FUTURE CLIMATE EXTREMES IN BOULDER COUNTY

the
ROCKY
MOUNTAIN
CLIMATE
Organization

Stephen Saunders
Tom Easley
Melissa Mezger

September 2016

FUTURE CLIMATE EXTREMES
IN BOULDER COUNTY

By
Stephen Saunders, Tom Easley,
and Melissa Mezger

A report by the
Rocky Mountain Climate Organization

September 2016

the
ROCKY
MOUNTAIN
CLIMATE
Organization

the
ROCKY
MOUNTAIN
CLIMATE
Organization

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

RMCO works in partnership with local governments, especially through two programs we administer for local government members: the Colorado Climate Network, which supports local climate programs, especially those focused on climate-related risks and preparedness actions, and Colorado Communities for Climate Action, which advocates for state and federal policies to complement local actions to reduce heat-trapping emissions.

The Rocky Mountain Climate Organization
PO Box 270444, Louisville, CO 80027
303-861-6481
www.rockymountainclimate.org

Acknowledgements

The authors wish to thank for providing counsel, information, comments on a draft of this report, or other assistance in preparing this report: Katy Bigner, Environmental Services Department, City of Fort Collins; Nolan Doesken, Colorado Climate Center, Colorado State University; Taryn Finnessey, Colorado Water Conservation Board; Alexander Gershunov, Scripps Institution of Oceanography, University of California, San Diego; Richard Hackett, Boulder County Land Use Department; Lori Hodges, Office of Emergency Management, Larimer County; Amber Horrie, Boulder County Land Use Department; Brett KenCairn, Climate + Sustainability Division, City of Boulder; Jeff Lukas, Western Water Assessment, University of Colorado, Boulder; Kelly Mahoney, Earth Systems Research Laboratory, National Oceanic and Atmospheric Administration; Imtiaz Rangwala, Western Water Assessment; Garry Sanfacon, Boulder County Flood Recovery; Lucinda Smith, Environmental Services Department, City of Fort Collins; Brad Udall, Colorado Water Institute, Colorado State University; and Jim Webster, Wildfire Partners Program, Boulder County.

We also thank for their assistance throughout this project Tim Katers and Anne Miller, Division of Local Government, Colorado Department of Local Affairs.

Cover photos by Sergeant Wallace Bonner (top left), Cliff Grassmick (top right), and Boulder County Land Use Department (bottom).

Printed on 100% recycled paper

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Climate change is projected to lead to increases in extreme temperature and precipitation in Boulder County, according to a comprehensive analysis of projections from the latest climate models. A companion report presents a parallel analysis for Larimer County. These are the two counties that were most impacted by recent wildfire and flooding disasters that led to five federal disaster designations in 2012–2013. These analyses are intended to help local governments and others in those counties better understand and prepare for the increased risks of wildfire and flooding expected to come with further climate change.

This report and its Larimer County companion are based on the most detailed analyses yet of how climate change may drive increased extreme conditions in Colorado. Although focused on just two counties, the results can be useful to all Coloradans interested in the challenges our state faces from climate change-related risks.

Records from a long-standing weather station in the City of Boulder provide information on the extent of temperature changes over time and provide context for the projections of future changes that comprise the heart of this analysis. The weather station's records show that the average number of 95°-plus days in Boulder so far this century (11) is more than twice the average of the previous century (5), and that the frequency of those days has increased over time.

Boulder: Number of 95°-plus days per year, 1900–2016

Weather station observations

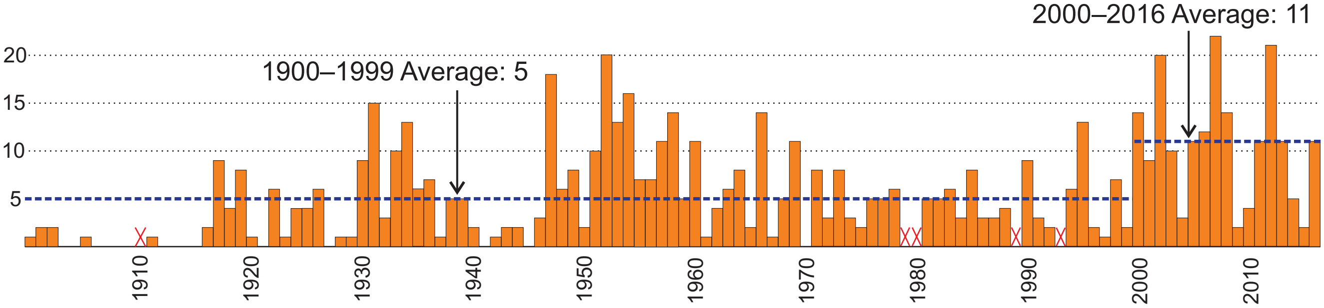


Figure ES-1. Days per year in Boulder with high temperatures of 95° or higher at Boulder's long-standing weather station. The years 1910, 1979, 1980, 1989, and 1993 have observations missing for more than 10 summer days and no counts for those years are shown or included in the averages. Days with highs of 95° or more averaged five per year in the previous century and 11 times a year in the first 17 years of this century. The trends (not shown graphically) over 100, 50, and 30 years are increases of 0.4, 1.5, and 2.3 days per decade, respectively.

In the first 17 years of this century, the frequency of 95°-plus days in Boulder has already doubled (to an average of 11), compared to the previous century (5).

Figure ES-2 on the next page shows projections of the future numbers of days per year with high temperatures of 95° or hotter in Boulder and vicinity, for four future 20-year time periods and for the four different scenarios of possible future heat-trapping emissions considered in this report.

Boulder and vicinity: Number of 95°-plus days per year

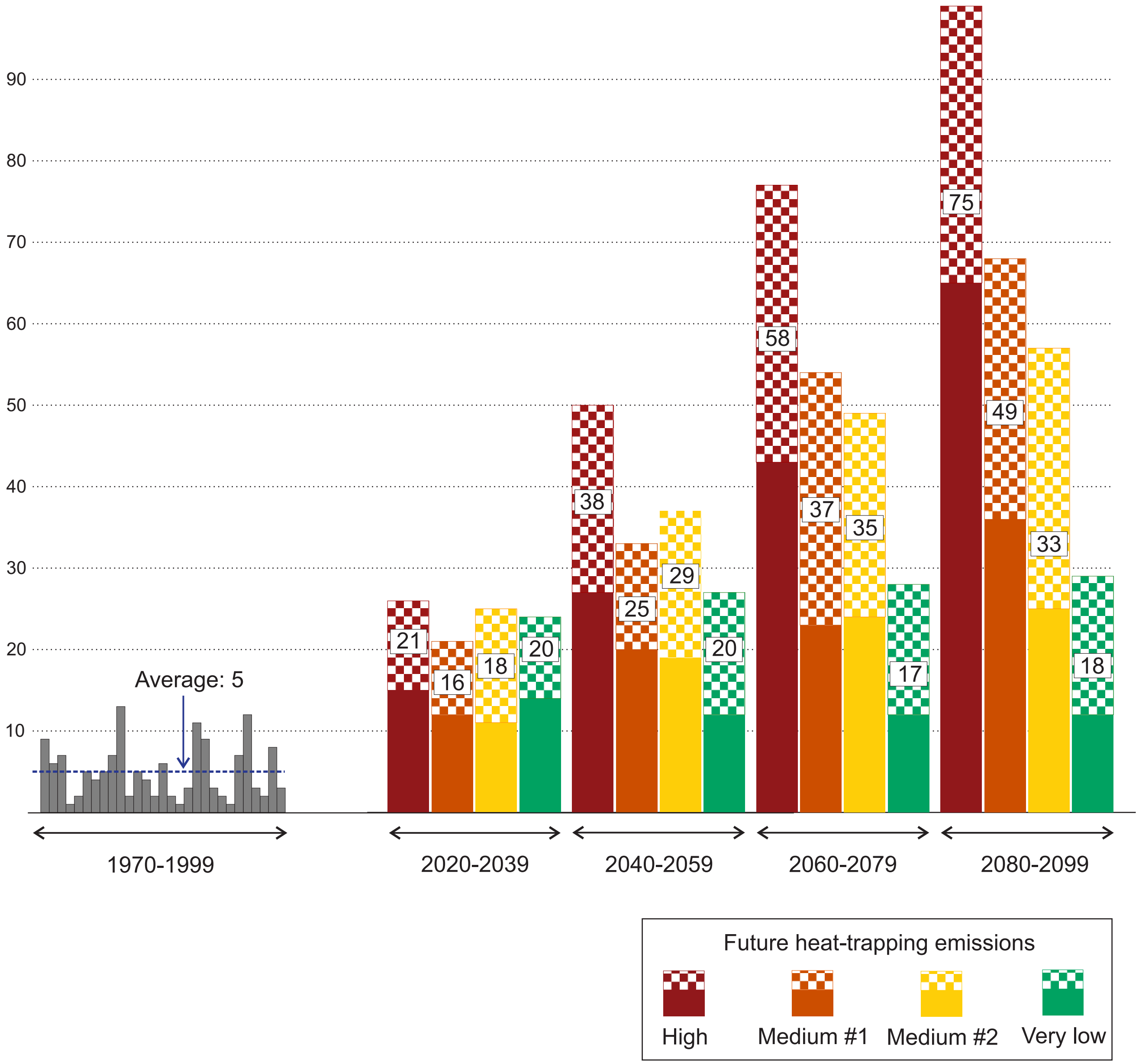


Figure ES-2. Number of days per year with daily highs of 95° and hotter in the Boulder and vicinity grid. The left side of the figure shows actual values for 1970–1999 from the gridded/observed dataset. The right side of the figure shows projections for four 20-year periods, and within each time period by emission scenario. For the projections, the checkered portions of the columns show the range from the 10th to the 90th percentiles of the available projections, and the numerals in the columns are the medians of the projections. The medium #1 scenario has lower emissions than the medium #2 scenario until about 2060, and then higher than medium #2; the projected changes in 95°-plus days shown here for these scenarios is consistent with their relative emissions.

With continued high increases in emissions, the median projections are that Boulder would average 38 days 95° or hotter per year by mid-century and 75 by late in the century.

Other results from the analysis of temperatures include the following for Boulder and vicinity, showing the medians of all projections and in parentheses the range from the 10th to the 90th percentiles, follow.

Days 100° or hotter:
- In recent years, almost never occurred.
- With high emissions, would occur on average 8 (4 to 20) times per year in mid-century and 35 (22 to 64) times late in the century.
- With very low emissions, would instead average twice a year (1 to 4 times) in both time periods.

The **30 hottest days a year**:
- In 1970–1999, averaged 93°.
- With high emissions, would average 99° (98° to 101°) in mid-century and 104° (102° to 108°) late in the century.
- With very low emissions, would instead average 97° (96° to 98°) then 97° (95° to 98°).

The median projection is that with high emissions in mid-century, July highs in Boulder would average 94°, 2° hotter than El Paso, Texas, in the recent past. By late in the century, July highs in Boulder would be 99°, approaching Tucson's recent average of 100.5°.

For precipitation, there is greater uncertainty in the projections from the models, for a variety of reasons. Still, the projections provide useful information. One of the strongest suggestions from the projections is that there could be a change in the frequency of heavy storms.

