Rainfall Analysis and Trends for the State Of Texas In 2015

<table>
<thead>
<tr>
<th>Abstract</th>
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</table>

This study investigates the extreme rainfall patterns over the state of Texas during 2015 when the state experienced tornadoes, flooding and El Niño, which contributed to massive rainfall around the state. Rainfall distribution pattern is one of the most important factors for hydrological modeling and agricultural purposes. Texas is at the crossroads of large-scale weather patterns and is affected by what is happening in the Pacific and Atlantic Oceans, particularly the El Niño and La Niña cycle. Texas suffered of damaging floods and record rainfall in May 2015 after years of severe drought, which started in 2010. According to the National Weather Service, in 2015 Texas suffered from severe rain and flash floods that caused an estimated 35 trillion gallons of water to fall on Texas, which was enough to cover the entire state in eight inches of water. In addition, this amount is enough to supply the world’s drinking water for 27 years.

In this study, an analysis was conducted through a network of approximately 1011 rain gauges maintained by the National Climatic Data Center NCDC and the United States Geological Survey covering the state of Texas. These stations provide data that are typically being recorded at 15- to 60-minute intervals from automated or manual readings. The stations provided the basis for 12 months of precipitation dataset in 2015. In addition, precipitation measurements were collected by 13 WSR-88D Weather Surveillance Radar-1988 Doppler Next Generation Weather Radar NEXRAD with Multi-sensor Precipitation Estimator (MPE) Stage III that cover the state of Texas and are maintained by the National Weather Service NWS. Radar data are available for 152366 grids a 4 × 4 km covering the entire state of Texas.
In general, numerous stations recorded rainfall that indicated that 2015 was the wettest year in the state records. The results of rain gauges and weather radar show that May and October were the wettest months in 2015 respectively, while the months with the least rainfall were April, November and June respectively. In addition, a correlation of radar estimates of rainfall to actual rain gauge dataset has been examined on monthly bases for 2015 and shows a deviation of 17% between the two products. Further studies are required to create model that performs reasonably well in generating rainfall dataset with less deviation and that takes into account errors from all possible factors affecting the accuracy of rainfall estimations.

**Introduction**

Texas' weather varies widely, from relatively dry in the west to humid in the east. The huge difference in weather has led scientists to divide Texas into ten climate regions: Northern Plains, Trans-Pecos Region, Texas Hill Country, Piney Woods, and South Texas. Robert Smith 2015. The National Climatic Data Center divides Texas into 10 climate divisions as shown in Figure 1. Texas experienced the driest weather in its record in 2011 culminating in the worst single-year drought in recorded history. Water levels were at historical lows, and as the land and plant life dried up, acres upon acres lit up with wildfires. The heat and extraordinarily dry weather of 2011 was part of a larger period of drought in the state that extended from 2010 to 2015, resulting in approximately $8.7 billion in agricultural losses. It is unlikely that was the end of the story. As the climate continues to warm, more droughts that are multi-year are expected with devastating impact to the state’s agriculture sector and drinking water (Climate Reality Project, 2016).

After several years of extreme drought, the dry spell ended for Texas with a splash in May 2015. It was the wettest month in 121 years of the state’s history with total precipitation of 8.93 inches NOAA, 2017. This precipitation broke the previous records set in 2004 by two inches. In 2015, the severe rains and flash floods caused an estimated 35 trillion gallons of water to fall on Texas, which is enough to cover the entire state in eight inches of water, according to the National Weather Service. In addition, this amount is enough to supply the world’s drinking water for 27 years. This has led experts to predict a higher volume of heavy rains later, based on climate models and phenomenal global weather patterns in 2015. Heavy rain conditions on the ground results in heavy run-off that goes directly into rivers, streams and areas prone to flash flooding. Most of the rainfall led to an unprecedented rise in the Blanco, Trinity and San Marcos rivers. Data from National Weather Services showed the water level rose from nearly 9 feet at 10:30 p.m. Saturday to more than 40 feet by 1 a.m. Sunday, eclipsing the record of 32 feet in Blanco River gauge at Wimberley. Wimberley and San Marcos town were devastated by Tidal Waves along the Blanco and San Marcos rivers.

Wimberley and San Marcos were devastated by tidal waves along the Blanco and San Marcos rivers. Most locations across South Central Texas had already received above normal amounts of rain (2.0 to 4.0 inches) during May 2015. Consequently, after the Blanco River flooded to record level, hundreds of homes were destroyed and 1,200 people became homeless in Hays County. In addition the heavy rains led to 31 deaths in Texas. (Daily Mail, 2015) (San Antonio News, 2015). The severe catastrophic weather conditions led Governor Abbott to declare a disaster in 24 counties and dispatch all available resources to aid those affected by this severe weather.
Each decade, the National Oceanic and Atmospheric Administration publish an updated list of 30-year climate normal for several thousand locations across the United States NCDC 2012. In recent decades, it has been observed that more rain relative to earlier periods has occurred. An analysis showed stations across different regions in south Texas have received larger amounts of rain falling during fewer days., these trends do not hold across all periods. A couple of studies have shown a 10–15 % increase in annual rainfall when comparing 1991–2012 averages to 1901–1960 baseline estimates Melillo et al.,(2014). Thus, the drought and flood events in Texas tend to follow each other.

Texas is at the crossroads of large-scale weather patterns as it is affected by what is happening in the Pacific and Atlantic Oceans (Waylen, 1998). Every three to twelve years, water on the surface of the Pacific Ocean becomes warm, which leads to heated air above it. This raises massive atmospheric current columns that bring a steady supply of airborne moisture to Texas. The Pacific Ocean has a strong effect on rainfall in wintertime while the Atlantic Ocean has a nominal effect on rainfall in the summer Marin Baxter, 2008.

