# Hot Enough Yet?

## The Future of Extreme Weather in Austin, Texas

Photo by Erik A. Ellison

A report for **A Nurtured World** and the **City of Austin**

April 2016

Prepared by the **Geos Institute**

A dynamic online summary of this report, with voiceover,
and a pdf of this report are available at
**http://climatewise.org/projects/1162-central-texas**

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# Introduction

**Austin, Texas** has experienced many temperature and precipitation extremes in the last decade. As climate change accelerates, we can expect more days of extreme heat, fewer overnight freezes, and more frequent periods of drought than there have been historically. Many of the long-term impacts can be avoided if emissions are reduced, creating a more positive future for residents of Austin.


Photo by Erik A. Ellison

Boat on Lake Travis during the 2011 drought

Most people experience climate through the extremes. Crops are affected when temperatures drop below freezing, and we change our behavior when the day's high is over 100° F. A Nurtured World, Geos Institute, and the City of Austin collaborated to assess recent past and future changes in extreme heat, low temperatures, extended drought, and wildfire. We used Global Climate Models (GCMs) adjusted to local scales to provide information on potential future conditions. Model documentation is provided in the methods section on page 18.

Climate change presents us with a serious challenge as we plan for the future. Our current planning strategies rely on historical data to anticipate future conditions. Yet due to climate change and its associated impacts, the future is no longer expected to resemble the past. Managers and policy makers are encouraged to begin to plan for an era of change, even if the precise rate or trajectory of such change is uncertain.

**NOTE:** Terms in red are defined in the glossary.

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The observed and projected future changes in extreme heat and heavy rainfall in the Austin area have numerous ongoing and potential future impacts to residents and the resources they rely on. As extreme heat and precipitation become more common, their impacts will worsen. People and resources will need to adapt.

Extreme heat affects human health through direct exposure and also because it leads to an increase in ground level ozone pollution. Higher levels of ground level ozone are linked to respiratory disease and heart disease. In the last decade, more people in the U.S. died from extreme heat than from any other weather-related cause.[1]

Extreme heat also leads to crop failures, loss of aquatic ecosystems, and loss of worker productivity for outdoor workers. Heat waves can cause roads and train tracks to buckle and other infrastructure to degrade, leading to potentially significant economic costs as well.

Drought and heavy rainfall can destroy crops and stress livestock. Droughts leave soils hardened, less productive, and more prone to flash flooding once rains return. Water for both people and nature can be scarce during extended periods of drought. Increased evaporation will contribute to a lack of water available for the region and exacerbate the impacts of droughts.

Whether or not wildfire will increase in Central Texas over the long term is uncertain. Wildfire is an important part of ecosystem processes, and is not necessarily negative. Increases in wildfire, however, could lead to reduced air and water quality, severe health impacts and greater need for emergency evacuations.

While preparing for impacts in the short-term is critical, reducing the overall magnitude of climate change through emissions reductions is the most effective option for protecting people from increasingly severe impacts over the long term.

Models show that climate change can be slowed and level off by about 2040–60 if drastic cuts in emissions are made.[2] Such action would allow us to avoid many of the most severe impacts of climate change, thereby saving both lives and money. A recent report from the Intergovernmental Panel on Climate Change (IPCC) demonstrates that reducing emissions is highly cost effective compared to the cost of the damages if climate change were to continue unabated.[3]

## SUMMARY OF PAST AND FUTURE CLIMATE EXTREMES IN AUSTIN, TEXAS

- The region has warmed by 2° F since the early 1900s.
- Frost free season is 10 days longer, on average, than the early 1900s.
- Extreme precipitation has become heavier and more frequent.
- Frequency of large wildfires has increased in Texas.
- Continued warming of 6-11° F by 2100 is expected if emissions remain high.
- With severe emissions reductions, warming could level off at 3–7° F by mid-century.
- Very few freezing nights are expected by 2050.
- Overnight temperature over 80° F could become common.
- Days over 100° F expected to become 2–5 times more common by mid-century.
- More year-to-year variation in precipitation is expected.
- Frequency of days with very low precipitation is expected to increase slightly by 2050.
- Soils are expected to become drier from heat and evaporation, even if precipitation increases.
- The area affected by wildfire is expected to increase through mid-century.
- Many of the most severe impacts can be avoided by reducing emissions.

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# Temperature Averages

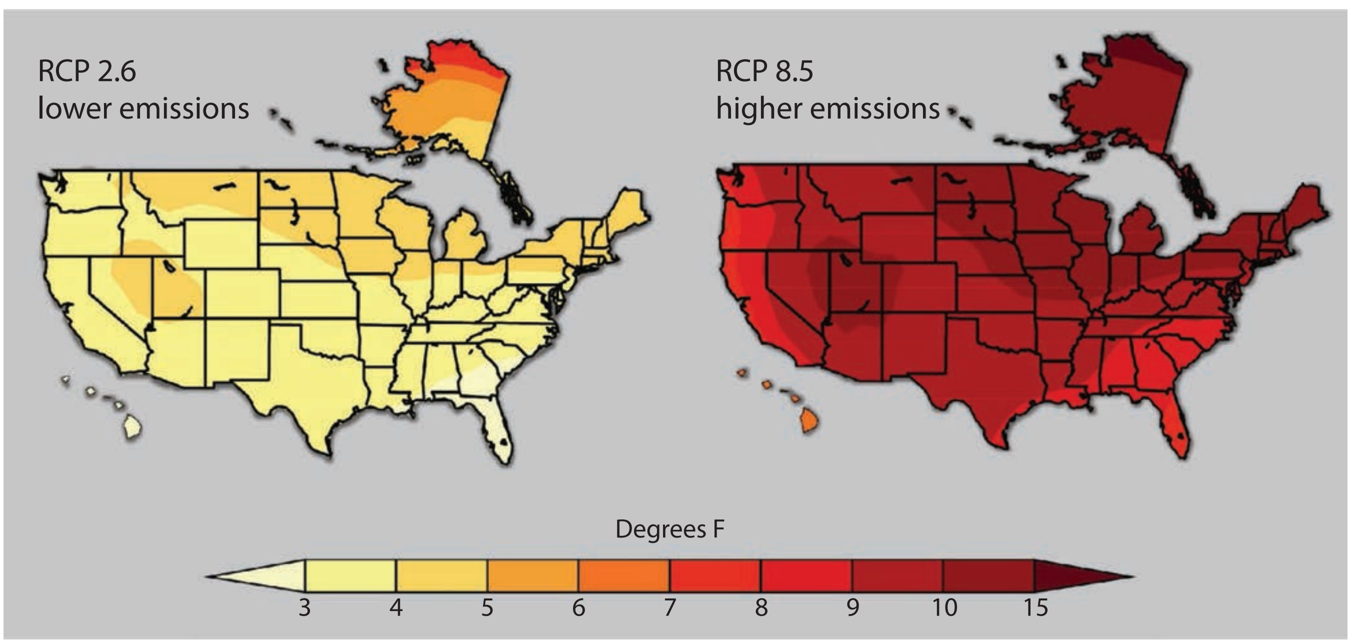
Average temperature in Texas has increased 2° F over the last century,[4] slightly more than the nation's average.[2] Continued warming is expected for Central Texas, as well as the rest of the nation, but emissions cuts could limit the magnitude of warming[2] (Fig. 1).

Based on models used for this project, temperature is projected to increase 3–7° F in the Austin area by 2040–69, whether or not emissions are reduced, because of greenhouse gases already released into the atmosphere. There are two main options for the future. If the international community works together to cut greenhouse gas emissions drastically (more than 70% by 2050[2]), warming could level off by the middle of the century. If emissions are not drastically reduced, the Austin area is projected to warm by 5.5–11.0° F by the end of this century (Table 1).

