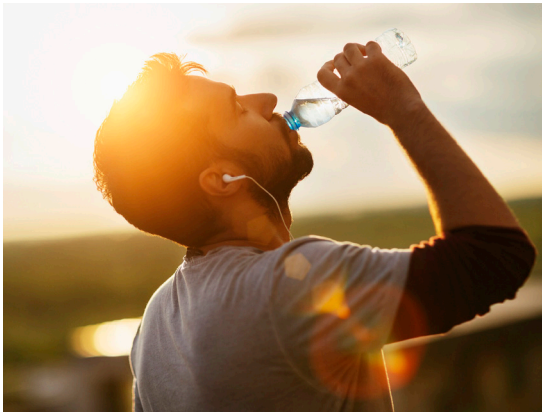


FUTURE EXTREME HEAT IN THE DENVER METRO AREA



A report to Denver Environmental Health

the
**ROCKY
MOUNTAIN
CLIMATE**
Organization

Stephen Saunders
Tom Easley
Melissa Mezger
June 2017

FUTURE EXTREME HEAT IN THE DENVER METRO AREA

By
Stephen Saunders, Tom Easley,
and Melissa Mezger

A report by the
Rocky Mountain Climate Organization

To
Denver Environmental Health

June 2017





The Rocky Mountain Climate Organization works to reduce climate disruption and its impacts to help keep the Interior West the special place we cherish. We do this in part by spreading the word about what a disrupted climate can do to us here and what we can do about it, through reports such as this, and also by advocating public and private actions.

RMCO does much of its work in partnership with local governments, including through the Colorado Climate Network, which supports local climate programs and is administered by RMCO for its members. The City and County of Denver is a charter member of the Network.

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Denver's Department of Environmental Health is dedicated to advancing Denver's environmental and public health goals. DEH works collaboratively with city, state, and community partners to conduct education, community engagement, and enforcement to ensure healthy people, healthy pets, and a sustainable environment. Our mission is to create a city with a world class environment and healthy communities for all ages and incomes, and where the well-being of our pets also matters. Through the Climate Action Plan, Denver Energy Challenge, and other programs, DEH works with partners to conserve energy, reduce greenhouse gasses, and promote sustainability.

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1. INTRODUCTION

This report describes how climate change is projected to lead to increases in extreme temperature in the Denver metropolitan area.

The City and County of Denver's Climate Adaptation Plan identified an increase in temperatures as one of the top three impacts Denver residents may face from climate change.¹ Denver Environmental Health commissioned this report to identify the extent to which climate change may lead to more extreme heat in the metro area. The purpose is to help not only the City and County government but also other local governments and institutions in the metro area and local residents better understand and prepare for the risks of extreme heat that could result from climate change.

The metro area already has seen an increase in extreme heat. As documented later in this report, 100°-plus days in Denver have gone from an average of 0.7 per year in 1967–1999 to 1.8 per year so far this century. This is an increase of more than 250 percent.

Future increases in extremely hot days could be much greater. On the current path of continued high emission increases, the median projections from 20 climate models are that a typical year in the Denver area in mid-century would average 7 days per year 100° or hotter and that the hottest year would have 25 such days. By late century, a typical year would have 34 such days and the hottest year would have 72.

On the other hand, we can avoid this future if global emissions are sharply reduced. With very low future emissions, the median projections are that a typical year in mid-century would have two 100°-plus days and late in the century only one—essentially unchanged from recent years. Even bringing about moderate reductions in emissions could cut by half or more the number of extremely hot days that could result from continued high emissions.

So this analysis shows how much the Denver metro area has at stake in the choice between continued high emissions or future emission reductions.

The analysis also illustrates the importance of actions to increase local resilience to the local impacts that could result from climate change. Preparedness actions undertaken now can help the metro area meet near-term challenges and also lay the foundation for addressing the greater risks we could face later in the century if people continue changing the climate.

Analysis overview

This report is similar to but more comprehensive than two earlier Rocky Mountain Climate Organization (RMCO) reports focused on Boulder and Larimer counties, which were funded by the Colorado Department of Local Affairs, using federal disaster recovery funds.² Those two reports were, as far as the authors know, the most detailed such analysis then done for any localities. This report, though, is even more detailed, as it adds projections of extreme heat in especially hot years, not just in typical years.

This report uses projections from global climate models that have been downscaled to produce local results and made available on an online archive.³ Similar downscaled projections have been used in many previous analyses, notably *Climate Change in Colorado: A Synthesis to Support Water Resources Management and Adaptation (Second Edition—August 2014)*,⁴ a report prepared by the Western Water Assessment (WWA) program at the University of Colorado Boulder for the state government's Colorado Water Conservation Board. This WWA report currently is the primary source on what climate change may be like in our state. In it, WWA reported that with continued high increases in future heat-trapping emissions, statewide average temperature could increase by mid-century by 3.5° to 6.5°*, compared to 1971–2000. With one possible intermediate emissions scenario (called medium #2 in this report—see the next page), the increase in average temperatures could be 2.5° to 5°. (These temperature ranges cover the middle 80 percent of the available projections from climate models, in the manner illustrated by Figure 4 on page 6).

*All temperatures presented here are in degrees Fahrenheit.

This analysis differs from and adds to the WWA report in several ways:

- First and most importantly, this report focuses on extreme conditions, not average conditions. It is one thing to know what climate models project for changes in average annual temperatures. It is another what the same models project for the future frequency and duration of heat waves.
- Second, to enable this analysis of future extremes, the data that were obtained and analyzed were individual projections of daily high and low temperatures. Projections for individual days have no particular reliability, but the projected frequency of particular conditions over extended periods (such as the 20-year periods used here) does have value. Analyzing daily data in this way is rare, as it requires starting with thousands of times of more individual projections that for a comparable analysis of average conditions.
- Third, this report considers projections from all four current scenarios for future levels of heat-trapping emissions (described on the next page). These scenarios have been developed by scientists to represent the range of possible emissions levels, and nobody yet knows which will most closely match the future.⁵ Considering all scenarios both identifies the range of possibilities and shows how our future climate will be determined by the extent of future actions to reduce emissions.
- Fourth, this analysis covers the full century, with results presented for four 20-year time periods. The first period covers the immediate planning horizon for local governments, and all four periods are needed to span the lifetimes of children alive today.

Geographic area

This analysis covers a grid of one-quarter of a degree of latitude by one-quarter of a degree of longitude, or about 14 miles by 18 miles. This is much of the Denver metro area, as shown below.

Denver metro grid for projections

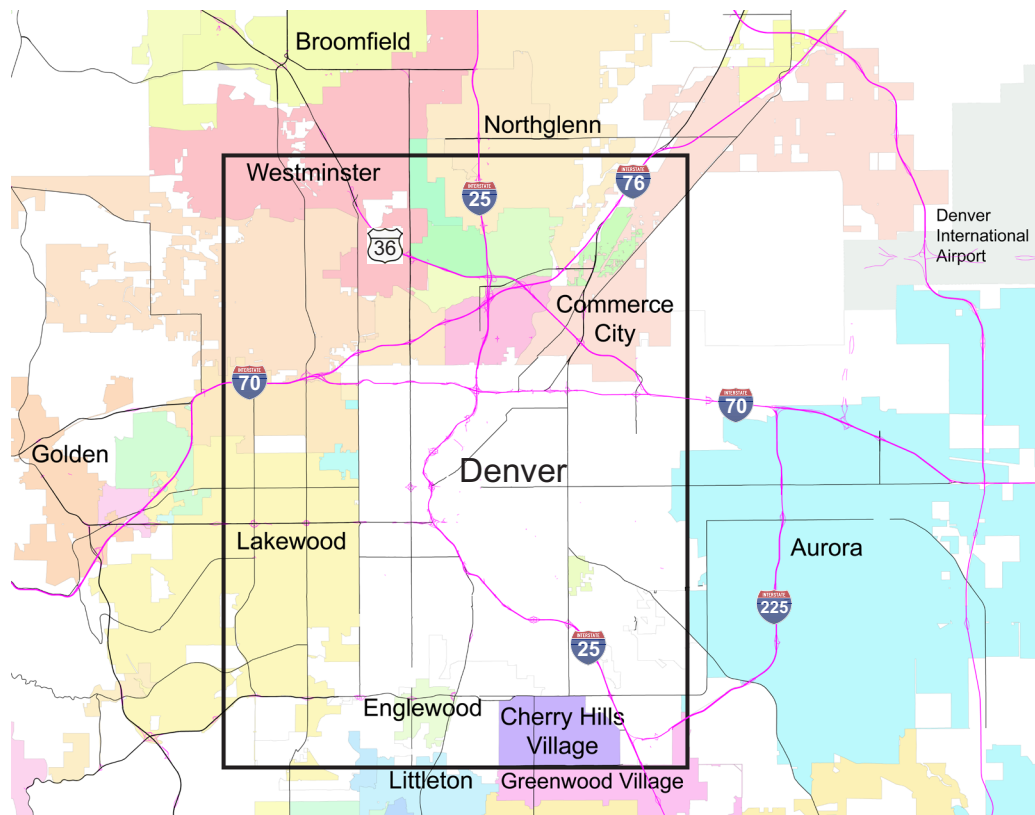


Figure 1. The area for which climate projections were analyzed.

