The Climate of San Angelo, Texas

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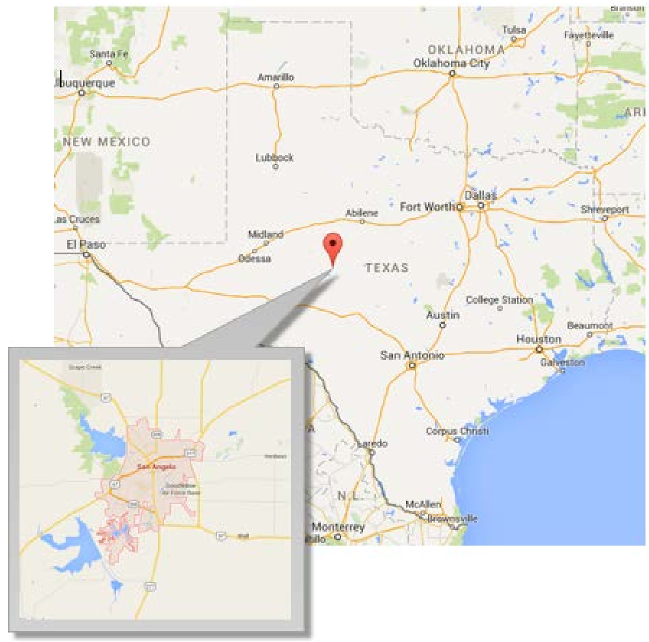
OVERVIEW

The city of San Angelo, TX is situated in the Concho Valley as the principal city inside of Tom Green County, just southeast of the Big Country within West Texas. San Angelo lies alongside the northern boundary of the Chihuahuan desert and the southwestern edge of the Edwards Plateau at an elevation of 1900 feet. The region's landscape consists mainly of grasslands and shrubbery, scattered with trees. The current population is approximately 99,000 and has been slowly increasing over the past several decades. Recently, this population increase has become more rapid, with a 10.1% increase over the past decade, and a 6.2% increase from 2010-2014.

The principal river within the region, the Concho River, is formed within the center of San Angelo by the merging of two rivers: the South Concho River and the North Concho River. The Concho River officially has three feeds, also including the Middle Concho River, merging with the South Concho River south of the city limits. Three lakes also surround the city: Twin Buttes Reservoir, O.C. Fisher Reservoir, and Lake Nasworthy.



The region within San Angelo falls at the boundary of where the weather of Central Texas and West Texas meet, and consists of a hot semi-arid climate, lying within one the most arid regions of Texas. This brings on a generally warmer, dry climate where temperatures average above freezing; however, cold temperatures and winter weather are possible a few times a year. Thunderstorms occur in the spring, summer, and fall, and frequently induce flooding of the rivers, especially after prolonged dryness. Beyond these events, the San Angelo skies are commonly pleasant and blue, consisting of 251 days of sunshine each year.

TEMPERATURE

The average annual temperature in San Angelo is 65 degrees, with an average high temperature of 78 degrees and an average low temperature of 52 degrees. July and August are the hottest months with average daytime maximum temperatures of 95 degrees. January is the coldest month with average maximum temperatures of 60 and nighttime lows of 33 degrees.

Summers (June, July, and August) are hot, ranging from an average high temperature of 94 to an average low temperature of 70. It is not unusual for temperatures to reach 100 degrees, with the city recording this temperature or higher on average 18 days per year. About 1 in 5 years record a maximum temperature of 108 degrees. The highest temperature ever recorded in San Angelo was 111 degrees reached 4 times, on July 15th, 1933, August 4th, 1943, July 27th, 1944, and July 29th, 1960.

In the winter (December, January, and February), temperatures range from an average high of 64 to an average low of 35. Although averages lay above freezing, it is expected for temperatures to drop below 32 degrees each year. On average, the city experiences 50 days with lows below freezing. About 1 in 5 years record a low of 9 degrees. The lowest temperature every recorded in San Angelo was -4 degrees on December 12, 1989.

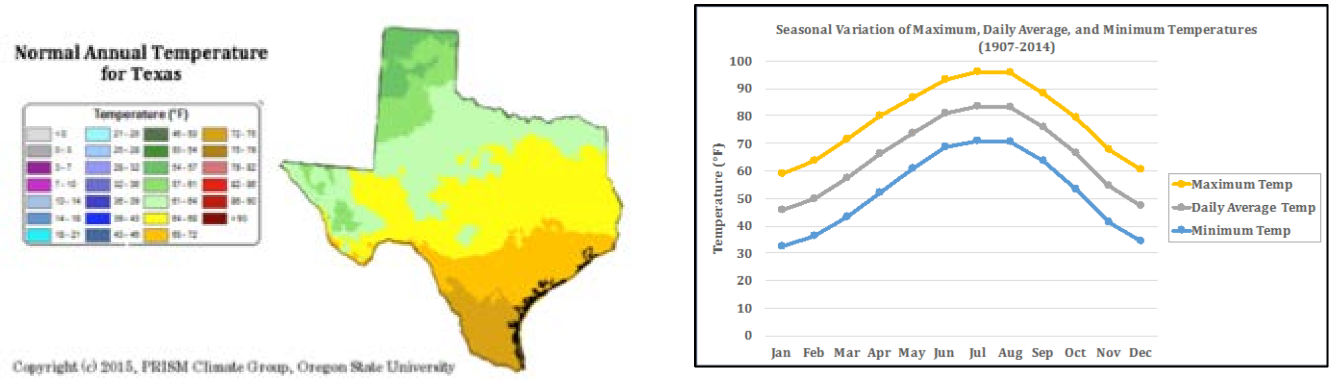


Figure 1: Texas average annual temperature in degrees F (left), and seasonal temperature variations for San Angelo showing maximum (yellow), daily average (gray), and minimum (blue) temperatures (right).

San Angelo averages a growing season of 233 days, with the first frost occurring around November 11 and the last frost occurring around March 26. These first and last freezes making up this growing season have large implications on the economy of the region and are not uncommon, with early autumn or late spring freezes causing tremendous impacts on the agriculture industry. Freezes may occur as early as October 31st and as late as April 11th. The earliest freeze on record was October 16th, 1940, and the latest was April 30th, 1908.

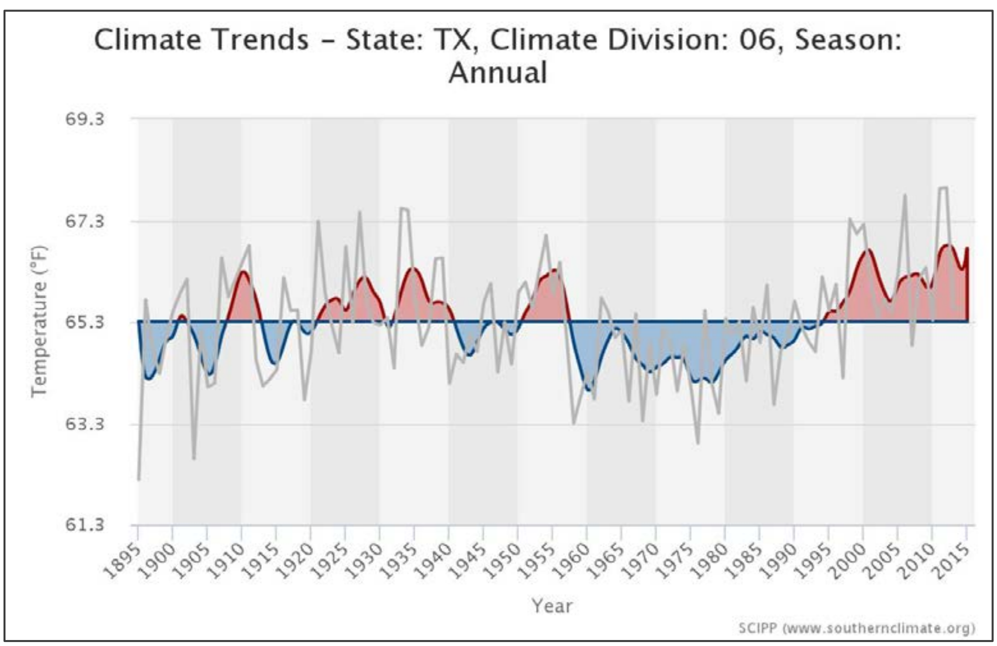


Figure 2: Average annual temperature for Edwards Plateau. Lines indicate annual average temperature from 1895-2015 (degrees F). Colors indicate a 5-year weighted mean temperature that was above (red) or below (blue) the long-term average.

Annual average temperatures can be variable, with temperatures as much as 3 degrees above or below the long-term (1895-2015) average. Although there is large year-to-year variability, the climate record shows extended periods of relatively warmer or colder temperatures. Since the late 1990s, temperatures have generally been running above the long-term average, following three decades of below-average temperatures, although individual years during warm periods can still end below normal and during cold periods can be above normal. The hottest year on record for San Angelo was 2011 (4.3 degrees above the long-term average) and the coldest year on record was 1909 (4.7 degrees below the long-term average).

PRECIPITATION

The average annual rainfall for San Angelo is 21.23 inches. Precipitation amounts vary per month, with a higher amount of rainfall during the summer and a lower amount during the winter. Most years average between 17 and 24 inches of precipitation. Measurable rainfall or snowfall occurs on average 63 days per year, with 6 days, on average, experiencing more than one inch of precipitation. The wettest months occur over May and October, reaching close to 3 inches. On the lower end, the driest months occur during December and January, with amounts as little as 0.88 inches. The greatest daily rainfall was 11.75 inches recorded on September 15, 1936. The most rainfall in a single month was 27.65 inches in September of 1936. The greatest annual rainfall was 40.88 inches in 1919. The lowest annual rainfall was 7.41 inches in 1956.