In general, 2015 was the warmest global year on record surpassing the previous records by more than 0.1 C0 State of The climate in 2015. Since 1970, average summer temperatures in the South have risen by as much as 3.3ºF with many of the fastest warming areas in Texas. Houston experiences about five days each year over 100ºF Figure 2. By 2100, Houston could expect some 70 days over 100ºF under a high emissions scenario, and an average temperature increase of 5.7ºF in summer. In fact, during the 2011 drought, Houston was not the only city that felt the increase in temperature, as many locations in Texas experienced more than 100 days over 100ºF.
The South

Fluctuations in temperature between the ocean and the atmosphere may influence the weather regionally in Texas and globally as well. Complexity in weather patterns resulting from variations in ocean temperatures is known as the El Niño-Southern Oscillation (ENSO) cycle. The cold phase of ENSO is called La Niña, which brings above-normal rainfall leading to devastating floods. Conversely, the warm phase called El Niño causes less rainfall leading to drought. La Niña and El Niño strength can vary considerably between cycles. In 2011, Texas experienced the driest year in its records, as influenced by the La Niña pattern. NOAA, 2016

The variability of Texas weather to both rigorous drought and floods is somewhat unusual compared to other states such as Arizona and Vermont. (Texas A&M AgriLife Extension Service, 2016). For example, Houston, Texas recovered from one drought followed by another one, and then had to recover from it. An El Niño was typically strong in 2015, but is not always followed by its counterpart, La Niña, which moves atmospheric moisture streams away from Texas, heightening the chance for drought.

Texas has been hit with many major floods throughout the years that have caused hundreds of deaths and billions of dollars in damage. American Metrology Society, 2016. Texas experienced 75 weather and climate disasters between 1980 and 2015 (NOAA, U.S. Billion-Dollar Weather and Climate Disasters, 2017). Texas has seen seven major catastrophic floods in its history in the last fifteen years compared to six in the last 25 years. Flash floods in 2015 have damaged homes and businesses, washed out roads and bridges, and resulted in 27 deaths across the state.

A peer-reviewed study from Utah State and Taiwanese researchers reported that an increase in rainfall and drought might be significant and attributable to either activity of human beings on nature or part of the region’s long-term drought cycle. The study linked the climate change to devastating Texas floods. Climate change leads to extreme downpours and unpredictable rains are on the rise. According to Climate Central, McAllen TX the city has experienced a 700-percent increase in heavy downpours since 1950 while Houston has seen a 167 percent rise in heavy downpours for the same period as shown in Figure 3 (The Climate Reality Project, 2016). The study includes some of the science underlying the link between global warming, sea surface temperatures (SSTs) and the El Niño Southern Oscillation.
ENSO global warming. The atmospheric burden of three dominate greenhouse gases CO2, CH4, N2O are responsible for global warming continued to increases globally in 2015. The study concludes, “There was a detectable effect of anthropogenic global warming in the physical processes that caused the persistent precipitation in May of 2015 over the southern Great Plains” (Simon, 2015).

Figure 3 Numbers of Heavy Downpours in Texas since 1950 Source: Climate Central, 2016

**Standardized Precipitation Index SPI**

The Standardized Precipitation Index SPI is a popular index to define and monitor drought severity on a range of timescales. The SPI is related to soil moisture, groundwater and reservoir storage. The precipitation is the only input parameter to determine the SPI, so it is a good tool to quantify the precipitation deficit to meet the demands of human activities and the environment (World Meteorological Organization, 2012). It is based on the cumulative probability of historic rainfall data of a station that is fitted to a gamma distribution. Table 1 show the cumulative probability of observed precipitation, which is then transformed into an index SPI values.

**Table 1 SPI & Cumulative Probabilities**

<table>
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<tr>
<th>SPI</th>
<th>Classification</th>
<th>Probability</th>
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<tbody>
<tr>
<td>2.00+</td>
<td>Extremely wet</td>
<td>2.3%</td>
</tr>
<tr>
<td>1.5 to 1.99</td>
<td>Very wet</td>
<td>4.4%</td>
</tr>
<tr>
<td>1.00 to 1.49</td>
<td>Moderately wet</td>
<td>9.2%</td>
</tr>
<tr>
<td>0 to 0.99</td>
<td>Mildly wet</td>
<td>34.1%</td>
</tr>
<tr>
<td>0 to -0.99</td>
<td>Mild drought</td>
<td>34.1%</td>
</tr>
<tr>
<td>-1 to –1.49</td>
<td>Moderate drought</td>
<td>9.2%</td>
</tr>
<tr>
<td>-1.5 to -1.99</td>
<td>Severe drought</td>
<td>4.4%</td>
</tr>
<tr>
<td>-2.0 &lt;</td>
<td>Extreme drought</td>
<td>2.3%</td>
</tr>
</tbody>
</table>

**Source:** World Meteorological Organization - User Guide No. 1090-2012.
Fig 4 Standardized Precipitation Index – Texas Jan. 2015

Fig 5 Standardized Precipitation Index – Texas Feb. 2015
Fig 6 Standardized Precipitation Index – Texas March. 2015

Fig 7 Standardized Precipitation Index – Texas April. 2015
Fig 8 Standardized Precipitation Index – Texas May. 2015

Fig 9 Standardized Precipitation Index – Texas June. 2015
Fig 10 Standardized Precipitation Index – Texas July, 2015

Fig 11 Standardized Precipitation Index – Texas Aug, 2015
Fig 12 Standardized Precipitation Index – Texas Sept. 2015

Fig 13 Standardized Precipitation Index – Texas Oct. 2015
Fig 14 Standardized Precipitation Index – Texas Nov. 2015

Fig 15 Standardized Precipitation Index – Texas Dec. 2015
Figure 16 Standard Precipitation Index 1898 – 2017 based on 72 months

Figure 17 – Standard Precipitation Index 1898 – 2017 based on 12 months

Source: Western Regional Climate Center, Desert Research Institute, NV, USA
Figure 4, January 2015, the SPI ranged from 0.4 at East Texas to 1.33 at Trans Pecos. In general, January was categorized as near normal drought conditions. It was near normal all over Texas, but with more moisture in the west, north and some regions along the Gulf of Mexico. These regions show abnormal to very moisture conditions.

Figure 5, February 2015, the SPI ranged from -0.26 at Upper Coast to 1.41 at Trans Pecos. In general, February was categorized as moist drought conditions. It was near normal to extremely moist conditions in the west of Texas compared to near normal to moderately moist conditions in east of Texas.

