Precipitation Swings and Whiplash Events: South Bend, IN (2010-2019)

An Honors Thesis (HONR 499)

by

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Abstract

This research paper focuses on extreme wet periods and dry periods that follow closely after one another. The primary focus of this paper is to determine the number and severity of whiplash precipitation events that occurred in South Bend, Indiana from the summers (including the shoulder months of May and September) of 2010 through 2019, or the extent of the decade. Precipitation data from this period of time is compared to that of the previous 30 years (1981-2010) to see how much precipitation has deviated from the 30-year averages. The reason for conducting this study relates to the importance of precipitation on the overall well-being of the city itself and the surrounding areas, as precipitation variations will be exacerbated by climate change. Most of the precipitation that falls in South Bend, IN falls during the summer months. The agriculture industry, for example, is a major presence in the areas surrounding the city of South Bend and data from this research could be vital to accurately estimating the impact climate change will have on the city and the region of Southwest Michigan and Northern Indiana in general.

Acknowledgements

I sincerely want to thank Dr. Petra Zimmermann for advising me through this project amidst difficult circumstances this semester. Her willingness to advise me through this project is greatly appreciated and represents furthermore the great desire and care she has to see her students succeed, and I am greatly blessed to have had her assistance in overseeing this project.

I would also like to thank my family and friends, the countless many that I have, that helped encourage me throughout these last four years, often in circumstances and situations none of us could have ever imagined. Their encouragement is the reason why I am who I am today, a man who is ready to bring change to the world, however big or small that may be.

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Process Analysis Statement

My inspiration for this project came from a combination of working with Samaritan's Purse in Houston, TX during the fall and spring of 2017 and 2018 along with some brainstorming. As recent as four years ago, I considered myself a climate change skeptic. Hurricane Harvey changed my entire view on the climate change crisis that our planet faces. All of the homeowners that I met around the Houston area were able to name another major flooding event that impacted them like how Hurricane Harvey impacted them. Not only where they able to name another flooding event like Hurricane Harvey, they were able to describe these events thoroughly and all of these events occurred since the start of the millennium. Hurricane Harvey is my biggest inspiration for this project because it completely changed my view on the climate change crisis through the personal testimonies of those affected by these changing weather patterns.

This past decade (2010-2019) was particularly notable in my home region of northern Indiana for extreme shifts in precipitation. Events like the severe drought of 2012 and the May 2019 flooding have raised the question of whether current land managing practices are sustainable, regarding agricultural practices and urban land practices which are especially pertinent to South Bend. South Bend is the closest "big" city to my home, thus why I chose the city for this project. Despite how fast the planet is warming, changes in climate still take years to be noticeable. This is why I decided to look at precipitation records over the whole decade versus one or two years. Precipitation records for every day between May 2010 and September 2019 were obtained from the National Center for Environmental Information (NCEI). More details regarding the thought process for analyzing this data are provided in the Data and Methods section.

The process of analyzing the information involved looking at the data from both the monthly level and the daily level. In order to successfully answer the questions presented in this thesis, I first had to come up with definitions of what a whiplash precipitation event was at both the monthly level and daily level. After conducting initial research into this phenomenon, documented in the Literature Review, I found that there was no quantifiable definition for a whiplash precipitation event. Most definitions of whiplash precipitation events were vague, defining it as a transition from extremely wet to extremely dry conditions and vice versa. The problem of how to define such an event was the biggest challenge in the entire process of completing this study.

The solution to the problem of definitions came through analyzing the “wet” streaks and “dry” streaks at the daily level by looking at the data to see if anything was particularly noticeable. All data for this project was obtained through the National Center of Environmental Information (NCEI) and monthly precipitation totals were calculated in excel using the data obtained. Doing so allowed me to come up with ways to define both types of streaks quantitatively. I was able to define a dry streak as a period of at least 10 days or more with only a trace of precipitation or no precipitation at all. Only one day with precipitation above a tenth of an inch was allowed to accommodate for potential outliers. Wet streaks were harder to define considering 1 event may produce enough rain to inflate the overall monthly total, as in the case of August 7, 2016. The juxtaposition of those wet and dry streaks was how I chose to define a whiplash precipitation event.

Overall, the objectives set out by this project were met amidst challenging circumstances with the 2020 coronavirus outbreak. The most important takeaway was that climate change is affecting my home region of Northern Indiana just as much as it is affecting other areas of the country like California and the Houston, TX area, despite the fact that the media coverage has been on a much smaller scale compared to other areas of the country. Climate change is a phenomenon that disproportionally affects the poor to a greater degree and those who claim to be advocates for the less fortunate of our society must begin to take climate change seriously, if they have not already.

Introduction

As the planet continues to move closer to a 1.5°C warmer world, the effects of climate change will continue to increase in America's heartland, including the city of South Bend, IN. Some of the effects could range from more extreme cold snaps, to more extreme heat waves over the summer. One of the most concerning impacts of climate change in the Midwest is variations in precipitation and the increased erratic nature of it. For example, May 2018 through April 2019 was the wettest period on record in the United States. For the first time ever, less than half of America's fields dedicated to corn planting had actually been planted by May 19. (Rippey, 2019)

Meanwhile, seven years earlier, the worst drought in half a century devastated the corn crop across all of Northern Indiana. A combination of record breaking warmth in the spring months and below normal snowmelt led to dry topsoil conditions before summer even started. The months of April and May had precipitation totals of 2.22 and 2.14 inches in South Bend, about 40% below normal for those months. This led to the worst crop conditions since the summer of 1988. As a result, many farmers across the area were forced to prematurely harvest or cut their corn crops entirely resulting in major financial losses. (Obergfell, n.d.)

However, the summer of 2012 would yield the wettest July of the 10-year period (2010-2019) with the final precipitation total reaching 6.48 inches in South Bend. This was 2.48 inches above average and immediately followed the second driest month of that year, June, which had a final precipitation total of only 1.54 inches, 2.25 inches below normal. However, despite the significant rains that fell in July, the damage had already been done by the extreme dryness that occurred in the spring and early summer. Matters would be worse as September and November saw precipitation totals that were 1.5 and 3.01 inches below normal.

The extreme drought of 2012 and the extreme precipitation totals that fell between May 2018 and April 2019 demonstrate the severity of which significant change in precipitation patterns can have on the area. This literature review provides a better understanding of the terminology that I will be using in this paper, including but not limited to the definitions of whiplash precipitation events, climate change, drought, flood, and climate.

Literature Review

i. South Bend's Climate

As Mark Twain famously said, climate is what you expect and weather is what you get. More specifically, climate can be defined as a statistical description of the weather over a period of time, usually a few decades. Temperature, along with precipitation and the distribution of precipitation during the course of the year are all components that factor into the climate of any given area. While climate can tell us what normal weather is for a specific time of the year, it cannot tell us what the actual weather is going to be for any given day. (Dessler, 2016, p. 1) The Koppen Climate Classification (a common climate classification system) for South Bend is "Dfa" which means it has a hot summer, humid continental climate. The warmest month out of the year is July with an average temperature of 73° F and the coldest month is January with an average temperature of 24° F. The average precipitation total in South Bend is 38 inches with a mostly even distribution. The exception is the summer months, or the growing season, tends to have slightly more precipitation. Due to its proximity to Lake Michigan, much of South Bend's precipitation in the winter falls as snow, with an average winter yielding 66 inches of snowfall in the city. Of this average, 20.6 inches falls in January. (South Bend, n.d.)

ii. Climate Change

According to the American Meteorological Society, climate change is “any systematic change in the long-term statistics of climate elements (such as temperature, pressure, or winds) sustained over several decades or longer”. (Dessler, 2016, pp. 4-5). There is increasing concern that our climate a century from now will be drastically warmer than it is even today. By the end of the century, places, such as Alaska, could be as much as 2°C warmer. For reference, we are currently 1°C warmer than before the industrial revolution and the Intergovernmental Panel on Climate Change (IPCC) has set a goal to keep warming under 1.5°C. In other words, drastic action needs to be taken on a global scale in order to curb climate change and limit some of its effects on the weather patterns. (Dessler, 2016, pp. 4-5).

