Chapter 3: Historical and Projected Climate in the Northern Rockies Region

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Introduction

Climate influences the ecosystem services we obtain from forest and rangelands. Climate is described by the long-term characteristics of precipitation, temperature, wind, snowfall, and other measures of weather that occur over a long period in a particular place, and is typically expressed as long-term average conditions. Resource management practices are implemented day-to-day in response to weather conditions; resource management strategies and plans are developed using our understanding of climate. With the need to consider climate change in planning and management, an understanding of how climate may change in the future in a resource management planning area is valuable. In this chapter, we present the current understanding of potential changes in climate for the Forest Service, U.S. Department of Agriculture (USFS) Northern Region and the Greater Yellowstone Area (GYA), hereafter called the Northern Rockies region.

Climate Model Projections: CMIP3 and CMIP5

Global climate models have been used to understand the nature of global climate by modeling how the atmosphere interacts with the ocean and the land surface. Scientists can use these models to pose questions about how changes in the atmospheric chemistry would affect global temperature and precipitation patterns. Given a set of plausible greenhouse gas scenarios, these models can be used to project potential future climate. These projections can be helpful in understanding how the environmental conditions of plants and animals might change in the future; how runoff and seasonal flows might vary with precipitation and timing of snowmelt; how wildfire and outbreaks of insects and disease might be affected by changes in climate; and how humans might respond in their use of the outdoors and natural resources.

The Coupled Model Intercomparison Project (CMIP) began in 1995 to coordinate a common set of experiments for evaluating changes in past and future global climate (Meehl et al. 2007). This approach allows comparison of results from different global climate models around the world and improves our understanding of the "range" of possible climate change. The third CMIP modeling experiments, or CMIP3, were used in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (Solomon et al. 2007); the latest experiments, or CMIP5, were used in the IPCC Fifth Assessment Report (Stocker et al. 2013).

A key difference between CMIP3 and CMIP5 is the set of emissions scenarios that drive, or force, the simulations of future climate (fig. 3.1, taken from Walsh et al. 2014). The CMIP3 simulations of the 21st century were forced with emissions scenarios from the Special Report on Emissions Scenarios (SRES) (Nakićenović et al. 2000). The CMIP3 scenarios represent futures with different combinations of global population growth and policies related to alternative energy and conventional fossil fuel sources (Solomon et al. 2007). The CMIP5 simulations of the 21st century are driven by scenarios describing representative concentration pathways (RCPs) (van Vuuren et al. 2011). The RCPs do not define emissions, but instead define concentrations of greenhouse gases and other agents influencing the climate system. RCPs present the range of current estimates for the evolution of radiative forcing, which is the total amount of extra energy entering the climate system throughout the 21st century and beyond. Projections made with RCP 2.6 show a total radiative forcing increase of 2.6 Watts per square meter (2.2 Watts per square yard) by 2100; projected increased radiative forcing through the scenarios of RCP 4.5, RCP 6.0, and RCP 8.5 indicate increases of 4.5, 6.0, and 8.5 Watts per square meter, respectively (3.75, 5.0, and 7.1 Watts per square yard, respectively). Unlike the SRES scenarios used in CMIP3, the RCPs in CMIP5 do not assume any particular climate policy actions. Rather, policy analysts and social scientists are free to develop mitigation scenarios that lead to one of the RCPs. Comparisons between CMIP3 and CMIP5 model results for Oregon and Washington are described in box 3.1.

Climate of the Northern Rockies Region

Historical Climate

For historical data, we drew from and contrasted three common gridded historical datasets; Parameter-elevation

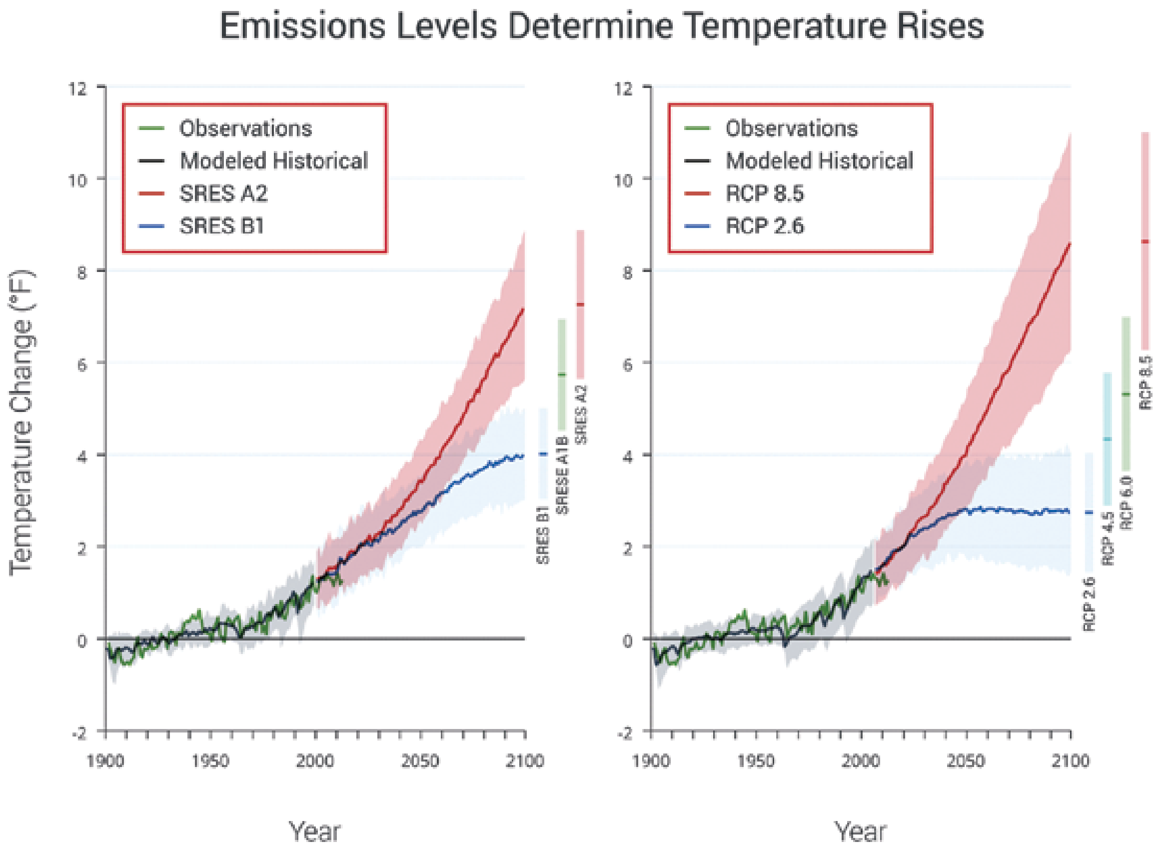

Figure 3.1—Comparison of global temperatures projected with emission levels from CMIP3 (left panel) and with emission levels from CMIP5 (right panel) (figure 2.4 from Walsh et al. 2014). Different amounts of heat-trapping gases released into the atmosphere by human activities produce different projected increases in Earth's temperature. In the figure, the red and blue lines represent a central estimate of global average temperature rise (relative to the 1901–1960 average) for a specific emissions pathway. The shaded areas for a given color indicate the range (5th to 95th percentile) of results from a suite of climate models. The bars to the right of each panel indicate projections in 2099 for additional emissions pathways. In all cases, temperatures are expected to rise, although the difference between lower and higher emissions pathways is substantial. (Left) The panel shows the two main scenarios (SRES – Special Report on Emissions Scenarios): A2 assumes continued increases in emissions throughout this century, and B1 assumes much slower increases in emissions beginning now and significant emissions reductions beginning around 2050, though not due explicitly to climate change policies. (Right) The panel shows results from the most recent generation of climate models (CMIP5) using the most recent emissions pathways (RCPs – Representative Concentration Pathways). The newest set includes both lower and higher pathways than did the previous set. The lowest emissions pathway shown here, RCP 2.6, assumes immediate and rapid reductions in emissions and would result in about 2.5 °F of warming in this century. The highest pathway, RCP 8.5, roughly similar to a continuation of the current path of global emissions increases, is projected to lead to more than 8 °F warming by 2100, with a high-end possibility of more than 11 °F (data from CMIP3, CMIP5, and NOAA NCDC). These results draw on raw GCM data summarized for the entire Earth rather than bias corrected to spatially downscaled GCM models for our regions depicted in all other graphics.

Regressions on Independent Slopes Model (PRISM) (PRISM Climate Group 2014), Maurer (Maurer et al. 2002), and TopoWx (Oyler et al. 2015b). These three gridded historical products are knowledge-based systems that use point measurements of precipitation, temperature, and other climatic factors to produce continuous, digital grid estimates of monthly, yearly, and event-based climatic parameters. Due to differences in the weather-station data used by these gridded products as well as the models and assumptions used to interpolate to a grid, these climate models do not always agree on the historical climate or trend for a region. This is especially true in the western mountains, where PRISM has been shown to have an artificial amplification of a warming trend (Oyler et al. 2015a). For this reason we chose to compare all models rather than the trend and values produced by a single model.

Box 3.1—Comparing CMIP3 and CMIP5 for Temperature and Precipitation Projections for Oregon and Washington

Model Evaluation

One way to evaluate a model's "skill" is to have it simulate (recreate) past climate and compare those results to observed climate. Both CMIP3 and CMIP5 models reproduce important characteristics of climate in the NRAP region fairly well, including wet winters, dry summers, annual temperature, and a 20th-century warming trend (~1.4 °F per century). However, both CMIP3 and CMIP5 models predict annual precipitation that is higher than observations (Mote and Salathé 2010; Rupp et al. 2013).

Future Temperature

- CMIP5 climate experiments based on RCP 4.5 and RCP 8.5 are warmer for the NRAP region, on average, than the CMIP3 scenarios based on SRES-B1 and SRES-A2.
- Most of the difference in temperature projections can be explained through increased forcing between the two sets of emissions-concentration scenarios, rather than modifications to the models between CMIP3 and CMIP5.

Future Precipitation

- CMIP3 and CMIP5 both project a slightly wetter future on average by the mid-21st century.
- CMIP3 and CMIP5 both project slightly drier summers and slightly wetter conditions the rest of the year.
- High natural variability in precipitation masks differences between CMIP3 and CMIP5.

Projected Climate

For an overview of projected climate in the Northern Rockies region, we use downscaled CMIP5 projections based on RCP 4.5 and RCP 8.5 scenarios (fig. 3.2). Output from global climate models is at a scale too coarse to represent climate dynamics in subregions and management areas relevant for the region. Many methods have been developed to bring climate projection information down to a scale that can be helpful to resource managers. We drew on climate projections that had been downscaled using the bias-correction and spatial disaggregation (BCSD) method (Maurer et al. 2007). We obtained the downscaled projection data from the Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections archive (U.S. Department of the Interior, Bureau of Reclamation 2013). We use projections from 36 climate models for RCP 4.5 and 34 climate models for RCP 8.5 (table 3.1). The variables available for each BCSD climate projection include monthly precipitation and monthly surface air temperature for the 1950–2099 period. Spatial resolution of the data is 1/8-degree latitude-longitude (~7.5 miles by 7.5 miles) and covers the entire region. We use a base period of 1970–2009 for the historical climate, and compare projections for two periods (2030–2059, 2070–2099) with this historical climate. These time periods were selected in an attempt to summarize climate that has influenced the current conditions (base period) and two future periods that will be relevant to long-term management action (such as road construction, hydrologic infrastructure, or vegetation planting).