Projected frequencies were analyzed for storms of different intensity—routine wet days with less than a quarter-inch of precipitation in a day, and three categories of heavier storms: a quarter- to a half-inch, a half-inch to an inch, and an inch or more per day. The frequency of the routine wet days is projected to change only a little. The median projections from the models suggest that storms of 1/4 to 1/2 inch of precipitation in a day may have some increase in their frequency, storms of 1/2 inch to one inch, more of an increase, and those of an inch or more, the largest percentage increase in their frequency. By late in the century with the two scenarios assuming the highest emissions then, the median of the projections is for about a 50% increase in the frequency of the one-inch-plus storms.

Although there is uncertainty with the precipitation projections, the models suggest that with each step up in the intensity of heavy storms, the more their frequency could increase.

For summers in the Boulder County mountains, where temperatures are projected to increase (as elsewhere), precipitation amounts are projected to be relatively unchanged and perhaps to decrease. The models do not suggest the type of increase in summer precipitation that would be needed to offset the impacts of higher temperatures on ecosystems, especially increased wildfire risks.

Summers in this area, likely to be much hotter, also could be drier, further increasing wildfire risks.

1. INTRODUCTION

This report describes how climate change is projected to lead to increases in extreme temperature and precipitation in Boulder County.

The report, along with a companion effort focused on Larimer County,[1] were funded by the Colorado Department of Local Affairs's Community Development Block Grant–Disaster Recovery fund under the Resilience Planning program, using federal disaster recovery funds. These two counties were the most heavily affected by the four Colorado wildfires and the September 2013 flooding (which affected 19 counties in total) that led to five federal disaster designations in 2012–2013. The purpose of the reports is to help local governments in these two counties better understand and prepare for the increased risks of wildfire and flooding expected to come with further climate change.

This report and its Larimer County companion are based on the most detailed analyses yet of how climate change may drive increased extreme conditions in Colorado. Although focused on just two counties, the results can be useful to all Coloradans interested in the challenges our state faces from climate change-related risks.

What Colorado will be like in the future depends to a large degree on whether the recent trajectory of steadily increasing human emissions of heat-trapping pollution continues or if emissions are reduced. On the current emissions path, the median projections from 20 climate models are that Boulder by mid-century would average 38 days every year 95° or hotter, and by late century 75 days. By mid-century, the 30 hottest days a year could average 99°, and by late century 104°. This would be quite different from the climate we have known in this area, which has averaged only five 95°-plus days a year and an average temperature of 93° for the hottest 30 days in a year.

The good news is that we can avoid the worst of these extremes if global emissions are curtailed. Quick action to bring global emissions to very low levels would lead to some additional increases in temperature extremes by 2020–2039, but then no further increases in the rest of the century.

However, even if new actions are taken to reduce emissions and thereby dial back the extent of climate change, additional weather extremes in the near future could require new thinking and new actions to maintain local resilience. Taking new preparedness actions now will turn out to be especially important if near-term increases in extremes are followed by the greater changes this analysis shows are possible.

How this analysis is different

The analysis completed for this report uses projections from global climate models that have been downscaled to produce local results and were obtained from an online archive available to reseachers.[2] 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)*,[3] a report by Western Water Assessment (WWA) at the University of Colorado for the Colorado Water Conservation Board. This currently is the primary source on what climate change may look like in our state. In it, WWA reported that with a high level of future heat-trapping emissions, statewide average temperature would increase by mid-century by 3.5° to 6.5° Fahrenheit, compared to 1971–2000, or, with one possible intermediate emissions scenario (called medium #2 in this report—see the next page), by 2.5° to 5°. (The ranges in these projections are from the 10th percentile to the 90th percentile of the possible results identified by many climate models.)

The analysis presented in this report differs from that WWA report and other previous analyses in several ways.

- First and most importantly, this report analyzes projections from climate models of future temperatures and precipitation for each of the days for this century, as opposed to averages for multi-year periods. The projections for individual days have no particular meaning, but an analysis of all projected daily values over an extended period of time makes possible an understanding of what the climate models project for the extent and frequency of extreme conditions.

- Second, as is truly possible only by analyzing daily data, this analysis focuses on extreme conditions, not average conditions.
- Third, this report considers projections from all four current scenarios for future levels of heat-trapping emissions, which are described on the next page. These scenarios have been developed by scientists to represent the range of possible emissions levels, and considering all scenarios is the best way to appreciate the range of possible futures that can be driven by different future emissions.[4]
- Fourth, this analysis covers projections for the full 21st Century, with results presented for four 20-year time periods, showing what could happen both during the current planning horizon for local governments and over the lifetimes of today's school children and preschoolers. Focusing on just one or two time periods obscures how the dimensions of climate change may grow over time.

Geographic areas analyzed

The projections we obtained are for two grids of one-eighth of a degree of latitude by one-eighth of a degree of longitude, a rectangle 7 miles by 9 miles, with one grid in the Boulder County mountains and one for the City of Boulder and vicinity, as shown in Figure 1 below.

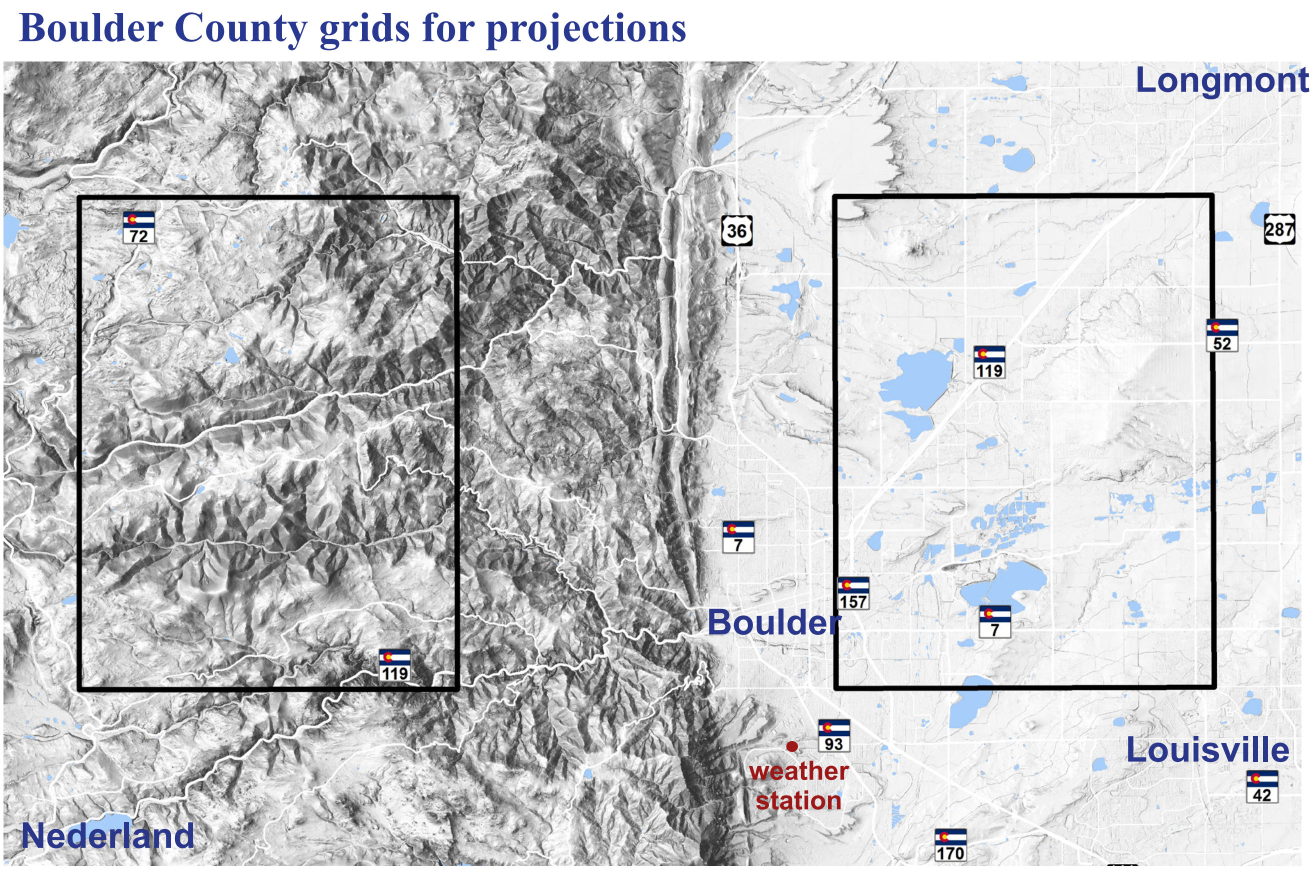


Figure 1. Boulder County grids for which climate projections were analyzed. The red dot shows the location of the weather station described on page 5. Map provided by Boulder County.[5]

Emissions scenarios

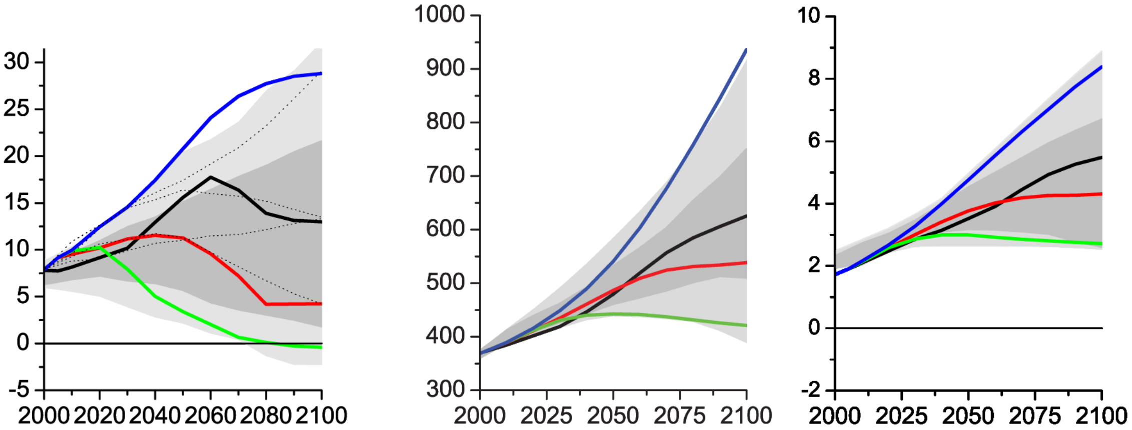
In modeling the future climate, assumptions about future levels of heat-trapping emissions are “in the driver’s seat” (to quote WWA)[6] because “emissions levels determine temperature rises” (now quoting the U.S. government’s Third National Climate Assessment).[7]

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

- What we call here the **high** scenario. Officially named Representative Concentration Pathway (RCP) 8.5, it assumes no reduction in the current trend of increasing emissions, and so can be considered a business-as-usual approach.
- A **medium #1** scenario. Officially known as RCP 6.0, it starts out with the lowest initial emissions levels of all scenarios but then sharply increases. After the 2060s, it leads to the second highest level of atmospheric concentrations of heat-trapping gases.
- A **medium #2** scenario, or RCP 4.5. It starts out with higher emissions than medium #1 but then has major reductions, especially after mid-century.
- A **very low** scenario, RCP 2.6. It assumes emissions cuts of more than 70% from current levels by 2050 and an elimination of net human emissions by about 2080. This would result in about 2.5°F of warming in this century.[8]

As shown in Figure 2 below, the two medium scenarios change their positions compared to each other during the century. Medium #1 starts out with lowest emissions of all. For a few decades it assumes lower emissions than medium #2 and leads to lower atmospheric concentrations of heat-trapping gases and so to less warming. After about 2060, the medium #1 scenario surpasses medium #2 on all those counts. This changing relative positions of these two scenarios is reflected in the local projections presented in this report. 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 about 50 years from now.