The biggest catalyst for the increase in whiplash events is climate change, which is caused by anthropogenic forces such as fossil fuels use. A whiplash event can simply be defined as a sudden transition from extremely wet to extremely dry conditions or vice versa. One of the impacts that climate change is having on farming in America relates to the use of nitrates in fertilizing fields. During droughts, those nitrates will stay in the soil as compared to normal conditions where the nitrates would be removed from the soil as the crops grew. When heavy rains do return after an extremely dry period, the nitrates that otherwise would have been removed from the soil due to plant growth instead flow into rivers that feed into the Gulf of Mexico and other big bodies of water. The result is algae blooms that choke off oxygen supplies to fish and contaminate the water supply of cities. (Robbins, 2019)

Temperature swings can also affect the rate of evapotranspiration in these agricultural areas of our country. Evapotranspiration involves both the evaporation of moisture originating from plants that are transpiring and from the soil itself. The spring of 2012 was particularly bad for agriculture as record temperatures, beginning in March, led to increased levels of evapotranspiration (Obergfell, n.d.). One of the affects this may have in the spring months is the development of false springs, where vegetation emerges too early in the year as a result of abnormally warm temperatures and is subsequently destroyed when temperatures return to normal or below normal. The development of the false spring in 2012 led to the destruction of millions of bushels of apples in Michigan amounting to losses of half of billion dollars. (Harvey, 2019)

iii. Drought

Between 2006 and 2015, the average temperature of the hottest day of the year anywhere in the world was 36.5°C. However, climate models predict that by the end of the century, 39% of the days between 2091 to 2100 will be hotter than 36°C. (Dessler, 2016, p. 152). Higher temperatures could pose a problem for future droughts in the sense that as temperatures increase, the rate of evapotranspiration also increases (Obergfell, n.d.). In a talk at the 2018 American Meteorological Society's conference, Elinor Martin presented even more troubling statistics. In the future, the duration, intensity, and frequency of both moderate and severe droughts are expected to increase. In areas where the overall precipitation trend is toward wetter than normal conditions, such as Indiana, there will be longer lasting and more intense droughts. (Martin 2018). Another concern with the increasing frequency of droughts is the increasing frequency of what is known as a "flash drought" where drought conditions rapidly occur over a given area. The 2012 Midwest drought between March and August was an example of this phenomenon. In May 2012, only 30% of the continental United States experienced abnormally dry conditions. By August, that number had doubled to 60%. The United States is not the only region that could be affected by these flash droughts. In 2018, a flash drought in eastern Australia led to the lowest level of livestock in a century. The landscape was quickly de-vegetated and the overall impact on agriculture was significant. (Flash Droughts, 2020).

iv. Flood

The other aspect of increasing temperatures worldwide is that as the air temperature rises, it is able to hold more moisture. This fact is also demonstrated in the research conducted by Elinor Martin, in "Future Projections of Global Drought and Pluvial Event Characteristics" (2018). Her research concludes that in areas that are experiencing a drying trend overall; pluvial (rainfall) events will be wetter, longer lasting, and more frequent. (Martin, 2018). This could be problematic in South Bend for a couple of reasons. Heavier downpours on already saturated soil will lead to increased runoff into rivers and streams. That means events like the February 2018 flooding will likely happen more often. As these extreme rainfall events occur more often, this will lead to a decrease in the amount of freshwater for use by humans and ecosystems. If the variability of important rainfall increases, the harmful effects on agriculture will increase. Increased intensity of rainfall will also lead to a rise in soil loss, another harmful impact to agriculture. (Dessler, 2016, pp. 152).

v. Whiplash Precipitation Event

The drought of 2012-2016 and the flooding that occurred during the winter of 2016-2017 in California present the perfect case study in terms of analyzing the negative impacts caused by such extreme shifts in precipitation. Generally, a whiplash precipitation event can be defined as a sudden shift from dry to wet or wet to dry weather conditions. Definitions may vary depending on sources. (Swain et al., p. 1) For the sake of this study, I will use a more specific definition in order to eliminate mild events and focus more on events that had pronounced impacts on South Bend and the surrounding areas. In a study posted to the Nature Climate Change in 2018 (Swain et al., p. 2), a team of scientists from the University of California modeled the likelihood of future whiplash events in California. California, like Indiana, has substantial importance to the country in terms of agriculture. Many produce items are almost exclusively grown in California's agriculture-rich Central Valley. In that study, scientists found that based on their models, episodes of heavy, seasonal rainfall could increase by 100-200%

across all of California. Strikingly, only modest increases in the total annual precipitation are expected. (Swain et al., p. 2) In other words, the data gained from this study only amplifies Elinor Martin's point that it is not necessarily the total annual precipitation that is going to increase or decrease for a given area but it is that variability of precipitation will increase, the reason for conducting this study for South Bend. (Martin, 2018)

vi. Adaptation

As temperature, precipitation, sea levels, and other components of the climate continue to change, coupled with the very high amount of funding needed to completely move away from fossil fuels, much of the strategy to combat climate change in the future revolves around adapting to the changes that do occur. Adaptation simply means responding to the negative impacts of climate change. There are a few advantages to adopting a strategy of adaptation. One advantage of adapting to climate change versus mitigating it is that there will be more time to eliminate uncertainty suggested by climate models. As evident in Elinor Martin's research (2018), not all of the climate models agreed on changes in drought or pluvial intensity in some areas of the world. Another advantage is that merely adapting versus mitigating climate change gives western countries, along with China and India, more time to make the necessary changes that will be needed to combat climate change. This will allow money to be moved towards this effort over a significant length of time versus all at once, a move that could save many nations from going bankrupt. (Dessler, 2016, pp. 178-179)

vii. Mitigation

Mitigation refers to reductions in emissions of carbon dioxide and other greenhouse gases, thus avoiding the impacts of climate change. It is universally agreed that warming above 2°C would be disastrous for the planet. However, in order to keep warming below that mark, global emissions of greenhouse gases would need to drop by 50-80% below today's emission values by 2050. A couple of strategies could make mitigation more of a possibility. The first strategy would be to get governments to limit the size of their populations, thus decreasing the amount of people on the planet altogether. This strategy would alleviate some of the demands on key industries like the beef industry, the biggest culprit for deforestation in the Amazon Rainforest. Another strategy would involve merely reducing the world's consumption of goods and services. This campaign arguably is already underway with the rise in popularity of plant-based or vegan diets. Decreasing the amount of energy consumed can already be done in everyday life. Merely limiting the duration of showers, turning off the lights after leaving a room, or not letting the faucet run while brushing your teeth are all practical ways to decrease energy usage and thus contribute to a global reduction in energy consumption. (Dessler, 2016, p. 183). Mitigation will have to occur in order to curb global warming below 1.5°C and prevent erratic swings in precipitation from completely decimating the agriculture industry around South Bend, IN.

Data and Methods

i. Data

A. Source/Level of Data

All of the numerical data used in this project is from the National Oceanic and Atmospheric Administration (NOAA). Specifically, the National Center for Environmental Information is where the precipitation records for South Bend, IN were obtained. The dataset used for this project encompasses ten years worth of all daily and monthly precipitation data from May to September of each year, starting from 2010 and ending with 2019. The reason why May and September were added is because these two months are also part of the growing season. Sometimes, precipitation streaks that are evident in June started in May while some streaks that started in August continue into September. Both scenarios can inflict serious consequences in the Northern Indiana/Southwest Lower Michigan region. In some cases, precipitation streaks started in the middle of one month and continued into the beginning of the next month, causing monthly precipitation totals for both months to be close to average despite the presence of a significant whiplash precipitation event. For these reasons, the precipitation data in this project is analyzed at both a monthly and daily level.

B. Climate Normals

In a typical year, most of the precipitation that falls in South Bend falls during the growing season. During the summer months, over 11 inches of precipitation falls in the area compared to 10 inches in the fall and only 6.85 inches during the winter. July is the wettest month of the year with an average precipitation total of 4 inches. From May to September, each month averages over 3.5 inches of precipitation. This makes sense due to the warmer temperatures that occur during the late spring, summer, and early fall months. As temperatures rise, the air can hold more moisture, which means when storm systems arrive during these months, more precipitation falls from the individual storms. One of the complications that may be arising in South Bend, along with other Midwest cities, is that longer durations of extremely warm temperatures could cause heavier rainfall spurts and increased evapotranspiration could lead to more flash droughts in the future. Unfortunately, South Bend’s precipitation data from 2010-2019 appears to be a harbinger of such fears.

ii. Methodology and Results (Monthly Level)

A. Monthly Averages 2010-2019

At the monthly level, data was broken down in two different methods. The first method of analyzing monthly data involved breaking down precipitation totals by year. Precipitation graphs for each year were created which showed how each month of this study compared to its 10-year average (2010-2019) and its 30-year average (1981-2010). The second method involved precipitation graphs of each month, to show how many Mays/Junes/etc. (Figs. 2 through 6) had precipitation above or below the 10-year average and the 30-year average for that particular month. The 10-year average for each month needed to be calculated in order to compare how this decade was similar or different to the previous 30 years.

