CLIMATE PROFILE FOR THE UPPER SANTA CRUZ RIVER WATERSHED

SANTA CRUZ COUNTY, ARIZONA

A REPORT BY THE CLIMATE ASSESSMENT FOR THE SOUTHWEST (CLIMAS)
– UNIVERSITY OF ARIZONA

ON BEHALF OF
ARIZONA LAND AND WATER TRUST

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Photo credit: Arizona Land and Water Trust

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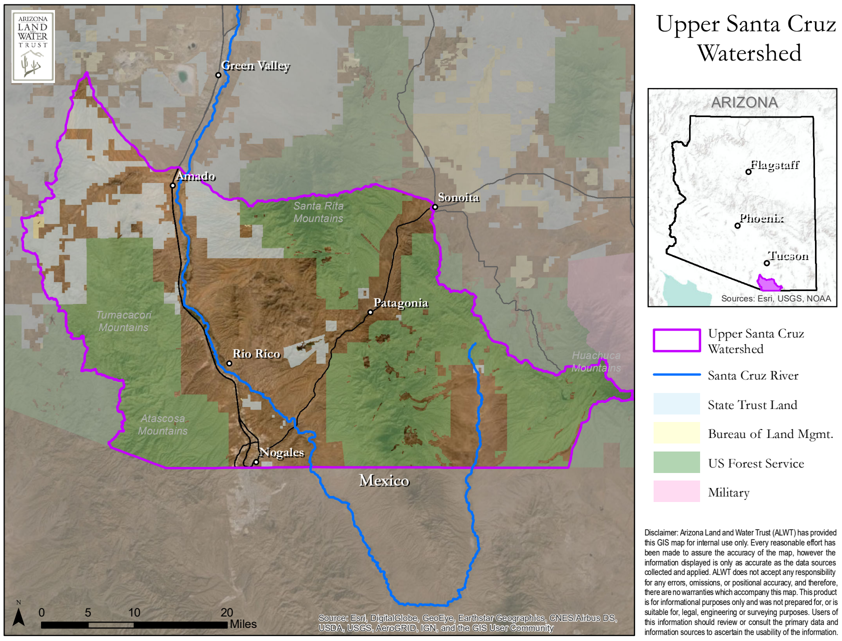
Introduction to the Climate Profile

Decisions about how to best manage natural resources or adapt to a changing climate often require long-term records–or data–about both daily ***weather***[1] and the area's ***climate***. Weather data, in its most basic form, is made up of measurements of temperature and precipitation taken at least once a day. When collected at the same locations for a long time, weather data gives us information about the climate of a place. For example, by looking at many years of weather data we can see how prone a region is to droughts, floods, heat waves or cold spells. These historical weather records also reveal ***climate trends***, such as whether a place is getting wetter or drier or warmer or cooler over long periods of time.

Projections of future climate conditions, commonly referred to as ***climate projections,*** are developed using computer-based climate models. These models provide us with estimates or ***scenarios*** of possible future climate conditions.

Both observed (historical) data and projected data can be useful in helping to make decisions about how to adapt to climate ***variability*** and change in the best interests of community members and natural resources.

This climate profile has been created for the Upper Santa Cruz Watershed (USCW) using the watershed boundaries (see Figure 1) to support Arizona Land and Water Trust's efforts to address climate change impacts in its long-term conservation agreements in the USCW. We used observed climate and weather data as well as projections of future climate for the climate analysis.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

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Figure 1: Upper Santa Cruz River Watershed location and boundaries. Map courtesy Arizona Land and Water Trust.

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[1] ***Bold/italizized*** terms are defined in the Glossary at the end of the report.

Baseline Climate Data for the Upper Santa Cruz Watershed

To better understand the past and current climate of the Upper Santa Cruz Watershed, we examined the instrumental weather and climate records from 1895 through the present using the Parameter-elevation Regression on Independent Slopes Model (PRISM)[2] dataset. PRISM uses regional weather station observations to estimate climate variables for 2.5-mile (4-km) areas in a continuous grid across the United States (Daly et al. 2002). PRISM accounts for variations in weather and climate due to complex terrain, rain shadows, elevation, and ***aspect*** – all of which affect weather and climate across the USCW.

The stations used in PRISM mainly come from the National Weather Service Cooperative Observer Program of the National Oceanic and Atmospheric Administration, which have the longest continuous record of weather data. Data from other weather stations are included if they have at least 20 years of data.

Although PRISM data is available as far back as 1895, we discovered some inconsistencies in the data for the USCW in the 1930s and 1940s, likely due to record-keeping problems at the time. In order to be confident in the data, we have chosen to start the historical data analysis for the USCW in 1950. This is a sufficiently long timeframe to provide robust historical data, but without introducing the possible data gaps in the decades before.

Temperature in Historical Perspective

We use a reference point of the climatological period of 1961 – 1990 to more easily show changes in temperature and precipitation over time. This reference period is also used in the most recent National Climate Assessment to elucidate climatic changes. Over this 30-year reference period, the annual average temperature across the USCW was 60.6° F. In Figure 2, the straight horizontal line represents the long-term average, and the orange line shows year-to-year average temperatures. Year-to-year the average annual temperature has ranged from below 58.7° F in 1964 to 64° F in 2017. Although year-to-year changes in temperature are natural and expected in this region, we see a fairly consistent upward trend in annual average temperatures since the late-1980s. **Every year since 1992 has seen average annual temperatures above the long-term average**.

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[2] Full URLs for all online resources are included in the Reference section.

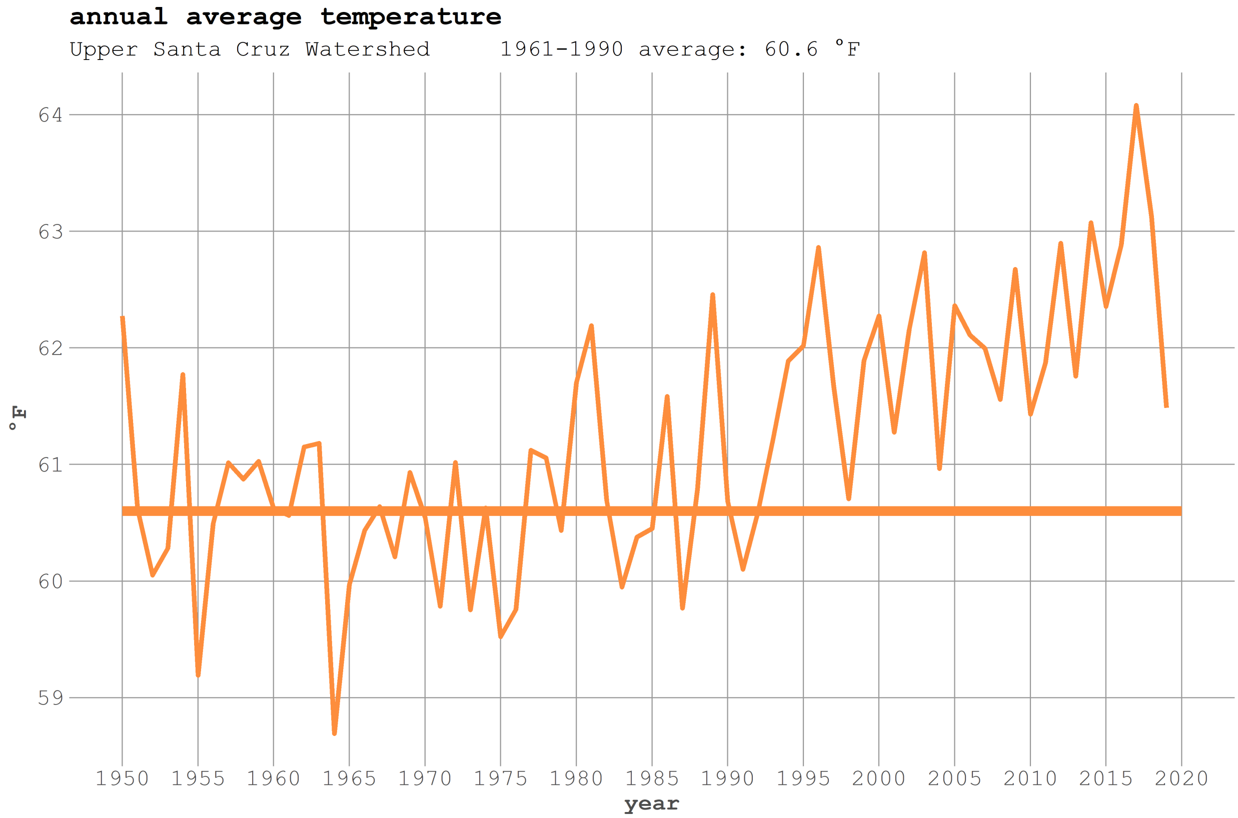

Figure 2: Annual average temperature in the USCW 1950 - 2019.

Disaggregating temperatures as average daily maximum, average daily minimum, as well as overall average allows us to identify patterns in how warming is occurring in the region. *Maximum* annual average temperature tells us the average of all the warmest, typically afternoon, daily temperature readings in an area. *Minimum* annual average temperature tells us the average of the lowest temperature readings, which typically occur in the early morning. The overall average is the average of both maximum and minimum temperatures for an area over a given time.

In Figure 3, we see that *minimum* annual average temperatures (shown in yellow) for the USCW have been above average since the early 1990s and have been rising faster than *maximums* (shown in red) – although both are rising. This pattern indicates that **the warming trend is mostly being driven by rising low temperatures**, such as days not being as cold and fewer cold days each year.

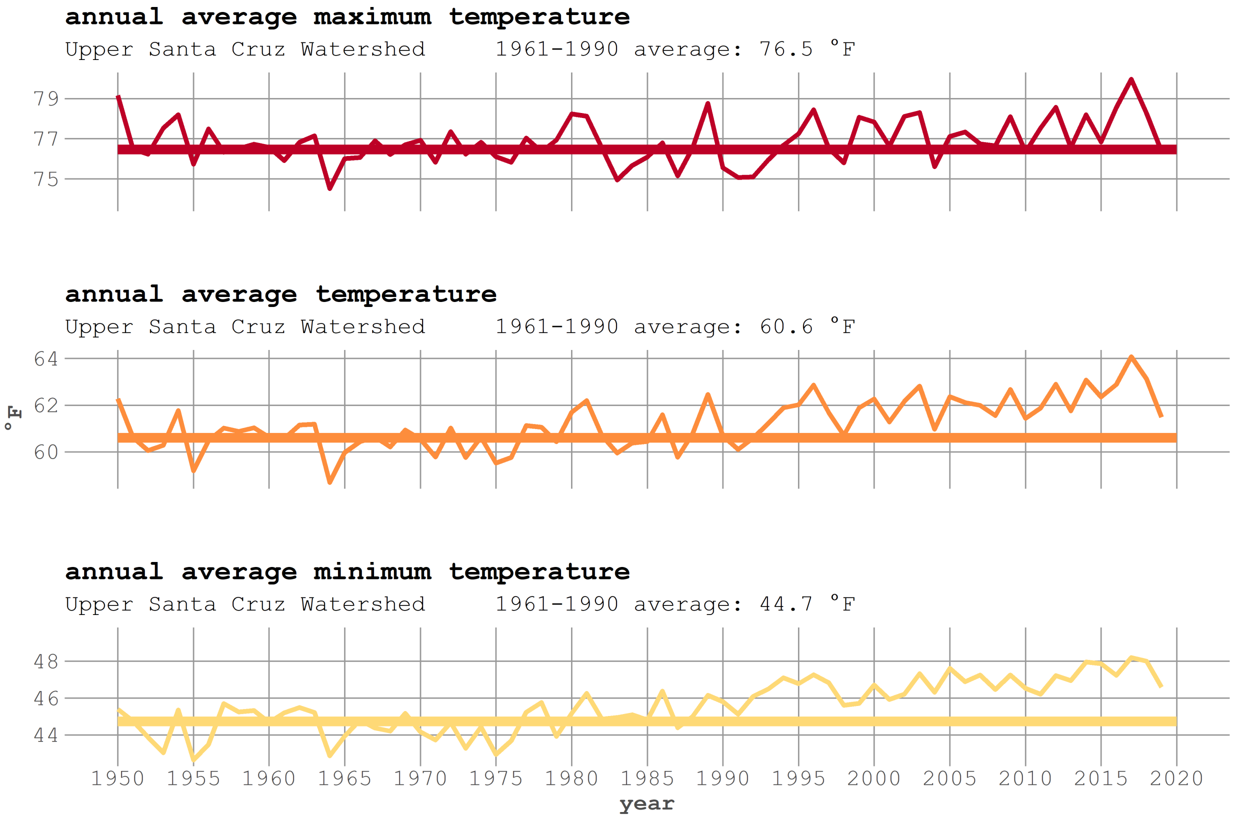

Figure 3: Maximum, average, and minimum annual temperatures in the USCW 1950 - 2019.

