Extreme Heat in Fort Collins

A report for the City of Fort Collins, February 2014

Fort Collins has had more hot days and heat waves this century than in earlier decades. With continued climate change, the forecast is for much more extreme heat, especially if future emissions of heat-trapping pollution are high. This illustrates what Fort Collins has at stake as humans change the climate and why reducing climate-changing pollution matters.

Trends in Hot Days and Heat Waves

The figure below shows the number of days per year 90° or hotter in Fort Collins since 1961. One measure of the change it shows is the linear trend—the straight line that statistical analysis identifies as the best fit for the data. The trend is an increase of 162 percent increase over 53 years, or of 3.8 such hot days

Single Days 90° or Hotter in Fort Collins, 1961–2013

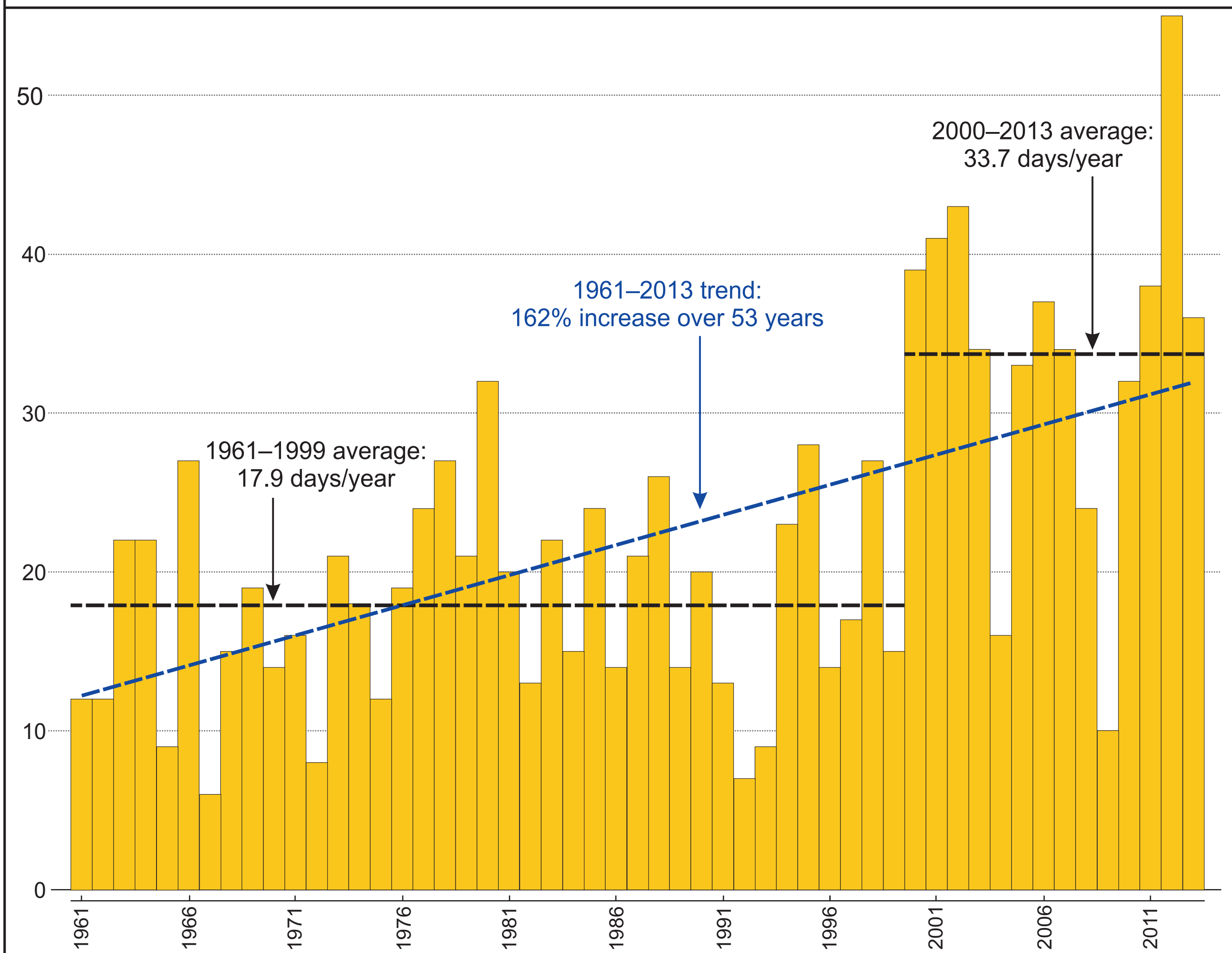

Figure 1. Number of days per year with maximum temperatures of 90° or hotter in Fort Collins, 1961–2013, showing averages for the 20th-century and 21st-century years in the period and the linear trend.

per decade. This trend is significant with more than a 99 percent confidence level, as are all such trends presented in this report.

Another way to express the change since 1961 is that the first 14 years of this century averaged 1.9 times as many 90° days per year as the previous 39 years did.

This information is from a new Rocky Mountain Climate Organization analysis of daily maximum temperatures records from a high-quality weather station at Colorado State University (CSU). The station is one of 24 in Colorado selected by the National Oceanic and Atmospheric Administration as part of the U.S. Historical Climatology Network, which is designed to assist in the detection of regional climate change. (See page 9 for information on this weather station and the analysis.)

The increase in hot days matters because of the impacts of extreme heat on human health and comfort, ecosystems, water resources, agriculture, and other resources and values. (See page 8.)

At the CSU weather station, for the 20th-century years covered by this analysis (1961–1999), days reaching 90° or more represent the top five percentile of all days. To measure trends in high temperatures, scientists sometimes analyze days above a certain temperature threshold and sometimes those in a certain percentile of occurrence.[1] In this case, 90° days and those in the hottest five percentile (using 1961–1999 as a baseline) are the same thing.

Also analyzed were the frequencies of three straight days at or above certain temperature levels. (Three straight days of 90° is one classic definition of a heat wave.[2]) These are non-overlapping hot stretches; three, four, or five days of particular temperatures would count as one event, and six straight days as two events.

Figure 2 below shows the results for three straight days of 90° or hotter. The linear trend is a total increase of 533 percent over 53 years, or an increase of 0.9 occurrence per decade.

Expressing the change over time another way, these heat waves have occurred so far in this century 2.6 times more often than they averaged in 1961–1999.

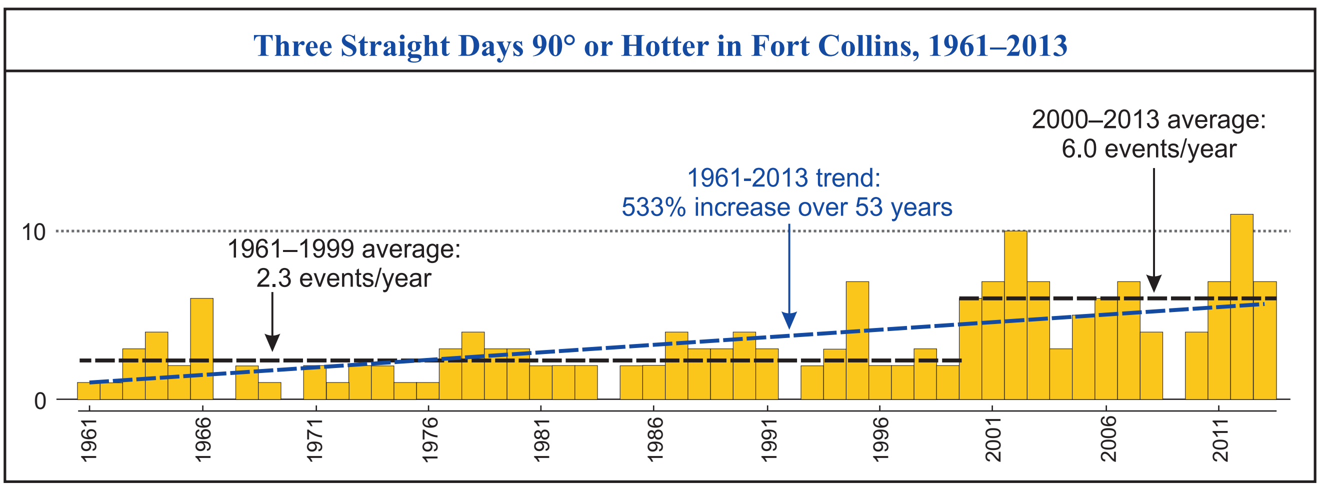

Figure 2. Occurrences per year of three straight days each with maximum temperatures of 90° or hotter; otherwise as in Figure 1.