An alarming trend that might be a sign of the changes to come was that May was, on average, the wettest month during the 10-year period with an average of 5.31 inches (Fig. 2). This was roughly 1.5 inches higher than the 30-year average. This total is also 1.3 inches higher than July's 30-year average of 4 inches, the wettest month of the year during the 30 years. The next wettest month during the 10-year period was June, averaging 4.42 inches of precipitation. This trend suggests that wet springs could be regular occurrences in the future as a result of climate change's impacts, resulting in warmer springs and air that is able to hold more moisture. July's 10-year precipitation average was slightly lower than the 30-year average coming in at 0.35 inches shorter with 3.65 inches (Fig. 4). August was near normal in terms of its 10-year average precipitation total with an average of 3.82 inches (Fig. 5). However, one caveat to this average is that August of 2016 featured an abnormally high precipitation total at 12.81 inches as a result of one event that dumped over 7 inches of rain in South Bend over the course of just a single day. September was the driest month with a 10-year precipitation average of 3.4 inches (Fig. 6). Considering the possibility of August being an outlier due to the exceptionally rainy month of August of 2016, the summer months, from July onward, were drier than normal.

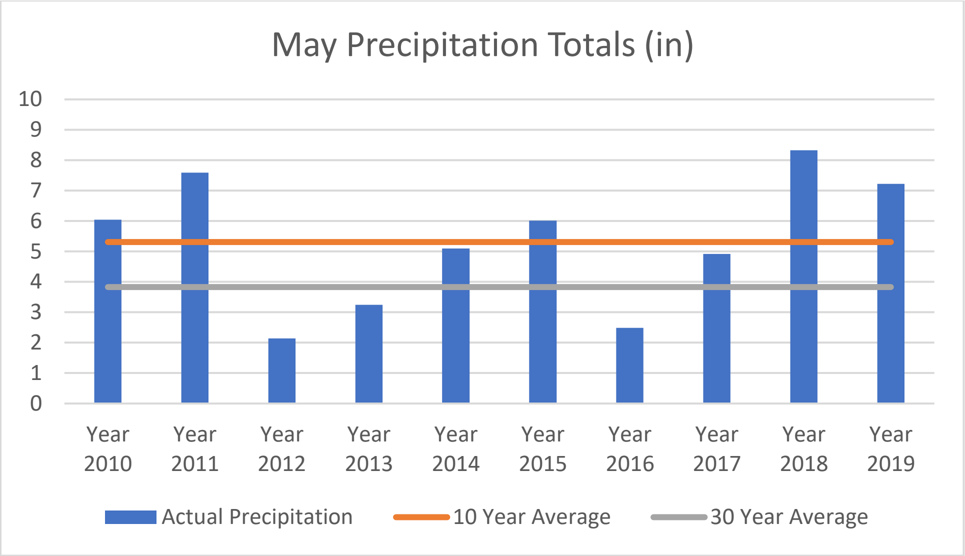

Fig. 2. May Precipitation totals and averages

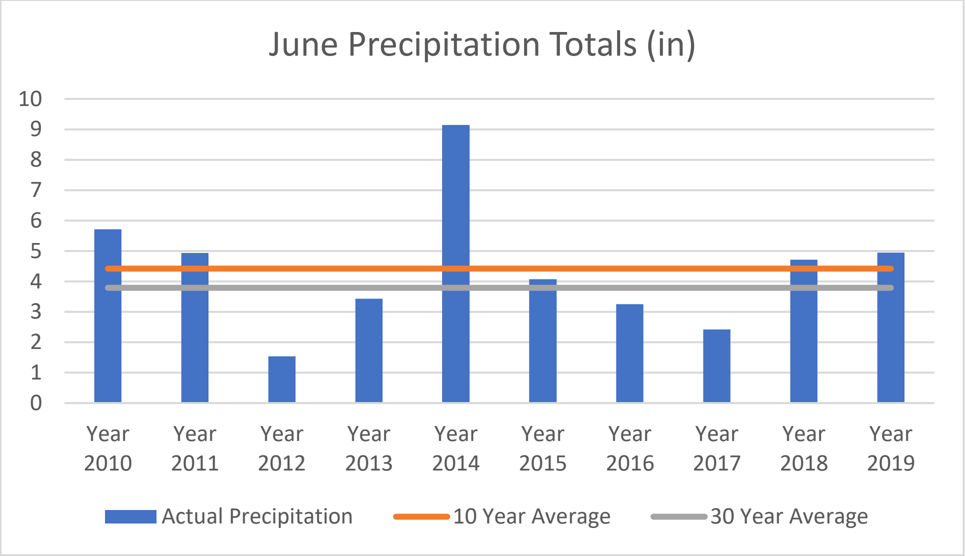

Fig. 3. June Precipitation totals and averages

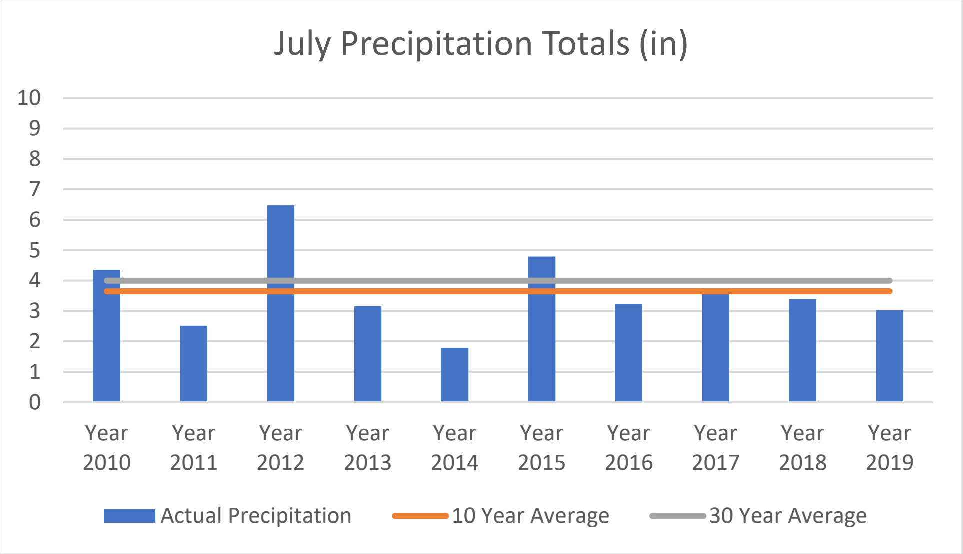

Fig. 4. July Precipitation totals and averages

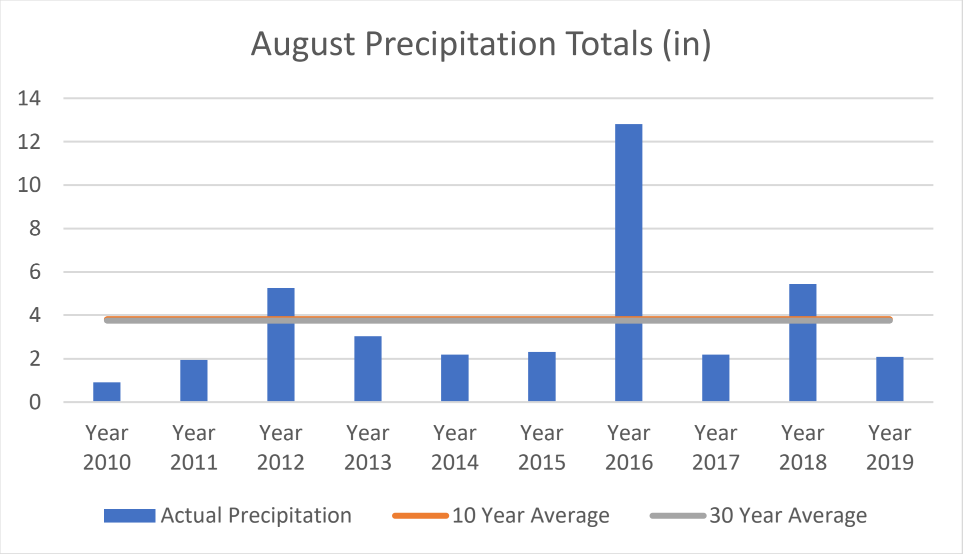

Fig. 5. August precipitation totals and averages

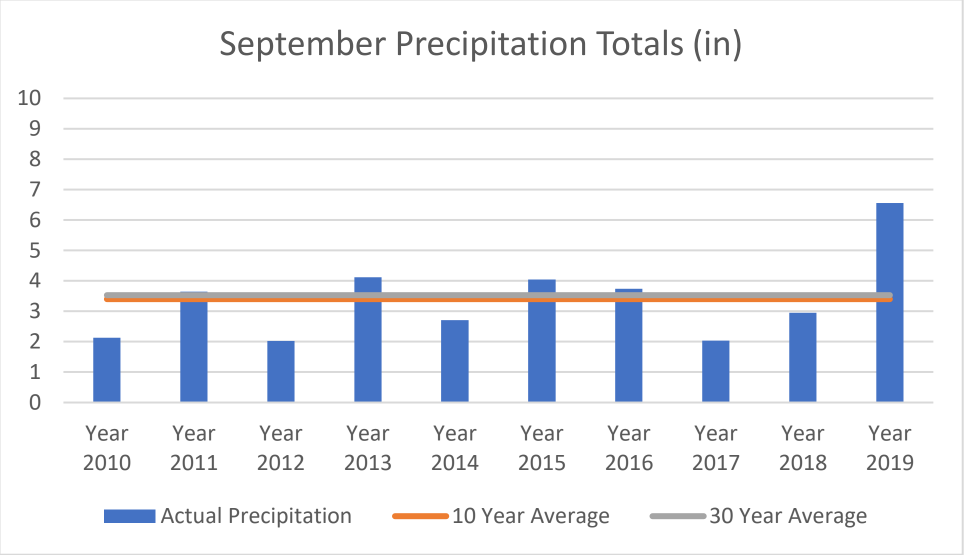

Fig. 6. September precipitation totals and averages

iii. Methodology and Results (Daily Levels)

A. Notable Wet Streaks

The process for selecting wet streaks, where the weather pattern involves repeated rainy episodes, involved examining consecutive days of precipitation versus absolute amounts of rainfall. The reasoning for looking at daily data in this manner is to exclude potential outliers where dry periods preceded and succeeded one or two days of very heavy rainfall. These outliers are not the main focus of this study with respect to the daily level.

The most notable wet streak to occur during the 10-year period (2010-2019) took place from May to early June of 2019. It was not the amount of rain that fell during this wet streak but rather the number of days in a row in which precipitation fell. From May 16 to May 30, in particular, 14 out of the 15 days had measurable precipitation with a 10 day streak of precipitation occurring from May 21 to May 30. The second most notable streak occurred in August of 2016. From August 12 to August 30, over

10 inches of rain fell with most of this occurring on August 15 (7.69 inches). While there were more dry days interspersed between the wet days, the sheer amount of precipitation that fell during this month caused August of 2016 to be the wettest month of the entire 10-year sequence. In many cases, even though the wet streaks and dry streaks were not always extreme, they often followed after each other, indicative of a whiplash precipitation event.

B. Notable Dry Streaks

The process for selecting dry streaks involved looking for periods of days where precipitation either did not occur or it was only a trace. Each dry streak was “permitted” 1-2 days of precipitation above 0.1 inch, as long as it was not part of a general system (e.g. the summer pop-up shower is an artifact of local heating, not larger atmospheric modes). Allowing one or two days of precipitation above 0.10 inches let me eliminate outliers, since they did not reflect the overall weather pattern that caused the dry conditions to ensue in the first place. During the 10-year period, there were 3 distinct dry periods worth mentioning. The first occurred from August 5, 2010 to September 1, 2010. August of 2010 was the driest month during the entire 10-year period with only 0.92 inches of precipitation. During that timeframe there were 22 days where no precipitation occurred and only one day where precipitation was above 0.10 inches (0.45 inches on August 21). The next two notable dry periods to occur were May 8 to May 30, 2012 and July 19 to August 13, 2015.

