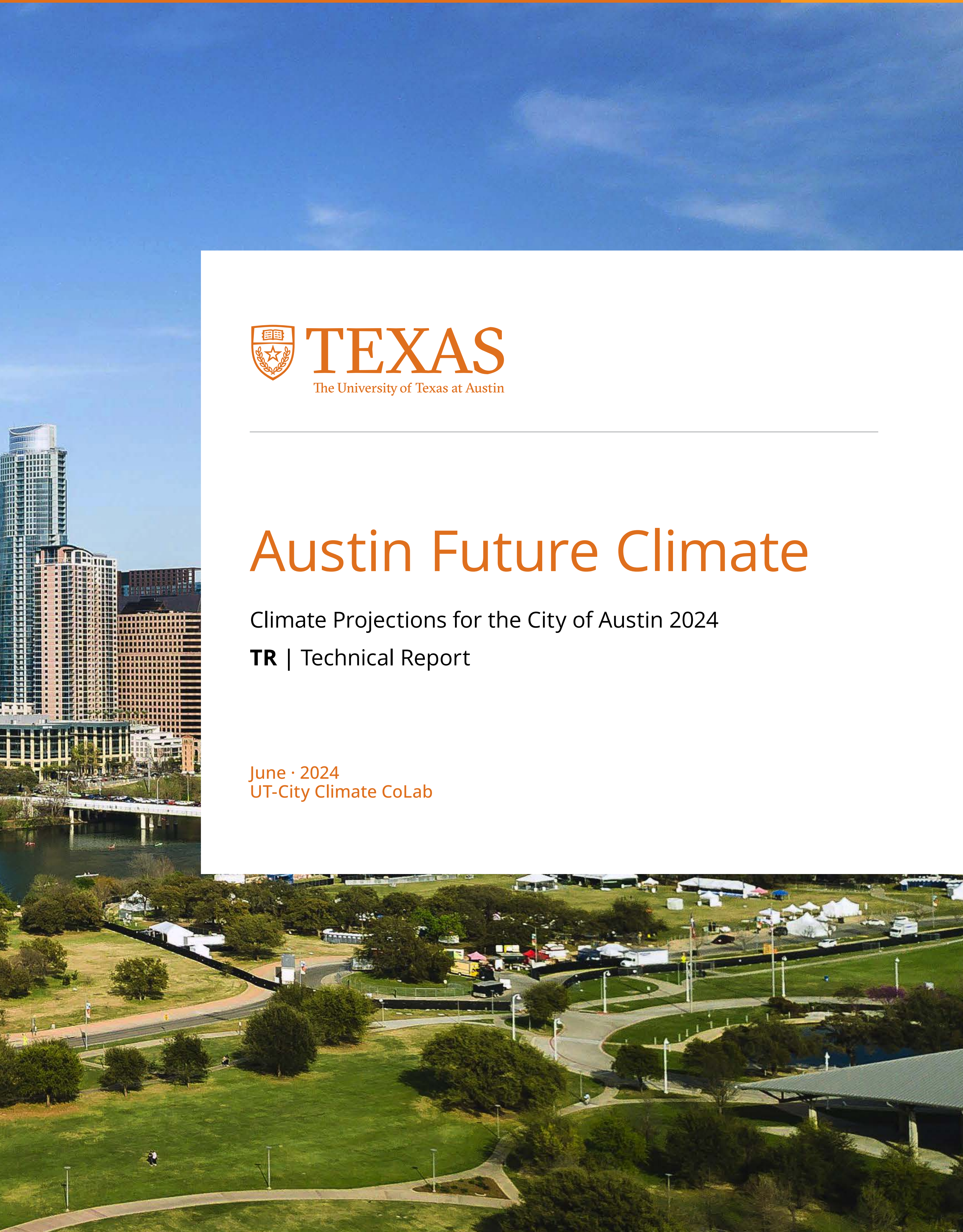

TEXAS
The University of Texas at Austin

Austin Future Climate

Climate Projections for the City of Austin 2024

TR | Technical Report

June · 2024
UT-City Climate CoLab

UT-City Climate CoLab

HTTPS://TEXUSLAB.ORG/COLAB

Additional technical details regarding the report, data, and analysis can be obtained by contacting:

Dev Niyogi, Manmeet Singh, and Zong-Liang Yang
Department of Earth and Planetary Sciences, and
Texas Extreme Weather and Urban Sustainability (TExUS) Lab
University of Texas at Austin
JGB 5.204
dev.niyogi@jsg.utexas.edu
www.jsg.utexas.edu/TExUS

and

Marc Coudert
Office of Resilience
City of Austin

How to cite:
Austin Future Climate: Climate Projections For the City of Austin, June 2024,
available from UT-City Climate CoLab [https://texuslab.org/colab].

Table of Contents

Summary of climate projections

In Austin, climate change is expected to cause hotter summers with more frequent heatwaves and fewer cold spells. Precipitation projections have high uncertainty, but the rainfall amount is expected to remain relatively unchanged. Austin is expected to experience more extremes, more variability in climate, and slight increase in windy days (fewer calm days).

These projections are based on “high” and “business as usual” emission scenarios. A “high” emission scenario refers to model projections where emissions from human activities are expected to increase. A “business as usual” emission scenario considers projections where emissions are considered to remain status quo. For the projections, the output is based on medians, not averages, and presented for near-future (2021–2040), mid-century (2041–2070) and end of the century (2071–2100) epochs.

HEAT

Temperatures are projected to rise. The heat index, which is the temperature after factoring in humidity, can increase by 2–10˚F in the future.

Summers are expected to be hotter. The maximum temperatures in summer are projected to be higher by 10˚F by the end of the century in the high emission scenario. In the future, temperatures are expected to breach 110˚F more frequently. The number of heatwave events, defined here as three or more consecutive days with excessively hot conditions (daily minimum: >78.1˚F, daily maximum: >102.5˚F), are expected to double from near century to end of century for both the “business as usual” and “high emissions” scenarios. The number of hot spell days, which is 2 or more consecutive days of maximum daily temperature above >102.5˚F, are also expected to increase by 2 to 3 times under high emission scenarios by the end of the century.

COLD

Fewer frost days and freeze spells are projected. Cold spells are projected to have similar duration as in the historical dataset.

The number of frost days, days with minimum daily temperature <32˚F, are expected to decrease by 2 to 3 times from mid-century to the end of the century. The freeze spells, 2 or more consecutive days with mean daily temperature <28˚F, will continue to be rare in the future, and cold spells, days with mean daily temperature <49˚F can be of a similar duration when they occur, relative to the historical period.

PRECIPITATION

Precipitation projections are uncertain, but the annual rainfall amount is relatively unchanged.

The frequency of extreme precipitation (>2 inches per day) is expected to increase slightly, as is the maximum 1-day precipitation value for each year. Annual precipitation amount, 5-day consecutive wet days precipitation amount, and number of wet days are projected to remain generally unchanged.

Overall, the future climate for Austin is projected to be hotter and more extreme with more variability. In this assessment, a “low” emissions scenario was not included, and the climate impacts would be less severe in that scenario. Also, independent of climate change Austin experiences urban heat island, which is not accounted for in the projections.

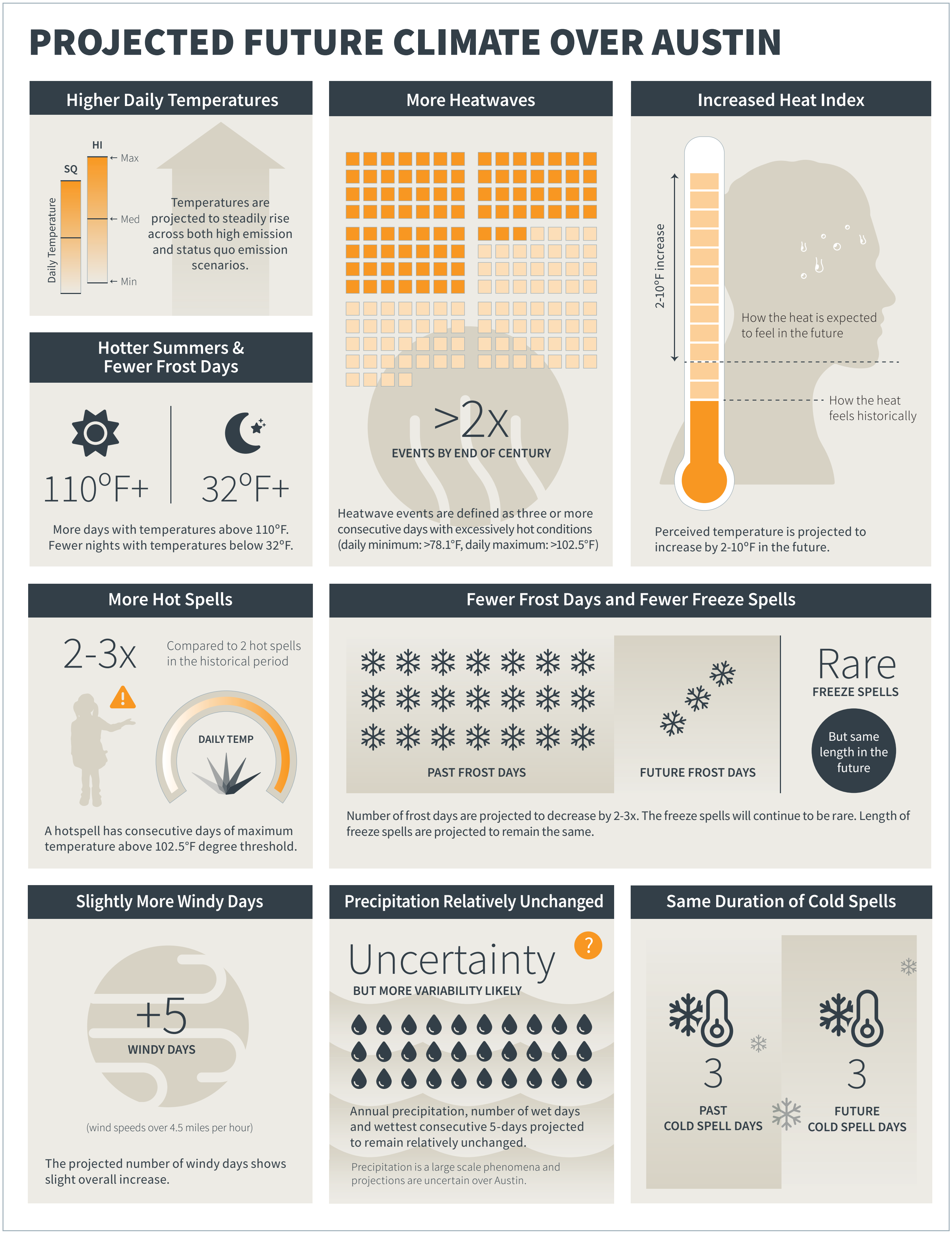

Figure 1 Summary of climate projections over Austin, Texas based on high and status quo emissions scenarios.

Preface

Austin, Texas has experienced a series of extreme climate events in recent years, including droughts, heatwaves, heavy rainfall, and the deep freeze that paralyzed the region. In response to these events, City departments and the broader community are keenly interested in the likely changes in the projected climate. Efforts are underway to develop partnerships, tools, and programs that can help develop solutions and resilience in the face of changing extremes. As part of these efforts, the City of Austin and the University of Texas at Austin have teamed up to establish the UT-City Climate CoLab, a climate collaborative that merges scientific advances from the academic research ecosystem with the practical needs and expertise of City professionals. This climate projection report is one of the outcomes produced by the UT-City Climate CoLab.