Precipitation in Historical Perspective

As is normal in the southwestern U.S., annual precipitation across the USCW is highly variable and has ranged from over 31 inches in 1983 to 10.5 inches in 1956. The average annual precipitation across the USCW for the reference period 1961 - 1990 was 19.6 inches (Figure 4). In Figure 4, green bars represent years with above-average precipitation and brown bars represent years with below-average precipitation.

The USCW has experienced periods of generally above-average precipitation (***pluvials***). The most distinct pluvial occurred from 1983 through 1987. Multi-year drought periods (multiple years with below-average precipitation), occurred between 1953 and 1963, 1968 - 1976, and most of the 2000s and 2010s. These drought periods were felt across a broad swath of the Southwest.

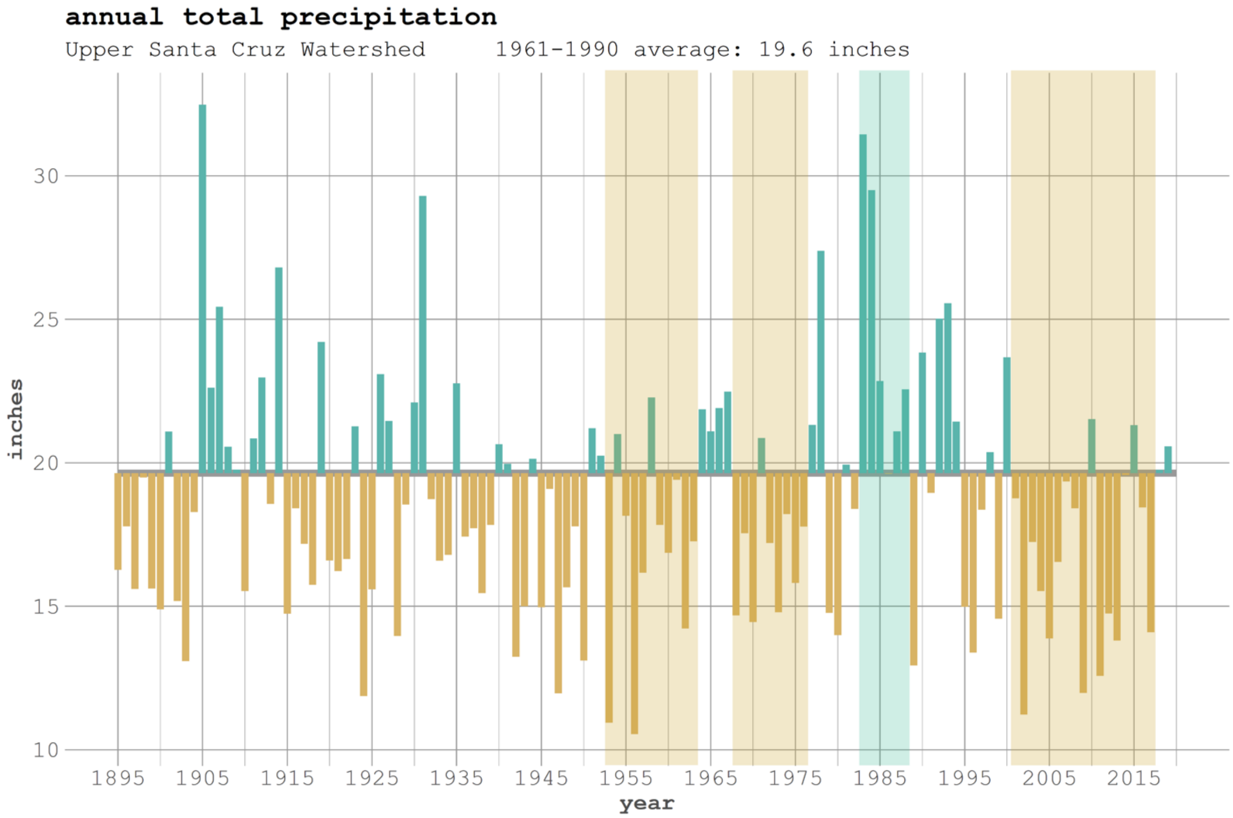

Figure 4: Annual average precipitation in the USCW 1950 - 2019.

Background: Projecting Future Climate Conditions

The Intergovernmental Panel on Climate Change (IPCC), which is the international body of the United Nations responsible for assessing climate changes and impacts across the globe, has used scenarios to project possible future climates for the world as a whole. Different levels of ***greenhouse gases (GHGs)*** released into the atmosphere will have different impacts on warming temperatures. In order to show this range of possible outcomes, climate scientists use ***Representative Concentration Pathways (RCPs)***, which are scenarios based on assumptions about global levels of economic activity, energy sources, population growth, and other socio-economic factors that influence the rate of GHG emissions. These scenarios are then used in Global Climate Models (GCMs) to estimate future global average temperatures and other climate variables.

Table 1 summarizes the assumptions and projections for the RCPs in Figure 5. Figure 5 illustrates the temperature changes expected with each scenario. The scenarios result in projected changes that are similar until the year 2050, but diverge at that point. This is due to the differences in when each scenario assumes GHG emissions will begin to be reduced.

Table 1. Assumptions and Projections for each Representative Concentration Pathway, represented in Figure 10.

Scenario	**Assumptions**	**Projected Temperature Increase**
RCP 2.6 *green line and shading*	"Best Case Scenario" - assumes that through policy intervention, GHG emissions begin decreasing by 2020 and decline to around zero by 2080, leading to a slight reduction in today's GHG levels by 2100.	Global average temperatures increase 2.5° F (1° C) by 2100 (relative to the 1986 – 2015 average).
RCP 4.5 *aqua line*	Assumes that GHG emissions will peak at around 50% higher than year 2000 levels in about 2040 and then fall.	Global average temperatures increase 4° F (1.8° C) by 2100 (relative to the 1986 – 2015 average).
RCP 8.5 *red line and shading*	"Business as Usual" - Assumes GHG emissions continue to grow at current rate through 2100.	Global average temperatures increase more than 8° F (3.7° C) by 2100 (relative to the 1986 – 2015 average).

Figure 5 shows the projected global temperature increases under the emissions scenarios described in Table 1. The green line represents the low emissions scenario (RCP 2.6). The blue line represents the moderate emissions scenario (RCP 4.5). The red line represents the high emissions, or business-as-usual, scenario (RCP 8.5). The black line represents the observed emissions (left panel) and the observed global temperature (right panel). Our global GHG emissions are closest to the red, RCP 8.5 line. Unfortunately, RCP 2.6 is no longer a realistic scenario. We include it here because it is still used as reference in a number of national and international documents. We can assume that future temperatures are likely to be closer to the business-as-usual (RCP 8.5) scenario temperature projections if the current emissions trend continues. Although there is a range of possible temperatures for each scenario, they all project rising temperatures.

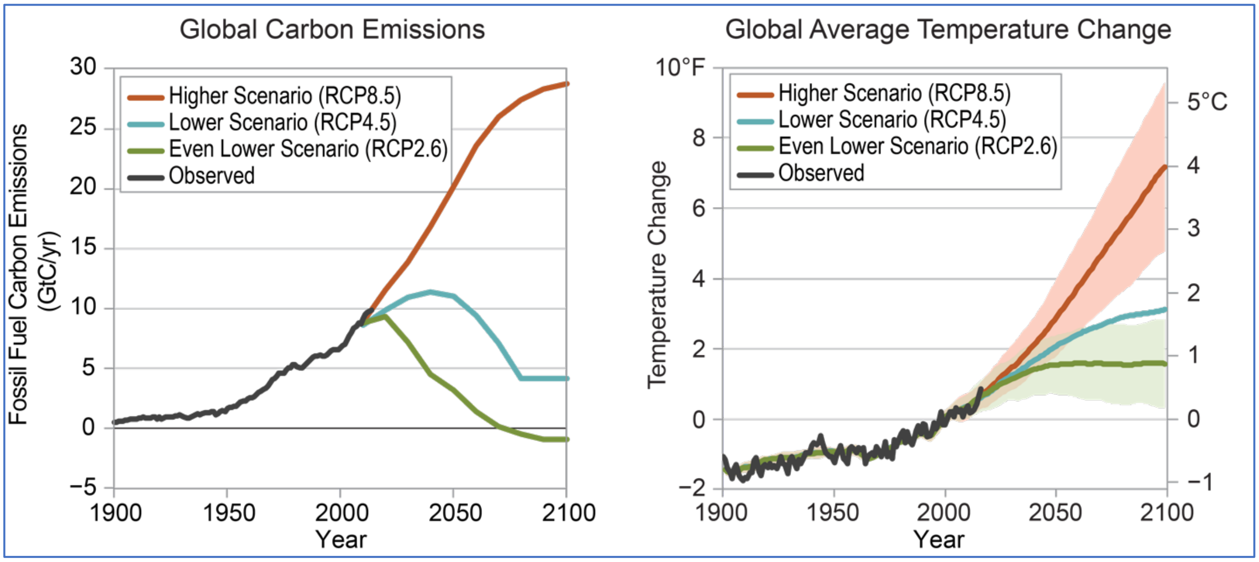

Figure 5: Observed and projected changes in global average temperature (right) depend on observed and projected emissions of carbon dioxide from fossil fuel combustion (left) and emissions of carbon dioxide and other heat-trapping gases from other human activities, including land use and land-use change. Source: Fourth National Climate Assessment; https://nca2018.globalchange.gov/chapter/2#fig-2-2Strengths and Limitations of Climate Models

Global and regional climate models represent, as accurately as possible, the complex atmospheric, oceanic, and other processes that affect the climate. Although they are not perfect representations of the Earth's systems, they have proven remarkably accurate in simulating the climate change we have experienced to date, particularly in the past 60 years, when we have greater confidence in observations. The observed signals of a changing climate continue to become stronger and clearer over time, giving climate scientists increased confidence in their findings (Jay et al. 2018).

Despite their increasing accuracy, climate models still have some limitations that should be kept in mind when seeking to understand projections for the globe or any given region.

- Climate model projections are not yet designed to operationally predict year-to-year variations in climate conditions; they capture long-term changes, such as changes over decades.
- Projections are based on a set of scenarios of possible GHG emissions and how those are likely to affect the climate system. These are possible future conditions – *not predictions* of future conditions.
- Climate scientists are confident in the direction of change the models show – things are getting warmer under all scenarios and in the observed record. However, there is less certainty about the ***magnitude of change***, or exactly how much warming will occur.

