Section II. Change Agents—Current and Future

Chapter 7. Climate Analysis

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Introduction

Weather, climate, and their variations are primary drivers of habitat structure and species distributions; climate envelope or bioclimatic envelope models are considered to be important conservations tools (Watling and others, 2013). Variations and long-term changes in weather and climate are thought to be one factor in habitat and species succession and are often part of state and transition models (Evers and others, 2013). Climate variations influence fire regimes (Littell and others, 2009; 2010) and hydrologic regimes can promote expansions of invasive plant species (Compagnoni and Adler, 2014; Jarnevich and Reynolds, 2011), and can affect mortality and establishment of tree species such as juniper (Romme and others, 2009). The climate of the future will be influenced by a combination of natural climate variability and anthropogenic factors. This chapter includes a description of the recent historical record of climate to give a context for the range and trend of projected future climate.

Natural and anthropogenic drivers of climate change, have the potential to change the landscape in fundamental ways, with potential consequences for natural communities and the potential to exacerbate many other Change Agents. The Wyoming Basin could experience changes in snowpack that could in turn alter water availability, including annual runoff and runoff seasonality. For example, climate warming (without any change to precipitation) is projected to lead to increased evapotranspiration from the watershed and decreased annual runoff (U.S. Department of the Interior Bureau of Reclamation, 2011a). According to the National Climate Assessment, “Climate change combined with other stressors is overwhelming the capacity of ecosystems to buffer the impacts from extreme events like fires, floods, and storms” (Groffman and others, 2014, p. 199). Furthermore, the timing, or phenology, of critical biological events, such as spring bud burst, emergence from overwintering, and the start of migrations, can shift, leading to effects on species and their habitats (Groffman and others, 2014). Small shifts in timing can also disrupt ecosystem functions like predator-prey relationships, mating behavior, or food availability for migrating birds (Ojima and others, 2013). Understanding the mechanisms by which climate acts on species and ecosystems is critically important to inform both biological and physical monitoring, as well as management and conservation strategies (Beever and Belant, 2012; Groffman and others, 2014).

This chapter describes the current climate of the Wyoming Basin, the range of potential climate change for the Wyoming Basin, and the reasonably foreseeable climate futures for ecosystems as they are understood now. The “reasonably foreseeable” concept is modeled after the same concept for “reasonably foreseeable development scenarios” required for BLM land use planning (U.S. Department of the Interior Bureau of Land Management, 2010) and is intended to reflect a range of potential future conditions due to natural variability and uncertainty in the global climate models. Climate data used and the assumptions and rationale for choices made are described. This chapter is a snapshot of the current state of knowledge about climate and climate change, but our understanding of climate is rapidly evolving. This chapter draws on existing observational and climate-projections databases and associated peer-reviewed reports and publications, and it includes some new analyses using these projections. The Climate Analysis section of the Appendix provides supplementary material on topics and figures.

Data Used—Observed and Paleoclimate Record of the Wyoming Basin

This chapter draws on observational data from weather stations dating back to the late 1800s, which became the National Atmospheric and Oceanic Administration (NOAA) National Weather Service Cooperative Observer (COOP) Network and Historical Climate Network, and the Climate Reference Network, established to document climate change by the NOAA National Climatic Data

Center (NCDC, http://www.ncdc.noaa.gov/crn/). Much of the discussion of the observed current climate of the Basin is informed by analysis from the Wyoming State Climate Office (WSCO, http://www.wrds.uwyo.edu/sco/; Curtis and Grimes, 2004) and the Western Regional Climate Center (http://www.wrcc.dri.edu/), derived from the data from these observing networks.

Because observing stations are not evenly distributed throughout the Wyoming Basin (see the Climate Analysis section of the Appendix), standard practice is to construct gridded observational datasets that interpolate between stations using statistical models to account for elevation and terrain; the resulting datasets are widely used by university and agency scientists and are used in operational weather models. Three observational gridded databases used in this report are (1) the Parameter-Elevation Regressions on Independent Slopes Model (PRISM) dataset (http://www.prism.oregonstate.edu/, DiLuzio and others, 2008), (2) the Bias-Corrected Spatial Disaggegation (BCSD) gridded dataset (Maurer and others, 2007; U.S. Department of the Interior Bureau of Reclamation, 2013), developed by a team including U.S. Department of the Interior Bureau of Reclamation (BOR) scientists, and (3) the Rehfeldt dataset, constructed by a U.S. Department of Agriculture Forest Service (hereafter, Forest Service) team for studies of ecological distributions (Rehfeldt and others, 2006). To evaluate the differences between a future period and the recent or current climate (sometimes called "climatology" or "historical"), we chose 1961−1990, which is also consistent with the climatology period used in the Colorado Plateau Rapid Ecoregional Assessment. Climate scientists prefer a 30-year (yr) averaging period because it is long enough to reduce the effects of natural year-to-year (or inter-annual) variability. The 1961−1990 period occurred before the recent warming in the 1990s and 2000s, and thus is more representative of conditions in which biomes would have been established. In some cases, we describe or cite studies that used a different period; in that case, we explicitly state the period used for averaging or for comparison.

There are a number of paleoclimate studies that extend our knowledge of the historical record of climate, providing a reconstruction of river flows (that is, a longer record—using tree-ring analysis—of temperature and streamflow in and around the Basin). These studies have been conducted by many researchers, and data collected through the Treeflow Web site (http://treeflow.info/) provides background and original citations, including work on the Colorado and Missouri Basins.

Data Used—Future Climate Projections

No single downscaled climate-projection product suited all the tasks we needed for projections. The Bureau of Land Management (BLM) directed that the dynamical downscaling by Hostetler and others (2011) be considered as part of the assessment of climate as a Change Agent, but other downscaled products have been the climate input for many peer reviewed ecological, hydrology, and bioclimatic/vegetation modeling studies that are relevant to the Conservation Elements and thus important analyses for this report (for example, Littell and others, 2009; Rehfeldt and others, 2009; Haak and others, 2010; Littell and others, 2010; Wenger and others, 2010a, b).

We used four downscaled climate products, which are each derived from output from the global change models (GCM) (table 7−1) (Intergovernmental Panel on Climate Change, 2007). These are (1) the statistically downscaled projections developed for the BOR, which we refer to as the "BCSD product" for the BCSD technique used to downscale the GCMs (Maurer and others, 2007; U.S. Department of the Interior Bureau of Reclamation, 2013), which was then post-processed through the Variable Infiltration Capacity (VIC) hydrologic model to generate BCSD hydrologic projections (U.S. Department of the Interior Bureau of Reclamation, 2011a) including variables like streamflow and soil moisture; (2) a statistically downscaled product by Forest Service scientists, which we refer to as the "Rehfeldt product" (Rehfeldt and others, 2009, 2012); and (3) a third statistically downscaled product:

the Western United States Stream Flow Metric Dataset (hereafter, WSMD), developed for the Forest Service (U.S. Department of Agriculture Forest Service, 2011; Wenger and others, 2011). It provides 12 streamflow variables, or metrics, most not in the BCSD dataset, which are intended to be useful for studying streams and riparian habitat. The WSMD product uses the same downscaling techniques as BCSD, also post-processed through the VIC hydrology model. A fourth product is the dynamically downscaled climate projection dataset developed by USGS scientists, which we refer to as the Hostetler product (Hostetler and others, 2011). Most of the analyses and graphics in this chapter use the BCSD downscaled data both because of the concerns about the Hostetler product for this region (see the Climate Analysis section of the Appendix), and because the BCSD product is widely used. Maurer (and related WRSD) and Rehfeldt downscaling are very similar for the variables we chose, which is not surprising given that they have similar statistical downscaling methodologies.

Table 7–1. Definitions of climate model acronyms and associated acronyms frequently used in Chapter 7—Climate Analysis and the Appendix.

Acronyms	Definitions
Global climate model (GCM) acronyms	
CCCM3	Canadian Centre for Climate Modeling and Analysis Coupled Global Model, version 3
ECHAM5	European Center Hamburg Model, version 5
GFDL2.0 and GFDL2.1	National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Laboratory Climate Model, versions 2.0 and 2.1
HADCM3	Hadley Centre Coupled Model, version 3 (United Kingdom Meteorology Office)
MIROC	Model for Interdisciplinary Research On Climate, version 3.2 (University of Tokyo)
PCM1	Parallel Climate Model, version 1 (National Center for Atmospheric Research)
Other acronyms pertaining to climate models	
BCSD	Bias-corrected spatial disaggregation
VIC	Variable Infiltration Capacity
WSMD	Western United States streamflow metric dataset

We refer to the group of GCM runs downscaled by each product as the “ensemble,” and the number of GCMs in that ensemble varies for each product. We generally report the average for the ensemble, the range of values for all the ensemble members, and the period to which it is compared (that is, the BCSD ensemble projects a warming for the Wyoming Basin of about 0.5–2.5 °C (0.8–4.5 °F) with an ensemble mean increase of about 1.5 °C (2.7 °F), compared to the 1961–1990 average. These products are discussed further in the Climate Analysis section in the Appendix.

The BCSD product is being widely used—for example, in the BOR SECURE Water Act Report and related planning activities (U.S. Department of the Interior Bureau of Reclamation, 2011a) and for ecological studies (Schlaepfer and others, 2012)—and is available from several data portals, including the USGS GeoData Portal. The WSMD is also being used in a number of studies supporting conservation planning (Wenger and others, 2011; Haak and others, 2010; Vose and others, 2012). In the Wyoming Climate Futures section of this chapter, we also describe climate analyses done for several chapters and technical reports of the National Climate Assessment (Groffman and others, 2014; Kunkel and others, 2013; Ojima and others, 2013; Walsh and others, 2014). The National Climate Assessment studies all used the same BCSD downscaling that is used extensively in this report and as well as two other downscaling products that are not used in analysis for this report: the dynamically downscaled product North American Regional Climate Change Assessment Program (Mearns and others, 2009), and daily data from the statistically downscaled product by Hayhoe and others (2004) and Hayhoe and others (2008).