C. Systematic or Random Occurrence

One of the main objectives of this study is to determine whether these changes that occurred in precipitation during the last decade reflected a trend. This is why the monthly data was broken down using the two methods stated earlier. This question can be answered by looking at the precipitation graphs for each specific month to determine whether or not these increases or decreases in precipitation were random or systematic. Having the 30-year and 10-year averages on these graphs also helps to answer these questions. Based on the data, I have determined that these changes were systematic in nature. My reasoning for that statement will be addressed later in this thesis.

Discussion

This section focuses on two specific instances of precipitation whiplash that occurred in June/July 2012 and June/July 2014 (other generalized discussion appears under the Conclusions). July 2012 featured a transition from extremely dry conditions to extremely wet conditions that led to the wettest July of the 10 year period (2010-2019). Conversely, June 2014 was the wettest June of the decade with 9.14 inches of precipitation which was immediately followed by the driest July of the decade with only 1.79 inches of precipitation. Both of these events were classic examples of whiplash precipitation episodes on both the monthly level as well as the daily level.

In Northern Indiana and Southern Michigan, the spring and summer of 2012 were notoriously bad for agriculture. Record temperatures in March increased evapotranspiration rates on the heels of what many would consider to have been a mild winter. Interestingly enough, the winter of 2011-2012 featured a moderately strong La Nina with peak temperature departures approaching 1.1°C below normal. (Climate Prediction Center, 2001). La Nina conditions typically bring stormier winters to the Ohio Valley and colder conditions across much of the northern half of the United States. (What is a La Nina?, n.d). Record temperatures in March 2012 were followed by abnormally dry conditions in May and June which led to the development of extreme-to-exceptional drought conditions across much of Northern Indiana and Southern Lower Michigan. (Obergfall, n.d). This dry streak would continue into the first 13 days of July which saw no recorded precipitation. Yet over the next seven days that would follow July 13, over 4 inches of rain fell. Another 2 inches of rain would fall before the end of the month but wet pattern didn't stop. Between August 1, 2012 and August 16, 2012, another 3.65 inches of rain would fall, accounting for over 65% of the precipitation that would fall during August of 2012 (5.26 inches).

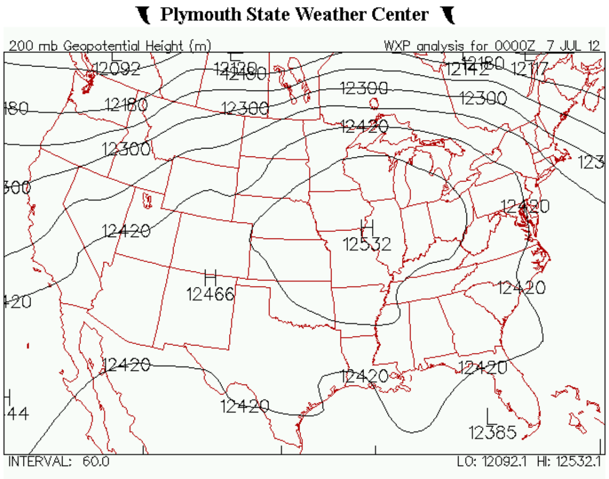

Fig. 7. 200 mb. Geopotential height over North America on July 7, 2012 (Source: Plymouth State)

Part of the reason why spring and early summer of 2012 were so dry is because of the orientation of the jet stream during these months. The particular image shown in Figure 7 is of the geopotential height on July 7, 2012. A classic summer weather pattern is unfolding in this image with a strong high pressure system centered right over the Mississippi River Valley. The jet stream orientation is only part of the reason for the extreme drought conditions of 2012 because this weather pattern, also known as a "Ring of Fire" setup, is common during the summer months. Not all "Ring of Fire" high pressure systems will be setup in the exact same way as in Figure 7, but generally, during the summer months, a strong high pressure system will emerge somewhere over the southern United States and thunderstorm complexes, which were often in the form of derechos during the summer of 2012, will move around the periphery of the high pressure system. (Atmospheric Blocking, n.d). The early northward migration of the jet stream during the spring 2012 was a contributing factor to the record warm temperatures that ensued and resultant increased evapotranspiration. Some locations in Indiana would end up breaking their all-time record high during this warm, dry stretch of weather, like Muncie, IN did on June 28, 2012. (Indiana, n.d).