Climate scientists increase their level of confidence by using multiple models in their analyses (not relying on just one source of data). The projection data presented in this report come from a combination of 32 climate models. As the 2018 Fourth National Climate Assessment notes, the biggest source of uncertainty in future climate projections is not within the climate models themselves, but in our choices as humans in how we respond to the climate crisis and how that affects the actual GHG emissions (Jay et al. 2018). Climate scientists have high confidence in our understanding of the greenhouse effect and the knowledge that human activities are changing the climate in unprecedented ways. **There is enough information to make decisions based on that understanding**.

Downscaled Climate Data

We used the Localized Constructed Analogs (LOCA) dataset for the projections of future climatic conditions presented in this report. LOCA is a technique for ***statistically downscaling*** global and spatially coarser model projections of future climate. The LOCA downscaled climate projections provide temperature and precipitation at grid cells that are 6 kilometers (3.7 miles) across. We included all LOCA cells that intersect with the USCW portrayed in Figure 1. LOCA preserves extreme hot days and heavy rain events better than the previous generation of statistical downscaling approaches and is used in the Fourth National Climate Assessment (Jay et al. 2018). The data cover the period 1950-2100, use 32 global climate models, and provide analyses based on the RCP 4.5 and 8.5 scenarios discussed above.

Projected Temperatures for the Upper Santa Cruz Watershed

Downscaled model projections for the USCW (Figure 6) show a range of possible future temperature increases, from almost 6° F higher than the 1961-1990 average for RCP 4.5 (orange line and shading) to over 11° F higher for RCP 8.5 (red line and shading) by the year 2100[3]. The average temperature for the USCW for the 1961-1990 reference period is about 60° F. By the end of the century, annual average temperature could be between 66° F (lower scenario) and 71° F (higher scenario). For comparison, the annual average temperature in Tucson, AZ now is approximately 68° F. **The projections for the USCW average temperature are even higher than projections for the global average temperature.**

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[3] Annual values of differences in average temperature relative to the period 1961-1990 and based on daily 1/16-degree Localized Constructed Analogs statistical downscaling of CMIP5 global climate model projections (loca.ucsd.edu) using RCPs 4.5 and 8.5. Averages are computed from data overlying the USCW area shown in Figure 1.

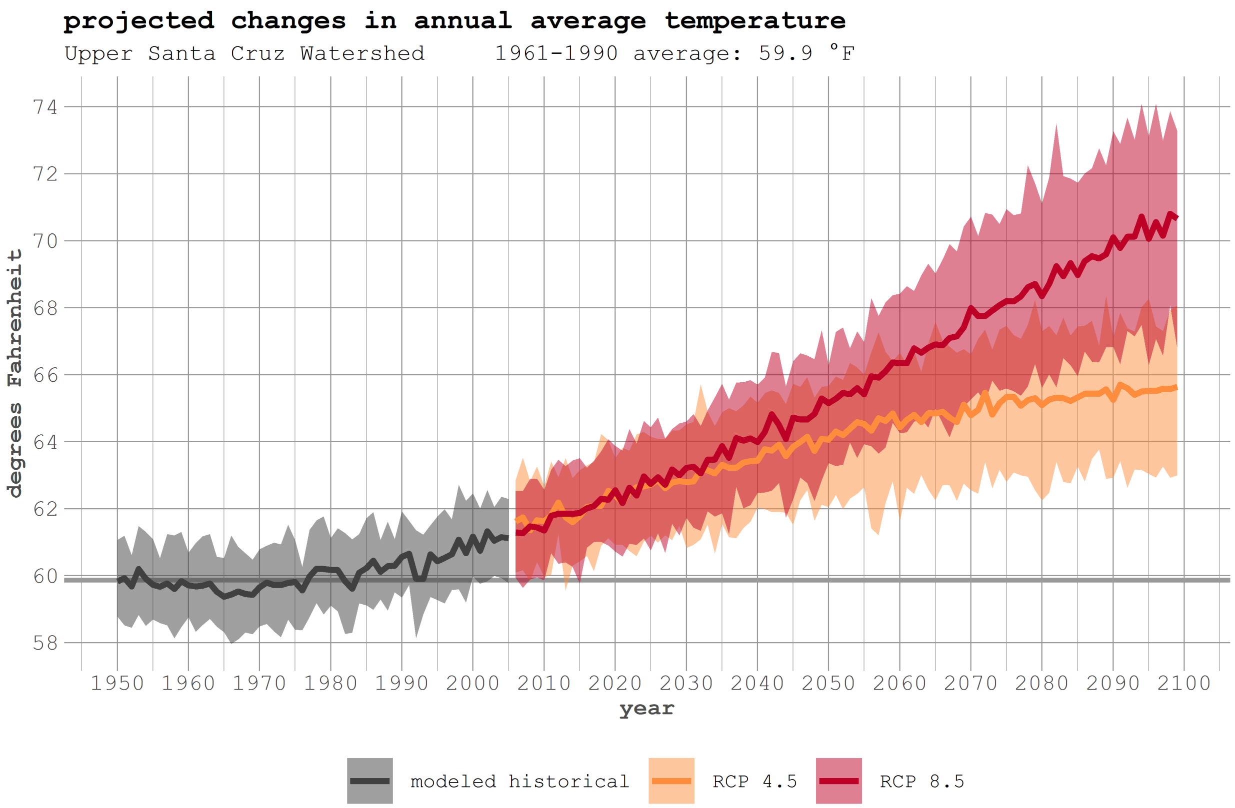

Figure 6: Projected changes in annual average temperature to 2100 for the USCW.

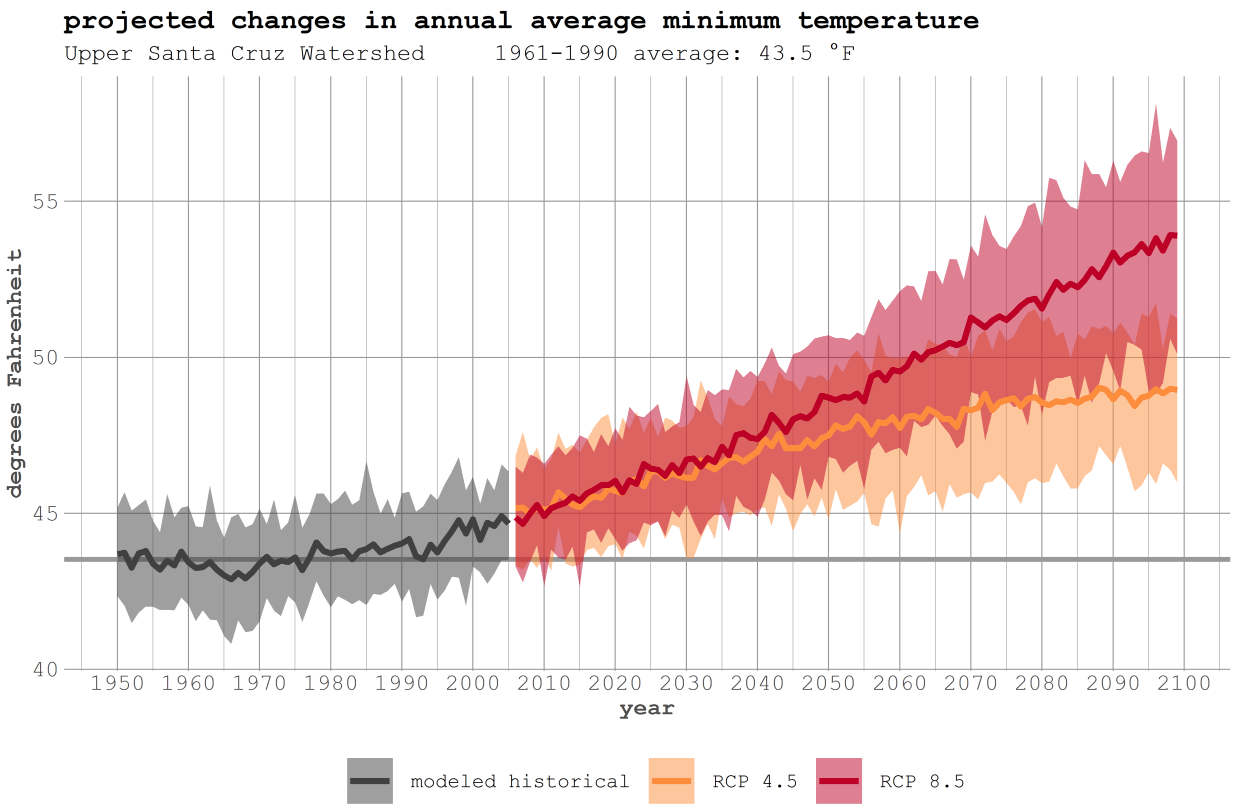

Figure 7: Projected changes in annual average minimum temperature to 2100 for the Upper Santa Cruz Watershed.

As noted in the discussion of observed temperature trends, rising minimum temperatures are driving a large portion of the overall warming trend. In the USCW, the annual average minimum temperature has been 43.5° F, but could reach to between 49° F and 54° F by the end of the century (Figure 7).

Precipitation Projections for the USCW

While the projections for *temperature* show increases in both scenarios, **the projections show less directional change in annual total *precipitation* for the USCW** (Figure 8).[4] The light blue line, representing the moderate scenario, projects a change of about 1 inch less in annual precipitation (total precipitation includes both rain and snow, which is measured as snow-water equivalent) by the end of the century. The dark blue line, representing the higher scenario, shows the potential for a reduction of about 2 inches in annual total precipitation by the end of the century. However, there is uncertainty in these projections, which is discussed in greater detail below. Because of the uncertainty, many climate scientists recommend assuming that annual

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[4] There is a slight difference between the modeled historical precipitation data and the observed record data. Figure 7 contains a modeled historical average of just over 18 inches per year, while the observed record is 19.6 inches per year. This is due to the challenge of accurately capturing a particularly complex precipitation regime in climate models. Because the observed record falls well within the model spread (grey shaded area), we retain confidence that the models are representing the climate system as well as currently possible.

total precipitation in the region on average will remain close to past climatological values, with year-to-year variation as we see now.