These downscaled products were useful for the Wyoming Basin Rapid Ecoregional Assessment (REA) because the BCSD and WSMD (in particular) used the downscaled climate projections as input for a hydrology model. They also provided projected hydroclimate variables, including soil moisture and streamflow, that were used to evaluate the potential consequences of projected climate change for the distribution of cutthroat trout (Chapter 18—Cutthroat Trout) and invasive plant species (Chapter 6—Terrestrial Invasive Plant Species). The Rehfeldt product was used to evaluate potential consequences of climate scenarios for the distribution of bioclimatic envelopes for biomes and plant species (see Sections III and IV). The Hostetler dynamically downscaled product is intended to better represent regional processes—a strength of dynamical downscaling—but has the disadvantage of being computationally expensive, so only a few models and runs are downscaled. This choice thus represents a limited range of the foreseeable futures. Therefore, we used the other three downscaled products to give a broader representation of the range of plausible and foreseeable futures for ecologically important variables.

The BLM's National direction for REAs was to consider projections for periods around 2030 and 2060. However, different downscaling products provide data from different periods. Rehfeldt and others (2006) provides 10-yr averages for around 2030 (for example, 2026–2035), 2060 and 2090. Hostetler and others (2011) provides averages for 2040–2069, and two series from 2010–2099; the BCSD dataset (Maurer and others, 2007) is available for all years through 2099, but the WSMD dataset provides only 10-yr averages around 2040 and 2080. Climate scientists generally consider 10 yr as a minimum averaging period, and prefer longer periods (30 yr is typical) to minimize the effects of natural variability. Given that BLM direction is to represent the conditions of the species and biomes in those end years, we chose the climate leading up to 2030 and 2060 as the most relevant in the analyses we generated (that is, a 15-yr period leading up to those end years: 2016–2030, 2046–2060, and 2076–2090). Time periods, GCMs downscaled, and other details for all downscaling products are in the Climate Analysis section of the Appendix.

As directed by the BLM, all analyses described use the output global climate models (GCMs) developed for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment (Intergovernmental Panel on Climate Change, 2007). This "generation" of models, often referred to as "CMIP3" for the third Coupled Model Intercomparison Project that coordinated them, was forced with several emissions scenarios from the IPCC Special Report on Emissions Scenarios (SRES). As required for the REA, we used the A2 emissions scenario, which follows a higher trajectory (that is, most warming, for CO_2 emissions by the end of the 21st century) (Nakicenovic and others, 2000). In some cases, we cite relevant studies that used A1B, which has somewhat lower emissions and more moderate warming. For example, the Western Streamflow dataset used GCMs forced by the A1B scenario. However, while the A2 scenario describes a higher emissions path compared to A1B and other scenarios (Nakicenovic and others, 2000), the several major emissions scenarios have similar results out to mid-century: the A1B emissions scenario is somewhat lower than A2 (but higher than B1) and shows a similar projection of global mean surface temperature until around the 2070s (fig. 2.23 in Walsh and others, 2014). According to the Intergovernmental Panel on Climate Change (2007), the distribution of CMIP3 climate projections do not appear to become dependent on the emissions pathway until about the mid-21st century. The Intergovernmental Panel on Climate Change (2007) does not offer a suggestion on whether any specific pathway is more likely than others, and this uncertainty about emissions pathway is a major source of uncertainty in the projections later in the 21st century. See further discussion in the Climate Analysis section in the Appendix.

While this work was in progress, the IPCC Fifth Assessment (Intergovernmental Panel on Climate Change, 2013) was released, including the output of the 5th generation of GCMs, often referred to as “CMIP5” for the 5th Coupled Model Intercomparison Project. An analysis comparing the two generations of GCM results for the full Wyoming Basin REA was beyond the scope of the REA. Lukas and others (2014) compare the two sets of projections (Lukas and others, 2014, section 3.2) and provide a map (Lukas and others, 2014, fig. 5–1) of temperature and precipitation projections for the western United States, including the Wyoming Basin. Their analysis for Colorado, including part of the southern Wyoming Basin, indicated that the two generations have similar results for temperature and precipitation. Lukas and others (2014) found that, compared to the A1B emissions scenario, the CMIP5 “Representative Concentration Pathway 4.5” scenario projects slightly less warming in the summer (about 0.9 ºC/0.5 ºF less than [<] A1B) and slightly more warming in the winter (about 0.9 ºC [0.5 ºF] more than A1B). The median change in annual temperature is also very similar between these two scenarios, as is the spread of model projections (see section 3.2 and sidebar 5−1 in Lukas and others, 2014). The CMIP5 precipitation projections forced by the same emissions pathway tend to be wetter in spring and summer and similar in fall and winter, with a <5 percent increase in annual precipitation change (see sidebar 5−1 in Lukas and others [2014]). Those authors did not make comparisons of the CMIP5 models to the A2 scenario, or for other emissions pathways used in the IPCC 5th Assessment; however, as described above the temperature changes for A2 and A1B do not diverge until after mid-century.

Reasonably Foreseeable Climate Futures

The “reasonably foreseeable” concept is modeled after the same concept for “reasonably foreseeable development futures,” used by BLM to guide management decisions as a part of its land use planning process (Benson, 2010; Bureau of Land Management, 2010). It is intended to reflect a range of plausible future conditions—that is, those that could be reasonably expected, and a range of these conditions. The reasonably foreseeable climate futures described later in this document “bracket” futures projected in the suite of GCMs downscaled by Hostetler, Rehfeldt, WSMD, and the larger suite of GCMs downscaled by Maurer and others (2007). The creators of the BCSD product excluded models that their evaluations indicated did not perform as well as others in the CMIP3 archive, about a third of the GCMs (Maurer and others, 2007; U.S. Department of the Interior Bureau of Reclamation, 2011b). The spread of the remaining models might be thought of as representing the range of reasonably foreseeable futures, given natural variability and uncertainty in the GCMs. By the 2030s, the range or spread of these 16 GCMs (the ensemble) project a warming for the Wyoming Basin of about 0.5−2.5 °C (0.8−4.5 °F) with an ensemble mean increase of about 1.5 °C (2.7 °F), compared to the 1961−1990 average. A group of GCMs is often referred to as an “ensemble,” with the average of all of the members (and sometimes multiple individual runs by some GCMs) called the “ensemble mean.” For precipitation, the reasonably foreseeable range of annual average precipitation change to 2030 varies across the GCMs from wetter conditions (increase of about 10 percent) to drier futures (13 percent), compared to the 1961−1990 average, with the ensemble mean near zero.

We provide here the range of GCMs around an ensemble mean, but not a confidence interval or standard deviation. While there are established methods for generating probabilistic risk statements or potential occurrence of a temperature above a given threshold for *observed* climate records, it is not appropriate to use a range of *projected* changes as a probability distribution or to generate such risk statements (Lukas and others, 2014). This is because using an ensemble of GCM projections this way would require that the individual model projections are equally likely, which is unlikely. Therefore, the range of projected changes for a particular variable, “is most appropriately used as a guide to expected tendencies, *not* [emphasis added] as a probability distribution that provides precise quantification of future risk,” (Lukas and others, 2014, p. 88). For further discussion of the challenges in developing probability distributions of future conditions from GCM ensembles, see sections 5-1 and 6-1 in Lukas and others (2014).

Climate of the Wyoming Basin

Climate can be first defined as the average weather, or more rigorously as the statistical description of weather variables in terms of their means and variability over a period of time from days to months to years and to thousands or even millions of years (Intergovernmental Panel on Climate Change, 2007). Relevant variables include temperature, precipitation, humidity, and atmospheric pressure or winds. A classical averaging period for these variables for analysis is 30 yr, defined by the World Meteorological Organization and used by many state climate offices and the National Weather Service. Climate can also be defined as the state of the climate system, including a statistical description; the word “climatology” is sometimes used interchangeably with climate to describe the climate of a defined period in the historical record or in projections of the future. Climate variability, then, refers to variations in the mean state and other statistics (for example, standard deviations and statistics of extremes) of the climate on any time or spatial scale beyond an individual weather event. This variability may be due to natural processes within the climate system (sometimes called internal variability), or man-made or anthropogenic forcing (external variability) (Lukas and others, 2014). Natural climate variations that affect the year-to-year and longer natural variations in Wyoming Basin’s climate include semi-predictable climate oscillations like the El Niño-Southern Oscillation, which influence storm tracks and other atmospheric dynamics affecting the Wyoming Basin, as well as more or less random fluctuations. Climate change can be defined as the variability in climate that is outside the range of expected patterns of natural variability, which is typically determined from studies on the impacts of man-made forcings like greenhouse gases as well as natural forcings like the El Niño-Southern Oscillation, volcanic eruptions and solar variability. Studies to unravel the effects of manmade and natural forcings are often called detection and attribution studies (see Mote and Redmond 2012; Hegerl and others, 2007). For a further description of the distinction between weather, climate variability, and climate change, see Section 1-3 in Lukas and others (2014), and for discussion of climate variability and change in studies that include the Wyoming Basin, see Mote and Redmond (2012), and McWethy and others (2010).

This section describes the recent observed climate and paleoclimate reconstructions for the Wyoming Basin, including trends and the global context for the region. The Wyoming Basin includes mountainous areas that are part of the Central and Northern Rockies, the Great Plains, and the headwaters of several major rivers, including the Upper Colorado, Green, Platte, and Upper Missouri Rivers (fig. 1–2). Topographically, it ranges from over 3,962 meters (m) (13,000 feet [ft]) elevation in the Wind River and surrounding mountains, with valleys around 1,220 m (4,000 ft) elevation (fig. 1–1). The mid-latitude (40º–46º N) and mid-continent location of the Wyoming Basin defines many aspects of its climate. Seasonal cycles dominate its climate, with upper-level winds directing air masses and storms generally west to east. The Basin’s combination of mountains and valleys and plains also defines many aspects of its climate, with its several mountain ranges lying in a general north-south direction, providing barriers that force the air currents moving in from the Pacific Ocean to rise and drop much of their moisture along the western slope. Moisture-laden storms from the east may also push air upslope on the eastern slopes, especially of the Bighorn Mountains. Due to this complex topography, temperature and precipitation can vary considerably over short distances, and make it difficult to divide the Wyoming Basin into homogeneous, climatological areas. However, NOAA and the Wyoming State Climate Office divide the state into several regions for the purposes of analysis. The following sections draw from these graphics maintained by the Wyoming State Climatologist's Office (WSCO) that show considerable variation in Wyoming's climate over time in both annual temperature and annual precipitation from 1895 to the present.