The currently cooler climates associated with the Rocky Mountains are evident as are the warmer parts of eastern Montana and South Dakota (fig. 3.2). All areas warmed under both projections, with a greater warming in RCP 8.5.

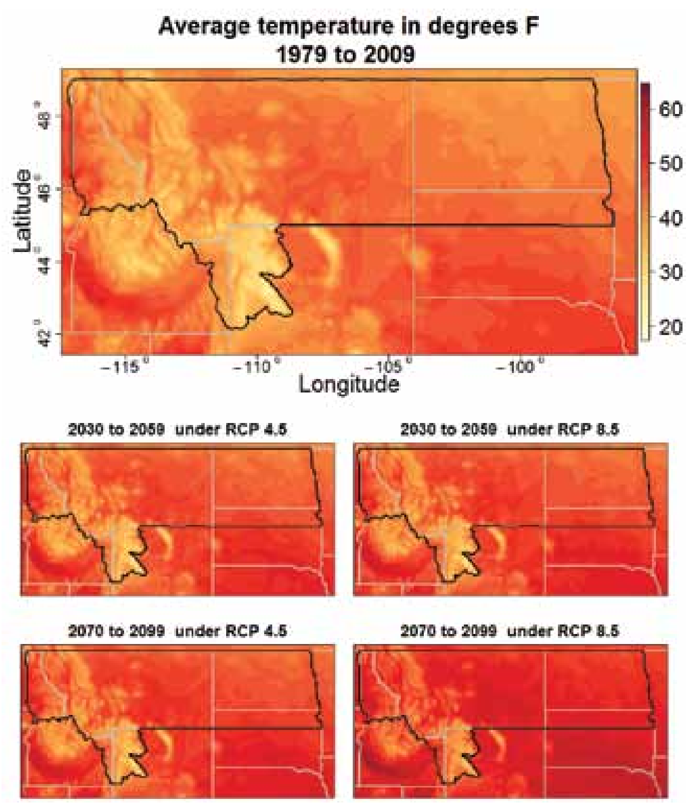

Figure 3.2—Historical (1970–2009) and projected (2030–2059 and 2070–2099) mean annual monthly temperature (°F) for Northern Rockies Adaptation Partnership Region (NRAP) under RCP 4.5 and RCP 8.5 scenarios. Projected climate results are the mean of 36 models for RCP 4.5 and 34 models for RCP 8.5 (see table 3.1). Spatial resolution of the data is 1/8-degree latitude-longitude.

Table 3.1—CMIP5 climate projections for RCP 4.5 and RCP 8.5 scenarios were obtained for these models using the Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections" archive at: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections. The first model run was selected for this analysis.

Institution	Climate model	RCP 4.5	RCP 8.5
Commonwealth Scientific and Industrial Research Organization and Bureau of Meteorology, Australia	ACCESS1-0	X	X
	ACCESS1-3	X	X
Beijing Climate Center, China Meteorological Administration	bcc-csm1-1	X	X
Beijing Climate Center, China Meteorological Administration	bcc-csm1-1-m	X	X
Canadian Centre for Climate Modelling and Analysis	CanESM2	X	X
National Center for Atmospheric Research	CCSM4	X	X
Community Earth System Model Contributors	CESM1-BGC	X	X
	CESM1-CAM5	X	X
Centro Euro-Mediterraneo per I Cambiamenti Climatici	CMCC-CM	X	X
Centre National de Recherches Météorologiques/ Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	CNRM-CM5	X	X
Commonwealth Scientific and Industrial Research Organization, Queensland Climate Change Centre of Excellence	CSIRO-Mk3-6-0	X	X
EC-EARTH consortium	EC-EARTH	X	X
Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, and Center for Earth System Science, Tsinghua University	FGOALS-g2	X	X
Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, and Center for Earth System Science, Tsinghua University	FGOALS-s2	X	X
The First Institute of Oceanography, State Oceanic Administration, China	FIO-ESM	X	X
NOAA Geophysical Fluid Dynamics Laboratory	GFDL-CM3	X	X
	GFDL-ESM2G	X	X
	GFDL-ESM2M	X	X
NASA Goddard Institute for Space Studies	GISS-E2-H-CC	X	
	GISS-E2-R	X	X
	GISS-E2-R-CC	X	
Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)	HADGEM2-AO	X	X
Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)	HADGEM2-CC	X	X
Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)	HADGEM2-ES	X	X
Institute for Numerical Mathematics	INM-CM4	X	X
Institut Pierre-Simon Laplace	IPSL-CM5A-LR	X	X
	IPSL-CM5A-MR	X	X
	IPSL-CM5B-LR	X	X
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC-ESM	X	X
	MIROC-ESM-CHEM	X	X
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC5	X	X
Max Planck Institute for Meteorology (MPI-M)	MPI-ESM-LR	X	X
Max Planck Institute for Meteorology (MPI-M)	MPI-ESM-MR	X	X
Meteorological Research Institute	MRI-CGCM3	X	X
Norwegian Climate Centre	NorESM1-M	X	X
Norwegian Climate Centre	MorESM1-ME	X	X

Average annual precipitation ranges from less than 6 inches to just over 85 inches with the wetter areas occurring in the northern parts of the mountains in Montana (fig. 3.3). See box 3.2 for key messages associated with the maps for the region.

Comparisons of CMIP5 Projections With the CMIP3 Projections Used in the Resource Chapters

The CMIP3 projections have been widely used in assessments such as the National Climate Assessment (Walsh et al. 2014) and the Forest Service, U.S. Department of Agriculture (USFS) Resource Planning Act Assessment (USDA FS 2012). Many of the resource chapters in this report are based on published literature using the CMIP3 projections developed by Littell et al. (2011); figure 3.4 compares the CMIP5 results used in this overview with CMIP3 projections of Littell et al. (2011) for use in natural resource assessments. There are many ways to compare projections, for example, by comparing the change in temperature with the change in precipitation over a common period. The downscaled projections from Littell et al. (2011) did not cover the entire Northern Rockies region (they cover the western area but stop at the Continental Divide). However, because we are interested in comparing

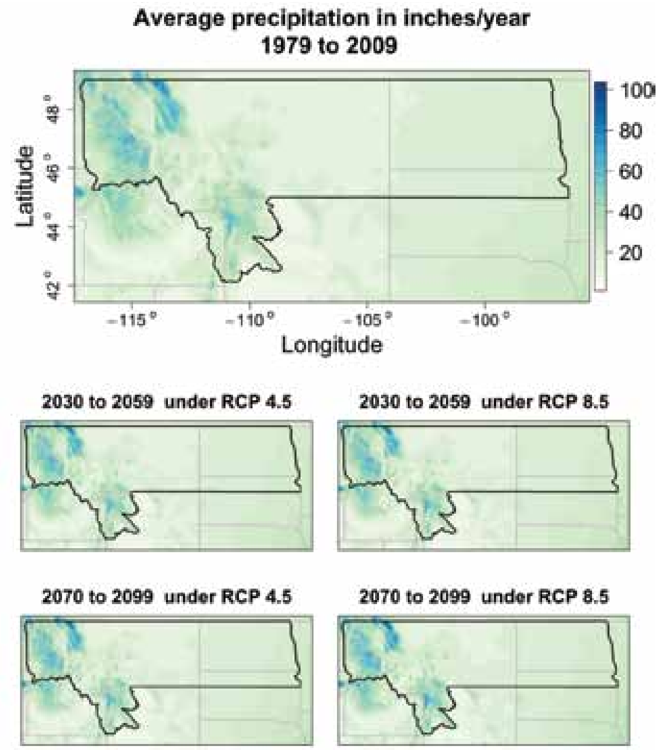

Figure 3.3—Historical (1970–2009) and projected (2030–2059 and 2070–2099) total annual precipitation (inches) under RCP 4.5 and RCP 8.5. Projected climate results are the mean of 36 models for RCP 4.5 and 34 models for RCP 8.5 (see table 3.1). Spatial resolution of the data is 1/8 degree latitude-longitude.

Box 3.2—Summary: Climatic Variability and Change for the Northern Rockies Region

- The mountainous Western Rockies, Central Rockies, Eastern Rockies, and Greater Yellowstone Area (GYA) subregions sit at the boundary between the warm, wet, maritime airflows from the Pacific Ocean, and the cooler, drier airflows from Canada. The Grassland subregion is influenced primarily by the cooler, drier airflows from Canada.
- Climatic variability in the mountainous areas of Idaho, Montana, and the GYA is strongly influenced by interactions with topography, elevation, and aspect.
- Historically, the coolest areas are found in the GYA, and the warmest areas are associated with grasslands in central Montana and into South Dakota and North Dakota.
- By the 2040s, mean annual monthly temperatures are projected to increase in the Northern Rockies region. The warmest areas continue to be associated with central Montana. For the Grassland subregion, projections show a pattern of a drier west and wetter east, with the mean of climate models showing a slight increase in the extent of the wetter eastern area.
- Projections for precipitation suggest a very slight increase in the future. Precipitation projections, in general, have much higher uncertainty than those for temperature.
- Seasonally, projected winter maximum temperature begins to rise above freezing (32 ^{o}F) in the mid-21st century in several of the subregions.
- Projected climate was derived from climate models in the Coupled Model Intercomparison Project version 5 (CMIP5) database, which was used in the most recent IPCC reports.
- Some chapters in this publication draw from existing scientific literature that used climate projections from the 2007 IPCC reports (CMIP3 database). In the mid-21st century (2040–2060), CMIP3 and CMIP5 temperature projections are similar, whereas CMIP5 precipitation projections are slightly wetter than those in CMIP3.