Photo by Steve Hopson, www.stevehopson.com

Austin City Limits Music Festival

**Figure 1** Projected change in surface air temperature from the historic period (1971–2000) to the end of the century (2071–2099), averaged over 30-year periods, from the National Climate Assessment.[2] The lower emissions scenario (left) assumes more than 70% cuts in emissions by 2050, while the higher emissions scenario (right) assumes continued higher emissions.[2]

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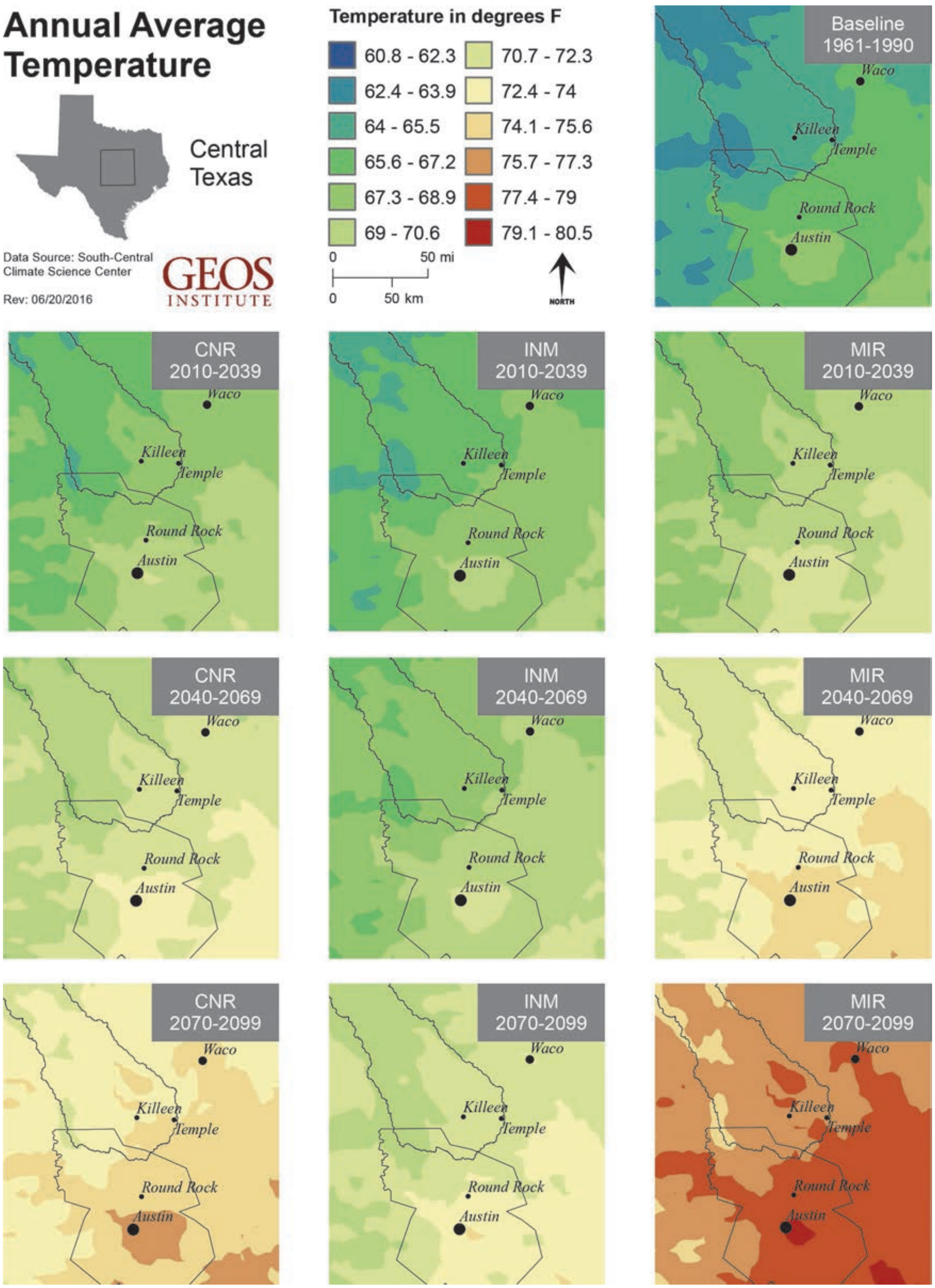
The projections for 2070–99 (Table 1) are less certain than mid-century projections due to uncertainty in emissions, models, and natural feedback loops. Natural feedback loops occur when warming induces the release of additional greenhouse gases from natural systems, such as the methane releases that are being observed in northern Russia.

**Table 1** Historical average and projected change in temperature across the CAMPO management region, averaged over 30-year periods and based on output from three different GCMs (CNR, INM and MIR), assuming continued higher emissions (RCP 8.5).

| | 1961–1990 | 2010–39 | 2040–69 | 2070–99 |
|---|---|---|---|---|
| **Annual** | 66.7° F | +1.5 to 3.6° F | +3.0 to 7.1° F | +5.5 to 11.0° F |
| **Spring** Mar, Apr, May | 69.3° F | +0.7 to 6.2° F | +3.8 to 11.4° F | +6.1 to 16.7° F |
| **Summer** Jun, Jul, Aug | 82.2° F | +1.0 to 3.7° F | +2.2 to 5.4° F | +3.1 to 8.7° F |
| **Fall** Sep, Oct, Nov | 64.9° F | -1.6 to +3.4° F | -2.1 to +7.0° F | -1.4 to +10.4° F |
| **Winter** Dec, Jan, Feb | 50.5° F | +2.5 to 4.2° F | +5.1 to 9.3° F | +9.7 to 14.7° F |

**NOTE:** Terms in red are defined in the glossary.

**Figure 2** Annual average temperature, averaged over 30-year periods, across Central Texas for the historical period (1961–1990) and three future time periods (2010–39, 2040–69, and 2070–99), based on three different GCMs (CNR, INM and MIR) and continued higher emissions (RCP 8.5).

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## Temperature Extremes

In addition to averages, the frequency of extreme temperatures has already begun to change. Throughout the central U.S., for instance, the frost-free season has lengthened by 10 days, as compared to 1900–1960.[2] Minimum temperatures below freezing are expected to be extremely rare in Austin by mid- to late-century (Table 2; Fig. 3, top).

While all three GCMs used in this study agreed on continued warming for the region, there was variation among them with respect to projected minimum temperatures. One model projected minimum nighttime temperatures above 80° F for close to 100 days per year, while another model projected minimum nighttime temperatures above 80° F for only 2 days per year by the end of the century (Fig. 3, bottom).

The National Climate Assessment shows that extreme heat events are expected to be 8–10° F hotter by 2081–2100, relative to those at the end of the last century.[2]

**Table 2*** Historical and projected number of days per year, averaged over 30-year periods, with minimum nighttime temperature below freezing, minimum nighttime temperature above 80° F, and maximum daytime temperature greater than 95°, 100°, and 110° F, at the Camp Mabry weather station in Austin, TX. Future projections based on three GCMs (CNR, INM and MIR) and continued higher emissions (RCP 8.5). Percent change is shown in parentheses.

| Number of days | 1961–1990 | 2010–39 | 2040–69 | 2070–99 |
|---|---|---|---|---|
| Min <32° F | 18 | 3–13 (–25 to –83%) | 0–8 (–55 to –100%) | 0 (-100%)* |
| Min >80° F | 0.4 | 0.4-2 (0 to +433%) | 0.5–20 (+33 to 4,766%) | 2–60 (+342 to 14,675%) |
| Max >95° F | 40 | 48–73 (+20 to 82%) | 60–99 (+50 to 147%) | 86–139 (+114 to 245%) |
| Max >100° F | 10 | 12–32 (+22 to 230%) | 22–50 (+126 to 417%) | 36–94 (+274 to 872%) |
| Max >110° F | 0 | 0.1–0.3 (NA) | 0.5–1.3 (NA) | 1.5–10.3 (NA) |

* **Note:** The data in Table 2 show 30-year averages, while the data in Figures 3 and 4 show annual projections. See the methods section for more details on each of these ways of presenting the data.

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Our analysis showed that, on average, extreme heat events are expected to be more frequent by the end of the century. Temperatures over 100° F are expected to become 2 to 5 times more frequent. Of note is the fact that recent extreme temperature records (2008 and 2011) are not predicted to occur by the models until later this century, indicating that actual extremes may be higher than the models predict (Fig. 4).