Temperature

The mid-latitude position and elevation contribute to the Wyoming Basin's relatively cool climate (fig. 7–1). According to the Wyoming State Climate Office, the warmest parts of the Wyoming Basin are the lower elevation areas such as the Bighorn Basin (see fig. 5−3 at http://www.wrds.uwyo.edu/sco/wyoclimate.html) and other lower elevation valleys. Temperatures also cool with increasing elevation by about 5–8 °C per 1,000 m (2.7–3.8 °F per 1,000 ft) a relationship known as lapse rate (Ray and others, 2010). Above about 1,830 m (6,000 ft) elevation the temperature rarely exceeds 38 ºC (100 ºF). Because of low humidity, there is often a large diurnal, or day-night, range in temperature, with summer nights almost invariably cool, the mean minimum temperature in July ranges from 10−16 ºC (50−60 ºF). With increasing elevation, temperatures drop rapidly; in the mountains at about 2,700 m (about 9,000 ft) elevation average maximums in July are around 21 ºC (70 ºF), the mountains and high valleys average lows in the middle of the summer are about 1−4.5 ºC (30−40 ºF) with occasional drops below freezing (0 ºC [32 ºF]). Time series of observed mean annual temperature for Wind River, Bighorn, Green and Bear, and Upper Platte basins show inter-annual variability in precipitation multi-year periods of warm or cooler than average conditions (see graphics for Wind River, and other climate divisions at http://www.wrds.uwyo.edu/sco/data/divisional_temp/divisional_temp.html). Although the natural variation in temperature varies by place, a standard deviation in temperature of plus or minus (±) 0.9 ºC (±1.5 ºF) is a typical value over the observed record from 1985 to the present.

The Wyoming Basin's climate has a distinct seasonal cycle, as shown in the WSCO plots of seasonal extremes in temperatures around the state (select stations including Cody, Casper, Rawlins, Worland, Kemmerer, and Basin, from http://www.wrds.uwyo.edu/sco/temperature/extremes/extremes.html). July is typically the warmest month, with mean maximum temperatures ranging 29−35 ºC (85−95 ºF), and January is typically the coldest month. The period of record varies by station, but many date to the later 1800s. According to the Wyoming State Climate Office (WSCO), in the wintertime it is characteristic to have rapid and frequent changes between mild and cold spells. Usually there are <10 cold waves per winter for a given area with most areas experiencing 5 or fewer. Most cold waves move southward on the east side of the Continental Divide. During winter warm spells, nighttime temperatures frequently remain above freezing; warm downslope winds, known as Chinooks, are common along the eastern slopes. Numerous valleys provide pockets for the collection of cold air at night, because mountain ranges prevent the wind from stirring the air, so valleys are often considerably colder than on nearby mountainsides. In Worland (located at ~1,220 m [4,000 ft] elevation in the lower Bighorn Basin), the mean January minimum temperature is –18 ºC (0 ºF) (http://www.wrds.uwyo.edu/sco/temperature/extremes/Worland-489770/Worland-489770.html), while in Cody (located at ~1,524 m [5,000 ft] on the west side of the valley) the mean January minimum is –12 ºC (11 ºF) (http://www.wrds.uwyo.edu/sco/temperature/extremes/Cody-481840/Cody-481840.html).

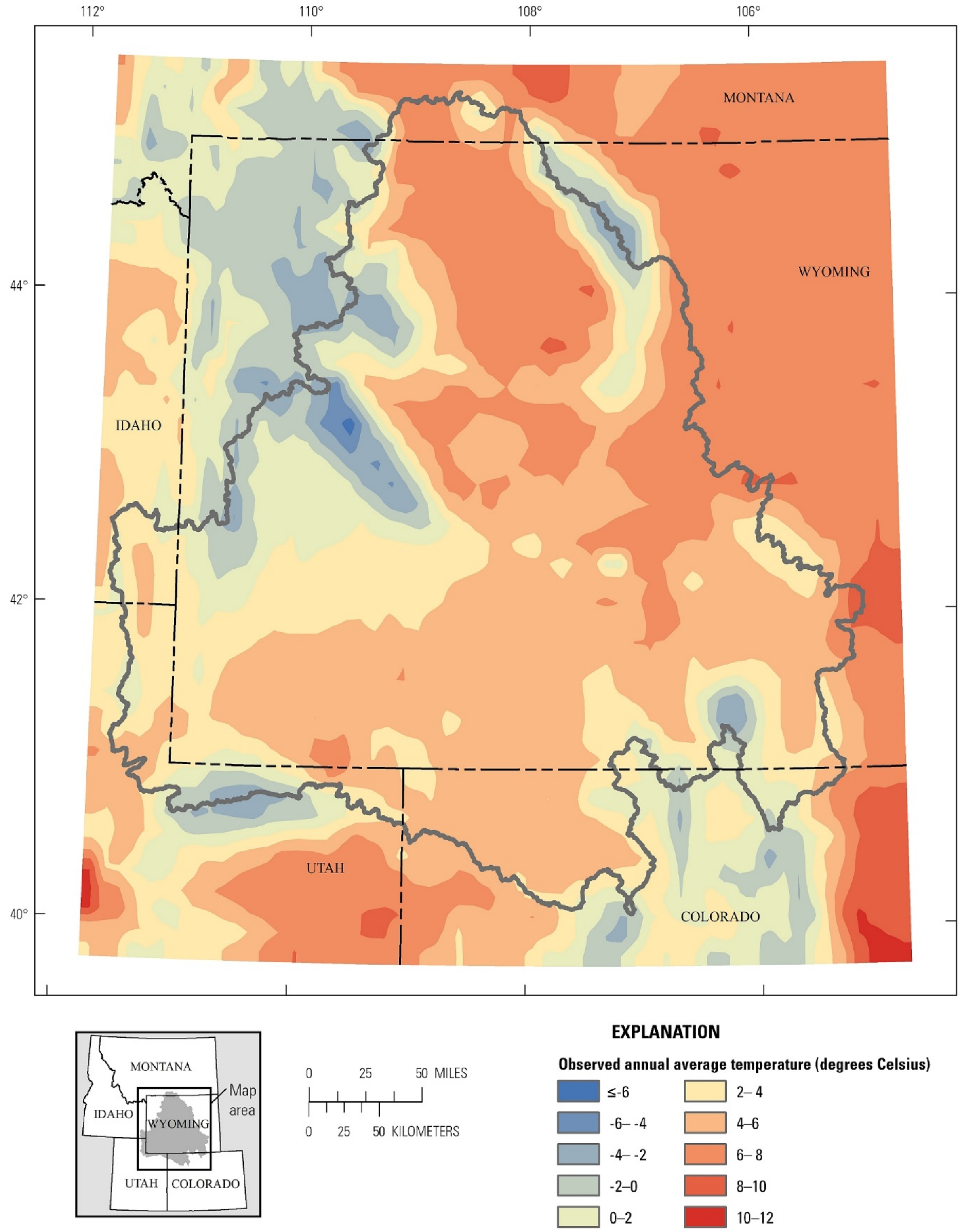

Figure 7–1. Observed Annual Average Temperature, 1961−1990 in the Wyoming Basin Rapid Ecoregional Assessment project area. [Bias-corrected spatial disaggegation data, 12 kilometer (7.5-mile) resolution]

Growing season is an ecologically important concept related to temperature, and projected changes in growing season will be discussed below. In the Wyoming Basin, early freezes in the fall and late in the spring are typical, resulting in short growing seasons. According to the WSCO, an agricultural definition of growing season is the freeze-free period, the number of days between the last 0 ºC (32 ºF) day in early summer and the first freeze in late summer (ecological definitions of growing season vary, and may be derived from metrics like chilling and forcing units, see for example, Chuine [2000]). In Wyoming's principal agricultural areas, the average growing season is about 125 days, however, in the mountains and high valleys, freezing temperatures may occur during the summer and growing seasons are shorter. At Farson near Sandy Creek, a tributary of the Green River, the average is 42 days, and even shorter for Star Valley and Jackson Hole (Curtis and Grimes [2004; chapter 3.1]). Cloudiness, humidity, and wind may also be ecologically important, but were beyond the scope of this report; the recent climatology of these variables is discussed in chapters 8, 9, and 11, respectively of Curtis and Grimes (2004).

Precipitation

Like temperature, precipitation varies among locations, with precipitation generally greater over the mountain ranges and higher elevations (fig. 7–2). Wyoming is the 5th driest state in the United States, and experienced moderate to severe drought for nearly a decade beginning in 1999 (Kunkel and others, 2013). The highest annual precipitation in the Wyoming Basin is about 100 centimeters (cm) (40 inches [in]) (fig. 7–2) in the mountains; these annual precipitation measures are a combination of snow water equivalent (SWE) and rain. The relatively dry southwestern part of the region is a high plateau nearly surrounded by mountain ranges, including those in Colorado and Utah. Time series of observed annual precipitation from 1895−2014 show the inter-annual variability and multi-year periods of wetter- or drier-than-average conditions (see plots on line at the Wyoming Water Resources Data System, for the Wind River, Bighorn, Green and Bear, and Upper Platte basins http://www.wrds.uwyo.edu/sco/data/divisional_precip/divisional_precip.html). Although the natural variation in precipitation varies by place, a standard deviation in precipitation of around ±5 percent is typical over the observed record from 1895 to the present.

According to WSCO data on the seasonal cycle of precipitation from around the Wyoming Basin, a precipitation peak occurs in May−June for most of the region with a secondary peak in September−October (fig. 7–3). In some higher-elevation areas where most precipitation falls as snow, the peak precipitation is in the winter, generally December or January. The lower Bighorn Basin provides a striking example of how topography influences precipitation: mountain ranges on both the west and the east block the flow of moisture laden air, and as a result, this Basin is the driest part of Wyoming with an annual precipitation of 13−20 centimeters (cm; 5−8 inches [in]). Worland, in the southern Bighorn Basin, has an annual mean of 18−20 cm (7−8 in). Laramie is also in a precipitation shadow; it has an annual mean of 25 cm (10 in), while 48 kilometers (km) (30 miles [mi]) to the west, Centennial, at 2,460 m (8074 ft), receives about 41 cm (16 in) per year (see http://www.wrds.uwyo.edu/sco/data/normals/1971-2000/coop_precip.html).