This projection follows a previous climate change assessment conducted for Austin in 2014, which utilized the IPCC AR5/CMIP5 dataset. Given the subsequent availability of the more recent IPCC AR6/CMIP6 products, an updated assessment became necessary. This update not only incorporates the newer global climate projections, enriched with newer knowledge and physics, but also employs newer models and methods for 'downscaling' these projections to the local or city scale.

The climate projections at a local scale are as much an art as a science. In this process, a number of expert-based choices and options are engaged in making the final product. Uncertainty exists in many decisions—which model or set of models to use from the global suite, what criteria can be used to select the sub-models, the downscaling tools and methods for processing the larger domain data to local scales, the bias-correction datasets, and how to represent and plot the final output to draw conclusions. With each of these choices, some conclusions can slightly alter, and therefore ensemble averages are often used. These averages can tune down the extreme outcomes, which sometimes are more likely than the average, but this also allows for more robust conclusions when there is strong agreement within the different models.

The above discussion will be notable when reviewing the temperature trends later in the report, which show a much more coherent warming signal. The precipitation patterns, on the other hand, have a wide range of variability and do not have a consistent signal. This does not mean the rainfall will not change; it simply means that the available models and tools did not produce a consistent signature for the domain over Austin. Therefore, the results need to be considered likely for a range of outcomes—increase, no change, decrease in rainfall—and a number of different variables need to be considered for making more robust conclusions.

Another important aspect to consider is that this document is designed for broader climate literacy and for engaging the City departments and the community about the climate and the adaptation/mitigation conversation. It is not a policy prescription or a legal document. Because of the engagement and literacy theme, this is a living document that will be updated as new datasets or analysis gets added. The conclusions could also change for some parts, and the most recent version therefore needs to be considered as the 'current' version, voiding the previous ones.

We hope this report will provide the foundation that is needed to develop the next steps in the climate landscape.

—The UT-City Climate CoLab

I. Introduction

With its location between the arid Southwest United States and the green Southeast area, Texas' capital city Austin is amongst the fastest-growing urban areas in the USA. Austin experiences a humid subtropical climate according to the Köppen climate classification system. Summers are long and hot, and the winters are short and mild. Austin's summers, with typical highs in the 90s Fahrenheit (34–36°C) or more, are hot and humid. Every year, there are more than a hundred days with highs above 90°F. Typically, from November 20 to arch 6 to the high temperature is 70°F (21°C) or higher; between April 14 and October 24, it is 80°F (27°C) or higher; and between May 30 and September 18, it is 90°F (32°C) or higher as a daily mean.

Austin's weather is variable because of moisture sources in response to changes in wind patterns and corresponding air mass influencing the region. When the weather turns hot and humid, it's common to have several days of moderate weather followed by days with increased humidity and heat. The opposite is also noted. Winds from the Gulf of Mexico bring humid air whereas winds from the west or southwest bring drier air from areas of West Texas or northern Mexico, resulting in lower humidity levels.

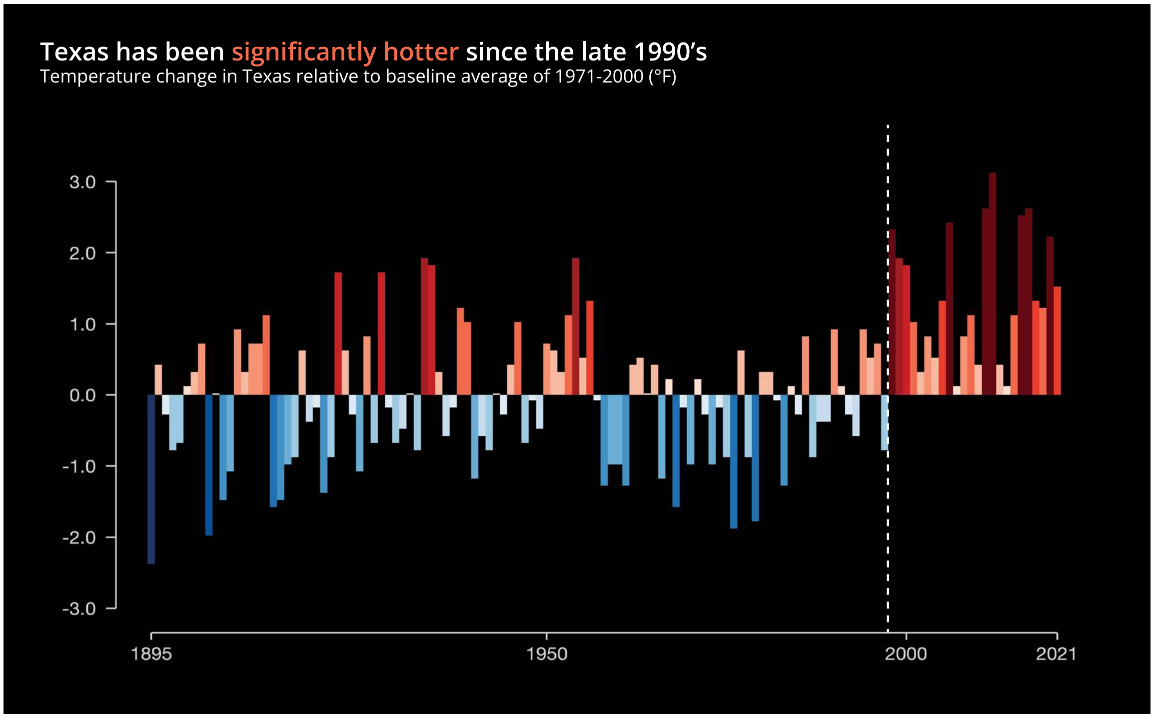

FIGURE 2 Temperature anomoly from 1895 to 2021 regularly included temperature drops below the baseline. This trend saw a sharp change from the late 1990s when the temperature change relative to the baseline no longer showed any drops in addition to regularly showing the highest increases.

Data Source: National Oceanic and Atmospheric Administration (NOAA)
*Note: Data from the period prior to 1971 is based on less accurate measurements.
https://showyourstripes.info/l/northamerica/usa/texas

As is customary in this part of Texas, severe weather can occur at any time of year. According to the most recent statistics, Austin is located in track of winter weather that can have freezing rains or ice. Also it is at the southernmost edge of Tornado Alley. The threat of storms and thunderstorms, which may bring high-speed winds and lightning as well as heavy rains and flash floods. For example, May 4, 1922, and May 27, 1997 tornado outbreaks in Central Texas were amongst the worst warm weather storms ever to hit the municipal boundaries. The year 2011 had been one of the driest years on record, with La Niña conditions. Drought-related wildfires erupted across Texas in the summer of 2011, most prominently the Bastrop County Complex Fire in the nearby city of Bastrop, which burned for over two weeks. In contrast, torrential rain and flash floods such as the 1981 Shoal Creek flood, 2013/2015 Halloween floods and 2018 floods following Hurricane Sergio have occurred in Austin and the surrounding areas.Recently, hail storms, microbursts, and wind damages have also been noted in Austin.

At a period when Lake Travis reached 146% of its maximum capacity, the Lower Colorado River Authority released four floodgates at the Mansfield Dam (214.7 m). As a result of the Llano River's unprecedented flow of silt, dirt, and debris into the Highland Lakes, Austin's primary source of drinking water, the city issued a mandatory boil-water advisory that was in effect from October 22 to October 29, 2018. Austin Water's capacity to process 300 million gallons of water per day was cut in half, and the infrastructure simply couldn't keep up with the city's daily water consumption, which averaged 120 million gallons. The city has been experiencing winter extremes as well. Austin is increasingly affected by winter weather as well as ice storms which have recently had very dramatic impacts.

Snowfall in Austin is rare. Most of Texas and Oklahoma, including Austin, were blanketed in snow in February 2021 from the Winter Storm Uri, which dumped record-breaking amounts of snow. Snowfall of 6.4 inches (16 centimeters) was recorded at Camp Mabry near Austin in February 2021, the highest since records began in 1948. The previous record for snowfall in the area was a three-day period in January 1985, when more than one inch (25 mm) fell in the area. An increase in energy demand necessitated the implementation of rolling blackouts between February 15 and 18. Some blackouts lasted more than 40 minutes while many people experienced outages that lasted several days, with an estimated 40% of Austin Energy customers without power at their peak. Water demand increased from 150 millions of gallons per day (MGD) on February 15 to a peak of 260 MGD on February 16, according to Austin Water, following reports of pipe failures that began on February 15. Due to an increase in demand on Tuesday, February 17th, water pressure in the Austin area dropped to 330 MGD, necessitating a boil-water alert that lasted until Wednesday, February 23rd, when it was restored.

The 2021 freeze has been linked to the changes in the exaggerated movement of the jet stream (strong winds in the Earth's upper atmosphere that typically blow from west to east) that is considered as an example of climatic changes. There is a need to plan for successive extremes. For the development of policies guided by

Figure 3 Winter Storm Uri hits Austin on February 10, 2021 with catastrophic impacts to the community. The storm has been recorded as the costliest in Texas history.

the need to plan, urban climate assessments are required. The urban climate assessments help the city authorities discuss the plausible challenges and the actions that need to be taken to deal with them. This report is an urban climate assessment for the city of Austin and is aimed to provide guidance on the climate for three decadal windows, viz, near century (2021-2040), mid-century (2041-2070) and end-century (2071-2100).

1.1 Austin has a climate projection in 2014. Why is this new one being provided?

The Intergovernmental Panel on Climate Change (IPCC) prepares the assessment reports (AR) on the present and future climate at a global scale. The latest report AR6 was published in 2021. IPCC reports are based on the Coupled Model Intercomparison Project (CMIP) which is a coordinated activity with participants from several climate modeling centers across the globe. Typically, every 5 years IPCC develops new assessments. In response, CMIP develops state-of-the-art modeling results that are coordinated globally by top research institutes. These are rigorous modeling studies that follow a well-documented experimental design which allows for intercomparison and transferability of results.

Understanding historical, present, and future climate changes that have been caused by natural unforced variability, or by changes in radiative forcing, is the primary purpose of the CMIP's activity. Model performance assessments from the past and quantifications of the components that contribute to forecast spread are included in this knowledge. In addition, idealized experiments are used to better understand the model's behaviors under various settings. The climate system's predictability is also studied, both on a temporal and spatial scale, and forecasts are carried out based on the current state of the climate.

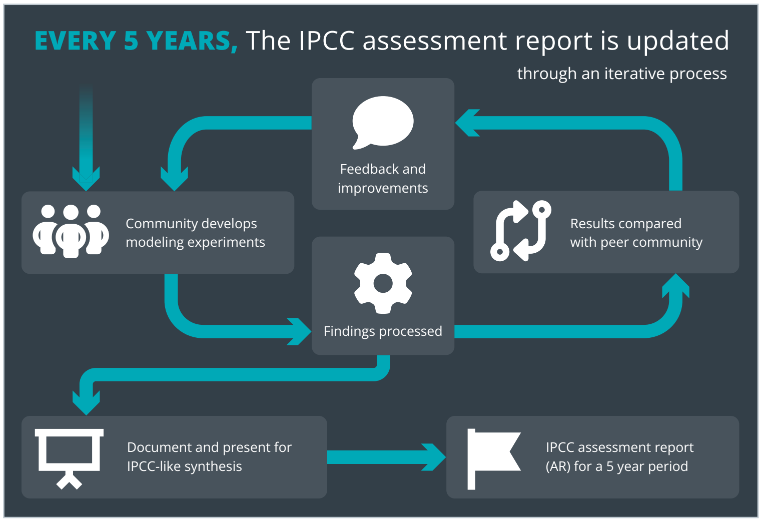

Figure 4 Multi-year process of natural variations and human-induced feedback to produce an IPCC AR Report for a 5 year period.