That the frequency of 90° hot stretches has increased even more than the frequency of single 90° days is important because heat waves have even greater impacts than single hot days do. (See page 8.)

Figure 3 below presents similar information for the frequency of single days 95° and hotter. These very hot days are much rarer than 90° days, representing the top one percentile of all days in 1961–1990 at the CSU weather station. The linear trend for 1961–2013 is an average increase of 1.4 such days per decade, which, given the rarity of these days, amounts to a total increase of 1,069 percent over 53 years. This percentage increase is nearly seven times as great as the percentage increase in the frequency of 90° days.

Expressing the change in 95° days another way, in the first years of the 21st-century, Fort Collins averaged three times as many such very hot days as in the last 39 years of the 20th century.

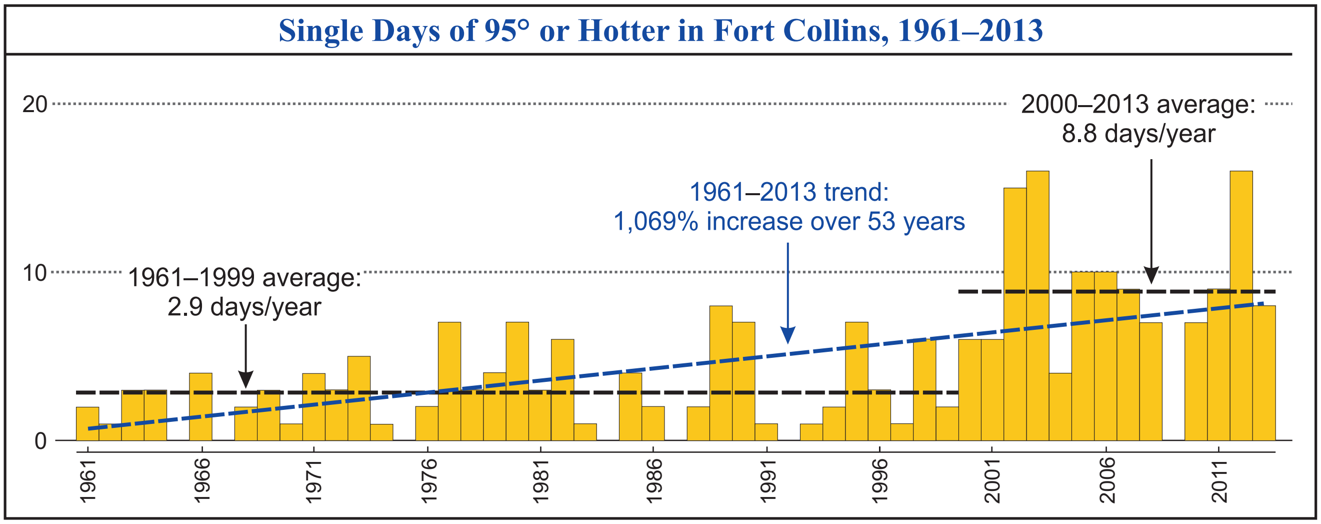

Figure 3. Days per year with maximum temperatures of 95°or hotter; otherwise as in Figure 1.

For more data on the frequencies of hot days and heat waves in Fort Collins from 1961 through 2013, based on thresholds of 90°, 95°, and 100°, see Table 1 on page 6 and Table 2 on page 11.

Future Hot Days and Heat Waves

To illustrate the potential effects of continued climate change on hot days and heat waves in Fort Collins, the report's authors obtained downscaled projections of daily maximum temperatures in the city from a global climate model. (See pages 9–10 for more details on the methodology for these projections.) Projections from the climate model were obtained spanning one 20-year period in the middle of the century (2046–2065) and another late in the century (2081–2100), for two alternative possible futures, one with a lower level of future emissions of heat-trapping pollution, and one with a medium-high level. For each time period/emissions scenario combination, three separate computer runs (or ensembles) of the model were obtained, which vary by having different starting assumptions.

Figure 4 on the next page shows the averages and ranges of the projections for the future annual frequencies of single days 95° or hotter. Figure 5 on the following page shows the same for three straight days 90° or hotter. To help place these projections in the proper perspective, figures 4 and 5 also show the historical rates of comparable hot days and hot stretches—exactly as in figures 2 and 3, except now re-sized to match the scale of the projected future occurrences.

The figures illustrate how much difference future pollution levels can make, shown by the differences for mid-century and especially for late in the century between projections based on lower emissions and those based on medium-high emissions. (See comparisons in the text on page 6 and in Table 1 on that page.)

For the numerical values of the projections shown in figures 4 and 5 as well as of projections of other types of hot days and hot stretches, see Table 1 on page 6 and Table 3 on page 12.