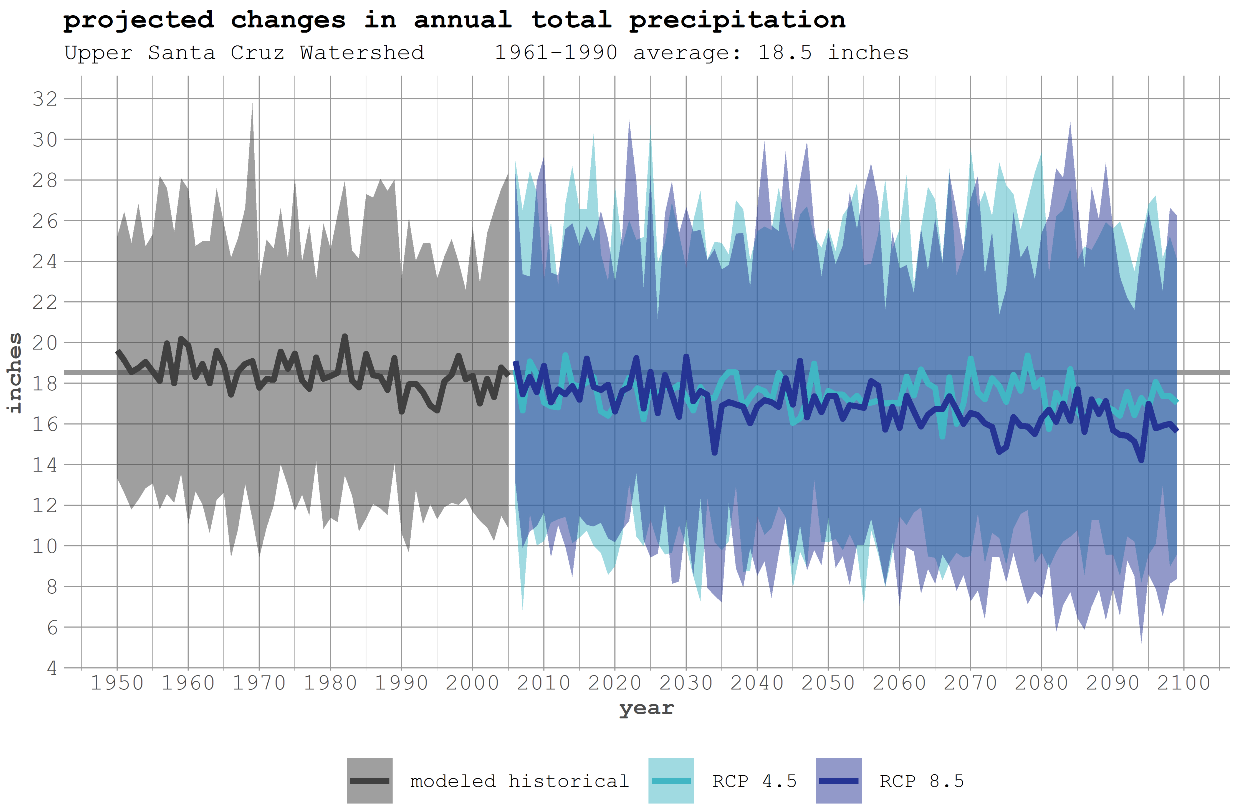

Figure 8: Projected changes in annual precipitation in the USCW.

Projections for seasonal precipitation give a fuller picture of how precipitation may change at different times of the year. The four figures below (Figures 9 - 12) show precipitation for each season. Both spring and summer precipitation could fall, based on these projections (Figures 10 and 11), with spring precipitation possibly declining about 1 inch by the end of the century and summer declining potentially as much as 2 inches.

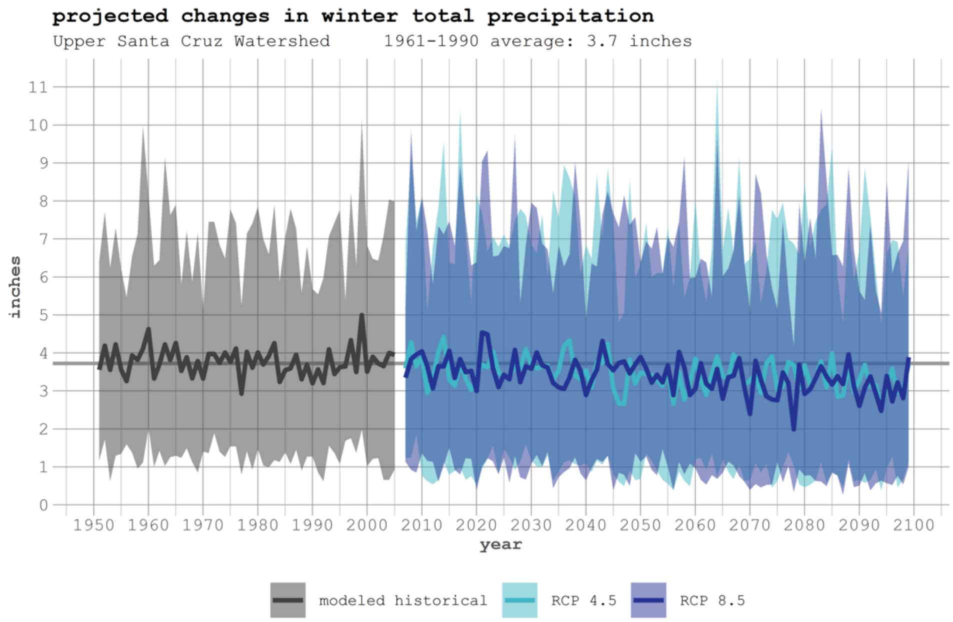

Figure 9: Projected changes in winter precipitation in the USCW.

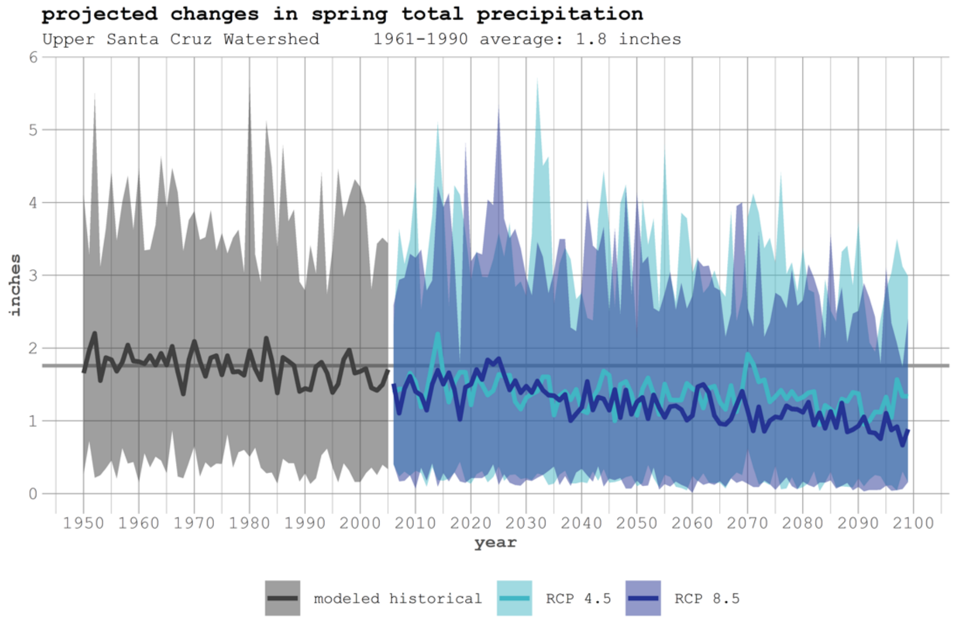

Figure 10: Projected changed in spring precipitation in the USCW

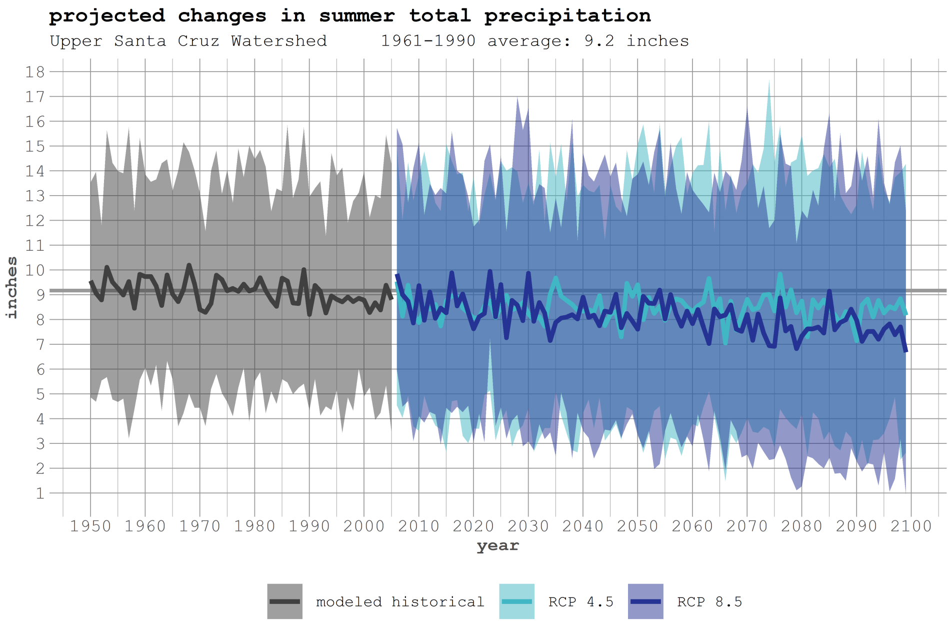

Figure 11: Projected changes in summer precipitation in the USCW

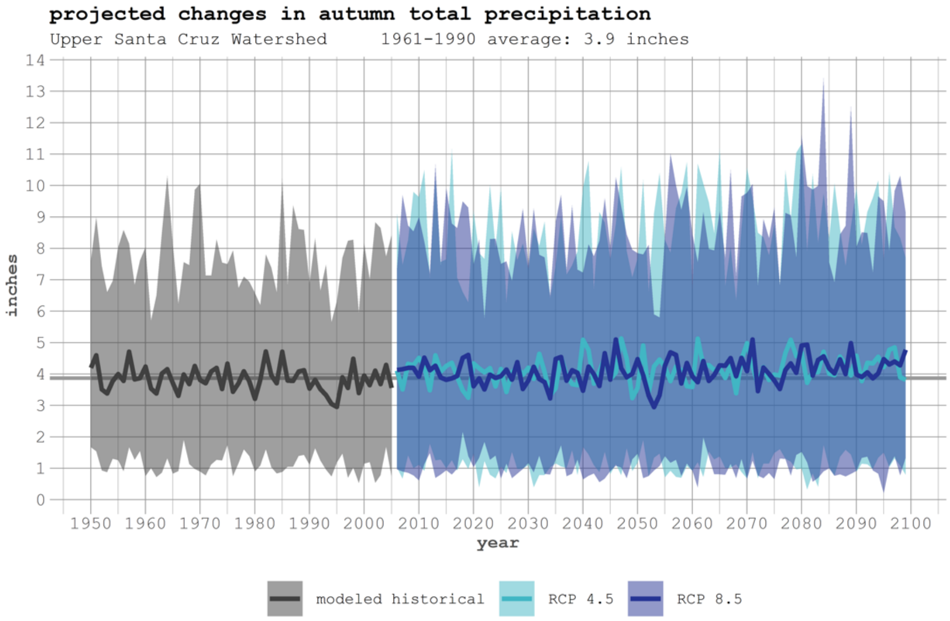

Figure 12: Projected changes in autumn precipitation in the USCW.