Figure 6, March 2015, the SPI ranged from -0.09 at Low Rolling Plains to 1.33 at Trans Pecos and Southern. In general, March was categorized as moderately to extremely moisture conditions in the west and east of Texas compared to near normal drought conditions in the north of Texas.

Figure 7, April 2015, the SPI ranged from 0.77 at High Plains to 1.94 at East Texas. In general, April was categorized as having moist conditions all over Texas. That means the amount of rain that fell during April was greater than the third standard deviation. The cold currents came down from the north of Texas and cooled the warmer air from the ocean. This led to an increase in the moisture content in the atmosphere.

Figure 8, May 2015, SPI ranged from 1.39 at Trans Pecos to 2.57 at High plains. In general, May was categorized as the wettest month in 2015 ranging from very moist conditions to exceptionally moist conditions all over Texas. That means the amount of rain that fell during May was greater than half standard deviation. Major flooding occurred during this month.

Figure 9, June 2015, the SPI ranged from 1.11 at Trans Pecos to 2.4 at High plains. In general, June was categorized as a wet month in 2015 ranging from moderately moist conditions to exceptionally moist conditions all over Texas. That means the amount of rain that fell during June was greater than the half standard deviation.

Figure 10, July 2015, the SPI ranged from -0.42 at East Texas to 0.94 at High plains. In general, July was categorized as having near normal drought conditions in 2015 ranging from near normal in the north central, east southern to moderately moist conditions in the north of Texas. That means the amount of rain that fell during July was less than the quarter standard deviation.

Figure 11, August 2015, the SPI ranged from -1.69 at East Texas to 0.81 at High plains. In general, August was categorized as having moderately dry conditions month in 2015 ranging from moderately dry in the north central and south to exceptionally dry conditions in the east to moderately moist conditions in the north of Texas.

Figure 12, September 2015, the SPI ranged from -1.62 at north central to 0.61 at upper coast. In general, September was categorized as an extremely dry month in 2015 ranging from near normal drought conditions in the north central, south and east to having abnormally moist conditions in the upper coast of Texas.

Figure 13, October 2015, the SPI ranged from -0.15 at Low Rolling Plains to 1.37 at North Central. In general, October was categorized as an abnormally moist month in 2015 ranging from abnormally moist conditions in the north, west and east to near normal drought conditions in the upper north central and southern of Texas.
Figure 14, November 2015, the SPI ranged from 1.23 at south to 2.85 at north central. In general, November was categorized as a moist month in 2015 ranging from very moist conditions at the upper coast, southern and low rolling plains to exceptionally moist conditions in the north central of Texas.

Figure 15, December 2015, the SPI ranged from -0.31 at Lower Valley to 2.0 at north central. In general, December was categorized as a moist month in 2015 ranging from moderately moist conditions at the high plains and Edwards Plateau to near moist drought conditions in the south central and lower valley of Texas.

Figure 16 and 17 represent the Standard Precipitation Index 1898 – 2017 based on 72 and 12 months. The SPI at these timescales reflects long-term precipitation patterns. A 12-month SPI is a comparison of the precipitation for 12 consecutive months with that recorded in the same 12 consecutive months in all previous years of available data and so on for a 72-month SPI World Meteorological Organization, 2012. Both SPIs tend to gravitate toward zero, which is near normal drought a condition unless a distinctive wet or dry trend is taking place. At longer timescales, the SPIs of these timescales are usually tied to stream flows, reservoir levels, and even groundwater levels.

**Precipitation in Texas**

Figure 18 shows the range of rainfall in Texas for 121 years between 1895 and 2015. Every year Texas has had at least 14.06" rainfall and has not exceeded 41.23", so the range is 27.17" Figure 20. The median 50% ile is 26.98" and the average annual rainfall is 27.17". The 75% ile is equaled or exceeded in only 25% of all the values above 30.65" in the 121 years. The 25% ile is equaled or exceeded in 75% of all values above 23.82" in the 121 years. In general, the trend line shows an increment of 0.2" every decade for the period between 1895 and 2015.
Figure 19 shows the range of rainfall in Texas for 25 years between 1991 and 2015. Every year Texas has had at least 14.7" rainfall and has not exceeded 41.23 " , so the range is 17.06". The median 50 %ile is 26.98" and the average annual rainfall is 28.63 ". The 75 %ile is equaled or exceeded in only 25 % of all the values above 30.65" in the 25 years. The 25 % ile is equaled or exceeded in 75 % of all values above 24.2" in the 25 years. In general, the trend line shows an increment of 1.6 " every decade for the period between 1991 and 2015.

Figure 20 shows the range of rainfall in Texas for 10 years between 2006 and 2015. Every year Texas has had at least 14.7" rainfall and has not exceeded 41.23 ", so the range is 26.53". The median 50 %ile is 25.58" and the average annual rainfall is 26.53 ". The 75 %ile is equaled or exceeded in only 25 % of all the values above 28.36" in the 10 years. The 25 %ile is equaled or exceeded in 75 % of all values above 24.03" in the 10 years. In general, the trend line shows an increment of 2.6 " every decade for the period between 2006 and 2015.
Figure 21 shows the range of rainfall in 2015. Texas has had at least 1.09" rainfall in February 2015 and has not exceeded 9.05" in May 2015, so the range is 7.96". The median 50%ile is 3.07" and the average annual rainfall is 3.44". The 75%ile is equaled or exceeded in only 25% of all the values above 3.89" in years. The 25%ile is equaled or exceeded in 75% of all values above 1.74" in 2015.
Temperature in Texas

In Figure 2, the lowest annual temperature between 1895 and 2015, (0 % ile) the value that is exceeded all the time is 62.3°F. Every year the temperature exceeds 62.3°F based on 121 years. The highest is the top of the list, (100 % ile) the one that has not been exceeded in the 121 years is 67.8°F, so the range is 5.5°F. The average annual temperature is 64.78°F in the 121 years. The median 50% is 64.8°F. The 75% is equalled or exceeded in 25% of all the values above 65.4°F in the 121 years. The 25% is equalled or exceeded in 75% of all values above 64°F in the 121 years. In general, we can see the trend line shows an increment of 0.09°F every decade for the period between 1895 and 2015.