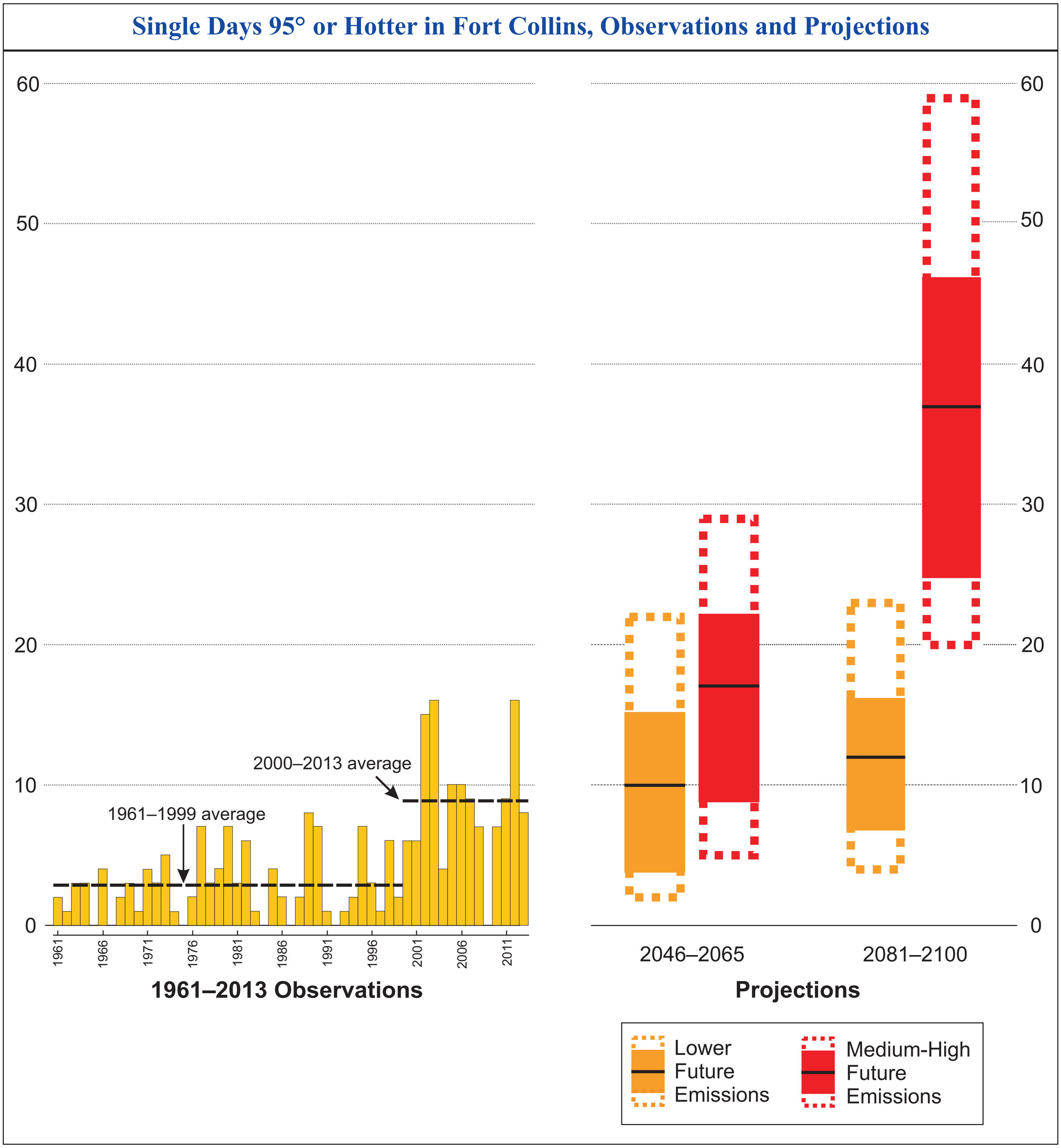

Figure 4. Days per year in Fort Collins with maximum temperatures of 95° or hotter: on the left, actual numbers for 1961–2013, and on the right projections for 2046–2065 and 2081–2100. For each future time period, projections are shown for two alternative futures, one with a lower level of future emissions of heat-trapping pollution and one with a medium-high level. For each pairing of 20-year period and emissions scenario, three computer runs of a climate model produced a total of 60 projections of annual occurrences of 95° days; the solid box shows the range of the middle 50 percent of the 60 projections; the dashed extensions show the ranges from the 10th to the 90th percentiles; and the solid line in the box shows the median of the projections. For the values of the projections shown in this figure, see Table 3 on page 12.

Three Straight Days 90° or Hotter in Fort Collins, Observations and Projections

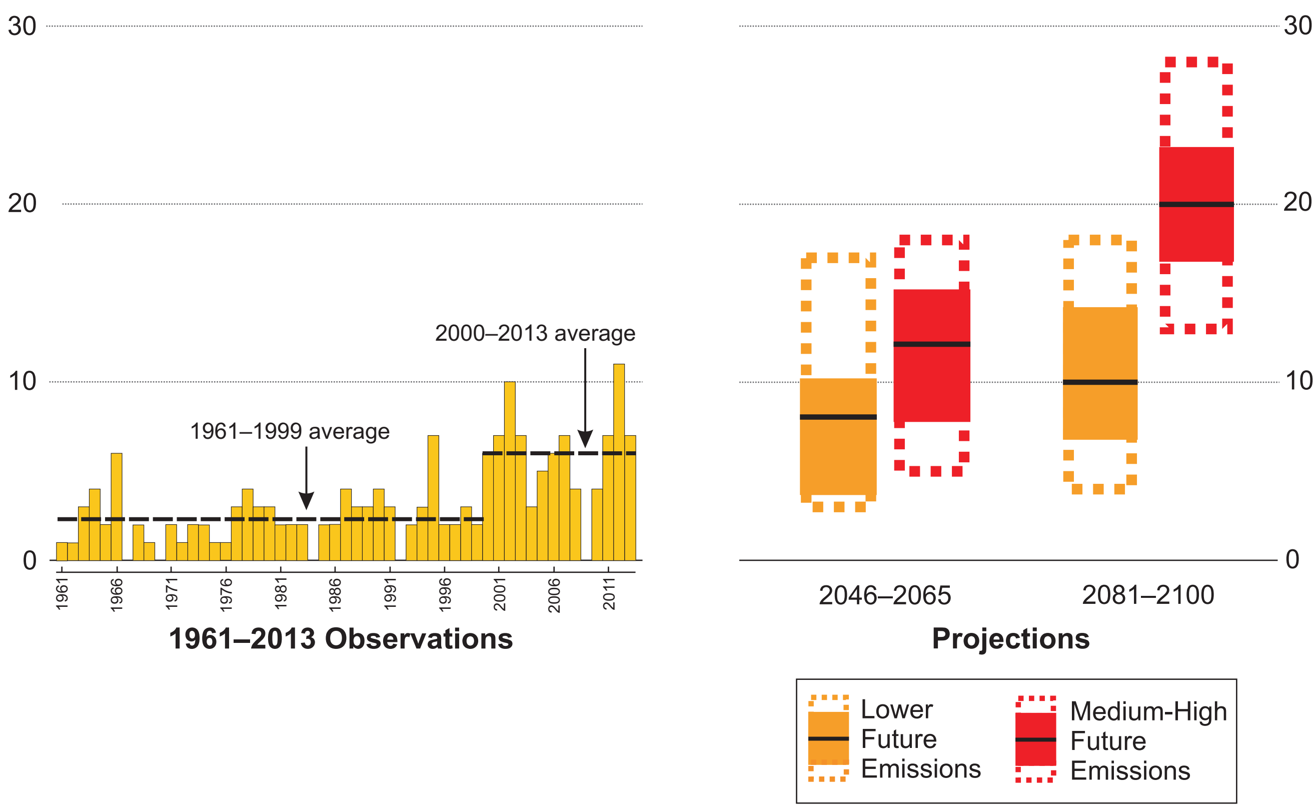

Figure 5. Numbers per year of three straight days each with maximum temperatures 90° or hotter; otherwise as in Figure 4. For the values of the projections shown in this figure, see Table 3 on page 12.

Future frequencies of single hot days and heat waves depend on future levels of heat-trapping pollution. If emissions are not limited, increases in hot days and heat waves could be several times greater than if emissions are held to a lower rate. This is one powerful illustration of the importance of reducing emissions.

Table 1 below pulls together the actual numbers of hot days and hot stretches in 1961–1999 and in 2000–2013 and the average projected numbers for the future (for both lower emissions of heat-trapping pollution and with medium-high emissions). The table also compares the actual numbers in 2000–2013 and the average projected future numbers to those of the last 39 years of the 20th century.

The table shows, for example, that the frequency of single 95° days, compared to 1961–1999:

- in 2000–2013 was three times higher;
- by mid-century could be about three and a half times higher if future emissions of heat-trapping pollution rise at a lower rate, or about six times higher if they rise at a medium-high rate; and
- near the end of the century could be about four times higher with lower future emissions, or about 13 times higher with medium-high emissions.

As another example, the frequency of three straight days of 90°, again compared to 1961–1999:

- in 2000–2013 was about two and a half times higher;
- by mid-century could be about that same three and a half times higher with lower future emissions, or about five times higher with medium-high emissions; and
- near the end of the century, could be about four times higher with lower emissions, or about nine times higher with medium-high emissions.