One of the goals of CMIP is to publish the findings of multi-model simulations in a standardized format to enable data sharing and comparison. In 1995, CMIP was formed as a joint project of the Working Group on Coupled Modeling (WGCM). One of the first CMIP experiments was to test the climate model's reaction compared to idealized forcing. The simulations were carried out by increasing CO2 emissions by one percent per year compounded over time. This was the first set of trials in which the model's reaction was compared to an increasing rate that was constant.

There have been several CMIP experiments since that time. The experiments still make use of simulations based on idealized forcings to reveal insights. As a result, these simulations must now be driven by estimates of previous changes in radiative forcing, as well as by estimations of future changes. The IPCC reports are updated every 5 years because the scientific understanding is rapidly changing and evolving in addition to the more accurate representation of processes. These processes are encoded as equations and consist of natural variations and human-induced feedback. This allows for the scientific community to develop the modeling experiments, process the findings, compare the results with the peer community, and provide continuous feedback while developing improvements off the feedback. The last phase is the documentation and presentation of findings for IPCC-like synthesis before the release of the IPCC assessment report for a 5-year period.

The IPCC and CMIP lifecycle require multi-year efforts and hence a 5-year update is considered. The 2014 assessment was developed from IPCC AR5 (5th assessment) which was a result of the 9 CMIP5 models. Since then, the CMIP6 results have been developed which were used in developing the IPCC 6th assessment released in August 2021. These assessments are available at a global scale and are used for developing future projections. Since the new CMIP and IPCC assessments are available, it is important to update the previous Austin climate assessments.

1.2 If IPCC assessments are available, why does the city need to have its own projection and this report?

The scope of IPCC AR6 is to conduct a global assessment. Its main purpose is to guide the global community on climate mitigation, adaptation, and the science of climate change. The document that gets developed is used in many follow-up negotiations and agreements between nations. They are also used for developing regional and national-scale policy goals and targets. Because of the size of the computational domain and intricacies of the computations, the climate information and model output is typically at a 1x1-degree latitude and longitude grid. This is roughly equivalent to a 100x100-km grid (or 60x60-mi grid).

For city-scale assessments, additional processing of the global model grids is needed. Austin is covered by one grid square, so assessing the information within that area requires what is known as bias-corrected downscaling. This means the global model future years climate projection is used as guidance to extrapolate from the available observations over the city. For Austin, the observations at Camp Mabry and Austin-Bergstrom International Airport have been considered as representative sites in this study.

It is also important to highlight that climate projections from global models are different from weather forecasts. Weather forecasts are predictions and have a high degree of local information and reliability whereas climate model projections are likely scenarios for a range of human (anthropogenic) and natural processes interacting with each other at planetary scales over the next century. As a result, these projections are fraught with a wide range of uncertainties and possibilities. To bring them to a more usable and local-scale relevance, this downscaling assessment is needed. More broadly, the City of Austin has climate-sensitive operations and is mandated to have climate-resilient assessments and policies/frameworks in place. The Office of Resilience & Sustainability, therefore, undertakes the coordination of these assessments as part of its operations.

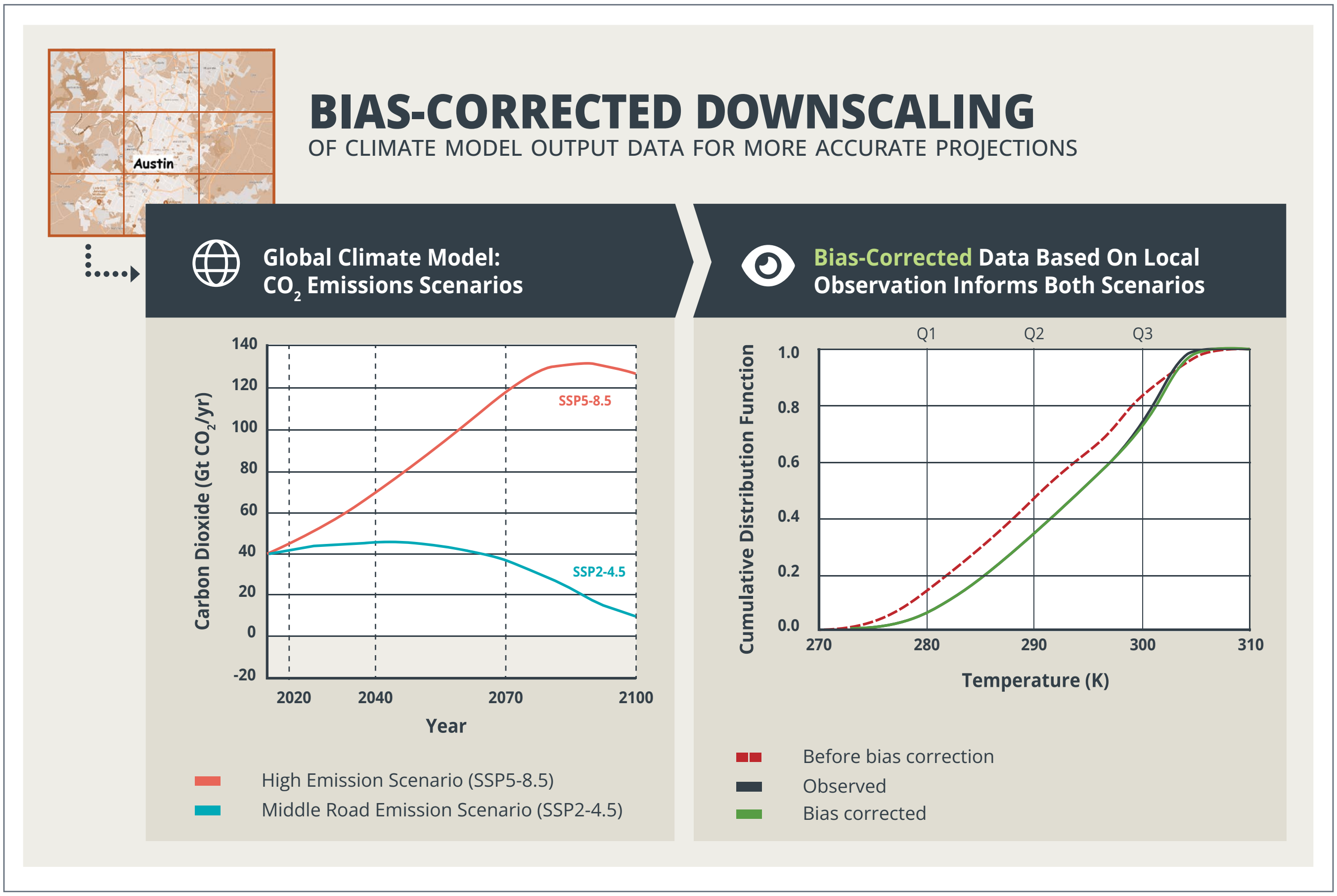

Figure 5 Additional processing of the global climate model grids for bias-corrected downscaling provides more localization.

1.3 What is different between the past and this updated assessment?

The major difference is the new CMIP and IPCC models and their scenarios. The older CMIP assessments were made by Representative Concentration Pathways (RCPs) and the updated assessment is based on the Shared Socioeconomic Pathways (SSPs). RCPs are designed to represent atmospheric concentrations of greenhouse gasses (GHG) and are consistent with a wide range of possible future changes in anthropogenic (i.e. human) GHG emissions. The RCPs are designed depending on the amount of GHGs that will be emitted in the years to come; a series of climate scenarios are considered possible. The RCPs were originally referred to as RCP2.6, RCP4.5, RCP6, and RCP8.5 based on a predicted range of radiative forcing levels in 2100.

The term "Shared Socioeconomic Pathways" (SSP) refers to a series of narratives exploring plausible global socio-economic changes until 2100. As part of various climate policies, SSPs are used to produce emission scenarios. The scenarios consist of SSP1 ("The Green Road" / sustainable development), SSP2 ("The Middle Road" / business as usual), SSP3 ("The Rocky Road" / rivalry between regions), SSP4 ("The Divided Road" / unequal growth), and SSP5 ("The Highway" / higher emissions scenario). In this updated assessment we use SSP1-2.6 and SSP5-8.5 which correspond to the SSP1 scenario with 2.6 W/m2 radiative forcing and the SSP5 scenario with 8.5 W/m2 radiative forcing. They are comparable to the RCP2.6 and RCP8.5 pathways from the previous assessment.

		Projections for Higher Emissions Scenario in Past Report vs. This Report					
		Near term (2021-2040)		Mid-century (2041-2070)		End-century (2071-2100)	
Climate Variables	Historical	2014	2024	2014	2024	2014	2024
Temperature							
Summer average high temperature (°F)	95.5	96.9	97.9	100.9	101.2	103.9	105.5
Cold nights (minimum temperature <32°F)	21	11.5	14	16.5	9	18.5	3
Warm nights (minimum temperature >80°F)	0	6	2	38	15	83	71
Hot days (maximum temperature >100°F	16	16.5	41	59.5	69	89.5	105
Very hot days (maximum temperature >110°F)	0	2	1	12	3	20	18
Precipitation							
Annual precipitation (inches)	32.4	31.46	32.6	33.06	32.7	32.46	32.1
Dry days (<0.01 inches in 24 hours)	250	244.5	248	245.6	253	252.3	258

Table 1 Comparison of this report (2024) with the previous climate projections (2014) which were based on CMIP5 data.
The table shows the median values and the range. The reference is the Austin Camp Mabry downscaled and bias corrected model ensemble, median.

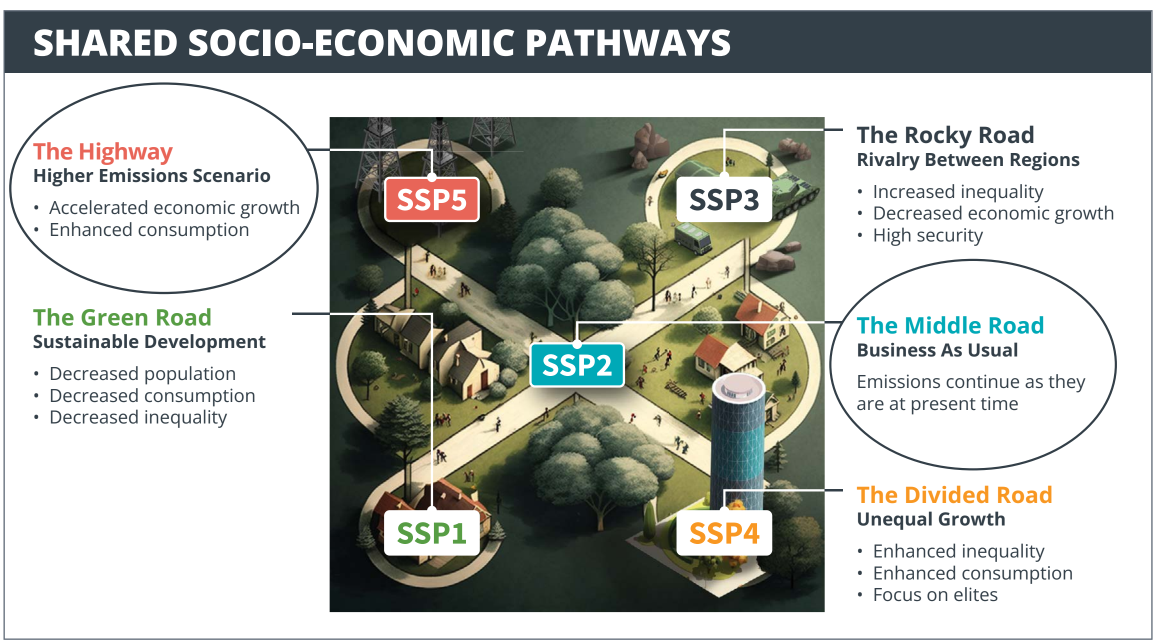

Figure 6 Summary of the different Shared Socio-Economic Pathways within IPCC/CMIP6 datasets. The Higher Emissions, and the Business as Usual scenarios are considered in this projection—marked as 'Highway' and 'The Middle Road'.