Although winter precipitation is not prevalent, on average it is experienced a couple of times per year. Snowfall is most common during the month of January, but can occur between the months of November and April. Most winters will have up to 2 inches of snow, with about one in four years receiving 4 or more inches. The overall average is 2.6 inches per year, falling on about 1 day per year. The most snow on a single day was 10.0 inches on January 16, 1919. The most snow in a single month was 13 inches in both January of 1926 and February of 1924. The most snow in a single year was 14.0 inches in 1926.

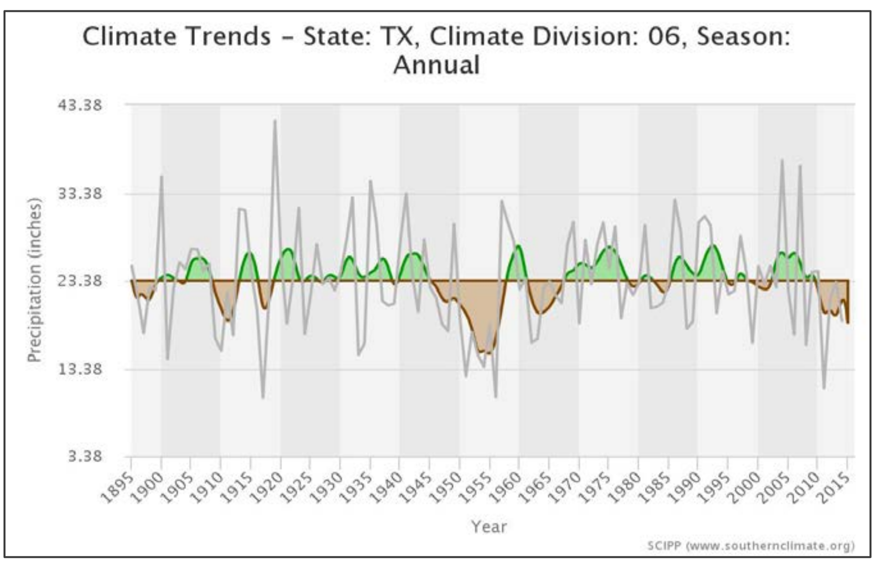


Figure 3: Annual precipitation for Edwards Plateau. Lines indicate total annual precipitation for each year from 1895-2015 (inches). Colors show weighted 5-year mean that was above normal (green) or below normal (brown).

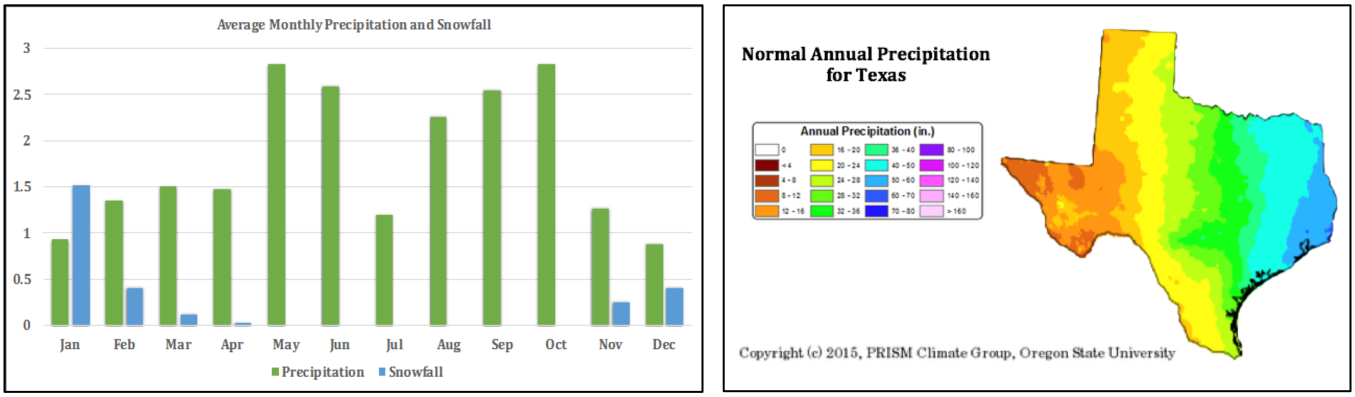


Figure 4: Average monthly precipitation (green) and snow (blue) for San Angelo (left), and average annual precipitation for Texas (right). Averages are based on data from 1981-2010 (in inches).

OTHER VARIABLES

Additional weather variables that affect San Angelo regularly include wind, relative humidity, and percent of cloud cover. Due to the flat terrain surrounding San Angelo, this region commonly experiences windy conditions. Generally, winds are dominant from the south, averaging 9.8 mph. Wind speeds greater than 15 mph occur out of this direction about 8% of the time. Alternatively, winds are considered calm 7.4% of the time. Winds tend to be most variable during the winter months, as well as having the highest prolonged speeds. Spring months commonly consist of high wind gusts associated with frontal systems, with April averaging the highest at 11.5 mph. The highest recorded wind gust was 81 mph on May 15, 1975.

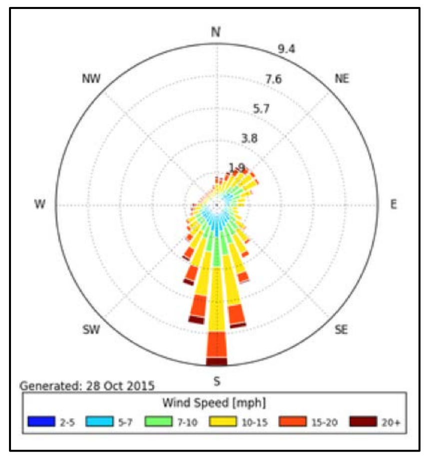


Figure 5: San Angelo wind rose, showing the annual distribution of wind direction and speed for the city.

Relative humidity, on average, ranges from 56-65% during the year. Humidity tends to be lower in the early spring and summer months, averaging down to 46%. Winter months and early spring tend to be cloudier than the rest of the year. The percentage of possible sunshine ranges from an average of about 55% in winter to about 75% in summer, with a yearly average of about 68%.

EXTREME WEATHER EVENTS

The region of West Texas experiences a wide variety of extreme weather events due to its location within the Central US. Hot and dry conditions lead commonly to heat waves, drought, and wildfires. The city's location is also far enough north to experience the southern edge of cold fronts that occur in the fall, winter and spring, and close enough to the Gulf of Mexico to have a plentiful supply of moisture to fuel storms. This combination produces severe storms, tornadoes, heavy rainfall with associated flooding, and winter storms.

Tornadoes

Although historically the threat for tornadoes is relatively low in San Angelo, there have been numerous lower level (EF0 or EF1) tornado outbreaks within Tom Green County. Significant tornadoes (defined as EF2 or greater on a scale from EF0 to EF5) are more rare, occurring only 4 times within the county since 1950. Tornadoes of EF2 or greater strength are more capable of doing significant damage resulting in injuries or fatalities.

Since 1950, West Central Texas has experienced 6 "violent" tornadoes (EF4-EF5), one of which hit Tom Green County. Known as "The Lakeview Tornado," this event was recorded as the deadliest tornado within the National Weather Service San Angelo County Warning Area since 1950. Measured as an EF4 tornado on May 11^{th}, 1953, the path struck northern San Angelo, recording up to ½ mile wide and traveling almost 10 miles. Overall, the tornado caused 13 fatalities, 159 injuries and $3.4 million in damages within Tom Green County. A few hours later, this storm produced an EF5 tornado in Waco, increasing the total fatalities to 510, ranking it as the deadliest tornado day in Texas up until 2011.

Table 1: Significant tornadoes (F2/EF2 intensity or greater) occurring in Tom Green County since 1880. Information on tornadoes prior to 1950 is not as complete because the National Weather Service did not keep systematic records until later.

Date	Time	Magnitude	Length	Width	Injuries	Deaths
5/11/1953	2:15 pm	F4	9.9 Miles	880 Yards	159	13
4/30/1952	6:30 pm	F3	0.5 Miles	100 Yards	6	0
5/14/1995	6:44 pm	F3	5 Miles	100 Yards	0	0
3/10/1973	1:40am	F2	0.3 Miles	70 Yards	7	1

Thunderstorms

Thunderstorms occur on about 35 days each year, predominantly in the spring and summer. Most of these are not severe. Severe thunderstorms are defined as having hail of one inch diameter or larger, winds of 50 knots (57 mph) or greater, or tornadoes. Of these, wind is the most common threat. Severe wind speeds occur within 25 miles of San Angelo on about 4 days per year. Of those, severe wind speeds of at least 70mph occur about once a year. According to records from the Storm Prediction Center, 384 severe thunderstorm wind events were recorded on a total of 166 days between 1955 and 2015. The highest recorded non-tornado wind speed in Tom Green County was 95 mph recorded in San Angelo in 2014.

Typically, there are about two days per year of hail exceeding one inch in diameter. From 1955-2014, 479 severe hail reports were recorded in Tom Green County, occurring on 212 days. Very large hail of 2-inch diameter or greater accounts for 10% of events, with 49 recorded events on 29 days. The largest hailstone was 5 inches in diameter, recorded in 1966.

As information collection improves, the number of severe storm events has increased. This is attributable to more systematic reporting, proliferation of observers (including media and storm chasers), and easier reporting methodologies such as smart-phone apps. Consequently, trends in the number of tornadoes, hail or wind events should be investigated closely and not necessarily attributed to changes in the actual frequency of events. However, damaging events such as EF2 tornadoes, 2-inch hail or 70 mph winds do not show observation trends as strongly; therefore, frequency of such events from early in the record may be compared to more recent frequency.