In addition to the frequency of extreme heat, average summer high temperatures are expected to continue to increase in Central Texas through the end of the century, if emissions are not reduced (Fig. 5).

**Figure 3** Observed and projected number of days per year with minimum temperatures below 32° F (top) and above 80° F (bottom) at the Camp Mabry weather station in Austin, TX. Projections based on three different GCMs (CNR, INM, MIR) and continued higher emissions (RCP 8.5).

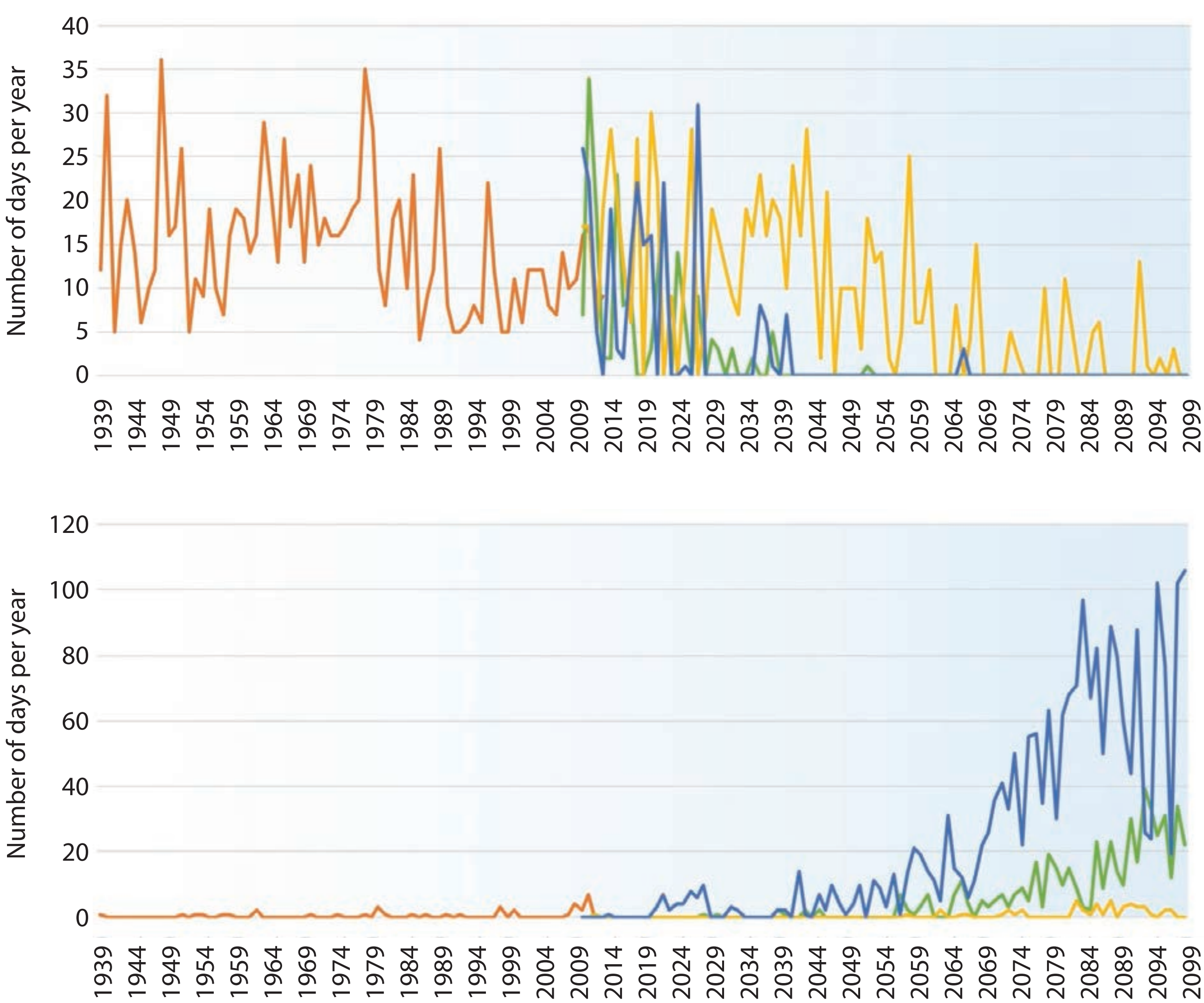

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**Figure 4** Observed and projected number of days per year with maximum temperatures above 95° F (top), 100° F (middle) and 110° F (bottom) at the Camp Mabry weather station in Austin, TX. Projections based on three different GCMs (CNR, INM, MIR) and continued higher emissions (RCP 8.5).