Emissions scenarios

In modeling the future climate, assumptions about future levels of heat-trapping emissions are “in the driver’s seat” (to quote Western Water Assessment)⁶ because “emissions levels determine temperature rises” (now quoting the U.S. government’s Third National Climate Assessment).⁷

The four scenarios comprising the latest generation of such inputs for modeling future climate are:⁸

- What we call here the **high** scenario. Officially known as Representative Concentration Pathway (or RCP) 8.5, it assumes no reduction in the current trend of annually increasing emissions, and so can be considered a business-as-usual approach. The high scenario is represented by the blue lines in Figure 2, below.
- A **medium #1** scenario. Officially known as RCP 6.0, it starts out with the lowest initial emissions levels of all scenarios but then has sharp increases. After the 2060s, it leads to the second highest level of atmospheric concentrations of heat-trapping gases. This scenario is represented by the black lines in Figure 2.
- A **medium #2** scenario, or RCP 4.5. It starts out with higher emissions than medium #1 but then has major reductions after mid-century, as shown by the red lines in Figure 2.
- A **very low** scenario, RCP 2.6. It assumes emissions cuts of more than 70 percent from current levels by 2050 and an elimination of net human emissions by about 2080—assumptions chosen to result in about 2.5° of average warming in this century. The very low scenario is represented by the green lines in Figure 2.

As shown below, the two medium scenarios change their positions compared to each other during the century. Medium #1 actually starts out with lowest emissions of all, but shortly after the middle of the century it surpasses medium #2. The changing relative positions of these two scenarios is reflected in the temperature projections based on them. We have chosen to call these scenarios medium #1 and medium #2 instead of their official designations, which are often interpreted to imply that RCP 6.0 should consistently yield more climate effect than RCP 4.5, which is not true until the second half of the century.

Scenarios of Future Heat-Trapping Emissions

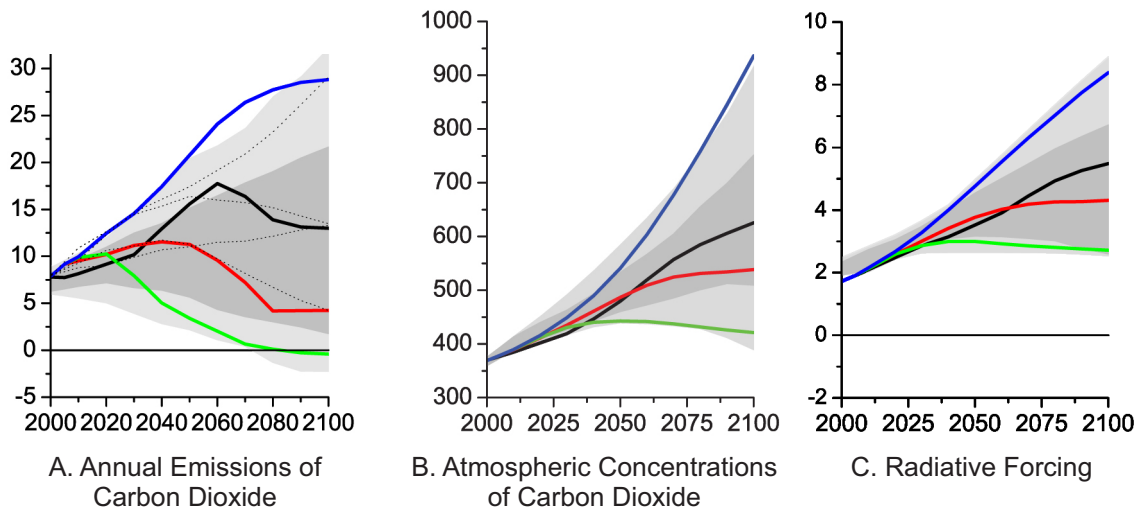


Figure 2. Key values for the four emissions scenarios used in this analysis: A, annual global emissions of carbon dioxide, the principal heat-trapping pollutant, in gigatons of carbon; B, atmospheric concentrations of carbon dioxide, in parts per million; and C, radiative forcing, or the average warming at Earth’s surface resulting from heat-trapping pollution, in watts per square meter. In all three parts of the figure, the blue lines represent the scenario identified as “high” in this report; the black lines, “medium #1”; the red lines, “medium #2”; and the green lines, “very low.” Figures provided by Detlef van Vuuren.⁹

Climate models

The climate projections used in this analysis were obtained by RMCO from an online archive created by the U.S. Bureau of Reclamation and other institutions.¹⁰ The projections are from the latest generation of climate models, known as CMIP5 models. (For details, see the Methodology section on page 18.) The climate projections available on this archive have been widely used by many researchers, including by Western Water Assessment for *Climate Change in Colorado* (see page 1).

The climate projections obtained are for daily maximum and minimum temperatures for January 1, 1950, through December 31, 2099. (The retrospective projections enable comparisons with the weather that actually occurred, for testing the models's accuracy.) From this online archive, one projection was obtained from each of all available models using the different emission scenarios—20 climate models for the high scenario, 12 for medium #1, 19 for medium #2, and 16 for the very low scenario.

In all, for this report 29 million individual projections of daily maximum and minimum temperatures were obtained, covering 150 years, 67 emissions scenario/climate model pairings, and the four small grids comprising the area analyzed here.

An excellent general discussion of the climate models is in WWA's *Climate Change in Colorado*, from which the following points are taken.¹¹

First, climate scientists have confidence that climate models can credibly project future climate conditions, for several reasons:

- The models are based on fundamental, well-understood scientific principles. (This is especially so for temperature, less so for precipitation.)
- The models are successful in replicating such climatic features as jet streams and ocean currents.
- Retrospective projections from the models successfully match historical climate conditions. (For comparisons for the Denver metro area, see pages 18–19.)

Second, projections from different models do differ, even with the same assumptions about future heat-trapping emissions. These differences reflect current scientific uncertainty on some key climate processes. When tested by how well the models retrospectively project the conditions of past years, combined results from all models are consistently more accurate than any single model is. But considering the range of the projections captures the current uncertainties of the models. Accordingly, in this report, as WWA also did in *Climate Change in Colorado*, we present both the median (the mid-point) of all projections, and also the range of the middle 80 percent of the projections (see page 6).

Third, despite recent improvements in climate models, they still have tendencies to over- or under-project certain climate aspects. For Colorado, the models used in this analysis, prior to any bias-correction, project a climate that is on average slightly cooler than the state's observed climate.¹² A simple "delta method" approach, as used by WWA for *Climate Change in Colorado* and by RMCO for this report, effectively cancels out much of this bias.¹³ See the Methodology section on page 18 for an explanation of the delta method used here.

For this report, 29 million projections of future daily temperatures were analyzed.

Precipitation Projections

Projections were also obtained for future precipitation. The projections suggest that more intense storms will become more frequent, but there is more uncertainty in the projections for precipitation than in those for temperature. See rockymountainclimate.org/extremes/denver for details.

2. TEMPERATURE EXTREMES

Recent increases in extreme heat

An analysis of the actual observations from the weather station at Stapleton Airport is the starting point for this report.¹⁴ Although the airport is now closed, the weather station is still in operation. With observations going back to 1948, it is the best source for metro-area weather data over that time.

The station's records demonstrate that the Denver metro area has already experienced an increase in extreme heat. One example is illustrated in Figure 3 below, showing the station's annual counts of days with high temperatures of 100° or higher.