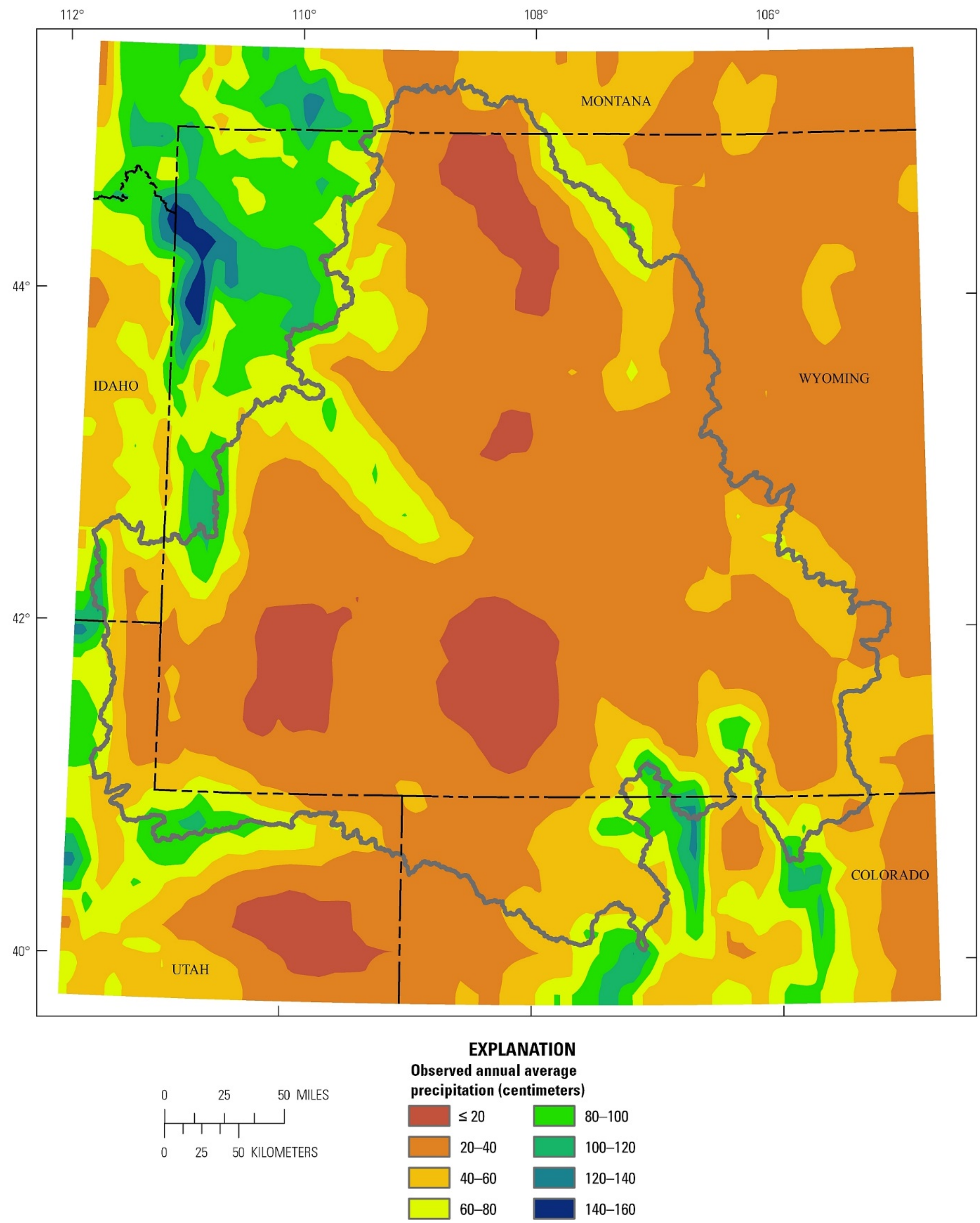

Figure 7–2. Observed annual average total precipitation 1961−1990 in the Wyoming Basin Ecoregional Assessment project area. [Bias-corrected spatial disaggegation data, 12 kilometer (7.5-mile) resolution]

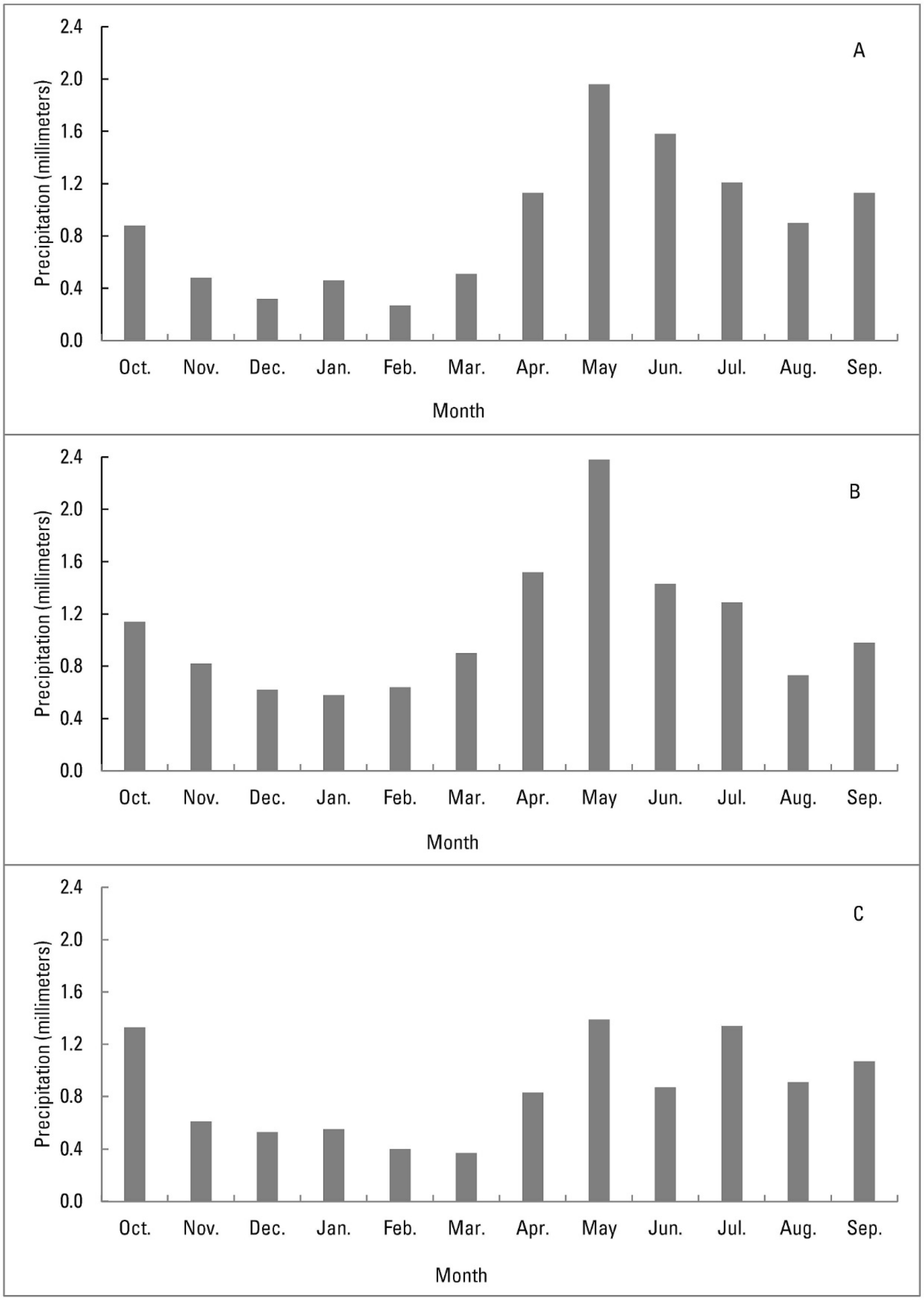

Figure 7–3. Seasonal cycle of precipitation from several locations in Wyoming for the water year October 1st to September 30th, for (*A*) Cody, (*B*) Casper; and (*C*) Baggs, Wyoming. [Data from the Wyoming State Climate Office]

The average number of days with measurable precipitation ranges from <53 days per year over the central, southwest and Bighorn basins to well over 160 days per year over the highest elevations across the state (fig. 4.3 in Curtis and Grimes, 2004). During the summer, showers are quite frequent but often deposit only a few hundredths of an inch. There are only four weather stations with long enough records of hourly precipitation measurements to study rain frequency: Casper, Cheyenne, Lander, and Sheridan. Analysis of hourly data for these stations by the WSCO shows that from 1949−2001, more than 70 percent of the time no precipitation fell, and of the remaining period, more than 75 percent occurred at a rate <0.67 cm (0.26 in) per hour. Occasionally, very heavy rain is associated with thunderstorms, and each year for any given area, there are several local storms with 2.5−5 cm (1−2 in) of rain in a 24-hour period.

Total annual snowfall ranges from 38−51 cm (15−20 in) in the lower Bighorn Basin to over 510 cm (200 in) in the higher mountain ranges (fig. 5.3 in Curtis and Grimes [2004]). Snow water equivalent (SWE) is a common snowpack measure that represents the amount of water contained within the snowpack and can be thought of as the depth of water that would theoretically result if you melted the entire snowpack instantaneously (Curtis and Grimes, 2004). Projected changes in SWE will be discussed in the Wyoming Basin Climate Futures section of this chapter.

Evaporation and related variables are ecologically important parameters for vegetation and thus to habitat; evapotranspiration and humidity are important aspects of fire risk. The average relative humidity is quite low especially in the lower elevation basin areas (fig. 9.1 in Curtis and Grimes [2004]) but with a high diurnal variation between day and the cooler nights, around 40−45 percent humidity during the summer, and lower in the winter. Low relative humidity, high percentage of sunshine, and rather high average wind speeds all contribute to a high rate of evaporation for May through September (the frost free period for which consistent records are available). The average amount of evaporation is about 104 cm (41 in), determined from evaporation pans at a few selected locations (Curtis and Grimes, 2004).