II. Methodology

The bulk of the methodology involved a combination of data extraction, data processing, data analysis, and data visualization techniques to assess the correlation between NEX-GDDP-CMIP6 (https://developers.google.com/earth-engine/datasets/catalog/NASA_GDDP-CMIP6) model outputs and observed data. The results helped identify the best models for further analysis and provided insights into the potential impacts of climate change in Austin.

2.1 How many models and scenarios are available in CMIP6? What have we used?

There are 49 different models and each has 5 or more shared socio-economic pathway scenarios that are available. From these models, we have considered the 7 best performing models (discussed ahead) from the NASA-NEX-GDD CMIP6 dataset. This NEX dataset is a dynamically downscaled at ~25 km spatial resolution bias corrected product based on the raw CMIP6 output.

2.2 How was the data processed?

The initial step involved preparing the data. The analysis environment was connected to Google Drive, facilitating easy access and storage of data. Authentication with the Google Earth Engine, a platform for

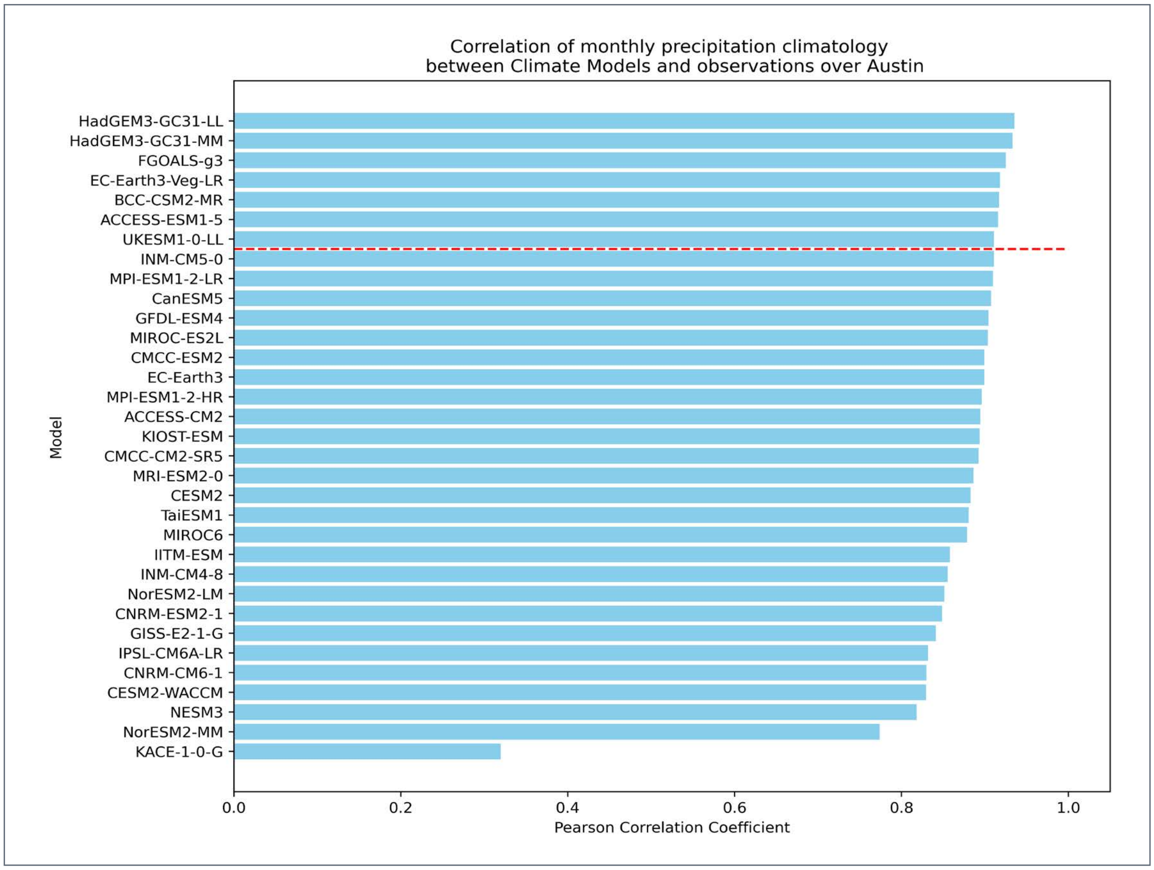

Figure 7 Histogram showing the correlation between CMIP6 data and observed monthly climatology precipitation at Camp Mabry.

analyzing and visualizing geospatial data, was then established. Essential python programming libraries for data processing, analysis, and visualization were imported. Weather station data was downloaded and the nearest weather stations to Austin were identified. Camp Mabry in Austin was selected for further analysis, and historical weather data for that station, including information on precipitation, temperature, and other weather elements, was extracted.

This data was processed to create a structured dataset with a date-time index. The values of various weather elements for the selected station were visualized to understand patterns and trends in the data. Specific weather variables, such as precipitation and temperature, were then selected for further analysis. The selected data was converted into a format suitable for climate analysis, known as NetCDF, which is commonly used in climate science for efficient handling of large datasets. The converted data was saved for subsequent use. The saved data was retrieved and analyzed for the selected climate models.

Data for specific variables, scenarios, and models were extracted from the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6) dataset, which provides global, high-resolution, bias-corrected climate change projections. The correlation between the seasonal cycle of precipitation from the NEX-GDDP-CMIP6 models and observed data at Camp Mabry was computed. This analysis helped determine how well the models matched the observed data. Models were filtered based on a correlation threshold, and seven best models for further analysis were identified. A histogram of the correlation values was created to visualize the distribution of correlations across models (Figure 7). The 90th percentile was annotated on the histogram to identify the top-performing models and the plot was saved for visualization.

Based on the correlation analysis, the best models were selected for further analysis. The selected models were used to further analyze and interpret the potential climate projection in Austin. Various scenarios

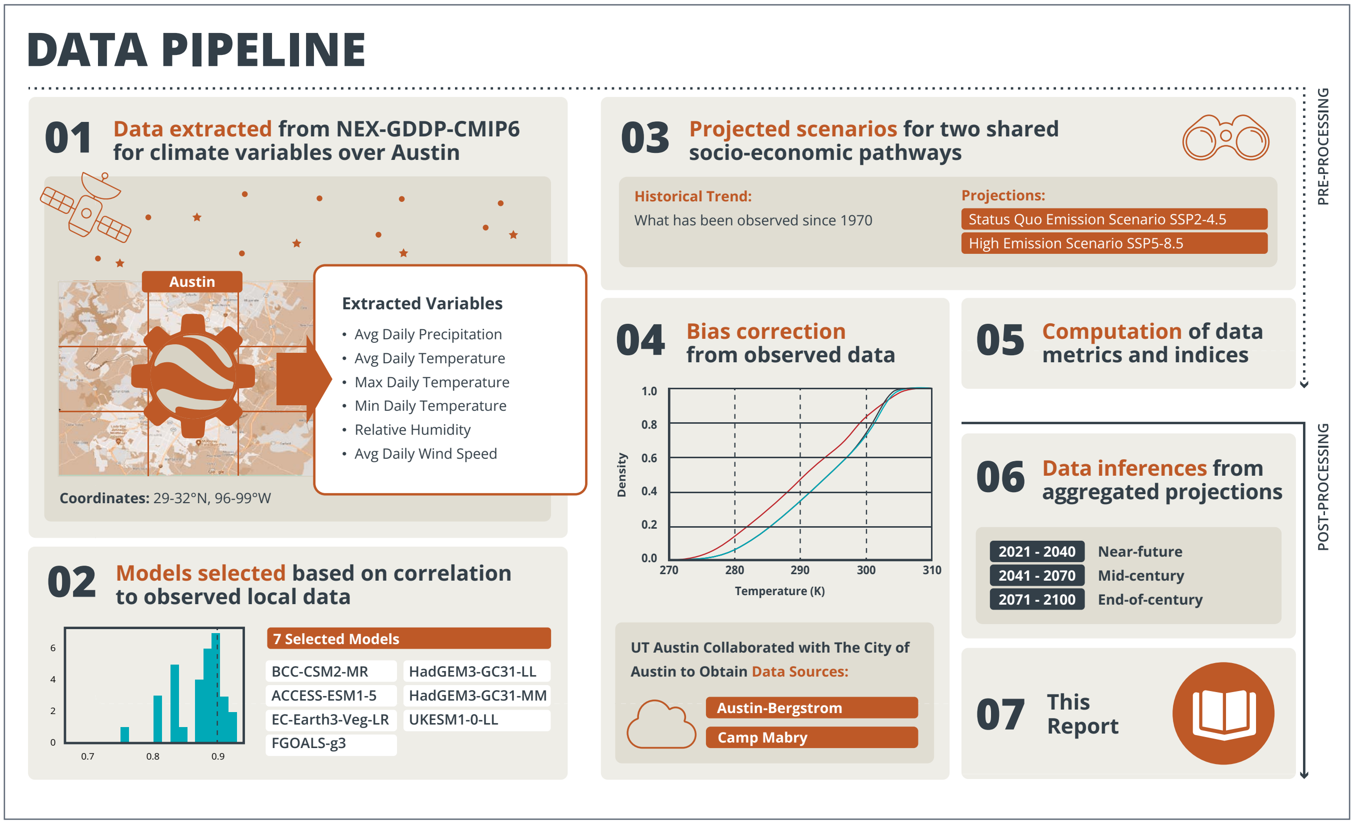

Figure 8 Pipeline of data extraction, data pre-processing, computation of metrics and indices, and data post-processing to generate the final report.

and variables were considered to assess the potential changes on temperature, precipitation, and other climate-related factors.

2.3 How was data and computational efficiency achieved?

A new package has been developed which generalizes the various processes involved such as subsetting, grid sizes, and calendars. The data was stored on the Texas Advanced Computing Cluster. The package runs on Google Colab.

2.4 How are we representing the data?

A box and whisker plot is a simple way to show how data values are spread out by showing the median (middle value), quartiles (the data divided into quarters), and any outliers. It uses a box to represent the middle 50% of the data, or interquartile range (IQR), with a line inside the box showing the median (middle value). Lines called whiskers extend from the box to show the range of the data. Any points outside the whiskers (outliers) are considered unusual and are not represented on the charts in this report.

Quartiles on a box and whisker plot are values that divide a dataset into four equal parts and arrange in order from smallest to largest values. The quartiles help visualize the spread and distribution of the data values in the plot and are determined as follows:

The first quartile (Q1) is the value below which lies 25% of the data. So, it represents the boundary of the lower portion of the data.

The second quartile (Q2) is the middle value, or the median, of the entire dataset. It divides the data into two equal halves based on its position in the dataset. This is not the same as an average, which is the sum of all values divided by the total number of values.