Hot Days and Hot Stretches per Year in Fort Collins
Observations and Projections

	Observations		2046–2065		2081-2100	
	1961–1999	2000–2013	Lower Emissions	Medium-High Emissions	Lower Emissions	Medium-High Emissions
Single Days						
90° or hotter	17.9	33.7 (188%)	43 (240%)	55 (307%)	49 (274%)	81 (453%)
95° or hotter	2.9	8.8 (303%)	10 (345%)	17 (586%)	12 (413%)	38 (1,310%)
100° or hotter	0.1	0.6 (600%)	1 (1,000%)	2 (2,000%)	1 (1,000%)	10 (10,000%)
3 Straight Days						
90° or hotter	2.3	6.0 (261%)	8 (348%)	12 (522%)	10 (435%)	21 (913%)
95° or hotter	0.2	0.5 (250%)	1 (500%)	2 (1,000%)	1 (500%)	8 (4,000%)
100° or hotter	0	0 (N/A)	0 (N/A)	0 (N/A)	0 (N/A)	2 (N/A)

Table 1. Average days per year with indicated maximum temperatures, and average occurrences per year of three straight days each with indicated maximum temperatures. For the future periods, the values shown are the medians of 60 projections; individual projections are for both higher and lower numbers of occurrences (see caption to Figure 4). The percentages in parentheses are comparisons to 1961–1999 averages.

Comparison to Average Temperatures

The analysis done for this report looked only at extreme temperatures, not average temperatures. However, it seems safe to suggest that the differences in projected extreme temperatures based on a lower-emissions future and on a medium-high future are proportionately greater than the differences in projected average temperatures. Figure 6 below, from a report prepared as an input for a forthcoming new national climate assessment by the U.S. government, shows projected changes in average temperature in the southwestern United States (including Colorado) using the same emissions scenarios used in this analysis. It shows that near the century's end future regional temperatures could average about 5° higher with lower future emissions or about 8° higher with medium-high emissions.

Projected Changes in Average Temperature in the Southwest

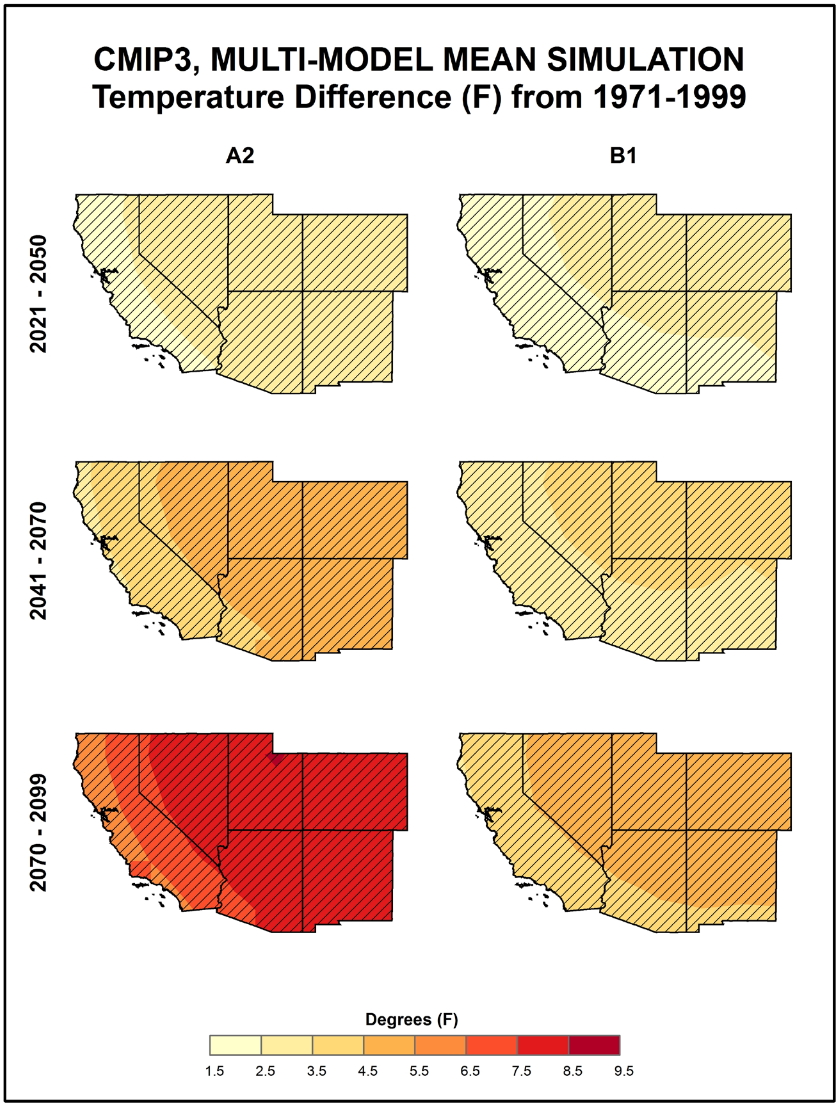

Figure 6. Projected changes in average annual temperatures, showing averages of projections from 15 downscaled global climate models for medium-high future emissions (labeled here as A2) and from 14 models for lower emissions (B1). Hatching indicates that more than half the simulations show a statistically significant change and that more than two-thirds agree on the direction of the change. Figure from the National Oceanic and Atmospheric Administration.[3]

Global and National Contexts

An excellent, up-to-date summary of the global and national contexts for this report's data on extreme heat in Fort Collins is available in the public review draft of the just-mentioned national climate change assessment, to be released later this year by the U.S. government. Among its relevant conclusions are:

- Many aspects of the global climate are changing rapidly, primarily from human influences. Natural drivers of climate (such as solar forcing and volcanoes) cannot explain the recent global increases in temperature; over the last five decades, those natural factors alone would actually have led to a slight cooling of the planet.[4]
- Average temperature in the United States has increased by about 1.5°F since record keeping began in 1895, with more than 80 percent of the increase since 1980. The most recent decade was the nation's hottest on record.[5]
- Heat waves have generally become more frequent across the United States in recent decades, with record numbers of occurrences of heat waves in the West in the early years of this century.[6]
- There is emerging evidence that most of the increases of heat wave severity over the United States are likely due to human influences on the climate. For example, research has found that human influences approximately doubled the probability of the record heat in Texas in the summer of 2011.[7]
- The number of extremely hot days is projected to continue to increase dramatically. Climate models project that the same summertime temperatures that ranked among the hottest 5 percent of summer days in 1950–1979 will occur at least 70 percent of the time by 2035-2064 in the United States if global emissions of heat-trapping pollution grow at a medium-high rate.[8] "In other words," the draft report says, "what now seems like an extreme heat wave will become commonplace."[9]

Impacts of More Extreme Heat

The observed and projected increases in hot days and hot stretches documented in this report have many potential impacts on the residents of Fort Collins. Extreme heat affects human health and comfort, ecosystems, water resources, agriculture, and other resources and values. Impacts are greater when extreme heat lasts for multiple days, creating a heat wave.[10]

According to the National Weather Service, in the last decade more Americans died from extreme heat than from any other weather-related cause (such as tornadoes, hurricanes, or floods).[11] From 1999 through 2009, extreme heat exposure caused or contributed to more than 7,800 deaths in the nation.[12] Heat-related deaths can be from heat stroke and related conditions and also from cardiovascular, respiratory, and other diseases; extreme heat also can increase non-lethal conditions requiring hospital care.[13] For example, according to a report on the Southwest region prepared for the new national climate change assessment, a 2006 California heat wave contributed to more than 140 deaths, 1,000 extra hospitalizations, and 16,000 extra emergency room visits.[14] Colorado health effects from extreme heat are not well documented.[15]