Scenarios of Future Heat-Trapping Emissions



A. Annual Emissions of Carbon Dioxide

B. Atmospheric Concentrations of Carbon Dioxide

C. Radiative Forcing

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, the radiative forcing, or the average warming at Earth’s surface, resulting from all heat-trapping pollutants, in watts per square meter at Earth’s surface. The blue lines represent the scenario called 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 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, and include one projection each from all available models with daily projections based on the different 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 both this report and the companion Larimer County report, 44 million individual projections of daily maximum and minimum temperatures and precipitation amounts were obtained, covering January 1, 1950–December 31, 2099, the four grids, and the 67 emissions scenario/climate model pairings. A projection of temperature or precipitation for a particular day does not have individual value, but enough of them over a sufficient period of time enables analysis of how often particular conditions are projected to occur in that period.

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). That report includes a thorough discussion of the climate models, 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.
- 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, including in periods with and without influence from human emissions of heat-trapping gases.

On this last point, see page 23 for examples of how retrospective projections from the models of local climate conditions for 1970–1999 match actual observations for that time.

Second, projections from different models often differ widely even with the same assumptions about future atmospheric concentrations of heat-trapping gases, reflecting scientific uncertainty on some key climate processes. The average of retrospective projections from all models is consistently more accurate in matching historic conditions than any single model, but the range of the projections should be emphasized in planning, as it captures current uncertainties about the future trajectory of the climate.

Third, despite recent improvements in climate models, they still exhibit particular biases, or systemic tendencies to over- or under-project certain climate aspects. For Colorado, the CMIP5 models used in this analysis, prior to any bias-correction, project a climate that is on average slightly cooler and considerably wetter than the state's observed climate. A simple "delta method" approach, as used by WWA for *Climate Change in Colorado* and by the Rocky Mountain Climate Organization for this report, can effectively cancel out much of this bias.

In the delta method, the output from a model for a future period of time is compared to its output for a historical period, leaving the model's projected difference—or delta—between the periods. For this report, each model's projected difference for each climate value was determined for each 20-year period for which results are presented, compared to that model's projection for 1970–1999. For temperature, that difference was then added to the historic value for the baseline period from the gridded observations described on the next page. For precipitation, results are presented simply as the percentage change in the modelled output for the future period compared to the baseline period. Both of these are common ways of presenting the data, and were also used by WWA in *Climate Change in Colorado.*

Fourth, for reasons summarized on pages 14–15, there are greater uncertainties with the precipitation projections presented here than for the temperature projections. The precipitation projections, much more than the temperature projections, should be taken just as plausible suggestions of future conditions.

All told, for this report and its Larimer County companion, 44 million projections of daily temperature and precipitation were analyzed.

2. TEMPERATURE EXTREMES

Our analysis of temperature extremes in Boulder County begins with the record of actual observations, obtained from the National Oceanic and Atmospheric Administration,[12] of extreme temperatures at Boulder's one long-standing weather station. This is both to determine the extent of any changes over time and to provide context for the projections of future changes that comprise the heart of this analysis.

Although this weather station has been in operation since 1893, it has been moved several times and has several years with significant missing data. It also is located outside the Boulder and vicinity grid used for the projections, as shown in Figure 1—at the base of the foothills on the west edge of the city, a location which could represent different climatic conditions (especially for precipitation) than in the grid. These factors make the station less useful for showing long-term trends and providing context for the projections. Still, as the only weather station close to either Boulder County grid and with sufficient observations for all but four years during the 1970–1999 baseline period used in this analysis, it offers the best weather station data to complement the temperature projections analyzed here.

Figure 3 below shows the weather station's records for the number of occurrences per year of days with high temperatures of 95° or higher. As the figure shows, the average number of 95°-plus days in Boulder so far this century (11) is more than twice the average of the previous century (5).

Boulder: Number of 95°-plus days per year, 1900–2016
Weather station observations

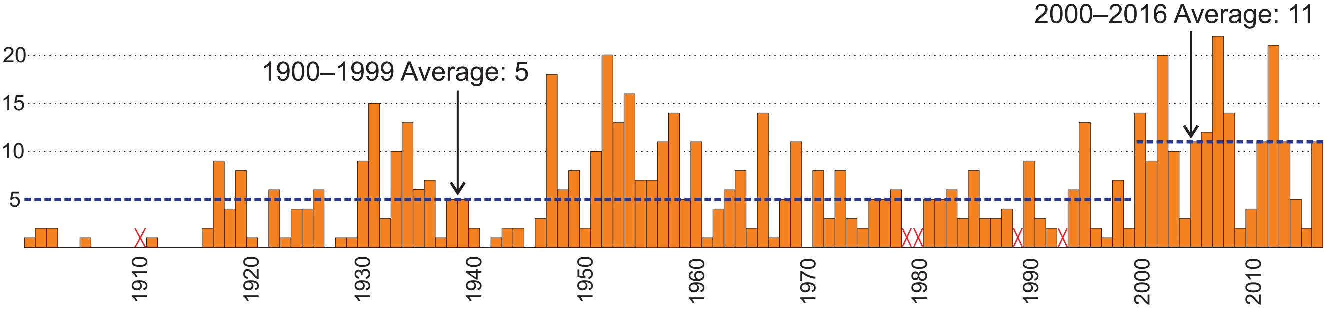


Figure 3. Days per year in Boulder with high temperatures of 95° or higher at Boulder's long-standing weather station. The years 1910, 1979, 1980, 1989, and 1993 have observations missing for more than 10 summer days, and no counts for those years are shown or included in the averages. Days with highs of 95° or more averaged five per year in the previous century and 11 times a year in the first 17 years of this century. The trends (not shown graphically) over 100, 50, and 30 years are increases of 0.4, 1.5, and 2.3 days per decade, respectively. The count for 2016 is through August 31.

In the first 17 years of this century, the frequency of 95°-plus days in Boulder has already doubled (to an average of 11), compared to the previous century (5).

Other data on extreme temperatures from this weather station are available online at www.rockymountainclimate.org/extremes.boulder.

Another source of temperature records is more consistent with the projections in this analysis— a data set of gridded observations from the same online database from which we obtained the projections.[13] This data set is derived from available records from the weather stations in an area, extrapolated to provide estimates of average daily temperatures and precipitation amounts across each 1/8 degree latitude-longitude grid in the country. The gridded observations for 1970–1999 are used as the baseline for our analysis, as this data covers the same grids used for the projections and includes values for all years in the baseline period. See page 23 for illustrative comparisons of temperature values for 1970–1999 from the long-standing Boulder weather station, from the gridded observations for the Boulder and vicinity grid, and from retrospective projections for that grid from the downscaled climate models.

The temperature projections obtained for this report were analyzed to identify future temperatures projected to occur with different levels of heat-trapping gases, for both average temperatures and a variety of measures of temperature extremes. For both averages and extremes, the models are generally consistent, especially from mid-century on, in showing that greater temperature increases would result from higher emissions, and lesser increases from lower emissions.

As one illustration, for **days with high temperatures of 95° or more** in Boulder and the vicinity, with the high emissions scenario:

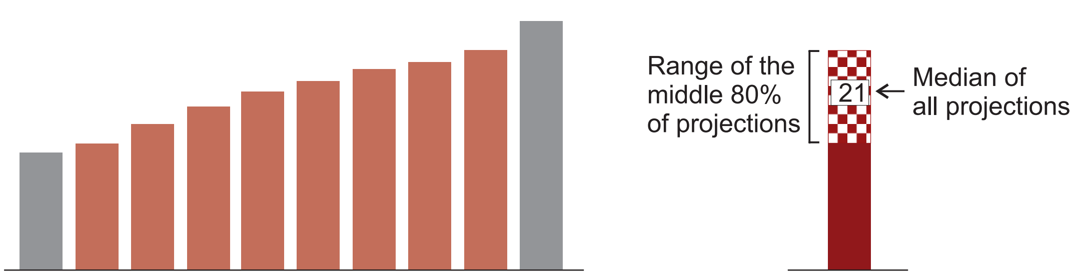
- The median projection is that those very hot days will occur an average of 21 times a year in 2020–2039. This would be another doubling of their frequency, compared to 2000–2016, using for those years the average frequency of these days at the Boulder weather station, as shown in Figure 3. (The gridded/observed data set does not include values for any years after 1999.)
- By mid-century (2040–2059), the median projection is for the frequency of 95°-plus days to nearly double again, to 38 times a year.
- By late century (2080–2099), the median projection is for the number of 95°-plus days to double yet again, to 75 times a year, equal to two and a half months a year of these days.

However, with reductions in the global levels of heat-trapping emissions, these increases in temperature extremes can be substantially reduced—especially if emissions are sharply reduced as reflected in the very low emissions scenario. With very low emissions, the median projection is that the frequency of 95°-plus days would not particularly increase any further after 2020–2039.

Figure 5 on the next page graphically illustrates these projections for 95°-plus days in Boulder and vicinity. To better understand this figure (and the next one, also dealing with temperatures), see Figure 4 below.

> In the recent past, Boulder averaged five days a year 95° or hotter. With continued high increases in emissions, the median projection is that Boulder would average 38 such days a year by mid-century and 75 by late in the century.

How the Figures Represent the Projections



Showing multiple projections . . .

In one summary column

Figure 4. Illustration of how individual projections (hypothetically here, 10 models) are represented in figures 5 and 6. For the summary column in the figures, the highest 10 percent and the lowest 10 percent of projections are not illustrated; the range of the remaining projections, the middle 80 percent, is shown by the checkered portion of the column. The median from all projections is shown by the numeral. The top of the solid portion of the column shows the value projected by 90 percent of all projections. The numerical values of the 10th percentile (the bottom of the checkered portion) and the 90th percentile (its top) are shown in Table 1.