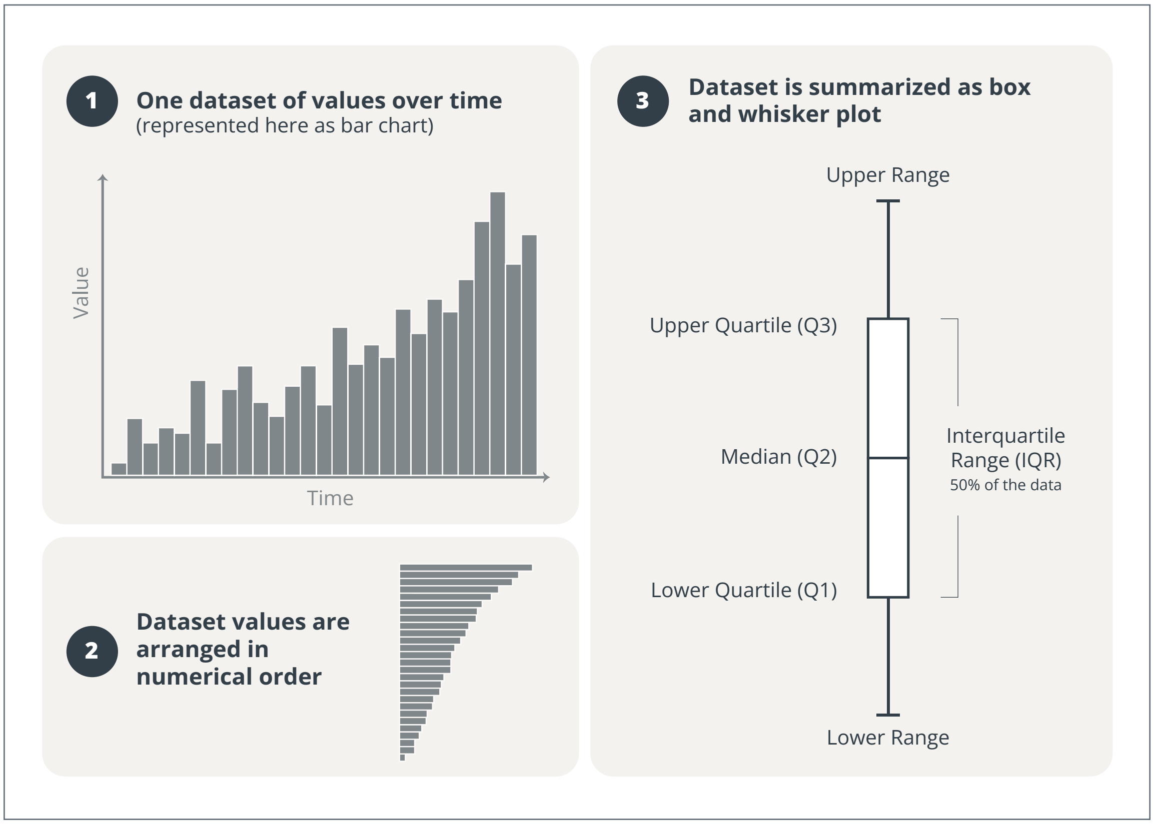

Figure 9 A box and whisker plot is a graph summarizing a set of data. The box shows how the middle 50% of the data values are distributed and the whiskers show the overall range.

The third quartile (Q3) is the value below which lies 75% of the data. It represents the boundary of the upper portion of the data.

The box shows where the majority of the data exists as it spans from the lower quartile (Q1) to the upper quartile (Q3), encompassing the IQR. The whiskers represent the full range of the data, excluding any unusual data. They extend from the box to the upper fence and lower fence values within a certain range. By using quartiles, the box and whisker plot gives a clear picture of how the data is spread out and helps us understand the overall pattern. Time series and trend plots were also generated and reviewed for consistency and trends.

2.5 What is the size of the data and where are these data?

A single file of 1-degree global resolution consisting of daily precipitation from the historical simulation (1850–2014) is about 50 gigabytes (GB) and for the future projections (2015–2100) is around 25 GB. Therefore, 450 ensemble members across all the models for historical and scenario simulations amount to more than 35 terabytes (TB) of data per variable. We used 7 variables (average daily precipitation, average daily temperature, maximum daily temperature, minimum daily temperature, surface relative humidity, zonal and meridional winds) taking the total disk space requirements to 250 TB. Storing this global data is challenging, and can be retrieved from the Earth System Grid Federation (ESGF) servers and also the Pangeo Cloud computing service. We subsetted the NASA-NEX CMIP6 data from Google Earth Engine over Camp Mabry Station in Austin. Downloading the datasets is a time-intensive task as subsetting and preprocessing incur extra computational costs.

Figure 10 Data pre-processing and methodology for urban climate change assessment used for this report.

III. Assessment

3.1 How is the temperature projected to change?

Summer maximum daily temperature in the historical period shows a median value of 95.48˚F.

- *In the status quo emission scenario:* The summer maximum daily temperature is expected to increase by 2–3˚F in the near-future, 4–5˚F through the mid century and by 6˚F at the end of the century.
- *For the high emission scenario:* The summer maximum daily temperature is expected to increase by 3–4˚F in the near-future. During the mid-century, it is projected to increase by 5–6˚F, and by the end of the century (2071–2100), it is expected to increase by 9–10˚F.

Days with maximum temperature greater than 100˚F occurred 16 times per year across the historical ensemble period.

- *In the status quo emission scenario:* Projected to increase to 41 days in the near-future, 53 days in the mid-century, and 71 days by the end of the century.
- *In the high emission scenario:* Projected to increase to 41 days in the near-future (2021–2040), 69 days in the mid-century (2041–2070), and 105 days by the end of the century (2071–2100).

Days with maximum temperature greater than 110˚F, which are historically rare, are projected to occur more frequently in both emission scenarios for mid-century and the end of the century.

- *In the status quo emission scenario:* Projections vary with a range of 0–12 in a year during the near-future (2021–2040), upto18 for the the mid-century (2041–2070), and a much larger variability of 0 to 25 days in a year by the end of the century (2071–2100).
- *In the high emission scenario:* Projections vary by 0–9 in a year during the near-future (2021–2040), vary from 0 to37 in a year during the mid-century (2041–2070), and could even go up to 83 days in a year by the end of the century (2071–2100).

The number of days with minimum temperature below 32˚F is typically 21 (median value) per year over Austin.

- *In the status quo emissions scenario:* The number of days is projected to decrease to 15 in the near-future, further reducing to 12 in the mid-century, and decrease to 8 by the end of the century.
- *In the high emissions scenario:* Projected to decrease to 14 in the near-future (2021–2040), to 9 in the mid-century (2041–2070), and to 3 by the end of the century (2071–2100).

3.2 Climate projections of precipitation are uncertain over Austin.

Frequency of extreme precipitation (>2 inches per day) ranged from 0–3 days for any year in the historical period.

- *In both emissions scenarios:* Projected to have larger variability and increase to up to 4 for any year for near-future, mid-century, and end of the century.

Maximum 1-day precipitation has a median value of 1.53 inches in the historical period.

- *In the status quo emissions scenario:* Projected to increase to 1.66 inches for the near-future (2021–240), 1.58 inches for the mid-century (2041–2070), and 1.68 inches by the end of the century (2071–2100).
- *In the high emissions scenario:* Projected to increase to 1.62 inches for the near-future (2021–240), 1.75 inches for the mid-century (2041–2070), and 1.8 inches by the end of the century (2071–2100).

Annual precipitation amount, wettest 5-day days precipitation amount, and number of wet days are projected to remain generally similar in the future. The historical wettest 5-day median value is 3.04 inches annually.

Climate projections are also being developed for the Lower Colorado River Basin as a part of Austin Water Forward project. Precipitation is a large-scale phenomena and the projections from the Austin Water Forward when available should be considered indicative of Austin.

3.3 How are other climate variables expected to change?

Heat index is the combined effect of temperature and humidity. The heat index across the historical period has a median of 81.6˚F.

- *In the status quo emissions scenario:* Expected to increase to as much as 86.48˚F by the end of century
- *In the high emissions scenario:* Expected to increase to as much as 91.06˚F by the end of the century.

Heatwave is defined as three or more consecutive days with excessively hot conditions (daily minimum: >78.1˚F, daily maximum: >102.5˚F), historically the range is up to 8 events in a given year.

- *In the status quo emissions scenario:* The number of heat waves are projected to increase by a factor of 2 with up to 17 in a year by the end of the century.
- *In the high emissions scenario:* The number of heat waves are projected to increase by a factor of 2.5 with up to 20 in a year by the end of the century.

Hot spells are defined as 2 or more consecutive days of maximum daily temperature above >102.5˚F.

- The length of hot spells is projected to increase to 1.5 to 3 times in the future.
- While the median for the historical baseline is 2 hot spells in a year over Austin, the future is projected to increase by a factor of 2–3 times and possibly longer duration of hot spells.

Cold spells over Austin are characterized by temperatures significantly below the normal or expected range for any time of year in the Austin region. They also last for at least two consecutive days with average daily temperature below 32˚F.

- The historical period indicates up to 2 cold spells in a year, each lasting about 2 days.
- *In both emissions scenarios:* Length is projected to remain the same, and the number is projected to decline by half.

The National Weather Service defines a freeze as a prolonged duration during which temperatures remain at or below 28 degrees. The number of freeze spell events are projected to decrease.

The number of windy days are defined as the days with wind speeds of more than 4.5 miles per hour.

- *In both emissions scenarios:* Expected to increase by up to 5 days in a year in the future.