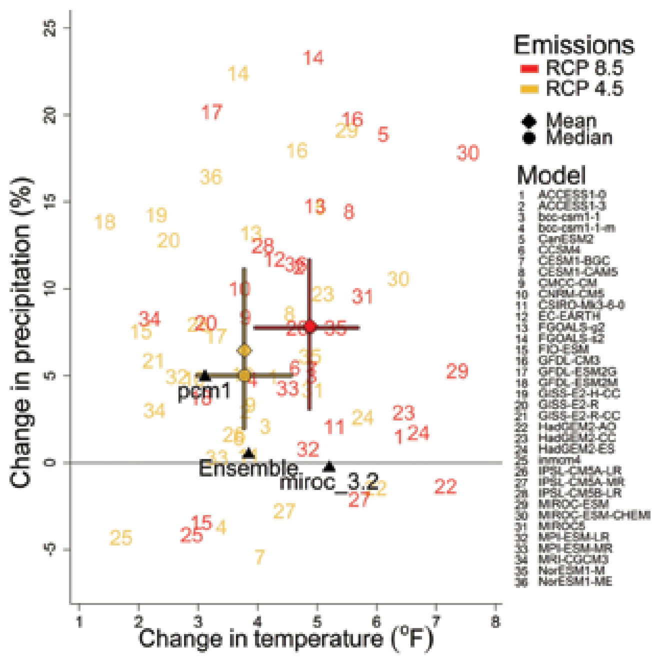

Figure 3.4—For the entire NRAP region, percent change in total annual precipitation (%) and change in mean annual temperature (°F) from the simulated historical climate (1979–2009) and the projected climate (2040–2060) using the CMIP5 RCP 4.5 and RCP 8.5 scenarios and the CMIP3 A1B scenario. Each CMIP5 model result is labeled by a number with a key in the legend (e.g., 29 is MIROC-ESM) in colors to indicate RCP 4.5 (yellow) and RCP 8.5 (red) (see table 3.1). The crosses in the middle represent the median and 25–75% of the RCP 4.5 and the RCP 8.5 projections used in this study. The mean values for the CMIP5 changes are shown on the figure as colored diamonds. The CMIP3 results are labeled in black triangles (Littell et al. 2011).

the differences in temperature and precipitation between the CMIP3 and CMIP5 models for the entire region, we estimated the change in temperature and precipitation using global results for the models that Littell et al. (2011) used: 10 CMIP3 model projections using the A1B scenario. We obtained these 1-degree global model projections for the entire Northern Rockies region (Jeremy Littell, U.S. Geological Survey, Alaska Science Center, Anchorage, AK, written communication, August 2014). Using these data, we estimate the change in temperature and percent change in precipitation between a future period (2040–2060) and a historical period (1979–2009) for the models that Littell et al. (2011) used and the CMIP5 models that used in this study. In figure 3.4, the projected change in mean annual temperature is shown on the horizontal axis, and the percent change in precipitation is shown on the vertical axis. Change is described as the difference in temperature (future mean annual value minus historical mean annual value) and percent change in precipitation (100 × [future mean annual value minus historical mean annual value]/historical mean annual value).

Across all models, projected change in temperature by the 2040–2060 period ranges from just under 2 °F to nearly 8 °F (fig. 3.4). Generally, the projected change for models using the RCP 8.5 scenario (shown in red) is greater than the change projected for the RCP 4.5 scenario (shown in yellow). Change in precipitation ranges across these CMIP5 models from a decrease of about 5 percent to an increase of 25 percent with a mean projected change of approximately 6 and 8 percent for RCP 4.5 and RCP 8.5, respectively. Change in the CMIP3 projections developed by Littell et al. (2011) is shown on this graph as pcm1, Ensemble (average of 10 model projections), and miroc_3.2 (where pcm1 and miroc_3.2 are individual climate models). We conclude that when this set of CMIP3 results (Littell et al. 2011) is compared with CMIP5 results for the Northern Rockies region, the CMIP3 results are in the same temperature range for 2040–2060, although CMIP5 precipitation projections are slightly wetter in the future (fig. 3.4).

Climatic Variability and Change in Northern Rockies Adaptation Partnership Subregions

The following five sections summarize historical and projected climate for the five Northern Rockies Adaptation Partnership subregions: Western Rockies, Central Rockies, Eastern Rockies, Greater Yellowstone Area, and Grassland (see figure 1.1 for location of subregions). Each section contains a set of figures based on a common template that we describe here. Key messages for each region are given in a series of boxes.

The first figure in each section shows the annual mean daily maximum temperature (°F), the annual mean daily minimum temperature (°F), and the total annual precipitation (inches) for 1949 through 2010. For these historical data, we drew from and contrasted three common gridded historical datasets; PRISM, Maurer, and TopoWx. In both temperature and precipitation there is variability, so we show the 10-year rolling average to highlight any short-term trends (bold lines).

The second figure in each section shows the historical modeled and projected annual mean of the daily maximum and minimum temperatures (°F), and total annual precipitation (inches) for the RCP 4.5 and the RCP 8.5 scenarios based on the CMIP5 $1/8^{th}$ degree BCSD data available on the Green Data Oasis (Lawrence Livermore National Laboratory n.d.). Typically, the scenario with the higher greenhouse gas concentrations (RCP 8.5) will show a higher temperature by 2100. In these figures, each model was backcast and we display the modeled historical data, which include all CMIP5 models that are bias corrected and downscaled in the same manner as the model projections. We overlay the 1/8-degree spatial resolution (about 7.5 miles) gridded historical observation dataset (blue line) (Maurer et al. 2002), which was used in the bias correction of the modeled data. The projections are shown in the colors used in figure 3.6: yellow for RCP 4.5 and red for RCP 8.5. The ensemble median from all models for each scenario is shown in the heavy line; the 5th and 95th percent quantiles for all models are shown by the shaded area. The precipitation projections have a greater variability than either temperature projection, and there is less confidence in any one particular model's projection for precipitation.

The third figure in each section shows the seasonal means of the daily maximum temperature (°F) for the historical and projected period. We use box plots here, where each box is an aggregation of 20 years of modeled historical or projected seasonal data. For example, the box labeled as 1960 represents the seasonal average of 1950 through 1969. The modeled historical boxes are gray, and boxes for projections use the same colors as in other figures: yellow for RCP 4.5 and red for RCP 8.5. The central line in each box is the median: the same number of modeled historical or projections lies above and below this line. The hinges or edges of the boxes are the first and third quartiles. Whiskers extend past the first and third quartile by 1.5 times the interquartile range.

The fourth figure in each section shows the seasonal means of the daily minimum temperature (°F) for the historical and projected period 1950–2100. The figure is set up in the same way as the third figure just described. We do not show the seasonal mean precipitation values as there is large variability and no discernible trend and hence, less confidence overall in the finer-scale precipitation projections.

Western Rockies Subregion

The primary results of analysis of historical and projected climate in the Western Rockies subregion are summarized in box 3.3, with specific detail in figs. 3.5, 3.6, 3.7, and 3.8.

Box. 3.3—Summary: Historical and Projected Climate for the Western Rockies Subregion

- This mountainous region sits at the boundary between warm, wet, maritime airflows from the Pacific Ocean, and cooler, drier airflows from Canada.
- Changes in climate affecting mountain snowpack will have important hydrologic implications.
- Over the historical period of record (1895–2012), the annual mean monthly minimum temperature increased by about 3.0 °F, while the annual mean monthly maximum temperature increased by about 0.6 °F. During the same period, annual mean monthly precipitation increased slightly, by an average of about 0.1 inch per month.
- Temperature is projected to increase 5 to 10 °F by 2100, including increases in both the annual mean monthly minimum and annual mean monthly maximum.
- Mean monthly maximum and minimum temperatures are projected to increase for all seasons. The mean monthly minimum temperature (spring and fall) and the mean monthly maximum temperature (winter) may rise above freezing.
- Seasonal precipitation is projected to be slightly higher in winter and spring, and slightly lower in summer than during the historical period of record.

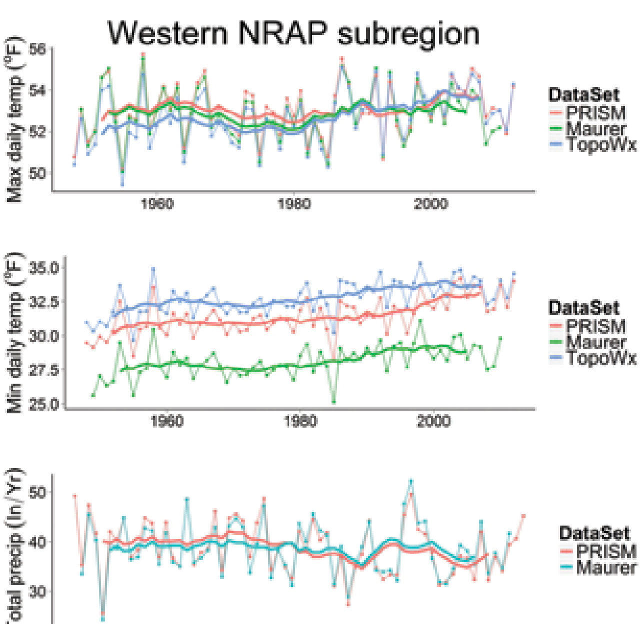

Figure 3.5—Annual historical mean monthly maximum temperature, annual mean monthly minimum temperature, and total annual precipitation from monthly gridded PRISM, Maurer and TopoWx for 1949 to 2010 for the NRAP Western subregion. The heavy lines are the 10-year rolling average to show short-term trends.

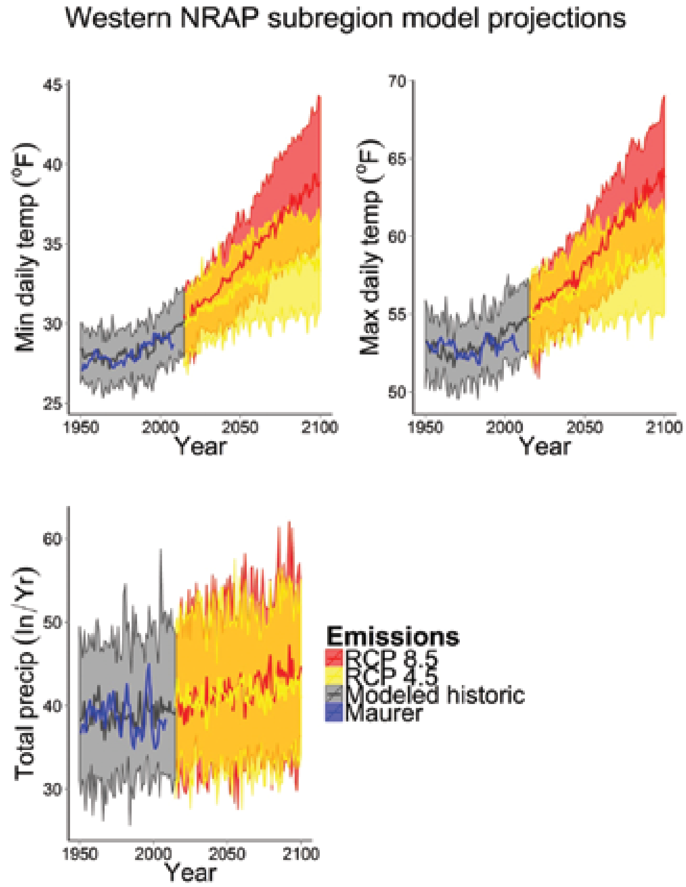

Figure 3.6—Historical modeled and projected annual mean monthly maximum temperature, annual mean monthly minimum temperature, and total annual precipitation for the RCP 4.5 and RCP 8.5 emission scenarios based on CMIP5 data for the NRAP Western subregion. Historic modeled results are indicated in gray, projections in colors. The shaded area shows the 5th and 95th percent quantiles for all models. The grey, red, or yellow heavy line illustrate ensemble median; the heavy blue line is the gridded historical observed data from Maurer et al. (2002).