![Figure 2 Texas Average Temperatures 1895 – 2015](image)

In Figure 3, the lowest annual temperature between 1991 and 2015, (0 % ile) the value that is exceeded all the time is 63.9°F. Every year we can expect to get more than 63.9°F based on twenty-five years. The highest is the top of the list, (100 % ile) the one that has not been exceeded in the twenty-five years is 64.8°F, so the range is 0.9°F. The average annual temperature is 65.608°F in twenty-five years. The median 50% is 65.5°F. The 75% is equalled or exceeded in only 25% of all the values above 66.5°F in the twenty-five years. The 25% is equalled or exceeded in 75% of all values above 65.1 in the twenty-five years. In general, we can see the trend line shows increase of 0.47°F every decade for the period between 1991 and 2015.
In Figure 24, the lowest annual temperature between 2006 and 2015, (0 % ile) the value that is exceeded all the time is 64.8 \text{F}^\circ. Every year we can expect to get more than 64.8 \text{F}^\circ based on ten years. The highest is the top of the list, (100 % ile) the one that has not been exceeded in the ten years is 67.1 \text{F}^\circ, so the range is 2.3 \text{F}^\circ. The average annual temperature is 67.8 \text{F}^\circ in ten years. The median 50 % ile is 65.92 \text{F}^\circ. The 75 % ile, equaled or exceeded in only 25 % of all the values above 67.42 \text{F}^\circ in the ten years. The 25 % ile, equaled or exceeded in 75 % of all values above 65.05 in the twenty five years. In general, we can see the trend line shows decreasing of 0.29 \text{F}^\circ every decade for the period between 2006 and 2015.
In Figure 25, the lowest annual average temperature in 2015, (0 % ile) the value that is exceeded all the time is 44 F0 in January 2015. The highest is the top of the list, (100 % ile) the one that has not been exceeded in the 2015 is 83.3 F0 in August 2015, so the range is 39.3 F0. The average annual temperature is 65.81 F0 in 2015. The median 50 % ile is 67.9 F0. The 75 % ile, equaled or exceeded in only 25 % of all the values above 75.45 F0 in the 2015. The 25 % ile, equaled or exceeded in 75 % of all values above 53.85 F0 in the 2015.

Figure 25 Texas Average Temperature 2015

Palmer Drought Severity Index (PDSI) in Texas

The PDSI is a good index to quantify long-term drought. The index uses available temperature and precipitation data to reflect excess rain by using a corresponding level reflected standardized range from -10 to 10. The 0.0 is normal, plus 2 is moderate rainfall, etc, while the minus 2 is moderate drought, minus 3 is severe drought, etc.

In Figure 26, the results identified that the severe drought years were 1896-1899, 1901-1902, 1909-1912,1916-1918,1921-1922,1927-1928,1933-1934,1939-1940,1951-1956, 1962-1965 and,1989-1990, 2008-2009,2011-2014. The PDSI mean during the 122 years was -0.18. This indicates that Texas had a near normal drought in the 122 years.

The driest year was in 1956 (PDSI, -6.25) categorized as an extreme drought, while the wettest year was 1941 (PDSI, 5.75) categorized as an extremely wet year. As the study concentrates on 2015, it is categorized as a very wet year. In general, the trend line shows an increment of 0.025 PDSI towards near normal drought every decade for the period between 1895 and 2015.
As shown in Figure 26, severe drought years were in 2008-2009 and 2011-2014. The PSDI mean during the ten years was -1.76. This indicates that Texas had mild drought in the twenty-five years. The driest year was in 2011 (PDSI, -5.66) categorized as extreme drought, while the wettest year was 2015 (PDSI, 3.36) categorized as extremely wet year. As the study concentrates on 2015, it is categorized as very wet year. In general, the trend line shows that the PSDI decreased with -1.76 towards (mild drought drought) every decade for the period between 1991 and 2015.
In Figure 28, the results identified that the severe drought years were in 2006, 2008-2009, and 2011-2014. The PSDI mean during the ten years was -1.68. This indicates that Texas had mild drought in the ten years. The driest year was in 2011 (PDSI, -5.66) categorized as extreme drought, while the wettest year was 2015 (PDSI, 3.36), categorized as an extremely wet year. As the study concentrates on 2015, it is categorized as a very wet year. In general, the trend line shows a PSDI increment of 0.15 towards near normal drought every decade for the period between 2006 and 2015.

![Figure 28 Texas Palmer Drought Severity Index (PDSI) 2006 – 2015](image)

As shown in Figure 29, 2015 was a wet year. The PSDI mean during the twelve months was 3.36. This indicates that Texas had a very moist year in 2015. The wettest month was June 2015 and it is categorized as a very wet month in 2015. In general, the trend line for 2015 was above normal, towards the wet zone.

![Figure 29 Texas Palmer Drought Severity Index (PDSI) 2015](image)
Data and Methods

Rain Gauge Precipitation Data

The State of Texas is the second largest state in the United States by both area (268,581 square miles) and population (27,862,596). It has a density population of 103.7 people per square mile (U.S. Census Bureau, 2015). The state has a wide variety of topographic, geologic, and hydrologic conditions. The proximity of rainfall patterns with different characteristics requires rain gauges to be used to determine accurate monthly and yearly rainfall distributions throughout Texas.

The first precipitation data set were obtained from rain gauge readings managed by the National Climate Data Center (NCDC) archive database. The NCDC archives global historical weather and climate data in addition to station history information are available online at https://www.ncdc.noaa.gov/cdo-web/search. The primary sources of the (NCDC) data are the US National Weather Service (NWS), Federal Aviation Administration (FAA), and cooperative observer stations in the United States of America, Puerto Rico, the US Virgin Islands, and various Pacific Islands. These data include monthly and annually measurements of precipitation. Only stations having twelve continuous monthly readings in 2015 and minimal missing data were included in the analysis.

The second precipitation dataset were obtained from rain gauge readings run by the United States Geological Survey (USGS). The USGS precipitation data were recorded at 15 intervals. All data were aggregated to monthly time scales using one of Excel's Pivot Table, its most powerful tool for analyzing massive data. Rain gauges that do not have a complete twelve-month's range of data in 2015, so they were excluded from analysis from any of the stations. In addition, minimal gap data like in rainfall breaking records were included in the analysis.