Boulder and vicinity: Number of 95°-plus days per year

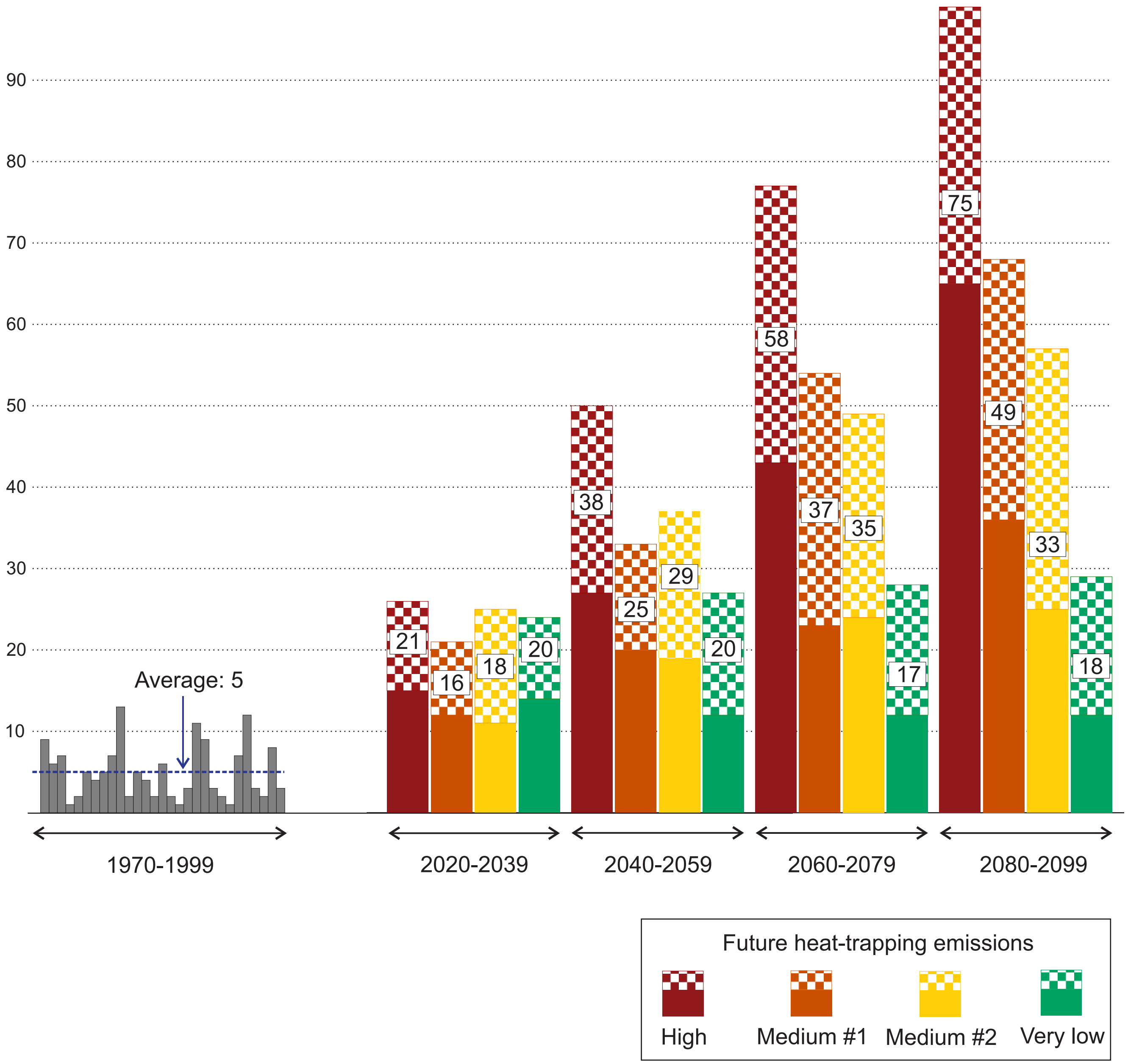


Figure 5. Days per year in the Boulder and vicinity grid with high temperatures of 95° or higher. The left side of the figure shows actual values for 1970–1999 from the gridded observations (see page 5). The right side of the figure shows projections for four 20-year periods, and within each time period by emissions scenario. As illustrated in Figure 4, for the projections, the checkered portions of the columns show the range from the 10th to the 90th percentiles of the available projections, and the numerals in the columns are the medians of the projections. The numerical values for the 10th and 90th percentiles are shown in Table 1 on pages 10 and 11. Note that, as shown in Figure 2 on page 3, the medium #1 scenario has lower emissions than the medium #2 scenario until about 2060, and then higher; the temperature projections shown here are consistent with their relative emissions.

The temperature projections correspond with levels of heat-trapping emissions. Higher emissions lead to greater projected temperature increases, and lower emissions lead to lesser increases.

Other projected increases in extreme temperatures in Boulder and vicinity are the following—presented as the medians of the relevant projections, with the 10th to the 90th percentiles following, in parentheses.

Days 100° or hotter:

- In recent years, almost never occurred.
- With high emissions, would average 8 times (4 to 20 times) a year in mid-century and 35 times (22 to 64 times) a year late in the century.
- With very low emissions, they would instead average twice a year (1 to 4 times) in both time periods.

The single hottest days of the year:

- Averaged 98° in 1970–1999.
- With high emissions, would typically reach 104° (103° to 106°) in mid-century and 109° (108° to 114°) late in the century.
- With very low emissions, would instead average 102° (100° to 103°) in mid-century and 102° (100° to 104°) late in the century.

The 30 hottest days a year (as illustrated in Figure 6 on the next page):

- In 1970–1999, averaged 93°.
- With high emissions, would average 99° (98° to 101°) in mid-century and 104° (102° to 108°) late in the century.
- With very low emissions, would instead average 97° (96° to 98°) then 97° (95° to 98°).

Table 1 on pages 10–11 presents the numerical values for the projections summarized above, which are also shown in figures 5 and 6, and for additional temperature values for the Boulder and vicinity grid. Table 2 on pages 12–13 presents similar temperature projections for the Boulder County mountains grid.

Two temperature values included in each of these tables show an extreme heat index used in a regional climate assessment of eight southwestern states (including Colorado) prepared as an input to the U.S. government's Third National Climate Assessment.[14] In our slightly modified version of this analysis, we calculated the number of degree-days per year by which projected daily high (or low) temperatures exceeded the threshold of the fifth hottest day (or night) of the year in 1970–1999. For the Boulder and vicinity grid, that threshold for daily high temperatures is 95.0°, and that for daily lows is 61.2°. In calculating degree-days above those thresholds, a day with a high temperature of 98° would represent 3 degree days, and a night with a low temperature of 65° would represent 3.8 degree-days.

For this **extreme heat index** for daily high temperatures in the Boulder and vicinity grid:

- In 1970–1999, the degree-days above the threshold averaged five per year.
- With high emissions, there would be 119 (71 to 181) such degree-days per year in mid-century and 393 (274 to 725) late in the century.
- With very low emissions, there would instead be an average of 49 (27 to 75) such degree-days in mid-century and 43 (28 to 71) in late century.

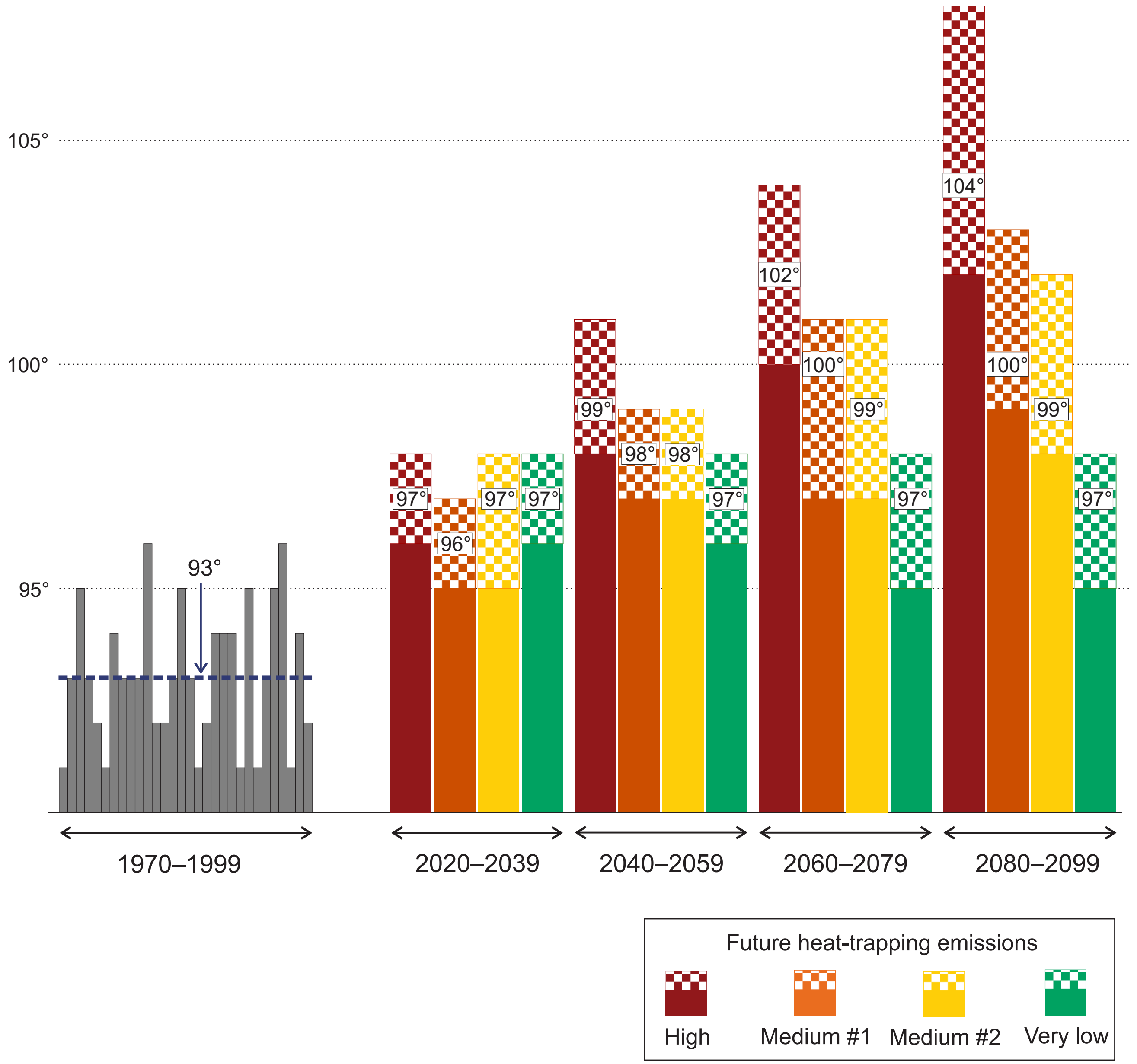
Data similar to the above are not available for other locations, but average high temperatures in July are, and our projections include monthly and seasonal temperatures (available at www.rockymountainclimate.org/extremes/boulder). With high emissions:

- **July highs** in Boulder in mid-century are projected to average 94° (92° to 96°), 2° hotter than the July average of El Paso, Texas, in 1970–1999.
- Boulder'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°.[15]

Turning to mountain temperatures, the **30 hottest days a year in the Boulder County mountains**:

- In 1970–1999, averaged 81°.
- With high emissions, would average 87° (86° to 89°) in mid-century and 92° (90° to 96°) late in the century.
- With very low emissions, would instead average 85° (83° to 86°) in both time periods.

With continued high emissions, Boulder's average July high temperatures are projected in mid-century to be 94°, 2° hotter than El Paso, Texas, in the recent past, and late in the century to be 99°, approaching Tucson, Arizona.



Boulder and vicinity: 30 hottest days in year
Average high temperatures

Figure 6. Average temperatures of the 30 hottest days per year in the Boulder and vicinity grid; otherwise as in Figure 5.

In the recent past, Boulder's 30 hottest days a year averaged 93°. With continued high increases in emissions, the median projection is that Boulder's 30 hottest days by mid-century would average 99°, and late in the century they would average 104°.