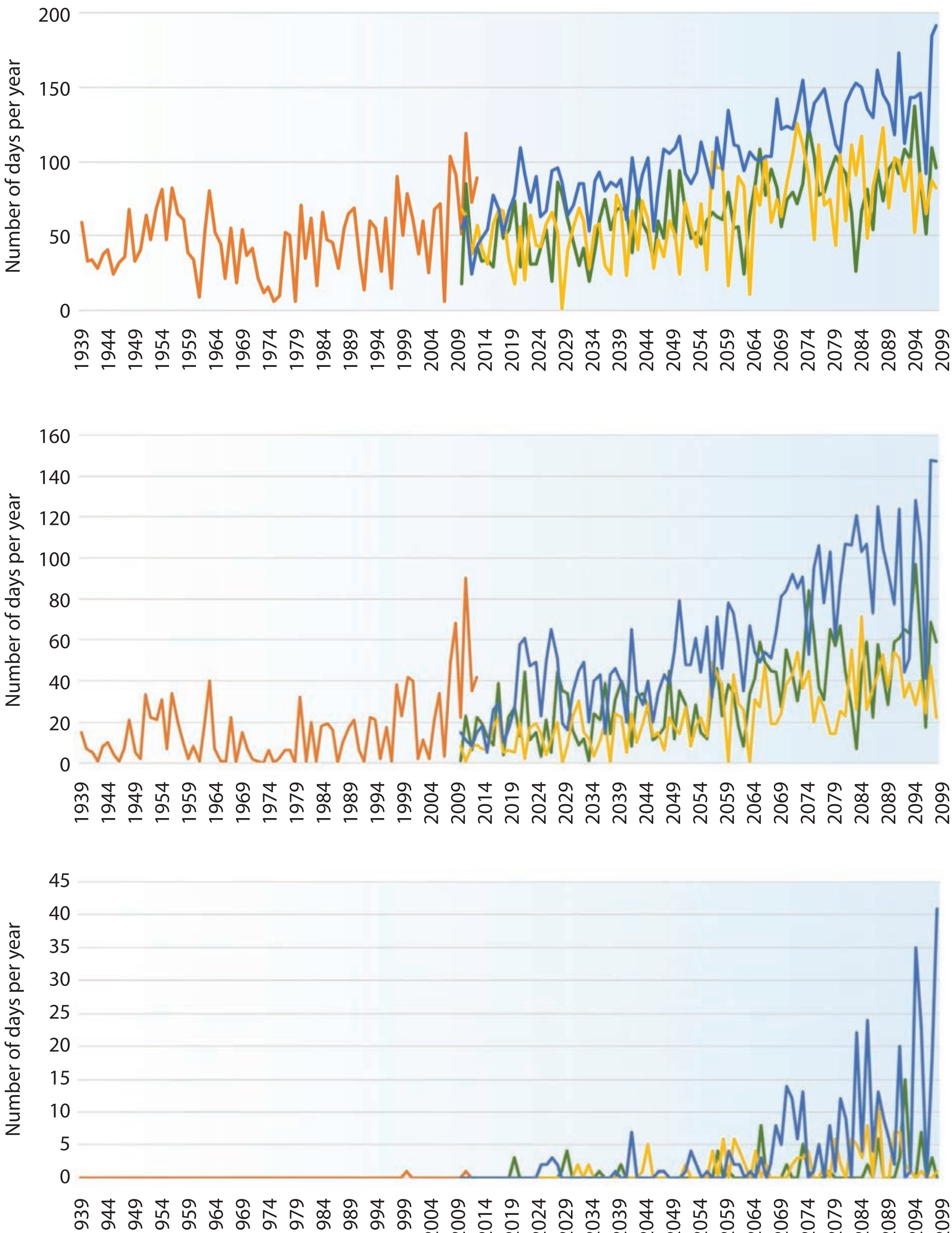
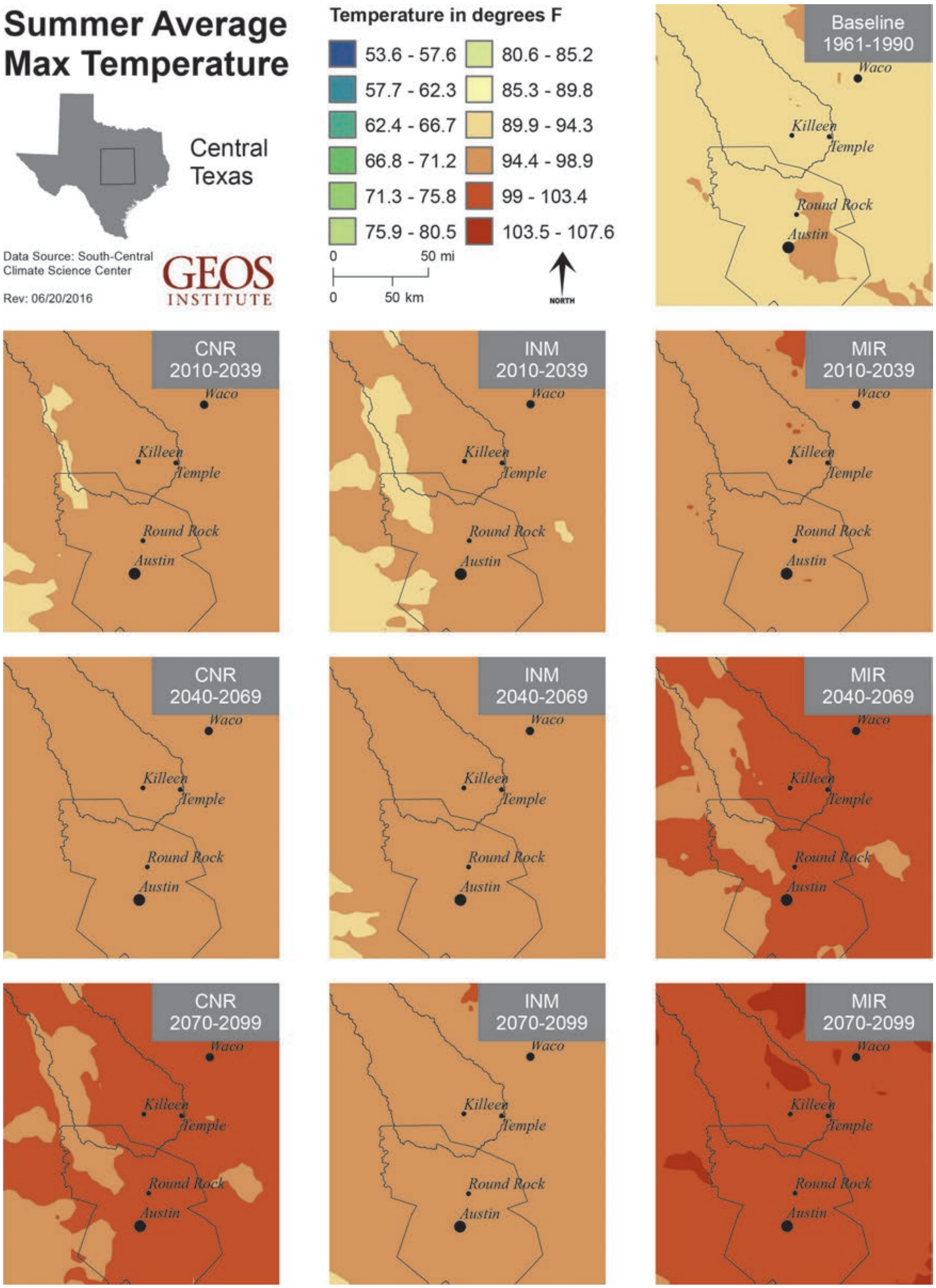


**Figure 5** Maximum summer temperature in Central Texas, averaged over 30-year periods, for the historical period (1961–1990) and three future time periods (2010–39, 2040–69, and 2070–99), based on three different GCMs (CNR, INM and MIR) and continued higher emissions (RCP 8.5). Additional seasons and variables are shown in Appendix A.

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## Precipitation Averages and Drought Stress

Average precipitation in Central Texas has increased slightly over the last century. The model projections for precipitation are far more variable than those for temperature, leading to high uncertainty associated with predicting future conditions. Projections for Central Texas show variability among models, with some showing increases in precipitation and others showing decreases (Table 3; Fig. 6).

Because evaporation is expected to increase with temperature, drier soil conditions are expected, as well as more drought stress, even if there are moderate increases in precipitation. Soil moisture in Central Texas (Fig. 7) is expected to decline by 5% to more than 15% if emissions continue unabated, and 1–10% if emissions are reduced.[2]

**Table 3** Historical and projected annual precipitation, in inches, across the CAMPO management region and averaged over 30-year periods, based on output from three GCMs (CNR, INM and MIR) and continued higher emissions (RCP 8.5). Percent change from historical is shown in parentheses.

| | 1961–1990 | 2010–39 | 2040–69 | 2070–99 |
|---|---|---|---|---|
| **Annual** | 33.4 inches | 31.5 to 36.2 in. (–5.8 to +8.3%) | 32.3 to 37.1 in. (–3.3 to +10.9%) | 28.4 to 36.8 in. (–15.1 to +10.0%) |
| **Spring** Mar, Apr, May | 10.1 inches | 9.0 to 12.3 in. (–10.6 to +22.6%) | 10.2 to 12.8 in. (+1.4 to +27.3%) | 10.0 to 13.2 in. (–0.9 to +31.3%) |
| **Summer** Jun, Jul, Aug | 7.1 inches | 7.0 to 8.2 in. (–1.0 to +16.5%) | 7.2 to 12.1 in. (+1.5 to +71.2%) | 6.2 to 8.0 in. (–11.7 to +13.9%) |
| **Fall** Sep, Oct, Nov | 9.7 inches | 8.5 to 10.3 in. (–12.2 to +7.2%) | 7.4 to 9.4 in. (+23.3 to +10.0%) | 6.5 to 9.4 in. (–32.5 to –2.1%) |
| **Winter** Dec, Jan, Feb | 6.7 inches | 6.0 to 7.5 in. (–10.5 to +11.8%) | 6.3 to 6.7 in. (–5.9 to 0.0%) | 5.7 to 7.1 in. (–15.1 to +6.7%) |

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**Figure 6** Average spring precipitation in Central Texas, averaged over 30-year periods, for the historical period (1961–1990) and three future time periods (2010–39, 2040–69, and 2070–99), based on three different GCMs (CNR, INM, MIR) and continued higher emissions (RCP 8.5). Additional seasons and variables are shown in Appendix A.