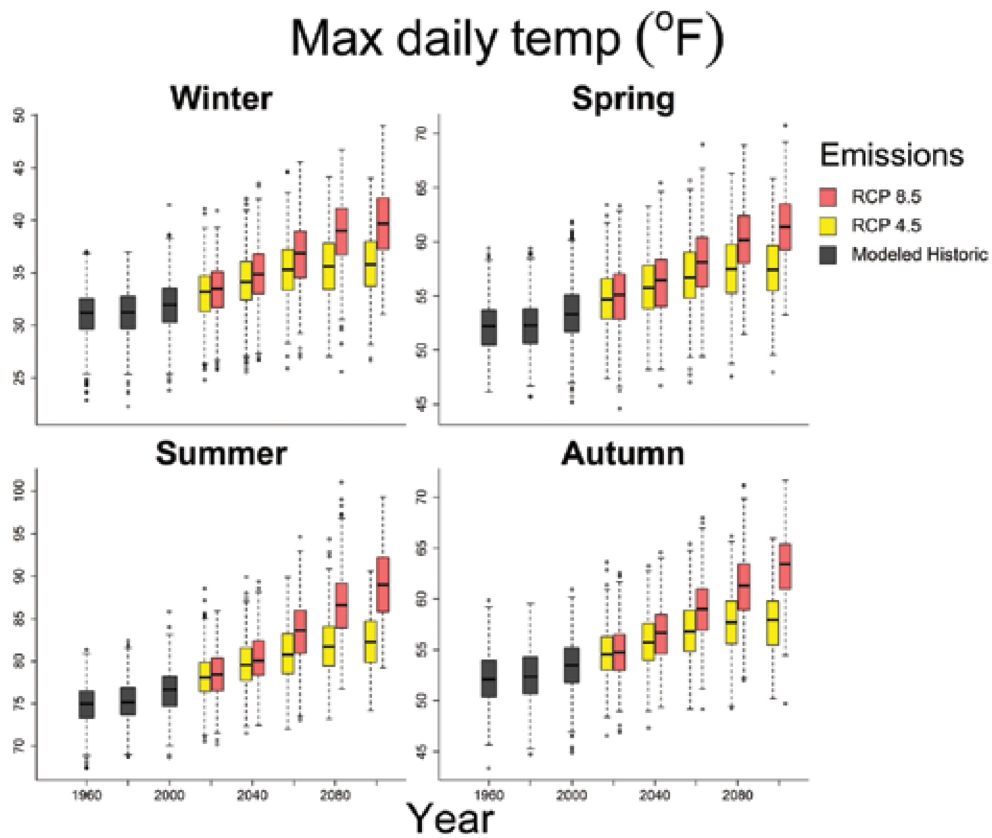

Figure 3.7—Seasonal mean monthly maximum temperature for 1950–2100 for the NRAP Western subregion. Each box is an aggregation of 20 years of modeled historical or projected seasonal data centered on the year listed (historical, grey boxes; RCP 4.5, yellow boxes; RCP 8.5, red boxes). For example, 1960 represents the seasonal average of 1950 to 1969. The central line in each box is the median. Hinges or edges of the boxes are the first and third quartiles; whiskers extend past the first and third quartile by 1.5 times the interquartile range (middle 50); points outside of the whiskers are extreme values.

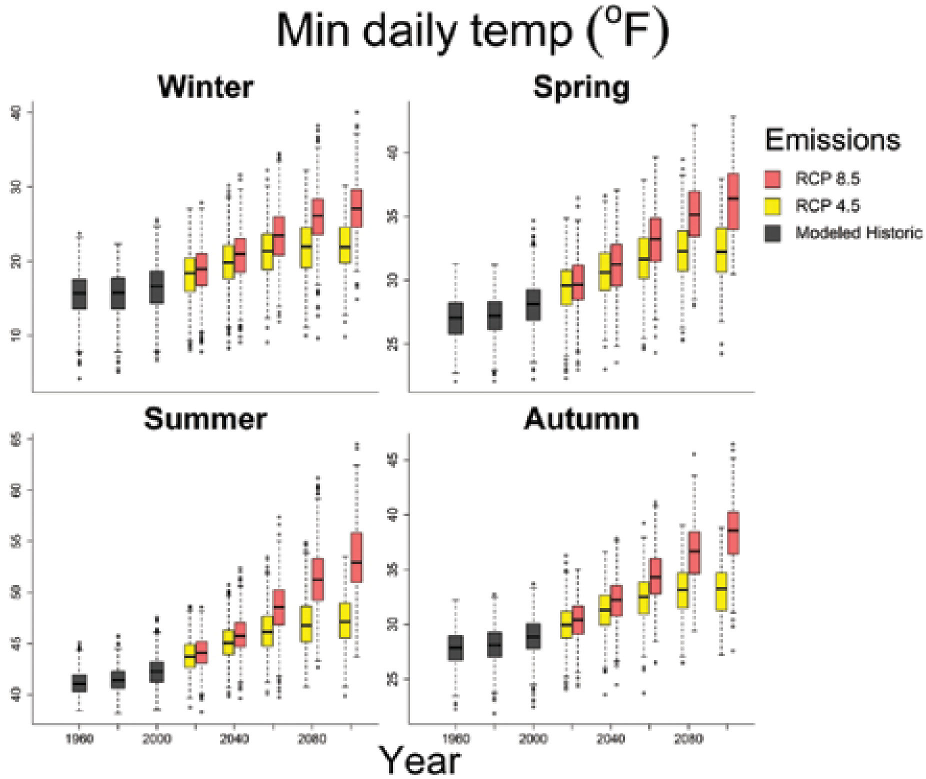

Figure 3.8—Seasonal mean monthly minimum temperature for 1950–2100 for the NRAP Western region. Each box is an aggregation of 20 years of modeled historical or projected seasonal data (historical, grey boxes; RCP 4.5, yellow boxes; RCP 8.5, red boxes). For example, 1960 represents the seasonal average of 1950 to 1969. The central line in each box is the median. Hinges or edges of the boxes are the first and third quartiles; whiskers extend past the first and third quartile by 1.5 times the interquartile range (middle 50); points outside of the whiskers are extreme values.

Central Rockies Subregion

The primary results of analysis of historical and projected climate in the Central Rockies subregion are summarized in box 3.4, with specific detail in figures 3.9, 3.10, 3.11, and 3.12.

Box. 3.4—Summary: Historical and Projected Climate for the Central Rockies Subregion

- This mountainous region sits at the boundary between warm, wet, maritime airflows from the Pacific Ocean, and cooler, drier airflows from Canada.
- Changes in climate affecting mountain snowpack will have important hydrologic implications.
- Over the historical period of record (1895–2012), the annual mean monthly minimum temperature increased by about 2.6 °F, while the annual mean monthly maximum temperature increased by about 1.3 °F.
- By 2100, temperature is projected to increase 6 to 12 °F for the annual mean monthly minimum, and 5 to 11 °F for the annual mean monthly maximum.
- Mean monthly minimum and maximum temperatures are projected to increase for all seasons. The mean monthly minimum temperature (spring and autumn) and the mean monthly maximum temperature (winter) may rise above freezing.
- Seasonal precipitation is projected to be slightly higher in winter and spring and slightly lower in summer than during the historical period of record.

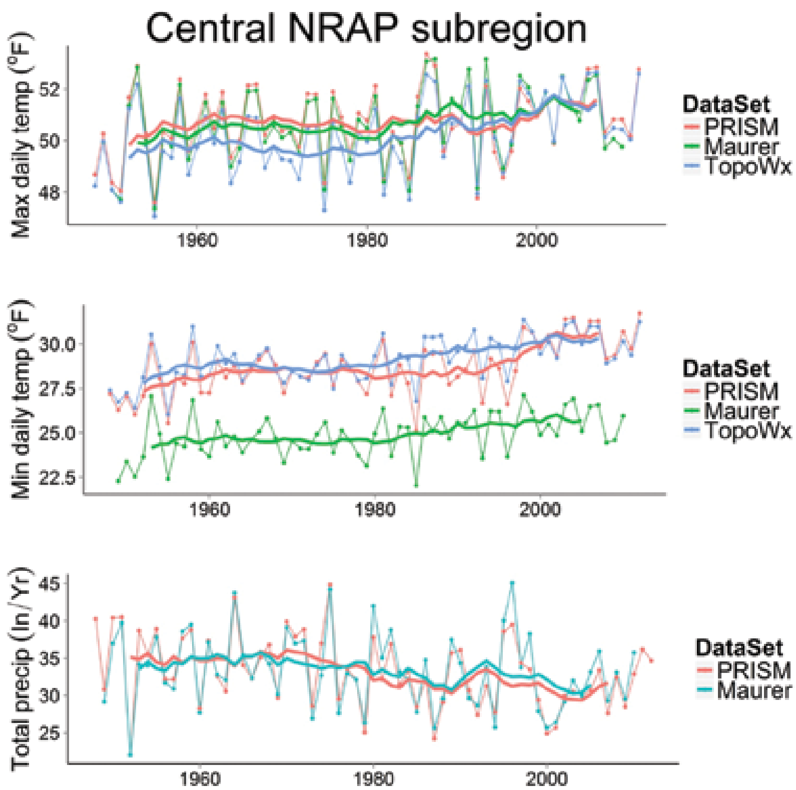

Figure 3.9—Annual historical mean monthly maximum temperature, annual mean monthly minimum temperature, and total annual precipitation from monthly gridded PRISM, Maurer and TopoWx for 1949 to 2010 for the NRAP Central subregion. The heavy lines are the 10-year rolling average that show short-term trends.