Flooding

Intermittently between the dry conditions of San Angelo, rainfall will occur, most commonly associated with thunderstorms in the spring and fall. The majority of this rainfall will consist of short bursts of heavy rain, and combined with the usually dry ground, flash flooding is the biggest threat. Areas particularly susceptible to this excessive rainfall include low water crossings located throughout San Angelo and greater Tom Green County. Flash flooding has occurred on average 4 times per year, and consists of 96% of all the flooding accounts since 1997. Tropical storms bringing heavy moisture from the gulf are commonly the cause of inducing this heavy onset of rain. One-day rainfall amounts average 2.7 inches of rain per event, with events of 2 inches or greater occurring on average once a year. Heavier one-day rainfall amounts equaling 4 inches or greater are rare, occurring on average 1 out of every 12 years.

Additionally, due to the presence of the South and North Concho Rivers flowing through the city, flash flooding can occur abruptly. In fact, the early progression of San Angelo is said by some to be attributed to the flooding of the South Concho River in 1882, where the occurrence of a town being flooded downstream led to the issuance of San Angelo as the county seat for Tom Green County.

Table 2: Top 10 rainfall totals (7-day rainfall amounts) for San Angelo, TX (based on data from 1918-2015)

Rank	Total (in.)	Ending Date
1	25.19	9/23/1936
2	11.40	10/6/1959
3	8.31	9/7/1986
4	7.42	5/29/2014
5	7.31	8/31/1911
6	7.16	6/3/1897
7	7.15	10/4/1927
8	6.97	7/21/1959
9	6.91	6/2/1987
10	6.67	10/13/1981

The most catastrophic flooding event occurred in 1936, when 25.19 inches of rain fell over seven days in September, with a total of 27.65 inches for that month. Additionally, this event holds the record for largest amount of rainfall for a single day, at 11.75 inches on September 15, 1936. Compared to the September rainfall average of 2.55 inches and annual rainfall average of 21.23, this is the most extraordinary amount of rainfall to occur in San Angelo's history. These conditions were a result of the interaction between a strong stationary front, an abundance of tropical moisture, and the remnants of a tropical storm. The event had an estimated damage of over $2 million after only the first 3 days, and prompted the construction of multiple lakes surrounding San Angelo, aiding in the prevention of another devastating flood and providing water during years of drought.

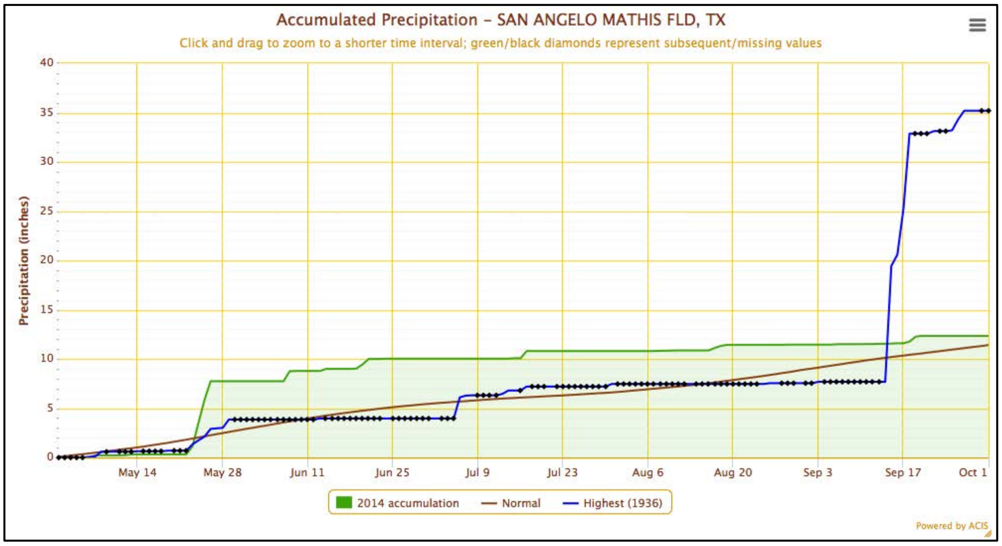


Figure 6: Comparison of the 1936 flood (blue) with the recent flooding in 2014 (green). The brown line indicates the 30-year normal (1981-2010).

Beyond single events of rainfall, sustained rainfall over an extended amount of time can occur in San Angelo. The city occasionally experiences multiple flash flood and heavy rainfall events that, accumulating throughout the year, increase the annual average precipitation above normal. These events can bring both positive and negative effects, as this long-term rainfall can suppress drought conditions and refill lake levels, but also accumulate to additional flooding.

The most recent precipitation events in 2015 revealed that for San Angelo, most of the year measured above normal. During this time, multiple flash-flood events throughout Texas led to a massive excess of rain, relieving much of the state of the five-year drought. The total rainfall for the year of 2015 was 26.79 inches. The pattern of this rainfall can be compared to the rainfall accumulation of 1987, one of the highest recorded precipitation years on record. The annual precipitation in 1987 measured 31.90 inches, falling within the top ten greatest amounts of annual precipitation for San Angelo.

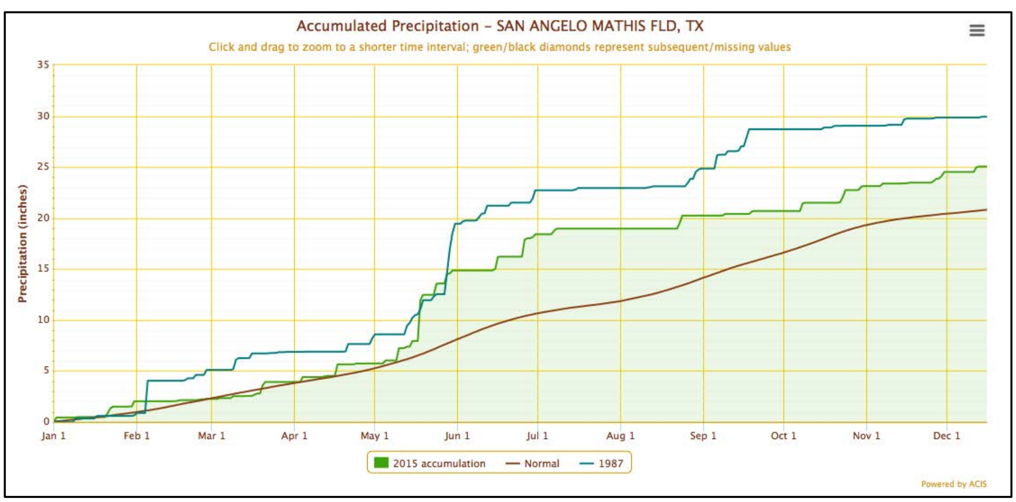
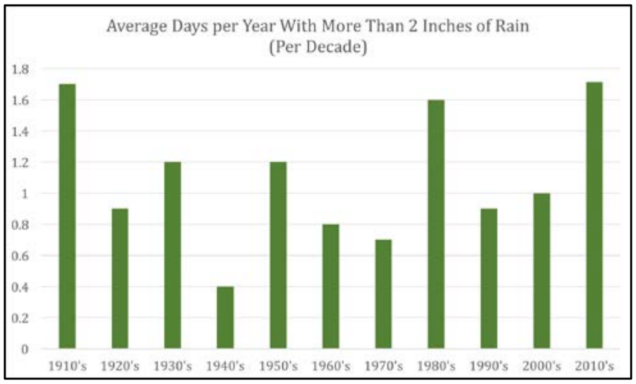
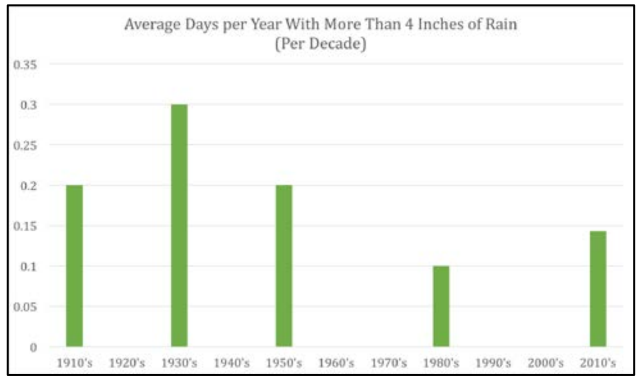


Figure 7: Rainfall accumulation for 2015 (green) compared to 1987 (blue). The brown line indicates the 30-year normal (1981-2010).





with more than two inches (left) and more than four inches (right) of rain.