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

Boulder and vicinity: Temperature extremes

Actual values for 1970–1999 and projections with climate change

		Projections with Different Emission Levels							
	1970-99	2020–2039				2040–2059			
	Actual	High	Med. #1	Med. #2	Very Low	High	Med. #1	Med. #2	Very Low
Daily high temps									
Days/yr greater than/ equal to (>=) 95°	5	21 *15–26*	16 *12–21*	18 *11–25*	20 *14–24*	38 *27–50*	25 *20–33*	29 *19–37*	20 *12–27*
Days per year >= 100°	0	2 *1–4*	1 *1–3*	2 *1–3*	2 *1–3*	8 *4–15*	3 *2–8*	5 *3–9*	2 *1–4*
Temperature of year's hottest day	98°	102° *101-103°*	101° *100-102°*	101° *100-103°*	102° *100-102°*	104° *103-106°*	103° *102-104°*	103° *102-105°*	102° *100-103°*
Avg temp of year's 5 hottest days	96°	100° *99–101°*	99° *99–100°*	100° *99–101°*	100° *98–101°*	103° *101-105°*	101° *100-102°*	101° *100-103°*	100° *99-102°*
Avg temp of year's 30 hottest days	93°	97° *96–98°*	96° *95–97°*	97° *95–98°*	97° *96–98°*	99° *98–101°*	98° *97–99°*	98° *97–99°*	97° *96–98°*
Temperature of yr's 30th hottest day	89°	93° *92–94°*	93° *91–93°*	93° *92–94°*	93° *92–94°*	96° *94–97°*	94° *93–95°*	95° *93–96°*	93° *92–94°*
Degree-days per year above 95.0°[1]	5	52 *32–71*	33 *25–58*	44 *29–64*	45 *31–62*	119 *71–181*	62 *52–108*	85 *58–124*	49 *27–75*
Average daily high in Jun-Jul-Aug	85°	89° *88–90°*	88° *87–89°*	89° *87–90°*	89° *88–90°*	91° *90–93°*	90° *88–91°*	90° *89–92°*	89° *87–90°*
Daily low temps									
Temperature of year's hottest night	65°	68° *67–69°*	67° *66–68°*	68° *67–69°*	68° *67–69°*	71° *68–72°*	69° *68–70°*	69° *68–71°*	68° *67–69°*
Avg temp of year's 5 hottest nights	63°	66° *65–67°*	66° *64–66°*	66° *65–67°*	66° *65–67°*	69° *66–70°*	66° *66–68°*	68° *66–70°*	66° *65–68°*
Degree-days per year above 61.2°[1]	8	65 *36–89*	38 *21–75*	56 *33–74*	56 *36–74*	152 *78–231*	73 *49–128*	102 *51–151*	58 *31–100*
Average nightly low in Jun-Jul-Aug	54°	58° *56–59°*	57° *56–58°*	57° *56–58°*	57° *56–58°*	59° *58–61°*	58° *57–59°*	59° *57–60°*	57° *56–59°*
Nights per year below 32°	150	130 *121–138*	136 *130–140*	130 *126–139*	131 *123–137*	119 *106–130*	127 *118–134*	124 *114–134*	128 *119–136*

[1] These temperatures are the average fifth highest maximum and minimum temperatures, respectively, in 1970–1999.

Table 1 (continues on next page). Eight values representing extreme daily high temperatures (top rows) and five representing extreme daily low temperatures (bottom rows) for the Boulder and vicinity grid. The actual values for 1970–1990 in the first column are from the gridded/observed data set (see main body text on page 5). For each climate value, the single numeral in the top row is the median of the projections from all climate models for that emissions scenario, and the numerals in italics in the second row are the values of the 10th and 90th percentiles of those projections.

Boulder and vicinity: Temperature extremes

Continued

Projections with Different Emission Levels

	2060–2079				2080–2099			
	High	**Med. #1**	**Med. #2**	**Very Low**	**High**	**Med. #1**	**Med. #2**	**Very Low**
Daily high temps								
Days/yr greater than/ equal to (>=) 95°	58 *43–77*	37 *23–54*	35 *24–49*	17 *12–28*	75 *65–99*	49 *36–68*	33 *25–57*	18 *12–29*
Days per year >= 100°	19 *10–34*	7 *3–14*	7 *3–10*	2 *1–4*	35 *22–64*	13 *6–27*	6 *4–14*	2 *1–4*
Temperature of year's hottest day	107° *105–110°*	104° *103–106°*	104° *102–106°*	101° *100–103°*	109° *108–114°*	105° *104–108°*	104° *102–107°*	102° *100–104°*
Avg temp of year's 5 hottest days	105° *104–108°*	103° *101–104°*	102° *101–104°*	100° *98–102°*	108° *106–112°*	104° *102–106°*	102° *101–105°*	100° *98–102°*
Avg temp of year's 30 hottest days	102° *100–104°*	100° *97–101°*	99° *97–101°*	97° *95–98°*	104° *102–108°*	100° *99–103°*	99° *98–102°*	97° *95–98°*
Temperature of yr's 30th hottest day	98° *96–101°*	96° *93–98°*	96° *93–97°*	93° *91–95°*	100° *99–105°*	97° *96–99°*	96° *94–98°*	93° *92–95°*
Degree-days per year above 95.0°[1]	237 *147–399*	123 *62–181*	108 *64–155*	40 *25–66*	393 *274–725*	176 *108–308*	96 *72–202*	43 *28–71*
Average daily high in Jun-Jul-Aug	94° *92–97°*	91° *89–94°*	91° *89–93°*	89° *87–91°*	97° *95–101°*	93° *91–95°*	91° *90–94°*	89° *87–91°*
Daily low temps								
Temperature of yr's hottest night	73° *71–75°*	71° *68–72°*	70° *68–72°*	68° *66–70°*	76° *73–79°*	72° *69–74°*	70° *68–73°*	68° *66–70°*
Avg temp of year's 5 hottest nights	71° *69–74°*	69° *66–70°*	68° *66–70°*	66° *65–68°*	74° *71–77°*	70° *67–72°*	68° *66–71°*	66° *64–68°*
Degree-days per year above 61.2°[1]	276 *160–450*	158 *62–230*	130 *59–219*	46 *31–91*	493 *272–819*	216 *94–375*	131 *64–265*	46 *26–105*
Average nightly low in Jun-Jul-Aug	62° *60–64°*	59° *58–61°*	59° *57–61°*	57° *56–59°*	64° *62–68°*	61° *59–63°*	59° *58–62°*	57° *56–59°*
Nights per year below 32°	105 *86–119*	117 *106–129*	120 *107–132*	130 *118–137*	87 *68–107*	102 *94–121*	112 *103–130*	128 *117–136*

[1] These temperatures are the average fifth highest maximum and minimum temperatures, respectively, in 1970–1999.

If global heat-trapping emissions are reduced to very low levels, extreme temperatures generally would stop increasing after 2020–2039.

Boulder County mountains: Temperature extremes

Actual values for 1970–1999 and projections with climate change

		Projections with Different Emission Levels							
	1970-99	**2020–2039**				**2040–2059**			
	Actual	**High**	**Med. #1**	**Med. #2**	**Very Low**	**High**	**Med. #1**	**Med. #2**	**Very Low**
Daily high temps									
Days/yr greater than/ equal to (>=) 80°	14	42 *32–50*	36 *29–41*	41 *28–49*	42 *31–47*	61 *51–73*	49 *39–56*	54 *37–64*	40 *30–52*
Days per yr >= 90°	0	1 *0–2*	0 *0–1*	0 *0–1*	0 *0–1*	3 *1–6*	1 *0–3*	1 *1–3*	1 *0–2*
Temperature of year's hottest day	85°	90° *88–91°*	89° *88–90°*	89° *88–91°*	89° *87–90°*	92° *90–94°*	90° *90–91°*	90° *90–92°*	89° *88–91°*
Avg temp of year's 5 hottest days	84°	88° *87–89°*	87° *86–88°*	88° *86–89°*	88° *86–88°*	90° *89–92°*	89° *88–90°*	89° *88–91°*	88° *87–89°*
Avg temp of year's 30 hottest days	81°	85° *84°–86°*	84° *83°–85°*	84° *83°–86°*	85° *83°–85°*	87° *86°–89°*	86° *85°–87°*	86° *85°–87°*	85° *83°–86°*
Temperature of yr's 30th hottest day	77°	81° *80–82°*	80° *79–81°*	81° *79–82°*	81° *80–82°*	83° *82–85°*	82° *81–83°*	83° *81–84°*	81° *79–82°*
Degree-days per year above 82.8°[1]	9	55 *34–71*	35 *26–60*	45 *29–69*	49 *33–66*	123 *74–188*	68 *53–116*	83 *58–126*	51 *28–76*
Average daily high in Jun-Jul-Aug	73°	77° *76–78°*	76° *75–77°*	77° *75–78°*	77° *76–78°*	79° *78–82°*	78° *77–79°*	79° *77–80°*	77° *76–78°*
Daily low temps									
Temperature of year's hottest night	52°	56° *55–57°*	56° *54–57°*	56° *55–57°*	56° *55–57°*	59° *56–60°*	57° *56–58°*	57° *56–59°*	56° *55–58°*
Avg temp of year's 5 hottest nights	51°	55° *53–56°*	54° *52–54°*	54° *53–55°*	54° *53–55°*	57° *55–58°*	55° *54–56°*	56° *54–57°*	54° *53–56°*
Degree-days per year above 49.3°[1]	8	68 *37–99*	41 *22–79*	60 *33–75*	60 *37–76*	159 *80–243*	78 *47–135*	103 *51–164*	63 *34–104*
Average nightly low in Jun-Jul-Aug	42°	46° *44–47°*	45° *44–46°*	45° *44–46°*	45° *44–46°*	47° *46–49°*	46° *44–47°*	47° *45–48°*	45° *44–46°*
Nights per year below 32°	230	209 *201–218*	212 *206–221*	208 *204–216*	210 *199–216*	194 *184–205*	203 *196–210*	203 *194–213*	206 *196–214*

[1] These temperatures are the average fifth highest maximum and minimum temperatures, respectively, in 1970–1999.

Table 2 (continues on next page). As Table 1, but with respect to the Boulder County mountains grid.

Boulder County mountains: Temperature extremes

Continued

Projections with Different Emission Levels

	2060–2079				2080–2099			
	High	**Med. #1**	**Med. #2**	**Very Low**	**High**	**Med. #1**	**Med. #2**	**Very Low**
Daily high temps								
Days/yr greater than/ equal to (>=) 80°	80 *68–97*	60 *45–77*	58 *45–74*	39 *27–55*	96 *86–118*	73 *60–91*	59 *49–79*	39 *29–57*
Days per year >= 90°	7 *4–21*	2 *1–5*	2 *1–4*	0 *0–1*	20 *10–50*	5 *1–11*	2 *1–5*	0 *0–1*
Temperature of year's hottest day	94° *93–97°*	92° *90–93°*	91° *89–93°*	89° *87–91°*	97° *95–102°*	93° *91–95°*	92° *90–94°*	89° *88–91°*
Avg temp of year's 5 hottest days	93° *92–96°*	91° *89–92°*	90° *88–92°*	87° *86–89°*	95° *94–100°*	91° *90–94°*	90° *89–93°*	87° *86–90°*
Avg temp of year's 30 hottest days	89° *88–92°*	87° *85–89°*	87° *85–88°*	84° *83–86°*	92° *90–96°*	88° *87–91°*	87° *86–89°*	85° *83–86°*
Temperature of yr's 30th hottest day	86° *84–88°*	83° *81–85°*	83° *81–85°*	81° *79–82°*	88° *87–93°*	85° *83°–87°*	83° *82–86°*	81° *80–83°*
Degree-days per yr above 82.8°[1]	235 *152–398*	128 *66–186*	111 *65–157*	43 *26–69*	385 *271–757*	180 *111–285*	102 *75–207*	45 *29–76*
Average daily high in Jun-Jul-Aug	82° *80–85°*	79° *77–81°*	80° *77–81°*	77° *75–79°*	85° *83–89°*	81° *79–83°*	79° *78–82°*	77° *75–79°*
Daily low temps								
Temperature of yr's hottest night	61° *59–63°*	59° *56–60°*	58° *56–60°*	56° *54–57°*	63° *61–67°*	60° *57–62°*	58° *56–61°*	56° *54–58°*
Avg temp of year's 5 hottest nights	59° *57–62°*	57° *54–58°*	56° *54–58°*	54° *53–56°*	61° *59–65°*	58° *55–60°*	56° *54–59°*	54° *52–56°*
Degree-days per year above 49.3°[1]	275 *162–454*	161 *63–239*	131 *65–219*	49 *32–90*	475 *258–805*	229 *101–346*	136 *65–256*	49 *26–107*
Average nightly low in Jun-Jul-Aug	50° *48–52°*	47° *45–49°*	47° *45–49°*	45° *44–47°*	52° *49–55°*	49° *47–51°*	47° *46–50°*	45° *44–47°*
Nights per year below 32°	182 *165–196*	192 *184–205*	199 *184–207*	205 *196–217*	165 *146–183*	180 *172–198*	195 *181–206*	210 *195–215*

[1] These temperatures are the average fifth highest maximum and minimum temperatures, respectively, in 1970–1999.