In this study, 1011 rain gages distributed at 744 stations for NCDC and 267 stations for USGS stations over the state of Texas. The earliest data dates vary considerably by state and region. The data are archived, retrieved, and used in general scientific or interpretive studies.

All the precipitation data from the USGS and NCDC stations have been analyzed for the available rainfall data between 1763 and 2015 for the same rain gauges (stations) in 2015 as shown in Figure 60. The purpose for this was to allocate the stations that subsequently indicated the areas and zones where rainfall records were broken in 2015.

All data have been processed by Geographic Information System (ArcMap) to visualize, summarize, analyze, compare, and interpret spatial precipitation data for each month in 2015 in 2D environments. Inverse distance weighted (IDW) interpolation have been used to predict a value for any unmeasured location, (IDW) uses the measured values surrounding the prediction rain gauge.(IDW), which assumes that each measured point has a local influence that diminishes with distance. It gives greater weights to points closest to the prediction location, and the weights diminish as a function of distance. Hence, the name inverse distance weighted (ESRI, 2017). ArcMap runs for about 19.50936 hours to generate maps for 12 months of 2015.
Figure 30 Distribution of rain gauges (stations) over the state of Texas in 2015

Weather Radar Precipitation Data

Precipitation measurements from weather radar provide precipitation data with much higher spatial resolution compared to rain gauges. These measurements have served meteorology and hydrology for decades (Krajewski and Smith, 2002). The installation of the Next Generation Weather Radar (NEXRAD) system across the United States was in the mid of 1990s by National Weather Service (NWS). This includes more than 160 WSR-88D (Weather Surveillance Radar-1988 Doppler) radar shown as in Figure (31). Texas has 13 National Doppler Radar Sites listed in table (2) and shown in Figure (34).
A Next Generation Weather Radar (NEXRAD) Multi-sensor Precipitation Estimator (MPE) Stage III measures precipitation products on hourly accumulation and have a spatial resolution of 4 km by 4 km on 152366 grids (Wang et al., 2007). The reason for using this type of sensor is that MEP algorithm is designed for optimal merging of radar and rain gauge estimations.

**Table (2) National Doppler Radar Sites in the state of Texas**

<table>
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<tr>
<th>WBAN #</th>
<th>STATION ID</th>
<th>STATION NAME</th>
<th>LAT N / LONG W (deg,min,sec)</th>
<th>ELEV (ft)</th>
<th>TOWER HEIGHT (m)</th>
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</tbody>
</table>
Although that radar represents better spatial rainfall variability compared with rain gauge networks, there are limitations of radar estimates due to data contamination and uncertainty issues such as hail particles, large raindrops, or melting. Also, underestimation occurs due to small raindrops, dry ice, attenuation, truncation error, and beam blockage (Smith et al., 1996; Legates, 2000; Xie et al., 2006).

Weather Surveillance Radar (WSR) data from the National Centers for Environmental Prediction (NCEP) have been used to analyze Hourly Digital Precipitation (HDP) radar estimates. The HDP data are stored in UNIX compressed (.Z) Gridded Binary data (GRIB) format. Each record has information such as resolution of the grid, time, variable, and level which created the field. In order to read the GRIB data, these data have to be compiled and run on a wide variety of UNIX platform decoding programs. R-program has been used for data manipulation, calculation and graphical display. The R-outputs are in garden-variety spreadsheets but with a Comma Separated Values extension (CSV).

As in rain gauges, an estimation of the values of intermediate points of independent variables (Radar Readings) is required to interpolate these values into numerical data. The Kriging Interpolation (KI) method has been used to construct new intermediate data points within the range of a discrete set of known precipitation data points. KI is a geostatistical method that generates or interpolates a probability surface that fits best to a scattered set of point values in two-dimensional space. It is different from other interpolation methods (Spatial Analyst tools) supported by R software and ArcGIS. It involves interactive investigation of the spatial behavior of the point values to generate best estimation for the output surface.

**Results and Analysis**

The following analysis of rainfall data in the various regions in Texas in 2015 is based on rain gauge trend analysis (Figures 34-45) and weather radar trend analysis (Figures 46-57).

- The rain gauge trend analysis shows the actual rainfall, monthly, as measured by the NCDC and USGS gauges. After each chart, there is an analysis of the data with a comparison of the monthly rainfall to the average yearly (2015) rainfall of 3.96 inches.

- The weather radar analysis shows the amount of rainfall measured by NOAA – MPE radar for each month with an analysis of the data for each month to map the precipitation from remotely sensed measurements during that month.

- After the analysis of the data from the rain gauges and radar sensors, there is a comparison between rain gauge rainfalls and weather radar estimates measured in Texas -2015. The comparison between the estimate from the network of rain and the weather radar to shows the deficiency between them then due to systematic errors such as the blockage of radar and sampling problems for both of them.

- Finally, the analysis of rain gauges across Texas indicates where rainfall records were broken in 2015 and posted their highest totals for 121 years of archived records. This also shows how Texas had an extreme rainfall in 2015, which lead to floods and disasters in 24 counties across Texas.
4.1 Rain Gauge Trend Analysis in 2015

![Rain Gauge Trend Analysis in 2015](image)

Figure 32 USGS & NCDC Rain Gauge Readings in January 2015

Figure 32 show that the northern part of Texas received the least amount of rainfall in January 2015. Some parts of east Texas received more rainfall compared to the other regions of Texas. In general, January 2015 was classified as a slightly dry month with a Palmer Drought Severity Index (PDSI) of 0.8 as shown in Figure 32. The average rainfall in January was 3.27 inches, which was 0.69 inches below the annual average rainfall of 3.96 inches.
The northern, western and west southern regions of Texas received the least amount of rainfall in February 2015. Figure 3 shows that some parts of east Texas received more amount of rainfall compared to all parts of Texas. In general, February 2015 was classified as slightly dry month with a Palmer Drought Severity Index (PDSI) of 0.5 as shown in Figure 30. The average rainfall in February was 1.241 inches, which is 2.719 inches below the annual average rainfall of 3.96 inches.