Global climate models consistently project increases in heat waves across the planet and in the United States, and scientists consistently project increased impacts from those heat waves. The U.S. government's 2009 national climate change assessment, as an example, reports that by late in this century annual heat-related deaths in Los Angeles are projected to increase by two to three times with lower future emissions and by five to seven times with higher future emissions.[16]

Extreme heat also is a major factor in widespread ecosystem effects, including the ignition and spread of wildfires. It is noteworthy that Colorado's most destructive wildfires in the past two years all began on very hot days:

- The High Park fire west of Fort Collins in 2012, which destroyed 259 homes and killed one person, started on a day that in Fort Collins had a high temperature of 93°, according to the daily temperature data analyzed for this report.
- The Waldo Canyon fire west of Colorado Springs in 2012, which burned 347 homes and killed two people, started when Colorado Springs had a record-tying high temperature for that date of 100°.[17]
- The Black Forest fire north of Colorado Springs in 2013, which burned 488 homes and killed two people, started on a day that in Colorado Springs had a record high for that date of 97°.[18]

Background on this Analysis

The observed temperatures reported here are from the Fort Collins weather station (National Weather Service identification number 05-3005), located on the Colorado State University (CSU) campus. The station is part of the U.S. Historical Climatology Network, a network of long-term, high-quality weather stations selected to track climate trends.[19] The data for this analysis were obtained through the National Climatic Data Center's Climate Data Online web interface.[20]

In 2002, a new transit center was built near the CSU weather station, leading to a small artificial increase in the temperature readings at the station, according to a draft analysis by Wendy Ryan and Nolan Doesken of CSU's Colorado Climate Center. Their draft, included as an appendix to this report, shows that the effect of the transit center has been an artificial increase of about 0.4° in the daily maximum temperatures recorded at the station during warm months. Had a full set of daily maximum temperature records for the station been available in tenths of a degree, for the analysis reported here the authors would have reduced the recorded maximum temperatures by 0.4° to adjust for this effect. However, the only full dataset available is in whole degrees—so that, for example, a recorded daily high temperature of 90° spans 89.5° to 90.4°. If those values were reduced by 0.4°, 40 percent of that range (from 89.5° to 89.8°) would be rounded to 89° rather than 90°. Therefore, following consultation with Doesken and with his concurrence, the authors adjusted the station's daily records for 2002 and later. For each second and fifth day recorded as having a high temperature of exactly 90°, those values were lowered to 89° before the counts were made of the numbers of single days and three straight days of 90° or hotter. (No adjustments were needed for days recorded as 91° and hotter, as the adjustments would not move them below the 90° threshold.) Similar adjustments were made to the counts of days recorded as exactly 95° or 100° for the analyses of the hot days and hot stretches beginning at those thresholds.

The counts for each year from 1961 through 2013 of single days and three straight days of 90°, 95°, and 100°, both with and without these adjustments, are shown in Table 2 on page 11.

The projected daily maximum temperatures reported here are from World Climate Research Program's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset, downscaled for United States locations by correlating large-scale model outputs with local climate observations, through a collaborative effort of federal agencies, universities, and others.[21] This effort is supported by the Office of Science, U.S. Department of Energy, and made available through Lawrence Livermore National Laboratory. Projections of daily maximum temperatures were obtained for a grid 1/8 of a degree in longitude by 1/8 of a degree in latitude, centered on 40.5625 degrees north latitude and -105.0625 degrees west longitude. That grid includes the location of the Fort Collins weather station used in this analysis.

Projections were obtained for every day from 2046 through 2065 and from 2081 through 2100, the two 20-year periods for which such data are available on the CMIP3 dataset. For each time period, projections were obtained for each of two scenarios of future emission levels of heat-trapping pollution: one identified in this report as "lower emissions," which is scenario B1 from the Special Report on Emissions Scenarios (SRES) by the Intergovernmental Panel on Climate Change (IPCC), and one identified as "medium-high emissions," which is scenario A2.[22] (See Figure 7 above.) For each combination of time period and

Scenarios of Future Emissions

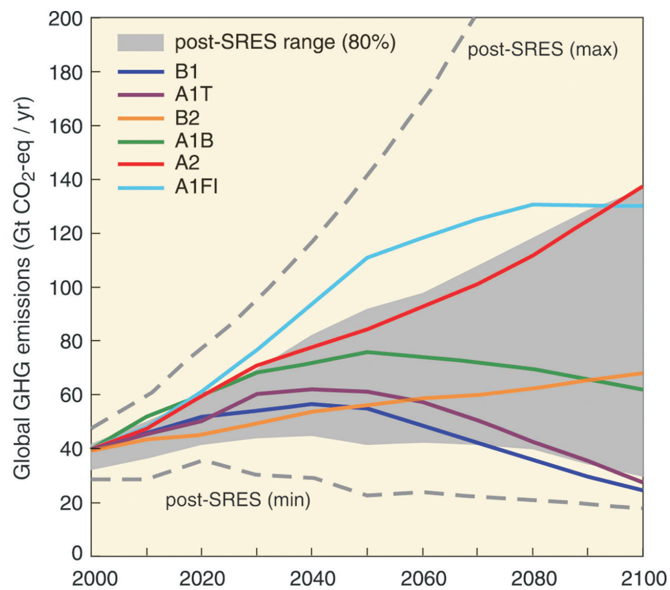

Figure 7. Annual levels of emissions of heat-trapping pollution assumed in selected emissions scenarios, including those cited in this report (B1, or "lower," and A2, or "medium-high"). Dashes indicate the range of newer, replacement ("post-SRES") scenarios now beginning to be used; the gray area represents the middle 80th percentile of their range. Figure from the IPCC.

emissions scenario, projections of daily maximum temperatures were obtained for the three available model runs of the Community Climate System Model, version 3, on the CMIP3 database. This climate model was originally developed by the National Center for Atmospheric Research in Boulder and subsequently refined through the contributions of many other scientists.

Retrospective projections of daily maximum temperatures were also obtained from all three model runs for a baseline period of 1961–1999 (see Table 4 on page 13), to yield the model's estimates of changes in the frequencies of hot days and hot stretches between the baseline period and the future periods. These differences were then added to the actual observed frequencies of hot days and hot stretches in Fort Collins for 1961–1999 to produce the projected future frequencies identified in this report. This method of adding modeled differences over time to actual observations is a common technique, used, for example, in U.S. government climate reports.[23]

In this manner, for each of the four time period/emissions scenario combinations, 60 different projections of annual occurrences of the frequencies of hot days and heat stretches were obtained—three projections, one from each model run, for each year in a 20-year period. From these 60 projections, the median values and the range of the projections for the annual occurrences were determined, as shown in figures 4 and 5 and tables 1 and 3.

Altogether, more than 19,000 recorded daily maximum temperatures and more than 130,000 projections of daily maximum temperatures were obtained and analyzed for this report.

No scenario with truly high emissions (such as scenario A1FI, shown in Figure 7 on the previous page) is available on the CMIP3 database, so the projections reported here are skewed toward the low end of possible future emissions. In fact, in some recent years, actual emissions have exceeded all scenarios shown in Figure 7.[24] On the other hand, future emissions could be lower than in any of the scenarios shown in Figure 7, none of which assume new policies to ward off climate change.[25] If future heat-trapping emissions are limited, further climate changes could be less than suggested by the B1 (or "lower") scenario used in this report. Newer, replacement emissions scenarios (now called "representative concentration pathways"), just beginning to be used, reflect a wider range of possible future emissions.