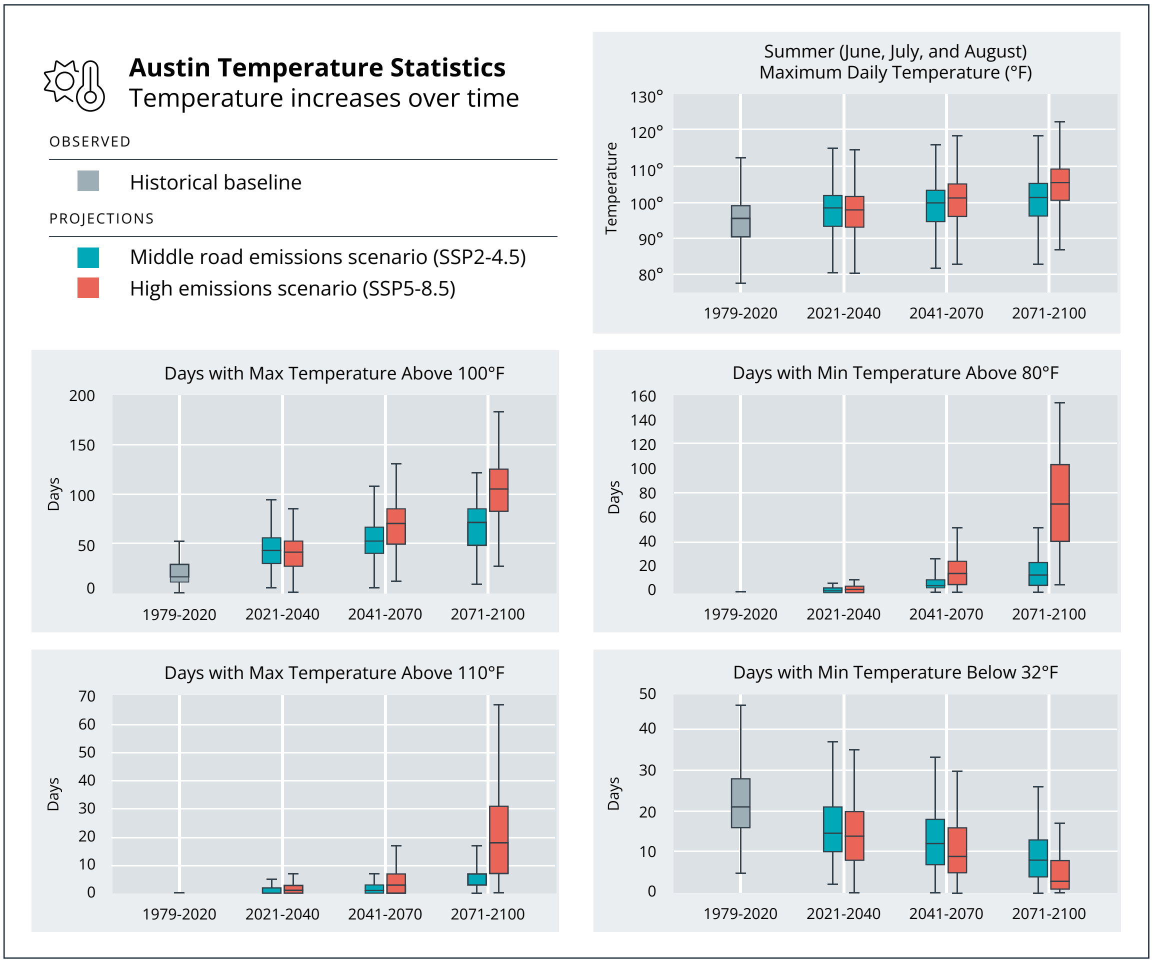

Figure 11 Temperature statistics over Austin plotted across 4 periods: historical (1979-2020), near-future (2021-2040), mid-century (2041-2070) and end of the century (2071-2100).

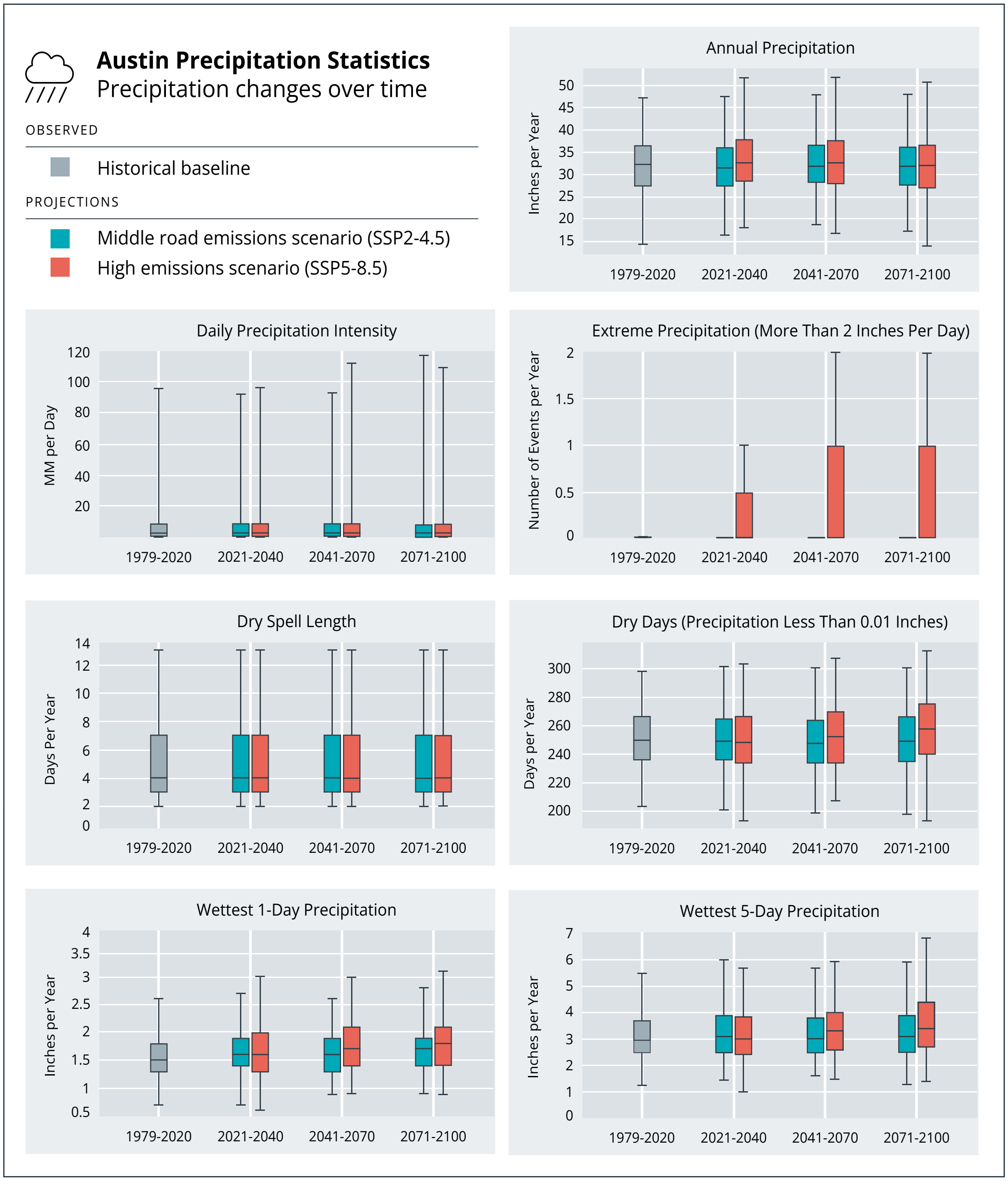

Figure 12 Precipitation statistics over Austin plotted across 4 periods: historical (1979-2020), near-future (2021-2040), mid-century (2041-2070) and end of the century (2071-2100).

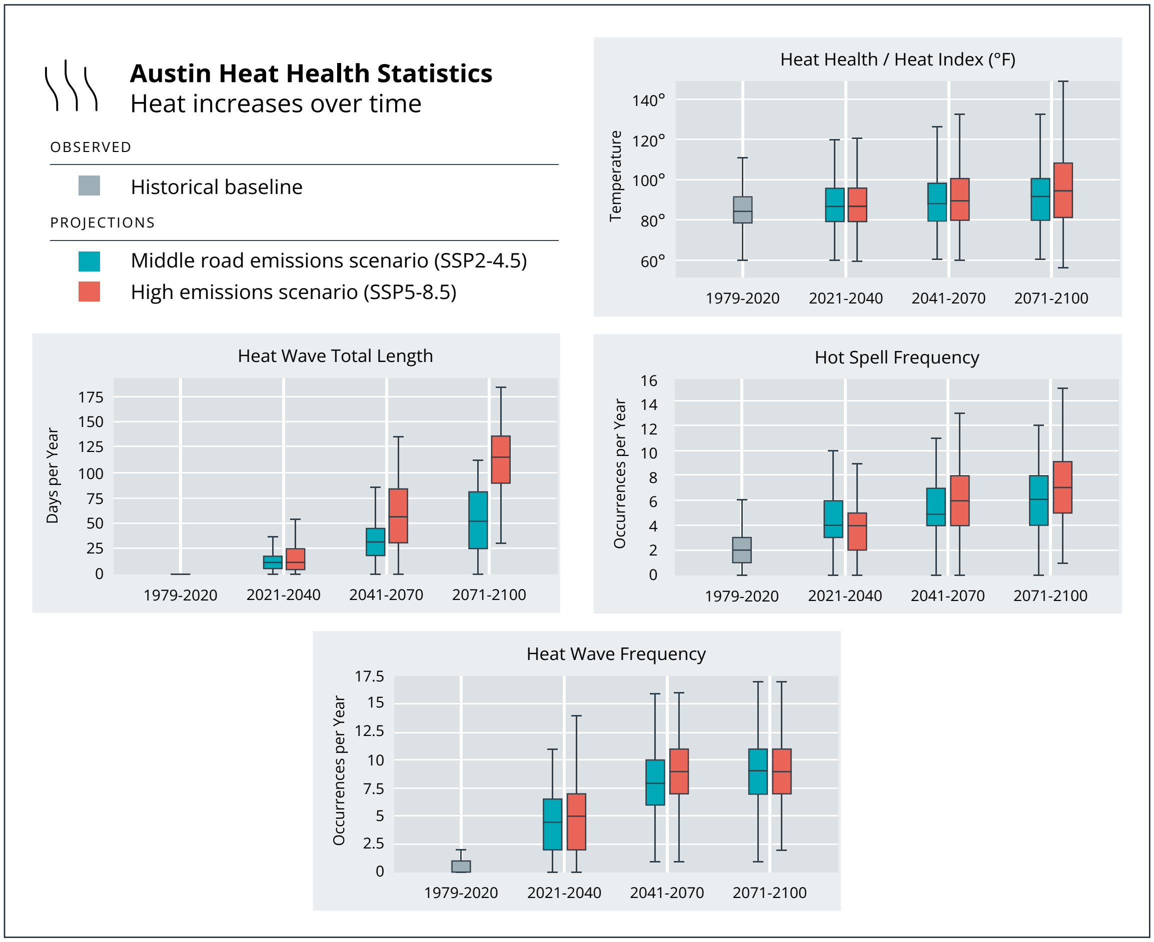

Figure 13 Heat health statistics over Austin plotted across 4 periods: historical (1979-2020), near-future (2021-2040), mid-century (2041-2070) and end of the century (2071-2100).