Uncertainty in Precipitation Projections

It is important to note that modeling precipitation for the Southwest has proven difficult due to the multiple phenomena that influence this region, including the El Niño Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), the North American Monsoon (NAM), and atmospheric rivers (narrow corridors of concentrated moisture in the atmosphere that generate extreme precipitation events in the western U.S.). Projections of annual average precipitation in the Southwest region are less certain than projections of future precipitation in other parts of the country (Gershunov et al. 2013)[5]. However, **even if there is no change in total precipitation, the USCW could become much drier as projected warmer temperatures will mean more evaporation of surface water and more transpiration (use of water by plants), which will further dry the soil, with the potential changes in soil moisture particularly large in the winter and spring (Figure 13).**

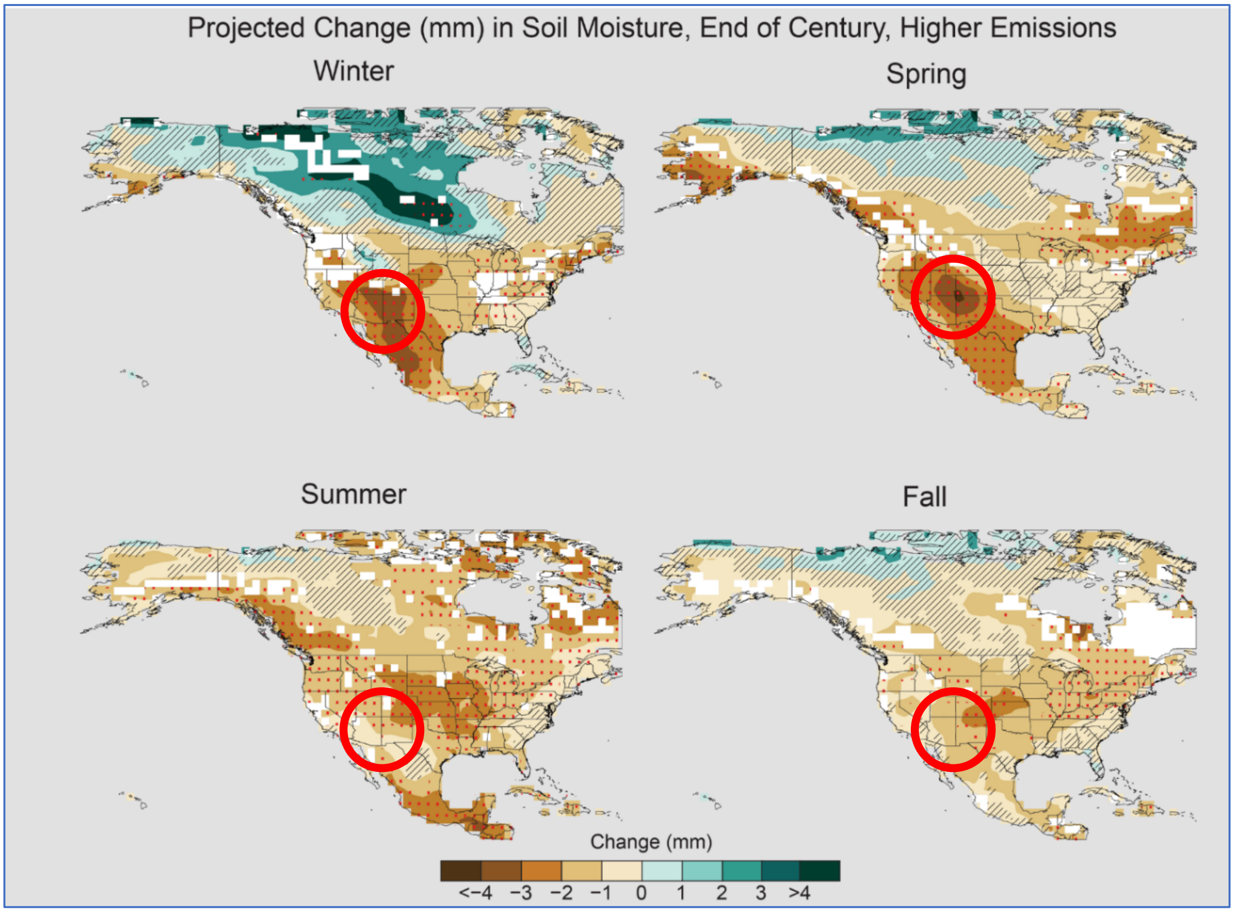

Figure 13 Projected changes in soil moisture by 2100 using the high emissions scenario. Source: https://science2017.globalchange.gov/chapter/8/

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[5] The authors of the 2013 Assessment of Climate Change in the Southwest United States expressed only medium-low confidence in projections related to precipitation changes in the region (Overpeck et al. 2013).

Changes in Character of Precipitation

Recent research on the North American Monsoon (NAM) points to changes that may affect the character of precipitation in the USCW. Warmer temperatures are related to expansion and intensification of the monsoon ridge, with a net result of fewer storms across Arizona during the peak of the monsoon season (late-July to mid-August) (Lahmers et al. 2016). This generally has led to a decline in seasonal precipitation totals during the last 30 years (1980–2010) as compared to the period from 1948–1979, particularly in low-elevation desert areas (Luong et al. 2017). Even though there have been fewer storms, the heaviest rain events have become more extreme (as measured by the amount of precipitation and wind gusts). This is because a warmer atmosphere can hold more moisture, which in turn can contribute to more extreme precipitation events. Between 1980 and 2010, during the latter part of the monsoon (mid-August to September), some higher elevation areas have experienced increases in total precipitation amounts as thunderstorms that develop over this high terrain have moved less frequently into the lower deserts. These storms have stayed in more mountainous areas, which also increases the flood potential in those areas (Lahmers et al. 2016). These patterns are projected to continue into the future**. While the overall average amount of precipitation may not change substantially, the USCW may receive that precipitation in fewer, but more intense storms** (Castro 2017).

Additionally, higher temperatures in the winter will result in more precipitation falling as rain than snow as well as the snowline moving to higher elevations. Higher spring temperatures will mean earlier snowmelt. The combination of these changes will likely lead to reduced snowpack and changes in the timing of streamflow. The impacts of these changes on streamflow, recharge rates, and other water availability issues are discussed in the Impacts section below.

Drought

Even without changes to annual average precipitation, rising temperatures are likely to make drought conditions worse because of increased evaporation of water from surface sources and transpiration from plants. Both streamflow levels and soil moisture levels are likely to be impacted. Paleoclimate records, in this case tree rings, indicate that in the past droughts lasting multiple decades (termed “megadroughts”) have occurred in the Southwest, with aridity as bad or worse than the worst droughts of the 20th century. These megadroughts, lasting at least 35 years, occurred about once or twice per thousand years. If temperatures rise by more than 9° F (5° C), the risk of megadrought in the Southwest will be almost 100% by 2100 (Ault et al. 2016). Megadroughts could occur an average of once every 200 years, based on moderate and high emissions scenarios (Ault et al. 2014). Shorter but still significant droughts lasting at least 11 years could occur 1.5 to 1.75 times per 100 years, under all future emissions scenarios.

Temperature Extremes

It is not just average temperatures that are changing. The USCW region is likely to experience changes in temperature extremes – both high and low temperatures – in the future. Between 1961 and 1990, the USCW experienced about 6 days each year where maximum temperatures reached or exceeded 100° F. However, temperature projections indicate that the area could have approximately 35 days above 100 even under the moderate RCP 4.5 scenario and as many at 80 days over 100 under the RCP 8.5 scenario.

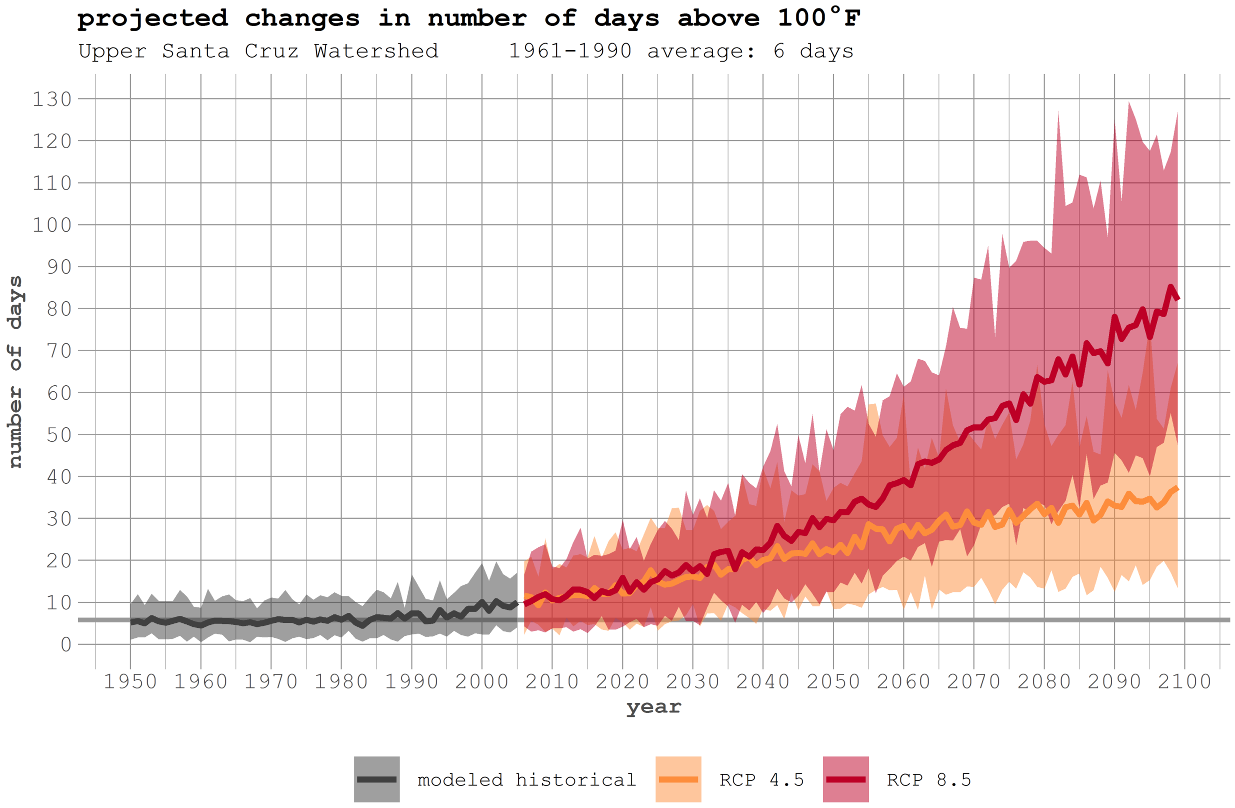

Figure 14: Projected changes in number of days about 100° F in the USCW; the region may see between 35 and 80 days above 100° F by the end of the century.

High temperatures can have greater impacts on people, animals, and plants when they last multiple days. Between 1961 and 1990, the USCW experienced an average of just over 1 incident of 2 or more days with high temperatures above 100° F. By the end of the century, such heatwaves could occur between 6 (moderate scenario) and 8 (higher scenario) times each year (Figure 15).