There are uncertainties with any climate projections of the type presented here. According to the draft of the forthcoming national climate change impact assessment, exactly how much climate will change over this century and beyond depends primarily on two factors: the extent of future emissions, and how sensitive the climate is to those emissions.[26] Over the next few decades, most uncertainty about the extent of climate change comes from natural climate variability and limits on scientists' ability to understand and model the Earth's climate system. By the second half of the century, however, the extent of future emissions becomes increasingly dominant in determining the future climate changes, especially with respect to temperature.[27] Projections of future temperatures are considered to have less uncertainty than projections of other climate variables, such as precipitation.[28] However, projections of daily temperature extremes are certainly less reliable than are projections of annual average temperatures.[29] Still, as shown by Table 4 on page 14, when the climate model used in this analysis is used to look backward, its calculations for the frequencies of hot days and hot stretches in Fort Collins in 1961–1999 match relatively well with the actual numbers for the same period, although the model results consistently show slightly lower occurrences of extreme heat than actually occurred. All of this indicates that the future projections presented here can at a minimum be taken as reasonable illustrations of plausible futures, although certainly not as firm predictions.

Additional details of the data analyzed for this report are contained in the tables on the three following pages. Table 2 on the next page shows the number of occurrences in each year from 1961 through 2013 of single days and three straight days of 90°, 95°, and 100°—including the counts both with and without the adjustments described above. Table 3 on page 12 shows detailed summaries of the data for the projections represented graphically in figures 4 and 5. Table 4 on page 13 shows the relative accuracy of the climate model used for these projections, when applied in a backward-looking manner, as illustrated by a comparison of the retrospective projections and actual observed values.

The Appendix comprised of the analysis by Wendy Ryan and Nolan Doesken, described above, follows page 14.

Observed Hot Days and Hot Stretches in Fort Collins

	Single Days			3 Straight Days		
	90°	95°	100°	90°	95°	100°
1961	12	2	0	1	0	0
1962	12	1	0	1	0	0
1963	22	3	0	3	0	0
1964	22	3	0	4	1	0
1965	9	0	0	2	0	0
1966	27	4	0	6	0	0
1967	6	0	0	0	0	0
1968	15	2	0	2	0	0
1969	19	3	0	1	0	0
1970	14	1	0	0	0	0
1971	16	4	0	2	0	0
1972	8	3	0	1	0	0
1973	21	5	1	2	0	0
1974	18	1	0	2	0	0
1975	12	0	0	1	0	0
1976	19	2	0	1	0	0
1977	24	7	0	3	1	0
1978	27	3	0	4	0	0
1979	21	4	0	3	1	0
1980	32	7	0	3	0	0
1981	20	3	0	2	0	0
1982	13	6	0	2	1	0
1983	22	1	0	2	0	0
1984	15	0	0	0	0	0
1985	24	4	0	2	0	0
1986	14	2	0	2	0	0
1987	21	0	0	4	0	0
1988	26	2	0	3	0	0
1989	14	8	0	3	2	0
1990	20	7	1	4	0	0
1991	13	1	0	3	0	0
1992	7	0	0	0	0	0
1993	9	1	0	2	0	0
1994	23	2	0	3	0	0
1995	28	7	0	7	0	0
1996	14	3	0	2	0	0
1997	17	1	0	2	0	0
1998	27	6	1	3	1	0
1999	15	2	0	2	0	0
2000	39	6	0	6	0	0
2001	41	6	0	7	0	0
2002	43 (44)	15 (19)	1	10 (11)	0 (2)	0
2003	34 (37)	16 (18)	1 (2)	7 (8)	2	0
2004	16 (18)	4 (5)	0	3 (4)	0 (1)	0
2005	33 (36)	10 (11)	3	5 (7)	1	0
2006	37 (39)	10 (11)	1 (2)	6	1	0
2007	34 (36)	9	0	2 (8)	0	0
2008	24 (26)	7 (9)	0	4 (5)	0	0
2009	10 (11)	0	0	0	0	0
2010	32 (35)	7 (8)	0	4 (5)	0	0
2011	38 (41)	9 (11)	0	7 (8)	0	0
2012	55 (57)	16 (19)	2 (3)	11	2	0 (1)
2013	36 (38)	8 (9)	0	7	1	0
1961–1999	17.9	2.9	0.1	2.3	0.2	0
2000–2013	33.7 (35.6)	8.8 (10.0)	0.6 (0.8)	6.0 (13.6)	0.5 (1.5)	0 (0.1)

Table 2. Numbers in Fort Collins in 1961–2013 of single days and three straight days with maximum temperatures at least as high as indicated. For 2002 and later, numbers in parentheses are recorded values prior to the adjustments described on page 9, in the cases in which adjustments were made.

Projected Hot Days and Hot Stretches per Year in Fort Collins

	Single Days 90°	Single Days 95°	Single Days 100°	3 Straight Days 90°	3 Straight Days 95°	3 Straight Days 100°
2046-2065						
Lower future emissions						
90th percentile projection	*66*	*22*	*2*	*17*	*3*	*1*
75th percentile projection	*54*	*15*	*1*	*10*	*1*	*0*
Median of 60 projections	43	10	1	8	1	0
25th percentile projection	*31*	*4*	*0*	*4*	*0*	*0*
10th percentile projection	*24*	*2*	*0*	*3*	*0*	*0*
Medium-high future emissions						
90th percentile projection	*73*	*29*	*4*	*18*	*4*	*0*
75th percentile projection	*63*	*22*	*2*	*15*	*4*	*0*
Median of 60 projections	55	17	2	12	2	0
25th percentile projection	*45*	*9*	*0*	*8*	*1*	*0*
10th percentile projection	*38*	*5*	*0*	*5*	*0*	*0*
2081-2100						
Lower future emissions						
90th percentile projection	*71*	*23*	*4*	*18*	*4*	*0*
75th percentile projection	*62*	*16*	*2*	*14*	*2*	*0*
Median of 60 projections	49	12	1	10	1	0
25th percentile projection	*40*	*7*	*0*	*7*	*0*	*0*
10th percentile projection	*29*	*4*	*0*	*4*	*0*	*0*
Medium-high future emissions						
90th percentile projection	*103*	*59*	*23*	*28*	*15*	*5*
75th percentile projection	*90*	*46*	*14*	*23*	*10*	*2*
Median of 60 projections	81	38	10	21	8	2
25th percentile projection	*71*	*25*	*3*	*17*	*4*	*0*
10th percentile projection	*61*	*20*	*0*	*13*	*1*	*0*

Table 3. Summaries of projections of numbers of single days and three straight days per year with maximum daily temperatures at least as high as indicated. Summaries are of 60 projections for each time period/emissions level pairing (see the caption to Figure 4). See page 9 for an explanation of emissions levels. The data in this table are the same as shown in figures 4 and 5.

Hot Days and Heat Waves in Fort Collins, 1961–1999 Model Projections vs. Actual Numbers		
	Model Projections	Actual Numbers
Single days 90°	12.1	17.9
Single days 95°	1.5	2.9
Single days 100°	0.1	0.1
3 straight days 90°	1.6	2.3
3 straight days 95°	0.1	0.2
3 straight days 100°	0	0

Table 4. Average numbers of days per year and of occurrences of three straight days per year in Fort Collins with maximum daily temperatures at least as high as indicated: on the left, averages of outputs from the downscaled climate model used in this report, applied retrospectively for 1961–1999, and on the right, actual numbers from the Fort Collins weather station used in this report. The model's backward-looking projections understate somewhat the past frequencies of hot days and heat waves, suggesting that its future projections may also do the same. No comparable model projections are available for 2001–2013.