Paleoclimate Reconstructions and Natural Climate Variability

The paleoclimate record provides a history of natural climate variability over longer periods than observational or instrumental records are available for. Historical records of climate (including records of streamflow) from before the instrumental record have been developed from tree-ring chronologies. Streamflow reconstructions are based on the finding that in semi-arid climates, the same climate factors, primarily precipitation and evapotranspiration, control both the growth of moisture-limited trees and the amount of runoff. By providing a longer window into the past, the tree-ring reconstructions are thought to describe the natural variability of climate more completely than the shorter record of stream gage observational records. The Treeflow website (http://treeflow.info) provides online access to these tree-ring chronologies from many research papers and provides background and original citations. Treeflow includes several rivers in the Wyoming Basin that are tributaries of the Colorado and Missouri Rivers, but no reconstructions are available for the North Platte tributary of the Missouri.

Two rivers in the Wyoming Basin for which there are reconstructions are the Little Popo Agie River near Lander, Wyoming (Watson and others, 2009; and see http://treeflow.info/upmo/littlepopoagie.html) and the Little Snake River near Lily, Colorado (Gray and others, 2011; also see http://treeflow.info/upco/littlesnake.html). Both show multi-year variations in streamflow in the reconstructed record; this indicates that there is significant natural variability on inter-annual to decadal time scales (fig. 7–4), including larger year to year variations than in the observed climate of the last century, and longer periods of low flow than observed in the past century. Gray and others (2011) find that, even in a millennial context, gaged flows for the very dry years of 1977 and

2002 on the Little Snake River were extremely dry, but also that droughts of much greater duration and magnitude than any in the instrumental record were regular features prior to 1900. These reconstructions also point to the unusual wetness of the gage period, and Gray and others (2011) suggests the potential for recent observations to paint an overly optimistic picture of regional water supplies. The natural variability seen in the paleoclimate record is part of the variability that is expected to contribute to climate change in the future.

The Changing Climate "Normal" and Trends

Two general ways that climate scientists analyze trends are to analyze data available to the beginning of the record in any given place (in the Wyoming Basin, some stations date to the 1880s, but in many places, the record is shorter), or to compare to a reference period, or "normal" to a later reference period (described below). Supporting studies for the 2008 National Climate Assessment looked at annual data by year and by season and found that temperatures in Wyoming have warmed by almost 1.1 ºC (2 ºF) in the past 30 years (Karl and others, 2008). For the Northern Great Plains area analyzed for the 2014 National Climate Assessment, Wyoming is part of region with a statistically significant increase in annual temperature as well as increases for all seasons: winter, spring, summer, and fall (fig. 8 in Kunkel and others, 2013). The Basin also is part of regional trends toward a wetter northern Great Plains that is projected to become more pronounced compared to the observed 1971−2000 baseline (Kunkel and others, 2013). However, Kunkel and others (2013) found no significant trends in precipitation. To support the National Climate Assessment, Louisiana State University (2012) generated plots of precipitation and temperature time series for all United States climate divisions, including those including the Wyoming Basin Climate Divisions. Time series plots can be generated to show periods of above- or below-average conditions for any of the climate divisions in the Wyoming Basin at http://charts.srcc.lsu.edu/trends/.

Another standard practice in the meteorological community is that a 30-yr period, or "normal," encompassing three full decades, is used as an averaging period to put recent or future climate conditions into a historical context; longer periods are also used. Thus, a reference such as "percent of average precipitation," has the normal or average conditions over a set baseline period embedded in that value. Typically this "normal" is updated every decade, and recently NOAA and the State Climatologists for the Wyoming Basin states changed all of their baselines for calculation from the previous normal (1971–2000) to the new 1981–2010 normal. While the 30-yr normal was not designed to be a metric of climate change, the change from the prior to the new normal reflects systematic changes in the regional and global climate that may be attributable to decadal-scale natural climate variability, as well as, human influence (Lukas and others, 2014).

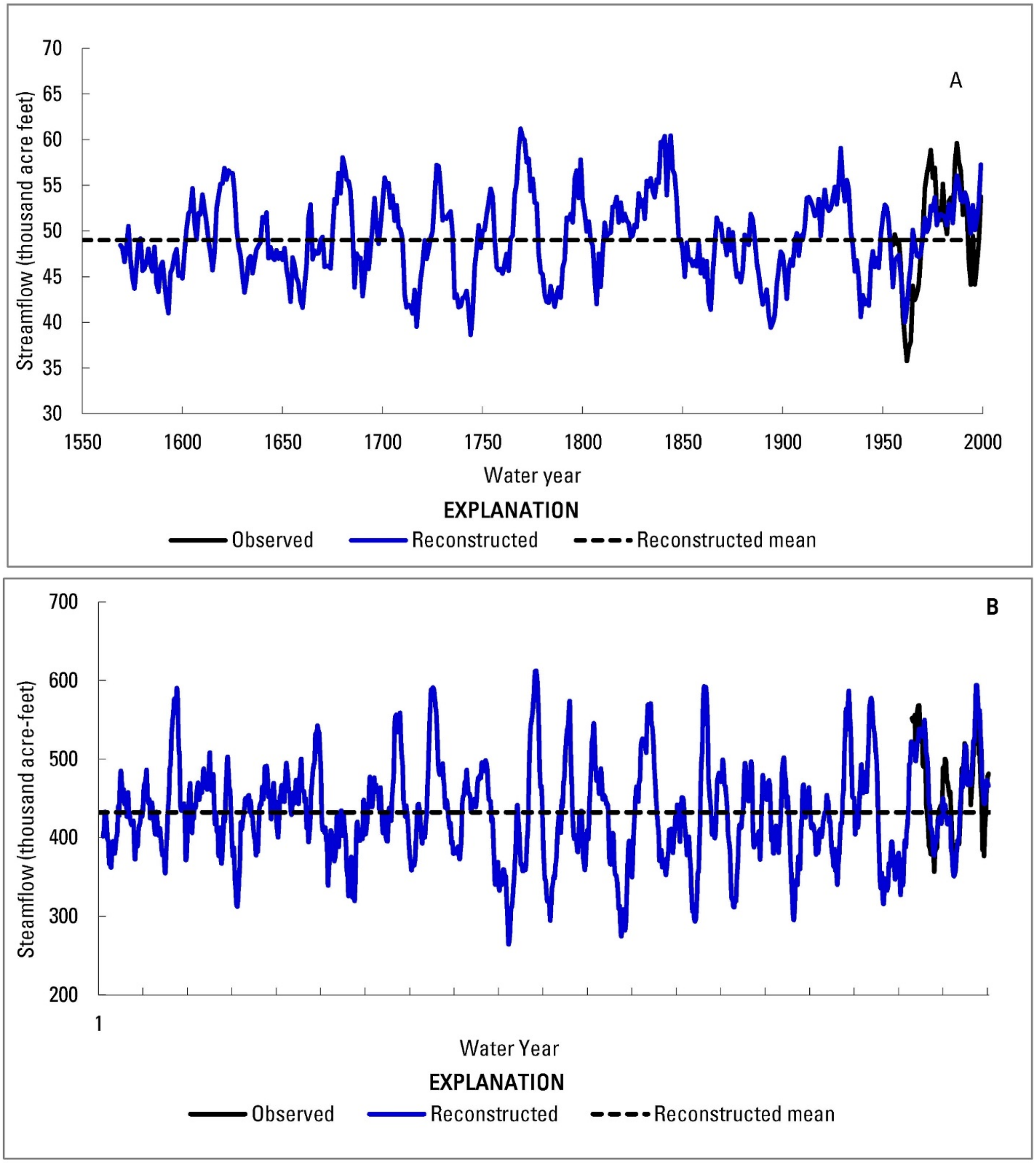

Figure 7–4. Observed and reconstructed annual streamflow in thousands of acre feet for (*A*) the Little Popo Agie River (a tributary of the Wind and Bighorn Rivers) 1560–1999, and (*B*) the Little Snake River 1996−2001. The 10-year running mean of reconstructed streamflow (blue) and observed streamflow are shown in black. The dashed line shows the long-term reconstructed mean. Both rivers show multi-year periods of above and below average annual streamflow. [After Treeflow.org, data from Treeflow.org]

When the 30-yr normal was updated to the new one, the decade of the 1970s was replaced in the baseline period with the 2000s (Lukas and others, 2014). The 2000s were significantly warmer than the 1970s over most of the world and the United States, and also drier than the 1970s in most of the western United States (Lukas and others, 2014), including the Wyoming Basin. Thus the new 1981–2010 normal is warmer and drier than the previous one (1970‒2000). The WSCO provides a comparison of the 1971‒2000 and 1981‒2010 normals on its website (http://www.wrds.uwyo.edu/sco/data/normals/normalmap.html). A new report by the Western Water Assessment indicates that, given that the current "normal" is warmer and drier than previous normals, historic or future conditions compared to it may appear to be cooler and wetter than compared to the previous normal (Lukas and others, 2014). For example, according to the NOAA Colorado Basin River Forecast Center, the 1981–2010 average natural streamflows used to compute the percent of average are lower than the previous normal throughout the Colorado River Basin (including the Green and Yampa Rivers), and the 1981–2010 April through July inflows to Lake Powell were 11 percent lower than the 1971–2000 inflows. In this report, we use a 1961−1990 baseline, or normal, intentionally to compare futures to a period before the most recent warming. Where we describe analyses done by other scientists, we provide the baseline they used, but it was beyond the scope of the report to reanalyze using a different climatological normal period.

The 2008 National Climate Assessment found that Wyoming temperatures have warmed by almost 1.1 ºC (2 ºF) in the past 30 yr (Karl and others, 2008). For the Northern Great Plains area analyzed for the 2014 National Climate Assessment, Wyoming is part of a region with a statistically significant increase in annual temperature as well as increases for all seasons: winter, spring, summer, and fall (fig. 8 in Kunkel and others, 2013). However, the relative contributions of natural and anthropogenic climate forcings are unclear. The Basin also is part of regional trends towards a wetter northern Great Plains that is projected to become more pronounced compared to the observed 1971−2000 baseline (Kunkel and others, 2013).

