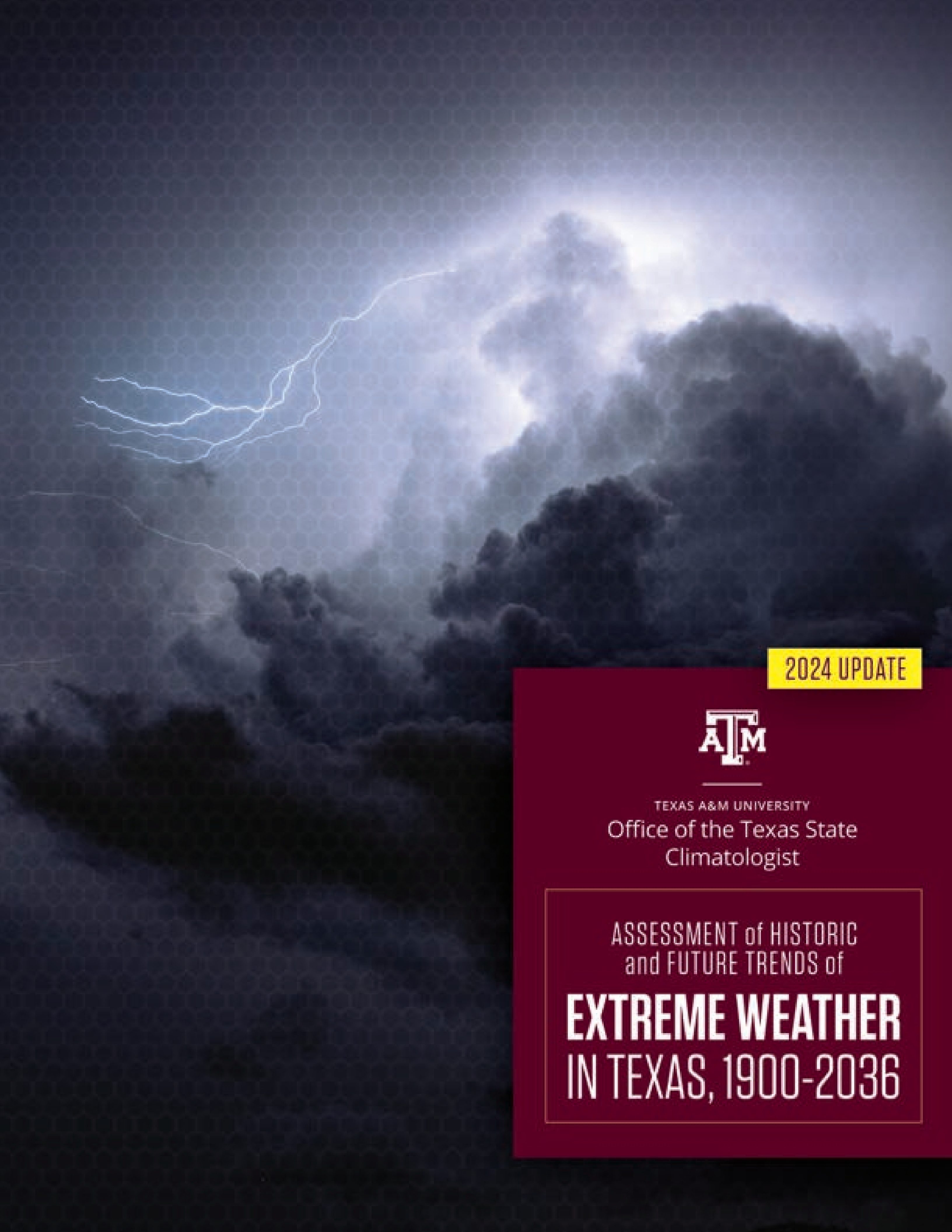

2024 UPDATE

TEXAS A&M UNIVERSITY
Office of the Texas State Climatologist

ASSESSMENT of HISTORIC and FUTURE TRENDS of

EXTREME WEATHER IN TEXAS, 1900-2036

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EXECUTIVE SUMMARY

This 2024 report, an update to the 2021 *Assessment of Historic and Future Trends of Extreme Weather in Texas, 1900-2036*, analyzes historic observations of temperature, precipitation, and extreme weather in Texas through 2023 and identifies ongoing and likely future trends out to the year 2036 and beyond. These trends represent climatological expectations; the actual weather from year to year and decade to decade will be heavily influenced by natural variability which at this point is largely unpredictable.

The average annual Texas surface temperature in 2036 is expected to be 3.0 °F warmer than the 1950-1999 average and 1.8 °F warmer than the 1991-2020 average. The number of 100-degree days at typical stations is expected to quadruple by 2036 compared to the 1970s and 1980s, with a higher frequency of 100-degree days in urban areas. Extreme monthly summertime temperature trends imply an increase of about 2 °F over the past fifty years. Meanwhile, extreme monthly wintertime temperatures are expected to continue to warm at an even faster rate, and the coolest days of the summer are expected to continue becoming warmer as well.

Texas precipitation has increased by 15% or more in parts of eastern Texas, but western Texas precipitation has been largely flat or declining. Precipitation trends to 2036 are likely to be dominated by natural variability. Extreme precipitation is expected to increase in intensity on average statewide by over 20% relative to 1950-1999 and 10% relative to 2001-2020. This translates to an increase in the frequency of extreme rain of over 100% relative to the climatological expected frequency in 1950-1999 and over 50% relative to 2001-2020. Historical trends so far represent an increase of extreme precipitation intensity by about 5-15% from 1980 to 2020, with considerable local variability.

Drought will continue to be driven largely by multidecadal precipitation variability, with long-term precipitation trends expected to be relatively small. Other factors affecting drought impacts, such as increased temperatures and improved plant water use efficiency, on balance decrease water availability but will cause drought impact trends to be highly sector-specific, with the impacts possibly smaller for agriculture than for surface water supply.

River flooding is subject to a similar mix of factors as drought. No long-term river flooding trend has been identified in the observations, nor is such a trend projected at this point, except perhaps for the most extreme floods and areas with normally high rainfall. Urban flooding is projected to increase, both as a simple matter of urban population increase and because of the projected increase of precipitation intensity, which drives flooding in fast-response drainages like those usually found in urban areas. The climate-driven trend in urban flood frequency should be similar to the climate-driven trend in extreme precipitation frequency: 100% in 2036 relative to 1950-1999 and 50% relative to 2000-2018.

Winter weather can be dangerous in Texas in part because it is relatively rare in most areas of the state. The frequency of extreme winter weather ought to decrease in Texas because the existence of winter weather is dependent on temperatures being cold enough to support winter weather. As the climate warms, the likelihood of winter weather decreases. Both extreme cold and snowfall either become less frequent or are expected to do so. Widespread snowfall events in Texas such as the one that took place in February 2021 are extremely rare.

Projections of severe weather associated with thunderstorms are difficult because the historical records are uneven and future thunderstorms are too small to be simulated with global climate models. Indirect evidence supports an increase in the number of days capable of producing severe thunderstorms and an increase in the frequency of very large hail in early springtime, but these possible trends are too uncertain to quantify.

The combination of coastal subsidence and sea level rise is contributing to or driving a general retreat of the Texas coastline, both along the barrier islands and in coastal wetlands. Relative sea level rise is expected to continue at similar average rates in the near future, as reduced groundwater extraction is balanced by accelerating sea level rise. Storm surges from hurricanes will tend to be more severe because of higher relative sea levels, and a possible increase in extreme hurricane intensity may further increase storm surge risk.

Weather and climate drivers of wildfire risk have enhanced the risk of wildfire in western Texas, due primarily to higher temperatures, while the upward trend in rainfall in eastern Texas has made weather conditions less favorable to wildfire in eastern Texas. Higher temperatures will continue to favor wildfires, while the overall trend will be sensitive to whether or not the trend toward increased precipitation continues.

Updates from the previous version of the report rely on two and a half additional years of data and on new science. The hot summers of 2022 and 2023 have enhanced the observed upward trend in 100-degree days. Recent research has led to increases in the estimated changes in extreme precipitation and in evaporation rates from lakes and reservoirs. In addition, new material has been added on changes in the growing season and changes in wildfire risk across Texas.

Funding for this report was provided by Texas 2036 and by Texas A&M University. We thank Andrew Dessler and three anonymous reviews, which helped to improve the content of the original report, OSC-202001, and are grateful for editorial assistance from Lauren Leining and Texas 2036.

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INTRODUCTION

Texas is vulnerable to a wide range of natural hazards, most of which are associated with weather and climate events. The natural environment has evolved partly in response to these natural hazards. For example, plant hardiness is largely determined by ability to survive extreme winter cold and drought. The built environment, including for example homes, roads, and power plants, is designed to a certain level of resilience to natural hazards. Human activities as fundamental to survival as food production and water supply are tailored to the particular combination of weather and climate risks at play in a given location.

The future of Texas depends on its resilience to the natural hazards of the future. It is up to Texans, both individually and collectively, to decide what level of resilience is appropriate, and at what cost, compared to the costs of damage and recovery on both an economic and societal level. Nobody knows which specific weather and climate events will befall Texas over the next couple of decades. But a wide variety of information can be used to estimate the risks of certain types of weather and climate events over that period.

The standard practice for estimating the risk of natural hazards has been to assume that future risk is equal to historical risk. This practice works only if the underlying climatic conditions are unchanging. However, Texas climate is affected by changing patterns of vegetation, irrigation, and urbanization. The Texas climate is also embedded in the global climate system, which is itself changing. All these factors have influenced historical trends in weather and climate extremes and will continue to influence trends in the future. Given a changing climate, historic trends may provide a better guide to future risk than mere historical averages.

The sponsors of these projections requested that projections be based primarily on existing trends. Doing so makes sense only if the causes of those trends are understood and are expected to continue. The scientific understanding of the causes of trends draws upon a large body of research, utilizing both observations and experiments with global climate models. This report presents trends for a variety of historic periods, and the projections are based on historic trends that are expected to continue according to currently available science.[i]

Several factors influence our ability to project historical trends into the future. First, historical data may not be sufficiently accurate or consistent over time to yield reliable trends. Second, natural climate variability and the randomness of extreme weather events can mask or even overwhelm any underlying long-term trends. Despite these limitations, there are sound reasons to expect continued change in a variety of aspects of extreme Texas weather, and knowledge of such likely changes can be very useful in a variety of planning contexts.

Trends are not the only potentially useful historic information. Some natural climate variations that occur on multidecadal time scales have a substantial effect on Texas weather. The present-day scientific ability to accurately predict such variations twenty years into the future is quite limited. Nonetheless, knowledge of these variations informs the understanding of past trends and suggests whether recent weather patterns are representative of typical future conditions.

This report addresses historical and future trends in extreme temperatures, extreme precipitation, severe thunderstorms, and hurricanes. It also addresses trends in drought, floods, wildfire, and coastal erosion, to the extent that these natural hazards are affected by changes in weather and climate. For each natural hazard, the report considers the quality of the historical data, the historical risk and trends (data permitting), the causes of any observed or expected trends, and the projection of trends of future risk. For context, this report also considers trends in annual average temperature and precipitation.

Expected typical conditions in 2036 are expressed as a change compared to average conditions in 1950-1999 and 1991-2020. The latter period corresponds to the "normals" period as defined by the National Centers for Environmental Information (NCEI). When weather is reported as being x degrees or x inches above or below normal in weather forecasts or reports, it is relative to the 1991-2020 period.

With all projections, there is considerable uncertainty as to how things will actually turn out. This report does not attempt to quantify that uncertainty; prudent planning recognizes that we cannot know whether reality will end up higher or lower than the best available present-day estimates.

This report was commissioned and sponsored by Texas 2036. The report content is solely the responsibility of the authors. A previous version of this report has been peer-reviewed; reviewer comments and responses are available from the Office of the State Climatologist. This updated report is based on data and published research through April 2024. The analyses that are original to this report are based on data from publicly accessible data sources. Analysis spreadsheets and software are available from the Office of the State Climatologist.

AVERAGE TEMPERATURES

While average temperatures do not themselves constitute weather and climate extremes, changes in average temperatures, either locally or globally, affect many aspects of extreme weather and climate trends. In addition, all else being equal, a change in average temperature would lead to a change in frequency of extreme temperatures, increasing hot extremes and decreasing cold extremes.

The National Centers for Environmental Information (NCEI) maintain very good analyses of monthly averages of daily maximum and minimum temperatures from 1895 to present throughout the lower 48 states.[ii] The annual average daily maximum and minimum temperatures in Texas over the period 1897-2023 exhibit year-to-year variations of 2 °F or more. Broadly speaking, Texas temperatures climbed slightly during the early part of the 20th century, declined somewhat until the 1970s, and rose thereafter. At this point, it is unlikely that any year through 2036 will have an average daily minimum temperature lower than the 20th century average.

The rate of temperature increase since 1895 has averaged 0.12 °F per decade, less than the global average of 0.17 °F per decade.[iii] Indeed, the southeastern United States, including eastern Texas, is almost the only land area on the globe whose temperature increase over the 20th century was nearly zero.[iv] More recently, the Texas temperature trend has been larger. Since 1950, the trend has been 0.29 °F per decade, and since 1975, 0.62 °F per decade. The global trend since 1975 was 0.36 °F per decade. Recent temperatures have increased in all seasons and in all regions of Texas.

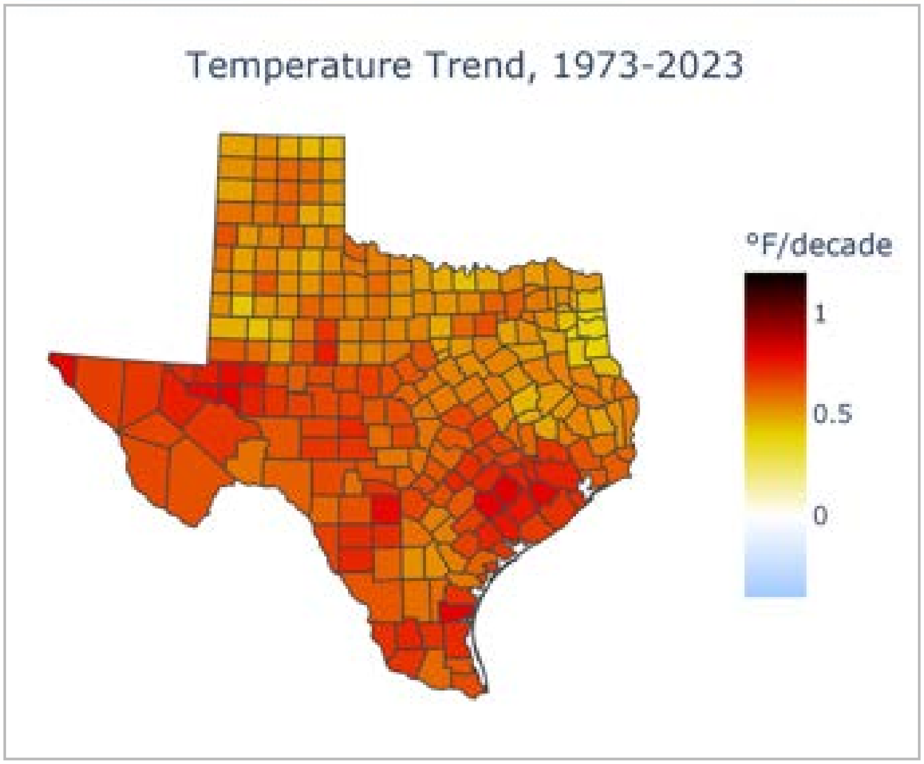
The historic Texas temperature trend simulated by CMIP5 global climate models for 1950-2020 is 0.32 °F per decade, and for 1975-2020, 0.55 °F per decade.[v] About 90% of models simulate a 1975-2020 trend between 0.25 and 0.88 °F per decade. The simulated current rate of increase in Texas, based on the average of climate model projections for 2020-2040 for the low-emissions representative concentration pathway (RCP) 4.5[vi], is around 0.62 °F per decade. Up to mid-century, climate projections are not very sensitive to the choice of emissions pathway.[vii]

On the whole, the agreement between models and observations is decent. Factors that cause observed trends to differ from simulated trends include inadequacies in the models, inaccuracies in observations, actual and simulated natural variability, and local land surface changes such as irrigation and afforestation.