About this Report

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Notes

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Appendix

Fort Collins Campus Weather Station (05-3005) Data Continuity Assessment

Evaluation of the impact of the construction of the Colorado State University Transit Center in 2002 on observed daily maximum and minimum temperatures.

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Introduction

The Fort Collins weather station (FCL) located on the campus of Colorado State University has been operated since 1889 and remains the backbone climate monitoring station for Fort Collins and one of the longest continuous climate records in the state of Colorado and the Rocky Mountain region. Since the late 1880's various meteorological elements have been recorded on at least a daily basis. Primary variables include temperature, precipitation and snowfall.

For much of the history of the campus weather station, Fort Collins was a small city, and the university was located in a semi-rural environment on the southern edge of the city. This began to change in the late 1950s as the campus expanded rapidly and the City of Fort Collins grew to the west south and east. Colorado State University has continued to develop, but the environment (buildings, streets and vegetation) immediately surrounding the weather station had remained largely unchanged from the 1960s forward There was a relatively large open area surrounding the weather station with predominantly grass and trees within a significant radius to the SE, S, SW and W. The prevailing daytime wind direction much of the year is from the SE suggesting a good, open exposure for this station despite its central campus location.

In 2002, construction of a new transit center (bus terminal) began just to the southeast of where the weather station is located. This new facility was located on the north side of CSU's Lory Student Center. This was completed and landscaped by early 2003. The results was an extensive concrete paved areas SE-S of the station to within only about 100 feet of where temperature measurements are taken. At that time, moving the weather station to a different and less disturbed location on campus was anticipated and planned, but very few suitable sites were found. One site (east of the old Fort Collins High School) was installed. However, in several weeks of overlap with the historic campus station, differences in temperature, humidity, wind and solar radiation were found to be large. At that point in 2002, University officials agreed to leave the weather station at its current location.

When the decision was made to leave the weather station in place, the landscape architect for CSU was enlisted to work with the contractors and the Colorado Climate Center to develop a landscape plan to attempt to mitigate the impact of the expanded paved areas. Until now, the impact of the construction of the transit center and the mitigating landscape had not been formally evaluated. However, recent observations of a rapid increase in the number of hot summer days since about 2000 motivated closer examination.

This analysis is intended to quantify the impact (if any) of the CSU Transit Center on the continuity and integrity of long-term temperature records from the Fort Collins weather station. Temperature data from the campus weather station are compared to data collected 4 miles away at the National Weather Service Cooperative weather station Fort Collins 4E (05-3006, FCL4E). This station is in a relatively open suburban area approximately 4 miles east of the CSU campus and on the east side of the Poudre River. No development has occurred in that area for over 20 years. One additional station was included in some of the analyses. FTC01 (Fort Collins 01) is an automated station that is part of the CoAgMet network. This station was mainly used to provide an independent comparison to help confirm the findings. This station is located on the west side of Fort Collins near the CSU foothills campus in a rural area and also has experienced little if any changes to the nearby landscape in the past 20 years. Figure 1 shows a map of the three stations with a photo below the station.

Figure 1: Map of stations (top) with photo below the site. Site A is FCL (campus), site B is FCL4E and site C is FTC01.

Methods

Daily temperature data were assembled for all stations for the available overlap period of September 1994 – August 2013. Using these data, several data comparison analyses were performed. The first is a double mass analysis. This is a widely used technique for detecting changes in time series with respect to each other. This analysis simply accumulates the observed temperatures at each station over time and plots them on a graph. If a change is detected in how one station compares to the other, it will alter the slope of the line.

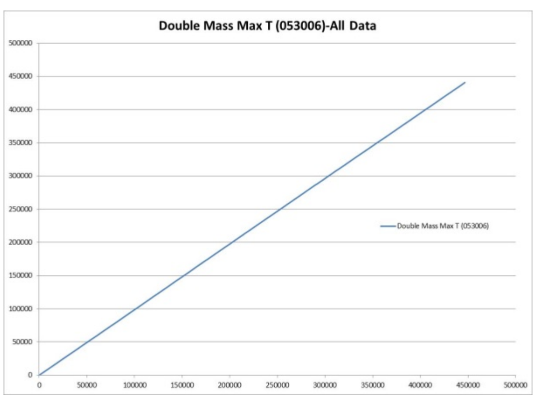
Next, mean monthly differences between the two stations were calculated for both maximum and minimum temperatures. This analysis would show if the bias between the two stations was consistent throughout the year, or if the differences had seasonality to them

The third analysis focuses on differences between the two stations only on hot days. Histograms of temperatures 85 degrees or higher, by month, for the pre-2002 and post-2002 records (2002 was removed from the dataset to remove the time when the greatest disturbance was present on campus) for both stations. Next, histograms of monthly temperature differences between FCL and FCL4E were created to detect changes in any given month, again for the pre-2002 and post-2002 records in order to assess any shift in temperatures. Finally , monthly mean differences for only temperatures >=85 F were calculated for May-September, again looking at the pre- and post-2002 periods to see if the relationship between the two stations changed after the CSU transit center was built and in operation.

Results

Double Mass Analysis

Figure 2 shows the double mass analysis for both maximum and minimum temperatures.



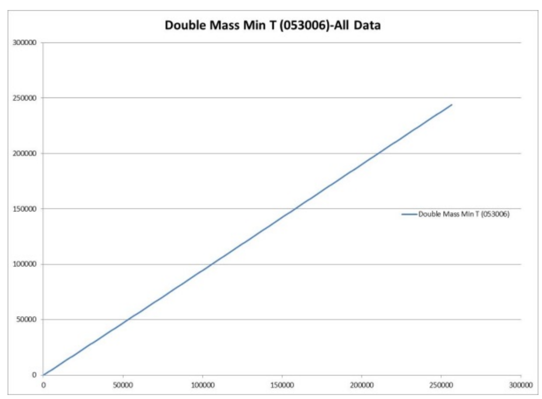


Figure 2: Double mass analysis for maximum (left) and minimum (right) temperatures between FCL (x-axis) and FCL4E (y-axis).

This analysis shows no significant changes in slope of either line (Tmax or Tmin) over this time period. A discontinuity to the climate record at either station would show up as a clear shift in the slopes of the lines in Figure 1. So to a first approximation, impact on temperature data continuity related to the construction of the transit center appears very small and insignificant.

Mean Monthly Differences (FCL – FCL4E)

The next analysis was to simply calculate monthly average differences between the two stations. Table 1 shows the results from this analysis.

Month	Max Diff (FCL-FCL4E)	Min Diff (FCL - FCL4E)
1	1.9	2.9
2	1.6	2.3
3	1.3	2.2
4	1.3	1.8
5	1.0	1.1
6	0.3	0.9
7	-0.3	1.2
8	-0.2	1.2
9	0.2	1.3
10	0.6	1.9
11	1.3	2.3
12	1.6	2.7

Table 1: Mean monthly differences in maximum and minimum temperatures. The difference is FCL minus FCL4E for the period 1994 – 2013.

The difference in the maximum temperature between the two stations varies throughout the year. In the winter months, FCL is systematically warmer than FCL4E by approximately 1-2 degrees F. However, during the summer months there is barely a difference between the maximum temperatures at the two locations. In fact, in July and August FCL daily maximum temperatures average slightly cooler than FCL 4E. The differences in the winter months are highest and likely being affected by differences in snow cover at the two locations and cold air pooling at FCL4E which is lower in elevation and closer the immediate valley of the Cache la Poudre River.