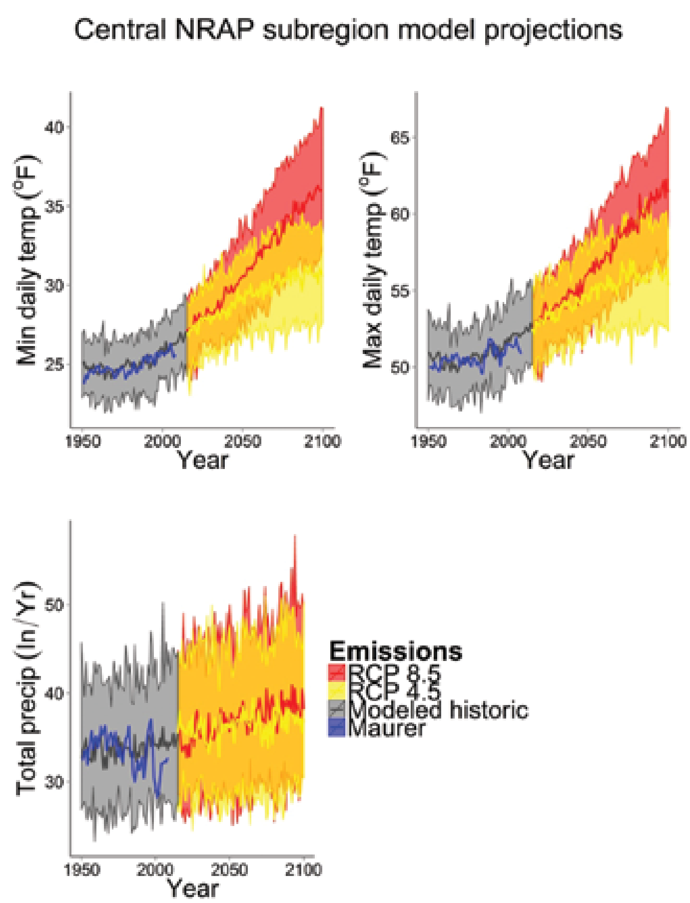

Figure 3.10—Historical modeled and projected annual mean monthly maximum temperature, annual mean monthly minimum temperature, and total annual precipitation for the RCP 4.5 and RCP 8.5 emission scenarios based on CMIP5 data for the NRAP Central subregion. Historic modeled results are indicated in gray, projections in colors. The shaded area shows the 5th and 95th percent quantiles for all models. The grey, red, or yellow heavy line illustrate ensemble median; the heavy blue line is the gridded historical observed data from Maurer et al. (2002).

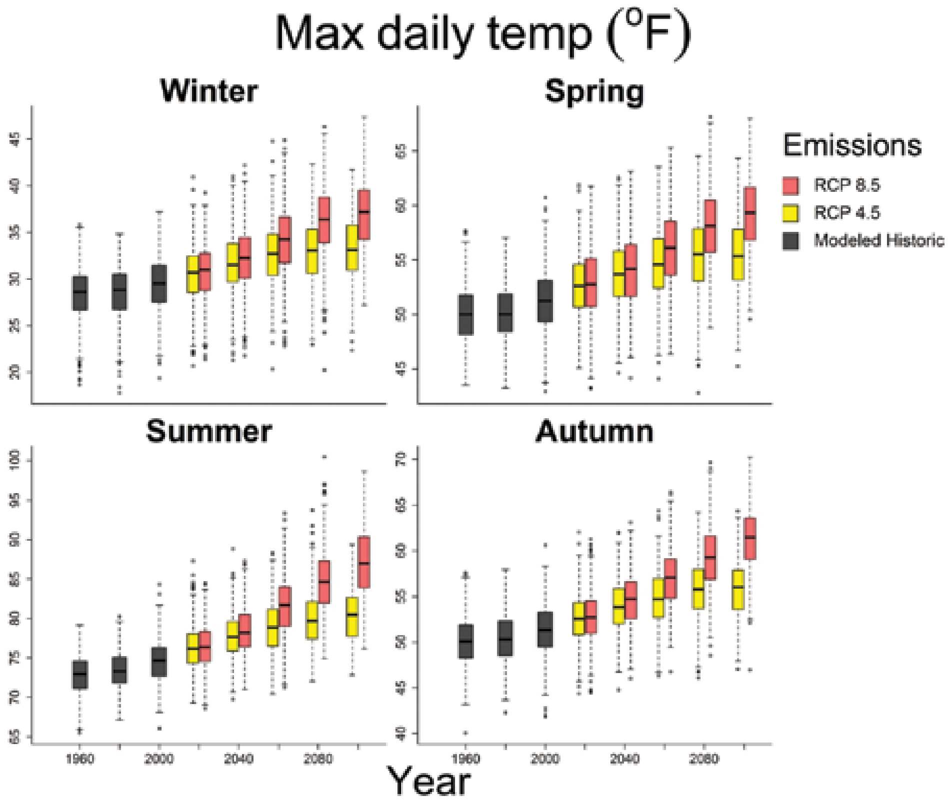

Figure 3.11—Seasonal mean monthly maximum temperature for 1950–2100 for the NRAP Central subregion. Each box is an aggregation of 20 years of modeled historical or projected seasonal data (historical, grey boxes; RCP 4.5, yellow boxes; RCP 8.5, red boxes). For example, 1960 represents the seasonal average of 1950 to 1969. The central line in each box is the median. Hinges or edges of the boxes are the first and third quartiles; whiskers extend past the first and third quartile by 1.5 times the interquartile range (middle 50); points outside of the whiskers are extreme values.

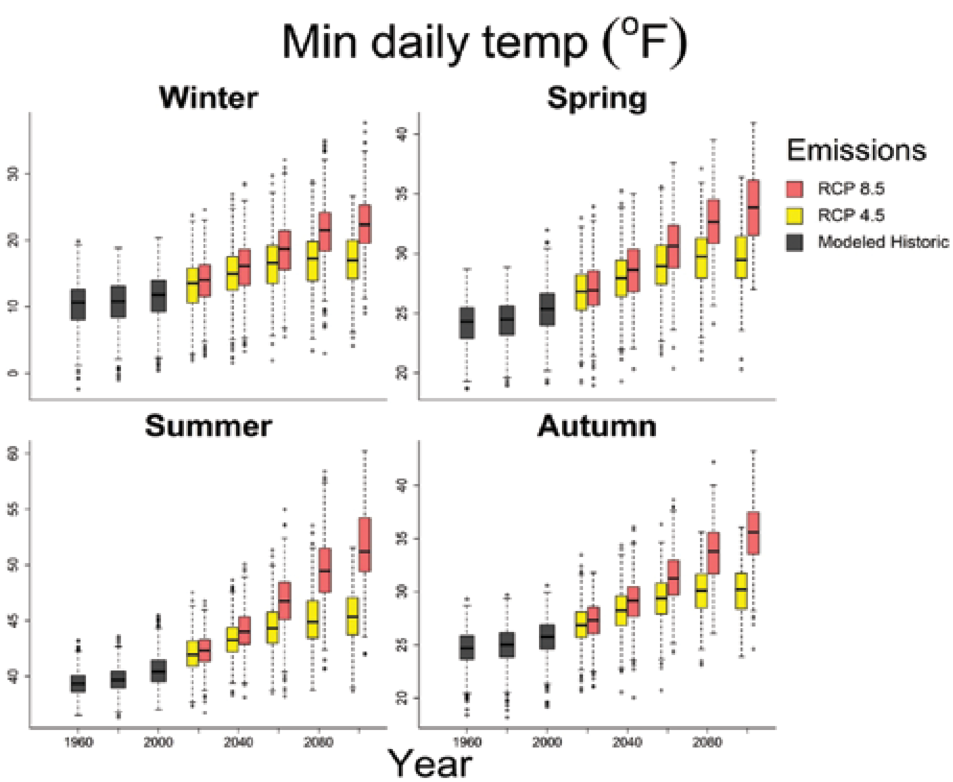

Figure 3.12—Seasonal mean monthly minimum temperature for 1950–2100. Each box is an aggregation of 20 years of modeled historical or projected seasonal data for the NRAP Central subregion (historical, grey boxes; RCP 4.5, yellow boxes; RCP 8.5, red boxes). For example, 1960 represents the seasonal average of 1950 to 1969. The central line in each box is the median. Hinges or edges of the boxes are the first and third quartiles; whiskers extend past the first and third quartile by 1.5 times the interquartile range (middle 50); points outside of the whiskers are extreme values.

Eastern Subregion

The primary results of analysis of historical and projected climate in the Eastern Rockies subregion are summarized in box 3.5, with specific detail in figures 3.13, 3.14, 3.15, and 3.16.

Box. 3.5—Summary: Historical and Projected Climate for the Eastern Rockies Subregion

- This mountainous region sits at the boundary between warm, wet, maritime airflows from the Pacific Ocean, and cooler, drier airflows from Canada.
- Changes in climate affecting mountain snowpack will have important hydrologic implications.
- Over the historical period of record (1895–2012), the annual mean monthly minimum temperature increased by about 2.2 °F, while the annual mean monthly maximum temperature increased by about 1.8 °F. During the same period, annual mean monthly precipitation was unchanged.
- By 2100, temperature is projected to increase 6 to 11 °F for the annual mean monthly minimum, and 5 to 11 °F for the annual mean monthly maximum.
- Mean monthly minimum and maximum temperatures are projected to increase for all seasons. The mean monthly minimum temperature (spring and fall) and the mean monthly maximum temperature (winter) may rise above freezing.
- Seasonal precipitation is projected to be slightly higher in winter and spring and slightly lower in summer than during the historical period of record.

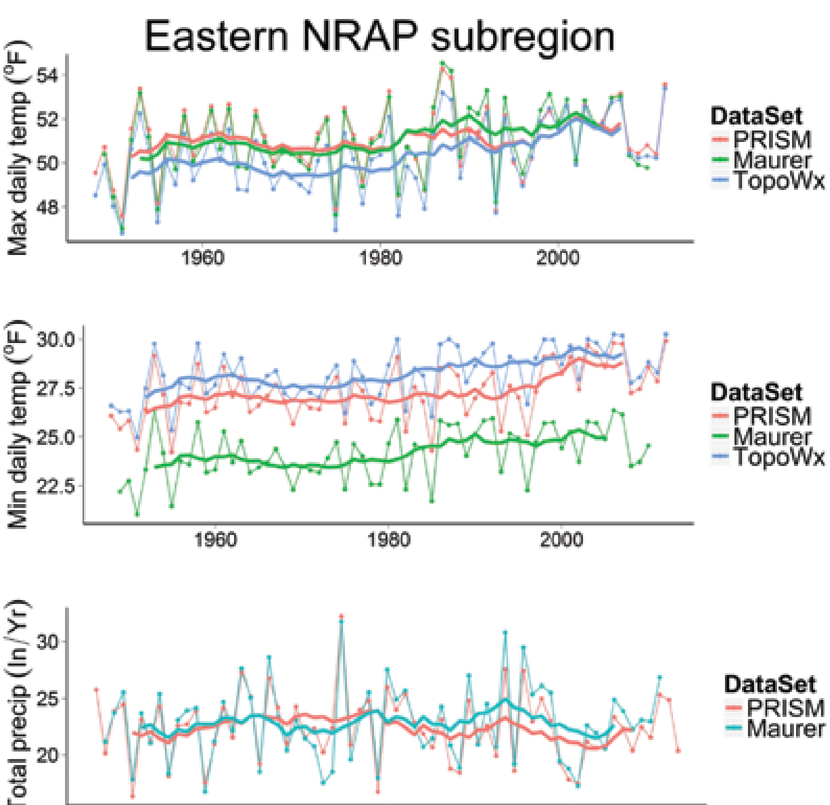

Figure 3.13—Annual historical mean monthly maximum temperature, annual mean monthly minimum temperature, and total annual precipitation from monthly gridded PRISM, Maurer and TopoWx for 1949 to 2010 for the NRAP Eastern subregion. The heavy lines are the 10-year rolling average that show short-term trends.