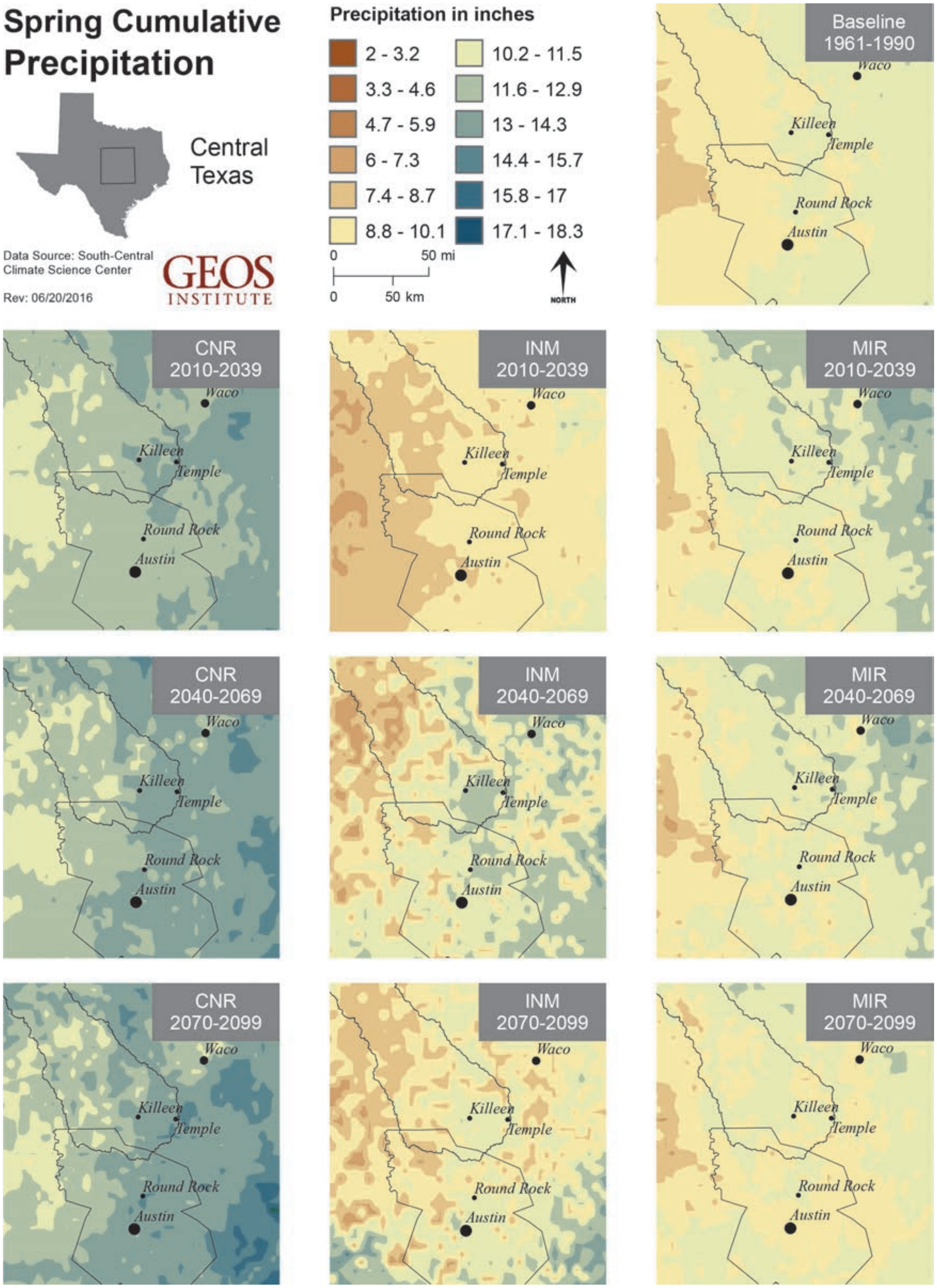


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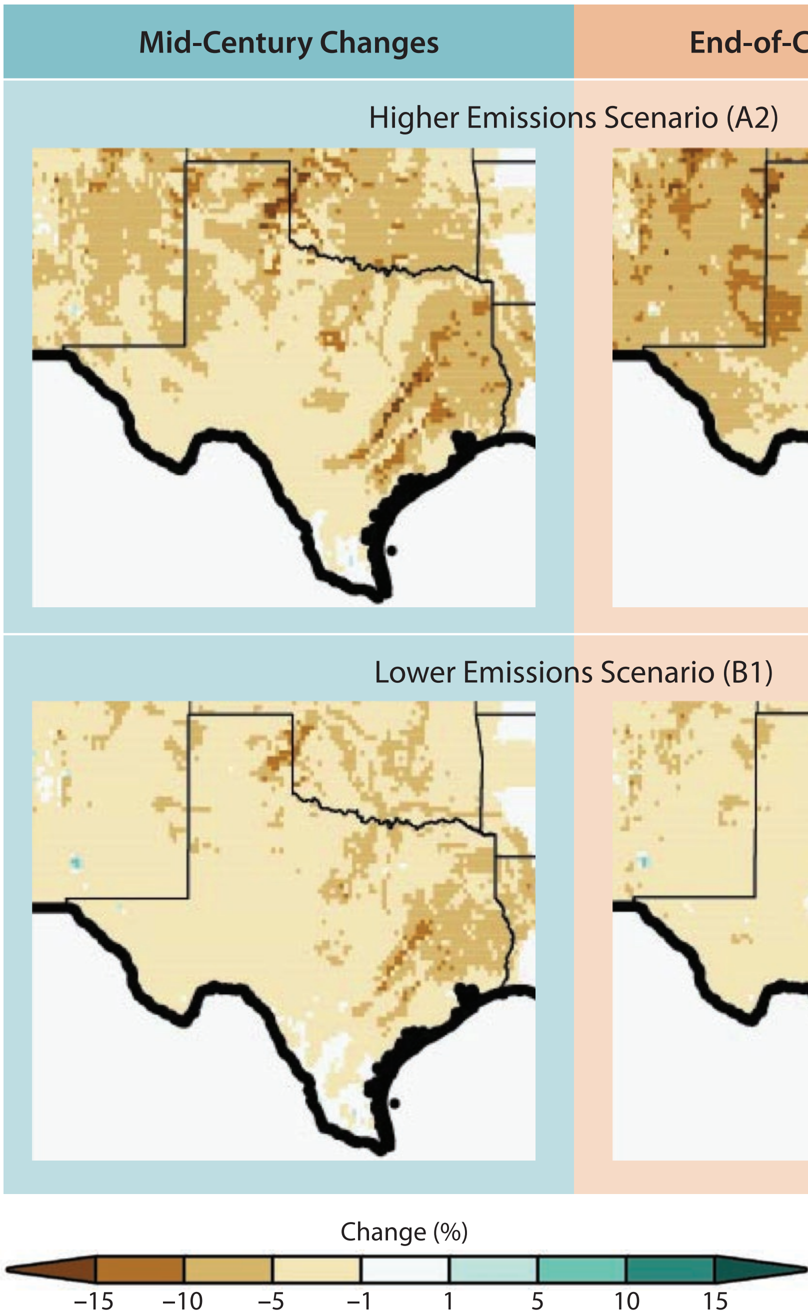
**Figure 7** Percent change in soil moisture compared to historical averages (1971–2000), as projected by the VIC model, for mid century (2041–2070) and late century (2071–2100) under a lower emissions scenario (B1) and a higher emissions scenario (A2), average over 30-year periods. This figure adapted from the National Climate Assessment.[2]

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## Precipitation Extremes

Extremes in precipitation, including both heavy downpours and drought, are becoming more common. Because warmer air can hold more moisture than cooler air, rainfall events have become heavier and more frequent. For Central Texas, heavy downpours are expected to become 2–3 times more frequent through the end of the century if emissions are not reduced; and 1–2 times more frequent if they are.[2] The changes in climate are also increasing the likelihood of severe drought, such as the Texas drought in 2011.[2]

In order to assess local extreme precipitation, decision-makers helped identify three meaningful frequencies to calculate: the number of days in Austin with less than 0.01 inches, more than 2 inches, and more than 10.2 inches of precipitation.

The number of days with less than 0.01 inches of precipitation was projected to increase over time (Table 4; Fig. 8, top).

The number of days with more than 2 inches of precipitation showed increasing variability over time, with more high values (up to 12 days per year) and more low values (more frequent 0's; Fig. 8, middle). This indicates increasing year-to-year variability.

The frequency of days with precipitation greater than 10.2 inches may increase, according to one model, but the other models showed little change (Table 4; Fig. 8, bottom). Very rare events, such as 10.2 inches of rain in a day, are difficult to model.