Figure 3 USGS & NCDC Rain Gauge Readings in February 2015
The northern part of Texas was drier than the north central, western and southern parts of Texas. Figure 3 shows that eastern region was wetter compared to other regions of Texas. In general, March 2015 was classified as an Abnormally Moist month with a Palmer Drought Severity Index (PDSI) of 0.5 as shown in Figure 30. The average rainfall in March was 3.904 inches. This amount is approximately the same 0.056 inches below the annual average rainfall of 3.96 inches.

Figure 34 USGS & NCDC Rain Gauge Readings in March 2015
Figure 35 shows April 2015 rainfall trend in Texas. In general, April 2015 was classified as a wet month with a Palmer Drought Severity Index (PDSI) of 2.1 as shown in Figure 30; the average rainfall in April was 4.67 inches. This amount is 0.71 above the annual average rainfall of 3.96 inches.
Figure 3 shows May 2015 rainfall trend in Texas. All regions of Texas received a rainfall in this month. In general, May 2015 was classified as Excessively Wet month with a Palmer Drought Severity Index (PDSI) of 4.8 as shown in Figure 3. The average rainfall in May was 10.8 inches. This amount is 6.84 inches above the annual average rainfall of 3.96 inches) been recorded in 2015.
Figure 37 shows June 2015 rainfall trend in Texas. The eastern region of Texas received a rainfall between 2.0 to 8.0 inches in this month compared to the north, central western and southern parts of Texas, which received from 0.0 to 4.0 inches. In general, June 2015 was classified as Excessively Wet month with a Palmer Drought Severity Index (PDSI) of 4.8 as shown in Figure 30. The average rainfall in June was 4.17 inches. This amount is 0.21 inches above the annual average rainfall of 3.96 inches been recorded in 2015.
Figure 38 shows July 2015 rainfall trend in Texas. The eastern and southern regions of Texas received a rainfall between 0.0 to 3.0 inches in this month compared to north, central western and western parts of Texas, which received from 1.0 to 5.0 inches, and some parts from 5 to 10 inches. In general, July 2015 was classified as near normal in the east to different degrees of wettest month with a Palmer Drought Severity Index (PDSI) of 5.0 as shown in Figure 30. The average rainfall in June was 1.354 inches. This amount is 2.606 inches below the annual average rainfall of 3.96 inches been recorded in 2015.
Figure 39 shows August 2015 rainfall trend in Texas. The north and southeast eastern regions of Texas received a rainfall between 4.0 to 8.0 inches in this month compared to other regions of Texas, which received from 0.0 to 4.0 inches. In general, August 2015 was classified as mildly dry to extremely wet month with a Palmer Drought Severity Index (PDSI) of 4.0 as shown in Figure 30. The average rainfall in August was 1.36 inches. This amount is below 2.60 inches the annual average rainfall 3.96 inches been recorded in 2015.
Figure 40 presents September 2015 rainfall trend in Texas. The southeast regions of Texas received a rainfall between 2.0 to 8.0 inches in this month compared to other regions of Texas, which received from 0.0 to 4.0 inches. In general, September 2015 was classified as severely dry to extremely wet month with a Palmer Drought Severity Index (PDSI) of 3.8 as shown in Figure 30. The average rainfall in August was 1.47 inches. This amount is 2.49 inches below the annual average rainfall 3.96 inches been recorded in 2015.
Figure 4 shows October 2015 rainfall trend in Texas. The south and east regions of Texas received a rainfall between 6.0 to 14.0 inches in this month compared to other regions of Texas, which received from 0.0 to 6.0 inches. In general, October 2015 was classified as mild drought to extremely wet month with a Palmer Drought Severity Index (PDSI) of 4.0 as shown in Figure 3. The average rainfall in August was 7.74 inches. This amount is 3.78 inches above the annual average rainfall 3.96 inches been recorded in 2015.
Figure 42 USGS & NCDC Rain Gauge Readings in November 2015

Figure 42 shows November 2015 rainfall trend in Texas. The east and central regions of Texas received a rainfall between 6.0 to 18.0 inches in this month compared to other regions of Texas, which received from 0.0 to 6.0 inches. In general, November 2015 was classified as slightly too extremely wet month with a Palmer Drought Severity Index (PDSI) of 4.5 as shown in Figure 30. The average rainfall in August was 4.52 inches. This amount is 0.56 inches above the annual average rainfall 3.96 inches been recorded in 2015.
Figure 4 shows December 2015 rainfall trend in Texas. The east and central regions of Texas received a rainfall between 4.0 to 18.0 inches in this month compared to other regions of Texas, which received from 0.0 to 4.0 inches. In general, November 2015 was classified as slightly too extremely wet month with a Palmer Drought Severity Index (PDSI) of 4.8 as shown in Figure 30. The average rainfall in August was 3.07 inches. This amount is below 0.89 inches the annual average rainfall 3.96 inches been recorded in 2015.

Figure 43 USGS & NCDC Rain Gauge Readings in December 2015

Figure 43 shows December 2015 rainfall trend in Texas. The east and central regions of Texas received a rainfall between 4.0 to 18.0 inches in this month compared to other regions of Texas, which received from 0.0 to 4.0 inches. In general, November 2015 was classified as slightly too extremely wet month with a Palmer Drought Severity Index (PDSI) of 4.8 as shown in Figure 30. The average rainfall in August was 3.07 inches. This amount is below 0.89 inches the annual average rainfall 3.96 inches been recorded in 2015.
4.2 Weather Radar Trend Analysis in 2015

Figure 4

Figure 4 shows the actual amount of rainfall in January 2015 as measured by NEXRAD Radar sensors provide the differences in precipitation distribution in all the regions. The central and southern regions of Texas received rainfall from 40 mm to 140 mm (1.57 to 5.51 inches). The east regions of Texas received a rainfall from 100 mm to 260 mm (3.93 to 10.23 inches). The west and northern regions of Texas received the least amount of rain compared to all the other regions of Texas from 00 mm to 100 mm (0.0 to 3.93 inches).
Figure 45 NOAA Weather Radar Readings in February 2015

Figure 45 shows the actual amount of rainfall in February 2015 as measured by NEXRAD Radar sensors provide the differences in precipitation distribution in all the regions. The southern region of Texas received a rainfall from 10 mm to 50 mm (0.9 to 1.96 inches). The east regions of Texas received a rainfall from 40 mm to 120 mm (1.57 to 4.72 inches). The north, central and west regions of Texas received the least amount of rain compared to all regions of Texas from 00 mm to 50 mm (0.0 to 1.96 inches).