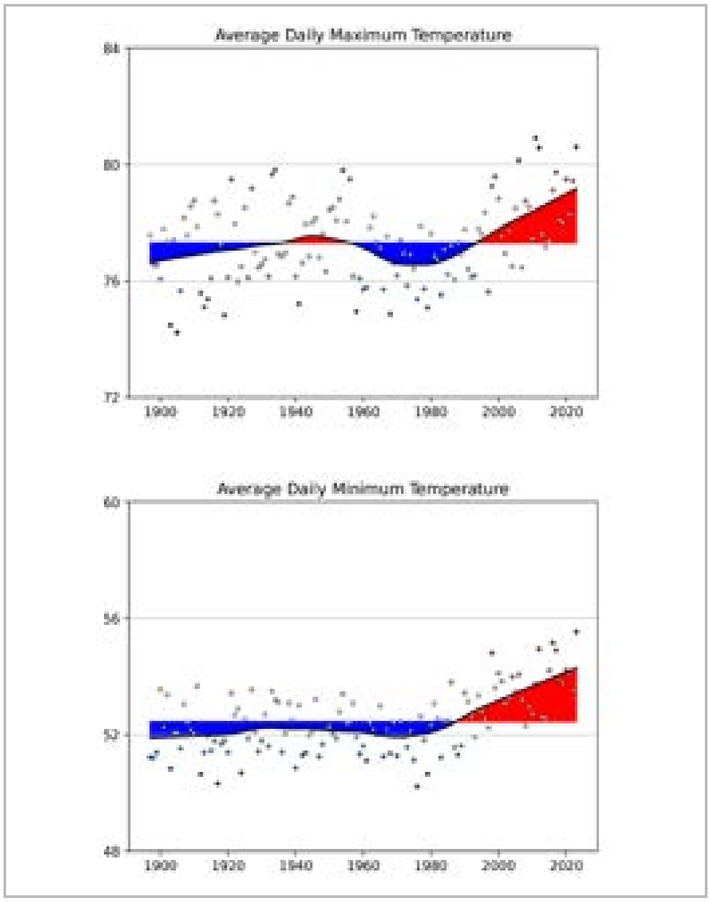
More recent model simulations from CMIP6 indicate even larger temperature increases on average, although that change is thought to be mostly due to an apparently unrealistically large climate sensitivity in several models.

Historical data and climate models lead to similar conclusions. If recent trends continue, as expected, a middle-of-the-road estimate of the overall rate of temperature increase in Texas would be about 0.6 °F per decade. This means that **average Texas temperatures in 2036 should be expected to be about 1.8 °F warmer than the 1991-2020 average and 3.0 °F warmer than the 1950-1999 average. This would make a typical year around 2036 warmer than all but the absolute warmest year experienced in Texas during 1895-2020**.[viii] Even a very conservative extrapolation, based on the average of the 1950-2020 and 1975-2020 trends, would make a typical year around 2036 warmer than all but the five warmest years on record so far.

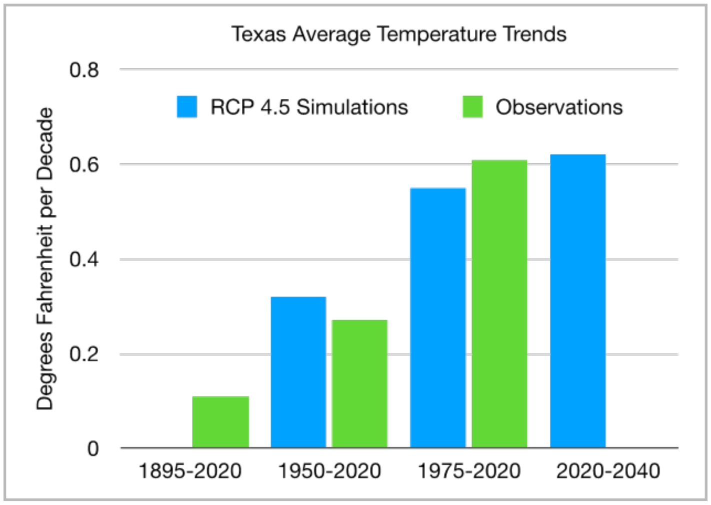
Temperature trends have been generally similar from season to season. During the period 1950-2020, summertime trends were smaller than trends in other seasons. During the period 1975-2020, wintertime trends were larger than trends in other seasons.



Temperature trends since 1973 according to NCEI nClimDiv data.



Texas annual average statewide daily maximum and minimum temperatures (°F), according to NCEI nClimDiv data.



Comparison of observed and simulated temperature trends in Texas

EXTREME TEMPERATURES

The projected changes in average temperature imply changes in unusually high or low temperatures as well. This assessment of extreme temperatures relies on two aggregated sets of temperature data: a set of stable stations (hereafter referred to as index stations)[ix] and a set with one composite station per county.[x]

To analyze actual trends in 100 °F days in Texas, the index stations were grouped into four regions and analyzed collectively within each region.[xi] Over the past 50 years, the linear trend shows an approximate tripling of the number of triple-digit days at stations in three of four regions. Given past and projected temperature trends, an overall quadrupling of the number of 100-degree days between the 1970s-1980s and 2036 appears to be a reasonable projection.

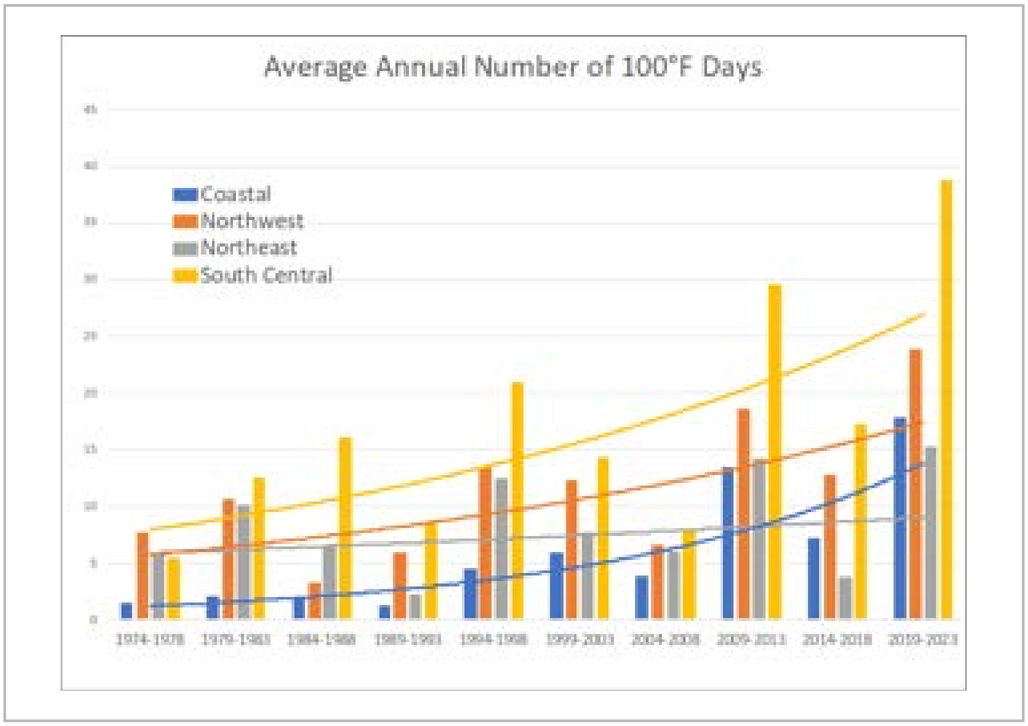
Although the number of truly urban stations in Texas is limited, the existence of urban heat islands has likely led to an enhancement of 100 °F days in urban areas. Presently, the limited data suggests that triple-digit days are rising at similar rates in urban and rural areas.

An alternative way of examining extreme heat trends is to consider the average hottest day in each month during June-September in each county in Texas.[xii] This metric is more sensitive to exceptional heat events than to sustained heat. It also enables us to use longer historical records, as this metric is not sensitive to changes in observing time.

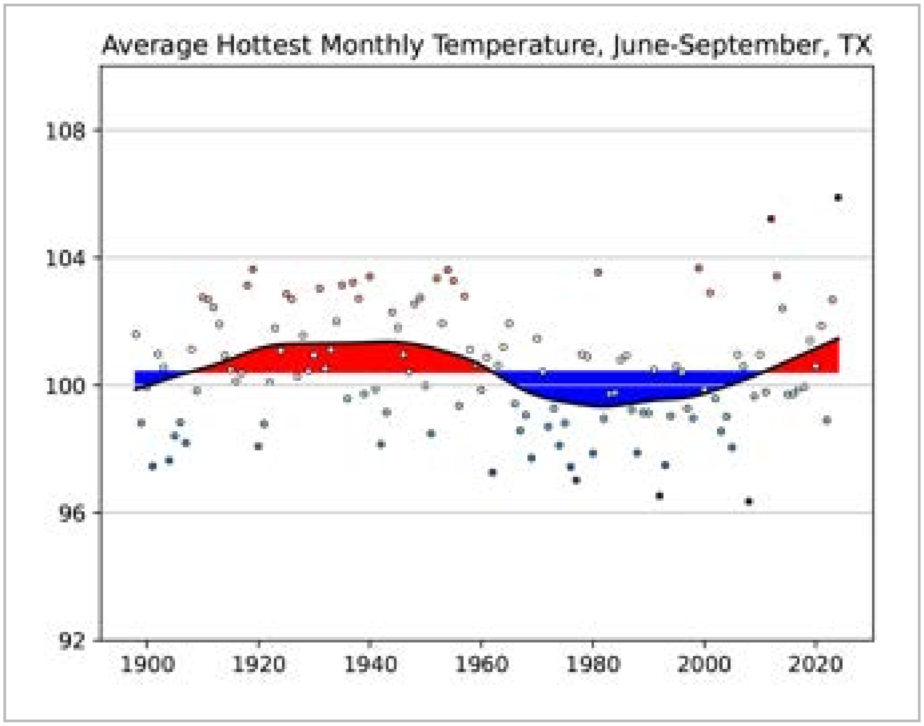
Looked at this way, the picture is mixed. Overall, during the first half of the temperature record, extreme monthly summertime temperatures tended to be higher than during the second half of the temperature record. This trend reflects the general pattern over the continental United States, where the most exceptional heat occurred back in the 1930s. The average daily maximum temperatures during the summer across the United States were actually highest in 1936, although the next four warmest were in 1999 and later, including 2022.[xiii] The cause of this downward trend, which is in contrast to mean and extreme temperatures in all other seasons, may be related to the expansion of irrigation in the mid-20th century.[xiv] Whatever the cause of the long-term slight downward trend, it appears to have reversed, with a substantial increase in extreme monthly heat in recent decades. Within Texas, recent extreme monthly high temperatures have tended to be higher than the historic mean, and there has been an increase of more than two degrees over the past fifty years.

Extreme low temperatures during the winter months exhibit a stronger and more robust trend.[xv] Despite year-to-year fluctuations that are much larger for extreme cold than extreme heat, there is a long-term warming trend in monthly extreme cold temperatures across Texas over the entire period of record as well as over the last half-century. Although they are much noisier, the absolute coldest temperature during winter shows similar long-term variations, with the extreme cold during 2021 easily identifiable.

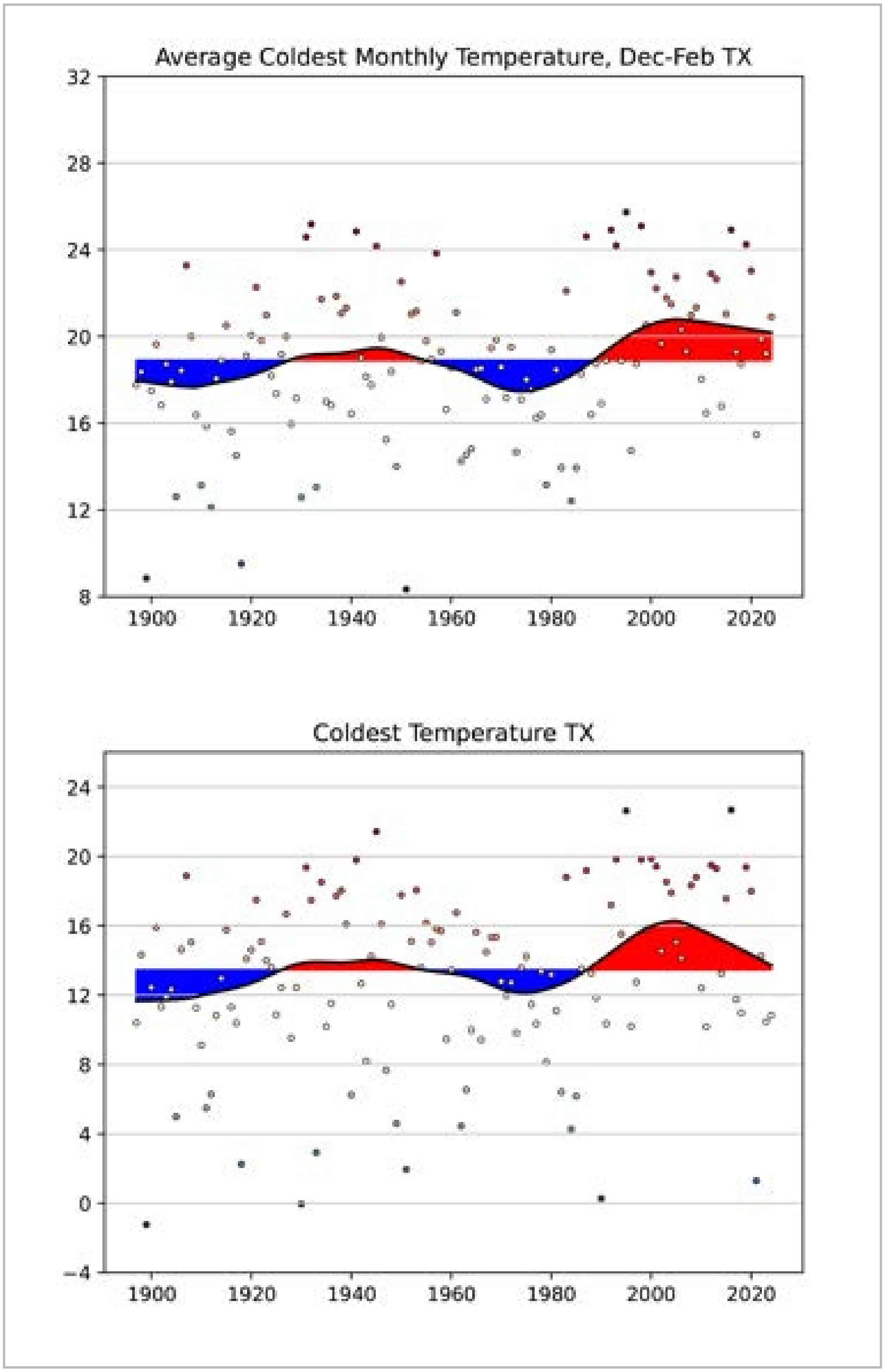
No matter the metric, extreme cold is no longer as extreme as it used to be. This is broadly consistent with expectations: extreme cold air comes from the Arctic, which in general is warming faster than other parts of the globe. There have been some studies in recent years debating whether loss of Arctic sea ice and overall Arctic warming leads to changes in weather patterns that favor more intense incursions of Arctic air[xvi], but this tendency, if present, has not been strong enough in Texas to stop the accelerating rise of extreme cold temperatures. This warming of extreme cold temperatures in Texas, much more rapid than warming of average temperatures, is consistent with what has been observed elsewhere in the Northern Hemisphere and is inconsistent with the argument that loss of Arctic sea ice is enhancing extreme cold over the continents.[xvii]



Trends and historic variability in index temperature stations in Texas, grouped by amount of urbanization. Arrows at top indicate data points that are above the margin of the graph. Trend lines are fit to the logarithm of 100 °F day counts to ensure non-negative values.



Hottest day of the month, June-September, at composite county stations across Texas, through 2023.



Average lowest temperature of the month, December-February, at composite county stations across Texas, and average lowest temperature overall.

Overall, extreme heat in recent decades has become more frequent and more severe, while extreme cold has become less frequent and less severe overall. Trends in extreme cold are much larger than trends in extreme heat, which is leading to an overall decrease in the range of annual temperature extremes over time. That trend is also apparent within summer, as the lowest temperatures during July and August have become substantially warmer.

In summary, extreme summer heat has reached values not seen since the early part of the 20th Century and is likely to surpass them by 2036. Triple-digit days are well on their way to being about four times as common by 2036 than they were in the 1970s and 1980s. Meanwhile, the expected warming of extreme wintertime temperatures would make typical wintertime extremes by 2036 milder than most of the winter extremes in the historic record. That said, extreme wintertime cold is more variable than other types of temperature extremes, so massively cold winter temperatures will continue to be possible.

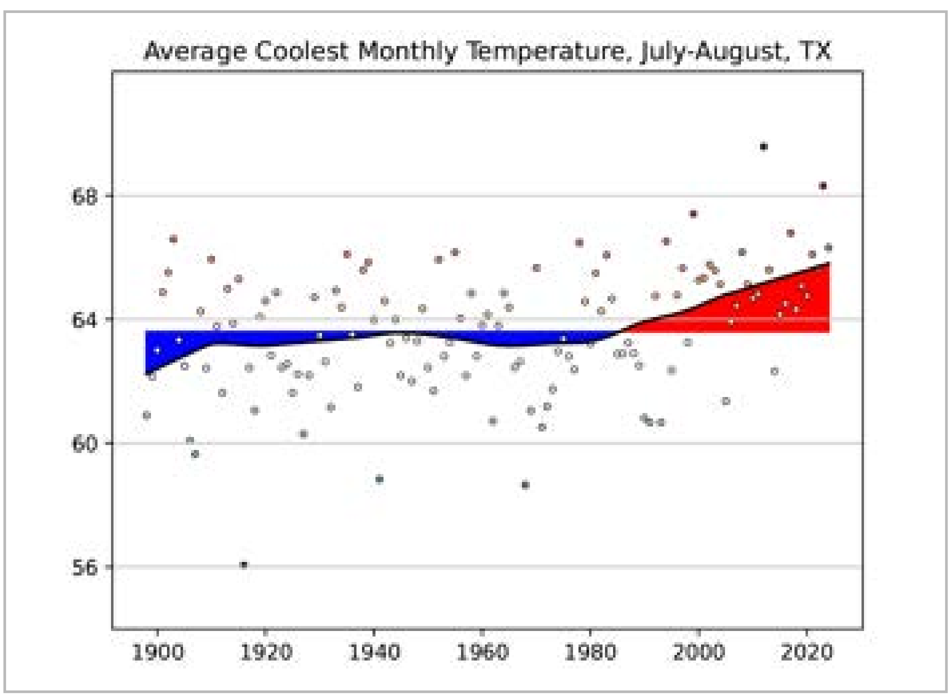
GROWING SEASON

The growing season is the period in which temperatures are favorable for plant growth. This may vary from plant to plant, as some can tolerate moderate freezes while others cannot tolerate frost. The warming trend of the past fifty years means that certain temperatures are last reached earlier in the spring and first reached later in the fall.