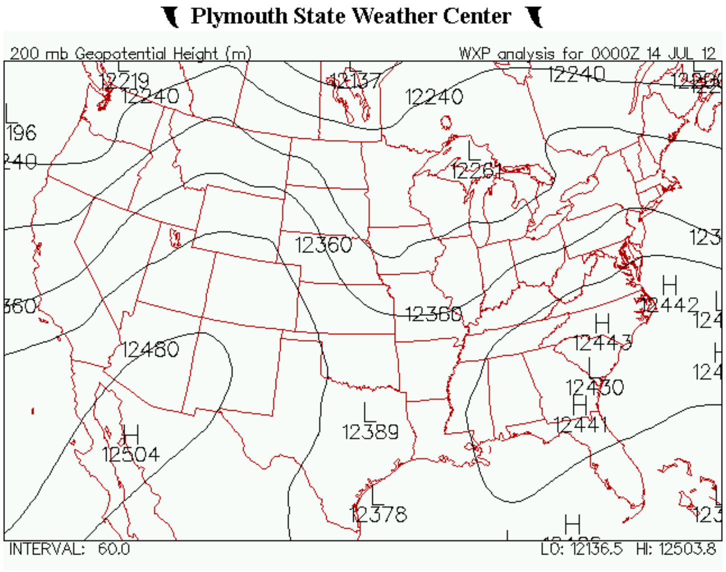

Fig. 8. 200 mb. Geopotential height over North America on July 14, 2012 (Source: Plymouth State)

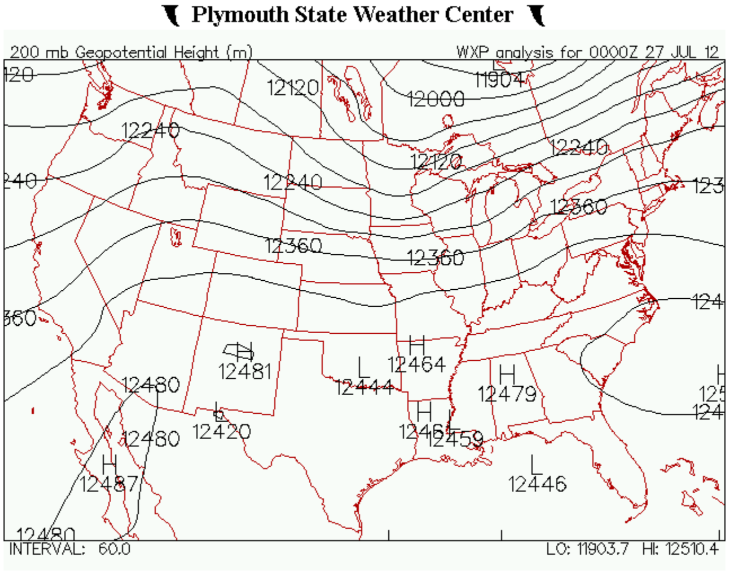

Fig. 9. 200 mb Geopotential height over North America on July 27, 2012 (Source: Plymouth State)

By the middle and end of the month, the “Ring of Fire” weather pattern begins to collapse and starts to become replaced by more of a zonal flow pattern by July 27 (Figure 9), as evidenced by the clustering of the contours in the northern half of the United States. The collapse of the high pressure system originally shown not only provided relief to a large section of the control in the form of lower temperatures, but it also provided more chances for thunderstorms. Lower temperatures meant that the rate of evapotranspiration would be lower and more thunderstorm chances meant more chances for soil moisture to be replenished. This sudden change in precipitation between June and July met the definition of a whiplash precipitation event.

For corn and soybean crops throughout the region, however, this relief was too little, too late. The damage caused by the drought conditions earlier that spring and summer were too much for many crops across the region. Estimates from the National Centers for Environmental Information (NCEI) indicate that the drought of 2012 was responsible for up to 30 billion dollars in damage. (The U.S Drought of 2012, 2015).

Another whiplash precipitation event occurred between June and July 2014 in which the weather conditions transitioned from extremely wet to extremely dry. This was the most notable whiplash precipitation event to occur during the entire decade considering the wettest June of the 10 year period (2010-2019) was immediately followed by the driest July of the 10 year period.

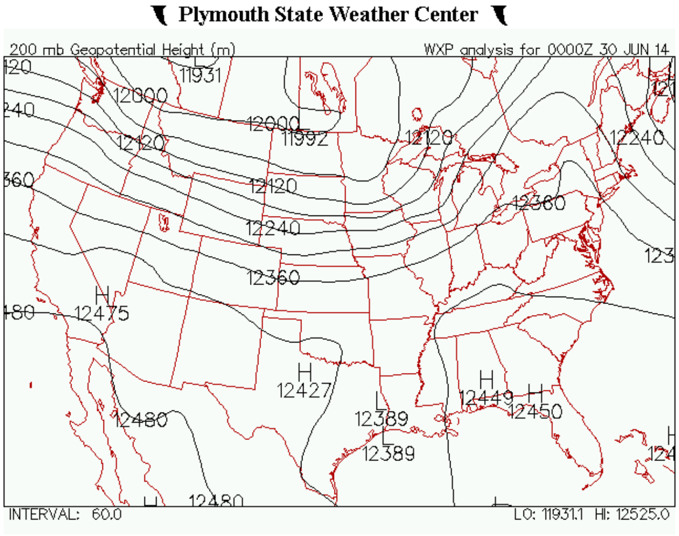

Fig. 10. 200 mb Geopotential height over North America on June 30, 2014 (Source: Plymouth State)

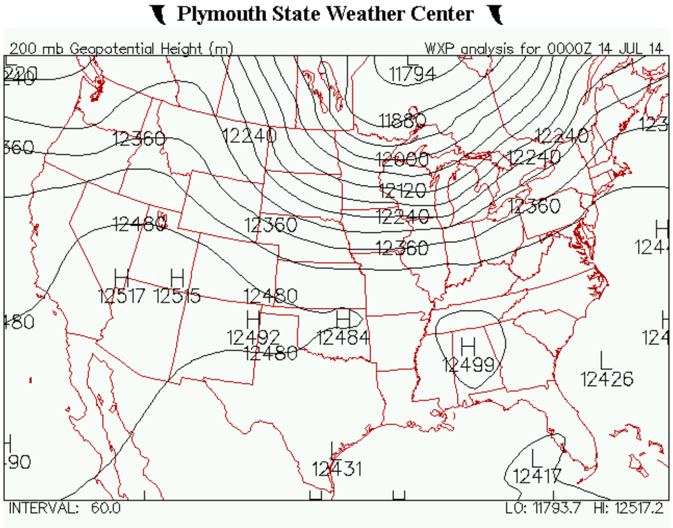

Fig. 11. 200 mb Geopotential height over North America on July 14, 2014 (Source: Plymouth State)

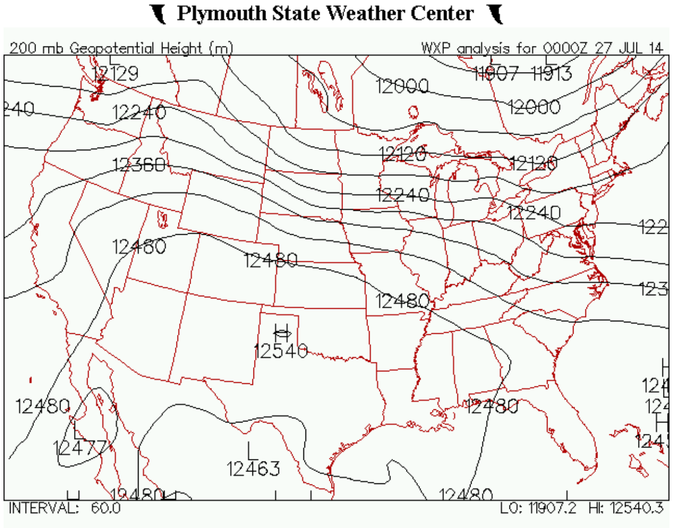

Fig. 12. 200 mb Geopotential height over North America on July 27, 2014 (Source: Plymouth State)

Much of June of 2014 featured an active weather pattern characterized by strong flow across the northern half of the United States, evidenced by Figure 10 from June 30. Higher air pressures were generally suppressed to the far southern United States, almost completely opposite of early July of 2012. 9.14 inches of rain would fall in South Bend during June of 2014 with several days above 0.5 inches of rain, indicative of persistent heavy thunderstorm activity.

Figure 11 shows a similar pattern from July 14, 2014, although jet stream flow across North America is more meridional compared to June 30 with a low centered near the Hudson Bay. The high pressure systems are generally confined to the Tennessee Valley and Four Corners Region. Much like the June 30 pattern which featured a derecho series across the southern Great Lakes, the pattern indicated on July 14 is largely reflective of cooler temperatures and stormier weather conditions.

However, by July 27, a high pressure system begins to gain strength over the southern Plains which eventually moves east towards Mississippi River Valley, signaling a period of hotter and drier weather conditions. Again, “Ring of Fire” setups with occasionally strong high pressure systems over the Great Lakes are typical during the summer months. What is not typical about this event is the repeated episodes of heavy rain that occurred during June which were immediately followed by a prolonged period of dry weather and high pressure over the region that led to June 2014 being the wettest June of the decade and July 2014 being the driest July of the decade.