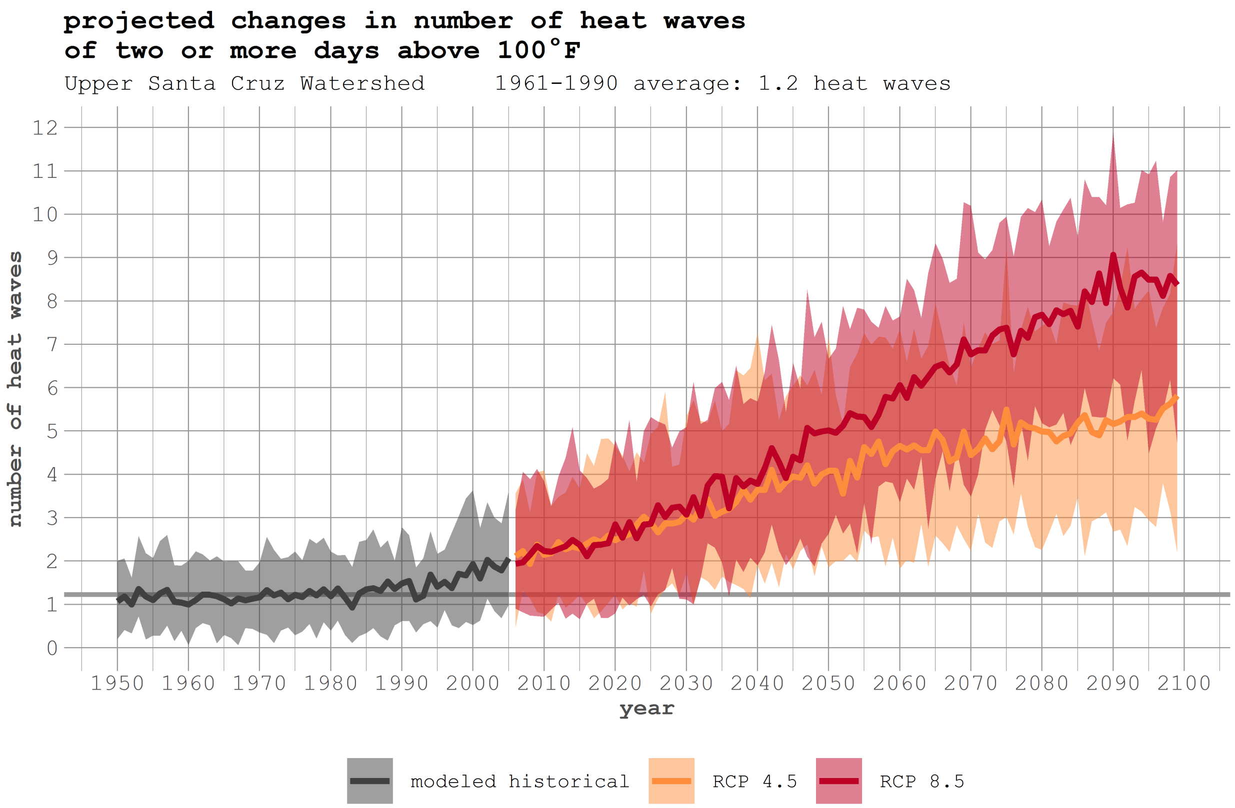

Figure 15: Projected changed in number of heat waves of two or more days above 100° F in the USCW; the region could experience between 6 and 8 such events per year by 2100.

Just as high temperature days are climbing, we see that low temperature days are declining. Between 1961 and 1990, the area experienced about 86 days each year with low temperatures dipping to 32° F or colder. Already since 1990, most years have not had even this average number of cold days. Under the moderate change scenario, the area could see just under 50 cold days each year. Under the higher scenario, there could be fewer than 25 cold days each year Figure 16).

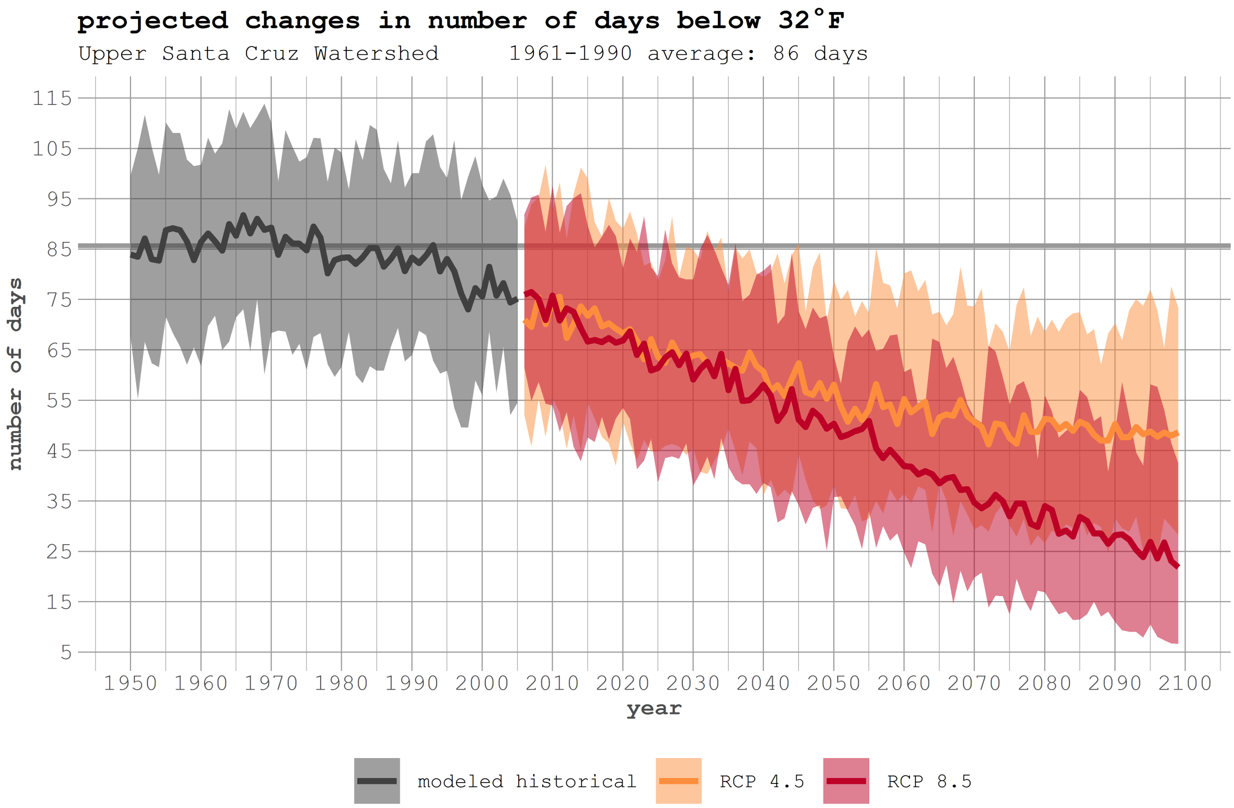

Figure 16: Projected changes in number of days with low temperatures below 32° F in the USCW; the region may experience as few as 25 cold days each year by 2100.

Growing Season

Warmer temperatures and fewer cold days have implications for plant growth and the agricultural industry in the USCW. The growing season is generally considered to be the time between the last freeze (<32° F) in the spring and the first freeze (<32° F) in the fall. The growing season in the USCW was about 200 days per year between 1961 and 1990. Based on the projected temperature changes for the USCW, the growing season is likely to increase by between about 40 days (lower scenario) and 70 days (higher scenario) by the end of the century (Figure 17). It is important to note that the longer growing season comes with higher temperatures, drier soils, and increased water demand by plants including agricultural crops.

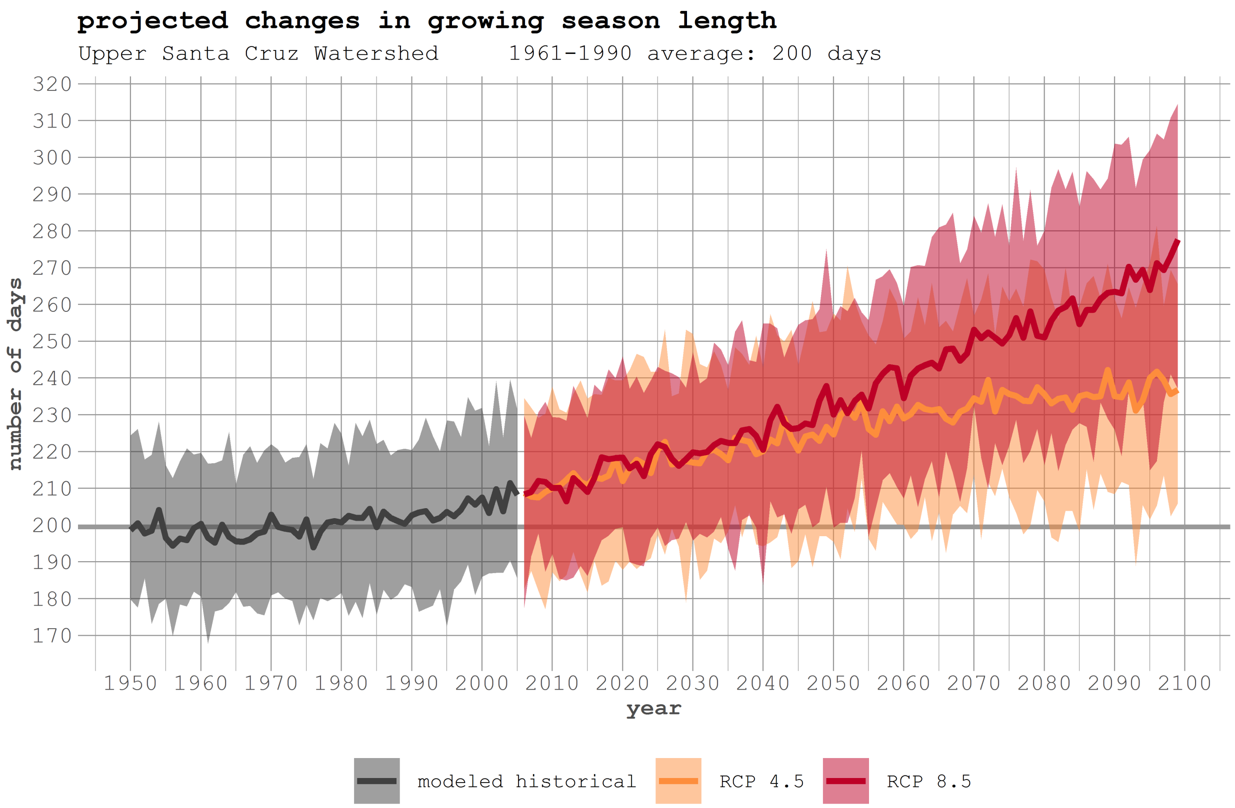

Figure 17: Projected changes in growing season length in the USCW; the region may see its growing season extended by between 40 and 70 days each year by 2100.

Precipitation Extremes

With the changes to the North American Monsoon discussed above, we might expect to see changes in extreme precipitation reflected in the climate projections. However, this is a situation in which the uncertainty in the model accuracy affects our ability to generate a clear picture of the future. Between 1961 and 1990 the USCW had an average of 12 days per year with precipitation totaling over 1 inch. The projection data do not indicate much change in this pattern (Figure 18) – it is likely that the frequency will stay approximately the same, with perhaps 1 – 2 fewer days above 1 inch. Figure 19 portrays the projected changes in number of days with precipitation above 2 inches, which indicates a slight up-tick from the long-term average of 1.8 days per year to between 2 and 3 days per year by the end of the century.

Another way to explore changes in extreme precipitation is by looking at the number of days each year without measurable precipitation (dry days). Over the reference period of 1961 – 1990, the USCW had an average of 267 days per year without precipitation. The model projections indicate that the region could experience an additional 8 (moderate scenario) to 20 (higher scenario) days without precipitation by the end of the century (Figure 20).