100°-plus days per year, 1948–2016 Stapleton Airport observations

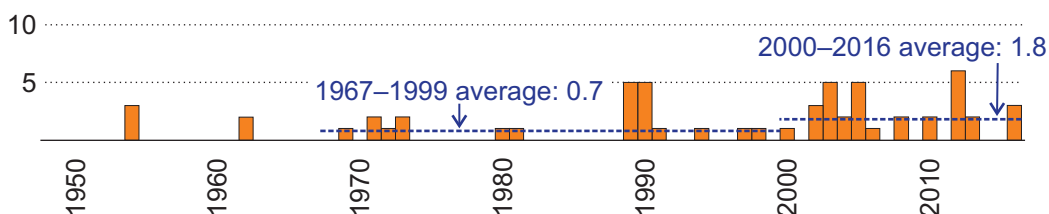


Figure 3. Days per year at Stapleton Airport with high temperatures of 100° or higher.¹⁵

As Figure 3 shows, in 1967–1999 (essentially the first two-thirds of the most recent 50 years), 100°-plus days averaged 0.7 per year. Since then—in the first 17 years of this century—they averaged 1.8 per year, more than a 250 percent increase.

Table 1 below presents numerical values for observed high temperatures at Stapleton Airport.

Daily high temperatures at Stapleton Airport

	1967–99 Average	2000–2016 Average	1967–2016 Trend Per Decade	1948–2016 Maximum
Average daily high in Jun-Jul-Aug	85°	86°	+0.43°	91° (2012)
Number of days 100° or hotter	0.7	1.8	+0.33	6 (2012)
Number of days 95° or hotter	9	15	+1.9	36 (2012)

Table 1. Observations of daily high temperatures at the weather station at Stapleton Airport.¹⁶ All 50-year trends are statistically significant to a 95 percent confidence level.

The annual frequency of 100°-plus days has increased by more than 250 percent from 1967–1999 to the first 17 years of this century.

Projections of future high temperatures

The projections of future daily high temperatures obtained for this report were analyzed to identify how 27 different measures of the Denver metro area’s climate may change over time in response to the different levels of heat-trapping gases assumed in the four emission scenarios. These 27 climate values include average daily temperatures for full years, for seasons, and for individual months; the annual frequencies of days above certain temperature thresholds; average temperatures for the hottest days in a year; and more. The projections of 12 of these climate values are in Table 2 on page 13–14. For the full results of this analysis, see the spreadsheet available at rockymountainclimate.org/extremes/denver.

This report’s first graphic presentation of the projections is in Figure 5 on the next page, which shows the average daily high temperatures in summers—in June, July, and August. In this and other figures that follow, separate projections are shown for each of four 20-year time periods and for each of the four emission scenarios. Figure 4 below illustrates how this report graphically shows both median projections and the middle 80 percent of the projections, which are presented in one summary column for each pairing of time period and emission scenario,.

How this report’s figures represent the projections

Combining multiple projections . . .

into one summary column

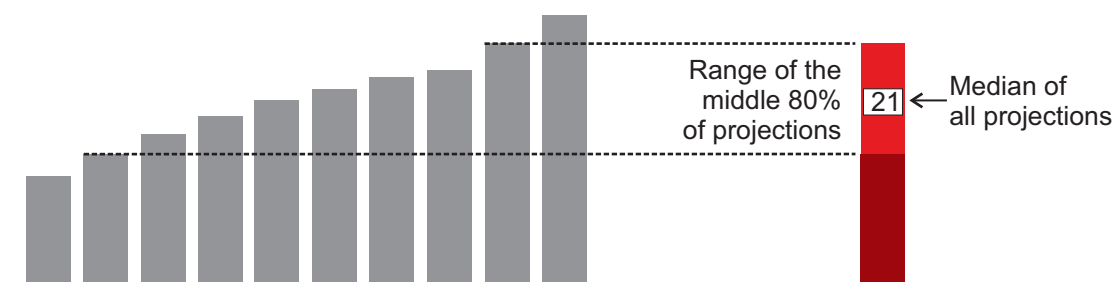


Figure 4. Illustration of how individual projections are represented in figures 5 through 8 on the following pages. On the left, of all projections (hypothetically here from 10 models), the middle 80 percent are combined into a single column (on the right), with that range shown by the lighter color of the upper portion of the column. Another way to express this is that the lighter portion of the column shows the range from the 10th percentile to the 90th percentile of all projections. The numeral in the column shows the median of all projections. The numerical values of the ranges of the middle 80 percent of the projections are in Table 2 on pages 13–14.

Ranges of the Projections

In the text of this report, unless clearly indicated otherwise, in presenting the results of projections, the median (or mid-point) of all projections is given first, followed in parentheses by the lower and upper bounds of the middle 80 percent of the projections.

Average high temperatures in summer Projected averages for 20-year periods

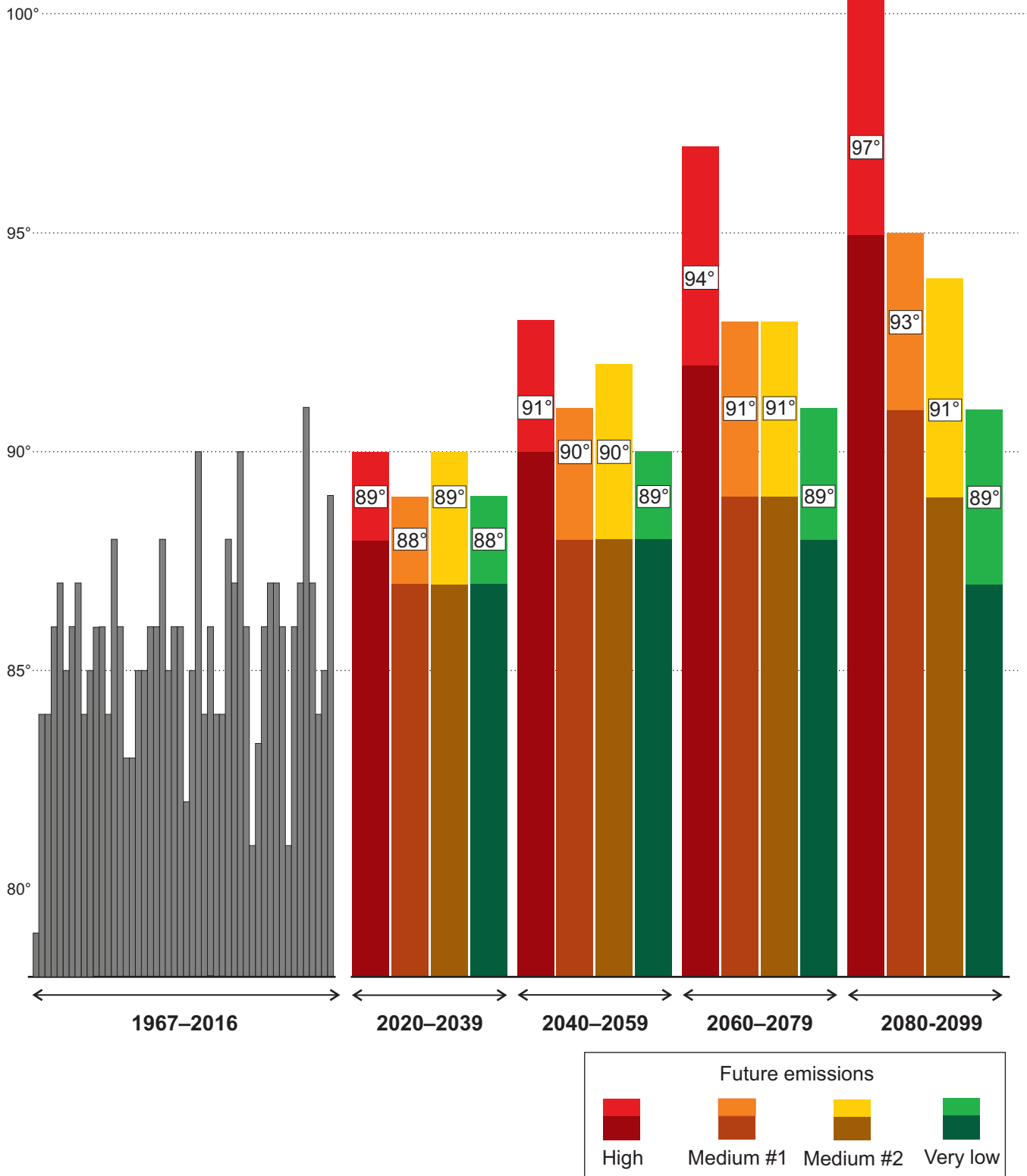


Figure 5. Average daily high temperatures in June, July, and August. On the left, for context, are actual values from the Stapleton Airport weather station.¹⁷ (See also Table 1 on page 5). On the right are projections for four future 20-year periods, separately for four emission scenarios (identified on page 3).¹⁸ The lighter colors on the tops of the columns show the range of the middle 80 percent of the projections, and the numerals are the medians, as illustrated in Figure 4. (For the values of the ranges of the projections, see Table 2 on pages 13 and 14.)

