annual precipitation in driving precipitation whiplash events across this region. Significantly increasing trends in precipitation whiplash frequency were also found across large regions, most notably southeastern Kansas and central Texas. La Niña events possibly stand out as a large scale feature that may play a role in a greater spatial extent of precipitation whiplash events across the SGP, although further investigation is required to verify this.

Goal 3: Examine observed trends and patterns with a focus on terrestrial conditions and relevant societal impacts (i.e. wildfires; infrastructure; health) via the analysis of a case study

The case study analysis highlighted the importance of understanding precipitation whiplash events on the S2S scale. Both 2017 and 2018 were above average in terms of annual accumulated rainfall totals, therefore an interannual analysis of these years would not find a precipitation whiplash event. However, a precipitation whiplash event occurred on the S2S scale which had severe societal impacts across the Oklahoma and Texas panhandle. The transition from pluvial-drought conditions also occurred during the Fall period again highlighting the importance of this time period.

Limitations and Future Work

It is important to note the study limitations, including the consideration of independent events for the 30-day rolling sum precipitation totals. The current methods leads to precipitation events possibly being biased late, therefore a better method would be to chose the strongest transition in the series however the current definition does not allow for this. Therefore, future investigation would be to expand this definition to include the intensity and duration of precipitation whiplash events across the SGP. In addition, due to the authors lack of knowledge in the broader areas of human health, infrastructure and wildfires the case study was not able to delve into those impacts as deeply. Therefore, future work includes teaming up with experts in those fields to continue this analysis into the societal impacts of this event.

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