Wyoming Basin Climate Futures

Changes in the Wyoming Basin's climate and implications for its biomes/habitats and species are occurring in a global climate-context, which is shifting the characteristic weather patterns across the globe and the continental United States. Although climate has varied throughout history, present conditions are rapidly changing (for example, as the warmer and drier 1981–2010 normal), and if trends continue, "novel" climate conditions may occur (Rehfeldt, 2006; Whitlock and others, 2003) compared to recent conditions. The Wyoming Basin is embedded in an observed continental pattern including a generally warmer western United States, and a regional trend towards a wetter northern Great Plains and a drier southern Great Plains; these patterns are projected to become more pronounced, compared to the 1971−2000 period that Kunkel and others (2013) analyzed; trends would be expected to be similar compared to a 1961−1990 baseline.

As an overview to the climate projections for the Wyoming Basin, we describe here the projected changes in climate across the continental United States using data from the same 2007 IPCC GCMs analyzed in this report (Ray and others, 2008; also see Mote and Redmond, 2012). Climate scientists deliberately use the term "projections" for the long-range future simulations by GCMs, rather than forecast or prediction, because the future outcomes are sensitive to future changes in related conditions (for example, emissions) and that projected changes are conditional on that emissions pathway. Relative to the 1950‒1999 baseline used in Ray and others (2008, fig. 5–1), the overall ensemble average (of all 22 GCMs in the CMIP3) projects an annual temperature increase of 1.8 ºC (2.5 ºF) (range = 0.83 to 1.93 ºC [1.5‒3.5 ºF] by 2025 (2015‒2035, the period used in Ray and others, 2008) and 2.2 ºC (4 ºF) by 2050 (2040−2060 average) (range = 1.8−3ºC [2.5−5.5 ºF] among the 16 GCMs) for the Wyoming Basin as a whole. The A1B emissions scenario used in that analysis is similar to the A2 scenario out to mid-century (see above and the Climate Analysis section of the Appendix). Up to about 2050, the annual average is projected to be greater than the annual summer average of 2.8 ºC (5 ºF) (range = 1.7−3.9 ºC [3 to 7 ºF] among the GCMs), which is more than the 1.7 ºC (3 ºF) (range = 1.1−2.8 ºC [2−5 ºF]) projected increase for the annual winter (December−February) average. The GCMs are approximately evenly divided in terms of projected increases or decreases in annual precipitation. Overall, more of the models project decreasing summer precipitation (especially in the western part of the Wyoming Basin) and increasing winter precipitation.

Reasonably Foreseeable Changes in Climate in the Wyoming Basin

A reasonably foreseeable range of projected changes in temperature, precipitation, and hydroclimate variables were developed for the Wyoming Basin from downscaled climate data as described in the Climate Analysis section in the Appendix. Because the future climate will vary due to natural inter-annual and decadal variability, and because there is uncertainty in models, figures provided later in this chapter illustrate a range of foreseeable future conditions. Specifically, we show projections from two downscaled GCMs and from an ensemble mean, all forced by the A2 emissions scenario.

To consider the range of foreseeable futures, it is important to understand that the range of future conditions includes the natural variability in the climate system (for example, decadal variability, El Niño, and other oscillations), uncertainty about future greenhouse gas emissions, and the range of uncertainties in the GCMs. The uncertainties in the GCMs include that the state of understanding is incomplete about of how global, regional, and local climate will respond to these emissions over the coming decades. Furthermore, there are differences among climate models in how they represent climate processes and therefore produce different climate projections for a given time period and location even when the same future emissions scenario drives the simulation. (For a discussion of climate models, and why climate model projections differ from each other, see chapter 3 and sidebar 3-1 in Lukas and others [2014]). Global temperatures, however, are expected to increase (Intergovernmental Panel on Climate Change, 2013). Consequently, natural resource managers can expect warmer temperatures in the future, although the magnitude and consequences of warming is uncertain. Summers are projected to warm more than winters (an increase of 4.5 ºF versus 3.5 ºF) (fig. 5.1 in Lukas and others, 2014).

The range of projected futures in the BCSD dataset is shown in figure 7–5 for a representative area in the central valley of the basin, to visualize the range of projected futures. This 16-GCM ensemble (including all of those used in this report) allows visualization of the range of possible futures, as well as inter-comparison of the different GCMs that were downscaled by Hostetler, Rehfeldt, and the Western Streamflow database. The range of model projections is described further in the Climate Analysis section in the Appendix. All model runs project an increase in temperature of ≥0.5 ºC (0.8 ºF) for the period 2016−2030 and the ensemble average projects an increase of about 1.4 ºC (2.5 ºF). For the latter period, 2046−2060, the ensemble average increase is about 2.7 ºC (4.9 ºF), with none of the ensemble members projecting increases less than 1.4 ºC (2.5 ºF). The BCSD dataset downscaled 16 GCMs from the 22 GCMs in the IPCC 2007 assessment; these GCMs eliminated the more poorly performing GCMs, retaining those which were evaluated to better simulate climate over the western United States. Therefore, this dataset can be considered to include a range of reasonably foreseeable futures, given natural variability and model uncertainty. Figure 7–5 shows that the GCMs downscaled in the various products used span a range of reasonably foreseeable futures, which can be described as:

- All models in a 16-GCM ensemble project warming by 2030 and further warming by 2060 (see Climate Analysis section of the Appendix). The ensemble mean change in precipitation by 2030 is near zero for the lower-elevation central valleys, and slightly wet (an increase of about 2 percent) for the higher elevation Wind River area compared to 1961−1990.
- By 2060, there is a wider spread in the projected futures for both temperature and precipitation, reflecting both uncertainty in the GCMs and in natural variability.
- The CMIP3 GCMs downscaled by Hostetler (ECHAM5 and GFDL2.0) are near the ensemble average for temperature; however, GFDL2.1, downscaled by Rehfeldt, is consistently among the warmer models.
- ECHAM5 is consistently among the cooler models, and similar to the GCMs downscaled by Rehfeldt.
- Although there is little agreement among the models in regards to change in the annual total of precipitation, analysis of the seasonal data project wetter winters and drier summers.
- Climate variability will continue in addition to the projected upward trend in temperature and precipitation. This is due to natural climate fluctuations such as the El Niño-Southern Oscillation and other variations, as well as uncertainty in model projections.

For both periods, the ensemble average for precipitation change is near zero, with a few more models projecting increasing rather than decreasing precipitation (fig. 7–5). For the latter period, the ensemble average for precipitation change is still near zero, but with a wider spread of possible futures among the models. Precipitation is difficult to project, partly because potential future changes in precipitation (unlike temperature projections) are smaller than the year-to-year and decade-to-decade variations observed in the historical record (Ray and others, 2008). According to the IPCC, “Models suggest that changes in mean precipitation amount, even where robust, will rise above natural variability more slowly than the temperature signal” (Intergovernmental Panel on Climate Change, 2007, p. 74). Recent work by Deser and others (2014) finds that given the natural variability, a precipitation signal is not expected to emerge (that is, become statistically significant) until the mid-21st century or later.

Figure 1.6 in Mote and Redmond (2012) provides an excellent illustration of the difference between the range of variability since 1950, as simulated by the GCMs, and the range of futures for both temperature and precipitation for a domain of the western United States west of 107.5° west longitude (roughly west of a line from Craig, Colo., north to Rawlins, Wyo.). They illustrate a clear upward trend in temperature, but show no obvious trend in precipitation for the large area analyzed. Despite the lack of trend in precipitation, the temperature increase alone could increase evaporation and plant water demand; thus, even without a decrease in precipitation, water availability for ecosystems could decrease if precipitation remains about average; this subject is discussed further in the hydroclimate section below.

The climate of the future will be a combination of natural variability in both temperature and precipitation as well as any trend due to greenhouse gas forcing, as it emerges from the noise of the natural variability. According to historical data from the WSCO, the long term (1895−2013) 1-standard deviation in annual precipitation for this area is about +/–5 percent. Consequently, similar ranges of natural variation could be expected in the future. Indeed, some of the variation among the GCMs is due to the different natural decadal variability represented in the different GCM runs.