**Table 4** Historical and projected number of days per year with precipitation less than 0.01 in., more than 2 in., and more than 10.2 in. at the Camp Mabry weather station in Austin, TX, averaged over 30-year periods. Projections based on three GCMs (CNR, INM and MIR) and continued higher emissions (RCP 8.5). Percent change from historic is shown in parentheses.

| Number of days | 1961–1990 | 2010–39 | 2040–69 | 2070–99 |
|---|---|---|---|---|
| Min <0.01 inch | 282 | 280–286 (–0 to +2%) | 283–293 (+0 to +4%) | 285–297 (+1 to +5%) |
| Max >2 inch | 2.3 | 1.8–3.3 (–24 to +40%) | 2.6–3.0 (+11 to +30%) | 2.1–3.8 (–9 to +61%) |
| Max >10.2 inch | 0* | 0–0.1 (NA) | 0–0.3 (NA) | 0 (NA) |

*A record rainfall event of 10.2 inches occurred in 2013, but this event was not captured in the weather station data for multiple potential reasons. First, the 24-hour period may be timed differently between weather station data and specific weather records, and second, the Camp Mabry station may not be the location of that specific rainfall record.

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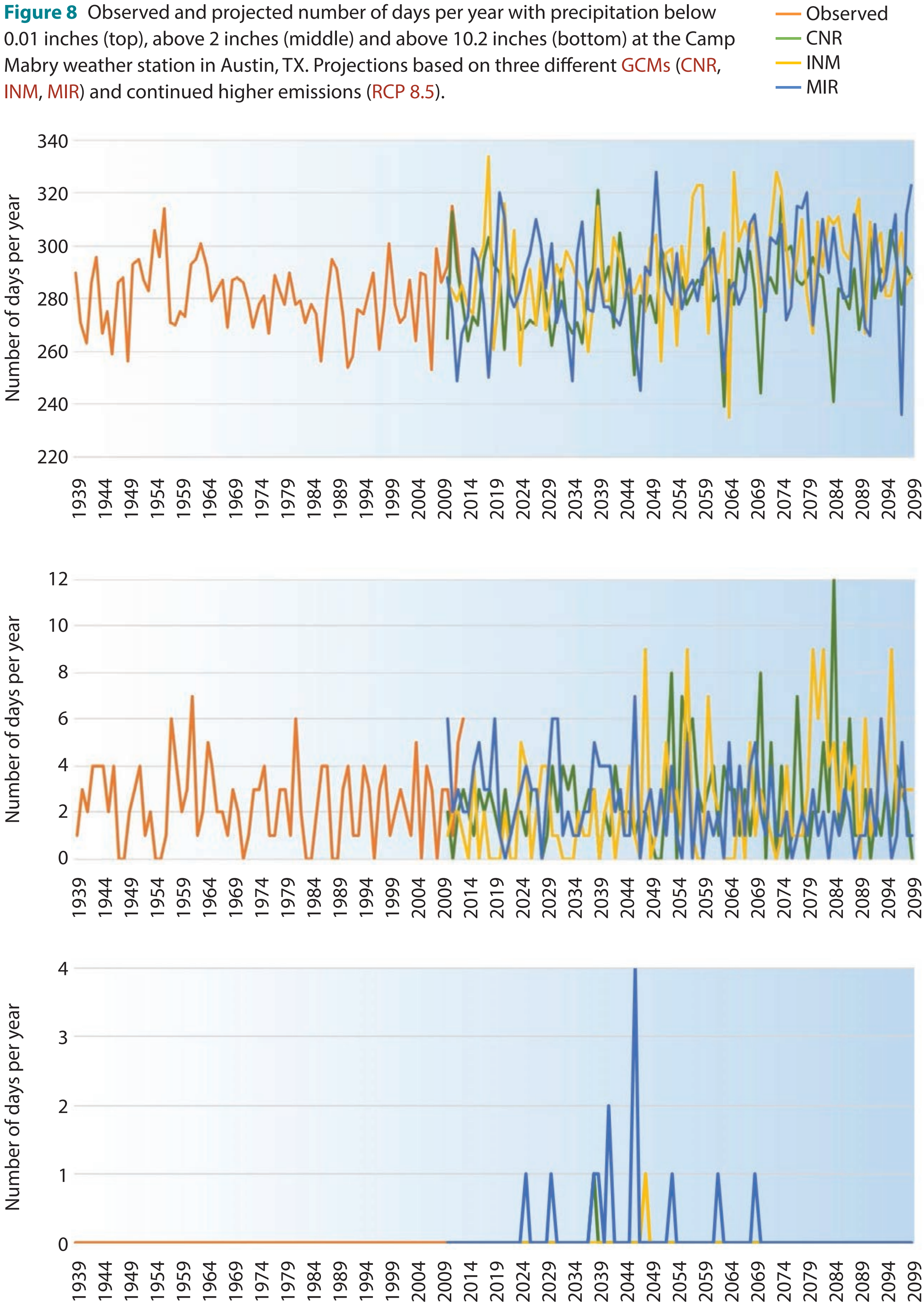
**Figure 8** Observed and projected number of days per year with precipitation below 0.01 inches (top), above 2 inches (middle) and above 10.2 inches (bottom) at the Camp Mabry weather station in Austin, TX. Projections based on three different GCMs (CNR, INM, MIR) and continued higher emissions (RCP 8.5).



## Wildfire

In the western U.S., wildfire is driven by a number of natural factors, including temperature, precipitation, wind, humidity, fuel availability, and lightning strikes, as well as human-caused fire starts. Natural factors are significantly affected by climate.[5]

Wildfire is also associated with large-scale climate patterns such as El Niño.[5] Wildfire activity increases during warm years, with relatively little activity in cool years. Since the mid-1980s the number of large fires and total area burned per year in the Southern Plains, which includes much of Texas, have increased.[6] Fire severity can also be expected to increase given warmer temperatures and drier soil conditions.[7]

In this section, we present the results of the MC1 model.[8] MC1 is a widely used model that provides estimates of future wildfire based on predicted vegetation and climate. MC1 has many limitations, which are described in the methods section.

Modeled wildfire projections for Central Texas were inconclusive. The MC1 model output for Central Texas projects an increase in area burned by mid-century (Table 5; Fig. 9), as climate-related shifts in the type of vegetation take place (Map 6 in Appendix A). Late-century wildfire projections are quite variable, with possible increases and decreases depending on the model (Fig. 9).

**Table 5** Annual average historic wildfire (averaged over 30-year periods) and projected change in wildfire (averaged over 10-year periods) across Central Texas. Projections from MC1 vegetation model using three GCMs (CSIRO, HadCM and MIR) and a higher emissions scenario (A2). Percent change from historical averages shown in parentheses.