Because of the regular increase of normal temperatures during springtime and the regular decrease during fall, the overall temperature trend can be converted directly to a trend in the length of the growing season. For example, in College Station, temperatures increase by 6°-8° per month during the spring and decline by 6°-10° during the fall. The observed increase of 0.6° per decade implies that, over the past five decades, the growing season starts a half month earlier and ends a half month later. This lengthening at both ends corresponds to an increase of growing season length by almost one week per decade.

Most Texas crops do not utilize the full growing season. Instead, they typically mature a certain number of days after planting. A race can develop between crops attempting to mature and temperatures rising enough to dry out soils. If a crop must grow into the summer and can barely tolerate the heat, the growing season for that crop may shorten, as increasing temperatures bring an early end to the growing season. Other crops that mature before heat becomes an issue may see no change in the length of their growing season whatsoever.

The key adaptation for farmers will be to plant earlier, keeping up with the shortening of the winter season.



Average lowest temperature of the month, July-August.

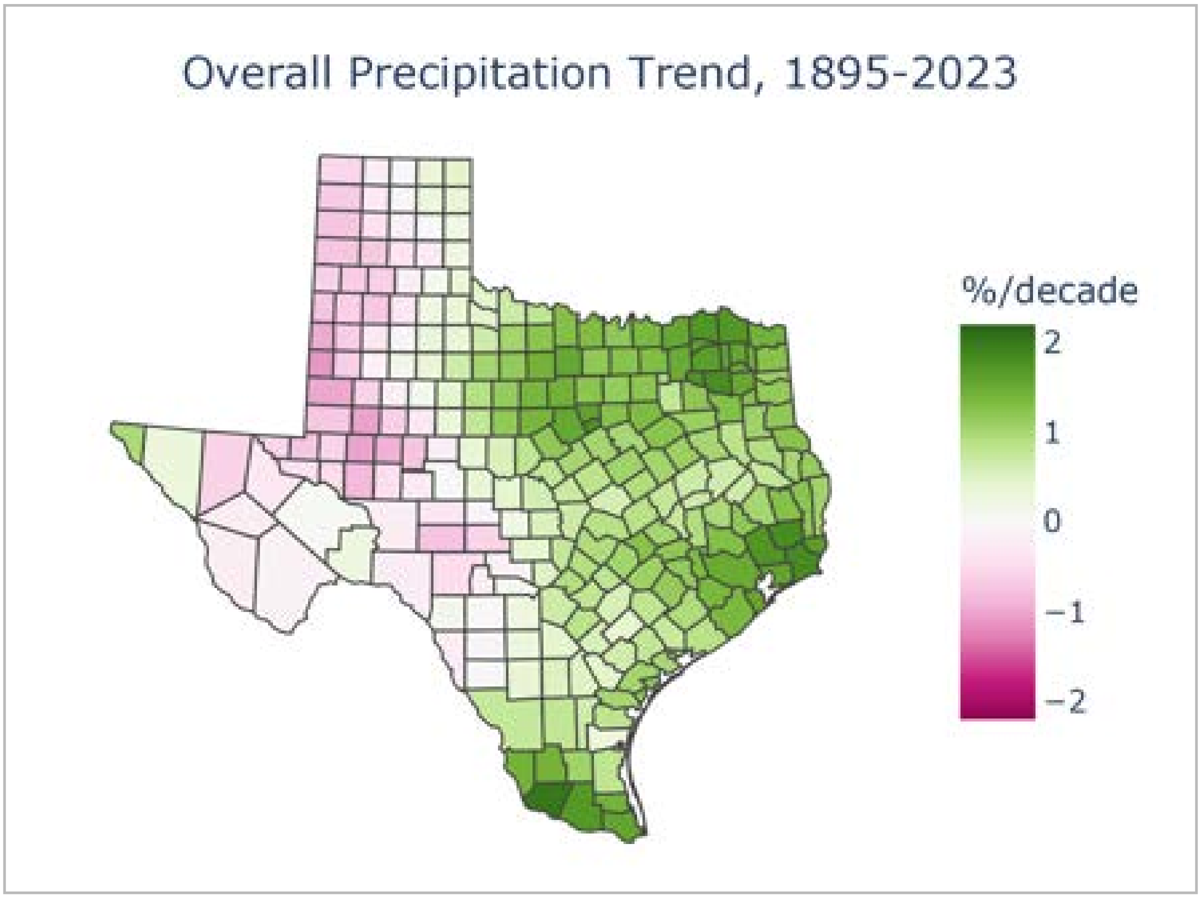
PRECIPITATION

Precipitation in Texas is quite variable, both in space and time. Much of the state has two rainy seasons, with the rainiest months on average being May, June, September, and October. In far West Texas, the wettest months are July and August, while far East Texas averages similar amounts in every month. Rainfall amounts increase from west to east, with the southeast corner of the state near Beaumont averaging over eight times the annual rainfall of some areas near El Paso.

The long-term trend of precipitation in Texas has been positive. Over the past century, parts of central and eastern Texas have experienced precipitation increases of 15% or more, while in much of the western part of the state the long-term trend is flat or even slightly downward.[xviii] The tendency for increasing precipitation in Texas is not consistent with the majority of global climate models, with the average simulated trend being -2.6% per century.[xix] Models and observations both tend to feature more positive (or less negative) trends toward northeastern Texas than toward southwestern Texas.[xx]

Superimposed on the generally upward precipitation trend is considerable variability. El Niño has a prominent influence on cool-season rainfall in Texas: during El Niño years, Texas tends to be wet, while during La Niña years, Texas tends to be dry. The natural variability driven by El Niño means that year-to-year swings in precipitation in Texas tend to be larger than in many other parts of the United States. This makes Texas both drought-prone and flood-prone.

The climate model projections provide weak evidence for a precipitation decline. Unlike earlier model projections, the latest CMIP6 projections do not have precipitation in summertime declining more than precipitation in other seasons.[xxi]



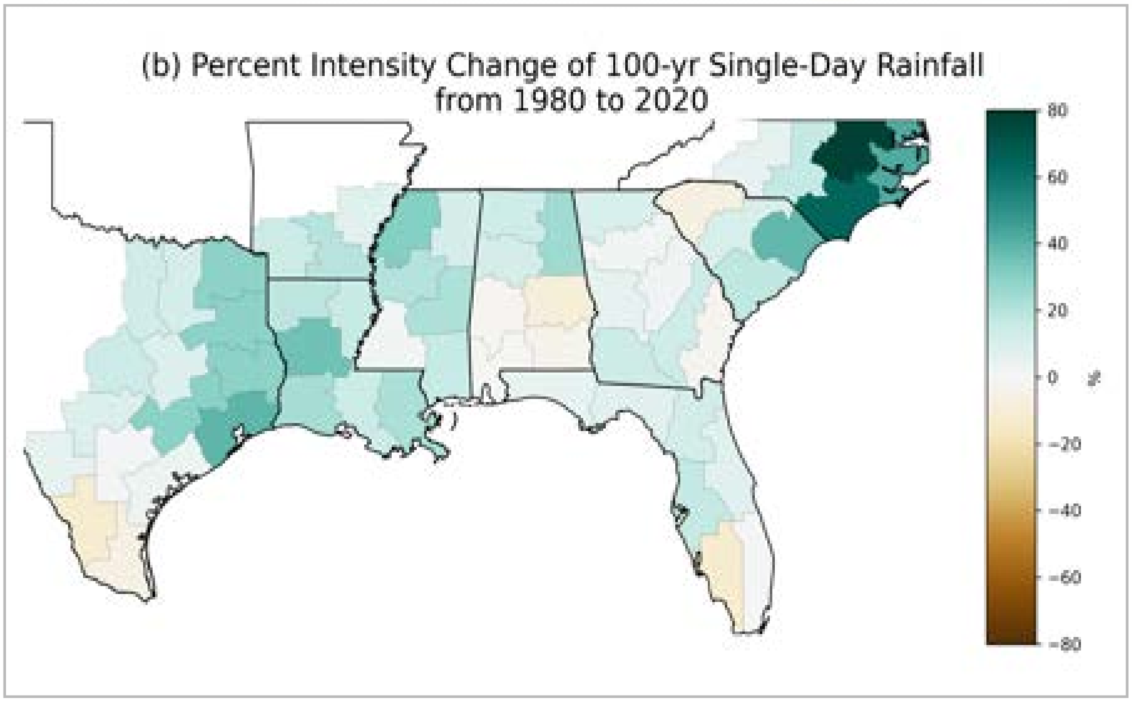
Precipitation trends since 1895 according to NCEI nClimDiv data.

EXTREME RAINFALL

Many studies have documented an increase in extreme rainfall in Texas and surrounding areas for a variety of durations and thresholds.[xxii] On average across the region, extreme one-day precipitation has increased by 5% to 15% since the latter part of the 20th century.[xxiii] Within Texas, the local experience of extreme rainfall varies widely from place to place, with some locations having experienced a decrease in intensity of extreme rainfall over the period of data availability while the majority of locations have experienced an increase.[xxiv] Much of the pattern is governed by the fact that Hurricane Harvey and Tropical Storm Imelda hit southeast Texas rather than South Texas.

All other things being equal, an increase in overall precipitation amounts would be expected to lead to an increase in extreme precipitation amounts, which inevitably implies an increase in the frequency of extreme precipitation above a given threshold. So the overall trend in Texas precipitation, discussed previously, contributes to the observed trend in extreme precipitation probabilities.

In addition to the overall precipitation effect, extreme rainfall is strongly affected by increased temperatures. A column of air that is producing rainfall will produce about 4% more rainfall for every °F of warming.[xxvi] The extra precipitation intensity can also affect storm structure, and climate change can alter weather patterns and the frequency of dangerous storms.



Percentage change in the intensity of one-day rainfall with a 1% probability of occurring in any given year, based on a time-dependent statistical fit of annual daily precipitation maxima at groups of composite stations.

The direct temperature effect appears to be most important over the long haul in most midlatitude locations such as Texas. Changes in storm frequency and in the intensity of updrafts are expected to be comparatively subtle.[xxvii]

As noted earlier, computer model projections of overall rainfall amounts in Texas are somewhat inconsistent, but in general they show an overall leveling off or slight decrease of precipitation amounts.[xxviii] This suggests that trends of extreme precipitation in the future will be dominated by the increasing temperature effect and changes in storm structure. The strongest influence should be temperatures near the moisture source for Texas extreme precipitation, that is, the tropical oceans and the Gulf of Mexico. Tropical ocean temperatures are not expected to rise as quickly as temperatures over land in Texas but would still be sufficient to produce an additional 2%-3% increase in extreme rainfall intensity from the temperature effect alone.[xxix] So extreme rainfall intensity and frequency are projected to continue increasing, though probably not as rapidly as they have increased in the past.

Rainfall risk is often characterized in terms of the 100-year rainfall event, which is an amount of rain over a given duration that has a 1% chance of occurring in any given year. If extreme rainfall amounts increase by just 20%, the 100-year rainfall event threshold is exceeded twice as often.[xxx] So the Gulf Coast's 15% median increase in the 100-year rainfall amount between 1980 and 2020 corresponds to a near doubling in the frequency of heavy rainfall exceeding the older 100-year threshold. **Based on projected temperatures and the dominance of the direct temperature effect on extreme rainfall, we anticipate an additional increase of about 10% in expected extreme rainfall intensity in 2036 compared to 2001-2020 and an overall increase of over 20% compared to 1950-1999. These changes in amount correspond to increases in the odds of extreme precipitation of over 50% and over 100%, respectively.**

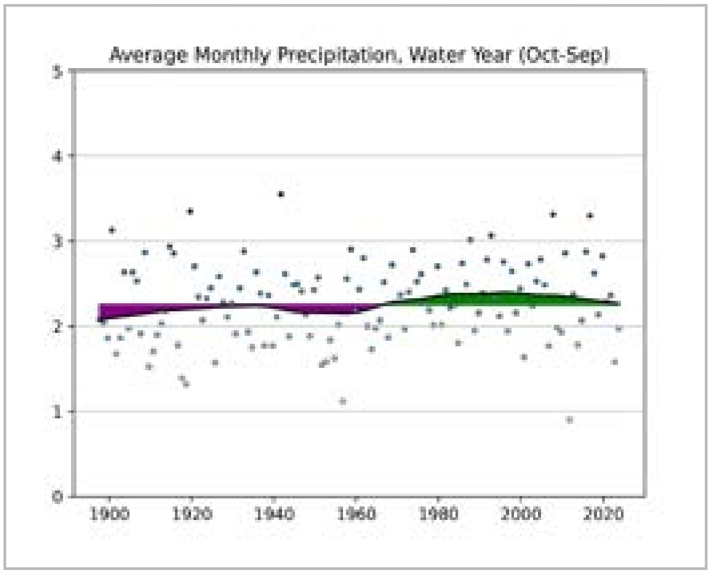
Note that the variations of extreme rainfall trends across Texas imply that one should not assume that recent extreme rainfall history in a given location is a suitable baseline for projecting future trends. While estimates of extreme rainfall risk based on historical data show a large uptick in Houston but less change in Dallas-Fort Worth[xxxi], climate change should be acting to increase the risk more uniformly across the entire state. The projected increase of extreme rainfall risk given above is relative to the expected past risk of extreme rainfall in a given location, not the actual occurrences of extreme rainfall in that location. Likewise, the actual extreme rainfall over the next few decades at any given location may defy the odds, either favorably or unfavorably.

DROUGHT

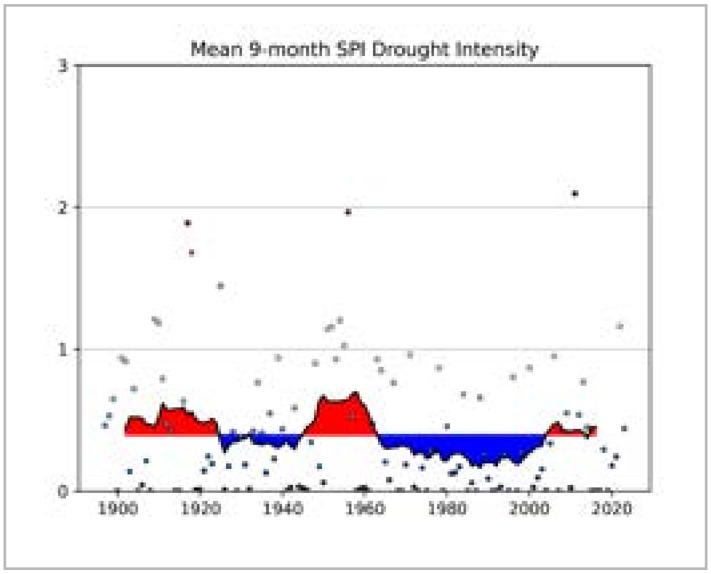
At first glance, the long-term increase in average rainfall should imply a decrease in drought as well. The linear trend in total statewide precipitation is nearly 1% per decade, but with considerable variation depending on the period considered.[xxxii]

The corresponding drought severity based on precipitation alone, as measured by the cumulative 9-month Standardized Precipitation Index (SPI), does indicate declines in severity. The change in cumulative dryness is -5.3% per decade since 1896, -12.8% per decade since 1950, and +11.1% per decade [these numbers need to be updated] since 1975. As noted with respect to precipitation, the change since 1950 is large in part because of the extended drought that occurred early in the 1950s. The rise of cumulative dryness since 1975, however, has happened despite a slight increase of precipitation over the same period.