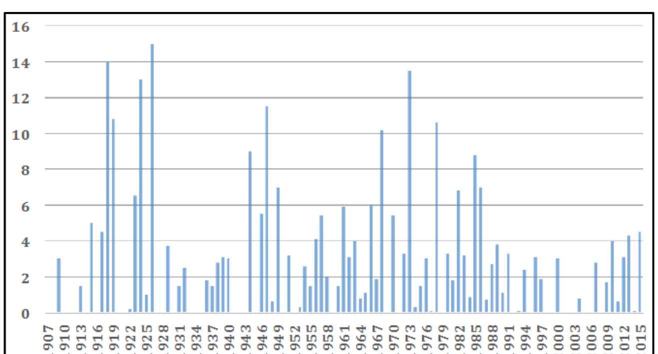
Winter Storms

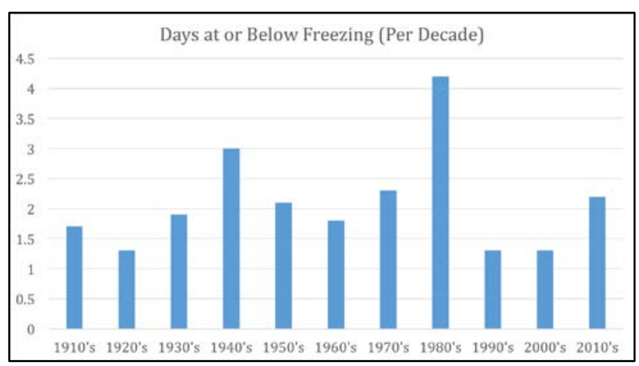
Winter weather activity varies across West Texas. There have been 8 events with heavy snowfall greater than 3 inches in Tom Green County in the last 18 years, however substantial snow amounts often do not reach San Angelo. The most common form of winter precipitation for the city consists of sleet or a mixture of sleet and snow. Occasionally winter storms will bring snowfall totals up to 4 or more inches, but most commonly the heaviest snow is recorded to the north, with San Angelo receiving an average of an inch or less. On average, 1 out of every 5 years will result in a snowfall event of 3 or more inches.

Table 3: Snowfall events of six inches or greater in San Angelo (since 1917).

Amount (in)	Ending Date
13.0	1/24/1926
13.0	2/25/1924
10.8	1/16/1919
9.0	1/14/1944
9.0	1/28/1926
8.8	1/21/1978
8.5	1/02/1947
6.8	1/13/1982
6.5	2/06/1923
6.5	11/27/1918

San Angelo's top 10 highest amounts consist of measurements of 6 inches or more. The greatest snowfall on record occurred in February of 1924 and again just 2 years later in January of 1926, reaching up to 13 inches over 2 days. The greatest snowfall in one day consisted of 10 inches in January of 1919. Although no year since 1982 has recorded an event of 6 inches or more, the years of 2000, 2010, and 2015 all had snowfall events with amounts above 3 inches. While heavy snowfall can impede city operations for an extended time, it typically does not cause much damage to infrastructure. Older structures and those not built to hold the weight of much snow could collapse in the heaviest events. Tree limbs





) and the annual days at or below freezing, per decade (right). Values are for the season ending in the indicated year (for example, 2011 is for the period November 2010 – April 2011).

may catch the snow, especially if it occurs while leaves are still on trees, causing limbs to break resulting in power outages and a threat to those walking underneath.

Ice storms, however, can do much more extensive damage. Snow and sleet will not stick to power lines, while freezing rain will coat the lines, causing them to collapse under the added weight. Multiple ice/sleet/freezing rain events have occurred in San Angelo during the last several decades. Two large, recent, ice storm events occurred during holiday periods in 2007 (April 7) and 2015 (January 1-2), with each producing 1/2 inch of ice across the region and causing numerous power outages, closed roads, and weather-related travel accidents. There seems to have been an increase in frequency since 2000 of ice storms, although records are limited prior to 1996.

Table 4: Major freezing rain and sleet events affecting Tom Green County since 1996. Descriptions of impacts were not routinely recorded in the Storm Event Database by the National Centers for Environmental Information before 1996. Events may have accumulated over more than one day; the date indicates the date on which the event ended.

(Ending) Date	Impacts
3/5/2015	1/5th inch of mostly sleet fell on roadways, closed most school districts.
2/28/2015	Freezing drizzle and rain led to icy roads and numerous accidents. The San Angelo Regional Airport was closed due to icy runways.
1/02/2015	Up to ¼ inch of freezing rain and sleet, conditions shut down transportation, caused over 100 accidents, Texas Community Hospital reached an inadequate amount of beds and staff.
12/05/2013	Up to ½ inch of sleet.
11/24/2013	Up to ¼ inch of freezing rain and sleet, multiple downed tree limbs and power lines.
2/01/2011	Mixture of thunder sleet, freezing rain and snow resulted in up to 1 inch of frozen precipitation, also produced high winds and bitter conditions, multiple water pipes burst and schools were closed area wide.
1/28/2009	Roads were icy with up to ¼ inch of ice.
4/07/2007	Thunder sleet followed by heavy snowfall, prolonged freezing temperatures set several records, and crop and property damages resulted in more than $90,000.
1/15/2007	Freezing rain led up to 2 inches of ice, weight of ice collapsed the Abilene television transmitter.
12/27/2000	Multiple accounts of freezing rain and sleet measuring at least ¼ inch. Some areas received up to 2 inches due to random pockets of thunderstorms.
2/02/1996	Freezing rain and below zero temperatures.

The presence, or lack thereof, of a layer of warm air between the surface and the cloud governs winter precipitation type. If there is an intervening layer of air that is above freezing, that may be sufficient to allow snowflakes and ice crystals falling from the cloud to melt. These liquid drops then re-freeze in the cooler air near the surface. If the warm layer is thin and the cold air near the surface is sufficiently deep, the liquid drops have time to re-freeze before reaching the surface, resulting in sleet or ice pellets. If the warm layer is thicker and the cold layer near the surface is shallow, the liquid drops do not have time to re-freeze and instead freeze on contact with objects on the surface, resulting in freezing rain. Structures above the ground are most susceptible to freezing rain because residual heat stored in the soil may cause the ground to remain above freezing, even as objects just a few inches above the soil are below freezing.

Winter precipitation type is difficult to forecast because there is little real-time data on the vertical profile of the atmosphere. Without this information, the depth or location of a warm layer cannot be determined in advance.

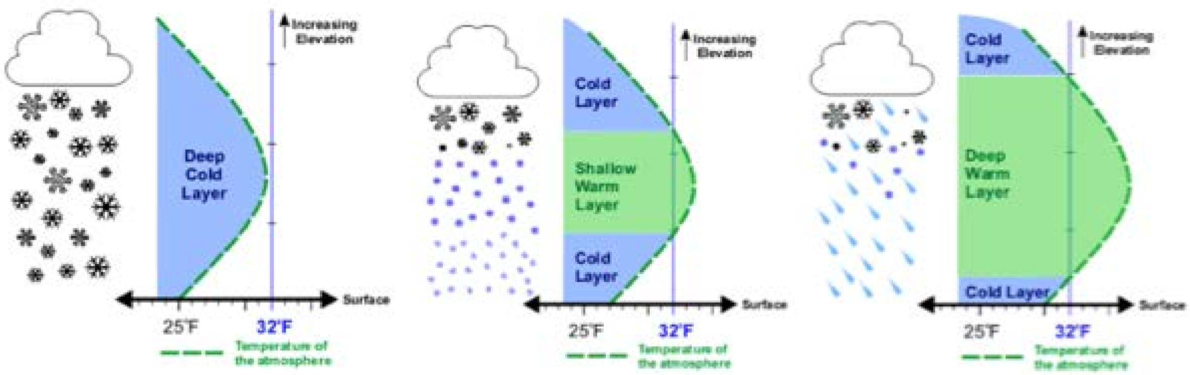


Figure 10: Snow (left) versus sleet (center) versus freezing rain (right) atmospheric profiles. For snow events, the temperature is below freezing throughout the entire layer from the cloud to the ground while for sleet events, there is a shallow layer of warm air that allows snow to melt and then re-freeze into ice pellets. Freezing rain occurs when the cold layer near the ground is too shallow to allow enough time for melted drops to freeze as they fall through; these drops then freeze on contact with the cold surface. *Source: National Weather Service.*

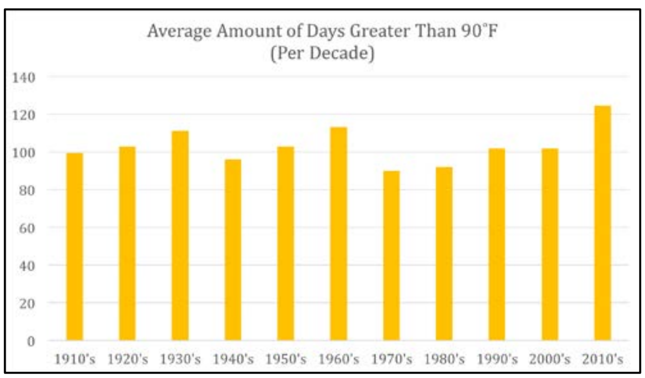
Extreme Heat

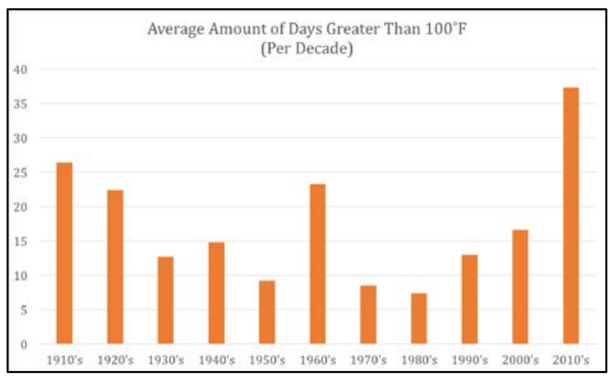
The climate and landscape of West Texas are conducive for excessive heat to occur. During the summer, large areas of high pressure commonly sit over this region, leading to sunny skies and a lack of rainfall. As these conditions persist and temperatures continue to remain hot, they form heat waves. Summers are defined by hot temperatures of 90 degrees or greater, occurring on average 108 times per year. Highs also commonly reach 100 degrees, with an average of 18 days per year in San Angelo. Although less frequently, temperatures may exceed 100 degrees, reaching 105 degrees on average 2 days per year.

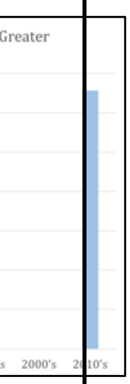
Table 5: Record consecutive days with high temperatures of 100 degrees or greater (1947-2015).