3. PRECIPITATION EXTREMES

Our analysis of precipitation extremes began, as the temperature analysis did (see page 5), with consideration of the precipitation records from the long-standing Boulder weather station. However, in the 38 years from 1978 to 2016, this weather station has 11 years with at least 31 days with no recorded precipitation records, leading us to conclude that it could be misleading to report results on the frequency of precipitation extremes at the station. (By contrast, we excluded only five years from 1900–2016 from our analysis of extreme temperatures from the station's records, as for that purpose we were not concerned about missing data for days in seasons other than summer.) Instead, we repeat here a conclusion from Western Water Assessment's *Climate Change in Colorado* (see page 1), that the records from 12 long-standing weather stations in the state show no statistically significant trends over the past 30, 50, or 100 years for the frequency of extreme precipitation events.[16] Similarly, RMCO's companion report on Larimer County (see page 1) found that at the long-standing Fort Collins weather station, which has nearly complete records, there were no significant trends of changes in extreme precipitation over those periods for that station.

We obtained projections on future precipitation for both the Boulder and vicinity grid and the Boulder County mountains grid. In this report, we focus on the mountains grid, because precipitation in the mountains both is more important for influencing wildfire risks and generally is more responsible for flooding in downstream cities and towns than is precipitation in the plains. The changes projected for the Boulder and vicinity grid, which are similar to those for the mountains grid, are available online at www.rockymountainclimate.org/extremes/boulder.

For the precipitation projections, more caveats are in order than for the temperature projections. First, the climate models are more uncertain for precipitation than for temperature on regional scales, particularly in mid-latitude areas (such as Colorado) between northern areas where precipitation increases are clearly projected and sub-tropical areas where decreases are clearly projected.[17]

Second, model variations are even larger for small areas (like the grids analyzed here) than for large ones. As an example, the projections for statewide precipitation amounts for mid-century in *Climate Change in Colorado* range from a 3 percent decrease to an 8 percent increase (the 10th to the 90th percentiles of the projections) with the high emissions scenario, compared to 1971–2000.[18] For the smaller Boulder County mountains grid, the corresponding projections from the same climate models range from -4 to +14 percent, as shown in Table 3 on pages 20-21.

Third, climate models are more accurate in projecting overall precipitation amounts than extreme precipitation events, which by definition are relatively rare.[19] This is illustrated by the projections we obtained and analyzed for this report. Retrospective projections from the climate models match closely with the gridded observations on overall precipitation amounts, but the models do not project as many extreme precipitation events as actually occur. For the 1970–1999 frequency in the Boulder County mountains grid of storms with **half an inch or more precipitation**:

- the gridded observations indicate there were on average 9 such days per year, but
- the median retrospective projection from the climate models is only 4 per year.

For storms of **an inch or more**, the models are off by even more:

- the gridded observations show an average of 1.8 per year, and
- the median retrospective projection is only 0.6 per year.

As explained on page 4, the "delta" method of analyzing the projections helps to compensate for this weakness of the models, by focusing on the percentage change in the models' projected frequency of heavy storms in the future compared to their projections for the baseline period.

Fourth, today's climate models do not do a good job of simulating the North American monsoon and thunderstorms that drive much of Colorado's summer precipitation, making summer projections for this area more uncertain.[20]

Finally, for many of the precipitation projections presented here, there is not a clear relationship between the assumed atmospheric concentrations of heat-trapping gases, which differ in the different scenarios, and the extents of the projected changes, as there is with the temperature projections.

Even with these caveats, the projections provide useful information.

The projections suggest there could be a change in the frequency of heavy storms. Figure 7 on the two following pages shows the projections for storms of different intensity—routine wet days, with less than a quarter-inch of precipitation in a day, and three categories of heavier storms: a quarter- to a half-inch, a half-inch to an inch, and an inch or more per day. The frequency of the routine wet days is projected to change only a little. The median projections from the models suggest that storms of 1/4 to 1/2 inch of precipitation in a day may have some increase in their frequency, storms of 1/2 inch to one inch, more of an increase, and those of an inch or more, the largest percentage increase in their frequency.

Even the scenarios with lower emissions lead to projections of increases in heavy storms, so these projections do not show the same kind of pattern as the temperature projections show, in which the extent of future emissions clearly drives the extent of future temperature increases. Not until late in the century, when the different emissions scenarios represent substantially different atmospheric concentrations of heat-trapping gases, do the projected changes in frequency appear to clearly differ based on the assumed emissions levels. By late in the century with the two scenarios that assume the highest emissions then, the medians of both sets of projections are for about a 50% increase in the frequency of the one-inch-plus storms.

Although there is uncertainty with the precipitation projections, the models suggest that with each step up in the intensity of heavy storms, the more their frequency could increase.

These projections are generally consistent within the clear scientific consensus that across most of the United States heavy precipitation events have become heavier and more frequent, and with further climate change are expected to increase across the entire country, even in areas where total precipitation is expected to decline.[21] This is because of the basic principle of physics that warmer air can hold more moisture, and so higher temperatures should lead to more precipitation extremes.[22] WWA's *Climate Change in Colorado* report reviewed recent research covering Colorado and stated that heavy winter storms may follow the general trend toward increases, but not necessarily summer storms.[23]

Boulder mountains: Frequency of storms by intensity

Comparisons to 1970–1999

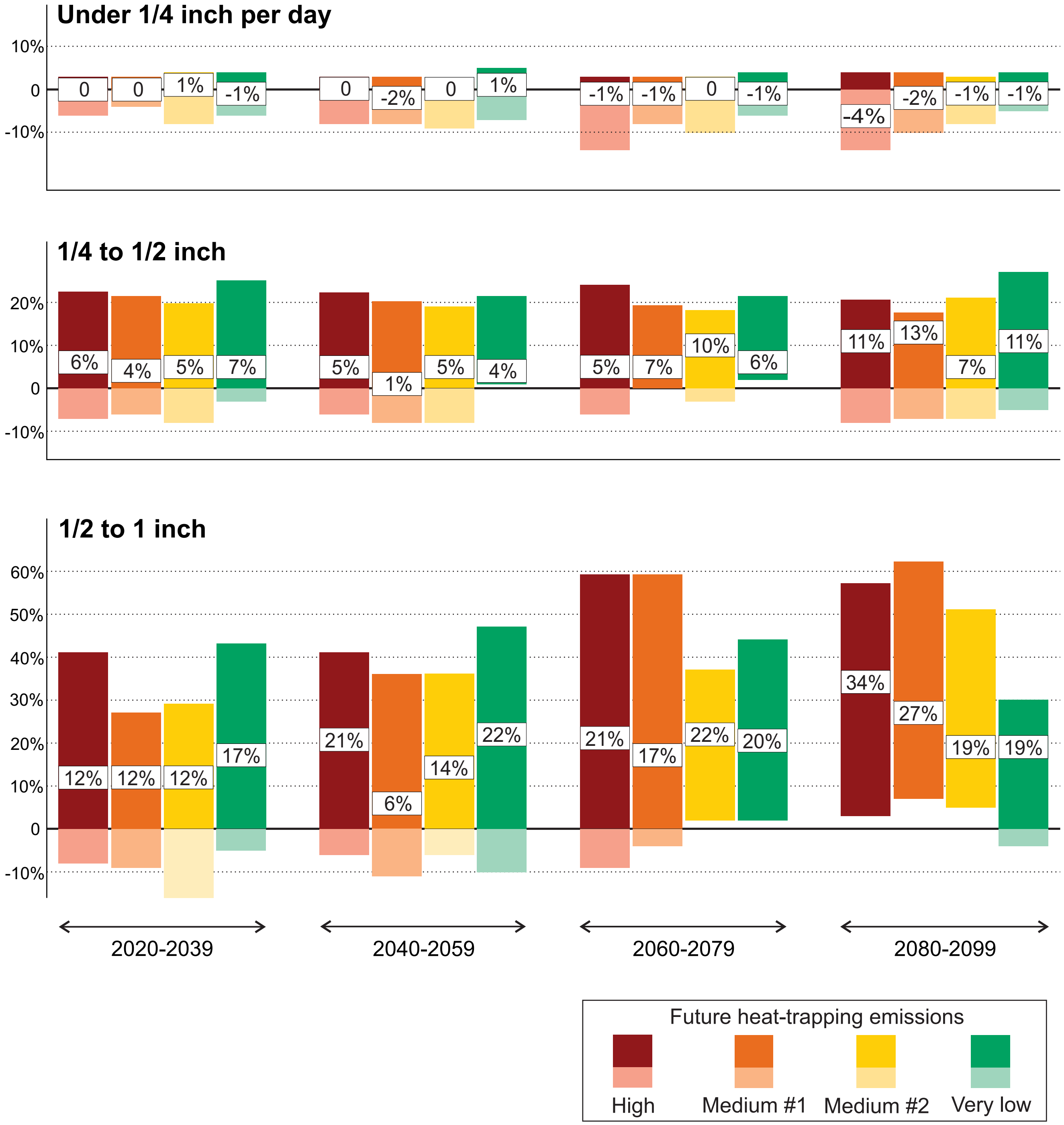
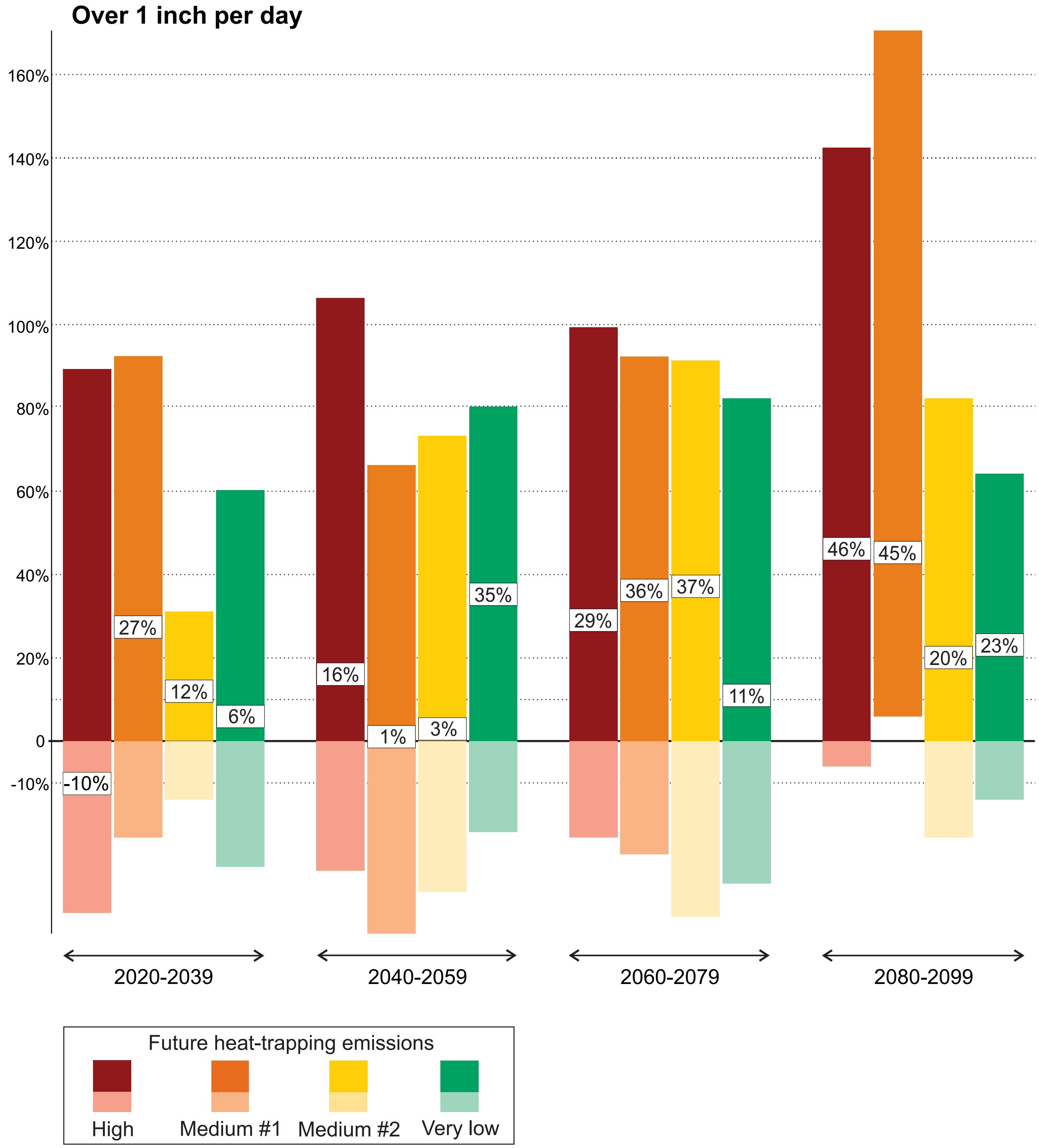