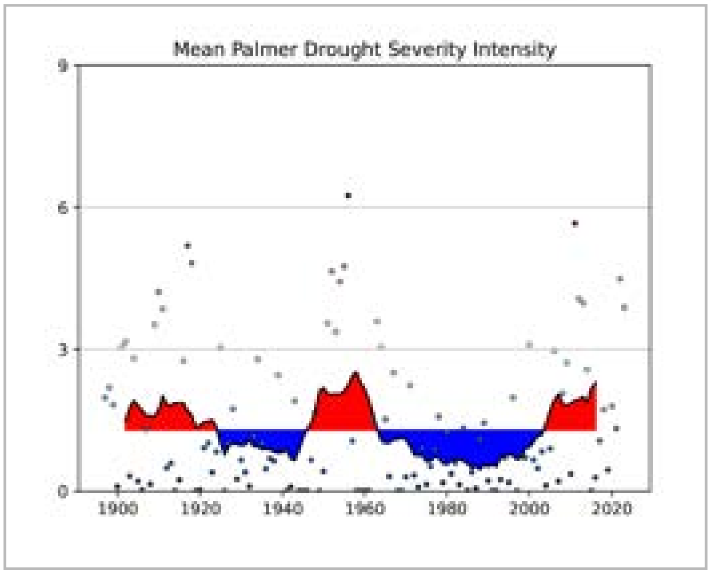
The explanation for this difference can be seen in the statewide precipitation graph. Note that the period of time from 1965 to 1985 featured very little precipitation variability, with statewide average precipitation ranging between 22" and 35". Since then, precipitation has become more variable, with 2011 water year precipitation below 14" and 2015 precipitation above 41". Greater precipitation variability leads to more intense droughts even if the overall precipitation amount does not change.



Statewide average monthly precipitation (in inches) during each water year (October-September), from NCEI's nClimDiv dataset. Average rainfall is about 2.3" per month, or about 27" per year.



Statewide annual cumulative drought severity, assessed using the SPI precipitation-only drought index.[xxxiii]



Statewide annual cumulative drought severity, assessed using the Palmer Drought Severity Index.

The historic record of precipitation variability is, itself, quite variable, with no clear trend over the period of record despite the recent uptick in variability. Climate models generally simulate an increase in interannual precipitation variability in Texas since 1950 but little or no change in interannual precipitation variability going forward.[xxxiv] The lack of future variability is itself anomalous compared to the rest of the Northern Hemisphere land areas, which tend to show an increase in variability in excess of the increase in average precipitation itself.[xxxv] So the recent trend of increased interannual variability is probably not going to continue apace through 2036, unless average precipitation itself continues to increase, and the precipitation variability experienced over 2000-2023 is probably representative of what should be expected through 2036.

Drought severity and impacts, however, involve much more than a lack of precipitation. The exact combination of factors determining the severity and impacts of a particular drought depend on the particular crop, water supply, or other system being affected, making it challenging to generalize trends in drought severity from conventional drought indices.[xxxvi]

Temperature affects drought directly, by increasing the rate of evaporation from the soil and from water bodies. Many drought indices, such as the Palmer Drought Severity Index (PDSI), attempt to include the effect of temperature on dryness.[xxxvii] Compared to rainfall-only SPI indices at various time scales, particularly the 9-month scale that the PDSI is most responsive to, the PDSI shows a less negative trend over the entire period and a larger positive trend recently.[xxxviii]

However, while the SPI neglects the temperature effect on drought entirely, the conventional PDSI may overestimate it.[xxxix] This is because, in addition to precipitation and temperature, carbon dioxide also affects drought. Elevated carbon dioxide levels improve the water use efficiency by plants, so would lead to increased soil moisture and decreased drought. Elevated carbon dioxide levels also increase biomass if plants are not otherwise water- or nutrient-limited, which might increase water use and decrease soil moisture. While these two effects work in opposite directions, the water use efficiency effect seems to be dominant, thereby allowing increased CO2 to lead to improved plant growth despite meteorological factors leading to increased drought, at least on a global scale.[xl] Nonetheless, improved plant health overall does not eliminate possible detrimental effects from drought accompanied by increased temperatures, particularly since decreased plant water use itself implies increased temperatures.[xli] Also, different plants respond to carbon dioxide (and heat stress) differently.[xlii] Lastly, global climate model simulations that attempt to incorporate changes in plant physiology still indicate a substantial decrease in future soil moisture across the Great Plains.[xliii]

While recent SPI values are near the long-term average, the SPI record indicates that much more severe precipitation deficits have occurred in the past. With warmer temperatures in recent decades, the recent series of droughts had impacts comparable to the droughts in the early and middle 20th century, despite smaller long-term precipitation deficits. This means that if (or when) another period of lack of precipitation develops like those in the early and middle 20th century, the higher temperatures will lead to unprecedented severe drought impacts.

Increased carbon dioxide does not reduce the temperature effect of evaporation from lakes and reservoirs or from bare soil. Historically, there has been an increase in the evaporative capacity of the atmosphere across most of Texas, especially in West Texas and the Panhandle, which is expected to continue due to robust projections of rising temperatures.[xliv] A continuation of the observed trend would lead to a roughly 7% increase in expected summertime evaporative losses from reservoirs in 2036 compared to 2000-2018, much larger than historic increases in precipitation.[xlv]

For hydrological drought, runoff is important. Changes in runoff depend on changes in soil moisture and changes in precipitation amount and intensity. Across the midlatitudes, there is on average a decrease of topsoil moisture but little change in deep soil moisture.[xlvi] This would favor a slight decrease in runoff for a given amount of precipitation. But the tendency for greater rainfall intensity[xlvii] leads to a greater runoff fraction and would contribute to a decrease in soil moisture. Climate models are consistent in predicting a decrease in runoff in parts of Texas during most months, but an increase in runoff during the wettest months.[xlviii] A broader analysis for the entire state of Texas is ongoing.

Overall, the most detailed recent study of simulated streamflow impacts finds a projected increase in both drought severity and flood severity for the two studied river basins. Those increases appear to be unaffected by errors in calculating the drought indices.[xlix]

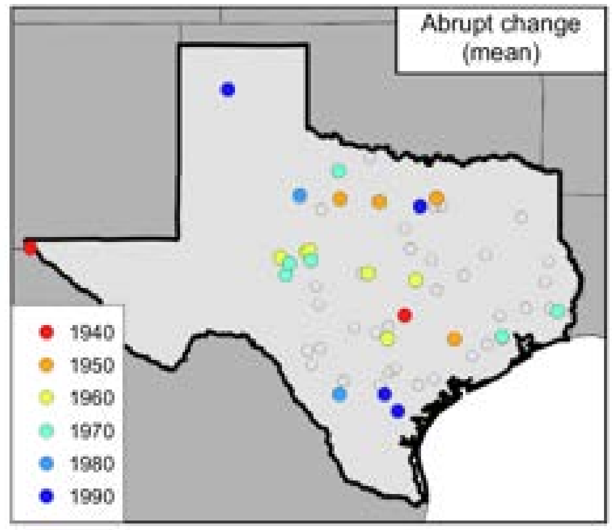
Despite all the nuances discussed above, the primary driver for changes in future drought remains changes in overall precipitation amount. In Texas, the projected slight decrease mentioned in the previous section would imply a small increase of drought intensity by itself. For agricultural drought, this small increase of meteorological drought could easily be neutralized by improved water use efficiency by plants, leading to no agricultural drought trend or even a reduction in drought susceptibility, though several other factors will come into play, not least the increasing temperatures. For hydrologic drought, the increase of surface water evaporation would worsen the impact of the increased meteorological drought.

Because of all the factors at play, it is impossible to make quantitative statewide projections of drought trends. The majority of factors point toward increased drought severity, including more erratic runoff into reservoirs. Nonetheless, any such underlying trend may be dwarfed during the next couple of decades by the impact of multidecadal variability, which historical records show is large for Texas. Also, as indicated by paleoclimate records, worse droughts have occurred in Texas than the climate data record alone would indicate. Future rainfall deficits comparable to those earlier in the 20th century will have greater impacts due to higher temperatures.[1]

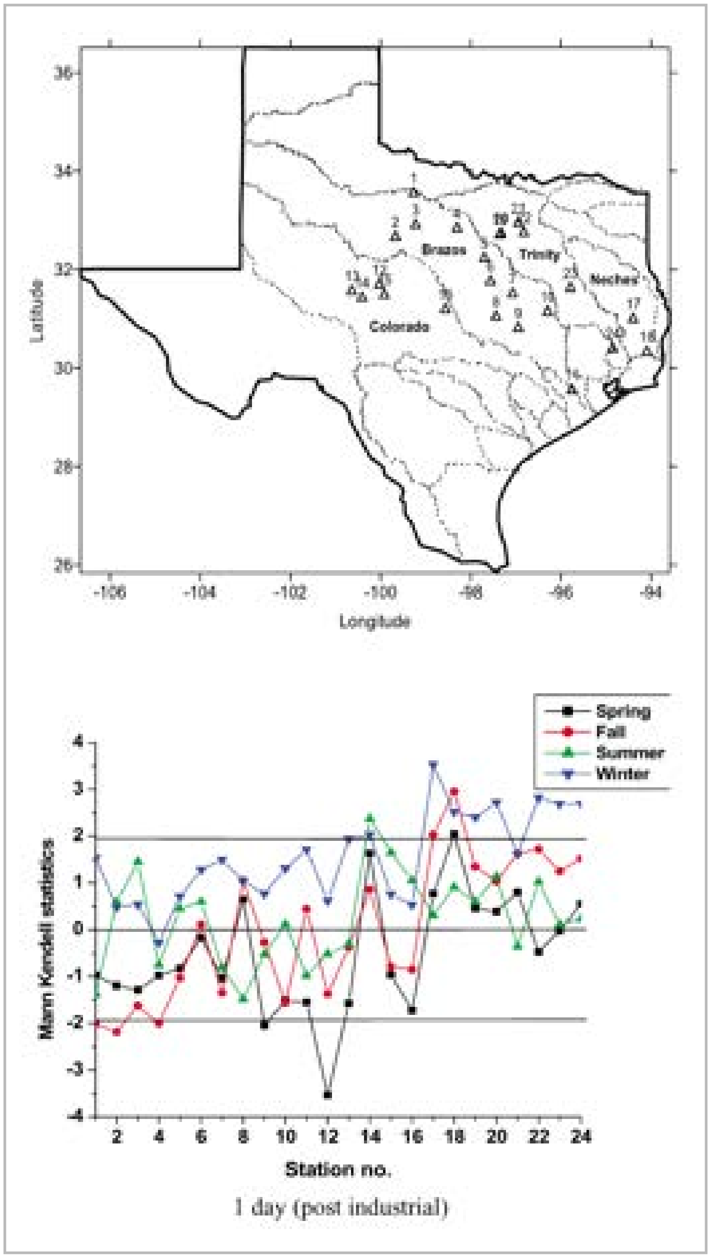
RIVER FLOODING

Texas has been impacted greatly by river flooding in the past, causing both fatalities and economic damage. In fact, Texas ranked highest amongst the United States in flood related fatalities during 1959-2005.[li] Throughout most of the state, intense daily and weekly precipitation events are the primary meteorological drivers correlated with the most extensive flooding.[lii] This would imply that a single or a short series of extreme precipitation events plays a dominant role in causing river flooding, and that antecedent soil conditions have limited impact. However, east and northeast Texas are the exception to this pattern, as extended wet periods are the primary meteorological drivers best correlated with extensive river flooding. This would imply that antecedent soil conditions- as controlled by seasonal precipitation and evaporation- play a dominant role in flood events in those areas.

Research has found a historical decrease in the magnitude of flood events at many river gauges, resulting from abrupt drops in flood magnitude.[liii] This can be attributed to the construction of reservoirs and dams for flood management throughout the 20th century. As substantial future reservoir construction is not anticipated, this trend driver will not continue. Projected increases in temperatures and precipitation intensity will have competing effects on river flooding. Increased precipitation intensity will lead to more precipitation-runoff events that suggest more river flooding in the future. In contrast, increased temperatures would mitigate flooding by decreasing soil moisture and increasing the capacity for soil to hold new rainfall. This would limit the amount of precipitation-runoff that would go into rivers and increases in river streamflow would be lower.



Location and the decade of occurrence of stations that experienced an abrupt change in the mean of annual maximum floods. Of these, 22 out of the 24 experienced a decrease in the mean. (Adapted from Figure 4 of Villarini and Smith, 2013)



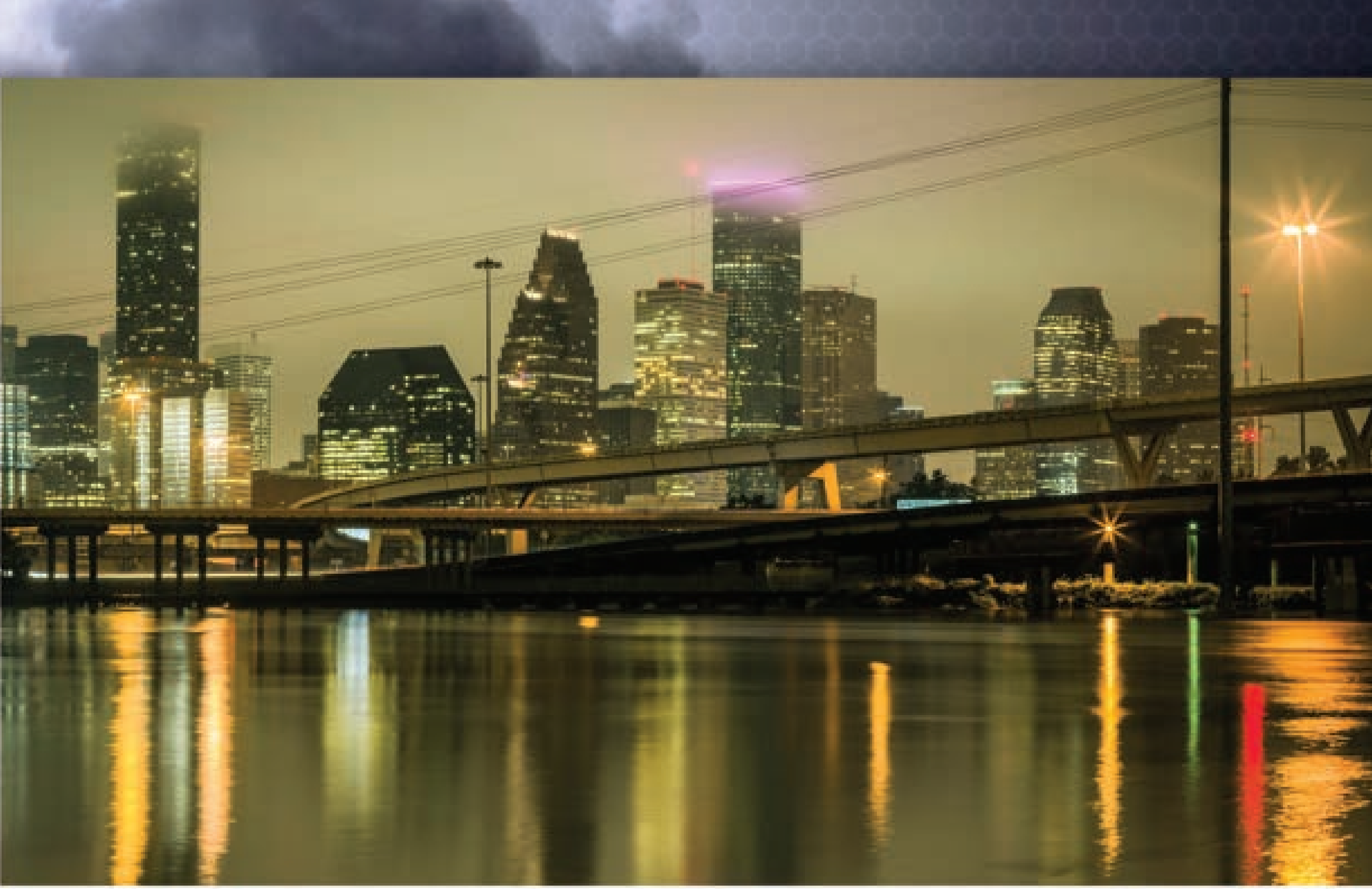
Top: *the locations of selected river gauges relative to river basins.*

Bottom: *the statistical trends of 1-day 95th percentile seasonal streamflow trends of each gauge after 1965. A Mann Kendall statistic greater than 1.96 indicates a significant increasing trend while a Mann Kendall statistic less than -1.96 indicates a significant decreasing trend. (Adapted from Figures 1 and 14 of Mishra et al., 2011)*

At the seasonal scale, there are mixed historical trends, with increased peak streamflow in the winter and decreased peak streamflow in the fall and spring that vary by climate zone.[liv] For the Trinity and Neches River Basins, both in east Texas where annual precipitation is greatest within the state, most gauges show statistically significant increases in winter extreme streamflow post-1965. While the other three seasons do not have statistically significant trends, there is still a general increasing trend in extreme streamflow for the Neches and Trinity River gauges. For the Colorado and Brazos River Basins (where annual precipitation decreases towards the west), there is an increasing trend in extreme streamflow in the winter since 1965, however, the spring and fall show a general decreasing trend.

Based on limited modeling studies, it appears that the effect of increased precipitation intensity will dominate over the effect of increased temperatures, leading to an increase in peak streamflow.[lv] The increase in streamflow is likely to be threshold-dependent, as soil moisture deficits will have the greatest percentage effect on runoff at low precipitation amounts. With very intense precipitation, such as with Hurricane Harvey, antecedent soil moisture will have almost no effect.[lvi]

In summary, river flooding in Texas is projected to have no substantial change through 2036. This is in large part due to the construction of dams and reservoirs for flood management in the 20th century. There is a mixture of historical trends categorized by season, and this does not bring forth a clear and coherent trend to project. Also, meteorological drivers of river flooding (increased rainfall intensity, decreased soil moisture) are projected to have competing influences. On balance, if an increasing trend is present in river flooding, it will be at the most extreme flood events or in the wettest parts of the state where there is so much rainfall that a decrease in soil moisture would have little mitigating impact.