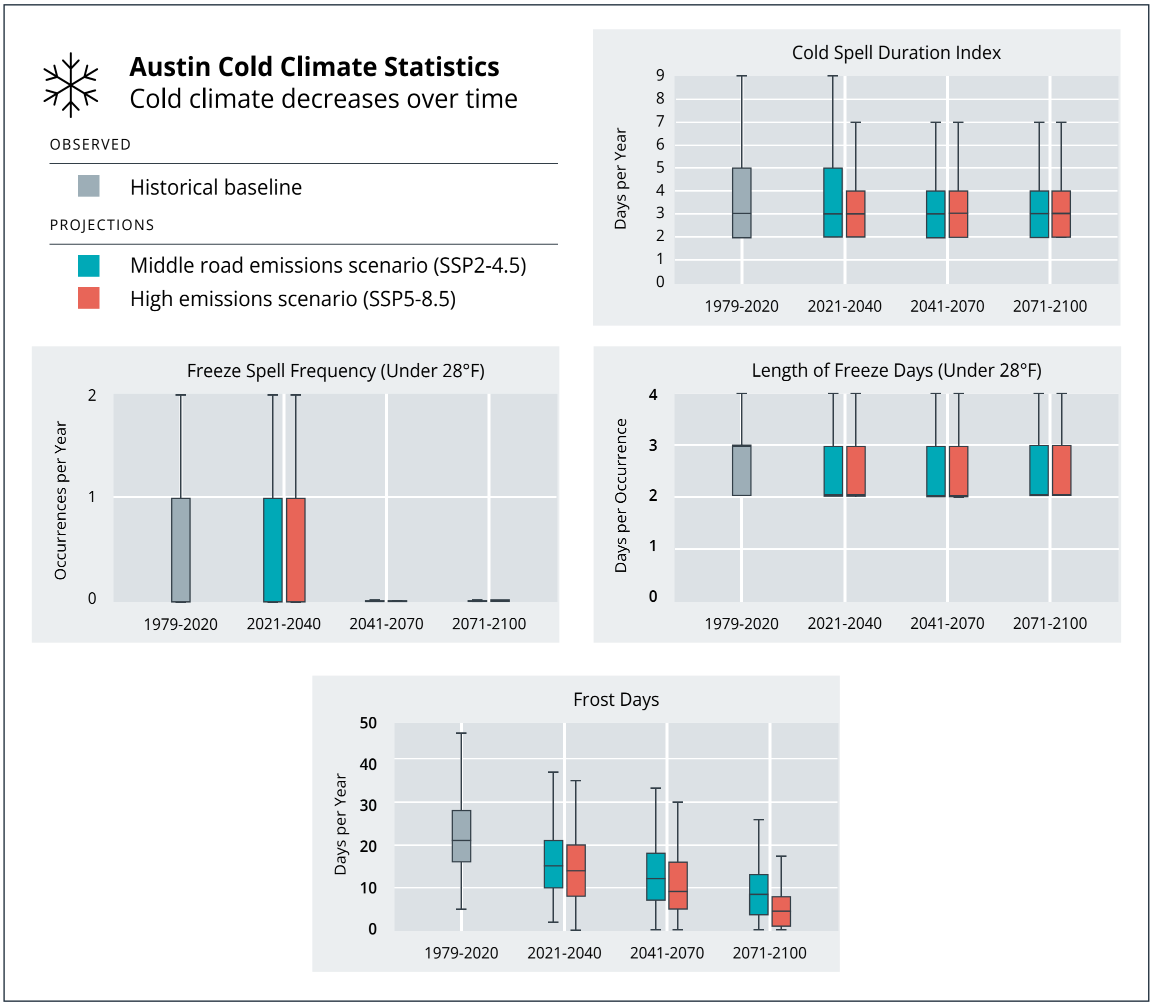

Figure 14 Cold climate statistics over Austin plotted across 4 periods: historical (1979-2020), near-future (2021-2040), mid-century (2041-2070) and end of the century (2071-2100).

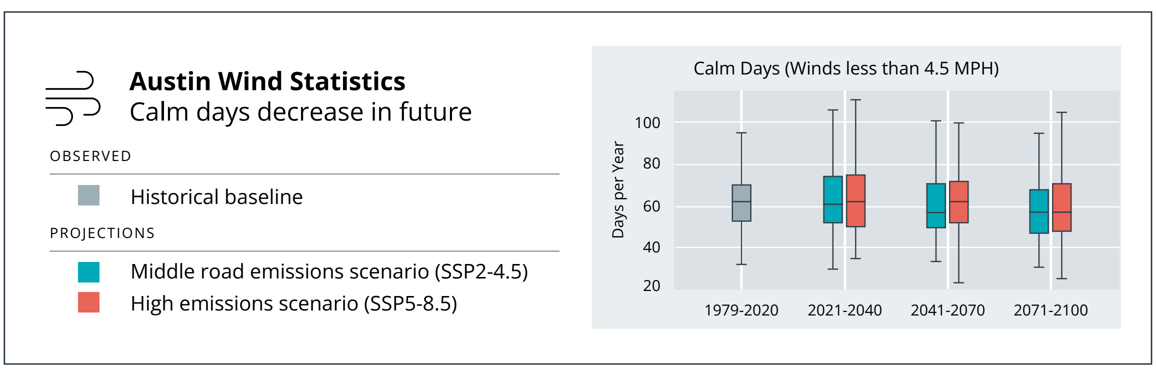

Figure 15 Wind statistics over Austin plotted across 4 periods: historical (1979-2020), near-future (2021-2040), mid-century (2041-2070) and end of the century (2071-2100).

Austin Temperature Statistics							
Summer (JJA) Maximum Daily Temperature (°F)							
Quartiles (Statistical Measures)	Historical Period (1979-2020)	Near Future (2021-2040)		Mid Century (2041-2070)		End of Century (2071-2100)	
		Middle Road	High	Middle Road	High	Middle Road	High
Upper Range	112	114.8	114.5	115.9	118.5	118.3	122.7
Q3	**99.1**	**102**	**101.7**	**103.2**	**105.1**	**105.1**	**109.3**
Q2 (Median)	**95.5**	**98.5**	**97.9**	**99.6**	**101.2**	**101.3**	**105.5**
Q1	**90.4**	**93.4**	**93.1**	**94.7**	**96.2**	**96.3**	**100.4**
Lower Range	77.3	80.5	80.3	81.9	82.8	83	86.9
Days with Max Temperature Above 110°F							
Quartiles (Statistical Measures)	Historical Period (1979-2020)	Near Future (2021-2040)		Mid Century (2041-2070)		End of Century (2071-2100)	
		Middle Road	High	Middle Road	High	Middle Road	High
Upper Range	0	5	7	7	17	17	67
Q3	**0**	**2**	**3**	**3**	**7**	**7**	**31**
Q2 (Median)	**0**	**0**	**1**	**1**	**3**	**3**	**18**
Q1	**0**	**0**	**0**	**0**	**0**	**0**	**7**
Lower Range	0	0	0	0	0	0	0
Days with Max Temperature Above 100°F							
Quartiles (Statistical Measures)	Historical Period (1979-2020)	Near Future (2021-2040)		Mid Century (2041-2070)		End of Century (2071-2100)	
		Middle Road	High	Middle Road	High	Middle Road	High
Upper Range	53	93	85	107	130	121	182
Q3	**28**	**55**	**52**	**67**	**85**	**85**	**125**
Q2 (Median)	**16**	**41**	**41**	**52**	**69**	**71**	**105**
Q1	**10**	**28**	**26**	**39**	**48**	**47**	**82**
Lower Range	0	5	0	5	11	8	26
Days with Min Temperature Above 80°F							
Quartiles (Statistical Measures)	Historical Period (1979-2020)	Near Future (2021-2040)		Mid Century (2041-2070)		End of Century (2071-2100)	
		Middle Road	High	Middle Road	High	Middle Road	High
Upper Range	0	7	10	20	52	52	152
Q3	**0**	**3**	**4**	**10**	**25**	**24**	**103**
Q2 (Median)	**0**	**1**	**2**	**5**	**15**	**14**	**71**
Q1	**0**	**0**	**0**	**3**	**6**	**5**	**41**
Lower Range	0	0	0	0	0	0	6
Days with Min Temperature Below 32°F							
Quartiles (Statistical Measures)	Historical Period (1979-2020)	Near Future (2021-2040)		Mid Century (2041-2070)		End of Century (2071-2100)	
		Middle Road	High	Middle Road	High	Middle Road	High
Upper Range	46	37	35	33	30	26	17
Q3	**28**	**21**	**20**	**18**	**16**	**13**	**8**
Q2 (Median)	**21**	**15**	**14**	**12**	**9**	**8**	**3**
Q1	**16**	**10**	**8**	**7**	**5**	**4**	**1**
Lower Range	5	2	0	0	0	0	0

Table 2 Austin temperature statistics across 4 periods: historical (1979-2020), near-future (2021-2040), mid-century (2041-2070) and end of the century (2071-2100).

Austin Precipitation Statistics								
Annual Precipitation (Inches)								
Quartiles	Historical Period (1979-2020)	Near Future (2021-2040)		Mid Century (2041-2070)		End of Century (2071-2100)		
		Middle Road	High	Middle Road	High	Middle Road	High	
Upper Range	47.3	47.6	51.7	48.2	51.9	48	50.7	
Q3	**36.7**	**36.1**	**37.9**	**36.7**	**37.7**	**36.3**	**36.7**	
Q2 (Median)	**32.4**	**31.6**	**32.6**	**31.8**	**32.7**	**31.8**	**32.1**	
Q1	**27.5**	**27.5**	**28.5**	**28.3**	**28.1**	**27.7**	**27**	
Lower Range	14.4	16.4	18.2	18.9	16.8	17.4	13.96	
Daily Precipitation Intensity (Millimeters per Day)								
Quartiles	Historical Period (1979-2020)	Near Future (2021-2040)		Mid Century (2041-2070)		End of Century (2071-2100)		
		Middle Road	High	Middle Road	High	Middle Road	High	
Upper Range	95.6	92.9	96.9	93.7	112	117.2	109.3	
Q3	**8.7**	**8.4**	**9.1**	**8.6**	**8.9**	**8.3**	**8.8**	
Q2 (Median)	**3**	**2.9**	**3.2**	**3**	**3**	**2.9**	**2.9**	
Q1	**0.6**	**0.6**	**0.7**	**0.6**	**0.6**	**0.6**	**0.6**	
Lower Range	0	0	0	0	0	0	0	
Dry Days (Precipitation <0.01 Inches per Year)								
Quartiles	Historical Period (1979-2020)	Near Future (2021-2040)		Mid Century (2041-2070)		End of Century (2071-2100)		
		Middle Road	High	Middle Road	High	Middle Road	High	
Upper Range	299	302	304	301	308	301	313	
Q3	**267**	**265**	**267**	**264**	**270**	**267**	**276**	
Q2 (Median)	**250**	**249**	**248**	**248**	**253**	**249**	**258**	
Q1	**236**	**236**	**234**	**234**	**234**	**235**	**240**	
Lower Range	203	201	193	199	207	198	193	
Dry Spell Total Length (Days per Year)								
Quartiles	Historical Period (1979-2020)	Near Future (2021-2040)		Mid Century (2041-2070)		End of Century (2071-2100)		
		Middle Road	High	Middle Road	High	Middle Road	High	
Upper Range	13	13	13	13	13	13	13	
Q3	**7**	**7**	**7**	**7**	**7**	**7**	**7**	
Q2 (Median)	**4**	**4**	**4**	**4**	**4**	**4**	**4**	
Q1	**3**	**3**	**3**	**3**	**3**	**3**	**3**	
Lower Range	2	2	2	2	2	2	2	
Maximum 1-Day Precipitation / Wettest Day Precipitation per Year (Inches)								
Quartiles	Historical Period (1979-2020)	Near Future (2021-2040)		Mid Century (2041-2070)		End of Century (2071-2100)		
		Middle Road	High	Middle Road	High	Middle Road	High	
Upper Range	2.6	2.7	3	2.6	3	2.8	3.1	
Q3	**1.8**	**1.9**	**2**	**1.9**	**2.1**	**1.9**	**2.1**	
Q2 (Median)	**1.5**	**1.7**	**1.6**	**1.6**	**1.7**	**1.7**	**1.8**	
Q1	**1.3**	**1.4**	**1.3**	**1.3**	**1.4**	**1.4**	**1.4**	
Lower Range	0.7	0.7	0.6	0.9	0.9	0.9	0.9	
Maximum 5-Day Precipitation / Wettest 5-Day Precipitation per Year (Inches)								
Quartiles	Historical Period (1979-2020)	Near Future (2021-2040)		Mid Century (2041-2070)		End of Century (2071-2100)		
		Middle Road	High	Middle Road	High	Middle Road	High	
Upper Range	5.5	6	5.7	5.7	5.9	5.9	6.8	
Q3	**3.7**	**3.9**	**3.8**	**3.8**	**4**	**3.9**	**4.4**	
Q2 (Median)	**3**	**3.1**	**3**	**3**	**3.3**	**3.1**	**3.4**	
Q1	**2.5**	**2.5**	**2.4**	**2.5**	**2.6**	**2.5**	**2.7**	
Lower Range	1.3	1.5	1	1.6	1.5	1.3	1.4	
Number of Extreme Precipitation Events (>2 Inches per Day) per Year								
Quartiles	Historical Period (1979-2020)	Near Future (2021-2040)		Mid Century (2041-2070)		End of Century (2071-2100)		
		Middle Road	High	Middle Road	High	Middle Road	High	
Upper Range	0	0	1	0	2	0	2	
Q3	**0**	**0**	**0.5**	**0**	**1**	**0**	**1**	
Q2 (Median)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	
Q1	**0**	**0**	**0**	**0**	**0**	**0**	**0**	
Lower Range	0	0	0	0	0	0	0	

Table 3 Austin precipitation statistics across 4 periods: historical (1979-2020), near-future (2021-2040), mid-century (2041-2070) and end of the century (2071-2100). Data to be used with caution, they have high uncertainty.