Figure 7 (continues on next page). Annual frequency of storms by size, in inches of precipitation per day, compared to average modeled values for 1970–1999 from all 20 climate models, in the Boulder County mountains grid. The columns represent the range of the middle 80 percent of projections, with darker colors representing projected increases and lighter colors projected decreases. The actual average frequencies of these storms in 1970–1999 were 137 days per year for days with less than 1/4 inch of precipitation, 18 days per year for storms with 1/4 inch or more but less than 1/2 inch, 7 days per year for storms with 1/2 inch or more but less than 1 inch, and 1.8 days per year for storms of 1 inch or more, according to the gridded/observed data (see main body text on page 5). For days with less than 1/4 inch, only those days with .01 inch or more of precipitation are counted.

Boulder mountains: Frequency of storms by intensity
Continued



In the following highlights of other precipitaton projections, the results are presented as the median of the projections, followed in parentheses by the 10th and the 90 percentiles of the individual projections. All are comparisons to modeled values for 1970–1999

Besides becoming more frequent, heavy storms may become more intense. That is, regardless of their frequency, the heaviest storms may produce more precipitation per day than in the past. Figure 8 on the next page shows that projected intensity of the three heaviest storms a year in the Boulder County mountain grid may increase, especially if emissions are high. For that scenario, the projections are for steps up in **the intensity of the three heaviest storms per year** over the century:

- In 2020–2039, a median projected increase of 2% (with projections ranging from a decrease of 7 percent to an increase of 14%);
- In 2040–2059, an increase of 5% (-3 to +17%);
- In 2060–2079, an increase of 8% (no change to +22%); and
- In 2080–2099, an increase of 11% (+4 to +30%).

For the overall amount of precipitation in a year, the models are considered more likely to be accurate. As shown in Table 3 on pages 20–21, the projections from individual models identify both increases and decreases, but the median projections across all time periods and for emissions scenarios are for increased precipitation. For the **amount of precipitation** in the Boulder County mountains grid:

- With high emissions, the amount per year is projected to change by a 5% increase (-4% to +14%) by mid-century and by an 8% increase (-6 to +19%) by late century.
- For the very low scenario, precipitation is projected to change by a 4% increase (-2 to +20%) by mid-century and a 6% increase (-3 to +15%) by late century.

However, for summer, precipitation amounts are projected to be relatively unchanged and perhaps to decrease. As pointed out above, summer precipitation projections for this area are less reliable than for other seasons. But the models do not suggest the type of increase in summer precipitation that would be needed to offset the impacts of higher temperatures on ecosystems, especially increased wildfire risks.[24]

Summer precipitation amounts in the mountains are projected to change:

- With high emissions, by a decrease of 1% (-16 to +11%) by mid-century and by a decrease of 5% (-28% to +20%) by late century.
- With very low emissions, by an increase of 2% (-1% to +10%) by mid-century and by an increase of 2% (-9% to +10%) by late century.

Summers in this area, likely to be much hotter, could
also be drier, further increasing wildfire risks.

Boulder County mountains: Changes in intensity of 3 heaviest storms per year
Comparisons to 1970–1999

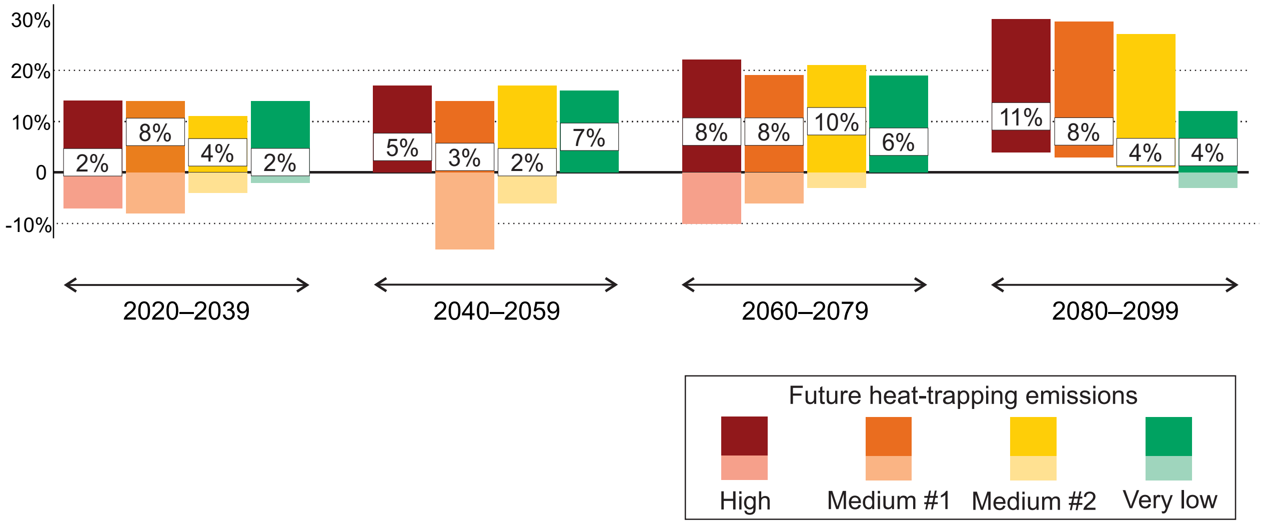


Figure 8. Projections of the average size of the three largest storms per year in the Boulder County mountain grid, compared to the average modeled value for 1970–1999. As in Figure 7, the columns represent the range of the middle 80 percent of projections, with darker colors representing projected increases and lighter colors projected decreases. The actual average size of these storms in 1970–1999 was 1.1 inches of precipitation in a day, according to the gridded observations.

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

Boulder County mountains: Changes in precipitation

Actual values for 1970–1999 and projected changes compared to 1970–1999

		Projections with Different Emission Levels							
	1970-99	2020–2039				2040–2059			
	Actual	High	Med. #1	Med. #2	Very Low	High	Med. #1	Med. #2	Very Low
Days w/ less than 0.25 in. precip	137	0% *-6/3%*	0% *-4/3%*	1% *-8/4%*	-2% *-6/4%*	0% *-8/3%*	-2% *-8/3%*	0% *-9/2%*	-2% *-7/5%*
Days w/ 0.25 in. to 0.5 in. precip	18	6% *-7/17%*	4% *-6/19%*	5% *-8/18%*	7% *-3/16%*	5% *-6/23%*	1% *-8/15%*	5% *-8/24%*	4% *1/22%*
Days w/ 0.5 in. to 1 in. precip	7	12% *-8/41%*	12% *-9/27%*	12% *-16/29%*	17% *-5/43%*	21% *-6/41%*	6% *-11/36%*	14% *-6/36%*	22% *-10/47%*
Days w/ 1 in. or more precip	2	-10% *-41/89%*	27% *-3/92%*	12% *-23/46%*	6% *-30/60%*	16% *-31/106%*	1% *-46/66%*	3% *-36/73%*	35% *-22/80%*
Days w/ 0.5 in. or more precip	9	9% *-11/42%*	19% *-8/27%*	15% *-14/31%*	15% *-7/44%*	16% *-8/48%*	3% *-15/42%*	15% *-7/41%*	22% *-11/52%*
Days w/ 0.5 in. or more, Dec-Jan-Feb	1.4	21% *-14/65%*	35% *-12/64%*	13% *-22/69%*	34% *-8/71%*	69% *-7/123%*	26% *-28/100%*	22% *-13/76%*	17% *-21/63%*
Days w/ 0.5 in. or more, Mar-Apr-May	4.1	3% *-21/44%*	18% *-8/36%*	16% *-13/41%*	13% *-7/61%*	18% *-18/47%*	10% *-12/41%*	7% *-15/44%*	17% *-2/54%*
Days w/ 0.5 in. or more, Jun-Jul-Aug	1.4	1% *-29/63%*	2% *-25/42%*	11% *-44/46%*	0% *-27/52%*	17% *-48/58%*	-16% *-37/30%*	11% *-41/50%*	18% *-33/76%*
Days w/ 0.5 in. or more, Sep-Oct-Nov	1.5	23% *-16/67%*	12% *-18/41%*	-6% *-29/28%*	15% *-28/48%*	12% *-39/62%*	-7% *-49/25%*	5% *-25/35%*	10% *-19/56%*
Precip in wettest day in year	1.4 in.	2% *-9/16%*	5% *-5/14%*	3% *-7/14%*	1% *-9/15%*	3% *-5–18%*	0% *-12/8%*	1% *-9/15%*	4% *-4/10%*
Avg precip in 3 wettest days in yr	1.1 in.	2% *-7/14%*	8% *-3/14%*	4% *-4/11%*	2% *-5/14%*	5% *-3/17%*	3% *-8/14%*	2% *-4/17%*	7% *-2/16%*
Precip amount in year	23.9 in.	5% *-3/12%*	4% *-1/9%*	1% *-2/9%*	4% *-3/14%*	5% *-4/14%*	1% *-4/13%*	1% *-5/14%*	4% *-2/20%*
Precip amount in Dec-Jan-Feb	4.7 in.	10% *-2/17%*	8% *-1/15%*	6% *0/18%*	7% *4/14%*	15% *2/24%*	9% *-1/20%*	6% *-3/16%*	6% *-2/18%*
Precip amount in Mar-Apr-May	8.7 in.	5% *-9/16%*	6% *-3/20%*	2% *-5/15%*	7% *-8/27%*	6% *-6/24%*	2% *-2/25%*	3% *-7/25%*	7% *-2/25%*
Precip amount in Jun-Jul-Aug	6.4 in.	0% *-11/11%*	1% *-6/4%*	-1% *-13/14%*	-1% *-7/7%*	-1% *-16/11%*	-3% *-7/0%*	-3% *-15/8%*	2% *-1/10%*
Precip amount in Sep-Oct-Nov	4.6 in.	5% *-10/12%*	1% *-6/8%*	-5% *-10/15%*	-1% *-6/11%*	-1% *-9/11%*	-5% *-10/7%*	2% *-6/11%*	1% *-10/16%*

Table 3 (continues on next page). Changes in precipitation in the Boulder County mountains grid, compared to average modeled values for 1970–1999 from all 20 climate models. As with tables 1 and 2, the actual values for 1970–1990 in the first column are from the gridded observations. For each climate value, the single numeral in the top row is the median of the projections from all climate models for that emission scenario, and the numerals in italics in the second row are the values of the 10th and 90th percentiles of those projections.