URBAN FLOODING

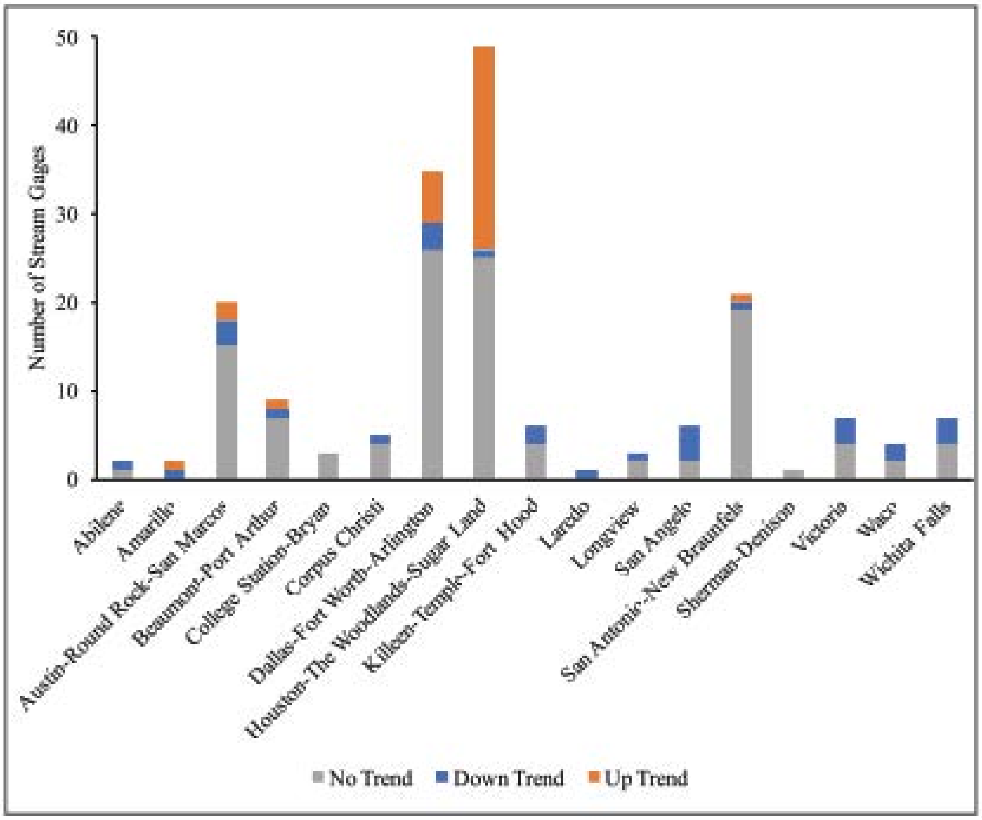
Urban flooding differs from river flooding in that catchments tend to be much smaller and the effects of urbanization are relevant for the projection of flooding in metropolitan areas. In general, urbanization greatly decreases or even eliminates the infiltration rates of the soil through the construction of impervious surfaces. For a given precipitation event, this greatly increases the precipitation runoff within a given basin and results in higher streamflow and flooding for urban rivers. Mitigation measures, such as detention ponds, can wholly or partly counter this effect.

Historic trends of urban flooding are variable and determined by local flood control factors. The distribution of impervious surfaces within a river basin, pre-existing land surfaces, alterations of land surfaces, pre-existing flood control impoundments that alter runoff flow, the terrain within a basin, etc. all vary from city to city in Texas. Nearly all metropolitan areas in the state contain gauges with increasing, decreasing, and neutral trends in flooding, the majority of those being neutral.[lvii] The degree of increasing and decreasing trend gauges varies from city to city, with the Houston metropolitan region standing out as a hotspot for increasing urban flooding trends (with over 60% of Texas's metropolitan increasing trend gauges in Harris County alone), whereas decreasing trends are spread among many metropolitan regions. A recent study has argued that the mere existence of Houston has intensified rainfall and increased streamflow twentyfold, but those findings may not be robust.[lviii]

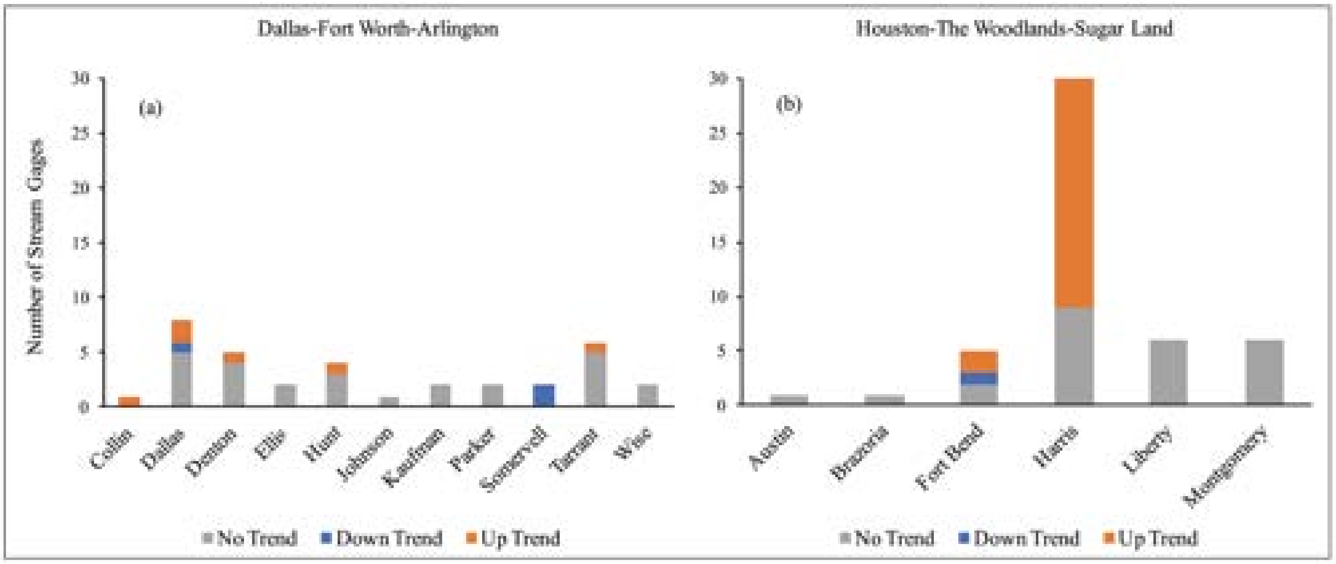
Local trends in the future may not necessarily reflect what has happened in the past. Many of the decreasing trend gauges are generally the gauges with a comparatively longer record of data (over 50 years) which are usually on major rivers which have been affected by dam/reservoir construction over the record period.[lix] As mentioned in the river flood section, little substantial reservoir construction is anticipated in the future. In addition, many of the increasing trend gauges tend to have a comparatively shorter record of data (25-50 years) where natural variability will have a larger influence on the calculated trend.

Regardless of the variable historical trends, Texas's urban population has increased by over 2% per year during 2000-2010, resulting in the largest urban area and the second largest urban population of the United States.[lx] As Texas's population continues to grow, its urban area is likely to continue to expand and become denser, and, in combination with the projected increase in intense precipitation, the effects of urbanization would result in an increase in precipitation runoff and urban flooding. Such a trend is supported by results from hydrological model simulations.[lxi]

Assuming that the flooding trends in small, rapidly-responding urban basins are driven climatologically by rainfall intensity, the change in frequency of extreme rainfall would translate directly to a change in the expected frequency of urban flooding: over 100% more in 2036 relative to climatological expectations for 1950-1999 and over 50% more relative to 2000-2018.



Number of examined stream gauges exhibiting no statistically significant trends, downward trends, and upwards trends in peak river flow, grouped by metropolitan area. (Figure 4 from Berg, 2018)



Closer examination of statistically significant gauge trends in a) Dallas-Fort Worth-Arlington and b) Houston-The Woodlands-Sugar Land areas (Figure 5 from Berg, 2018)

WINTER PRECIPITATION

Winter precipitation is rare enough in Texas to be automatically disruptive in most areas. Snow and sleet are most common across northern Texas, the Panhandle, west-central Texas, and far west Texas.[lxii] However, snow has been reported on occasion in every county in Texas.

In the southern part of the state and in coastal regions, snow is rare, but nonetheless, large accumulations of snow are possible. Notable events include 1895 from Galveston to Beaumont (nearly two feet of snowfall accumulation)[lxiii], 1985 in San Antonio (over a foot), and 2004 in Victoria (nearly a foot).[lxiv] Given these rare events, it is perhaps not totally unbelievable that the one-day snowfall record for Texas is held not by a Panhandle city but by Hillsboro, north of Waco, with 26" in 1929. These sorts of extremely unusual but highly disruptive snow events have not been studied in a climate change context and they are too rare for any trends to be robustly detected in the historical record.

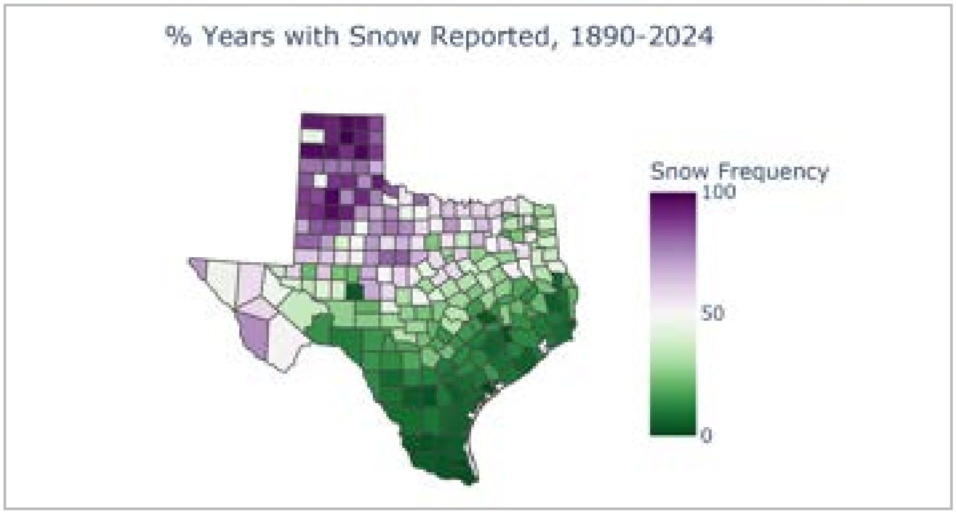
Given the size of Texas and the typical scale of snowstorms at this latitude, it is rare for individual snowstorms to affect most of the state simultaneously. One such event was on February 14-16, 2021, while Texas was in the grip of a cold wave of historic proportions. That snowstorm was also historic, one of only four snowstorms in the historical record to have brought measurable snow to most of the state of Texas.

Two of the four largest snowstorms geographically were also two of the largest snowstorms in terms of maximum snowfall amount: the 1895 and 1929 snowstorms. While it's not possible to reliably estimate a trend from such a small number of events, it is clear that such snowstorms have not increased in frequency.

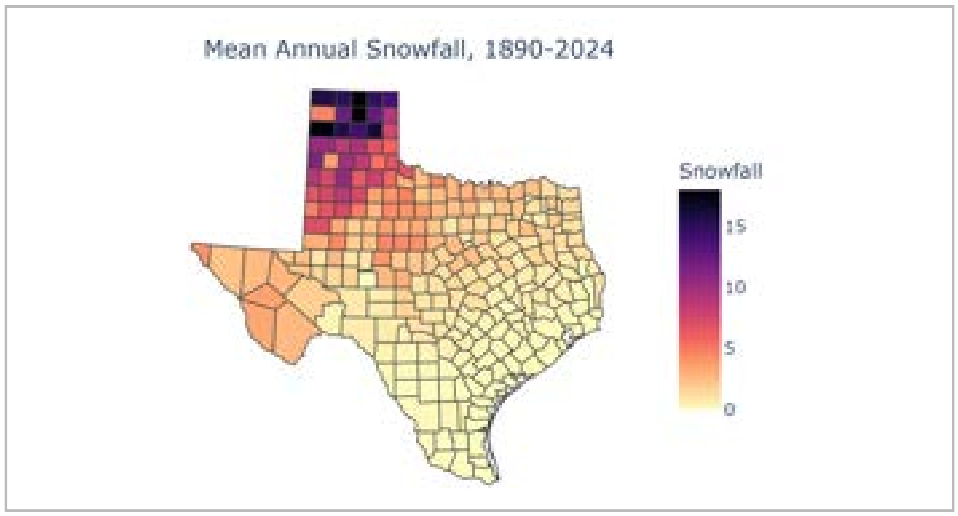
Farther to the northeast, where snow is more common, **there is no noticeable trend in the frequency of 2" or greater snowfalls from 1930 to 2007.**[lxv] **Because the determining factor for snowfall in northwest Texas is typically air temperature, a reasonable expectation is that snowfall frequency and intensity will decrease in the future, somewhat reducing the snow hazard. In climate model projections, the risk of snowfall consistently decreases in climates like that of Texas.**[lxvi]

Freezing rain is highly disruptive to vehicular travel and to electric power transmission. Freezing rain can occur when a warm layer of air aloft overlays subfreezing air near the surface. In Texas, this happens when a strong cold front stalls across Texas as an upper-air disturbance picks up warmer, humid air from over the Gulf of Mexico and carries it northward above the shallow cold air. Freezing rain is most common in the northeastern part of the state.

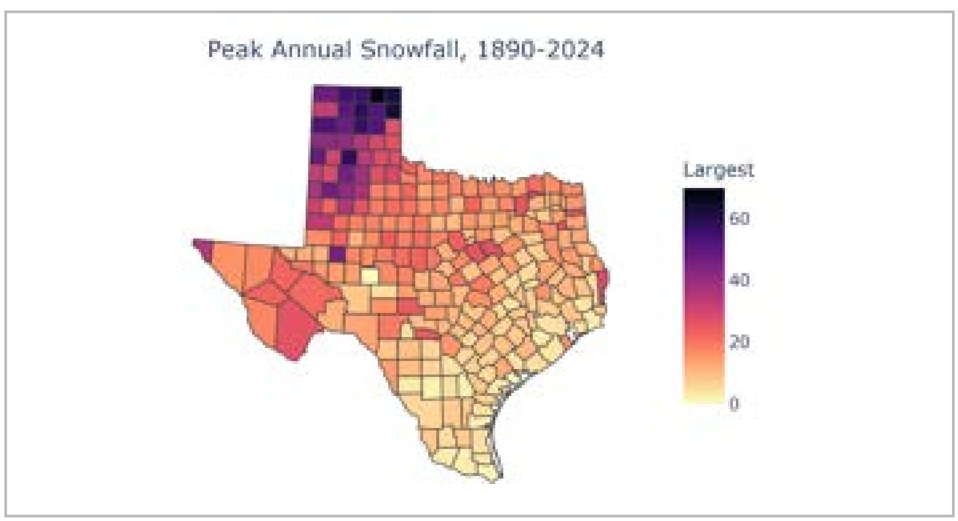
The climate data record for freezing rain observations is quite sparse compared to snow and rain. Freezing rain trends in Texas during the last half of the 20th century were mixed.[lxvii] Because freezing rain is strongly dependent on temperature conditions, one might expect a decrease in the threat of freezing rain over time. However, the weather patterns that produce freezing rain are rather specific, and changes in the frequency of those weather patterns could easily amplify or neutralize any temperature-driven trend. **So the expectation of a decline in freezing rain frequency is tentative, and the magnitude of such a decline is as yet unknown.**