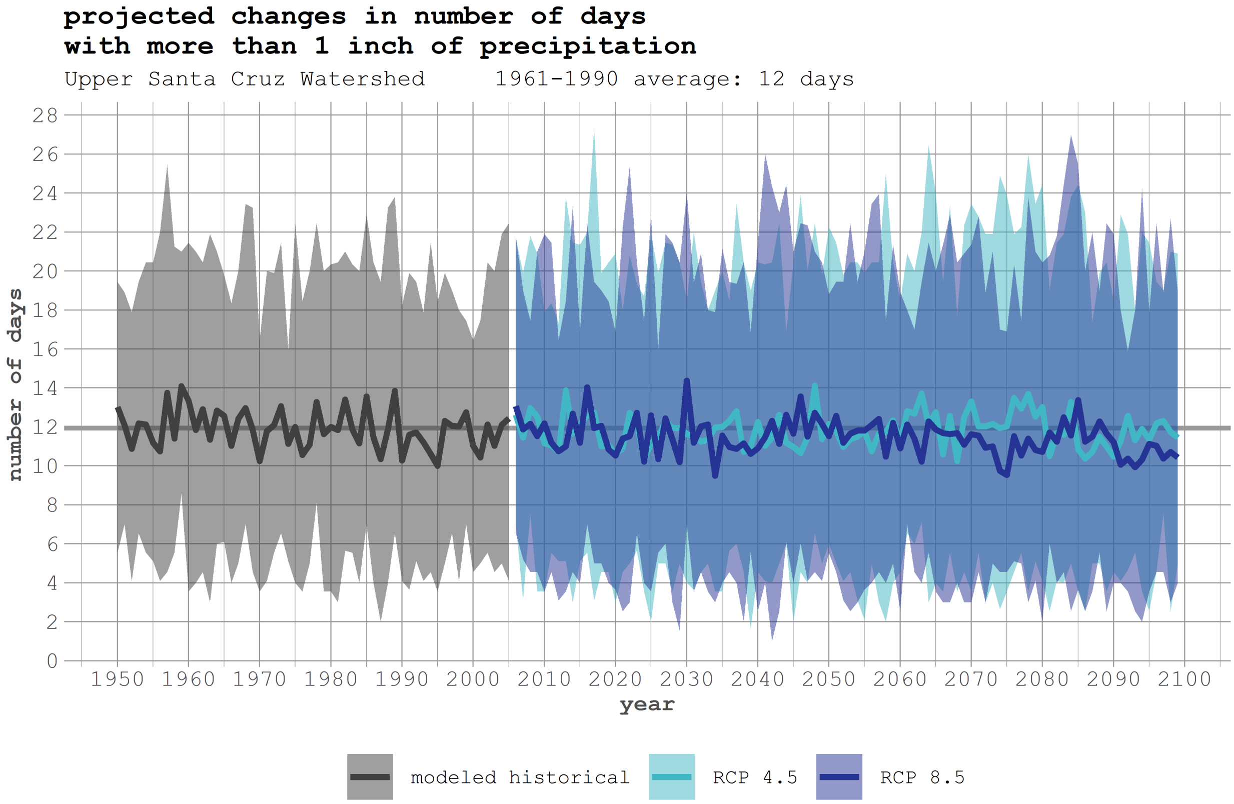

Figure 18: Projected changes in number of days with more than 1 inch of precipitation each year; the USCW averages about 12 days with precipitation above 1 inch each year – this average frequency is projected to continue in the future.

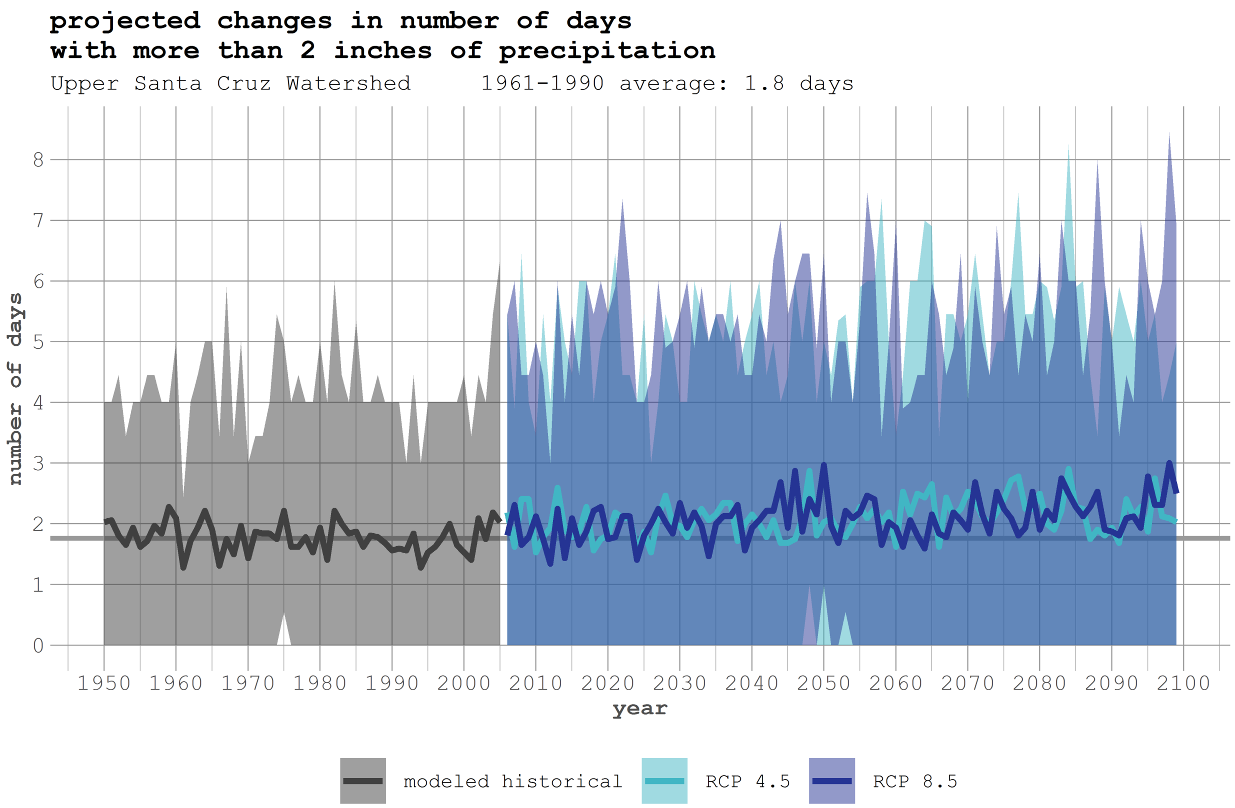

Figure 19: Projected changes in number of days with more than 2 inches of precipitation each year; the USCW averages a little less than 2 days each year with precipitation above 2 inches and may experience 2 – 3 days of this amount of precipitation each year in the future.

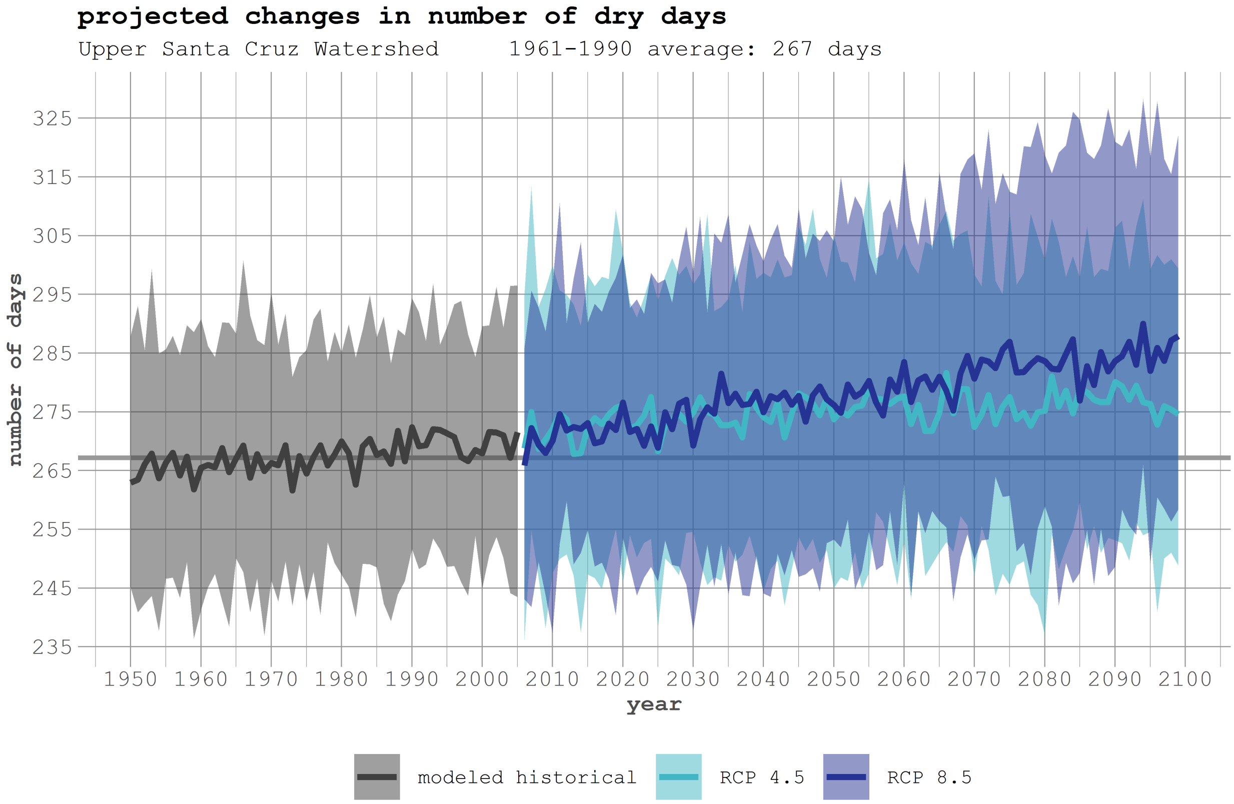

Figure 20: Projected changes in number of days without measurable precipitation in the USCW; the region currently averages 267 dry days each year and may experience 275 – 287 dry days each year by 2100.

What we know about changes in precipitation dynamics encourages us to anticipate about the same or slightly less overall precipitation falling in fewer, but larger storms than in the past. This pattern suggests additional days with extreme precipitation each year. Although current climate models do not fully represent processes that lead to high rainfall amounts, recent observations during the monsoon already are documenting increases in extreme precipitation amounts, a trend that climate scientists anticipate continuing (Luong et al. 2017; Castro 2017).

Impacts of Climate Change

The previous section of this report identified the climate drivers affecting the USCW – the changes in the climatic system that will have impacts on the natural and social systems of the region. This section discusses the impacts of those changes in greater depth.

This overview of climate change impacts is based on a literature review of impacts to the general region of southern Arizona. The information provided here can help to place the USCW-specific climate projections into a more practical context. This section does not provide impacts analyses specific to the USCW, except where noted.

Water Availability

Declines in spring snowpack are already being experienced in the Southwest U.S., and the escalating effect of warming will only exacerbate this. Models show a marked reduction in spring snow accumulation in mountain watersheds across the Southwest U.S. (Cayan et al. 2013). The most marked projected declines in snowfall are seen at higher elevations in Arizona and New Mexico (Wi et al. 2012).

Precipitation falling more as rain rather than snow, coupled with earlier snowmelt and in some cases greater sublimation and evapotranspiration, will cause a reduction in late-spring and summer runoff (Cayan et al. 2013). According to the Bureau of Reclamation (2016a) analysis of streamflow projections across the entire Colorado River Basin, streamflow is likely to be reduced in the second half of the 21st century and the peak timing of flow is likely to shift to earlier in the spring . These changes are due to a combination of rising temperatures, falling snowpack, and rising demand for water especially for municipal and industrial use (U.S. Department of the Interior Bureau of Reclamation 2016b).

Figure 21 displays the average streamflow projections for the decades 2020s, 2050s, and 2070s from the Reclamation's Colorado River Basin study. A reduction in streamflow becomes evident in the 2050s (green line) and both a reduction in streamflow and change in peak flow timing are evident in the 2070s (red line), when compared to the 1990s (black line).