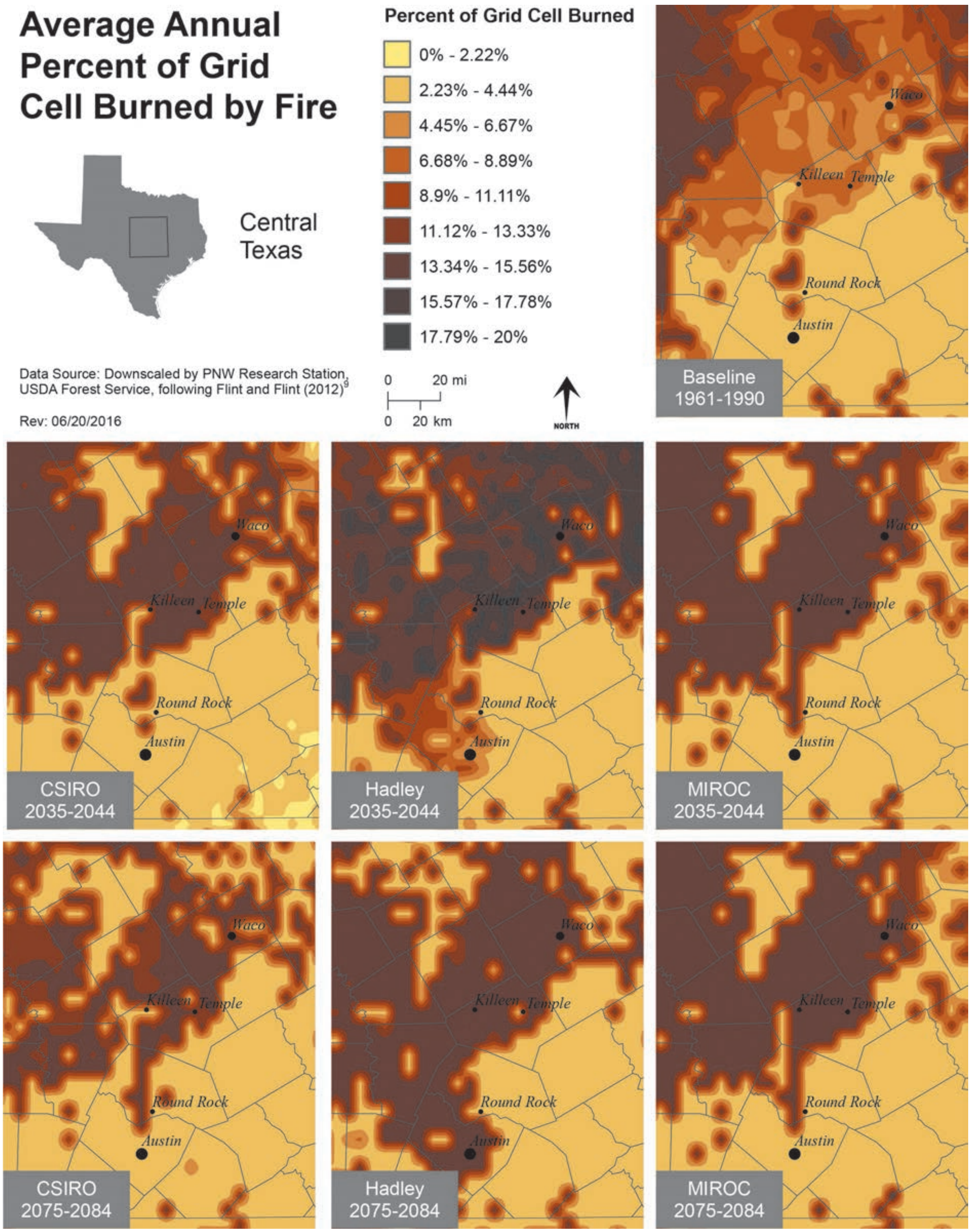
| Variable | 1961–1990 | 2035–44 | 2075–84 |
|---|---|---|---|
| Percent burned* | 8.9% | 8.7–10.9 (–2 to +23%) | 7.5–9.7 (–16 to +9%) |
| Biomass consumed** | 16.6 $g/m^2$ | 12.6–21.2 (–24 to +28%) | 10.7–19.2 (–36 to +16%) |

*Percent burned refers to the overall area (percent of grid cells) burned in a wildfire.

**Biomass consumed refers to the amount of vegetation burned. A grass fire, for instance, would have lower biomass consumed when compared to a forest fire, even if the percent burned is the same.

**NOTE:** Terms in red are defined in the glossary.

**Figure 9** Average percent of the area burned each year, based on output from the MC1 vegetation model, three GCMs (CSIRO, HadCM, MIR), and a higher emissions scenario (A2). The historical period, averaged over 30-years, is compared to mid- and late-century periods, averaged over 10 years.

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# Methods

## *National Temperature Averages*

National temperature projections presented in Figure 1 come from the third National Climate Assessment.[2] These data were developed using a suite (or "ensemble") of Global Climate Models (GCMs). GCMs are used to simulate the Earth's systems and project future conditions. The Intergovernmental Panel on Climate Change (IPCC), the leading international body of climate scientists, has evaluated and adopted a suite of the more representative models for use in climate projections.[10] Within that suite of models, there is still much variation among output. Some models indicate faster warming than others, and precipitation projections are highly variable across the globe.

In addition to the different models, there are also numerous different potential trajectories for greenhouse gas concentrations in the atmosphere; these are called "Representative Concentration Pathways" (RCPs). Figure 1 shows a low emissions pathway (RCP 2.6) and a high emissions pathway (RCP 8.5). RCP 2.6 assumes climate stabilization, with greenhouse gas emissions peaking by 2020 due to international collaboration. RCP 8.5 is considered a "business as usual" path with continued higher emissions throughout this century. For a more details on the methods used for Figure 1, see the National Climate Assessment[2].

## *Local Temperature and Precipitation Averages*

We calculated annual and seasonal temperature (Table 1) and precipitation (Table 3) across the CAMPO study area, averaged over 30-year periods. These data are also shown in a series of maps for the larger Central Texas area (Figs. 2 and 6; Maps 3-5 in Appendix A). We also mapped maximum summer temperature (Fig. 5) and minimum winter temperature (Map 2 in Appendix A), averaged over 30-year periods for the larger Central Texas area. The CAMPO study area boundaries are shown on Map 1 (Appendix A). The Central Texas areas are 'as shown' in each of the associated maps for Central Texas.

**Historical** PRISM data[11,12] were used for calculating historical temperature and precipitation vales, averaged over 30-year periods. PRISM is a set of gridded climate data from numerous weather stations, which are then run through a statistical mapping system to reflect geographic complexities at high resolution.

**Projected** We obtained downscaled model output for nine GCMs (CCSM4, CNRM-CM5, HadGEM2-CC, INM_CM4, IPSL-CM5A-LR,

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MIROC5, MPI-ESM-LR, MRI-CGCM3, CSIRO-Mk3-6-0), at a resolution of 5 $km^2$ from the South Central Climate Science Center. In order to adequately represent the variation among models, we graphed average annual precipitation and temperature using all nine different GCMs. From these nine, we chose three models that reflected the full range of output, from faster warming to slower, and from lower precipitation to higher, as well as one approximately in the middle. These three models included CNRM-CM5 (from the National Center for Meteorological Research in France), MIROC5 (from the Center for Climate System Research in Japan), and INM-CM4 (from the Institute for Numerical Mathematics in Russia).

We obtained data based on a higher emissions (RCP 8.5) pathway. We chose RCP 8.5 because it most closely aligns with the "business as usual" path that the international community is currently on. However, changes in attitudes and technology could result in drastic emissions cuts. If that happens, the best case outcome would be for temperature rise to level off between 2040–60. Unfortunately, if emissions are lowered only slightly or even moderately, natural processes are expected to result in additional emissions (from forest fires, thawing peat, and others) thereby resulting in higher emissions anyway.

Global models result in course-scale climate projections (cell sizes range from 1–5 degrees latitude/longitude per side). Projections at this scale are not necessarily useful for decision making at the local and regional level. In order to make the model outputs more useful, scientists have developed methods to "downscale" them to locally-relevant scales. The output from the GCMs for this project were statistically downscaled to 5 $km^2$ following the methods of Hayhoe and Stoner 2013.[13]

## *Local Temperature and Precipitation Extremes*

**Thresholds** We used output from three GCMs (CNRM-CM5, MIROC5, and INM-CM4) to calculate the frequency of extreme temperature and precipitation events in Austin, Texas. To determine which 'thresholds' to calculate, input was received by project partners (The City of Austin and A Nurtured World). Selected temperature and precipitation thresholds included:

- number of days per year above 95°, 100°, and 110° F
- number of days with minimum temperatures below freezing or above 80° F
- number of days per year with precipitation below 0.01 inches, above 2 inches, and above 10.2 inches

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**Historical** We used observational data to calculate the number of days per year that met the thresholds historically. We obtained daily observed maximum and minimum temperature and daily precipitation values, spanning 1939–2013, from the Camp Mabry weather station in Austin, Texas (Fig. 10). The station is part of the U.S. Historical Climatology Network, which is a collection of long term weather stations selected to track climate trends. Data are available online at http://www.ncdc.noaa.gov.


**Figure 10** Location of the Camp Mabry weather station in Austin, Texas (Lat/Long = 30.320/–97.760).

**Projected** We calculated the projected number of days per year that met or exceeded the thresholds described above for the years spanning 2010-2099. These were calculated using the same three downscaled GCMs (CNRM-CM5, MIROC5, and INM-CM4) as before, based on continued higher emissions (RCP 8.5). Spatial data were clipped to a single location grid cell (Lat/ Long = 30.3475/–97.7812), which was nearest to the Camp Mabry weather station.

**Calibrating Model Projections** The downscaled GCMs can be used to project frequencies of extreme temperature and precipitation events for both future time periods and past (historical) time periods. Projections for historical time periods were used to calibrate, or adjust for biases in each model.