Average summer high temperatures

The projections shown by Figure 5 on the previous page include:

- With the high emissions scenario, the median projection is that summertime highs in mid-century (2040–2059) would average 91°. (The middle 80 percent of these projections ranges from 90° to 93°.) Comparing that to the data in Table 1 on page 5, that median projection means that a typical summer in mid-century could be about 6° hotter than in 1967–1999—and as hot as the hottest summer on record.
- With high emissions late in the century (2080–2099), summertime highs could average 97° (95° to 101°). That means that a typical summer late in the century could average about 12° hotter than in 1967–1999.
- However, with reductions in the global levels of heat-trapping emissions to very low levels, Denver summers would be far less hot. Projections are for summertime highs of 89° (88 to 90°) in mid-century and 89° (87° to 91°) late in the century. These median projections are for about a 3° increase in average summertime highs compared to 1967–1999.

The projections for the two intermediate emission scenarios also show that the extent of future emissions corresponds to the extent of future temperature increases. For these two scenarios, it is worth pointing out again that they change positions during the century as to which represents more emissions than the other, as shown in Figure 2 on page 3. That is why the medium #1 scenario starts out with lower projected temperatures than medium #2, but ends the century with higher projected temperatures.

So, across all emission scenarios, the climate models are consistent in projecting that higher emissions lead to higher temperatures and that lower emissions lead to lesser temperature increases.

With continued high emissions, summers in the Denver area in the middle of the century could average about six degrees higher than in 1967–1999. Late in the century, summers could be about 12 degrees hotter.

But with very low emissions, summers throughout the century might average only about 3 degrees hotter.

100°-plus days in typical and extreme years

A clear measure of extreme heat in Denver is the number of days with high temperatures of 100° or higher. As previously indicated, the frequency of these days has already gone up over the past 50 years. The frequency of these extremely hot days could go up much more markedly, especially if high increases in annual heat-trapping emissions continue.

Figure 6 on the next page presents the projections for 100°-plus days in typical years.

As Figure 6 below shows:

- With the high emissions scenario, typical mid-century years are projected to have seven (three to 13) 100°-plus days, and typical years late in the century 34 (22 to 65).
- However, with very low future emissions, typical years in mid-century are projected to have only two (one to three) 100°-plus days and late in the century only one (one to three). This would be on a par with the actual average at Stapleton of 1.8 such days per year so far this century.

Days 100° or hotter in *typical* years Projected averages for 20-year periods

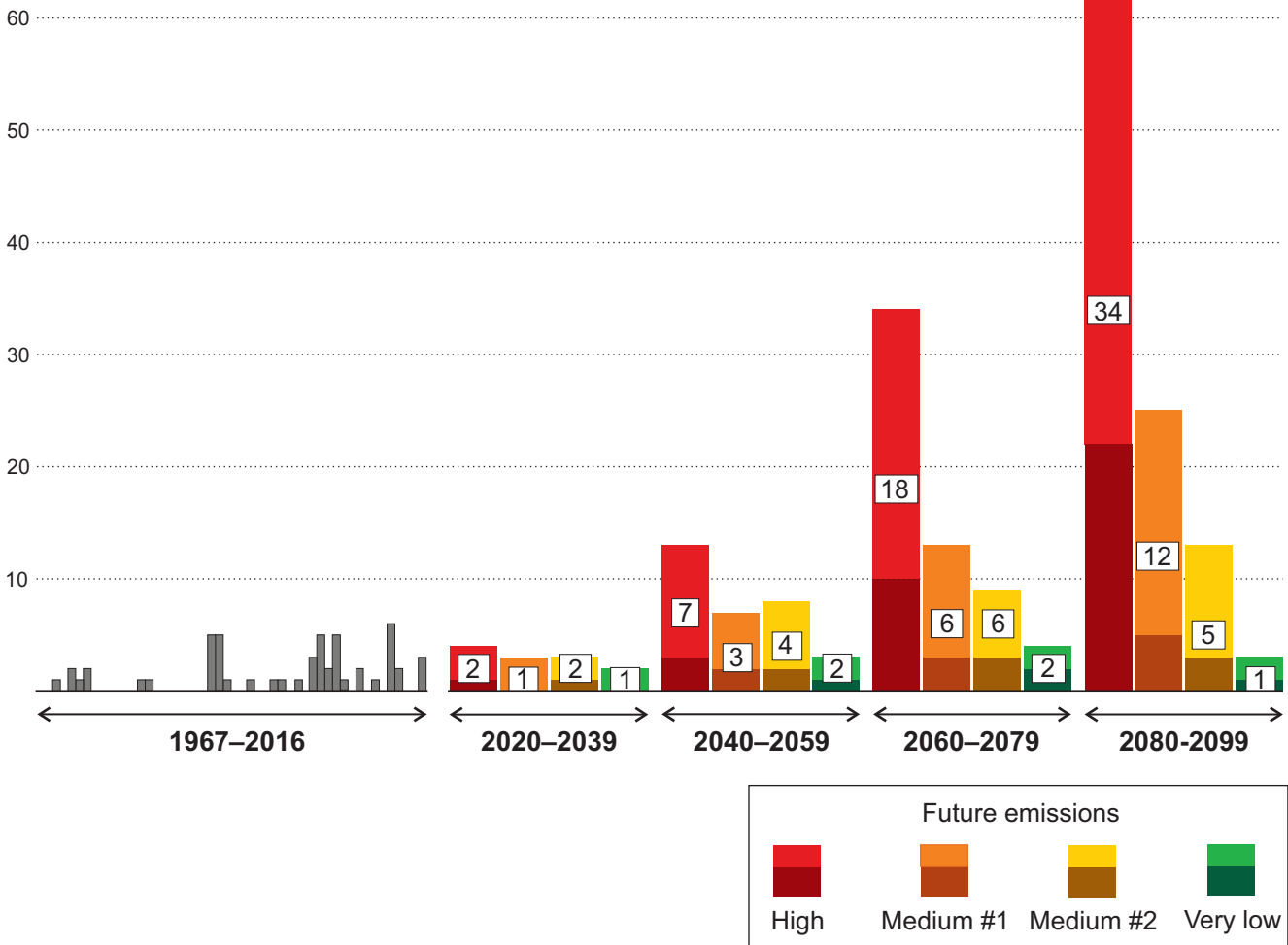


Figure 6. The number of days per year with high temperatures of 100° or hotter. For context, on the left are actual numbers from the Stapleton Airport weather station.¹⁹ On the right are projections for the typical years in each future 20-year period, separately for each emission scenario.²⁰ Shown are the medians of projections and the ranges of the middle 80 percent of the projections, as illustrated in Figure 4. For the numerical values of the ranges of the projections, see Table 2 on pages 13 and 14.

With continued high emissions, the Denver area could average about a week of 100°-plus days per year in the middle of the century, and more than a month of those days late in the century. But with very low emissions, the frequency of 100°-plus days would not increase over recent years.