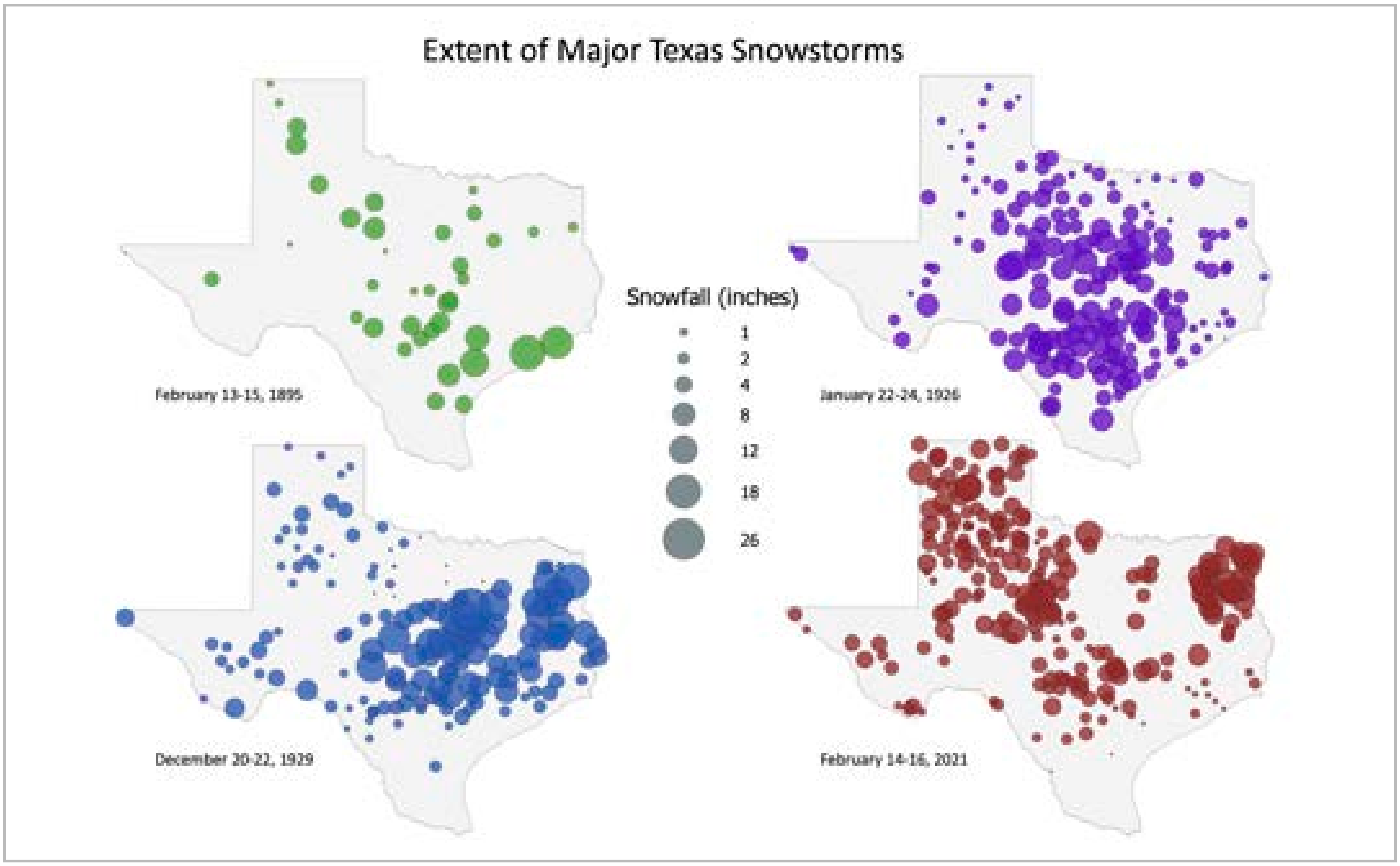
Percentage of calendar years with snow reported at county index stations. Some stations did not measure and report snow consistently.



Average calendar year snowfall at county index stations. Some stations did not measure and report snow consistently.



Maximum calendar year snowfall at county index stations. Some stations did not measure and report snow consistently.



Distribution of reported snowfall totals for the four largest Texas snowstorms on record. Note that stations are distributed unevenly geographically and over time; locations between reported snowfalls are likely to have received snow as well.

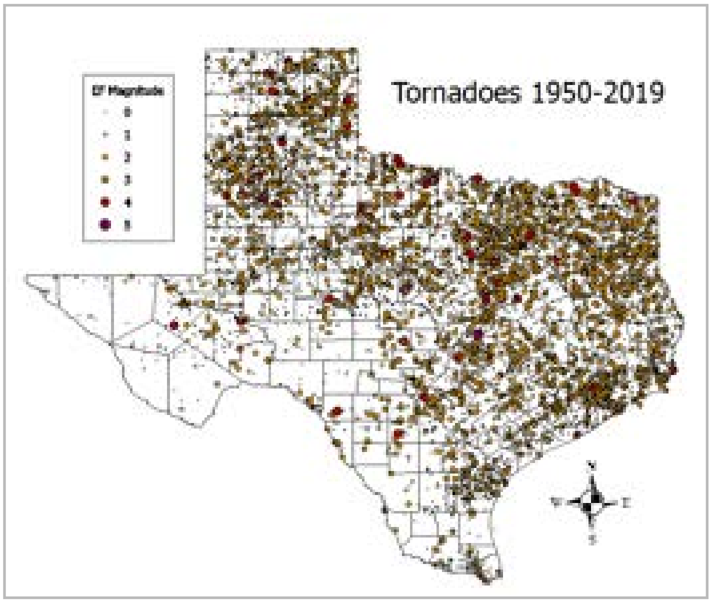
SEVERE THUNDERSTORMS

There is no reliable, long-term record of severe thunderstorms or the severe weather they produce: tornadoes, hail, and strong winds. Reporting methods and magnitude scales have changed over time for tornadoes and hail events.

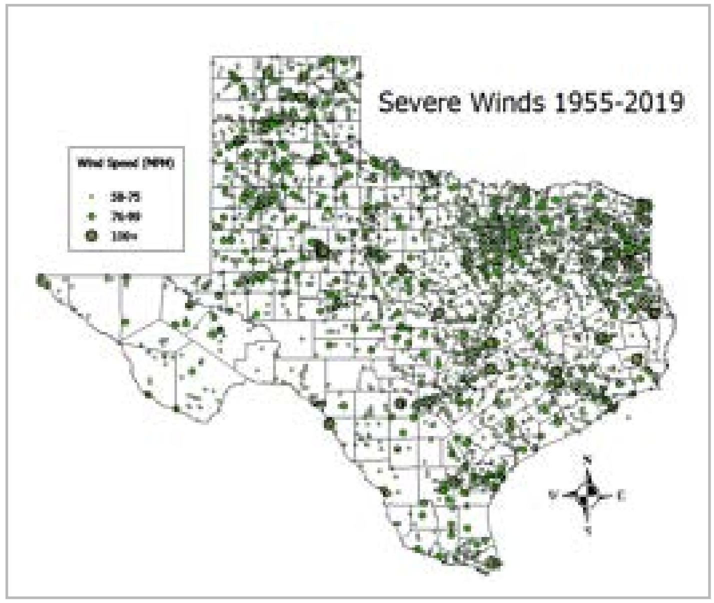
Maps of the historic distribution of tornadoes, hail, and strong winds make it clear that no corner of the state is immune to severe thunderstorms.[lxviii] The dense clusters of observed events around major metropolitan areas such as Dallas-Fort Worth reflect the enhanced likelihood that a severe thunderstorm there will be witnessed or will cause damage. It is also possible to detect lines of severe weather reports along some major highways, such as Interstate 20 near Midland. The strong dependence of report location on population density gives an indication of how changes in severe thunderstorm reports over time are more strongly affected by changes in population than by changes in severe thunderstorms themselves.[lxix]

Not only is the climate data record for severe thunderstorms poor, severe thunderstorms are too small to be simulated directly by present-day climate models. Therefore, when assessing trends in severe thunderstorms, it is necessary to consider indirect indicators of severe thunderstorm frequency and intensity such as wind shear and convective instability, both of which favor severe storms.

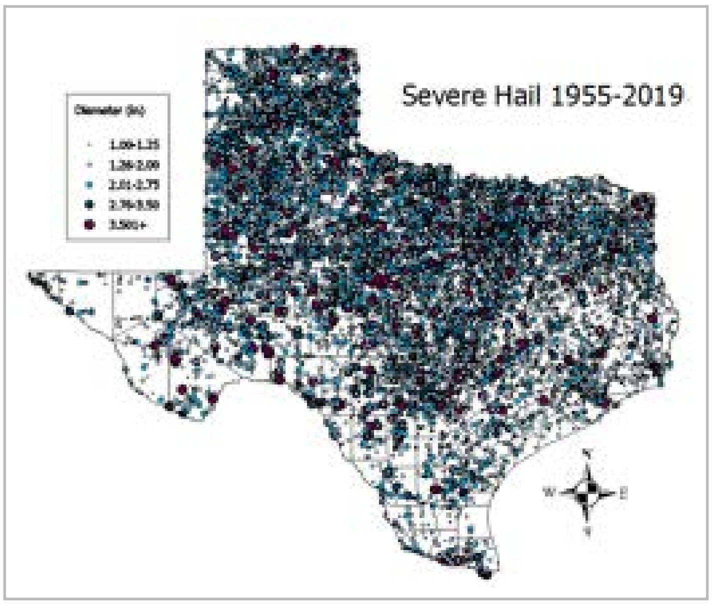
Over the past few decades, the severe storm environment over Texas has changed in complex and opposing ways.[lxx] The amount of energy available for convection has decreased, and the amount of energy needed to initiate convection has increased at the same time. This suggests that environmental conditions have become less favorable for the occurrence of thunderstorms. However, the amount of low-level shear has increased, which would be expected to make thunderstorms more likely to become severe once they develop. Changes in severe storm environments have not been uniform throughout the year, with environments becoming more favorable for severe thunderstorms and significant hail in Texas early in the spring and less favorable later in the spring.



Locations and magnitudes of tornadoes in Texas, 1950-2019. Data from https://www.spc.noaa.gov/gis/svrgis.



Locations and magnitudes of potentially damaging thunderstorm winds in Texas, 1950-2019. Data from https://www.spc.noaa.gov/gis/svrgis.



Locations and magnitudes of severe hail in Texas, 1950-2019. Data from https://www.spc.noaa.gov/gis/svrgis.

Climate model simulations imply different prospects going forward. As temperatures increase, the amount of energy available to fuel these storms is simulated to increase as temperature and low-level moisture increase.[lxxi] Even though shear will likely decrease as the temperature gradient from the poles to the equator weakens, the increase in instability is projected to overwhelm any decrease in low level shear.[lxxii] This results in an overall increase in the number of days capable of producing severe thunderstorms.

With these complex trends and partially contradictory information between models and observations, there is low confidence in any ongoing trend in the overall frequency and severity of severe thunderstorms.

Regarding the specific hazards of thunderstorms, lightning occurs most often during the months of May and June. Severe wind is most prevalent during the summer months from disorganized storm systems in the High Plains of Texas.[lxxiii] **The most robust trend in tornado activity is a tendency of more tornadoes in large outbreaks, but the factors apparently driving that trend are not projected to continue. Warmer temperatures are likely to lead to less hail overall, particularly during the summer, but increases in available thunderstorm energy may lead to an increase of the risk of very large hail earlier in springtime.[lxxv]**

HURRICANES AND COASTAL EROSION

Sea level rise and storm intensity both affect coastal flooding and erosion.

The change in ocean height relative to coastal lands, called relative sea level rise, is one of many factors affecting coastal erosion. Relative sea level rise is a combination of three factors: eustatic sea level rise, local variations in sea level rise, and relative land motion. Eustatic sea level rise is the change in global mean ocean height and is primarily the result of increasing temperatures that cause thermal expansion and melting glaciers and ice sheets. Local variations are produced by changes in wind patterns and ocean currents and are minor for the Gulf of Mexico. Relative land motion in coastal Texas is dominated by coastal subsidence.

Subsidence is a gradual lowering of land-surface elevation and is the result of the extraction of groundwater, oil, or gas or increasing sediment loading or infrastructure construction. As the coast of Texas slowly sinks, water potentially encroaches landward so quickly that it can exceed natural sediment accretion rates. In the state of Texas, the rate of subsidence ranges from less than 0.6 ft/century to as much as 2.5 ft/century.[lxxvii] The variations are due to historical differences in oil, gas, or groundwater extraction and sediment loading, resulting in generally larger rates of subsidence in southeast Texas than in south Texas.[lxxviii]

The combination of local subsidence, eustatic sea level rise, and changes in sediment deposition and transport have produced a retreat of the Texas coastline along nearly the entire length of its barrier islands.[lxxix] In Galveston Bay and probably other bays and estuaries behind the barrier islands,

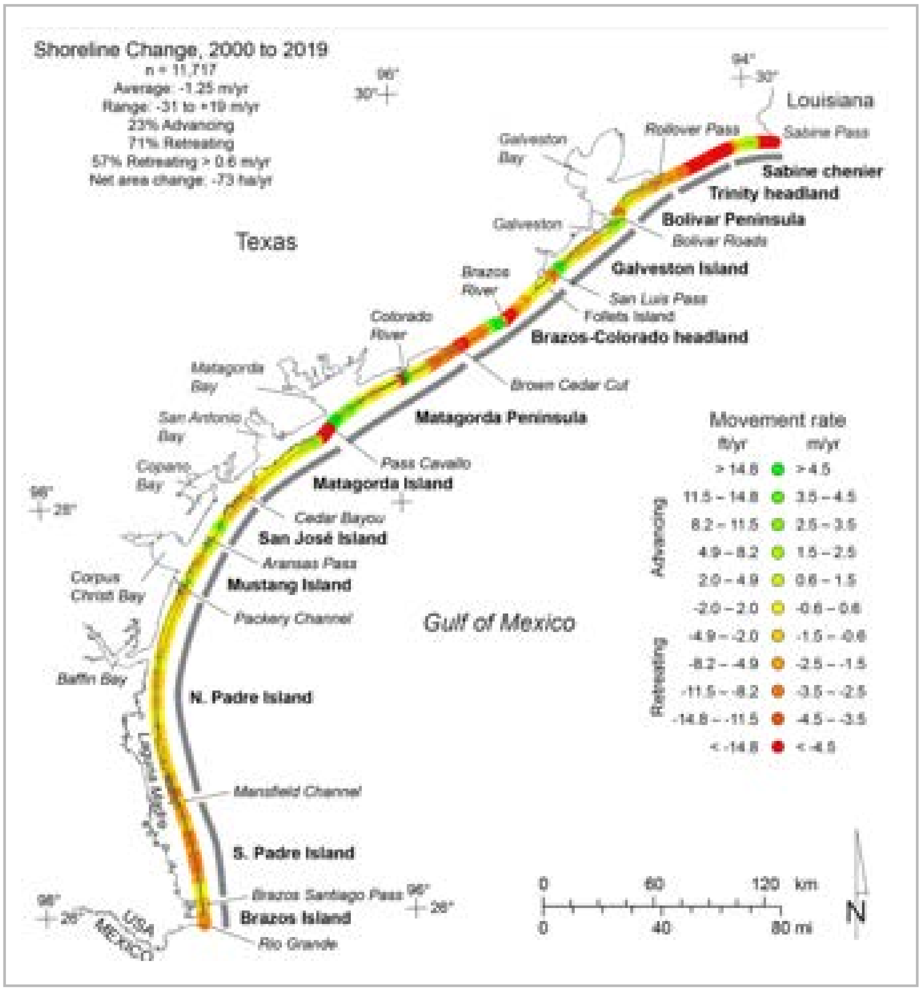
	Station ID		RSLR	95% C
Sabine Pass	8770580	1958-2020	2.02 ft/century	+/- 0.24
Galveston Pier 21	8771450	1904-2023	2.18 ft/century	+/- 0.07
Freeport Harbor	8772471	1954-2023	1.18 ft/century	+/- 0.20
Rockport	8774770	1937-2023	1.97 ft/century	+/- 0.15
Corpus Christi	8775870	1983-2022	1.80 ft/century	+/- 0.32
Port Mansfield	8778490	1963-2023	1.21 ft/century	+/- 0.21
Port Isabel	8779770	1944-2023	1.42 ft/century	+/- 0.10
S. Padre Island	8779748	1958-2023	1.37 ft/century	+/- 0.16

Relative sea-level rise (RSLR) and 95% confidence interval (95% C) at selected Texas tide gauges through 2023.[lxxvi]

sediment deposition is not keeping up with relative sea level rise, leading to loss of coastal wetlands. In many areas there has been a decrease in extraction of groundwater and other resources as the problems associated with coastal subsidence have become clearer, resulting in a reduction in coastal subsidence. However, eustatic sea level has shown indications of acceleration,[lxxxi] so on balance the near-term future rate of coastline retreat may be expected to be similar to historic rates.

Rising sea levels lead directly to increased risk of storm surge from hurricanes, as the storm surge is on top of an elevated baseline. Given typical return periods for storm surges along the Gulf Coast,[lxxxii] a 1 meter relative sea level rise produces a doubling of storm surge risk, as a surge that would in the past have been expected have a 1% chance of occurring in any given year would in the future have a 2% chance of occurring in any given year. **The places along the coast with the largest rates of relative sea level rise may have a doubled storm surge risk by 2050 relative to the risk at the beginning of the 20th century, purely due to the relative sea level rise itself.**

An additional element of enhanced risk is provided by an expected increase in the intensity of very strong hurricanes, despite an expected lack of increase, or even a decrease, in hurricane frequency overall.[lxxxiii] Different research studies have produced some conflicting results, and local trends over the western Gulf of Mexico will also be affected by changes in wind patterns for which global climate models have little predictive skill. While some recent research has pointed to an apparent trend for United States tropical cyclones to move more slowly at landfall, much like Hurricane Harvey, other research suggests that Texas may be spared from such a slowdown.[lxxxiv] At this point, the enhanced risk is difficult to quantify, but substantial scientific progress on this topic is likely as climate models become better able to simulate the storms themselves.



Net rates of coastal advance (positive) or retreat (negative) for the Texas Gulf shoreline between Sabine Pass and the Rio Grande, calculated from shoreline positions between 2000 and 2019. Longer-term changes are similar. From Paine and Caudle (2020).