We used each of the three GCMs to calculate the historical frequencies (number of days per year) that thresholds were surpassed, averaged over the 30-year period from 1961 to 1990. We then compared the actual historic frequencies for this time period to the modeled frequencies for the same time period. The difference between the two was then used as a calibration factor that was applied to the projected future frequencies

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of extreme temperature and precipitation, average over 30-year periods (Tables 2 and 4). This method is a common approach to calibrating models to better align with actual observed climate.[14]

The calibration factor was also applied to annual projected frequencies in order to display year-to-year data in graph form (Figs. 3, 4, and 8). However, using this calibration approach means that, in some cases, the data in the figures do not align perfectly with the data in the tables. Mathematically, this occurred when the model output predicted few or zero days per year (as in several of the years shown in the figures for late century freezing days) and applying the calibration factor resulted in a prediction of a 'negative day'. When applying the calibration factor resulted in a 'negative day', the results were presented in the figures as zero. Thus, the tables of 30-year averages are more robust calculations, while the graphs provide a visual display of trends.

## Wildfire and Vegetation

Wildfire and vegetation projections are presented in Table 5, Figure 9, and Maps 6 & 7 in Appendix A. These data are output from the MC1 dynamic vegetation model.[8] This model provides output on vegetation and wildfire based on climate data inputs. MC1 explicitly simulates vegetation dynamics, nutrient cycles and dynamic impacts of disturbance due to fire and has been used in analyses of vegetation responses to climate change.[15]

For historical information on wildfire and vegetation, MC1 was run using PRISM climate data.[13,14] PRISM is a dataset developed by the PRISM Climate Group to provide fine-scale information on historical climate (1895–present). The historical projections were compared to future projections using downscaled GCM output in order to assess changes in wildfire extent and biomass consumed by fire. GCMs used as input to MC1 included Hadley CM3 (HadCM), MIROC 3.2 (MIR), and CSIRO MK3.5 (CSIRO) under a higher emissions scenario (A2) from the IPCC Third Assessment.[16]

The A2 emissions scenario assumed continuously increasing world population and continued economic development without coordinated international efforts to reduce emissions.[17] Downscaled MC1 output data were obtained from the US Forest Service Pacific Northwest Research Station Mapped Atmosphere-Plant-Soil System (MAPSS) Team. Downscaling was done following the methods of Flint and Flint.[9] The MAPSS Team uses these three GCMs listed above as input to the MC1 model because they provide certain input variables (such as water vapor) that the MC1 model needs.

**NOTE:** Terms in red are defined in the glossary.

The MC1 model has many limitations. First, it only models native vegetation and does not account for land use change (i.e. agriculture and development), introduced species (i.e. non-native grasses), or human caused fire ignition. Second, it assumes immediate shifts from one type of mature vegetation to another. A lag time, which is not considered in the model, is expected between changes in climate conditions and establishment and maturation of new vegetation types on the ground – this lag time could be decades or even centuries.

Even with its limitations, the MC1 model provides valuable information about potential changes in wildfire. It is important to use the output in conjunction with a solid understanding of historical conditions and wildfire patterns.

## Glossary

**30-year** averages are standard timeframes for reporting climate variables, because weather varies day to day, month to month, and year to year. Scientists consider the climate to consist of the average weather over longer periods of time, usually 30 years. Many variables can be assessed, including average temperature or precipitation, average maximum temperature, average minimum precipitation, and average winter snowpack.

**A2** emissions scenario is described in the IPCC's Special Report on Emissions Scenarios[17] (SRES) from 2000. This emissions scenario was used for projections that were published in the IPCC Third Assessment Report[16] from 2001, and assumed continuously increasing world population and continued economic development without coordinated international efforts to reduce emissions.

**B1** emissions scenario is another SRES scenario (see A2) from 2000[17], but this one assumes slower population growth and a more collaborative and ecologically friendly world.

**CAMPO** is the Capital Area Metropolitan Organization, which covers Bastrop, Burnet, Caldwell, Hays, Travis, and Williamson Counties in Texas. CAMPO coordinates transportation planning with cities, counties, and agencies. See Appendix A for a map of the CAMPO area.

**CNR** (CNRM-CM5[18]) is a GCM developed by the National Center for Meteorological Research in France. It is one of a many models used to produce the projections in the IPCC's Fifth Assessment Report.[19]

**CSIRO** (CSIRO-MK3.5)[20] is a GCM developed by the Centre for Australian Weather and Climate Research. It is one of many models used to produce the projections in the IPCC's Third Assessment Report.[17]

**El Niño** is a phase of the "El Niño Southern Oscillation" (ENSO) that is associated with high surface pressure over the western Pacific, resulting in cooler and wetter conditions in the Southeastern U.S., including Texas.

**Global Climate Models** (GCMs) are complex land-ocean-atmosphere models that simulate the functioning of the Earth's systems and are often used to model the earth's climate and project future changes.

**HadCM** (HadCM3[21]) is a GCM developed by the Hadley Centre in the United Kingdom. It is one of many models used to produce the projections in the IPCC's Third Assessment Report.[17]

**IPCC** is the Intergovernmental Panel on Climate Change, a leading scientific body under the auspices of the United Nations. The IPCC issues regular reports that cover scientific, technical, and socioeconomic information relative to understanding the basis of risk of human-induced climate change, impacts, and options, including both mitigation (reducing greenhouse gases) and adaptation (protecting people and resources from impacts).

**INM** (INM-CM4[22]) is a GCM developed by the Russian Academy of Sciences. It is one of many models used to produce the projections in the IPCC's Fifth Assessment Report.[19]

**MC1**[8] Dynamic Global Vegetation Model (DGVM) is a computer program that simulates shifts in potential vegetation and the associated biogeochemical and hydrological cycles as a response to shifts in climate. DGVMs use time series climate data and, given constraints of latitude, topography, and soil characteristics, simulate monthly or daily dynamics of ecosystem processes. The MC1 DGVM has a complex fire module that provides output on changes in wildfire extent, biomass consumed by wildfire, and carbon storage in vegetation. It was created by scientists at the USDA Forest Service's Pacific Northwest Research Station.

**MIR** (MIROC[23]) is a GCM developed by the Center for Climate System Research in Japan. It is one of many models used to produce the projections in the IPCC's Third Assessment Report.[16] In this report, we used MIROC5 for climate projections and MIROC3.2 for wildfire projections.

**National Climate Assessment** (NCA) is a large scale collaborative effort of more than 300 of the nation's leading scientists, guided by a 60-member Federal panel and reviewed by the National Academy of Sciences, to assess the patterns and impacts of climate change on the United States. The Global Change Research Program releases a NCA report approximately every 4 years. The latest report[2] was released in 2014 and is available at nca2014.globalchange.gov. The NCA bases its climate projections on the models and emissions pathways developed for the IPCC reports.[16,19]

**PRISM** Climate Data[11,12] (www.prism.oregonstate.edu) is a dataset developed by the PRISM Climate Group to provide fine-scale information on historical climate (1895–present). The PRISM Climate Group gathers climate observations from a wide range of monitoring networks, applies sophisticated quality control measures, and develops spatial climate datasets to reveal short- and long-term climate patterns.

**RCP 2.6**[24] is a representative concentration pathway (RCP) that assumes that international socioeconomic conditions develop in a way that results in climate stabilization. This RCP was used for projections that were published in the IPCC Fifth Assessment Report[19] from 2014, and assumed that greenhouse gas emissions peak by 2020 due to international collaboration.

**RCP 8.5**[25] is a representative concentration pathway (RCP) that assumes continued rise in greenhouse gas emissions throughout this century. This RCP was used for projections that were published in the IPCC Fifth Assessment Report[19] from 2014.

**Uncertainty** as a scientific term refers to the quantitative variability among data points. When variability is high, it becomes more difficult to predict the value of any one data point, even if an overall trend is significant.

**VIC** Hydrologic Model[26] is a computer simulation of water and energy balances across largescale watersheds, developed at the University of Washington and applied to river basins across the globe. VIC stands for Variable Infiltration Capacity. It can be accessed at http://www.hydro.washington.edu/Lettenmaier/Models/VIC/

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