Rank	Most Consecutive Days and Dates of 100 Degrees or Greater (1947 - present)
1	28 (July 2 - July 29, 2011)
2	26 (July 30 - August 24, 2010)
3	18 (June 18 - July 5, 1969)
4	17 (August 15 - August 31, 2011)
5	16 (July 28 - August 12, 2012)
6	16 (June 6 - June 21, 2011)
7	15 (July 27 - August 10, 1970)
8	15 (July 12 - July 26, 1963)
9	14 (August 7 - August 20, 1969)
10	14 (August 2 - August 15, 2015)

Although hot summers are a known fact of living in this region, it does not lessen the impacts to the area. The longer the excessive heat lasts the more complications occur such as adverse health effects, water issues, agriculture impacts, and the onset of drought.







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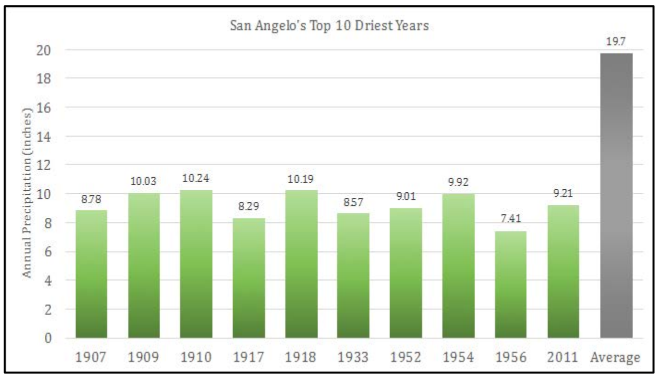
Summer heat impacts can be intensified when nighttime temperatures remain warm, particularly at 80 degrees or greater. These warm nights are not frequent for San Angelo, averaging less than one day per year. Recently however, 2011 surpassed all years on record for amount of warm nights, consisting of 15 days. Further, research has shown that risks for heat related illnesses are higher when there are consecutive days with nighttime temperatures of 80 degrees or greater. There are 9 events on record where 80 degrees occurred consecutively for longer than one day in San Angelo, with the longest at 6 days occurring in 2011. The year of 2011 broke numerous heat records including consistent warmest months on record, 100 days of 100 degrees or higher, and is currently one of the warmest years on record.

Records of temperatures across the region seem to suggest an increase in the occurrence and consecutive measuring of 100-degree days for San Angelo over the last several decades, especially during the last period of drought from 2010-2015. However, the trend of experiencing 100-degree days can be seen to occur in patterns, dating back to the 1900's.

Drought

One of the major derivatives of the excessive heat in San Angelo is the historically persistent drought. With an already low average amount of precipitation at 16.7 inches, San Angelo commonly experiences years that dip far below this number. 1956 is the driest year on record, measuring at only 7.41 inches. Recently, only 9.21 inches was recorded in 2011. The city has experienced 29 drought periods between the years of 1946 and 2012, occurring over an averaged 40% of this time period. Droughts in San Angelo average a duration of 10 months. The longest drought period during this time occurred for 67 consecutive months, from February 1962 until September 1967.



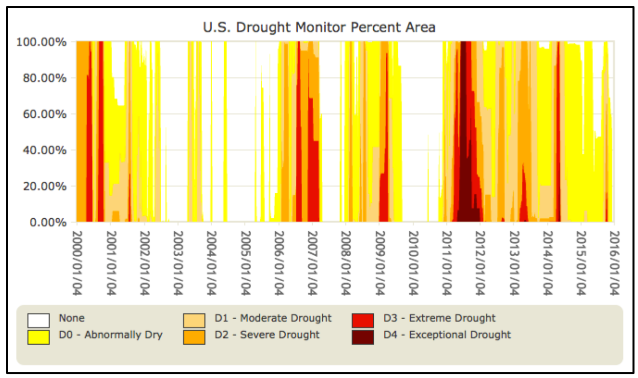


Figure 12: San Angelo's top 10 driest years represented by annual precipitation amounts and compared to average (left), and the percent of area within Tom Green County that has been classified as in a D0-D4 drought category (right) from 2000-2015.

Some of the most severe droughts on record occurred during the years of 1916-1918, 1954-1956, and 2010-2015. Most recently, the drought of 2011 broke numerous records for the city and is currently the most severe drought on record. Along with the record-breaking heat, the entire state of Texas surpassed records including consecutive drought months, driest months, and driest year on record.

The presence of drought has a lasting impression as the region experiences multiple periods of severe drought (D2) or higher. Based on drought records between 2000-2015, San Angelo experiences severe drought (D2) for an average of 20 weeks per year. Similarly, extreme drought (D3) is experienced on average 9 weeks per year, and exceptional drought (D4) is experienced on average 2 weeks per year.

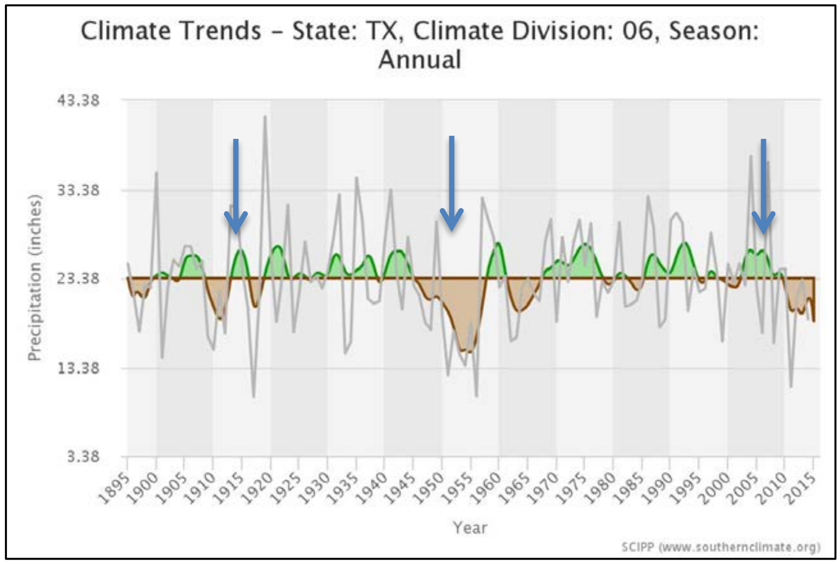


Figure 13: Historical droughts in San Angelo pointed out (blue arrows) on the Annual Precipitation Map of Tom Green County.

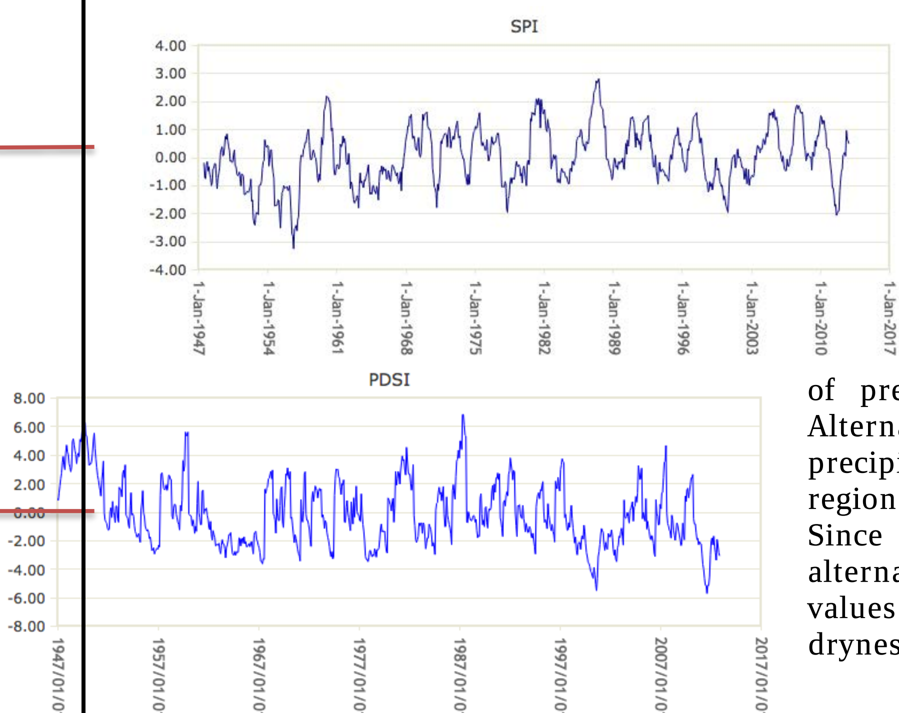


Figure 14: (top) The Standardized Precipitation Index (SPI) and (bottom) the Palmer Drought Severity Index (PDSI). These graphs show the different observed stages compared to normal (red line).

Although the complexity of drought limits the ability to model conditions exactly, indices such as the Standardized Precipitation Index (SPI) and the Palmer Drought Severity Index (PDSI) are used to help monitor drought. The SPI is based on measuring precipitation only, comparing the actual precipitation to the probability of precipitation for the same time period. Alternately, the PDSI is calculated by both precipitation and temperature data, categorizing regions between levels of wetness and dryness. Since 1947, both of these indices display an alternating trend between positive and negative values for San Angelo, signifying periods of both dryness and moisture.