Days 100° or hotter in *extreme years* Projections for the hottest year in each 20-year period

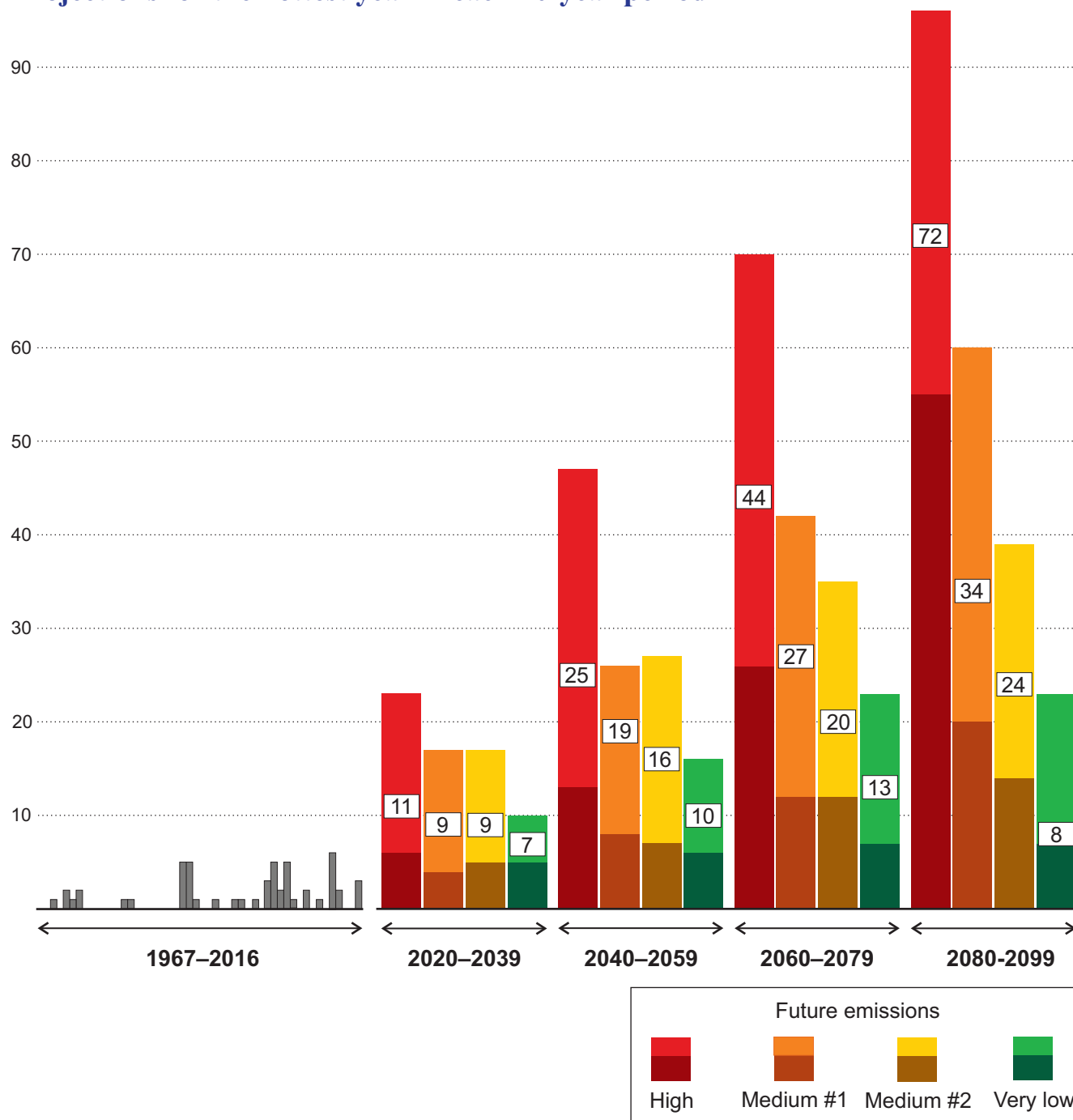


Figure 7. As Figure 6, but for the projected hottest individual year in each 20-year period.

The projections shown in Figure 7 above are for *extreme years*. These projections are for what the models identify as the hottest individual year in each of the 20-year periods. (By contrast, Figure 6 on the previous page shows projections for *typical years*—in other words, the projected average annual frequency for each 20-year period.) For extreme years:

- With high future emissions, the hottest year in mid-century could have 25 (13 to 47) 100°-plus days. The hottest year near the end of the century could have 72 (55 to 96) such days.
- With very low future emissions, the hottest year in the middle of the century could instead have 10 (six to 16) 100°-plus days. The hottest year late in the century could have eight (seven to 23).

Consecutive 100°-plus days

Figure 8 on the following page shows projections for the longest stretch of consecutive 100°-plus days in the hottest individual year in each 20-year period. These could be the longest-lasting extreme heat waves that Denver might experience.

For historical context, the longest stretch of consecutive 100°-plus days at Stapleton Airport is five (in 1989, 2005, and 2012). As shown in Figure 8:

- With high emissions, the hottest year in mid-century could have extreme heat waves of consecutive 100°-plus days lasting 11 (six to 19) days.
- Also with high emissions, the hottest year late in the century could have 100°-plus heat waves lasting 38 (23 to 75) days.
- However, with very low future emissions, the projections are that the hottest years in the future periods could have stretches of 100°-plus days only a little longer than in recent years—six such straight days (five to 11) in the hottest years both in mid-century and late in the century.

With high emissions, the hottest year in the middle of the century could have about 11 straight days 100° or hotter.

The hottest year late in the century could have more than a month straight of such extremely hot days.

A fundamentally transformed climate

Similar detailed projections of future conditions have not been done for many other locations, but the projections for Denver's future can be compared to actual historic conditions elsewhere. This helps to bring home how different the Denver area's future climate would be if the projected increases with high emissions were to materialize.

The projections for the Denver area include monthly and seasonal temperatures (available at www.rockymountainclimate.org/extremes/denver). Comparing Denver's projected average daily high temperatures in July with actual records for other locations in the recent past:

- With high emissions, July high temperatures in Denver in mid-century are projected to average 94° (92° to 96°). The median projection would be 2° hotter than the July average of El Paso, Texas, in 1970–1999.²¹
- Again with high emissions, Denver's July highs late in the century are projected to average 99° (97° to 103°), approaching the recent average in Tucson, Arizona, of 100.5°.²²

Another basis for comparison is the consecutive number of 100°-plus days. For that:

- With high emissions, projections for the hottest year in Denver late in the century are for 38 (23 to 75) straight 100°-plus days (as shown in Figure 8), which compares to Tucson's record of 39 consecutive 100°-plus days.²³

With continued high emissions, Denver late in the century could experience extreme heat about like that of Tucson in recent years.

Consecutive days 100° or hotter in extreme years Projections for the hottest year in each 20-year period