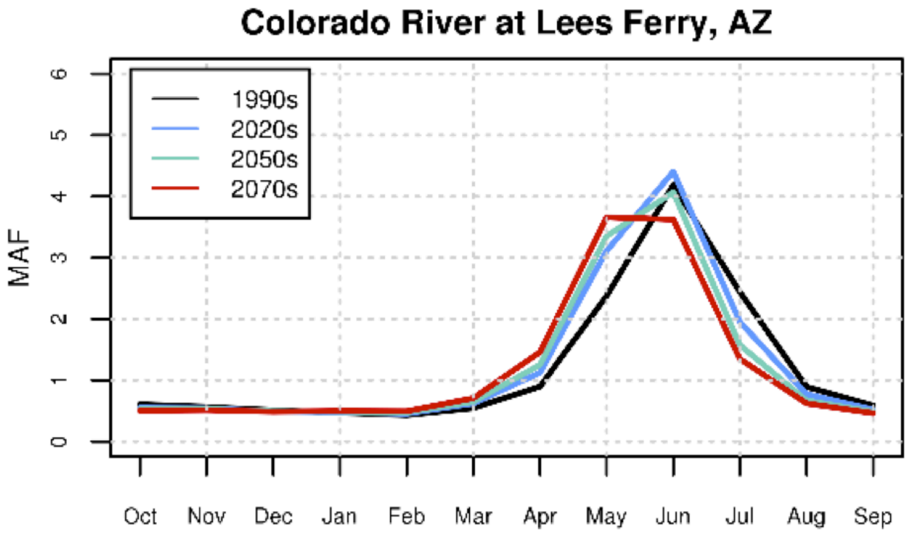

Figure 21: Projected streamflow for the Colorado River at Lees Ferry, AZ. Source: (U.S. Department of the Interior Bureau of Reclamation 2016b).

Studies on aquifer recharge rates in the San Pedro watershed, which shares characteristics with the USCW, indicate that recharge rates will decline over this century by approximately 30% (Meixner et al. 2016). The greatest reduction will come from mountain system recharge, which is negatively affected by the changes in snowfall and snowpack described above. Meixner et al. (2016) note a possibility of a small increase in focused recharge because of higher intensity storms and water running in washes and streams.

In the USCW, streamflow and aquifer recharge may be more impacted by urban water use and other management decisions than directly by climate change impacts (Shamir et al. 2015; Scott et al. 2012). However, higher temperatures will contribute to reductions in surface water including rivers, streams, and water holding tanks, because of increased evaporation rates. Lower recharge rates and continued groundwater pumping both contribute to an increase in depth-to-water in wells and increased drilling costs.

The Bureau of Reclamation currently is conducting a technical assessment of water resources in the Lower Santa Cruz River Basin, with consideration of potential impacts from climate change (https://www.usbr.gov/lc/phoenix/programs/lscrbasin/LSCRBStudy.html). Being an adjacent watershed to the west and north, results from this work may provide additional insight on future water availability for the USCW related to issues like groundwater levels, as well as on adaptation and mitigation strategies.

Water Quality

There are three main impacts to water quality from rising temperatures and changes in precipitation patterns: the effects of wildfires on surface water, the effects of drought, and the interaction between extreme precipitation and non-point source pollution. Wildfires, especially very large fires, can significantly alter landscapes and watersheds. When rainfall occurs up to a few years after a fire, erosion increases and changes in runoff greatly increase the amount of sediment that is transported downstream, in some cases increasing it up to 20 times normal levels (Garfin et al. 2016). Stormwater runoff from a burned area can also include higher concentrations of trace elements, organic carbon, pH and nitrates and sulfates (Smith et al. 2011).

More frequent and longer droughts, and associated low stream and reservoir levels, can increase the concentrations of nutrients in streams, such as ammonia and nitrate, potentially raising the likelihood of harmful algal blooms and low oxygen conditions (Geogakakos et al. 2014).

With higher temperatures, more precipitation falls as rain instead of snow, increasing the amount of pollutants that wash from the ground and paved surfaces into streams and reservoirs as compared to what would derive through slow percolation from snowmelt (Geogakakos et al. 2014).

Wildfire

Given climate change projections, substantial increases in the area burned by wildfires are projected in the future (Hurteau et al. 2014). The National Research Council (2011) estimates a 380% increase in area burned in the Southwest with a 1° C (roughly 2° F) increase in average temperatures. Under higher emissions scenarios, fire frequency could increase 25% and the frequency of very large fires (greater than 12,000 acres) could triple (Gonzalez et al. 2018). In addition to the effect of the warming trend, human-caused fires are also increasing. The majority of contemporary fires in the United States are human-started; for the period of 1992–2013, 84% of ignitions were human-caused (Balch et al. 2017), and that rate is increasing (Cattau et al. 2020). However, lightning-caused fires are still more common than human-caused in the Southwest (Balch et al. 2017).

In specific areas, the occurrence of larger, more frequent fires may be tempered if fuels are less available or flammable in any given year (due to drought or past fires, for example) (Littell et al. 2018). Despite the overall trend in larger, more frequent fires, there will still be year-to-year variability in fire events.

Invasive grasses, like Lehmann lovegrass and buffelgrass, as well as the transition to woody plants, increases fire risk in grasslands (Aslan et al. 2018). This creates a positive feedback loop in which fire further harms native species that are not fire adapted and contributes to even more rapid shift away from a native grassland ecosystem. Fire management that encouraged fire suppression has also contributed to encroachment of creosote and mesquite in grassland systems (Aslan et al. 2018).

Post-fire flooding

The combination of more frequent, larger forest fires and more extreme precipitation can lead to more post-fire flood events, although post-fire debris flows can occur with relatively “normal” storms (Garfin et al. 2016). Post-fire floods can decrease water quality by pushing sediment into water sources, with effects lasting up to 10 years after the fire. Neighborhoods and community water systems in the wildland-urban interface (WUI) may be at greater risk from wildfire and post-fire floods/debris flows (Garfin et al., 2016).

Post-fire floods can also impact streamflow by changing the geomorphology of a basin, create hazards because of debris flows on roads, houses, and other infrastructure, and damage ecosystems by eroding and denuding landscapes.

Flooding

More extreme storms are likely to increase flood risks, particularly in places that are already flood-prone, such as areas near rivers, creeks, and washes. Adjacent areas that do not regularly flood now could become flood-prone with larger storm events. The study of changes in aquifer recharge rates discussed above noted the possibility of increased flows in washes and small streams, for example (Meixner et al. 2016). In the USCW, one study found that the impact of groundwater pumping may offset changes in flood magnitude in the Santa Cruz River in such a way as to keep riverine flood risks about the same in the future, despite the potential for more extreme storms (Duan et al. 2017). However, this is only one study and should be considered within the context of the broader trends.

Agriculture

Even if precipitation totals remain relatively consistent into the future, rising temperatures will lead to drier soils and increased water demand by plants. Current projections indicate a reducing in soil moisture across the whole country, with the Southwest experiencing drops of 2 – 3mm, particularly in the winter and spring, by the end of the century (Wehner et al. 2017).

Warming and drying are already negatively impacting rangeland conditions and available forage. Hotter temperatures can increase the heat stress on livestock and contribute to disease proliferation (Hatfield et al. 2014; Gaughan et al. 2009). These conditions may lead to pressures to buy additional feed, reduce herd size, lease additional grazing land, or overgraze rangeland (Frisvold et al. 2013). Using more heat-adapted varieties of livestock is another possible adaptation strategy (see for example, Anderson et al. 2015). Ranchers in Santa Cruz County likely use many of these coping mechanisms already to deal with current and recent conditions. Longer-term adaptation strategies should draw on the management practices ranchers find most effective and most flexible.

Most agriculture land in Santa Cruz County is not irrigated. For those crops that are irrigated, increasingly dry conditions may raise questions about the viability of alternative irrigation practices. However, there are trade-offs to consider with new irrigation approaches. For example, drip irrigation is not necessarily a straightforward solution because, while it requires less water to be applied than with flood irrigation, crop evapotranspiration is higher using drip irrigation (as are crop yields) and less water can percolate back into the ground to recharge groundwater (Ward and Pulido-Velazquez 2008).

Studies of irrigated agriculture across the state have found that alfalfa, a commonly used feed crop for livestock, requires substantial amounts of water (6.4 acre feet/acre) (Frisvold 2013, p.224). Alfalfa quality can also be diminished by high temperatures, a phenomenon referred to as summer slump. “Water stress, low root carbohydrate levels, and high temperatures cause premature flowering and thus low yield. Summer-slump alfalfa is usually low in quality and not suitable for lactating dairy animals" (Elias et al. 2015, 23). Other crops require less water/acre (for example, other hay crops use 4.2 acre feet/acre in Arizona) and could be part of adaptation strategies if ranchers determine that they are suitable replacements for alfalfa.

Warming temperatures may increase pest persistence because pests will not be killed off by cold winter temperatures (Frisvold et al. 2013). Additionally, invasive nonnative or alien insect pests (introduced into the region intentionally or unintentionally) that are more adapted to hotter temperatures could present a risk to agricultural production (Gonzalez et al. 2018).

Ecosystems

Rising temperatures are negatively impacting grassland ecosystems like those found in the USCW. In particular, "warm drought" – drought in which the driving factor is higher temperatures rather than lower precipitation – seems to slow the recovery of native grasses and opens the door for non-native species and woody shrubs to move in (Moran et al. 2014). This pattern seems to be exacerbated by a reduction in spring precipitation, which is projected to occur in the USCW (see Figure 10 above) (Bodner and Robles 2017). In particular, Lehmann lovegrass is a problem for native grasslands because it often moves in to degraded grasslands first (Moran et al. 2014).

In the riparian areas, tamarisk is encroaching on riparian habitat (Aslan et al. 2018; Zavaleta 2000). In addition to outcompeting native tree species, tamarisk also uses excessive water, which contributes to the further reduction of available surface and groundwater.

There are 29 species listed as threatened, endangered, or a candidate for one of those categories in Santa Cruz County (https://ecos.fws.gov/ecp/report/species-listings-by-current-range-county?fips=04023), all of which are adversely affected by habitat changes such as those described above.

Glossary

Aspect: A surface feature of land: the direction a slope faces. A slope's aspect determines the amount of sun exposure it receives, so aspect affects temperature, humidity, and the type and amount of vegetation in a particular place.

Climate: The averages and patterns of weather over time for a particular area, such as temperature, precipitation, humidity, and wind.

Climate projections: Estimates of future climatic conditions, usually made with mathematical models using different rates of greenhouse gas emissions to create different possible future scenarios.

Climate trends: Changes in climate in a particular area that have been observed over time, such as increases or decreases in average temperatures or the amount of annual precipitation.

Downscaling: Various methods that use data from global climate models to derive climate information for smaller areas of the world, such as specific regions (U.S. Southwest, for example).

Greenhouse gas (GHG): Any of the atmospheric gases that absorbs longwave, or infrared, radiation that otherwise would pass from the Earth's surface through the atmosphere and into outer space. They include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (NO_2), and water vapor.

Magnitude of change: In climate models, the magnitude of change is how much the climate is projected to change over a given period of time. Climate scientists generally have more confidence in models' ability to project the *direction* of change, such as whether it will be hotter in the future; but not exactly how much hotter it will be.

Pluvial: A period of time, often multiple years, in which a particular area experiences abundant or well-above average precipitation.

Representative Concentration Pathways (RCP): Scenarios of different levels of greenhouse gas emissions that are used to estimate future global temperatures. The four RCPs used by the Intergovernmental Panel on Climate Change are 2.6, 4.5, 6.0, and 8.5; the numbers represent changes in radiative forcing, or the amount of outgoing infrared radiation relative to incoming shortwave solar radiation, at the top of the atmosphere.

Scenario: A description of a possible future state of the world. Scenarios do not represent what will happen; they represent what could happen, given our activities and choices.

Statistical downscaling: Correlating historical local and regional observations with data from global climate models to derive climate projections at local and regional scales.

Variability: A term to describe year-to-year changes in climatic conditions such as annual temperature and precipitation.

Weather: The day-to-day conditions in a particular area, such as temperature, precipitation, humidity, and wind.

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