Conclusions

Through this study, two distinct conclusions can be made regarding the variability of precipitation that fell in South Bend, IN between 2010 and 2019. The first distinct conclusion that can be made is that the late spring months are noticeably wetter than their 30-year averages. As noted in the Data/Methods section, May was the wettest month during the decade with an average precipitation total of 5.31 inches. This 10-year average was 1.48 inches greater than the 30-year average. During the previous 30 years, May was the second wettest month of the year. Behind May was the month of June which on average had 4.42 inches of precipitation during the decade. Both of these averages are higher than the 30-year average of the wettest month of the year, July. As you head into July, August, and September, 2010-2019 precipitation averages drop closer to normal or even below normal.

The second conclusion that can be made as a result of this study is that the mid to late summer months of July, August, and September were noticeably drier than the previous 30 years. August's 10-year average is the closest to normal, but that is only because of a major rainfall event in August of 2016 which dumped over 7 inches of rain in South Bend, IN over the course of one day. This one event caused the average precipitation total for August to be near normal for the 10-year period and must be taken into account when assessing the overall wetness or dryness of that month; it also indicates the importance of examining variability along with general averages. July saw an average of 3.65 inches, 0.35 inches below the 30-year average. September saw an average of 3.4 inches which was roughly 0.10 inches below the 30-year average.

The point of focus of this study was whether or not whiplash precipitation events are increasing in frequency in South Bend, IN. That question could not be answered just by this study alone. However, concerning precipitation trends are appearing with regards to wetter springs/early summers and drier mid to late summers. The two events that could truly be considered whiplash precipitation events were the two episodes discussed in the discussion section. Outside of those two events, other occurrences of wet streaks immediately followed by dry streaks and vice versa appear to be more nebulous. In order to definitively determine whether or not the frequency of these whiplash precipitation events is increasing, more analysis will need to be conducted of precipitation data from the previous 30 years. Even then, 10 years is a small window of time compared to the grand scheme of climate history.

The trends toward wetter springs and drier late summers cannot be ignored. If May of 2019 was a harbinger of the future, then farmers, grocery stores, government agencies, etc., need to start preparing if they are not already prepared. Even if in the next 5-10 years governments around the world start to transition all sectors of their economies away from fossil fuels, the effects of climate change will not necessarily vanish the moment such action takes place. The effects of climate change, induced by the burning of fossil fuels, will likely be felt many years after emissions decrease before weather patterns begin to return to normal. This means that much of our response to climate change needs to be focused on mitigation and adaptation. Wetter springs and drier summers may mean that it is time for farmers to transition to growing crops that have shorter growing times and/or mature quicker. These precipitation trends may also mean that it is time to head to biology/genetics for answers in order to produce crops that are more drought resistant/mature quicker. 10 years may not be a long enough time frame to answer bigger questions like whether or not the frequency of whiplash precipitation events is increasing, but it is certainly a sufficient amount of time to detect noticeable changes in precipitation, that could continue for as long as countries continue to burn massive amounts of fossil fuels.

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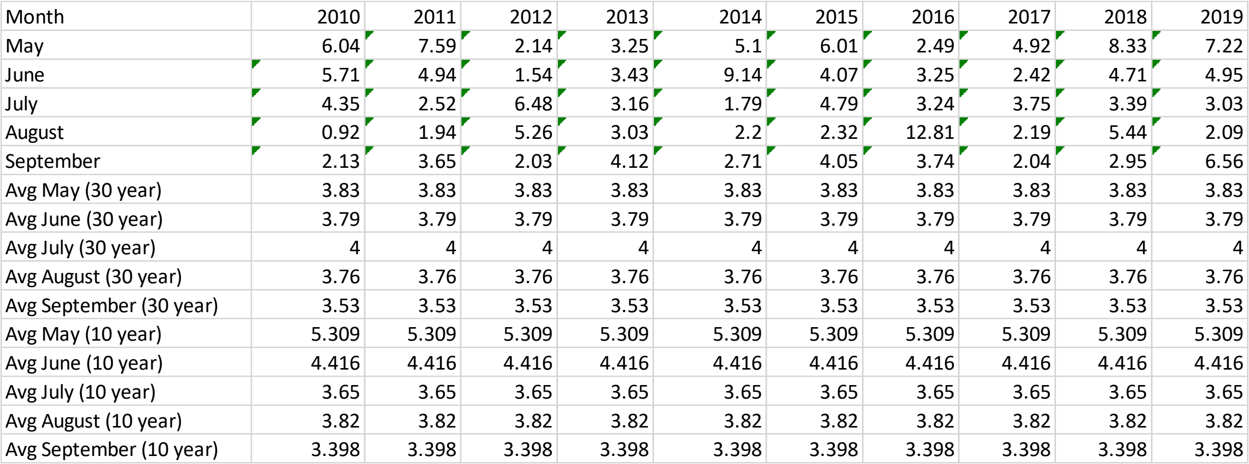
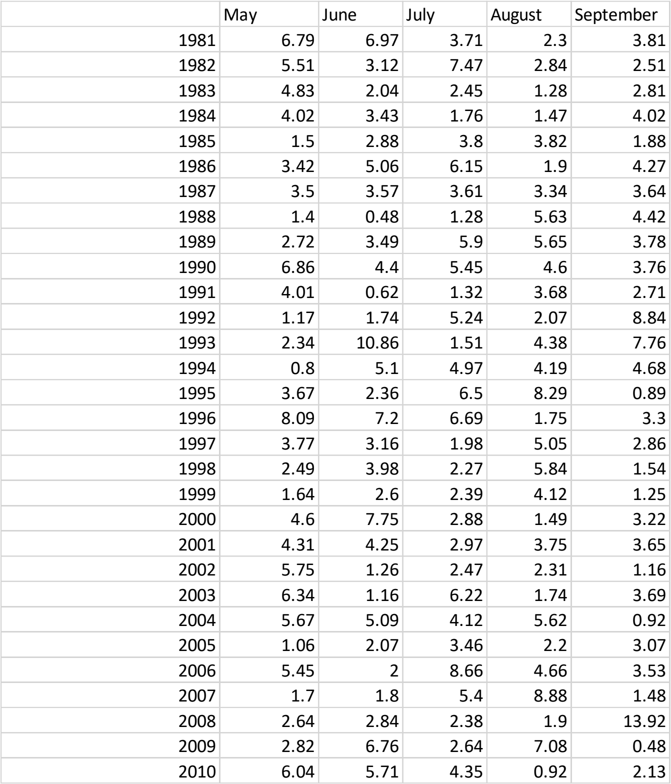
Appendix



Month	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
May	6.04	7.59	2.14	3.25	5.1	6.01	2.49	4.92	8.33	7.22
June	5.71	4.94	1.54	3.43	9.14	4.07	3.25	2.42	4.71	4.95
July	4.35	2.52	6.48	3.16	1.79	4.79	3.24	3.75	3.39	3.03
August	0.92	1.94	5.26	3.03	2.2	2.32	12.81	2.19	5.44	2.09
September	2.13	3.65	2.03	4.12	2.71	4.05	3.74	2.04	2.95	6.56
Avg May (30 year)	3.83	3.83	3.83	3.83	3.83	3.83	3.83	3.83	3.83	3.83
Avg June (30 year)	3.79	3.79	3.79	3.79	3.79	3.79	3.79	3.79	3.79	3.79
Avg July (30 year)	4	4	4	4	4	4	4	4	4	4
Avg August (30 year)	3.76	3.76	3.76	3.76	3.76	3.76	3.76	3.76	3.76	3.76
Avg September (30 year)	3.53	3.53	3.53	3.53	3.53	3.53	3.53	3.53	3.53	3.53
Avg May (10 year)	5.309	5.309	5.309	5.309	5.309	5.309	5.309	5.309	5.309	5.309
Avg June (10 year)	4.416	4.416	4.416	4.416	4.416	4.416	4.416	4.416	4.416	4.416
Avg July (10 year)	3.65	3.65	3.65	3.65	3.65	3.65	3.65	3.65	3.65	3.65
Avg August (10 year)	3.82	3.82	3.82	3.82	3.82	3.82	3.82	3.82	3.82	3.82
Avg September (10 year)	3.398	3.398	3.398	3.398	3.398	3.398	3.398	3.398	3.398	3.398

Table 1: Precipitation totals for the summer months (including May and September) of each year along with 10-year (2010-2019) and 30-year (1981-2010) averages