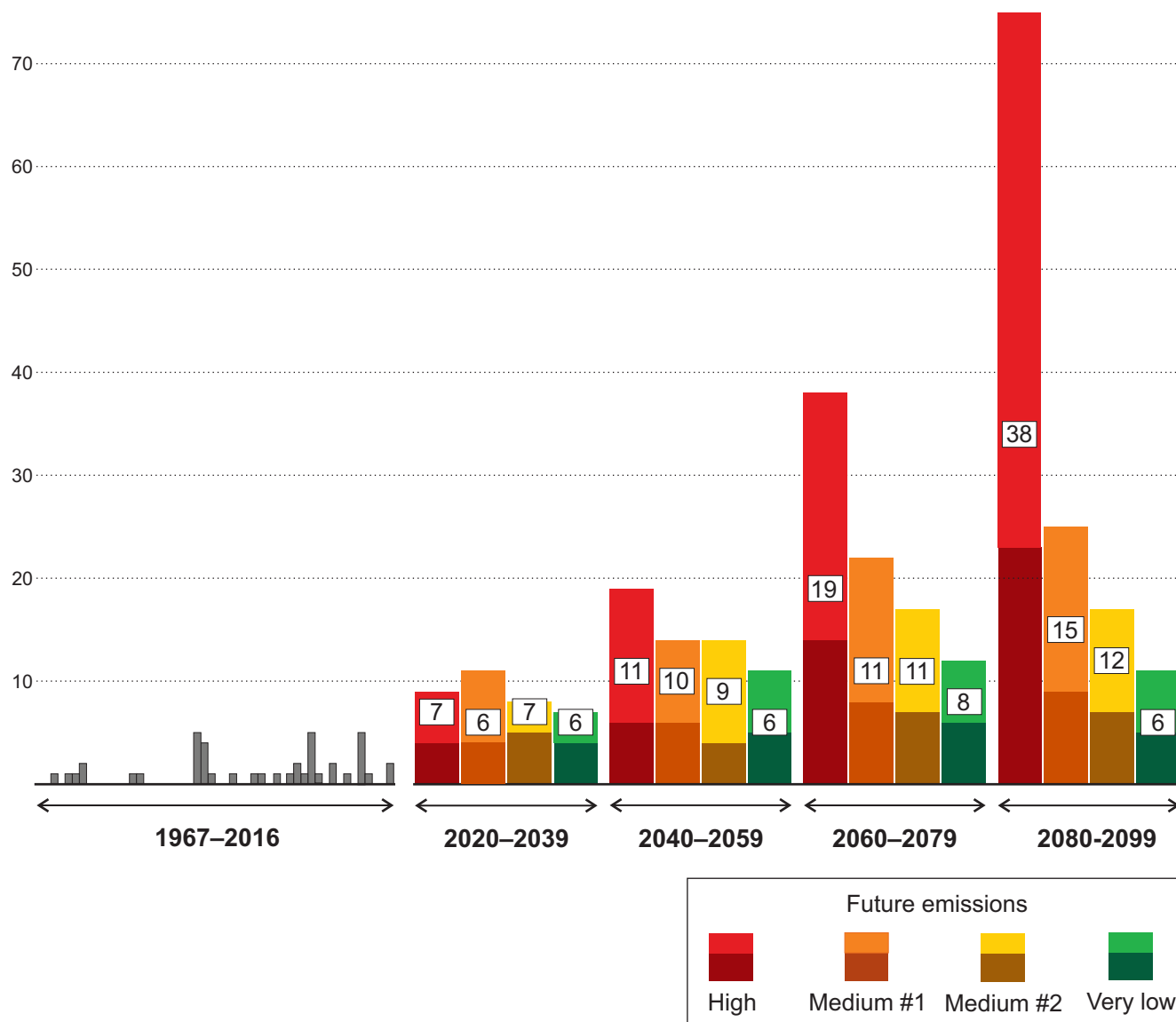


Figure 8. The maximum number of consecutive days in a year with high temperatures of 100° or hotter. For context, on the left are actual values from the Stapleton Airport weather station (maximum: five such consecutive days in 1989, 2005, and 2012).²⁴ On the right are projections for the single hottest year in each future 20-year period, separately for each emission scenario.²⁵ Shown are the medians of projections and the range of the middle 80 percent of the projections, as illustrated in Figure 4. See Table 2 on pages 13 and 14 for the numerical values.

Additional Projections

The projections for more temperature values, including seasonal and monthly projections, can be found online at www.rockymountainclimate.org/extremes/denver.

Daily high temperatures in Denver area

	1967-99 Actual	Projections with Different Emission Levels							
		2020-2039				2040-2059			
		High	Med. #1	Med. #2	Very Low	High	Med. #1	Med. #2	Very Low
Typical years									
Average daily high in Jun-Jul-Aug	85°	89° <i>88-90°</i>	88° <i>87-89°</i>	89° <i>87-90°</i>	88° <i>87-89°</i>	91° <i>90-93°</i>	90° <i>88-91°</i>	90° <i>88-92°</i>	89° <i>88-90°</i>
Number of days 100° or hotter	0.7	2 <i>1-4</i>	1 <i>0-3</i>	2 <i>1-3</i>	1 <i>0-1</i>	7 <i>3-13</i>	3 <i>2-7</i>	4 <i>2-8</i>	2 <i>1-3</i>
Longest stretch of 100°-plus days	0.7	1 <i>1-2</i>	1 <i>0-2</i>	1 <i>1-2</i>	1 <i>0-1</i>	3 <i>2-5</i>	1 <i>1-3</i>	2 <i>1-3</i>	1 <i>1-2</i>
Number of days 95° or hotter	9	19 <i>14-24</i>	14 <i>11-19</i>	16 <i>11-23</i>	13 <i>8-15</i>	35 <i>24-48</i>	23 <i>18-30</i>	26 <i>18-35</i>	18 <i>14-23</i>
Avg high temp of yr's 30 hottest days	93°	97° <i>96-98°</i>	96° <i>95-97°</i>	97° <i>95-98°</i>	96° <i>95-97°</i>	99° <i>98-101°</i>	98° <i>97-99°</i>	98° <i>97-99°</i>	97° <i>96-98°</i>
High temperature of hottest day	99°	102° <i>100°-102°</i>	100° <i>100°-102°</i>	101° <i>100-103°</i>	100° <i>99-101°</i>	104° <i>102-106°</i>	102° <i>102-103°</i>	102° <i>102-104°</i>	101° <i>101-103°</i>
Extreme years									
Average daily high in Jun-Jul-Aug	90°	92° <i>90-95°</i>	91° <i>89-93°</i>	92° <i>89-93°</i>	91° <i>89-92°</i>	94° <i>92-97°</i>	92° <i>91-95°</i>	94° <i>91-96°</i>	93° <i>90-94°</i>
Number of days 100° or hotter	5	11 <i>6-23</i>	9 <i>4-17</i>	9 <i>5-17</i>	7 <i>5-10</i>	25 <i>13-47</i>	19 <i>8-26</i>	16 <i>7-27</i>	10 <i>6-16</i>
Longest stretch of 100°-plus days	5	7 <i>4-9</i>	6 <i>4-11</i>	7 <i>5-8</i>	6 <i>4-7</i>	11 <i>6-19</i>	10 <i>6-14</i>	9 <i>4-14</i>	6 <i>5-11</i>
Number of days 95° or hotter	22	37 <i>25-58</i>	32 <i>21-42</i>	32 <i>22-43</i>	26 <i>16-39</i>	55 <i>45-75</i>	42 <i>35-54</i>	50 <i>33-65</i>	39 <i>28-47</i>
Avg high temp of yr's 30 hottest days	99°	100° <i>98-102°</i>	99° <i>97-101°</i>	99° <i>98-102°</i>	99° <i>97-100°</i>	102° <i>100-105°</i>	102° <i>100-103°</i>	101° <i>99-103</i>	101° <i>98-102°</i>
High temperature of hottest day	104°	106° <i>104-108°</i>	104° <i>103-107°</i>	105° <i>102-108°</i>	104° <i>103-107°</i>	108° <i>104-111°</i>	107° <i>104-108°</i>	107° <i>104-110°</i>	107° <i>103-110°</i>

Table 2 (continued on next page). Daily high temperatures for the Denver metro area. On the left, for context, actual values for 1970-1999 from the Stapleton Airport weather station.²⁶ On the right, projections from downscaled global climate models for the indicated time periods and for four emission scenarios (identified on page 3).²⁷ The values for typical years in the top half of the table are of annual averages across all years in a particular time period. The values for extreme years in the bottom half of the table are for the hottest individual years in the periods. For the projections, the top row is the median of the projections from all climate models for that emissions scenario, and the second row (in italics) shows the range of the middle 80 percent of those projections.

Daily high temperatures in Denver area

Continued

Projections with Different Emission Levels

	2060–2079				2080–2099			
	High	Med. #1	Med. #2	Very Low	High	Med. #1	Med. #2	Very Low
Typical years								
Average daily high in Jun-Jul-Aug	94° 92–97°	91° 89–93°	91° 89–93°	89° 88–91°	97 95–101°	93° 91–95°	91° 89–94°	89° 87–91°
Number of days 100° or hotter	18 10–34	6 3–13	6 3–9	2 1–4	34 22–65	12 5–25	5 3–13	1 1–3
Consecutive 100°-plus days in yr	6 3–15	3 1–6	3 2–4	1 1–2	13 7–30	5 2–8	3 2–5	1 1–2
Number of days 95° or hotter	56 40–75	35 21–52	33 21–46	19 12–25	77 62–98	46 33–66	31 23–54	17 11–26
Avg high temp of yr's 30 hottest days	102° 100–104°	100° 97–101°	99° 97–101°	97° 96–99°	104° 103–108°	101° 99–103°	99° 98–102°	97° 96–99°
High temperature of hottest day	106° 105°–109°	104° 102°–105°	103° 102–105°	102° 101–103°	109° 108–113°	105° 103–108°	104° 102–106°	102° 101–103°
Extreme years								
Average daily high in Jun-Jul-Aug	98° 94–101°	95° 92–97°	94° 91–97°	92° 90–94°	100° 97–105°	96° 93–98°	94° 92–97°	92° 90–94°
Number of days 100° or hotter	44 26–70	27 12–42	20 12–35	13 7–23	72 55–96	34 20–60	24 14–39	8 7–23
Consecutive 100°-plus days in yr	19 14–38	11 8–22	11 7–17	8 6–12	38 23–75	15 9–25	12 7–17	6 5–11
Number of days 95° or hotter	80 65–98	59 47–75	51 34–71	39 24–52	99 78–127	74 51–88	56 42–76	38 27–50
Avg high temp of yr's 30 hottest days	105° 102–109°	102° 101–105°	102° 100–104°	101° 99–103°	109° 106–113°	104° 102–107°	102° 100–105°	100° 99–103°
High temperature of hottest day	110° 108–114°	107° 104–111°	108° 105–112°	107° 105–108°	113° 112–118°	109° 108–114°	108° 105–111°	106° 105–108°

Projections of Low Temperatures

This analysis of climate projections also considered changes in daily low temperatures, typically occurring in the nighttime. Changes in nighttime temperatures can be important for several reasons, including that Colorado’s cool nights have historically provided a break from daytime highs and reduced the health and other impacts of heat waves.²⁸

As Table 3 below (and on the next page) shows, the climate models project that nighttime low temperatures will not increase in the Denver area by quite as much as daytime high temperatures. With high emissions, for example:

- In mid-century, the average temperature of the 30 hottest nights in a year in the Denver area is projected to increase by 4° (3° to 6°) beyond 1967–1999 actual values. For the average high temperature of the 30 hottest days, the projected increase is 6° (5° to 8°).
- Late in the century, the average of the 30 hottest nights is projected to increase by 9° (6° to 12°) compared to 1967–1999, and the 30 hottest days by 11° (10° to 15°).