Figure 46 NOAA Weather Radar Readings in March 2015
Figure 46 shows the actual amount of rainfall in March 2015 as measured by NEXRAD Radar sensors provide the differences in precipitation distribution in all the regions. The east and south regions of Texas received a rainfall from 100 mm to 350 mm (3.93 to 13.77 inches). The central region of Texas received a rainfall from 50 mm to 100 mm (1.96 to 3.93 inches). The north and west regions of Texas received the least amount of rain compared to all regions of Texas from 00 mm to 100 mm (0.0 to 3.93 inches).

Figure 47 NOAA Weather Radar Readings in April 2015

Figure 47 shows the actual amount of rainfall in April 2015 as measured by NEXRAD Radar sensors provide the differences in precipitation distribution in all the regions. The east and south regions of Texas have received a rainfall from 100 mm to 400 mm (3.93 to 15.78 inches). The central and north regions of Texas received a rainfall from 50 mm to 250 mm (1.96 to 9.84 inches). The west region of Texas received the least amount of rain compared to all regions of Texas from 00 mm to 100 mm (0.0 to 3.93 inches).
Figure 48 NOAA Weather Radar Readings in May 2015

Figure 48 shows the actual amount of rainfall in May 2015 as measured by NEXRAD Radar sensors provide the differences in precipitation distribution in all the regions. All regions of Texas excluding the west region of Texas received a rainfall from 150 mm to 700 mm (3.93 to 15.78 inches). The west region of Texas received the least amount of rain compared to all regions of Texas from 00 mm to 150 mm (0.0 to 5.9 inches).

Figure 49 NOAA Weather Radar Readings in June 2015
Figure 49 shows the actual amount of rainfall in June 2015 as measured by NEXRAD Radar sensors provide the differences in precipitation distribution in all the regions. In general, all regions of Texas received a rainfall from 50 mm to 450 mm (1.96 to 17.71 inches).

Figure 50 NOA Weather Radar Readings in July 2015

Figure 50 shows the actual amount of rainfall in July 2015 as measured by NEXRAD Radar sensors provide the differences in precipitation distribution in all the regions. The north and west regions of Texas received a rainfall from 50 mm to 300 mm (1.96 to 11.81 inches). The east and south regions of Texas has received the least amount of rain compared to all parts of Texas from 00 mm to 100 mm (0.0 to 3.93 inches).

Figure 51 NOA Weather Radar Readings in August 2015
Figure 51 shows the actual amount of rainfall in August 2015 as measured by NEXRAD Radar sensors provide the differences in precipitation distribution in all the regions. In general, all regions of Texas received a rainfall from 00 mm to 140 mm (00 to 5.51 inches) except the coast with Gulf of Mexico, which received rainfall from 120 mm to 260 mm (4.72 to 10.23 inches).

![September rainfall map](image)

**Figure 52 NOAA Weather Radar Readings in September 2015**

Figure 52 shows the actual amount of rainfall in September 2015 as measured by NEXRAD Radar sensors provide the differences in precipitation distribution in all the regions. In general, all regions of Texas received a rainfall from 00 mm to 100 mm (00 to 3.93 inches) except the regions along and adjacent to the coast of Mexico Gulf, which received rainfall from 100 mm to 350 mm (3.93 to 13.77 inches).

![October rainfall map](image)

**Figure 53 NOAA Weather Radar Readings in October 2015**
Figure 53 shows the actual amount of rainfall in October 2015 as measured by NEXRAD Radar sensors provide the differences in precipitation distribution in all the regions. In general, all regions of Texas received a rainfall from 50 mm to 250 mm (1.96 to 9.84 inches) except some regions in the east and close to the Gulf of Mexico, which received rainfall from 200 mm to 600 mm (7.87 to 23.62 inches).

![Figure 53](image1.png)

**Figure 53 NOAA Weather Radar Readings in November 2015**

Figure 54 shows the actual amount of rainfall in November 2015 as measured by NEXRAD Radar sensors provide the differences in precipitation distribution in all the regions. In general, all regions of Texas received a rainfall from 0 mm to 150 mm (00 to 5.9 inches) except some regions in the east, which received rainfall from 150 mm to 400 mm (5.9 to 15.74 inches).

![Figure 54](image2.png)

**Figure 54 NOAA Weather Radar Readings in November 2015**

Figure 55 shows the actual amount of rainfall in December 2015 as measured by NEXRAD Radar sensors provide the differences in precipitation distribution in all the regions. In general, all regions of Texas received a rainfall from 0 mm to 150 mm (00 to 5.9 inches) except some regions in the east, which received rainfall from 150 mm to 400 mm (5.9 to 15.74 inches).

![Figure 55](image3.png)

**Figure 55 NOAA Weather Radar Readings in December 2015**
Figure 5 shows the actual amount of rainfall in December 2015 as measured by NEXRAD Radar sensors. The differences in precipitation distribution in all the regions are provided. In general, all regions of Texas received a rainfall from 0 mm to 100 mm (0 to 3.93 inches) except some regions in the east, which received rainfall from 150 mm to 400 mm (5.9 to 15.74 inches).

**Comparison between Rain Gauge Rainfalls Measured and Radar Estimates in Texas -2015**

Both rain gauges and weather radar sensors constitute important devices for operational precipitation monitoring. Gauges provide accurate yet spotty precipitation estimates, while radar sensors offer high temporal and spatial resolution yet at a limited absolute accuracy. The deficiency between both can be calibrated in future studies in order to improve the quantitative precipitation estimation (QPE) in the area of interest.