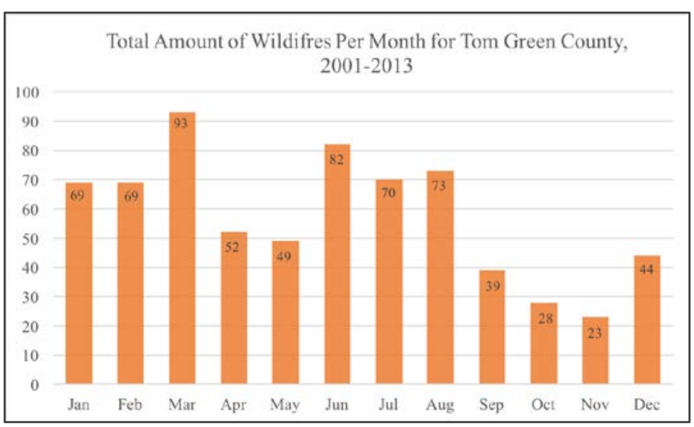
Wildfires

These hot and dry conditions across West Texas, when paired with high winds, are commonly conducive for wildfires to form. Years that experience a wet (identified as 110% of normal) summer followed by a dry (identified as 90% of normal) winter are notably more susceptible to wildfires. This is attributable to the expansive growth of greenery during a season of heavy rainfall, which then turns into a substantial amount of fuel during the succeeding dry winter. Although San Angelo typically experiences a greater density of wildfires outside of the city limits, the damage by these fires can be detrimental to surrounding farmlands. There have been multiple billion-dollar wildfire events in Texas, especially noting the last decade, occurring in 2006, 2008, 2009, 2011, and 2015. During the record-breaking heat and drought in 2011, wildfires burned over 3.7 million acres across Texas that year, averaging a million dollars per day during the spring season in relief efforts. The Wildcat Fire, which forced an evacuation out of the city of San Angelo, occurred during that spring season of wildfires. As the largest wildfire to the hit the city on record, the event burned 159,308 acres over a matter of 20 days, and led to the loss of numerous homes, livestock, and property.

Table 6: Significant wildfires and associated acres burned that have occurred within Tom Green County from 1996-2015.

Date	Acres Burned
4/30/2011	159,308
4/22/2011	12,659
8/19/2015	5,200
6/23/2011	4,300
4/9/2011	2,930
6/23/2011	1,000
2/17/2011	500
8/28/2015	374
1/19/2006	325
12/3/2005	N/A

Wildfires are a natural component of the physical land, providing environmental benefits by shaping vegetation and ecological communities. Fire can be a beneficial tool in maintaining the health of pastures and controlling invasive species such as juniper. Even in extreme drought, prescribed fire can be used safely when daily weather conditions allow. However, these events become a hazard when the damages affect life or property. Since 1996, the frequency of large wildfires has increased, along with an increase of the acres burned per event. Throughout these years, the increase of development within susceptible areas may attribute to the greater risk in damages.



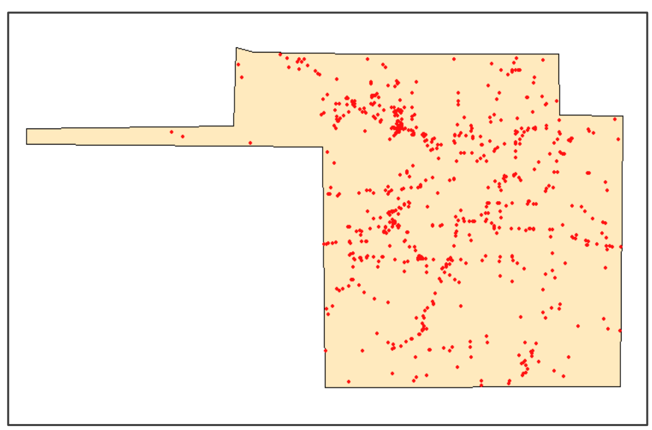


Figure 15: Wildfire occurrences in Tom Green County from 2001-2013 displayed per month (left) and by location (right). *Source: United States Department of Agriculture Forest Service.*

MODELING FUTURE CLIMATE CONDITIONS

For cities and their departments charged with managing and maintaining public infrastructure and services, climate change matters because it introduces changes to the atmosphere that cannot be predicted, based on an asssessment of historical data. Infrastructure, building codes and many other types of planning are all built on the assumption that past climate can reliably predict the range of future conditions expected in a given place: the hundred-year flood event, the risk of summer heat waves, even the length of the growing season. For many decades, that assumption has been relatively accurate. Today, however, climate is changing so rapidly and affecting dynamics in the Earth's climate system so profoundly that, one thing we know for sure is that using the past as a guide to the future will give us the wrong answer.

These rapid changes in the climate system are the motivation for developing long-term climate projections for San Angelo. Through relying on a combination of long-term historical observations, Global Climate Model (GCM) simulations, and "downscaling" methods that transfer the global simulations to time scales and geographic scales that are locally-relevant, it is possible to identify the direction of future trends. For some climate variables, it is even possible to identify the likely magnitude of expected changes, within a range of natural variability, scientific uncertainty, and range of human choices. As we cannot predict human behavior over several decades, specifically related to the emissions of heat-trapping gases, scientists develop projections by running multiple scenarios to learn about how the Earth's climate system will respond to atmospheric changes driven by humans through increased population, and/or increased use of renewable energy or fossil fuels (Walsh et al. 2014). Natural variability is accounted for in these models by the process of averaging climate variables and projected impacts over 20-year periods. However, even though natural variability will continue to occur, by the second half of the century, human choices will become the key determinant of future climate change, through their influence on temperatures and ocean and atmospheric circulation patterns (Walsh et al. 2014).

To produce plausible projections of the future climate of San Angelo, we averaged multiple models, examined projections based on multiple scenarios of emissions of heat-trapping gases, averaged the data over longer (20-year) time periods, and downscaled the global model outputs to locally-relevant scales. Downscaling incorporates new information—in this case, long-term observations from the San Angelo Regional Airport—into GCM projections, to produce local-scale projections of tempreature, precipitation, and other variables at a given location. The confidence in these climate model projections depend on several factors, including but not limited to: certain physical processes not fully understood yet in climate models and small scale processes much smaller than the resolution of current GCM's. Approximations, based on evidence from the best available science, are used to address these issues; however, approximations lead to *scientific uncertainties* in model simulations of climate (Walsh et al. 2014). Since climate models differ in the way they represent various processes, different models produce slightly different projections of change. In this project, we apply the best practice of using 8 different models in order to represent this range of projected outcomes. Research shows that the average of a large set of model simulations is nearly always closer to reality than any individual model or subset of models. To encompass the range of possible futures, we developed projections for San Angelo based on two scenarios of varying emissions amounts, one higher and one lower, as is represented in the graphics below.

CLIMATE PROJECTIONS FOR SAN ANGELO

This section will highlight the specific downscaled projections performed for San Angelo, concentrating on the temperature and precipitation threshold values identified as significant by the community. As mentioned earlier, each threshold projection shown below contains both a higher and lower scenario to account for the range of possible futures. In the figures below, the range of models in the lower scenario is shown in shaded orange, with the mean of the models shown as an orange line, and the range of models in the higher scenario is shown in shaded red, with the mean of the models shown as a red line. The black line in the figures show historical observations from 1950 to 2016. Projections will start to vary greater between the higher and lower scenarios around the year 2050. This report will generally highlight the higher scenario conditions, as current observations and data most resemble this track.

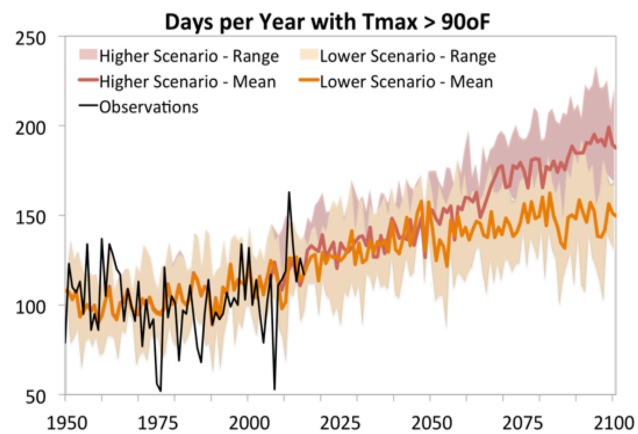
TEMPERATURES

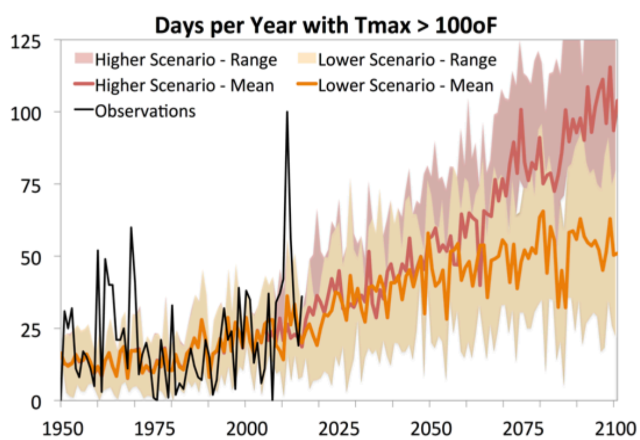
Since the 1950's, temperatures have been increasing across the entire state of Texas. Temperatures in San Angelo are projected to continue to increase, both during the day and at night, along with longer multi-day heat waves.

Daytime Temperatures

San Angelo will experience many more frequent extreme heat days, which is defined by the city as a maximum daily temperature and/or heat index of 90˚F or greater. As stated earlier in this document, extreme daytime temperatures in San Angelo are historically prevalent during the summer, reaching 90˚F on average 108 times per year, 100˚F on average 18 times per year, and less frequently, 105˚F on average 2 times per year. The frequency of these extreme temperatures, notably at 90˚F and 100˚F, have been rising since the early 1990's. This trend is represented by the black line in Figures 16 and 17.