	May	June	July	August	September
1981	6.79	6.97	3.71	2.3	3.81
1982	5.51	3.12	7.47	2.84	2.51
1983	4.83	2.04	2.45	1.28	2.81
1984	4.02	3.43	1.76	1.47	4.02
1985	1.5	2.88	3.8	3.82	1.88
1986	3.42	5.06	6.15	1.9	4.27
1987	3.5	3.57	3.61	3.34	3.64
1988	1.4	0.48	1.28	5.63	4.42
1989	2.72	3.49	5.9	5.65	3.78
1990	6.86	4.4	5.45	4.6	3.76
1991	4.01	0.62	1.32	3.68	2.71
1992	1.17	1.74	5.24	2.07	8.84
1993	2.34	10.86	1.51	4.38	7.76
1994	0.8	5.1	4.97	4.19	4.68
1995	3.67	2.36	6.5	8.29	0.89
1996	8.09	7.2	6.69	1.75	3.3
1997	3.77	3.16	1.98	5.05	2.86
1998	2.49	3.98	2.27	5.84	1.54
1999	1.64	2.6	2.39	4.12	1.25
2000	4.6	7.75	2.88	1.49	3.22
2001	4.31	4.25	2.97	3.75	3.65
2002	5.75	1.26	2.47	2.31	1.16
2003	6.34	1.16	6.22	1.74	3.69
2004	5.67	5.09	4.12	5.62	0.92
2005	1.06	2.07	3.46	2.2	3.07
2006	5.45	2	8.66	4.66	3.53
2007	1.7	1.8	5.4	8.88	1.48
2008	2.64	2.84	2.38	1.9	13.92
2009	2.82	6.76	2.64	7.08	0.48
2010	6.04	5.71	4.35	0.92	2.13

Table 2: Monthly precipitation totals for the summer months (including May and September) from 1981 to 2010

	May	June	July	August	September
10 year min	2.14	1.54	1.79	0.92	2.03
10 year max	8.33	9.14	6.48	12.81	6.56
30 year min	0.8	0.48	1.28	0.92	0.48
30 year max	8.09	10.86	8.66	8.88	13.92
10 year variability	6.19	7.6	4.69	11.89	4.53
30 year variability	7.29	10.38	7.38	7.96	13.44
# of years above 10 year	5	5	4	3	5
# of years below 10 year	5	5	6	7	5

Table 3: Monthly precipitation averages (Both 10-year and 30-year) for the summer months (including May and September)

Year 2010	Actual Precipitation	10 Year Average	30 Year Average
May	6.04	5.31	3.83
June	5.71	4.42	3.79
July	4.35	3.65	4
August	0.92	3.82	3.76
September	2.13	3.4	3.53

Table 4: Monthly precipitation totals for 2010 compared to 10-year and 30-year averages

Year 2011	Actual Precipitation	10 Year Average	30 Year Average
May	7.59	5.31	3.83
June	4.94	4.42	3.79
July	2.52	3.65	4
August	1.94	3.82	3.76
September	3.65	3.4	3.53

Table 5: Monthly precipitation totals for 2011 compared to 10-year and 30 year averages

Year 2012	Actual Precipitation	10 Year Average	30 Year Average
May	2.14	5.31	3.83
June	1.54	4.42	3.79
July	6.48	3.65	4
August	5.26	3.82	3.76
September	2.03	3.4	3.53

Table 6: Monthly precipitation totals for 2012 compared to 10-year and 30 year averages

Year 2013	Actual Precipitation	10 Year Average	30 Year Average
May	3.25	5.31	3.83
June	3.43	4.42	3.79
July	3.16	3.65	4
August	3.03	3.82	3.76
September	4.12	3.4	3.53

Table 7: Monthly precipitation totals for 2013 compared to 10-year and 30 year averages

Year 2014	Actual Precipitation	10 Year Average	30 Year Average
May	5.4	5.31	3.83
June	9.14	4.42	3.79
July	1.79	3.65	4
August	2.2	3.82	3.76
September	2.71	3.4	3.53

Table 8: Monthly precipitation totals for 2014 compared to 10-year and 30 year averages

Year 2015	Actual Precipitation	10 Year Average	30 Year Average
May	6.01	5.31	3.83
June	4.07	4.42	3.79
July	4.79	3.65	4
August	2.32	3.82	3.76
September	4.05	3.4	3.53

Table 9: Monthly precipitation totals for 2015 compared to 10-year and 30 year averages

Year 2016	Actual Precipitation	10 Year Average	30 Year Average
May	2.49	5.31	3.83
June	3.25	4.42	3.79
July	3.24	3.65	4
August	12.81	3.82	3.76
September	3.74	3.4	3.53

Table 10: Monthly precipitation totals for 2016 compared to 10-year and 30 year averages

Year 2017	Actual Precipitation	10 Year Average	30 Year Average
May	4.92	5.31	3.83
June	2.42	4.42	3.79
July	3.75	3.65	4
August	2.19	3.82	3.76
September	2.04	3.4	3.53

Table 11: Monthly precipitation totals for 2017 compared to 10-year and 30 year averages

Year 2018	Actual Precipitation	10 Year Average	30 Year Average
May	8.33	5.31	3.83
June	4.71	4.42	3.79
July	3.39	3.65	4
August	5.44	3.82	3.76
September	2.95	3.4	3.53

Table 12: Monthly precipitation totals for 2018 compared to 10-year and 30 year averages

Year 2019	Actual Precipitation	10 Year Average	30 Year Average
May	7.22	5.31	3.83
June	4.95	4.42	3.79
July	3.03	3.65	4
August	2.09	3.82	3.76
September	6.56	3.4	3.53

Table 13: Monthly precipitation totals for 2019 compared to 10-year and 30 year averages

May	Actual Precipitation	10 Year Average	30 Year Average
Year 2010	6.04	5.31	3.83
Year 2011	7.59	5.31	3.83
Year 2012	2.14	5.31	3.83
Year 2013	3.25	5.31	3.83
Year 2014	5.1	5.31	3.83
Year 2015	6.01	5.31	3.83
Year 2016	2.49	5.31	3.83
Year 2017	4.92	5.31	3.83
Year 2018	8.33	5.31	3.83
Year 2019	7.22	5.31	3.83

Table 14: May precipitation totals for each year of 10-year period (2010-2019) compared to 10-year (2010-2019) and 30-year (1981-2010) averages

June	Actual Precipitation	10 Year Average	30 Year Average
Year 2010	5.71	4.42	3.79
Year 2011	4.94	4.42	3.79
Year 2012	1.54	4.42	3.79
Year 2013	3.43	4.42	3.79
Year 2014	9.14	4.42	3.79
Year 2015	4.07	4.42	3.79
Year 2016	3.25	4.42	3.79
Year 2017	2.42	4.42	3.79
Year 2018	4.71	4.42	3.79
Year 2019	4.95	4.42	3.79

Table 15: June precipitation totals for each year of 10-year period (2010-2019) compared to 10-year (2010-2019) and 30-year (1981-2010) averages

July	Actual Precipitation	10 Year Average	30 Year Average
Year 2010	4.35	3.65	4
Year 2011	2.52	3.65	4
Year 2012	6.48	3.65	4
Year 2013	3.16	3.65	4
Year 2014	1.79	3.65	4
Year 2015	4.79	3.65	4
Year 2016	3.24	3.65	4
Year 2017	3.75	3.65	4
Year 2018	3.39	3.65	4
Year 2019	3.03	3.65	4

Table 16: July precipitation totals for each year of 10-year period (2010-2019) compared to 10-year (2010-2019) and 30-year (1981-2010) averages

August	Actual Precipitation	10 Year Average	30 Year Average
Year 2010	0.92	3.82	3.76
Year 2011	1.94	3.82	3.76
Year 2012	5.26	3.82	3.76
Year 2013	3.03	3.82	3.76
Year 2014	2.2	3.82	3.76
Year 2015	2.32	3.82	3.76
Year 2016	12.81	3.82	3.76
Year 2017	2.19	3.82	3.76
Year 2018	5.44	3.82	3.76
Year 2019	2.09	3.82	3.76

Table 17: August precipitation totals for each year of 10-year period (2010-2019) compared to 10-year (2010-2019) and 30-year (1981-2010) averages

September	Actual Precipitation	10 Year Average	30 Year Average
Year 2010	2.13	3.4	3.53
Year 2011	3.65	3.4	3.53
Year 2012	2.03	3.4	3.53
Year 2013	4.12	3.4	3.53
Year 2014	2.71	3.4	3.53
Year 2015	4.05	3.4	3.53
Year 2016	3.74	3.4	3.53
Year 2017	2.04	3.4	3.53
Year 2018	2.95	3.4	3.53
Year 2019	6.56	3.4	3.53

Table 18: September precipitation totals for each year of 10-year period (2010-2019) compared to 10-year (2010-2019) and 30-year (1981-2010) averages