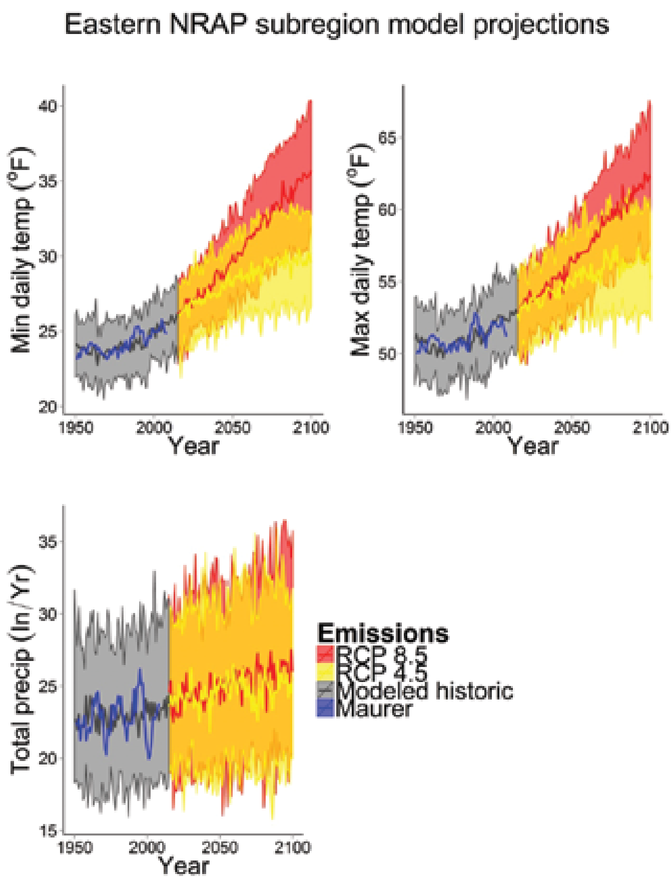

Figure 3.14—Historical modeled and projected annual mean monthly maximum temperature, annual mean monthly minimum temperature, and total annual precipitation for the RCP 4.5 and RCP 8.5 emission scenarios based on CMIP5 data for the NRAP Eastern subregion. Historic modeled results are indicated in gray, projections in colors. The 5th and 95th percent quantiles for all models are shown by the shaded area. The ensemble median is illustrated by the grey, red, or yellow heavy line; the heavy blue line is the gridded historical observed data from Maurer et al. (2002).

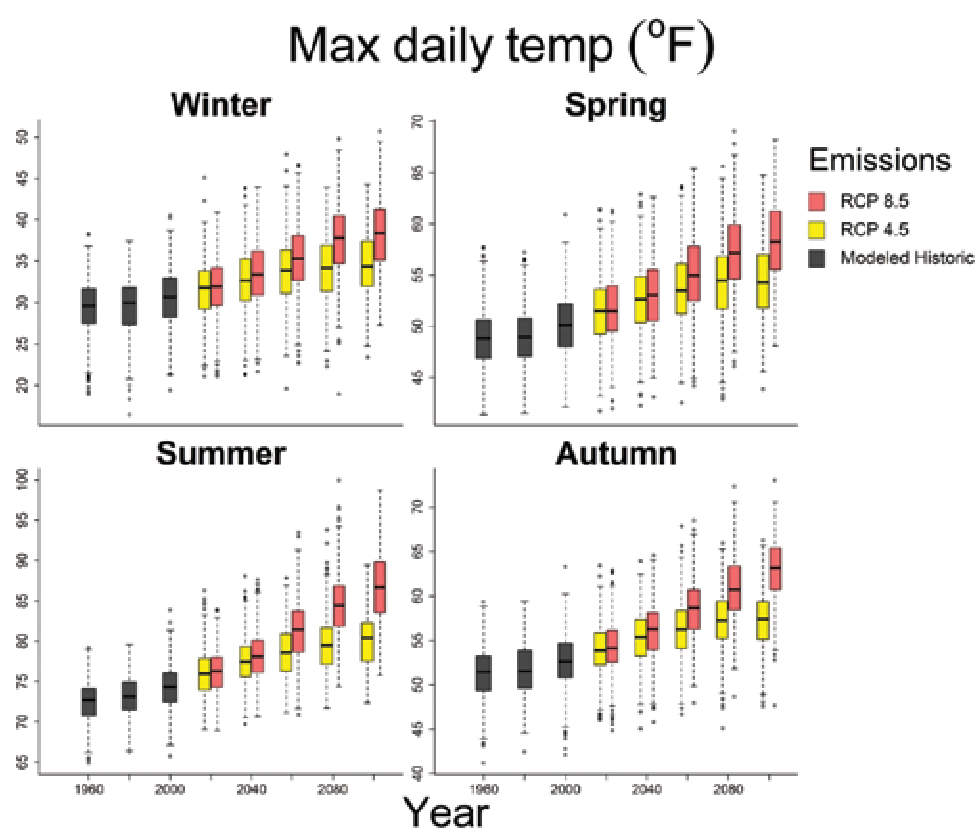

Figure 3.15—Seasonal mean monthly maximum temperature for 1950–2100 for the NRAP Eastern subregion. Each box is an aggregation of 20 years of modeled historical or projected seasonal data (historical, grey boxes; RCP 4.5, yellow boxes; RCP 8.5, red boxes). For example, 1960 represents the seasonal average of 1950 to 1969. The central line in each box is the median. Hinges or edges of the boxes are the first and third quartiles; whiskers extend past the first and third quartile by 1.5 times the interquartile range (middle 50); points outside of the whiskers are extreme values.

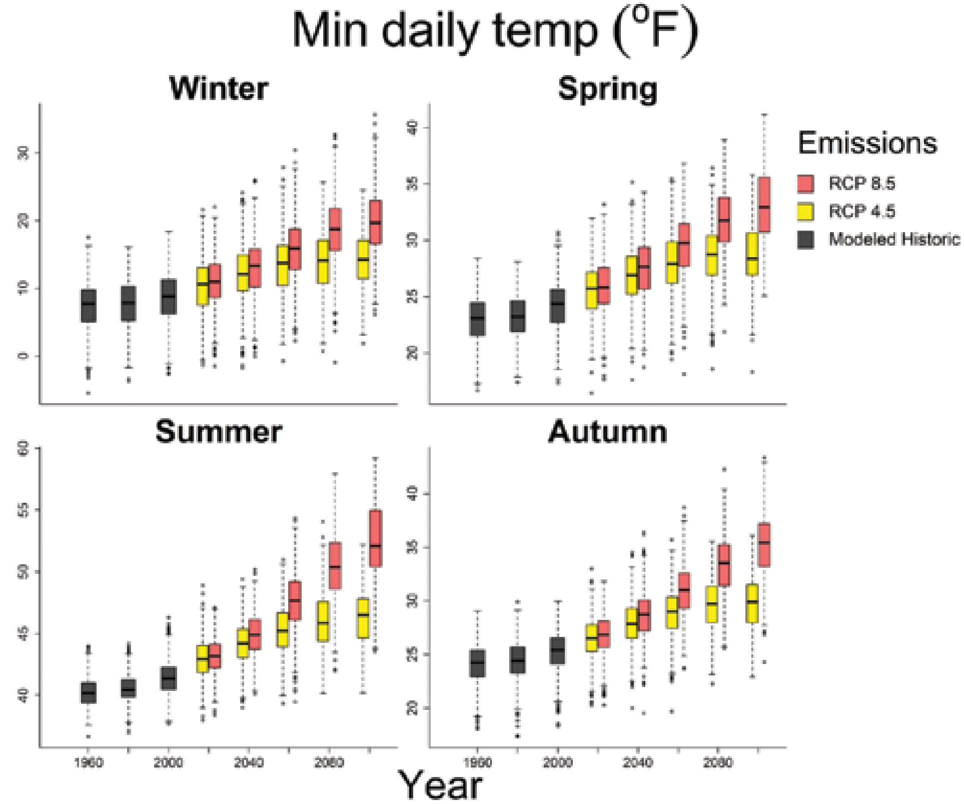

Figure 3.16—Seasonal mean monthly minimum temperature for 1950–2100 for the NRAP Eastern subregion. Each box is an aggregation of 20 years of modeled historical or projected seasonal data (historical, grey boxes; RCP 4.5, yellow boxes; RCP 8.5, red boxes). For example, 1960 represents the seasonal average of 1950 to 1969. The central line in each box is the median. Hinges or edges of the boxes are the first and third quartiles; whiskers extend past the first and third quartile by 1.5 times the interquartile range (middle 50); points outside of the whiskers are extreme values.

Greater Yellowstone Area Subregion

The primary results of analysis of historical and projected climate in the Greater Yellowstone Area subregion are summarized in box 3.6, with specific detail in figures 3.17, 3.18, 3.19, and 3.20.

Box. 3.6—Summary: Historical and Projected Climate for the Greater Yellowstone Area Subregion

- In the Greater Yellowstone Area subregion, climatic variability is strongly influenced by interactions with topography, elevation, and aspect.
- Over the historical period of record (1895–2012), the annual mean monthly minimum temperature increased by about 2.9 °F, while the annual mean monthly maximum temperature increased by about 1.2 °F.
- By 2100, temperature is projected to increase 5 to 10 °F for the annual mean monthly minimum, and 7 to 12 °F for the annual mean monthly maximum.
- Annual mean monthly precipitation is projected to increase slightly by 2100, although projections for precipitation have high uncertainty compared to temperature projections.
- Winter maximum temperature is projected to increase above freezing in the mid-21st century. Summer temperatures are projected to increase 5 °F by 2060 and 10 °F by 2100

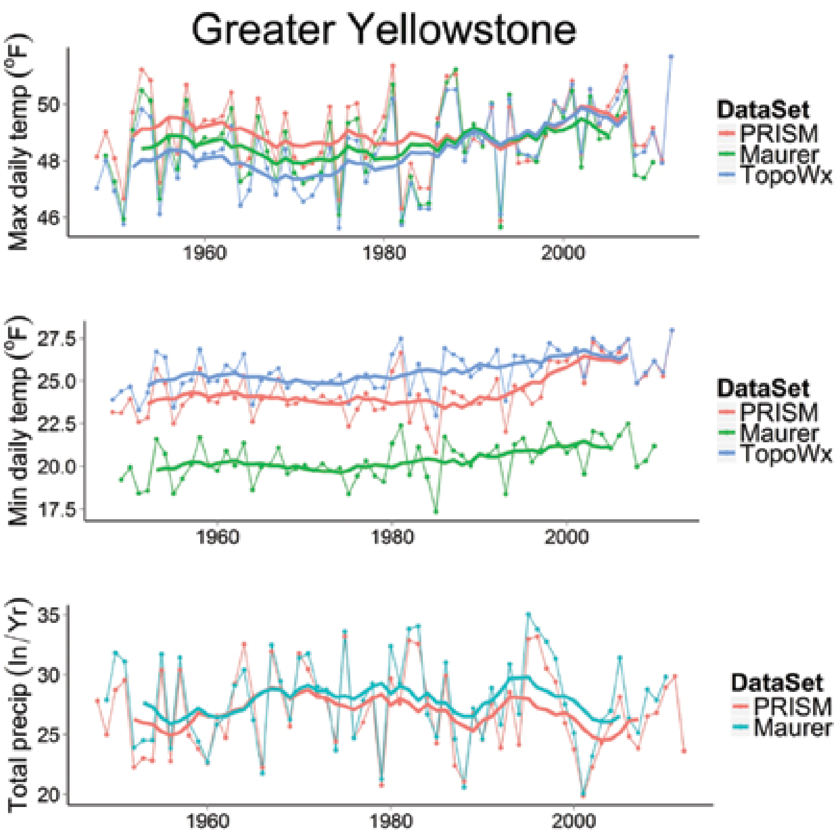

Figure 3.17—Annual historical mean monthly maximum temperature, annual mean monthly minimum temperature, and total annual precipitation from monthly gridded PRISM, Maurer and TopoWx for 1949 to 2010 for the NRAP Greater Yellowstone subregion. The heavy lines are the 10-year rolling average that show short-term trends.