Boulder County mountains: Changes in precipitation
continued

	Projections with Different Emission Levels							
	2060–2079				**2080–2099**			
	High	**Med. #1**	**Med. #2**	**Very Low**	**High**	**Med. #1**	**Med. #2**	**Very Low**
Days w/ less than 0.25 in. precip	-1% *-14/3%*	-1% *-8/3%*	0% *-10/3%*	-1% *-6/4%*	-4% *-14/4%*	-2% *-10/4%*	-1% *-8/3%*	-1% *-5/4%*
Days w/ 0.25 in. to 0.5 in. precip	5% *-6/24%*	7% *0/19%*	10% *-3/23%*	6% *2/22%*	11% *-8/24%*	13% *2/25%*	7% *-7/25%*	11% *-5/27%*
Days w/ 0.5 in. to 1 in. precip	21% *-9/59%*	17% *-4/59%*	22% *2/37%*	20% *2–44%*	34% *3/57%*	27% *7/62%*	19% *5/51%*	19% *-4/30%*
Days w/ 1 in. or more precip	29% *-23/99%*	36% *-27/92%*	37% *-42/91%*	11% *-34–84%*	46% *-6/142%*	45% *6/158%*	20% *-23/82%*	23% *-14/64%*
Days w/ 0.5 in. or more precip	21% *-10/65%*	18% *-6/62%*	21% *0/42%*	15% *-2–50%*	36% *4/67%*	25% *8/68%*	19% *8/55%*	19% *-5/35%*
Days w/ 0.5 in. or more, Dec-Jan-Feb	52% *21/161%*	26% *-36/98%*	31% *-4/111%*	34% *-21–63%*	108% *55/207%*	48% *39/117%*	57% *10/111%*	38% *-8/92%*
Days w/ 0.5 in. or more, Mar-Apr-May	21% *-19/76%*	20% *-7/64%*	18% *-6/58%*	19% *-8/48%*	27% *0/61%*	26% *7/68%*	23% *-3/58%*	15% *-3/57%*
Days w/ 0.5 in. or more, Jun-Jul-Aug	-5% *-55/77%*	15% *-25/74%*	31% *-28/84%*	25% *-6/73%*	-5% *-49/109%*	15% *-54/77%*	18% *-29/70%*	0% *-36/37%*
Days w/ 0.5 in. or more, Sep-Oct-Nov	23% *-17/41%*	23% *-35/42%*	16% *-24/45%*	7% *-28/58%*	31% *-29/73%*	25% *-20/58%*	22% *-28/56%*	7% *-30/40%*
Precip in wettest day in year	6% *-4/22%*	6% *-7/18%*	8% *-5/22%*	4% *-8/20%*	9% *-1/30%*	8% *1/25%*	6% *-2/20%*	2% *-5/10%*
Avg precip in 3 wettest days in yr	8% *0/22%*	8% *-6/19%*	10% *-3/21%*	6% *-6/19%*	11% *4/30%*	8% *3/27%*	4% *1/20%*	4% *-3/12%*
Precip amount in year	6% *-5/19%*	4% *0/18%*	7% *-1/17%*	6% *0/16%*	8% *-6/19%*	11% *0/23%*	2% *-2/18%*	6% *-3/15%*
Precip amount in Dec-Jan-Feb	19% *3/30%*	11% *1/17%*	13% *3/24%*	8% *-3/18%*	28% *8/52%*	16% *6/23%*	12% *4/21%*	9% *0/20%*
Precip amount in Mar-Apr-May	6% *-12/26%*	9% *-8–35%*	7% *-4/24%*	9% *0/30%*	8% *-4/20%*	13% *-4/43%*	3% *-3/34%*	10% *-2/33%*
Precip amount in Jun-Jul-Aug	-4% *-22/7%*	0% *-7/13%*	2% *-12/19%*	3% *-5/10%*	-5% *-28/20%*	3% *-11/12%*	-1% *-12/16%*	2% *-9/10%*
Precip amount in Sep-Oct-Nov	2% *-17/11%*	-1% *-9/11%*	2% *-7/13%*	2% *-11/11%*	4% *-11/17%*	7% *-9/11%*	4% *-8/9%*	2% *-8/7%*

4. METHODOLOGY

Climate projections

The climate projections used in this analysis were obtained from the 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.[25] From this website, users can obtain archived downscaled projections of monthly or daily data from global climate models according to user-specified criteria including location, climate models, ensembles (individual model runs) from those models, and emissions scenarios. In addition to the collaborating organizations responsible for the online archive, we acknowledge 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, the "CMIP5" models, which we used in this analysis.

The projections the Rocky Mountain Climate Organization (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 1/8-degree latitude-longitude grids. 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 described on page 4, RMCO used what climate scientists commonly call the "delta method," in which each model's projections for a future period is compared to its projections for the baseline period (in this case, 1970–1999), and that projected difference is added to actual values for the baseline period, effectively eliminating most biases from individual models (such as over- or under-estimating temperatures or precipitation amounts). For temperatures, the projected differences were added to the actual values for the baseline period used in our delta calculations are from the gridded observations. For precipitation, results are presented in terms of the percentage change between the projections for future periods and retrospective projections for the baseline period.

Comparison of data sets

One way to assess the accuracy of climate models is to compare their retrospective projections for a historical period with actual observations for that period. Table 4 on the next page shows what three different data sets show as averages for 1970–1999 for three illustrative values each for temperature and precipitation. The three data sets are the gridded observations described on page 5, in this case for the Boulder and vicinity grid; the observation records from the Boulder weather station described on page 5; and the retrospective projections from the models considered in this analysis. As explained on page 5, the weather station is located outside the grid used for the other data sets and is at the edge of the foothills, which could lead to differences in local weather compared to the grid.

The comparison in Table 4 illustrates how the climate models under-represent extreme storms. According to the gridded observations data, Boulder and vicinity averaged five storms a year in 1970–1999 with half an inch or precipitation or more per day, and 0.9 with an inch or more. The median retrospective projections from the models are instead only half to a third as many per year, respectively.

Boulder: Comparison of data sets for 1970–1999

	Gridded/ Observed	**Weather Station**	**Climate Models**
Daily high temps			
Days/year greater than/equal to 95°	5	5	4 *2–6*
Avg temp of year's 30 hottest days	93°	92°	92° *91–93°*
Average daily high in Jun-Jul-Aug	85°	84°	86° *86–86°*
Precipitation			
Days/year w/ 0.5 in. or more precip	5	N/A[1]	3 *2–3*
Days/year w/ 1 in. or more precip	0.9	N/A[1]	0.3 *0.2–0.5*
Precip amount in year in inches	16	N/A[1]	16 *16–16*

[1] The precipitation data from the weather station have too many years with missing data for meaningful averages, as explained on page 14.

Table 4. Comparison of selected temperature and precipitation values for 1970–1999 for the Boulder area: from the gridded observations data set for the Boulder and vicinity grid; from the nearby long-standing Boulder weather station; and from projections by the climate models for the grid. 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 there are not multiple projections for different emissions scenarios.

Statistical significance

RMCO has generally not calculated the statistical significance of all the data presented in the figures and tables, as doing so would require redoing our analysis to convert hundreds of individual sets of projections from the 20-year averages reported here to annual series. Of several projections of particular climate values based on particular emissions scenarios, nearly all trends for 2000–2099 are statistically significant to a 95% confidence level. However, projections for the frequency of days with less than 1/4 of an inch of precipitation, shown in Figure 8, are not statistically significant for any of the four emissions scenarios.

NOTES

1. S. Saunders, T. Easley, and M. Mezger, *Future Climate Extremes in Larimer County* (Louisville, CO: Rocky Mountain Climate Organization (RMCO), 2016), at www.rockymountainclimate.org/extremes.larimer.

2. U.S. Bureau of Reclamation and others, "Downscaled CMIP3 and CMIP5 climate and hyrdrology projections," http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/#Welcome. See also U.S. Bureau of Reclamation, 2013, Downscaled CMIP3 and CMIP5 Climate Projections: Release of Downscaled CMIP5 Climate Projections, Comparison with Preceding Information, and Summary of User Needs, at http://gdodcp.ucllnl.org/downscaled_cmip_projections/techmemo/downscaled_climate.pdf.

3. J. Lukas and others, *Climate Change in Colorado: A Synthesis to Support Water Resources Management and Adaptation (Second Edition—August 2014)*, (Boulder: Universiry of Colorado Boulder, 2014), report by Western Water Assessment, University of Colorado Boulder, to the Colorado Water Conservation Board, http://wwa.colorado.edu/climate/co2014report/Climate_Change_CO_Report_2014_FINAL.pdf.

4. For general information on the emissions scenarios, see Lukas and others (see previous note) pp. 41–43.

5. Map provided by Amber Horrie, Land Use GIS Specialist, Boulder County Land Use Department.

6. Lukas and others (see note 3), p. 41.

7. On individual scenarios, see 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; and Lukas and others, pp. 41–43.

8. Walsh and others (see note 7), pp. 26, 30.

9. Figures provided by Detlef 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.

10. See note 2.

11. Lukas and others, pp. 37–50.

12. 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.

13. See note 2. 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.

14. A. Gershunov and others, "Chapter 7: Future climate: Projected extremes," in *Assessment of Climate Change in the Southwest United States: A Report Prepared for the National Climate Assessment*, G. Garfin and others, editors (Washington: Island Press, 2013), p. 130. In the original version of the extreme heat index described in this report, which is there called a heat wave index, the threshold for the calculation of degree-days is the 95th percentile of May to September maximum or minimum temperatures for the baseline period. The threshold used here, the average fifth hottest day of the year in the baseline period, is a similar but not identical value.

15. El Paso and Tucscon 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/.

16. Lukas and others, p. 34.

17. Walsh and others, p. 33. See also Lukas and others, p. 45.

18. Lukas and others, p. 64.

19. Gershunov and others, K. Mahoney and others, “High-resolution downscaled simulations of warm-season extreme precipitation events in the Colorado Front Range under past and future climates,” *Journal of Climate*, volume 26 (2013), pp. 8671– 8689.

20. Gershunov and others, pp. 134–135; Lukas and others, p. 45; Mahoney and others.

21. Walsh and others, pp. 36-37.

22. Gershunov and others, p. 133.

23. Lukas and others, p. 81.

24. J. M. Vose, D. L. Peterson, and T. Patel-Weynand, editors, *Effects of Climatic Variability and Change on Forest Ecosystems: A Comprehensive Science Synthesis for the U.S. Forest Sector* (Portland: U.S. Forest Service, 2012), p. 73.

25. See note 2.