Models project this trend to continue. Figures 16 and 17 also illustrate the projected amount of days San Angelo will experience the temperature thresholds of 90˚F, 100˚F and 105˚F. Under a lower future climate scenario, the number of days at these thresholds will





temperature at or above 90˚F and 100˚F for a lower emissions scenario (orange line) and higher scenario (red line). Shaded areas indicate the range of model projections, and colored lines indicate the average of all models. Black line shows historical observations from 1950-2016.

continue to increase until about the year 2050, at which point the average number for the three thresholds will approximately level off, apart from natural temperature variation. Days at 90˚F or greater will occur on average about 150 times per year, 100˚F or greater will occur on average about 50 times per year, and 105˚F or greater will occur on average about 15 times per year. (Figures 16 and 17, orange line and shaded area).

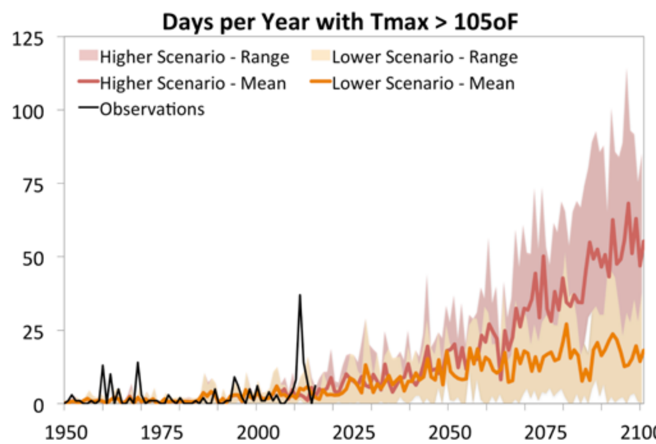


Figure 17: Projection of days with a maximum temperature at or above 105˚F for a lower emissions scenario (orange line) and higher scenario (red line). Shaded areas indicate the range of model projections, and colored lines indicate the average of all models. Black line shows historical observations from 1950-2016.

Temperature changes represented by the higher future climate scenario for days at or greater than 90˚F, 100˚F and 105˚F are similar to the changes projected from the lower scenario until about the year 2050, where the likelihood of all extreme temperatures will continue to increase (Figures 16 and 17, red line and shaded area). Days at 90˚F or greater will occur most commonly, with the average increasing to about 200 days per year by the end of the century, with some years experiencing as many as 225 days per year or as little as 150 days per year.

Similarly, the average amount of days at 100˚F or greater will increase to about 100 days per year, with some years reaching over 125 days per year or as little as 75 days per year. Potentially, the most notable extreme temperature change will be seen in the amount of 105˚F days, as this threshold is currently less frequently experienced. By the end of the century, the average amount of days at 105˚F or greater will occur about 50 times per year, with some years experiencing over 100 days per year or as little as 25 days per year.

Heat Waves

For some decision making in San Angelo, it is not as important to know how many days per year the city reaches a certain temperature, but instead how many *days in a row* the city reaches that temperature. The average length and maximum length of heat waves for San Angelo are projected to increase into the end of the century for temperatures 90˚F and greater. Historically, the average length of heat waves—where each day reaches at least 100°F—is about 3 days. By the year 2050, this is projected to double, based on both low and high climate scenarios, with the average length of 100°F heat waves lasting about 6 days. By the year 2100, the average length of heat waves could be as high as 10 days, based on the higher scenario. The maximum length of heat waves is also projected to increase. Currently, the longest heat waves (in which every day reaches at least 100°F) average about 15 days. By the year 2050, the longest heat waves in which consecutive days have temperatures at or above 100°F will be about 20 days; by 2100 this average will increase to 50 days, with up to 90-day heat waves possible, based on the higher scenario (Figure 18).

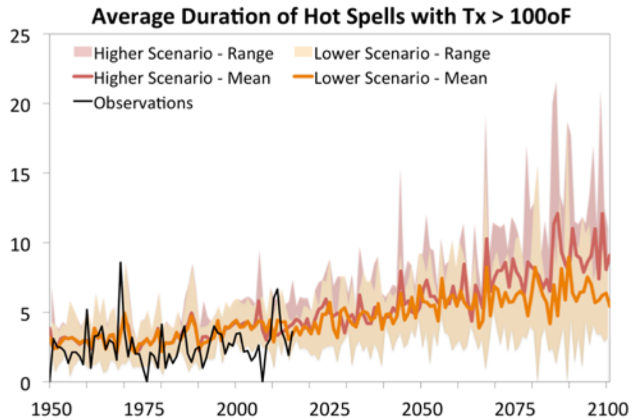


Figure 18: Projections of the average duration of heat waves and maximum length of heat waves, for days at or greater than 100˚F, for a lower climate scenario (orange line) and a higher climate scenario (red line). Shaded areas indicate the range of model projections, and colored lines indicate the average of all models. Black line shows historical observations from 1950-2016.

Similarly, the average length of heat waves of at least 105˚F is also projected to increase. Historically, San Angelo experiences heat waves of at least 105˚F for a length of about 2 days per year. By the year 2100, the average length is expected to double based on higher climate scenarios. Additionally, the maximum length of heat waves will increase from an averaged 5 days historically to about 25 days by 2010, with up to 50-day heat waves possible, based on the higher scenario.

Nighttime temperatures

While maximum temperatures are important for public health, water, and other concerns, greater impacts to public health can be caused by warm nighttime temperatures because there is little opportunity for people, especially the elderly, those who lack adequate cooling or who suffer from an underlying health condition, to recover from the depletion that comes with prolonged exposure to heat. Heat waves, during which the nighttime temperature stays at or above 80°F for multiple days in a row, are projected to increase for San Angelo.

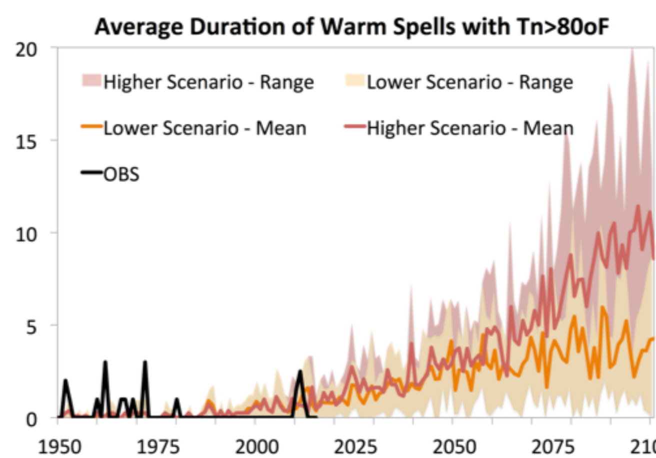


Figure 19: Projections of nights with a minimum temperature at or above 80˚F for a lower climate scenario (orange line) and a higher climate scenario (red line). Shaded areas indicate the range of model projections, and colored lines indicate the average of all models. Black line shows historical observations from 1950-2016.

Although uncommon, the city experiences an average of one day per year where minimum temperatures stay at or above 80°F. Historically since 1907, this has occurred on 39 separate occurrences, with only a quarter of these events lasting longer than one day. By 2050, the average duration in which the temperature does not cool below 80˚F will increase to about 3 consecutive days, and by 2100 this number will rise to about 10 consecutive days, based on the higher scenario (Figure 19).

The longest nighttime heat waves will also become even longer. Currently, the longest heatwave with minimum temperatures of 80˚F or above was 6 consecutive days occurring in 2011. By 2050 the longest heat wave with consecutive days of minimum temperatures staying at or above 80°F will be about 5 days long, and by 2100 this number will increase to an averaged 40 days with as high as 80 days in a row, based on the higher scenario. This many consecutive nights where temperatures do not drop below 80°F, coupled with daytime temperatures above 100°F, could result in many more heat-related illnesses and deaths, and could affect wildlife, the availability and integrity of their habitat, and the functioning of ecosystems.

PRECIPITATION

Although San Angelo has a drier, semi-arid climate, when the city experiences precipitation it is often in the form of an extreme event, such as heavy rainfall or winter precipitation. Unlike with temperature, precipitation in San Angelo is extremely variable and therefore more difficult to identify large trends for the future. Even with this large variability, the models suggest that there may be a slight increase in extreme precipitation events by 2100, which is consistent with atmospheric dynamics, given that warmer air holds more moisture. Generally, there will be a small increase of heavy rainfall events, and a decrease in winter precipitation events.