The difference in the minimum temperature between the two stations also shows a seasonal pattern with the campus weather station warmer than FCL 4E all year but especially during mid-winter. The minimum temperature bias shows FCL warmer than FCL 4E by 0.9 degrees F in June increasing to a maximum difference of +2.9 F in January. The differences vary quite systematically month to month suggesting a consistent and repeating relationship.

Month	Max Diff (FCL-FCL4E) pre-2002	Max Diff (FCL-FCL4E) post-2002	Min Diff (FCL - FCL4E) pre-2002	Min Diff (FCL - FCL4E) post-2002
May	0.9	1.0	1.4	1.0
June	0.2	0.4	1.0	0.8
July	-0.4	-0.2	1.2	1.1
Aug	-0.5	-0.2	1.3	1.1
Sept	0.0	0.3	1.4	1.3
Oct	0.5	0.6	2.2	1.6

Table 2: Mean monthly temperature differences between FCL and FCL4E from May –October for the period 1994 – 2013.

Table 2 shows these monthly temperature differences between FCL and FCL 4E for pre-disturbance and post-disturbance years for the warm season months. Potentially, these months with high sun angle and lighter ambient winds speeds are when we might expect heating influences from the CSU transit center to be maximized. However, differences between the two periods were found to be very small on the maximum temperature with the numbers showing a very slight warming at FCL over the range of all daily maximum temperatures. The numbers for minimum temperature actually indicate a slight cooling at FCL after the 2002 disturbance period. These results assume no change to the surroundings or instrumentation of FCL 4E.

Month	Max Diff (FCL-FCL4E) pre-2002	Max Diff (FCL-FCL4E) post-2002
May	-0.2	-0.3
June	-0.3	-0.2
July	-0.8	-0.4
Aug	-0.7	-0.4
Sept	-1.0	-0.5
Oct	-0.3	0.2

Table 3: Mean monthly temperature differences between FCL and FCL4E from May –October of days with maximum temperature >=85F only for the period 1994 – 2013.

Because of the growing interest in hot temperature extremes, an analysis of only the hottest days of the year where the daily maximum temperature reached or exceeded 85F was performed examining pre- and post-disturbance periods (Table 3). Again, very minor shifts are noted during the warm season months. The differences are negligible during May and June but are slightly larger in the subsequent months. On average, the post 2002 bias is about 0.4F warming for the FCL station from July-October. The majority of months show FCL 4E warmer than FCL, but the post-2002 data show FCL slightly warming which decreases the differences calculated between the two locations (i.e. less negative).

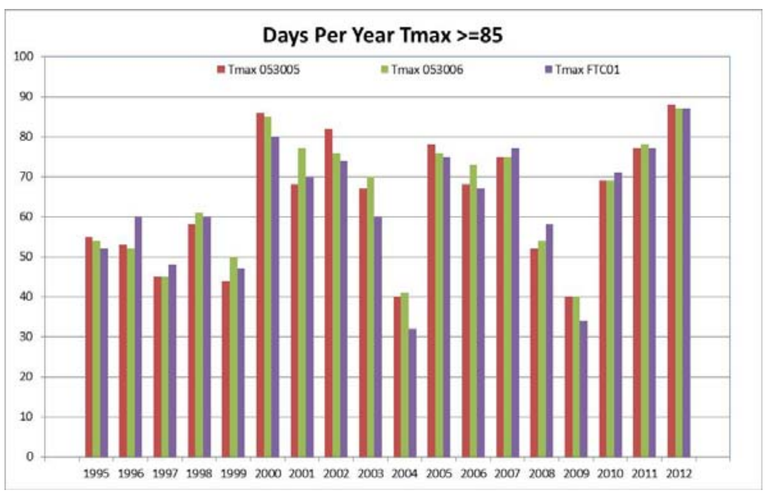


Figure 3: Days per year with daily maximum temperature >=85 F for FCL (red), FCL 4E(green) and FTC01(purple) for the period 1994 – 2013.

In order to assess if the 2002 disturbance is affecting the number of days >=85 since the installation of the transit center, the number of days per year with maximums >=85 were investigated. Figure 3 shows a time series for FCL, FCL4E and FTC01 of the number of days per year with temperatures >=85 degrees. All three stations show similar time series characteristics with a sharp increase in the number of days with maximum temperatures of 85F or higher beginning in 2000 but with notably fewer hot summer days in 2004 and again in 2009. The time series shows no consistent bias between the three stations and no major changes post-2002 after the transit center was built.

In order to fully assess the recent warm period on the data continuity, each station was assessed independently for the pre- and post-disturbance periods. Histograms on the high end of the distribution (85F-103F) were created (Figure 4). It is clear that all three stations (FCL, FCL43 and FTC01) have been experiencing more daily maximum temperatures of 94F degrees and greater in the period since 2002 than they did in the period prior to 2002. This analysis suggests that the transit center, while it may have contributed a slight warming to the FCL station, is likely not the only contributing factor since 2 other nearby stations are exhibiting the same type of warming as the campus station.

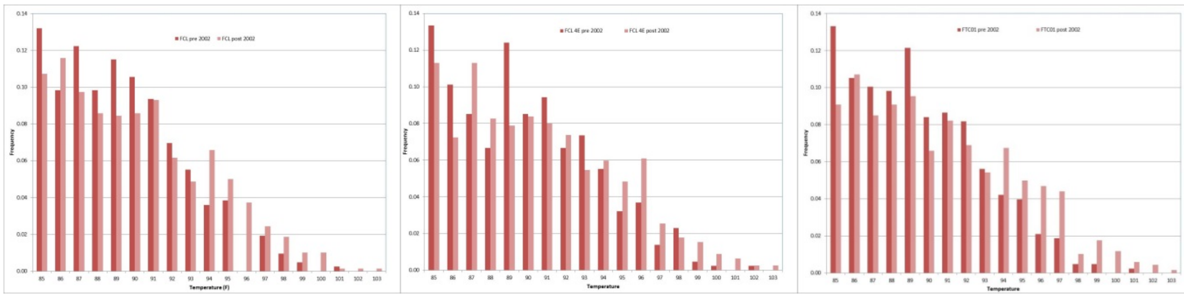


Figure 4: Histograms focusing on the warm end of the distribution from 85-103 F degrees for FCL (top left), FCL4E (top right), and FTC01 (bottom) for the period 1994 – 2013.

Conclusions

The Fort Collins campus weather station data have been compared to two other weather stations in Fort Collins to quantify the effect of the transit center on long-term temperature records. From the analyses above, the transit center is having a detectable but very small effect on elevating temperatures at the campus weather station. Only about 0.4F degrees of warming can be contributed to warming on hot days (days with a maximum temperature of 85F or greater July – October) at the campus station compared to the station 4 miles to the east with much less urbanization. Although not much of the warming can be attributed to the transit center construction, there is a clear warming trend in recent years that is quite noticeable at all three locations that were analyzed. The post-2002 period shows higher frequencies of temperatures 94 degrees or more. This increase in daily maximum temperatures of 94F and greater is likely a shift in regional temperatures because it is seen consistently at all three locations which cover most areas of town. The two comparison sites are located in non-urbanized areas and have experienced little change over the analyzed period.

Ongoing analysis of this warming is integral for assessing continuity and climate trends in the long term temperature records at the Fort Collins campus weather station.