Nighttime low temperatures in Denver area

	1967-99 Actual	Projections with Different Emission Levels							
		2020–2039				2040–2059			
		High	Med. #1	Med. #2	Very Low	High	Med. #1	Med. #2	Very Low
Typical years									
Average nighttime lows in Jun-Jul-Aug	56°	59° 57–60°	58° 57–59°	58° 57–59°	58° 57–59°	60° 59–62°	59° 58–60°	60° 58–61°	59° 57–60°
Avg temp of year's 30 hottest nights	62°	64° 63–65°	64° 63–64°	64° 63–65°	64° 63–65°	66° 65–68°	65° 64–65°	65° 64–66°	64° 63–65°
Temperature of year's hottest night	67°	68° 68–69°	68° 67–69°	68° 67–69°	68° 67–69°	70° 69–72°	69° 68–70°	69° 68–71°	68° 67–70°
Days in year's frost-free growing season*	153	167 158–175	169 165–172	166 159–173	170 158–173	174 166–186	172 167–177	170 163–181	166 161–184
Extreme years									
Average nighttime lows in Jun-Jul-Aug	60°	62° 60–63°	60° 60–61°	61° 60–62°	61° 60–62°	63° 62–65°	61° 60–63°	62° 61–64°	61° 60–63°
Avg temp of year's 30 hottest nights	65°	68° 66–70°	67° 66–68°	68° 66–69°	68° 67–68°	70° 68–72°	68° 67–69°	69° 68–71°	68° 66–70°
Temperature of year's hottest night	71°	72° 70–74°	71° 69–72°	71° 70–74°	72° 70–73°	74° 72–76°	73° 70–74°	73° 72–75°	72° 71–73°
Days in year's frost-free growing season*	175	190 169–210	189 184–201	190 168–195	189 168–201	198 184–210	193 185–197	196 174–216	192 171–211

Table 3 (continued on next page). As Table 2, but with respect to daily low temperatures (typically occurring in the nighttime).

*For the frost-free growing season, the baseline actual values are for 1970–1999 and are from an observed/gridded dataset; see the Methodology discussion on page 18.

One impact of a changing climate associated with changes in nighttime low temperatures is a change in the length of the growing season for many plants—that is, in the number of days in a year that are frost-free, with nighttime temperatures staying above 32°. As shown in Table 3:

- The Denver area’s growing season averaged 153 days in 1967–1999.
- With high future emissions, the growing season in the Denver area could average 174 days (166 to 186 days) in the middle of the century, and 195 days (181 to 215 days) late in the century.
- With very low future emissions, the growing season is projected to instead average 166 days (161 to 184 days) in mid-century and 168 days (158 to 180 days) late in the century.

Nighttime low temperatures in Denver area

Continued

	Projections with Different Emission Levels							
	2060–2079				2080–2099			
	High	Med. #1	Med. #2	Very Low	High	Med. #1	Med. #2	Very Low
Typical years								
Average nighttime lows in Jun-Jul-Aug	63° 61–65°	60° 59–61°	60° 58–62°	58° 57–60°	65° 63–69°	61° 60–63°	60° 59–63°	58° 57–60°
Avg temp of year’s 30 hottest nights	68° 67–71°	66° 65–67°	66° 64–67°	64° 63–65°	71° 68–74°	66° 65–68°	66° 64–68°	64° 63–66°
Temperature of year’s hottest night	73° 71–75°	70° 69–71°	70° 68–72°	68° 67–70°	75° 73–78°	71° 70–72°	70° 69–72°	68° 67–70°
Days in year’s frost-free growing season	184 173–197	172 169–187	173 169–188	170 159–178	194 181–215	181 172–192	174 163–192	168 158–180
Extreme years								
Average nighttime lows in Jun-Jul-Aug	66° 64–69°	63° 62–64°	63° 61–65°	61° 59–63°	69° 66–72°	63° 62–65°	63° 62–65°	61° 60–63°
Avg temp of year’s 30 hottest nights	73° 70–76°	69° 68–71°	69° 68–72°	67° 66–70°	76° 73–79°	70° 69–72°	70° 68–72°	68° 66–70°
Temperature of year’s hottest night	77° 75–79°	74° 72–75°	73° 72–75°	72° 69–74°	79° 77–81°	74° 73–76°	73° 72–76°	73° 69–75°
Days in year’s frost-free growing season	200 191–222	198 188–215	197 180–211	188 169–207	220 203–247	210 190–219	195 180–237	193 173–213

3. CONCLUSIONS

Many conclusions can be drawn from the data presented in this report, including the following.

First, there already has been an increase in extreme heat in the Denver area. An example is that the frequency of 100°-plus days at the Stapleton Airport weather station has increased from 0.7 day per year in 1967–1999 to 1.8 days per year in the first 17 years of this century.

Second, climate models are consistent in projecting additional further increases in extreme heat. Depending on the levels of future emissions of heat-trapping pollution, those increases may far surpass those that have already occurred, especially in the middle of the century and beyond.

For 2020–2039, the first of the four 20-year periods that were analyzed, the projected increases differ relatively little based on different emission scenarios. For example, for all four scenarios, the median projections are that typical summers will have average high temperatures of 88° or 89°, and will average one or two days per year that are 100° or hotter.

Later in the century, though, as the scenarios differ more in their assumed atmospheric concentrations of heat-trapping gases, the temperature projections also vary more, with higher emissions leading to more extreme heat. These differences are greater late in the century, when the scenarios have diverged the most.

In the middle of the century (2040–2059) for typical years:

- With continued high emissions, the projections are for seven (three to 13) 100°-plus days.
- With very low emissions, the projections are instead for only two (one to three) such days.

Near the end of the century (2080–2099):

- With high emissions, typical years are projected to average 34 (22 to 65) 100°-plus days.
- With very low emissions, there could instead be only one (one to three).

Even more important may be the projections for *extreme* years, not typical years. Projections for the hottest individual year in mid-century are:

- With high emissions, the extreme year would have a total of 25 (13 to 47) 100°-plus days, and its longest heat wave would have 11 (six to 19) straight days of 100° or hotter.
- With very low emissions, the projections are instead for a total of 10 (six to 16) 100°-plus days.

The hottest year late in the century:

- With high emissions, would have a total of 72 (55 to 96) 100°-plus days, and its longest heat wave would have 38 (23 to 75) straight days of 100° or hotter.
- With very low emissions instead, the hottest year instead could have a total of eight (seven to 23) 100°-plus days.

The Denver area's projected increases in extreme heat show how much it matters locally whether global heat-trapping emissions continue increasing or are reduced enough to head off the worst possible impacts of climate change. What is at stake is whether the local climate remains similar to what we have long enjoyed here, or becomes fundamentally altered.

The projections also underscore the need for preparedness actions to address the possible impacts of extreme heat. It is not the purpose of this report to document the impacts of more extreme heat, but they clearly could be profound. Heat waves can cause misery and mortality, especially in areas like Denver where many homes are not air conditioned.²⁹ Other impacts could include increased energy costs for cooling buildings, loss of outdoor recreation when temperatures exceed what people can tolerate, increased water demands for irrigating crops and lawns, and loss of urban trees and landscape plantings that cannot survive in extreme heat.³⁰ Preparedness actions taken now, though, can reduce the short-term risks that already loom and lay the foundation for tackling the greater risks that could follow.³¹

4. METHODOLOGY

Climate projections

The climate projections used in this analysis were obtained from an online archive created by a consortium of partners: the U.S. Bureau of Reclamation, Climate Analytics Group, Climate Central, Lawrence Livermore National Laboratory, Santa Clara University, Scripps Institution of Oceanography, U.S. Army Corps of Engineers, U.S. Geological Survey, and National Center for Atmospheric Research and maintained on a website operated by Santa Clara University.³² The Rocky Mountain Climate Organization acknowledges and expresses appreciation to those collaborating organizations responsible for the online archive and also to the World Climate Research Program's Working Group on Coupled Modelling and the climate modeling groups for producing and making available their model output, and the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison and the Global Organization for Earth System Science Portals for their additional support with respect to the latest generation of models, which we used in this analysis.