WILDFIRES

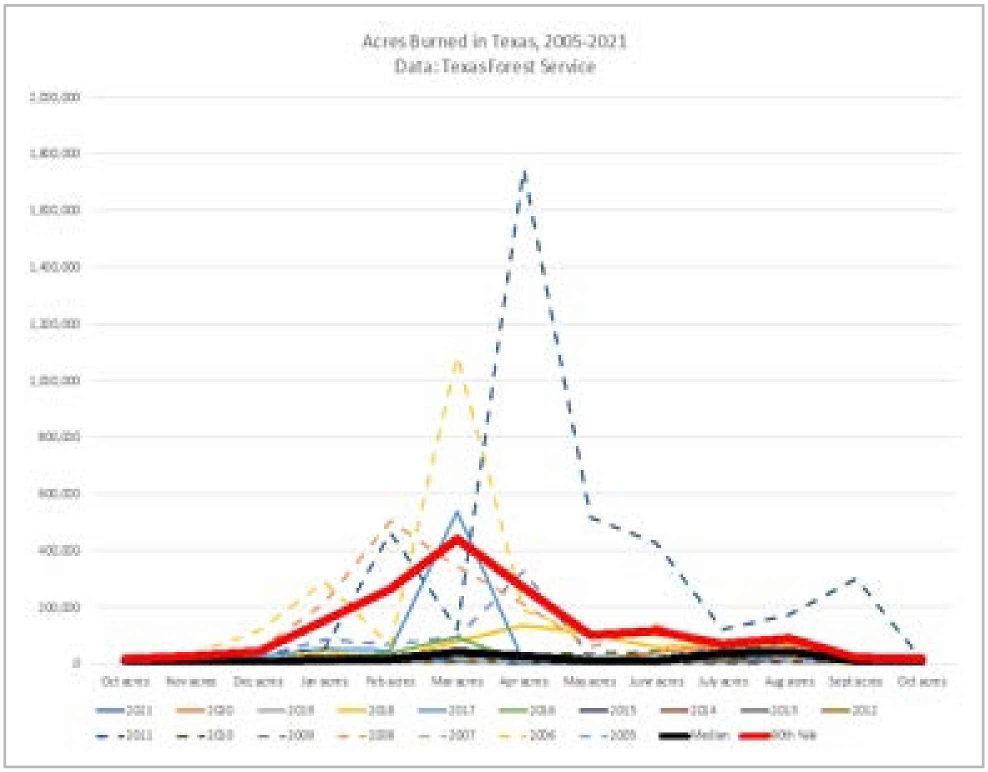
The state of Texas has two primary wildfire seasons. The late winter and early spring wildfire season carries with it the greatest risk of large wildfires in the state. This was most recently seen in the Smokehouse Creek fire in late February 2024, which was the largest Texas wildfire on record and fifth-largest in the United States. Comprehensive data since 2005 from the Texas A&M Forest Service illustrates the erratic nature of the spring wildfire season, with only a few years exceeding 100,000 acres burned and the 90th percentile of burned acreage peaking at a little over 400,000 acres in March.

Almost all large wildfires occur in the western half of the state, particularly in the Panhandle, High Plains, Low Rolling Plains, and Trans Pecos regions. These wildfires require a particular set of circumstances that make them distinct from most wildfires in the western United States.[lxxxvi] First, ample rain is required during the preceding summer to produce dense growth of annual and perennial grasses. After these grasses die or become dormant with the onset of wintertime cold, they are susceptible to ignition and burning following any period of dry weather. Then, a certain type of weather pattern is associated with large wildfire outbreaks in the Southern Plains: strong winds from the southwest or west, high temperatures, and very low humidity. Such conditions may occur only a few times during the spring wildfire season, but they can lead to dozens of rapidly-spreading fires. The spring wildfire season comes to a close as temperatures warm and moisture permits the regrowth of grasses. During the drought of 2011, however, spring rains were insufficient to terminate the wildfire season, and the risk of large wildfires remained through most of the year.

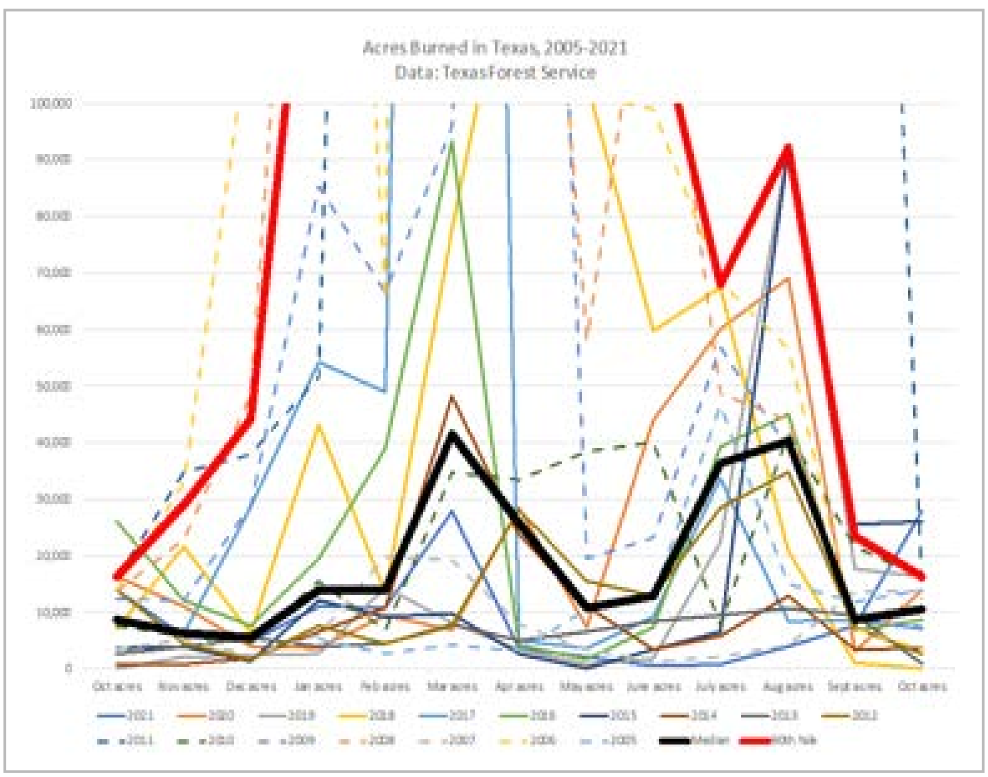
It's necessary to zoom in on monthly burned acreage totals of 100,000 or less to see the summer wildfire season. In a typical year, more land is burned during the summertime than during the spring. This summer wildfire season is much more regular than the spring wildfire season and affects the entire state. It is driven by the heat of the summer, whereby a period without rain can allow grasses and litter to dry out and easily catch fire. Wind speeds during the summer are typically much lower than during the spring, so summer wildfires tend to be much smaller. The one recent exception is 2011, when a landfalling tropical storm interacted with a cold front to produce strong, gusty winds that allowed wildfires such as the 2011 Bastrop fire to spread rapidly.

Prior to wildfire surveys and comprehensive record-keeping, wildfires spanning several million acres, much larger than any modern wildfires, took place around the turn of the 20th century. Subsequently, fire suppression and agricultural land management combined to dramatically reduce the size of wildfires. Wildfire acreage burned appears to have remained relatively low through the rest of the 20th century but increased dramatically in the 21st century.[lxxxvii]

There is weak statistical evidence for a slight decline in the frequency of unusually strong winds speeds across the southern Great Plains.[lxxxviii] One future climate simulation predicts an increase in average wind speed across most of Texas in all seasons.[lxxxix] On the whole, expectations for wind speed trends lack robustness.



Total acres burned in Texas, Texas A&M Forest Service data.[lxxxv] Earlier years are represented by dashed lines. The thick red line corresponds to the 90th percentile of acreage burned and the thick black line corresponds to median acreage burned.



Total acres burned in Texas, 2005-2021, showing monthly totals of 100,000 acres or less. The thick red line is the 90th percentile, while the thick black line is the median.

Low humidity and surface dryness are closely related. Low humidity refers to the extremely dry weather accompanying wildfire outbreaks across Texas, while surface dryness refers to the lack of moisture in dry, dormant, or otherwise combustible vegetation. Surface dryness is strongly influenced by weather conditions, but it is a consequence of desiccation of vegetation over an extended period of time rather than simply lack of humidity on a particular day.

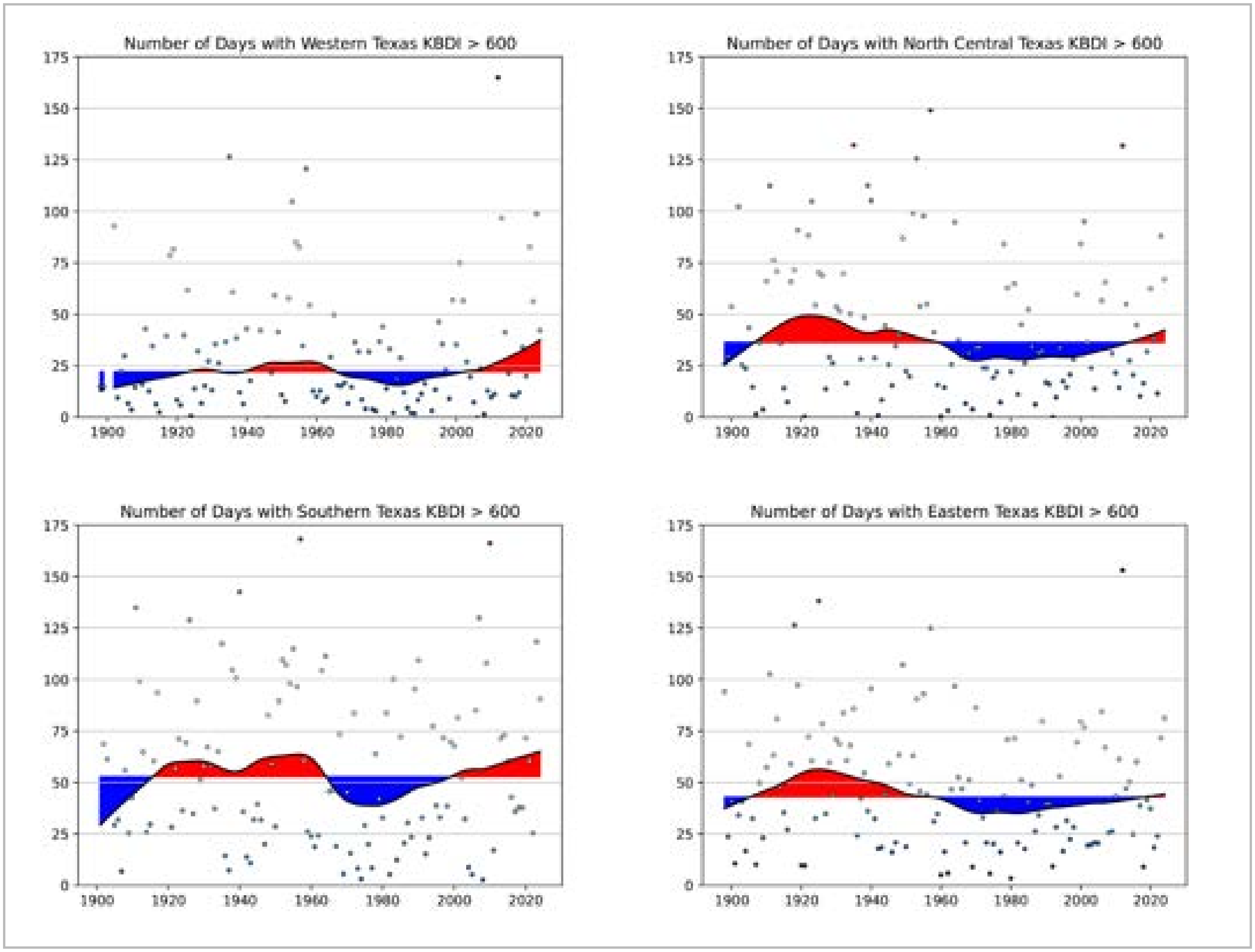
Vapor pressure deficit, an indicator of the ability of moisture to evaporate, is projected to increase as temperatures rise and carbon dioxide fertilization reduces transpiration, leading to both lower humidity and increased surface dryness.[xc] **Overall, increased dryness should extend the wildfire season in places where the fire season is presently constrained by low levels of aridity, such as eastern Texas. At the same time, increased temperatures should allow very dry conditions to develop earlier in the year, lengthening both the spring and summer wildfire seasons.**

Changes in fuel load involve two competing effects: increased aridity leading to reduced plant growth, and increased carbon dioxide leading to increased plant growth. Multiple papers predict wildfires in the Southwest (including Texas) will change differently than elsewhere in the country as fuel load gradually becomes the determining limit on fires.[xcii] However, these papers fail to take into account the fact that the amount of dry grass on rangeland depends on grazing intensity. If climate conditions lead to decreases in forage availability, ranchers are likely to respond by reducing herd sizes, ultimately keeping fuel availability relatively constant. Meanwhile, **the area of the state commonly affected by wildfires may expand eastward as fuels become drier faster in a warmer climate.**

Historical trends in wildfires depend on fire suppression activities, both for limiting the growth of individual fires in the short range and allowing the increase in shrubby fuels on unburned land in the long run. This makes historical variations in acreage burned an unreliable indicator of climate change effects. Instead, we examine the Keetch-Byram Drought Index (KBDI), a commonly-used indicator of fire susceptibility. This index is a better reflection of fire susceptibility during the summer wildfire season than the spring wildfire season. Spring wildfire are much more sensitive to changes in day-to-day weather conditions, as discussed above.

All four regions of Texas show similar fluctuations in the number of days with the KBDI above 600. Other thresholds show similar temporal patterns. Meanwhile, the long-term trends are driven by changes in both temperature and precipitation, with increasing temperatures increasing fire risk and increasing precipitation in central and eastern Texas decreasing fire risk. Where rainfall has been steady or decreased, the number of days with KBDI above 600 is higher than at any time in the historical record. Where rainfall has increased, the number of days with KBDI above 600 is not higher than ever but is nonetheless above the long-term average.

The increase in number of high KBDI days confirms that climate change is increasing the number of days susceptible to wildfire. The increase has been most dramatic in western Texas, where steady or declining precipitation has failed to mitigate the drying effect of increasing temperatures, according to this particular measure of wildfire risk.



Annual variations in the number of day in which the KBDI exceeds 600, computed using county composite stations and partitioned by climate division into four regions: western (High Plains, Low Rolling Plains, Trans Pecos), north central (North-Central, Edwards Plateau), southern (South-Central, Southern, Lower Valley), and eastern (East, Coastal Plain).

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[ii]Online data archive: ftp://ftp.ncei.noaa.gov/pub/data/cirs/climdiv/
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[v]The historical simulations and projections are based on CMIP5 multi-model ensemble output from the Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections archive at https://gdo-dcp.ucllnl.org/downscaled_cmip_projections
The first available ensemble member from the combined Historic and RCP 4.5 was used from each of the following models for temperature and from the combined Historic and RCP 8.5 for precipitation. A ^ means only RCP 4.5 simulations were available from a particular model, so it was not included in the precipitation ensemble.

Modeling Center (or Group)	Institute ID	Model Name
Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia	CSIRO-BOM	ACCESS1.0 ACCESS1.3^
Beijing Climate Center, China Meteorological Administration	BCC	BCC-CSM1.1 BCC-CSM1.1(m)
Canadian Centre for Climate Modelling and Analysis	CCCMA	CanESM2
National Center for Atmospheric Research	NCAR	CCSM4
Community Earth System Model Contributors	NSF-DOE-NCAR	CESM1(BGC) CESM1(CAM5)
Centro Euro-Mediterraneo per I Cambiamenti Climatici	CMCC	CMCC-CM
Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	CNRM-CERFACS	CNRM-CM5
Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	CSIRO-QCCCE	CSIRO-Mk3.6.0
EC-EARTH consortium	EC-EARTH	EC-EARTH^
LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS, Tsinghua University	LASG-CESS	FGOALS-g2
LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences	LASG-IAP	FGOALS-s2^
The First Institute of Oceanography, SOA, China	FIO	FIO-ESM

NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL	GFDL-CM3 GFDL-ESM2G GFDL-ESM2M
NASA Goddard Institute for Space Studies	NASA GISS	GISS-E2-H-CC^ GISS-E2-R GISS-E2-R-CC^
National Institute of Meteorological Research/Korea Meteorological Administration	NIMR/KMA	HadGEM2-AO
Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)	MOHC (additional realizations by INPE)	HadGEM2-CC HadGEM2-ES
Institute for Numerical Mathematics	INM	INM-CM4
Institut Pierre-Simon Laplace	IPSL	IPSL-CM5A-LR^ IPSL-CM5A-MR IPSL-CM5B-LR
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC	MIROC-ESM MIROC-ESM-CHEM
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC	MIROC5
Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)	MPI-M	MPI-ESM-MR MPI-ESM-LR
Meteorological Research Institute	MRI	MRI-CGCM3
Norwegian Climate Centre	NCC	NorESM1-M NorESM1-ME^

The 1/8-degree BCSD (bias-corrected and statistically-downscaled) model output was downloaded as a geographically averaged ensemble mean over a latitude-longitude box centered on Texas: 27.5°-35.5°N, 94.25°-104.0°W, inclusive.