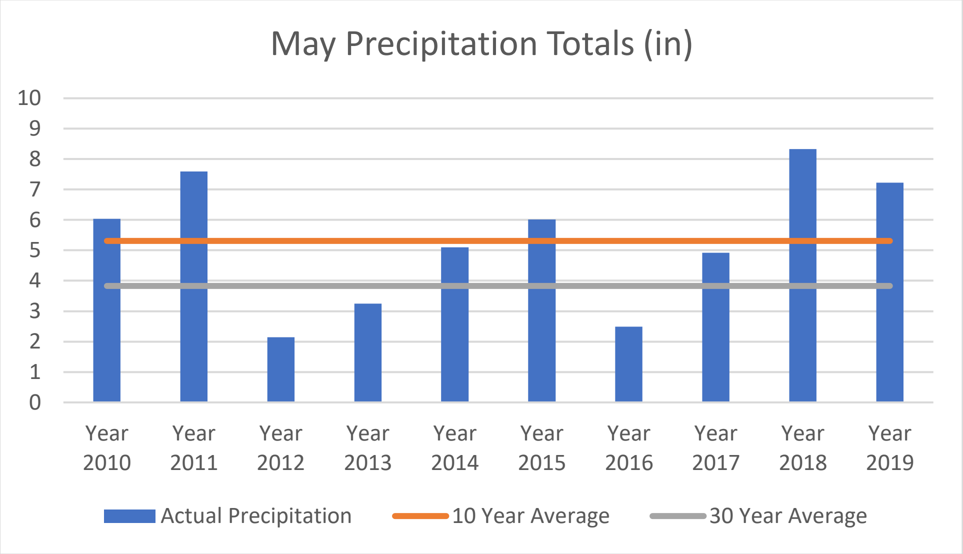


Fig. 2. May Precipitation totals and averages

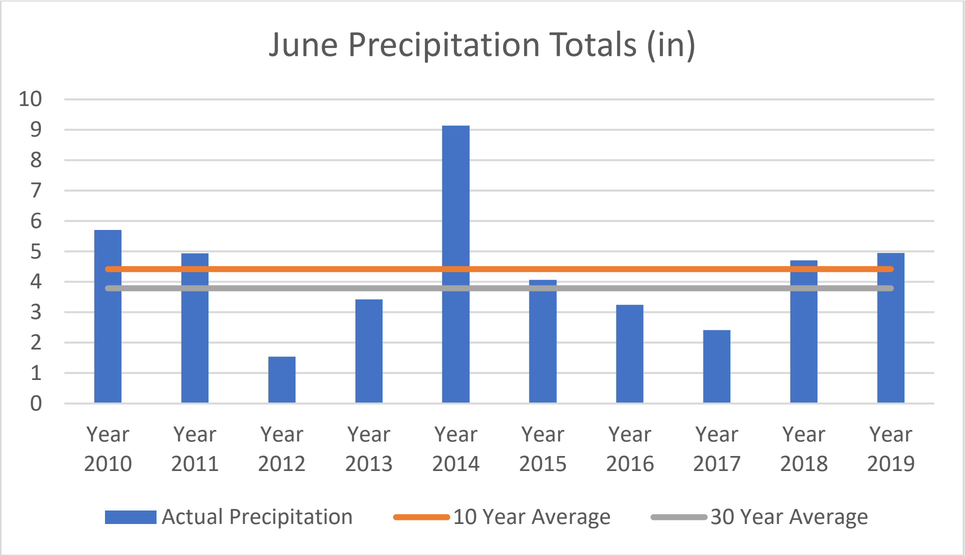


Fig. 3. June Precipitation totals and averages

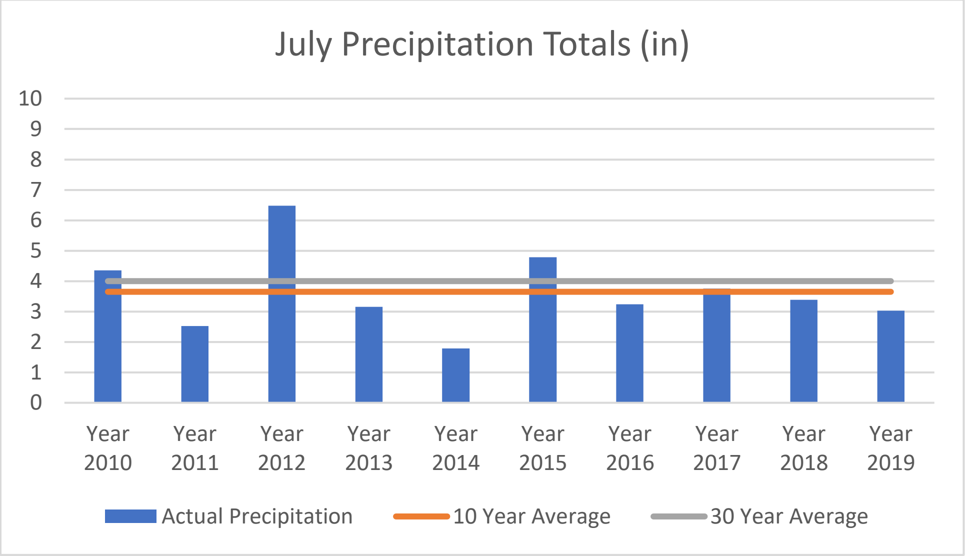


Fig. 4. July Precipitation totals and averages

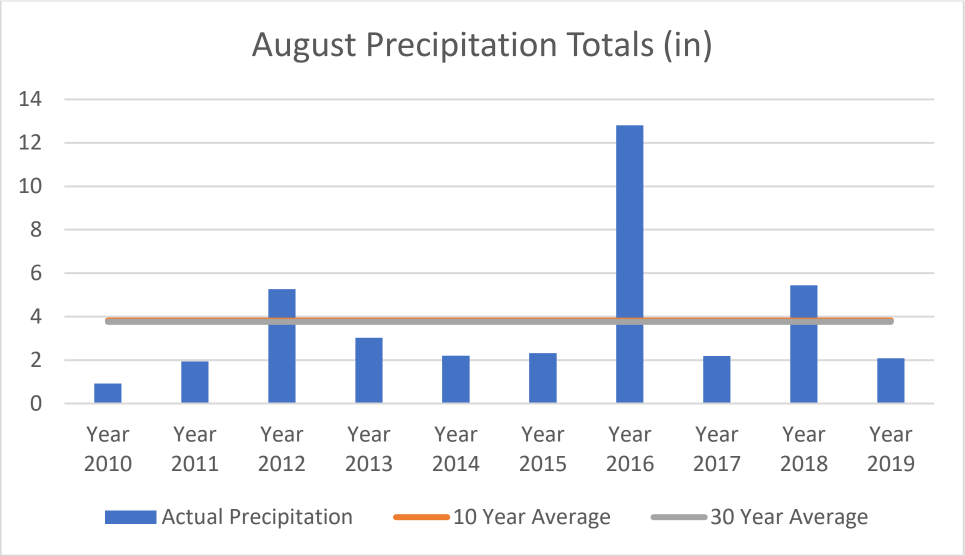


Fig. 5. August Precipitation totals and averages

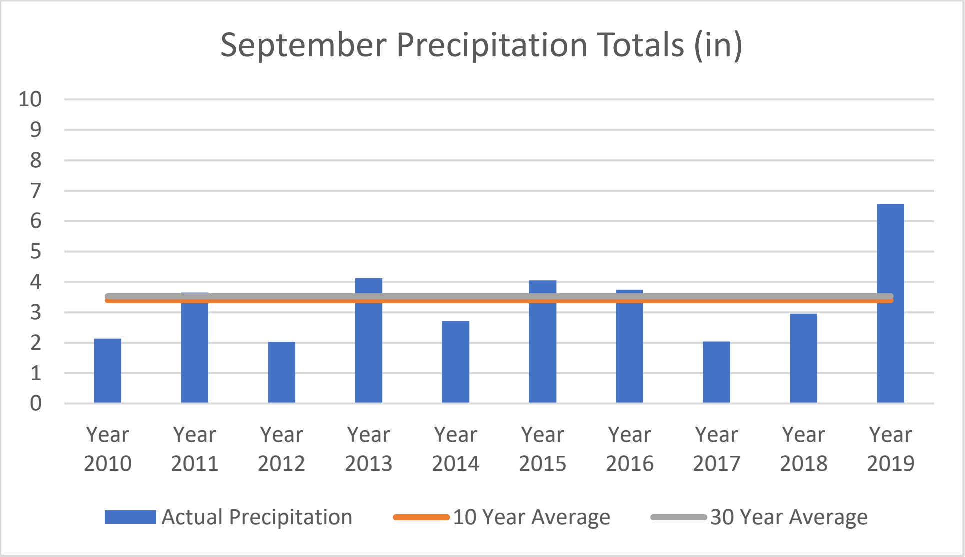


Fig. 6. September Precipitation totals and averages