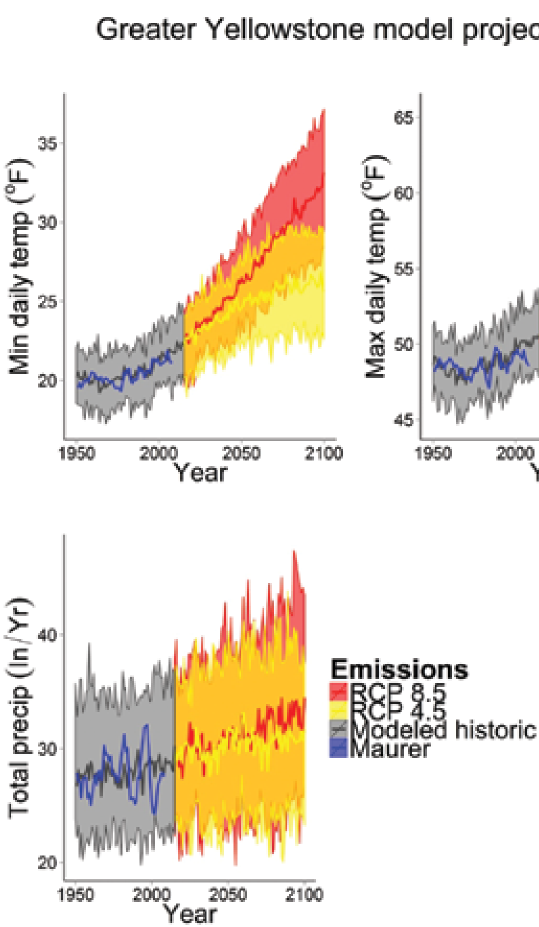

Figure 3.18—Historical modeled and projected annual mean monthly maximum temperature, annual mean monthly minimum temperature, and total annual precipitation for the RCP 4.5 and RCP 8.5 emission scenarios based on CMIP5 data for the NRAP Greater Yellowstone subregion. Historic modeled results are indicated in gray, projections in colors. The shaded area shows the 5th and 95th percent quantiles for all models. The grey, red, or yellow heavy line illustrate ensemble median; the heavy blue line is the gridded historical observed data from Maurer et al. (2002).

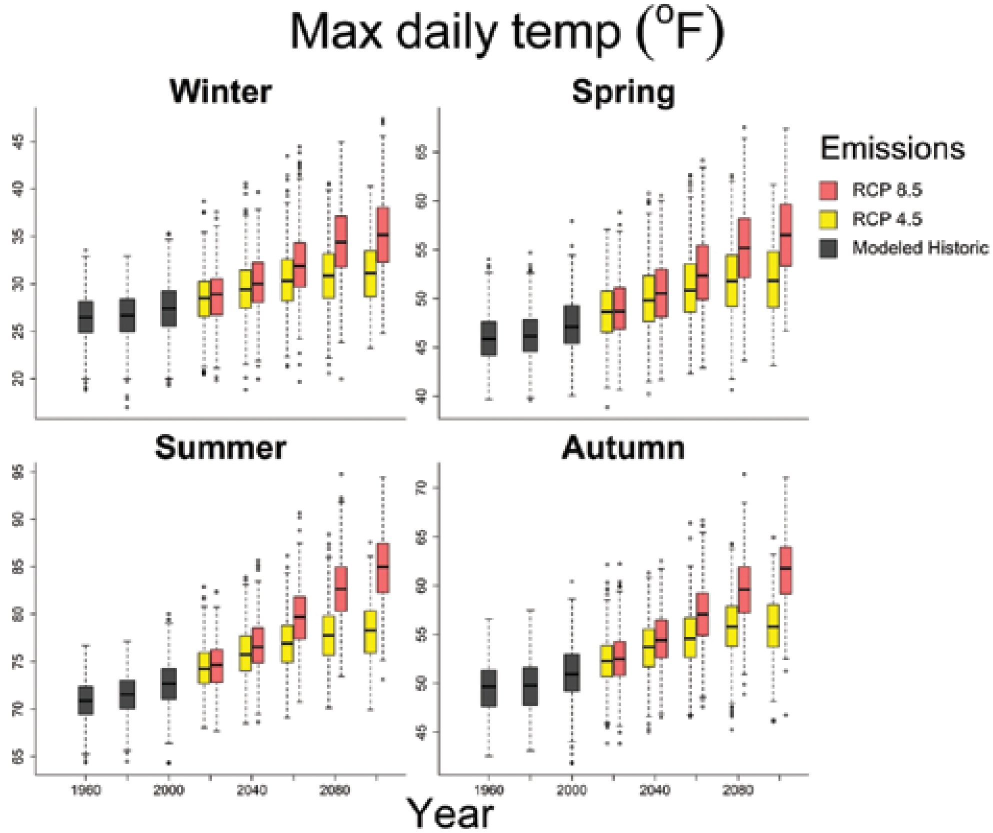

Figure 3.19—Seasonal mean monthly maximum temperature for 1950–2100 for the NRAP Greater Yellowstone subregion. Each box is an aggregation of 20 years of modeled historical or projected seasonal data (historical, grey boxes; RCP 4.5, yellow boxes; RCP 8.5, red boxes). For example, 1960 represents the seasonal average of 1950 to 1969. The central line in each box is the median. Hinges or edges of the boxes are the first and third quartiles; whiskers extend past the first and third quartile by 1.5 times the interquartile range (middle 50); points outside of the whiskers are extreme values.

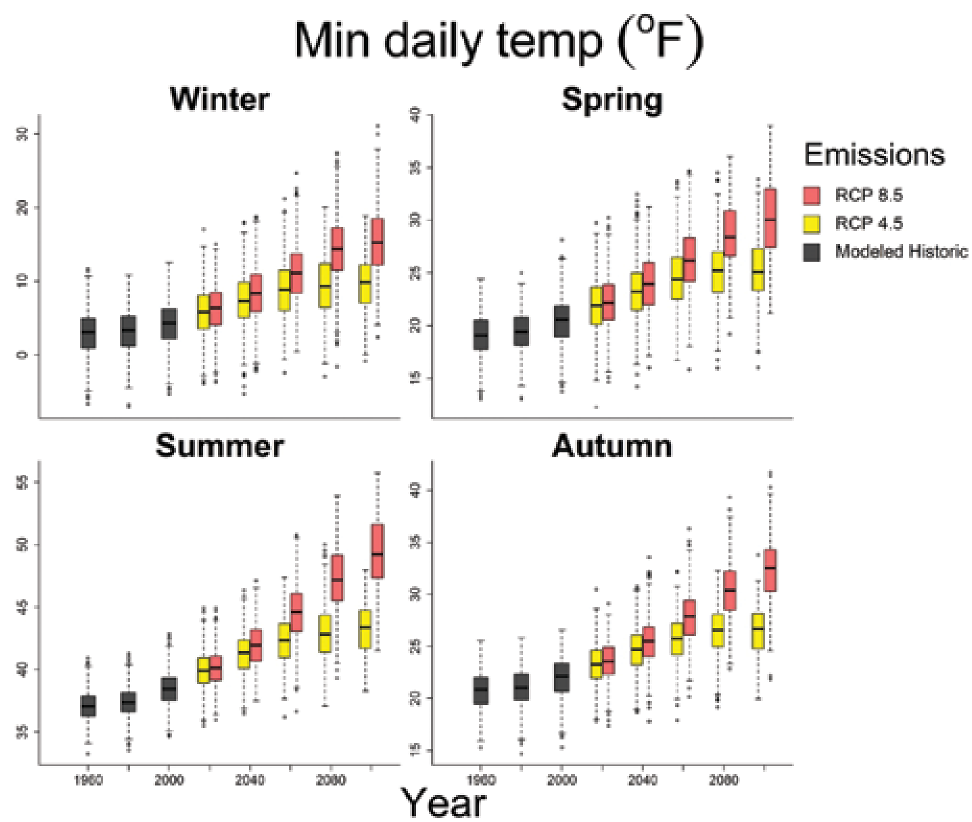

Figure 3.20—Seasonal mean monthly minimum temperature for 1950–2100 for the NRAP Greater Yellowstone subregion. Each box is an aggregation of 20 years of modeled historical or projected seasonal data (historical, grey boxes; RCP 4.5, yellow boxes; RCP 8.5, red boxes). For example, 1960 represents the seasonal average of 1950 to 1969. The central line in each box is the median. Hinges or edges of the boxes are the first and third quartiles; whiskers extend past the first and third quartile by 1.5 times the interquartile range (middle 50); points outside of the whiskers are extreme values.

Grassland Subregion

The primary results of analysis of historical and projected climate in the Grassland subregion are summarized in box 3.7, with specific detail in figures 3.21, 3.22, 3.23, and 3.24.

Box. 3.7—Summary: Historical and Projected Climate for the Grassland Subregion

- Warming trends indicate that future climate will be similar to the area south of this subregion.
- Even with little or no change in precipitation, there is the potential for summer drying or drought due to the increased heat and increased evapotranspiration.
- Early snowmelt from the west will imply changes in streamflow, with implications for streamflow and temperature and therefore reservoir management and stream ecology.
- There is a pattern of a drier west and wetter east, with the average of climate models showing a shift toward a slightly larger area of the wetter east.