Austin Heat Health Statistics							
Heat Index (°F)							
Quartiles	Historical Period (1979-2020)	Near Future (2021-2040)		Mid Century (2041-2070)		End of Century (2071-2100)	
		Middle Road	High	Middle Road	High	Middle Road	High
Upper Range	105.4	114	114.5	119.7	125	125	140.4
Q3	**88.3**	**91.9**	**92.1**	**94.4**	**96.6**	**96.5**	**103.5**
Q2 (Median)	**81.6**	**83.5**	**84**	**85.2**	**88.4**	**86.5**	**91**
Q1	**76.9**	**77.2**	**77.2**	**77.4**	**77.7**	**77.7**	**78.9**
Lower Range	59.9	59.9	59.4	60.7	60	60.3	56.5
Heat Wave Frequency (Occurrences per Year)							
Quartiles	Historical Period (1979-2020)	Near Future (2021-2040)		Mid Century (2041-2070)		End of Century (2071-2100)	
		Middle Road	High	Middle Road	High	Middle Road	High
Upper Range	2	11	14	16	16	17	17
Q3	**1**	**6.5**	**7**	**10**	**11**	**11**	**11**
Q2 (Median)	**0**	**4.5**	**5**	**8**	**9**	**9**	**9**
Q1	**0**	**2**	**2**	**6**	**7**	**7**	**7**
Lower Range	0	0	0	1	1	1	2
Heat Wave Total Length (Days per Year)							
Quartiles	Historical Period (1979-2020)	Near Future (2021-2040)		Mid Century (2041-2070)		End of Century (2071-2100)	
		Middle Road	High	Middle Road	High	Middle Road	High
Upper Range	0	37	55	87	136	112	185
Q3	**0**	**19**	**26**	**46**	**85**	**82**	**137**
Q2 (Median)	**0**	**12**	**13**	**33**	**56**	**53**	**116**
Q1	**0**	**6**	**5**	**19**	**31**	**26**	**90**
Lower Range	0	0	0	0	0	0	31
Hot Spell Frequency (Occurrences per Year)							
Quartiles	Historical Period (1979-2020)	Near Future (2021-2040)		Mid Century (2041-2070)		End of Century (2071-2100)	
		Middle Road	High	Middle Road	High	Middle Road	High
Upper Range	6	10	9	11	13	12	15
Q3	**3**	**6**	**5**	**7**	**8**	**8**	**9**
Q2 (Median)	**2**	**4**	**4**	**5**	**6**	**6**	**7**
Q1	**1**	**3**	**2**	**4**	**4**	**4**	**5**
Lower Range	0	0	0	0	0	0	1

Table 4 Austin heat health statistics across 4 periods: historical (1979-2020), near-future (2021-2040), mid-century (2041-2070) and end of the century (2071-2100).

Austin Cold Climate Statistics							
Cold Spell Duration Index (Days per Year)							
Quartiles	Historical Period (1979-2020)	Near Future (2021-2040)		Mid Century (2041-2070)		End of Century (2071-2100)	
		Middle Road	High	Middle Road	High	Middle Road	High
Upper Range	9	9	7	7	7	7	7
Q3	**5**	**5**	**4**	**4**	**4**	**4**	**4**
Q2 (Median)	**3**	**3**	**3**	**3**	**3**	**3**	**3**
Q1	**2**	**2**	**2**	**2**	**2**	**2**	**2**
Lower Range	2	2	2	2	2	2	2
Freeze Spell Frequency (Under 28°F) (Occurrences per Year)							
Quartiles	Historical Period (1979-2020)	Near Future (2021-2040)		Mid Century (2041-2070)		End of Century (2071-2100)	
		Middle Road	High	Middle Road	High	Middle Road	High
Upper Range	2	2	2	0	0	0	0
Q3	**1**	**1**	**1**	**0**	**0**	**0**	**0**
Q2 (Median)	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Q1	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Lower Range	0	0	0	0	0	0	0
Length of Freeze Days (Under 28°F) (Days per Occurrence)							
Quartiles	Historical Period (1979-2020)	Near Future (2021-2040)		Mid Century (2041-2070)		End of Century (2071-2100)	
		Middle Road	High	Middle Road	High	Middle Road	High
Upper Range	4	4	4	4	4	4	4
Q3	**3**	**3**	**3**	**3**	**3**	**3**	**3**
Q2 (Median)	**3**	**2**	**2**	**2**	**2**	**2**	**2**
Q1	**2**	**2**	**2**	**2**	**2**	**2**	**2**
Lower Range	2	2	2	2	2	2	2
Frost Days (Days per Year)							
Quartiles	Historical Period (1979-2020)	Near Future (2021-2040)		Mid Century (2041-2070)		End of Century (2071-2100)	
		Middle Road	High	Middle Road	High	Middle Road	High
Upper Range	46	37	35	33	30	26	17
Q3	**28**	**21**	**20**	**18**	**16**	**13**	**8**
Q2 (Median)	**21**	**15**	**14**	**12**	**9**	**8**	**3**
Q1	**16**	**10**	**8**	**7**	**5**	**4**	**1**
Lower Range	5	2	0	0	0	0	0

Table 5 Austin cold climate statistics across 4 periods: historical (1979-2020), near-future (2021-2040), mid-century (2041-2070) and end of the century (2071-2100).

Austin Wind Statistics							
Calm Days per Year (Winds <4.5 mph)							
Quartiles	Historical Period (1979-2020)	Near Future (2021-2040)		Mid Century (2041-2070)		End of Century (2071-2100)	
		Middle Road	High	Middle Road	High	Middle Road	High
Upper Range	95	106	111	101	100	95	105
Q3	**70**	**74**	**75**	**71**	**72**	**68**	**71**
Q2 (Median)	**62**	**61**	**62**	**57**	**62**	**57**	**57**
Q1	**53**	**52**	**50**	**50**	**52**	**47**	**48**
Lower Range	32	30	35	34	23	31	25

Table 6 Austin wind statistics across 4 periods: historical (1979-2020), near-future (2021-2040), mid-century (2041-2070) and end of the century (2071-2100).

IV. Conclusion

This report highlights the findings related to climate projections for Austin, Texas. We used the largest available dynamically downscaled, bias-corrected data (NASA-NEX CMIP6) from the updated IPCC AR6 CMIP6 global projections. We extracted the data over Austin and chose 7 climate models capable of simulating the seasonal cycle over the city. Of the selected models, bias correction was performed using quantile mapping approach to account for the systematic errors in the simulated dataset. Computation of climate indices was performed for three future periods: (i) near-future: 2021–2040, (ii) mid-century: 2041–2070, and (iii) end of the century: 2071–2100, for the high (SSP585) and status quo (SSP245) emission scenarios. The results were computed for different climate indices for temperature, precipitation, heat health metrics, cold spells, and winds.

Overall, the future climate for Austin is projected to be hotter and more extreme. In Austin, climate change is expected to cause hotter summers with more frequent heatwaves and fewer cold spells. Austin is expected to experience a slight increase in windy days (fewer calm days).

Temperatures are projected to rise. The heat index can increase by 2–10°F in the future. The maximum temperatures in summer are projected to be higher by 10°F by end of the century in the high emission scenario. In the future, temperatures are expected to breach 110°F more frequently. The number of heatwave events are expected to double from near-future to end of century. The number of hot spell days are also expected to increase by 2 to 3 times under high emission scenarios by the end of the century.

With the warming in Austin's climate, fewer frost days and cold spells are expected, and are projected to have similar length as in the historical dataset.

Figure 16 Lady Bird Lake along the Lady Bird Hike and Bike Trail in Austin, Texas.

The number of frost days are expected to decrease by 2 to 3 times from mid-century to the end of the century. Cold spells will continue to be rare in the future, and when they occur can be of a similar duration relative to the historical period.

Precipitation projections are uncertain, but rainfall amount is expected to remain the same. The frequency of extreme precipitation (>2 inches per day) is expected to increase slightly, and so is the maximum 1-day precipitation value for each year. Annual precipitation amount, 5-day consecutive wet days precipitation amount, and number of wet days are projected to remain generally similar.

Finally, it is important to highlight that climate projections are not as deterministic as weather forecasts. They are indicative of possible changes in the city's climate as simulated by large scale global models. The global models and this projection do not account for the growth and urbanization Austin is experiencing. Cities such as Austin experience an 'urban heat island' effect, which is expected to cause additional heat stress. Urban areas also change rainfall and these interactions are not considered. The projections are expected to be updated in the future as newer models and understanding becomes available. The next IPCC Assessment will have a city-focused special report, and some of the uncertainties would likely be addressed. The findings are prone to high uncertainty, but also represent the state of science and understanding related to downscaling climate information and developing projections. This report is for informational and climate engagement, literacy purposes, and is neither policy prescriptive nor advocacy leaning. As the science and methodology evolves, the report findings and conclusions will be updated. As such, the projection report should be considered a living document, and no liability is assumed while using the findings from this study. Indeed, the findings from this study should be supplemented with many other factors, studies, and expert consultation in arriving at follow-up adaptation, mitigation or any related decisions.

The UT-City Climate CoLab will continue to work with different scientific communities and stakeholders in an endeavor to build the knowledgebase, data, tools, and climate partnerships for Austin.

Acknowledgements

This projection study is an outcome of the UT-City Climate CoLab.

The work benefited from the National Aeronautics and Space Administration (NASA) Interdisciplinary Science (IDS) 80NSSC20K1262 and 80NSSC20K1268, NOAA NIHHIS NA21OAR4310146, the Department of Energy (DOE) Urban Integrated Field Lab (IFL) and National Science Foundation (NSF) grants, Jackson School of Geosciences William Stamps Farish Chair endowment, UT Austin Vice President for Research, Scholarship and Creative Endeavors (OVPR) Planet Texas 2050—a UT Austin grand challenge, and Good Systems—Smart Cities.

The climate downscaling activities were led by Dev Niyogi, Manmeet Singh, and Zong-Liang Yang from the Jackson School of Geosciences at UT Austin. Marc Coudert and Zach Baumer from the City of Austin, managed and contributed to the project.

Vanessa Sanchez, Information Studies Graduate Student at UT Austin, provided expert graphic design and editing for the report.

John Nielsen-Gammon, Texas State Climatologist, Victor Murphy from NWS San Antonio, Johanna Arendt from Travis County, and Allysa Dallmann from UT Austin, are gratefully acknowledged for their many discussions and contributions.

Appendix A

LIST OF FIGURES AND TABLES

Appendix B

ACRONYMS

AR	Assessment Report
CMIP6	Coupled Model Intercomparison Project Phase 6
GHGs	Greenhouse Gasses
IPCC	Intergovernmental Panel on Climate Change
IQR	Interquartile Range
RCPs	Representative Concentration Pathways
SSPs	Shared Socio-economic Pathways
WGCM	Working Group on Coupled Modeling