The data for this research is based on the Next Generation Weather Radar (NEXRAD) system across Texas run by the National Weather Service (NWS). This includes 13 WSR88D (Weather Surveillance Radar-1988 Doppler) radar sensors, and 1011 rain gauges within weather stations run by NCDC and USGS. The comparison between both methods aims to provide a general overview of the benefits resulting from integrated analysis of radar and rain gauge information and to assess the relationships between the two types of data in Texas during 2015.

**Figure 56 Weather Radar Verse Rain Gauges in Texas- 2015**

Figure 56 shows the difference between the data from rain gauges verses weather radar sensors. Although there is a difference in readings between the weather radar curve and the rain gauge curve, both readings fluctuate approximately in the same wave. In general, the significant difference between the two is related to topographic interference with the radar outcomes leading to differences between radar and rain gage readings. Another factor is the radar location, as the standard deviation increases more dramatically after a certain distance of miles (Espinosa, 2015).
Xie et al. (2006) pointed out in their study that among the 10 gauge radar pairs, there were seven pairs that gauged rainfall with larger value than MPE, while there were three pairs that MPE had with larger values than the rain gauges. This was due to great spatial variation of storm rainfall; a large rainfall rate observed by the rain gauges may not have represented the real average rainfall within a radar cell, resulting in a great difference between the gauge and radar observations.

The current research provides the output validation of radar readings that are used to predict the rainfall measured by rain gauges amounts as shown in Figure 57. In order to fix the difference between radar and rain gauges readings, it is essential to calibrate radar datasets using available rain gage readings (absolute amount) in order to manipulate rainfall observations between rain gages using the spatial variation observed in the radar readings.

![Figure 57 Fitness Correlations between Weather Radar V Rain Gauges in Texas -2015](image)

**Record Breaking Rainfall in Texas – 2015**

Figure 58 shows the NOAA and USGS stations that subsequently indicated the areas and zones where rainfall records were broken in 2015. (509) rain gauges across Texas broke rainfall records in 2015 since 1895, according to the April precipitation summary released by the National Weather Service last week.

The unusual weather events in Texas during 2015 were one of the factors behind breaking rainfall records. Texas had three extremes rainfall and flooding that really boosted the rainfall numbers in May (23-24) and (24-25 and 30-31) October in 2015. The storm in October 24th and 25th was at the upper level trough combined with a cold front and copious moisture produced heavy rainfall across much of south central Texas The heaviest rainfall amounts were generally along and east of the Interstate 35 corridor, where 4 to 6 inch amounts were common. Some of the highest recorded totals were 14.45” near Fayetteville (Fayette County), 11.81” near Anderson Mill (Travis County) and 11.08” near La Grange (Fayette County). In October 30 and 31, the A warm front combined with an upper level trough and abundant moisture produced heavy rainfall and severe weather across much of south central Texas caused a big flood.
Conclusion and Recommendations

Precipitation trends generally appeared to increase throughout the state of Texas in 2015. There was a strong correlation between the Palmer Drought Severity Index (PDSI) and the Standardized Precipitation Index (SPI) even with precipitation varying monthly. Additionally, it showed a transition from an overall decrease in west Texas to an overall increase in east Texas. This contributed to one aspect of the study’s goal: to show the combined effects of the two cycles, El Niño-Southern Oscillation (ENSO) cycle and the cold phase of La Niña (NENSO), both of which limited or increased rainfall throughout the state during 2015.

In regard to the distribution trends of the rain gauges, Figures 32 to 43 showed prolonged variability in total monthly rainfall received over each (climatic region). Furthermore, the months of May and October were the wettest month in 2015 respectively. The next wettest months were April, November and June respectively.

In regard to the monthly weather radar distribution trends throughout the state as shown in Figures 44 to 55, they matched the overall results of the rain gauges, but with a deviation in the amount of total rainfall recorded as shown in Figures 56. The deviation between weather radar estimations and rain gauge estimations might be explained by possible topographic interference, whereas the elevation differential between radar stations and the rain gauges are because some radio waves are interrupted by the intervening mountains and therefore, never reach the rain gage locations to interact with the rainfall at specific sites.

In this study, the correlation of such radar estimates of rainfall to actual rain gauge dataset was examined on monthly bases for all of 2015. Figure 57 compares the radar data to actual recorded rainfall at the rain gages in order to find the appropriate adjustment factor (ground truth) for each particular storm event. The coefficient of determination, (R2) was 70.83 %, which is larger than 70 % conforms within an acceptable range based on conclusions by Moore, 2013.
Therefore, the results confirm that the correlation between radar and rain gauges performs reasonably, but the results could be enhanced by undertaking more studies with a different time series to reduce the effect of such factors as topographic interference and ground truthing of Doppler radar estimates. This would improve the prediction of future outcomes.

In regard to the new rainfall records during 2015, Figure 3 shows that based on the data from the rain gauges. There were (503) stations out of 1011 stations that had new rainfall records in 2015 since record keeping began in the state in 1895, and the stations with the new records were concentrated in the north, south and along the Gulf of Mexico. Precipitation patterns are changing, with more infrequent but heavier downpours and sea level rise is putting low-lying coastal communities in particular at Galveston and Houston at increased risk of storms in the future.

**Recommendations**

Extreme rainfall event such as the ones that took place in 2015 can happen any year in Texas. The State should be prepared to mitigate such events and make use of the additional volumes of water that such extreme years can bring. Some measures that can be considered include:

- Forecasts, early warning and response systems should create new models for risk sharing / social protection schemes. In addition, issuing accurate and specific warnings within of a few hours or even a few minutes can minimize the number of fatalities in the zones.

- Engineers and planners should try to modify the susceptibility to flood damage and disruption through designing long-lasting, critical infrastructure that planning for extreme events to the actual risk.

- Development of building codes in floodplain zoning ordinances rather than regular building codes. This can be implemented by setting specifications to anchorage structures to prevent flotation of buildings during floods. In addition, restrict use of materials that deteriorate when wetted and ensure a proper structural design can withstand the effects of water pressure and flood velocities.

- Proper design and location of services and utilities can reduce flood loss potentials. The local governments have to control rapid and unplanned urbanization in hazardous areas, extend roads or sewer and water mains or their access in flood hazard areas. In addition to select location of libraries, schools, post offices, and other public and government facilities away from the flood hazard zones.
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