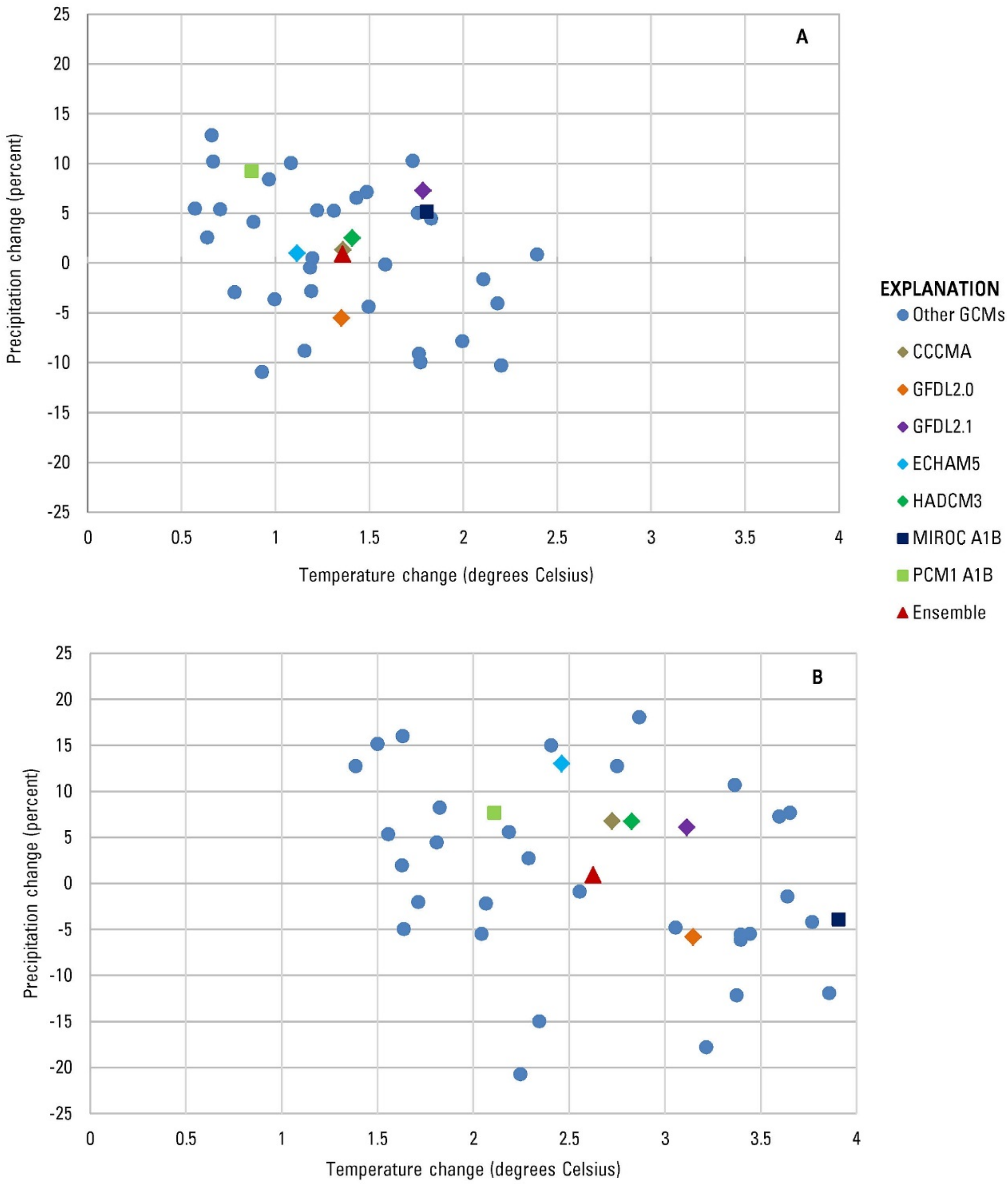

Figure 7–5. Range of futures in global climate models (GCMs) for the central Wyoming Basin. Annual temperature and precipitation changes between the current (1961−1990) and (*A*) 2016−2030 and (*B*) 2046−2060 downscaled for a region in the central Wyoming Basin show the range of futures in 16 GCMs downscaled by bias-corrected spatial disaggegation (BCSD). There are multiple runs of some GCMs for 36 total runs. Downscaled GCMs used in this report are labeled on the graph, including ECHAM5, GFDL2.0 GFDL2.1, CCCMA, and HADCM3, and the 36-member ensemble mean (ENS) were all forced by the A2 emissions scenario. PCM1 and MIROC, part of the Western Streamflow dataset, were forced by the A1B scenario. The long term (1895−2013) 1-standard deviation in annual precipitation for this area is about +/-5 percent. [Data from bias-corrected spatial disaggegation, 12-kilometer (7.5-mile) resolution]

How climate variability may change in the future as a result of anthropogenic climate change is an active topic of research. Kharin and others (2013) analyzed the CMIP5 GCMs and found the models projected an increase in the annual extremes of daily precipitation of 5−10 percent for 2046−2065 (fig. 4 in Kharin and others, 2013), an increase of 2−4 °C (4−7 °F) in the 20-yr return value for annual warm temperature extremes (that is, the extreme warm temperature is warmer), and an increase of 2−6 °C (4−10 °F) in the 20-yr return value for annual cold temperature extremes (that is, the extreme cold temperature is also warmer). These projections by Kharin and others (2013) are statistically significant for the Wyoming Basin and the analyses are for changes in the 20-year return period (that is, a change in the probability of occurrence of a 20-year event or equivalently, an annual exceedance probability of 5% [p = 5%]).

Temperature Projections

Figures 7–6 to 7–8 show both recent climatology (1961−1990) and future climate projections for 2030 and 2060 in the Wyoming Basin derived from the BCSD downscaled product for the ECHAM5 model, the GFDL2.1 model and a multi-model ensemble mean. Average annual (fig. 7–6), January (fig. 7–7), and July (fig. 7–8) temperatures in the Wyoming Basin are all projected to be warmer by 2030. The downscaled futures represented by the three GCMs are all within the range of reasonably foreseeable conditions, with the warmest temperatures projected by the GFLD2.1 model. By 2060, the ensemble average for annual average temperatures is projected to increase by about 2.7 ºC (4.9 ºF). According to these projections, by 2030, a larger area could experience higher temperatures than current climate, with further expansion of these areas by 2060 and 2090. The climate zones and warmer temperatures typical of the lower-elevation valleys are projected to be displaced upward in elevation to the higher plateaus and valleys, such as the Red Desert. Projected temperatures for both July, typically the warmest month, and January, typically the coldest month, are warmer and could reach ecological temperature thresholds. For example, there may be fewer cold nights that control pine beetle populations, or more warm days in the summer that reach thresholds relevant to fire risk.

To look at projected changes in the seasonal cycle, figure 7–9 shows an example area in the Bighorn Mountains that compares the monthly average temperatures from 1961−1990 climatology to the mid-21st century, for which projections indicate that typical summer temperatures in 2050 could be as warm as or warmer than the hottest 10 percent of summers that occurred between 1950 and 1999 (fig. 7–9). This graphic is consistent with the seasonal shift in temperatures described above in the section on the global context for climate futures.

The National Climate Assessment technical report on the climate of the Great Plains (Kunkel and others, 2013) includes an analysis of daily data from the North American Regional Climate Change Assessment dynamical downscaling, using the same CMIP3 GCMs and A2 scenario used in this report. Kunkel and others (2013) find that, due to projected warming temperatures, the length of the frost-free season (similar to the growing season) could extend 21−36 days in Wyoming (fig. 21 in Kunkel and others, 2013) by the 2041−2070 time period compared to 1980−2000. This result is statistically significant for all of Wyoming, with more than 50 percent of the models projecting a statistically significant change and more than 67 percent agreeing on the direction of change. They also find 15−40 fewer days with minimum temperature <0 ºC (32 ºF), with the greatest projected changes in the western side of the Basin (fig. 19 in Kunkel and others, 2013). With respect to high temperatures, the models projected up to 15 more days a year when maximum temperature is greater than 35 ºC (95 ºF) (fig. 17 in Kunkel and others, 2013), with the largest increases in the high central valley including the areas around Rock Springs and Rawlins.

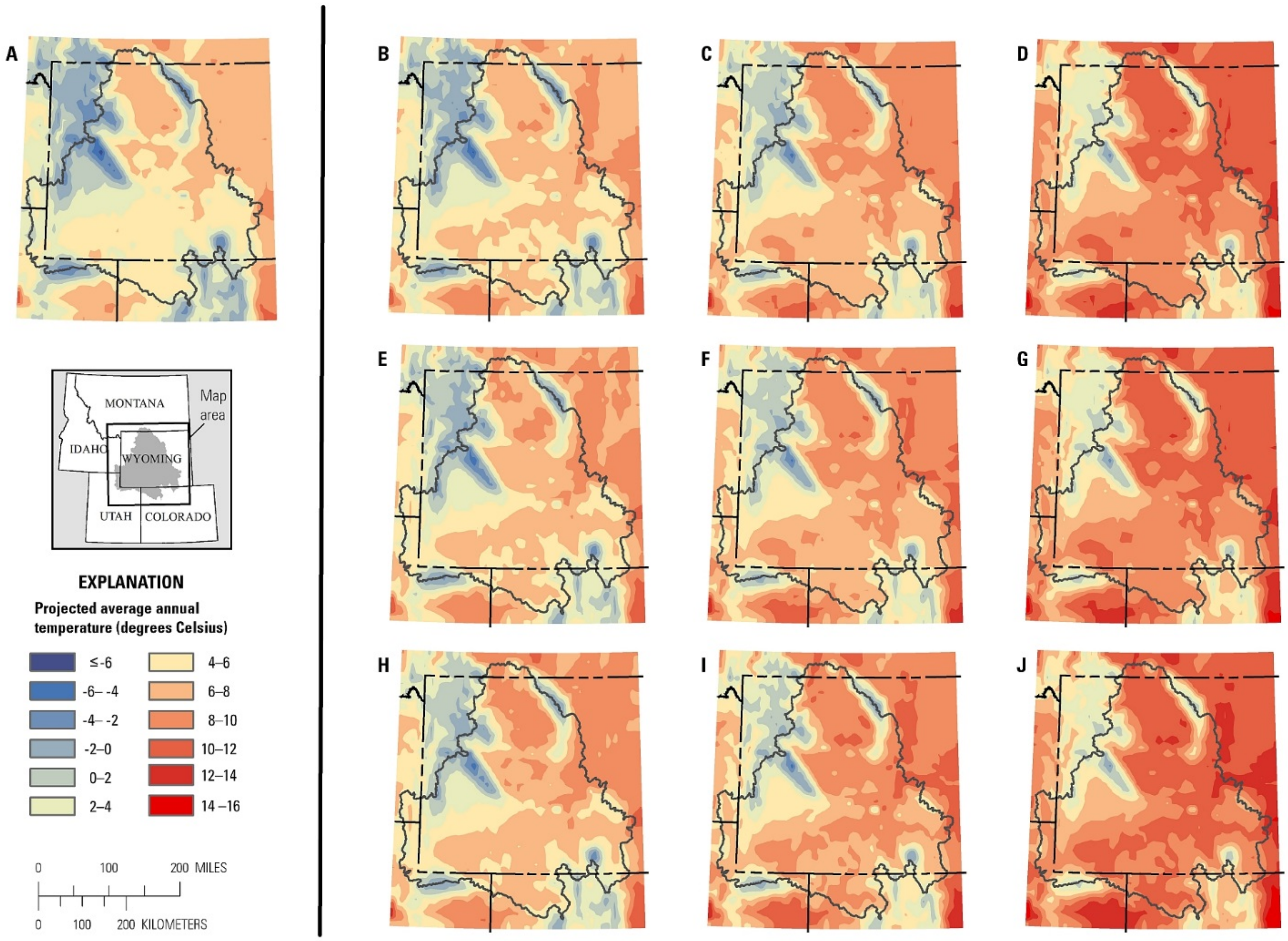

Figure 7–6. Historical and projected average annual temperatures for the Wyoming Basin Ecoregional Assessment project area. (A) Average annual temperature during the historical period (1961−1990); ECHAM5 model projections for (B)) 2016−2030, (C) 2046− 2060, and (D) 2076−2090; ensemble mean projections for (E) 2016−2030, (F) 2046− 2060, and (G) 2076−2090; and GFDL2.1 model projections for (H) 2016−2030, (I) 2046−2060, and (J) 2076−2090. [Bias-corrected spatial disaggegation data, 12 kilometer (7.5-mile) resolution]