Heavy Rainfall Events

Previously mentioned, San Angelo most commonly receives rainfall in short downbursts, often leading to flash flooding. One-day rainfall events average 2.7 inches of rain, with events of 2 inches or greater occurring about once a year. One-day rainfall events of 4 inches or greater are rare, occurring 1 out of every 12 years. Although precipitation projections are highly variable,

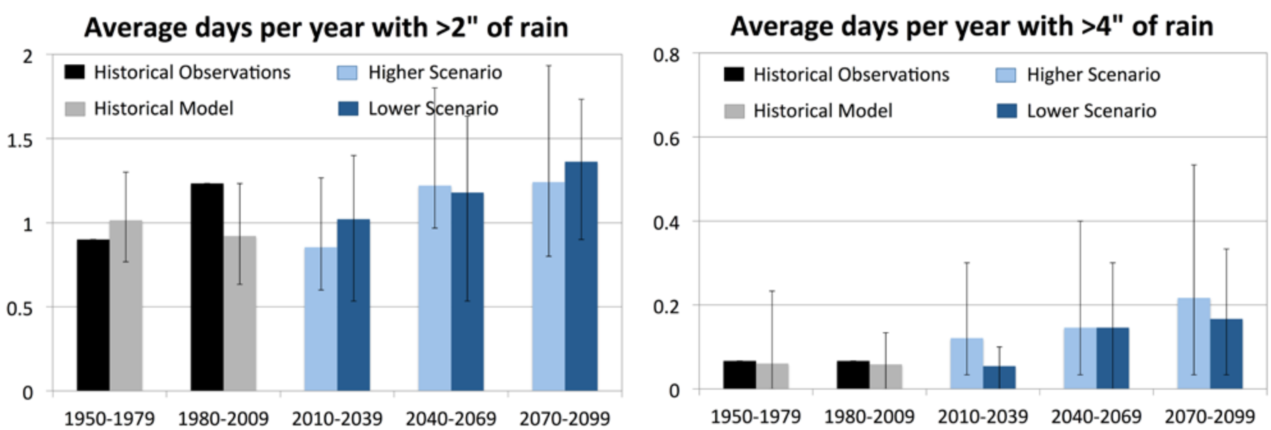


Figure 20: Projections of the number of days per year with precipitation greater than 2.5 inches. Thin black lines show the range in model projections. (Note: 0.5 on the y-axis is equivalent to 1 in 2 years).

there is a trend for a slight increase of 2-inch rainfall events by the turn of the century (Figure 20, left). By 2050, the city may experience as many as 1.5 events per year, and by 2100, it may increase to almost two events per year. Rainfall events of 4 inches or greater will continue to be rare, however, by 2100 these events may occur as frequently as every 4 years (Figure 20, right).

Winter Precipitation

San Angelo receives winter precipitation most commonly in the form of sleet or a mixture of sleet and snow. It is difficult to analyze these varying types of winter precipitation in models; however, we can analyze when precipitation falls on days with cold temperatures. Winter precipitation forms when high temperatures stay at or below 35˚F, therefore models account for days experiencing precipitation when high temperatures were near below 35˚F. Projections show a decrease in the amount of days with cold precipitation, with less than one event per year by 2100 (Figure 21). As precipitation is highly variable, this decrease in winter weather is mostly attributable to the projected decrease in cold temperature days. Therefore, winter precipitation events will still occur, just less frequently.

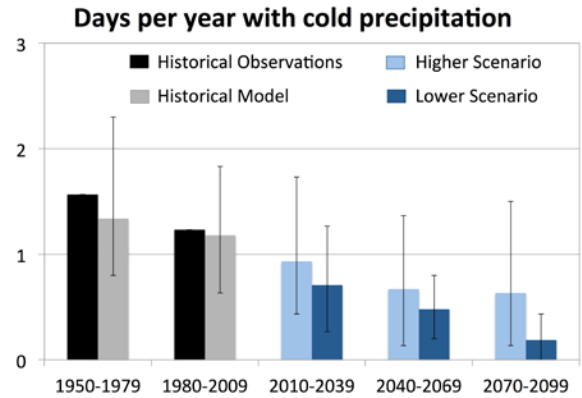


Figure 21: Projections of days per year with cold precipitation (defined here as precipitation falling when temperatures are at or below 35˚F), displayed in bar graphs representing every twenty years. The black bar represents historical observations, and the gray bar is an average of all climate models. Future projections are shown in light blue (higher scenario) and dark blue (lower scenario) for each twenty-year period. The black line represents the variability of each bar.

Drought

It is difficult to model drought, given the interactions of the many factors involved, such as temperature, precipitation, and soil moisture. However, as it was mentioned that San Angelo is most susceptible to the effects of drought, specifically wildfires, during years that have a wet growing season followed by a dry winter, we can model the projected frequency of these precipitation patterns. We modeled both the future amount of precipitation during the growing season, as well as the frequency of a wet growing season followed by a dry winter. We classified the growing season, also noted as summer, as the months from May through October, since this is when San Angelo receives most of its annual precipitation. As precipitation is extremely variable, there is no notable change in future summer precipitation (Figure 22, left). Similarly,

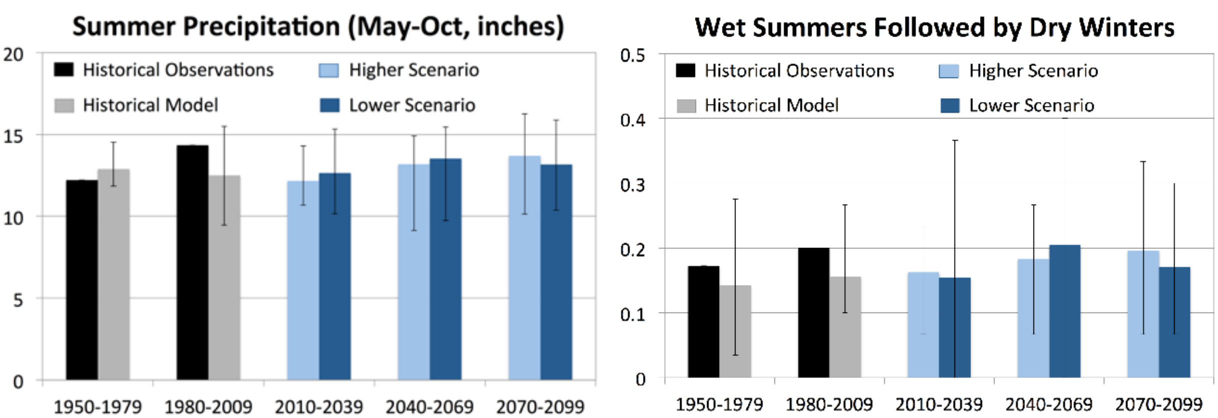


Figure 22: Projections of days per year with cold precipitation (defined here as precipitation falling when temperatures are at or below 35˚F), displayed in bar graphs representing every twenty years. The black bar represents historical observations, and the gray bar is an average of all climate models. Future projections are shown in light blue (higher scenario) and dark blue (lower scenario) for each twenty-year period. The black line represents the variability of each bar.

according to model projections, wet summers followed by dry winters may occur, but not any more or less frequently than they have occurred in the past (Figure 22, right). However, even though precipitation may remain about the same, the projected increase of hot temperatures will increase evaporation, drying out soils and vegetation, and potentially increasing conditions for wildfires.

Summary

Model projections for San Angelo are consistent with observed trends and projections for the South-Central U.S. Current trends of increasing temperatures are projected to continue, resulting in more frequent extreme heat days, notably at 90˚F or greater, 100˚F or greater, and 105˚F or greater. The frequency of warm nights, identified as when minimum temperatures stay at or above 80˚F, will increase. There is also a greater risk of prolonged, multi-day heat events, based on the occurrence of daytime maximum and nighttime minimum temperatures.

The projections of changes in precipitation are variable, and therefore not as consistent. Projections show a slight increase in days with heavy rainfall events of 2 inches or greater, with a slight increase but still highly variable chance for events with rainfall of 4 inches or greater. Projections also show little change in average summer precipitation, compared with historical summer precipitation variations. Also, wet growing seasons followed by dry winters are not projected to substantially change, however, the increase of extreme temperatures may increase conditions conducive for wildfires. Winter precipitation events, classified as when precipitation falls when temperatures are near freezing, will decrease, mostly attributable to the decrease of cold days. By the end of the century, although much less frequent, some years will still experience winter precipitation including snow, ice, or sleet.

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About the Project

The Issue

Many cities already experience a variety of extreme weather and climate related events from ice storms and floods to heat waves and droughts. Frequently, when they look at projections of future environmental conditions, those projections present either *a)* averages that do not help with the wide swings in extreme events that will actually cause problems, or *b)* such wide differences between minimum and maximum values that planning is difficult. One way to address this challenge is to use the concept of thresholds. The threshold concept helps users define at what points weather events have caused problems historically, determine when projected future changes could cause problems, and helps translate climate projections into decision and action points that managers can use on a daily basis.

The Project

Thanks to the generous support of the National Oceanic and Atmospheric Administration (NOAA), the City of San Angelo worked collaboratively with the project team over a one-year period to identify critical extreme weather thresholds for the City and community, analyze the best available climate projections to identify potential future changes relative to those thresholds, interpret that information, and develop and implement strategies to prepare for those impacts.

The Project Team

In addition to City leadership and expertise, this project brings together an experienced team from six organizations:

- ***Adaptation International*** and the ***Institute for Social and Environmental Transition (ISET)***, two organizations experienced in working with communities to increase climate resilience and prepare for the impacts of a changing climate;
- Three of NOAA's Regionally Integrated Science and Assessment Programs (RISAs): the ***Western Water Assessment (WAA)***, the ***Climate Assessment of the Southwest (CLIMAS)*** and the ***Southern Climate Impacts Planning Program (SCIPP)***;
- ***ATMOS Research***, with extensive experience in developing and applying high-resolution climate projections to impact analyses in cities, regions, and states across the United States.

The Results

San Angelo received relevant climate and extreme weather information that is customized and specific to the thresholds identified during the project, an opportunity for multi-sector and inter-departmental collaboration convened and facilitated by an outside organization, and seed funding to facilitate use of thresholds in a climate preparedness project. Community leaders and city staff can use the climate and extreme weather information to support climate action, motivate participation, increase general climate literacy, and ultimately increase community resilience.

This report was developed under a grant from NOAA Sectoral Applications Research Program (SARP), NA14OAR4310248, in association with Adaptation International (Sascha Petersen, Lead Investigator), the Institute for Social and Environmental Transition (ISET), Atmos Research, the Southern Climate Impacts Planning Program (SCIPP) and the Climate Assessment of the Southwest (CLIMAS).