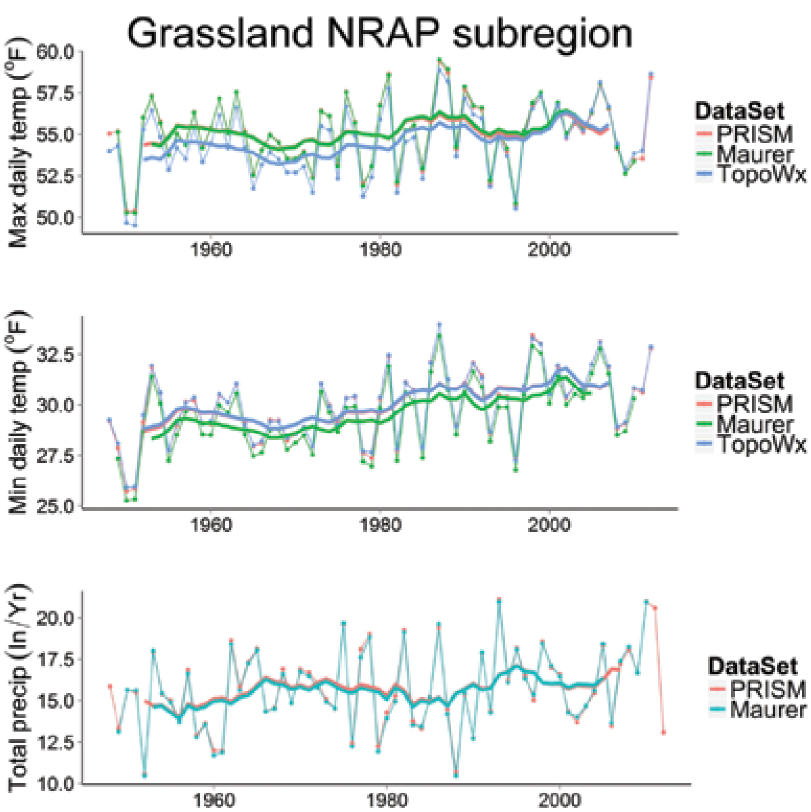

Figure 3.21—Annual historical mean monthly maximum temperature, annual mean monthly minimum temperature, and total annual precipitation from monthly gridded PRISM, Maurer and TopoWx for 1949 to 2010 for the NRAP Grassland subregion. The heavy lines are the 10-year rolling average that show short-term trends.

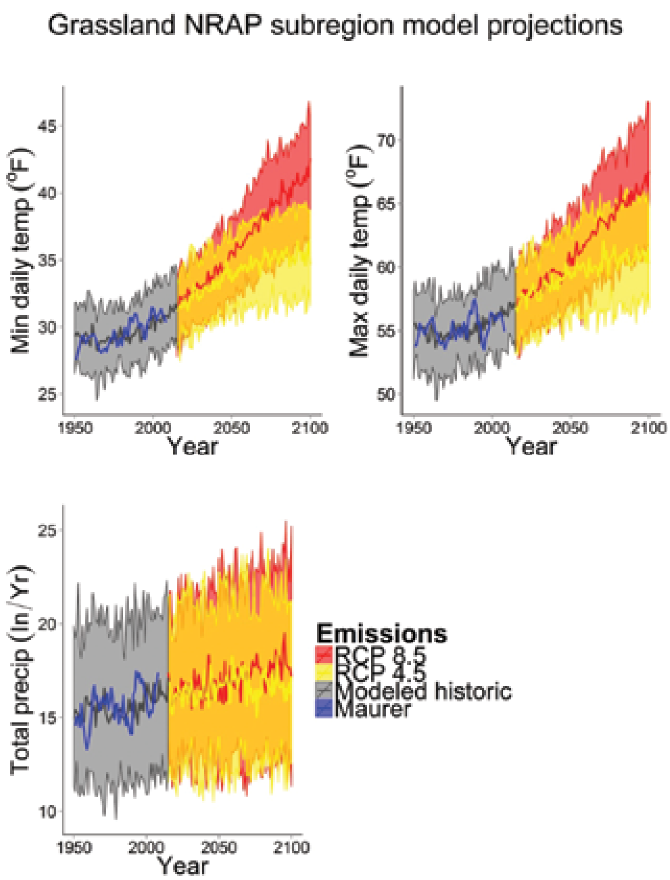

Figure 3.22—Historical modeled and projected annual mean monthly maximum temperature, annual mean monthly minimum temperature, and total annual precipitation for the RCP 4.5 and RCP 8.5 emission scenarios based on CMIP5 data for the NRAP Grassland subregion. Historic modeled results are indicated in gray, projections in colors. The shaded area shows the 5th and 95th percent quantiles for all models. The grey, red, or yellow heavy line illustrate ensemble median; the heavy blue line is the gridded historical observed data from Maurer et al. (2002).

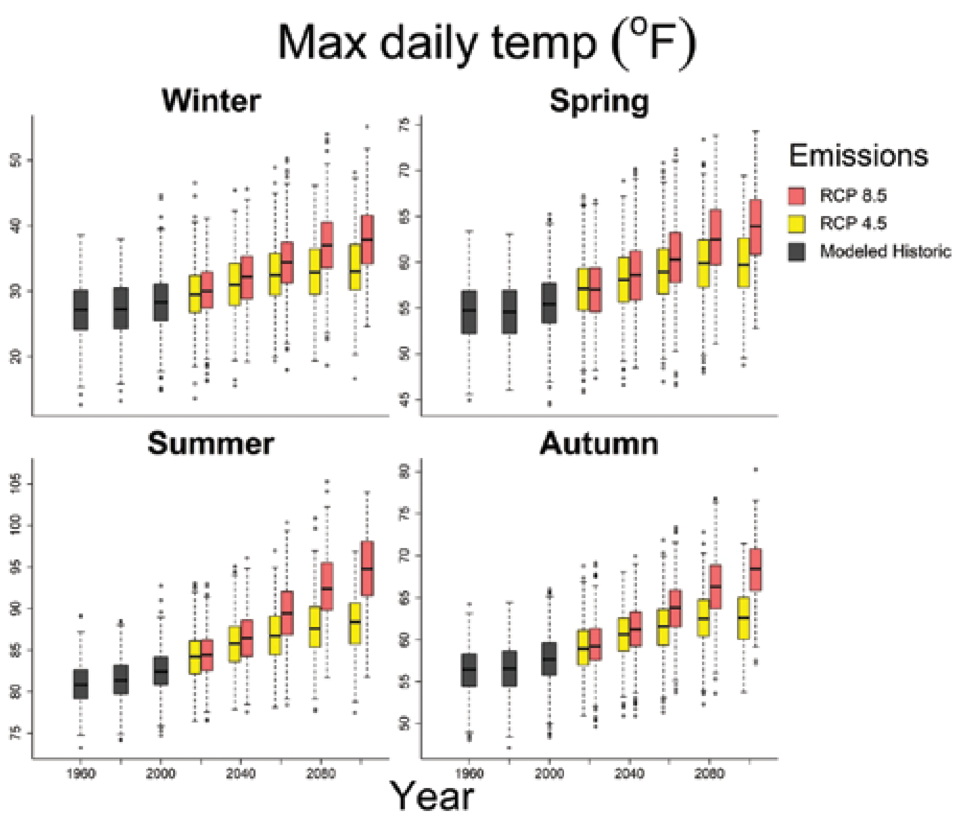

Figure 3.23—Seasonal mean monthly maximum temperature for 1950–2100 for the NRAP Grassland subregion. Each box is an aggregation of 20 years of modeled historical or projected seasonal data (historical, grey boxes; RCP 4.5, yellow boxes; RCP 8.5, red boxes). For example, 1960 represents the seasonal average of 1950 to 1969. The central line in each box is the median. Hinges or edges of the boxes are the first and third quartiles; whiskers extend past the first and third quartile by 1.5 times the interquartile range (middle 50); points outside of the whiskers are extreme values.

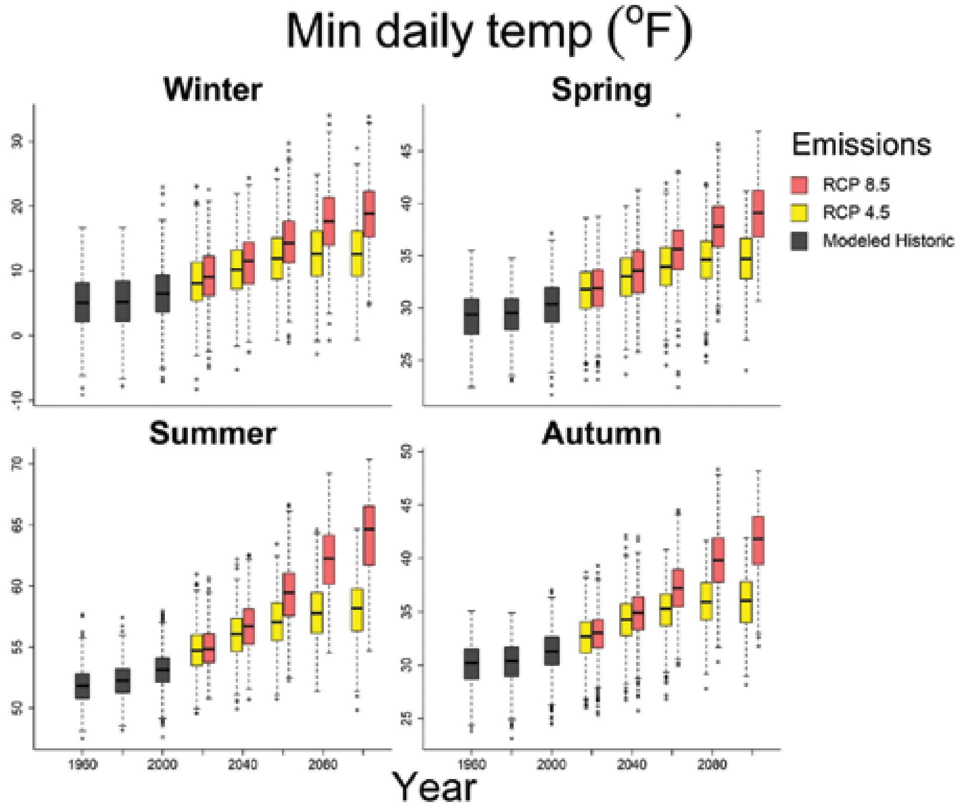

Figure 3.24—Seasonal mean monthly minimum temperature for 1950–2100 for the NRAP Grassland subregion (historical, grey boxes; RCP 4.5, yellow boxes; RCP 8.5, red boxes). Each box is an aggregation of 20 years of modeled historical or projected seasonal data. For example, 1960 represents the seasonal average of 1950 to 1969. The central line in each box is the median. Hinges or edges of the boxes are the first and third quartiles; whiskers extend past the first and third quartile by 1.5 times the interquartile range (middle 50); points outside of the whiskers are extreme values.

Acknowledgments

We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups (listed in table 3.1) for producing and making available their model output. For CMIP the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

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