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[viii]1900-1999 average: 64.6 °F. 2000-2018 average: 66.0 °F. 2036 projection: 67.6 °F. Warmest year on record: 2012 (67.8 °F).

[ix]The stations are chosen for their geographical representativeness, data completeness, and lack of substantial changes in station location. These stations, and which of four regions of the state in which they are found (NW: Northwest, NE: Northeast, S: South, and C: Coastal), are listed here:

Urban: El Paso Intl Airport (NW); San Antonio Intl Airport (S); Dallas Love Field (NE); Houston Hobby Airport (C).

Semi-Urban: Hereford (NW); Huntsville (NE); College Station Easterwood Field (S); Harlingen (C); Corpus Christi Intl Airport (C); Brownfield (NW)

Rural: Dalhart FAA Airport (NW); Luling (S); Midland Intl Airport (NW); Lufkin Angelina Co Airport (NE); Amarillo Intl Airport (NW); Victoria Regional Airport (C); Beeville 5 NE (S); Crosbyton (NW); Centerville (NE)

In order to retain a sufficient number of homogeneous stations, the index data record only covers the period 1950-present.

[x]The county temperature stations are created as follows: using SC-ACIS web services, every daily maximum/minimum temperature observation is retrieved for a given county. Each year, starting in 1890, a station with no more than ten missing days is identified. If no such station exists, data for that year is marked as missing. If at least one such station exists, data from the station with the longest period-of-record is chosen. This data becomes the year's data for that county. The process is repeated for each year through June 2021. Compared to the index stations, the county stations are much less homogeneous. In particular, different stations would have taken observations at different times, which can skew average temperatures. Because of this, we only use the county stations to identify trends in monthly temperature extremes. Such block maxima are relatively insensitive to time-of-observation artifacts.

[xi]A reference temperature was identified for each station, corresponding to the hottest 5% of summer days. Temperature probabilities and trends were collectively analyzed for all stations within a region relative to the reference temperatures. Finally, the regional temperature distributions and trends were applied to the temperatures of a typical station within each region to assess changes in 100 °F days. Because 100 °F day counts are a nonlinear function of temperature and because counts cannot be negative, trends were analyzed on the basis of a linear fit to the time series of the logarithm of annual 100 °F day counts.

[xii]Each year's value consists of the average of four temperatures: the hottest temperature in June, the hottest temperature in July, the hottest temperature in August, and the hottest temperature in September. For example, if at the station being used for Travis County the highest temperature during June 2008 was 95, in July 2008 98, in August 2008 100, and in September 2008 97, the average hottest day in 2008 would be 97.5.

[xiii]USGCRP, 2017: *Climate Science Special Report: Fourth National Climate Assessment, Volume I.* U.S. Global Change Research Program, 470 pp.

[xiv]Nikiel, C. A., and E. A. B. Eltahir, 2019: Summer Climate Change in the Midwest and Great Plains due to Agricultural Development during the Twentieth Century. *Journal of Climate*, **32,** 5583-5599.
[xv]Calculated from county stations as the average of the lowest temperatures recorded during each of December, January, and February, and assigned to January's year.
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Blackport, R., J. A. Screen, K. van der Wiel, and R. Bintanja, 2019: Minimal influence of reduced Arctic sea ice on coincident cold winters in mid-latitudes. *Nature Climate Change*, **9,** 697-704.
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[xviii]The county precipitation stations were created following the same method as the county temperature stations.
[xix]Precipitation from single ensemble members from the Historical+RCP4.5 CMIP5 runs were averaged over the box 25°N-37.5°N, 95°W-105°W and downloaded from the KNMI Climate Explorer. The models were: ACCESS1-0 ACCESS1-3 bcc-csm1-1 bcc-csm1-1-m BNU-ESM CanESM2 CCSM4 CESM1-BGC CESM1-CAM5 CMCC-CM CMCC-CMS CNRM-CM5 CSIRO-Mk3-6-0 EC-EARTH FGOALS-g2 FIO-ESM GFDL-CM3 GFDL-ESM2G GFDL-ESM2M GISS-E2-H GISS-E2-H GISS-E2-H GISS-E2-H-CC GISS-E2-R GISS-E2-R GISS-E2-R GISS-E2-R-CC HadGEM2-AO HadGEM2-CC HadGEM2-ES inmcm4 IPSL-CM5A-LR IPSL-CM5A-MR IPSL-CM5B-LR MIROC5 MIROC-ESM MIROC-ESM-CHEM MPI-ESM-LR MPI-ESM-MR MRI-CGCM3 NorESM1-M NorESM1-ME.
[xx]Maloney, E. D., and Coauthors, 2014: North American Climate in CMIP5 Experiments: Part III: Assessment of Twenty-First-Century Projections. *Journal of Climate*, **27,** 2230-2270.
[xxi]Bukovsky at al. (2017) argued for a plausible tendency for less precipitation in Texas in the summertime in CMIP5 models, but CMIP6 model simulations do not have a clear summertime drying signal in Texas.
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[xxii]Easterling, D. R., and Coauthors, 2017: Precipitation change in the United States. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*, D. J. Wuebbles, D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, and T. K. Maycock, Eds., U.S. Global Change Research Program, 207-230.
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[xxiv]One year block maxima of 1-day precipitation totals for composite stations in each county were fit to a GEV distribution with linearly time-dependent location and scale parameters using the climetRemes Python library. The trend in frequency of extreme rainfall was calculated using the time-dependent PDF, with CMIP5 historical and RCP 4.5 projected global mean surface temperature as a covariate. Citation for software package:

Paciorek, C. J., D. A. Stone, and M. F. Wehner, 2018: Quantifying statistical uncertainty in the attribution of human influence on severe weather. *Weather and Climate Extremes*, **20,** 69-80.

[xxv]Jorgensen, S., and J. Nielsen-Gammon, 2024: Nonstationarity in extreme precipitation return values along the United States Gulf and Southeastern coasts. *Journal of Hydrometeorology*, **25,** in press.

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[xxvii]Pfahl, S., P. A. O'Gorman, and E. M. Fischer, 2017: Understanding the regional pattern of projected future changes in extreme precipitation. *Nature Climate Change*, **7,** 423.

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[xxix]Based on the 2035 global temperature projection by Kirtman et al. (0.4 °C increase by 2036 compared to 2010-2018) and the ratio of Gulf of Mexico to global temperature increases by Collins et al. (75%-100%).

Kirtman, B., and Coauthors, 2013: Near-term Climate Change: Projections and Predictability. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker, and Coauthors, Eds., Cambridge University Press.

Capotondi, A., and Coauthors, 2015: Understanding ENSO Diversity. *Bulletin of the American Meteorological Society*, **96,** 921-938, Collins, M., and Coauthors, 2013: Long-term Climate Change: Projections, Commitments and Irreversibility. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker, and Coauthors, Eds., Cambridge University Press.

[xxx]Based on the county precipitation station analysis, the odds of extreme (once per decade or so) one-day precipitation decrease by a factor of two for every 20% increase in precipitation amount.

[xxxi]Based on the updated NOAA Atlas 14 values for Texas, which are used for flood risk calculations.

Perica, S., S. Pavlovic, M. St. Laurent, C. Trypaluk, D. Unruh, and O. Wilhite, 2018: NOAA Atlas 14: Precipitation-Frequency Atlas of the United States, Volume 11 Version 2.0: Texas, 40 pp.

[xxxii]Online data archive: ftp://ftp.ncdc.noaa.gov/pub/data/cirs/climdiv/

Vose, R. S., and Coauthors, 2014: Improved historical temperature and precipitation time series for U.S. climate divisions. *Journal of Applied Meteorology and Climatology*, **53,** 1232-1251.

[xxxiii]Data and analysis archive label: climdiv-sp09st-v1.0.0-20190204 and SP09

Online data archive: ftp://ftp.ncdc.noaa.gov/pub/data/cirs/climdiv/

Overall yearly drought severity is computed by summing the negative statewide 9-month SPI values for a given year and dividing by 12 to obtain an average annual drought intensity.

[xxxiv]The historic simulations and projections are based on the CMIP5 multi-model ensemble output, as with Footnote iv for temperature, with the following differences: Model simulations using the RCP8.5 scenario are extracted, to improve signal-to-noise ratio. Precipitation is summed for each water year, October-September, rather than each calendar year, in order to better reflect the potential for dryness during the growing season and so as to not divide cool-season precipitation variability associated with El Niño across two separate years. The water year precipitation is converted to anomalies by subtracting the centered 29-year mean for each simulation, with the 1950-1978 mean used for calculating anomalies in 1950-1964. Interannual precipitation variance is then calculated using the same 29-year intervals, and variance time series are created from the overlapping 29-year periods.

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[xxxvi]Nielsen-Gammon, J. W., and Coauthors, 2020: Unprecedented Drought Challenges for Texas Water Resources in a Changing Climate: What Do Researchers and Stakeholders Need to Know? *Earth's Future*, **8,** e2020EF001552.

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[xxxviii]Data and analysis archive label: climdiv-pdsist.v1.0-.0-20190204

Online data archive: ftp://ftp.ncdc.noaa.gov/pub/data/cirs/climdiv/

Vose, R. S., and Coauthors, 2014: Improved historical temperature and precipitation time series for U.S. climate divisions. *Journal of Applied Meteorology and Climatology*, **53,** 1232-1251.

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Berg, A., and Coauthors, 2016: Land-atmosphere feedbacks amplify aridity increase over land under global warming. *Nature Climate Change*, **6,** 869-+.
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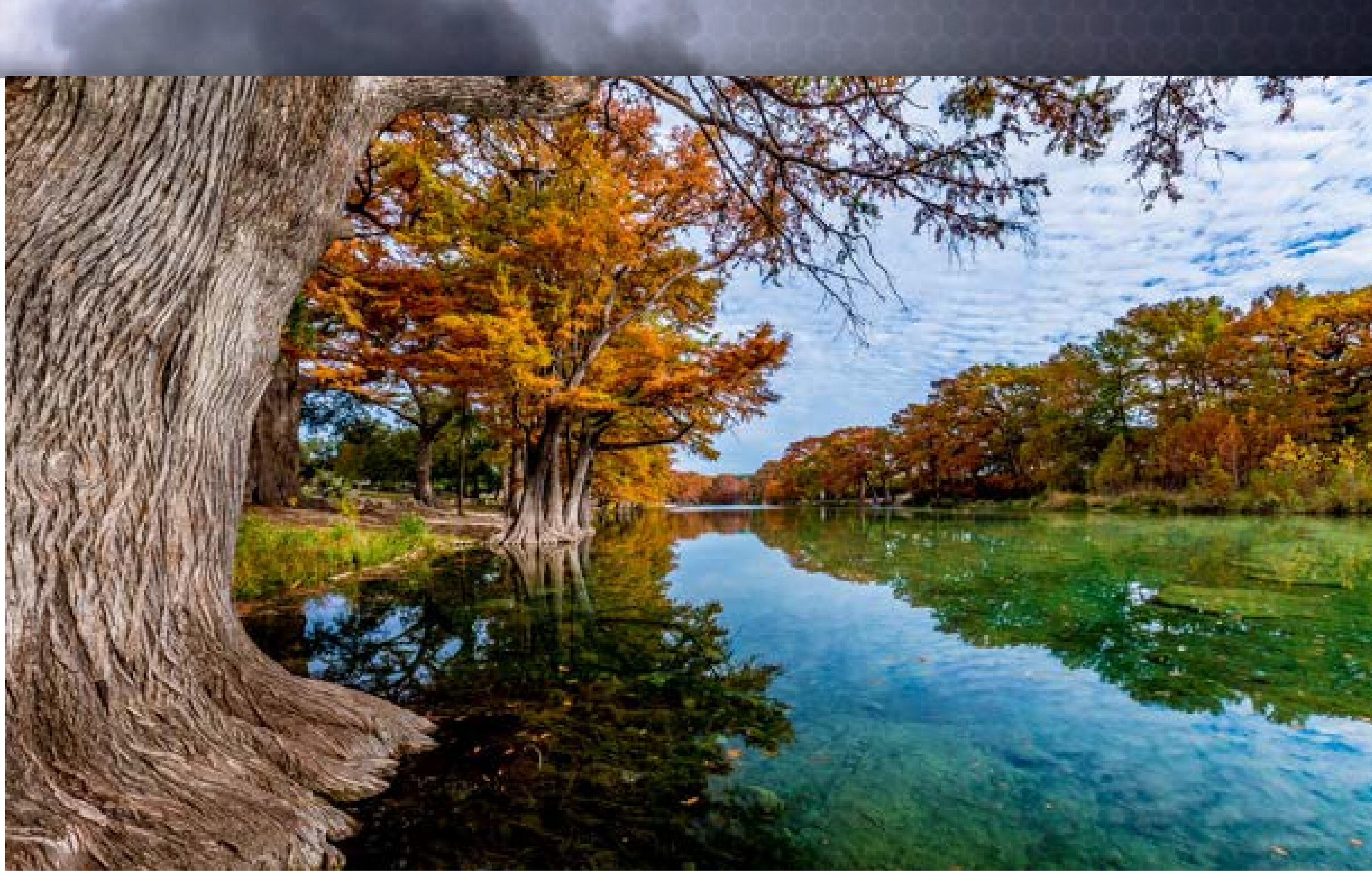

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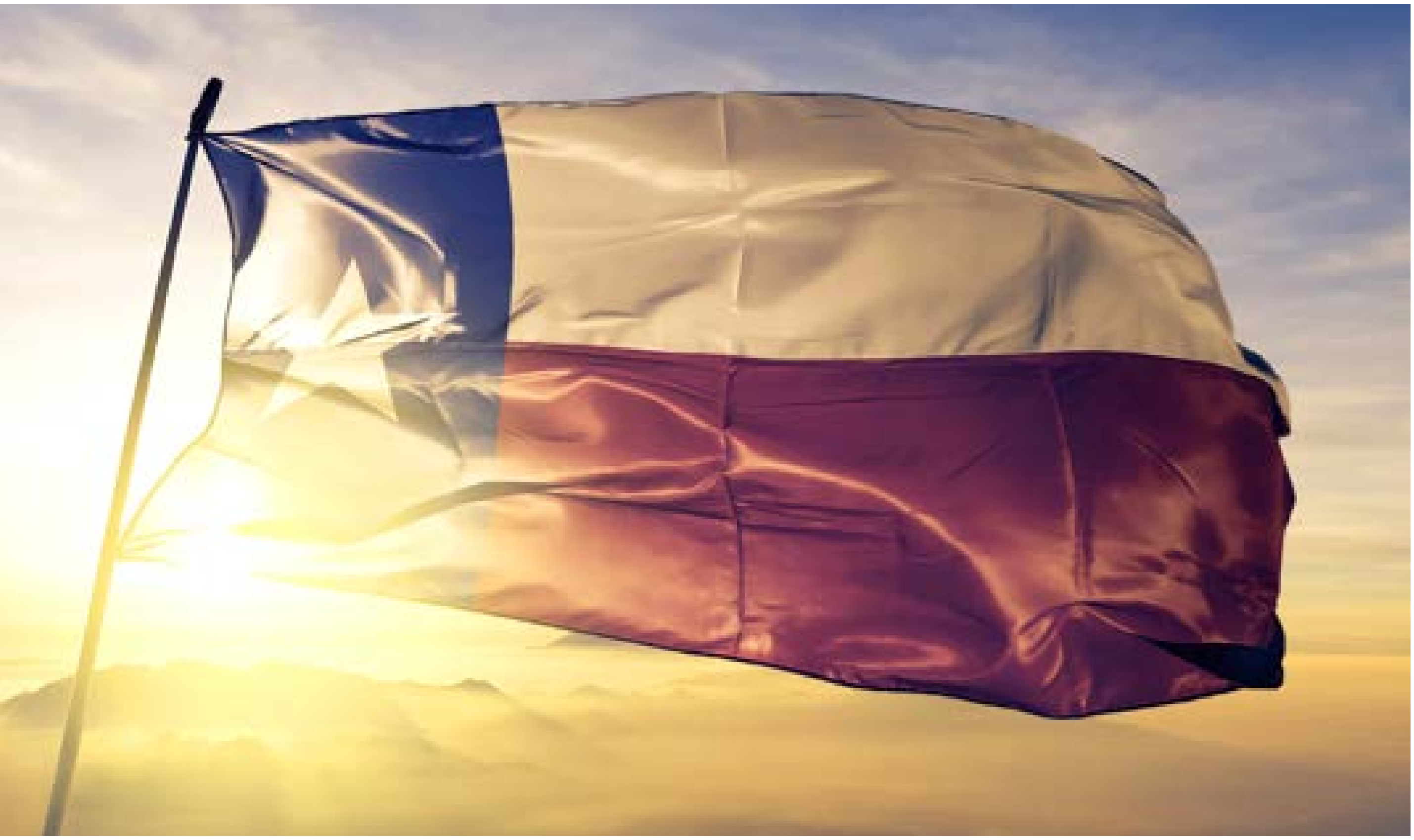

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