The projections RMCO obtained are of daily climate values for maximum temperatures, minimum temperatures, and precipitation amounts from the latest generation of climate models, known as CMIP5 models, downscaled to produce results for grids 1/8 of a degree of longitude by 1/8 of a degree of latitude. RMCO obtained and averaged the projections for four such grids, comprising the area indicated in Figure 1 on page 2. The projections obtained are from the first listed ensemble from each available climate model for each emissions scenario—20 models for the high emission scenario (officially known as Representative Concentration Pathway, or RCP, 8.5); 12 for the medium #1 scenario (RCP 6.0); 19 for the medium #2 scenario (RCP 4.5), and 16 for the very low scenario (RCP 2.6). (For an explanation of why we used these descriptions of the scenarios, see page 3.)

As mentioned on page 4, RMCO used what climate scientists commonly call the “delta method,” in which each model's projections for a future period are compared to its projections for a baseline period (in this case, 1970–1999), and the projected differences are added to actual values for the baseline period. Those actual values are from an observed/gridded dataset on the same archive, in which records from weather stations have been extrapolated to provide a historic baseline for each 1/8-degree grid, both to provide an observation-based baseline for the projections and to enable the downscaling to a local scale of projections from the global climate models. This delta approach effectively eliminates most biases from individual models (such as over- or under-estimating temperatures), according to the Western Water Assessment program at the University of Colorado, Boulder, which used the same approach in the climate projections it analyzed in *Climate Change in Colorado*.³³

For the projections for future precipitation in the Denver metro area, including an explanation of why they are not as reliable as the projections for temperature, see www.rockymountainclimate.org/extremes/denver.

Comparison of data sets

One way to assess the accuracy of climate models is to compare their retrospective projections for past years with actual observations for those years. Table 4 on the next page shows data from three different data sets for 1970–1999 for three illustrative temperature values. The three data sets are (1) the observed/gridded dataset described above; (2) the observation records of actual conditions at the Stapleton Airport weather station described on page 5; and (3) the averages of retrospective projections from the 20 models considered in this analysis. The retrospective projections from the models, being for historic conditions, are not in this case driven by any assumptions of future levels of heat-trapping emissions, so each model has one such set of projections, not multiple projections for different emissions scenarios.

Comparison of data sets for 1970–1999

	Gridded/ Observed	Weather Station	Climate Models
Daily high temperatures			
Average daily highs in June-July-August	85°	85°	85°
Average number of days per year with highs 100° or hotter	0.3	0.7	0.1
Average number of days per year with highs 95° or hotter	5	9	4
Average temperature of year's 30 hottest days	92°	93°	93°

Table 4. Comparison of selected temperature values for 1970–1999 for the Denver metro area: from the observed/gridded data set described on page 18, for the Denver area analyzed in this report, as shown in Figure 1 on page 3;³⁴ from the Stapleton Airport weather station;³⁵ and from average projections from all 20 climate models used for this analysis.³⁶

NOTES

1. City and County of Denver, *Climate Adaptation Plan* (Denver: Department of Environmental Health, City and County of Denver, 2014), https://www.denvergov.org/content/dam/denvergov/Portals/771/documents/Climate/Climate_Adaptation_Final%20with%20letter.pdf.
2. S. Saunders, T. Easley, and M. Mezger, *Future Climate Extremes in Boulder County and Future Climate Extremes in Larimer County* (Louisville, CO: Rocky Mountain Climate Organization (RMCO), 2016), <http://www.rockymountainclimate.org/extremes/boulder> and www.rockymountainclimate.org/extremes/larimer, respectively.
3. U.S. Bureau of Reclamation and others, “Downscaled CMIP3 and CMIP5 climate and hydrology projections,” http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/#Welcome. See also L. Brekke and others, 2013, “Downscaled CMIP3 and CMIP5 climate projections: Release of downscaled CMIP5 climate projections, comparison with preceding information, and summary of user needs,” http://gdodcp.ucllnl.org/downscaled_cmip_projections/techmemo/downscaled_climate.pdf.
4. J. Lukas and others, *Climate Change in Colorado: A Synthesis to Support Water Resources Management and Adaptation (Second Edition—August 2014)*, (Boulder: University of Colorado Boulder, 2014), report by Western Water Assessment, University of Colorado Boulder, to the Colorado Water Conservation Board, http://www.colorado.edu/climate/co2014report/Climate_Change_CO_Report_2014_FINAL.pdf.
5. For general information on the emissions scenarios, see Lukas and others (see previous note), pp. 41–43.
6. Lukas and others (see note 4), p. 41.
7. J. Walsh and others, “Chapter 2: Our changing climate,” in *Climate Change Impacts in the United States: The Third National Climate Assessment*, J. M. Melillo, T. C. Richmond, and G. W. Yohe, editors (Washington: U.S. Global Change Research Program, 2014), p. 30, http://s3.amazonaws.com/nca2014/high/NCA3_Climate_Change_Impacts_in_the_United%20States_HighRes.pdf?download=1.
8. Walsh and others (see previous note), pp. 26, 30; and Lukas and others (see note 4), pp. 41–43.
9. Figures provided by D. van Vuuren, University of Utrecht, and are the same as in D. van Vuuren and others, “The representative concentration pathways: an overview,” *Climatic Change*, vol. 109 (2011), pp. 5–31, <https://link.springer.com/article/10.1007/s10584-011-0148-z>.
10. Bureau of Reclamation and others (see note 3).
11. Lukas and others (see note 4), pp. 37–50.
12. Lukas and others (see note 4), p. 45.
13. Lukas and others (see note 4), p.45.
14. Data obtained from National Centers for Environmental Information, NOAA, “Daily observation data,” <http://gis.ncdc.noaa.gov/map/viewer/#app=cdo&cfg=cdo&theme=daily&layers=111&node=gis>.
15. National Centers for Environmental Information (see note 14).
16. National Centers for Environmental Information (see note 14).
17. National Centers for Environmental Information (see note 14).
18. Bureau of Reclamation and others (see note 3). See also E. P. Maurer and others, “A long-term hydrologically-based data set of land surface fluxes and states for the conterminous United States,” *Journal of Climate*, volume 5 (2002), pp. 3237–3251, <http://journals.ametsoc.org/doi/pdf/10.1175/1520-0442%282002%29015%3C3237%3AALTHBD%3E2.0.CO%3B2>.
19. National Centers for Environmental Information (see note 14).
20. Bureau of Reclamation and others (see note 3).
21. El Paso temperature data obtained from the Western Regional Climate Center, “Cooperative climatological data

- summaries: NOAA cooperative stations—temperature and precipitation,” <http://wrcc.dri.edu/climatedata/climsum/>.
22. Tucson temperature data from the Western Regional Climate Center (see previous note).
 23. D. Smith, “Tucson’s hot streak ends; 39 consecutive 100-degree days,” *Tucson Sentinel*, July 10, 2013, http://www.tucsonsentinel.com/local/report/071013_hot_streak/tucson-hot-streak-ends-39-consecutive-100-degree-days/.
 24. National Centers for Environmental Information (see note 14).
 25. Bureau of Reclamation and others (see note 3).
 26. National Centers for Environmental Information (see note 14).
 27. Bureau of Reclamation and others (see note 3).
 28. R. McKeown, “Chapter 10: Public health sector,” in *Colorado Climate Change Vulnerability Study*, E. Gordon and D. Ojima, editors, report to the Colorado Energy Office (Boulder: University of Colorado, Boulder, 2015), http://www.colorado.edu/climate/co2015vulnerability/co_vulnerability_report_2015_final.pdf.
 29. McKeown (see previous note).
 30. *Colorado Climate Change Vulnerability Study* (see note 28) and *Climate Change Impacts in the United States* (see note 7).
 31. Panel on Adapting to the Impacts of Climate Change, National Research Council of the National Academies, *Adapting to the Impacts of Climate Change* (Washington, DC: National Academies Press, 2010), http://www.nap.edu/download.php?record_id=12783#.
 32. Bureau of Reclamation and others (see note 3).
 33. Lukas and others (see note 4), p. 34.
 34. Bureau of Reclamation and others (see note 3).
 35. National Centers for Environmental Information (see note 14).
 36. Bureau of Reclamation and others (see note 3).