Another way to look at temperature extremes is the temperature of the most extreme and rare cold and hot days, defined as those having a 5 percent chance of occurring during any given year. According to studies that are part of the National Climate Assessment, the projected temperature increases on such extreme days are larger than for the average temperature. Thus, previously bitter cold winter days could become much less frequent across most of the contiguous United States, including the Wyoming Basin, but hot days could be hotter and more frequent (fig. 2.19 in Walsh and others, 2014). How climate variability may change in the future as a result of anthropogenic climate change is an active topic of research. Kharin and others (2013) analyzed the CMIP5 GCMs and found, a projected increase of 2−4 °C (35.6−39.2) in the 20-yr return value for annual warm temperature extremes (that is, the extreme warm temperature is warmer), and a projected increase of 2−6 °C (35.6−42.8) in the 20-yr return value for annual cold temperature extremes (that is, the extreme cold temperature is also warmer) (fig. 5 in Kharin and others, 2013). Their findings are all statistically significant for the Wyoming Basin area, and their analyses are for changes in the 20-year return period; that is, a change in the probability of occurrence of a 20-year event or equivalently, an annual exceedance probability of $p = 5$ percent.

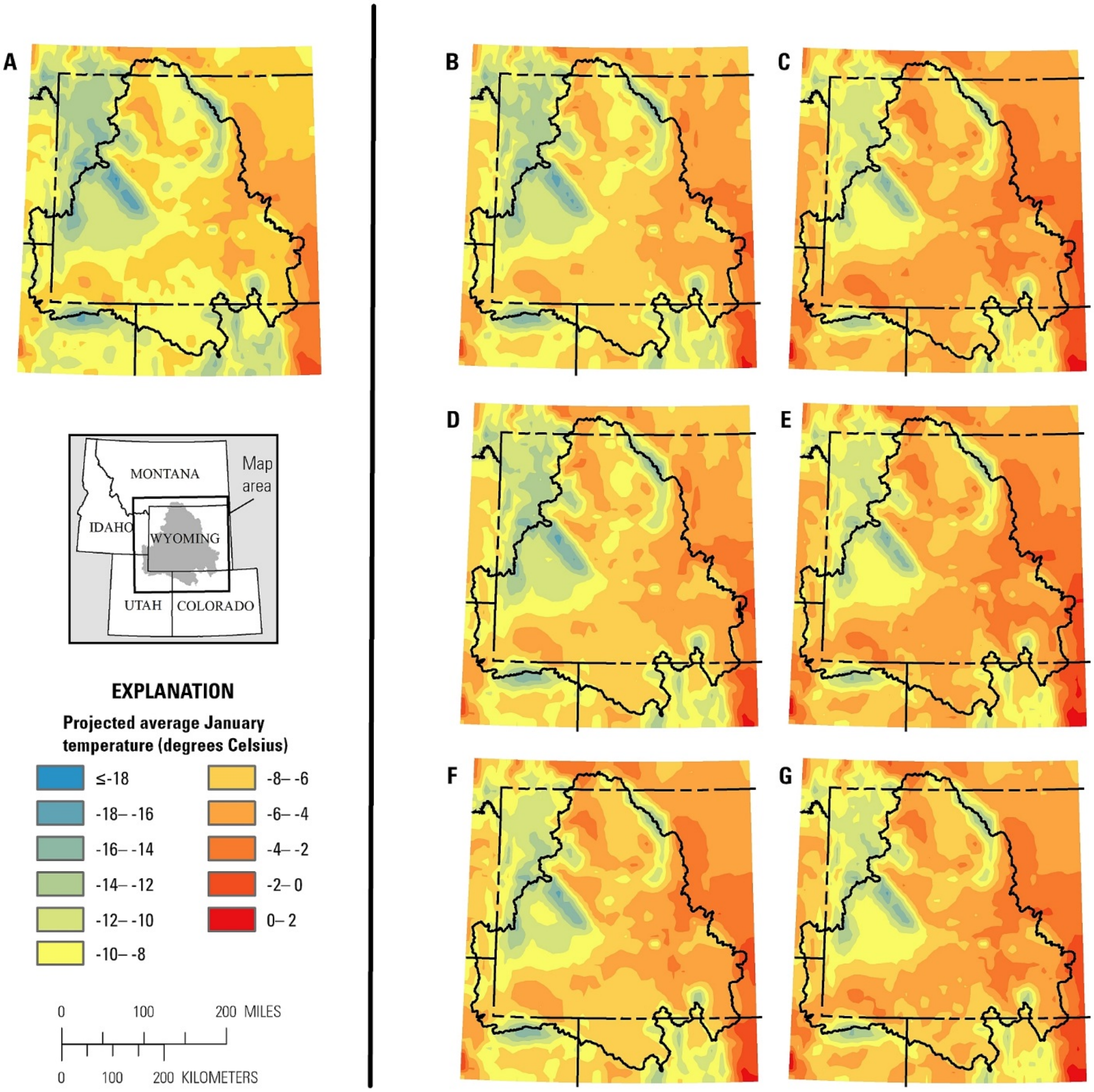

Figure 7–7. Historical and projected average annual January (typically the coldest month) temperatures in the Wyoming Basin Ecoregional Assessment project area. (A) Average January temperature during the historical period (1961−1990); ECHAM5 model projections for (B)) 2016−2030 and (C) 2046− 2060; ensemble mean projections for (D) 2016−2030 and (E) 2046− 2060; and GFDL2.1 model projections for (F) 2016−2030 and (G) 2046−2060. [Bias-corrected spatial disaggegation data, 12 kilometer (7.5-mile) resolution]

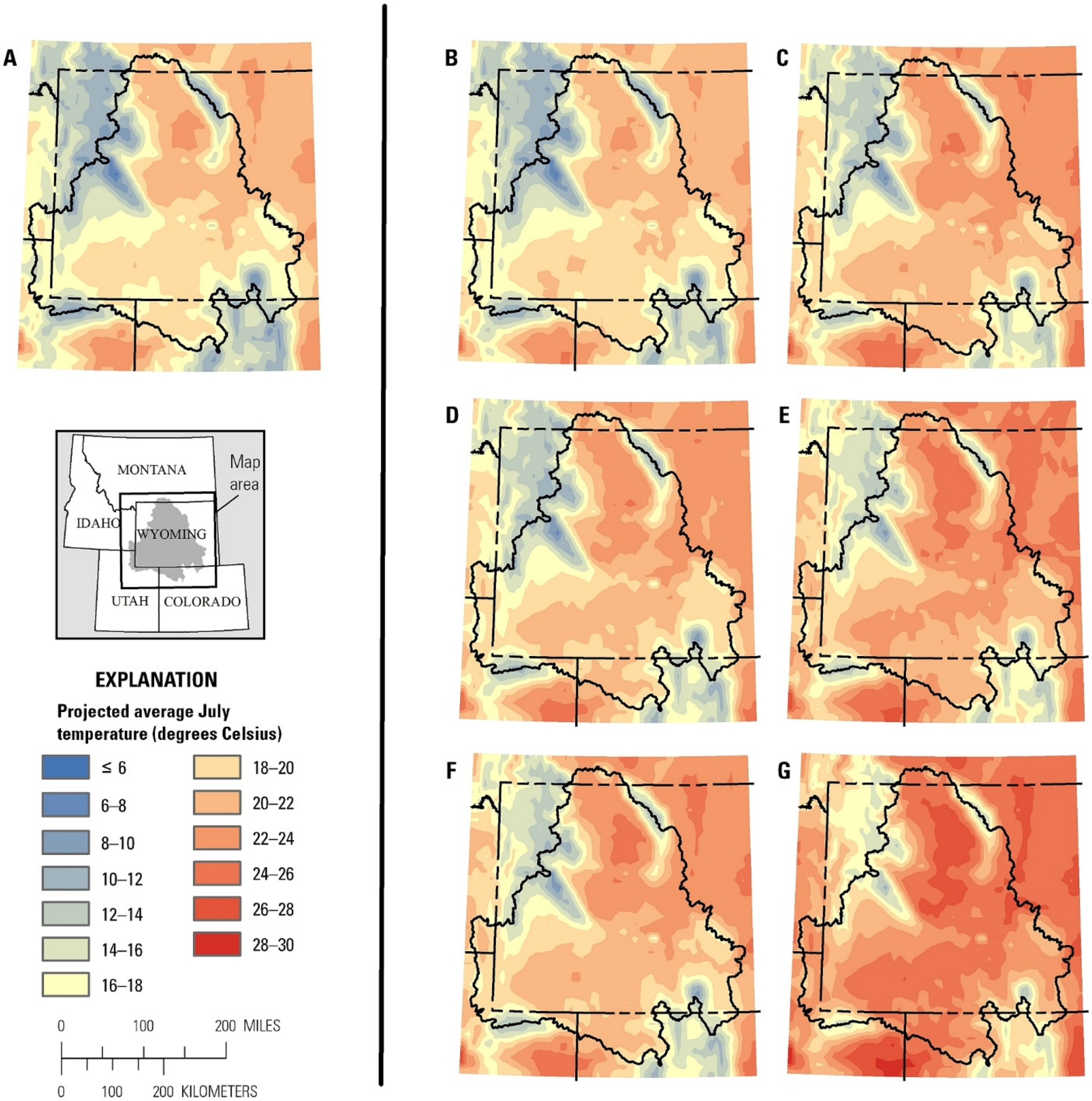

Figure 7–8. Historical and projected average July (typically the warmest month) temperatures in the Wyoming Basin Ecoregional Assessment project area. (A) Average July temperature during the historical period (1961−1990); ECHAM5 model projections for (B)) 2016−2030 and (C) 2046− 2060; ensemble mean projections for (D) 2016−2030 and (E) 2046− 2060; and GFDL2.1 model projections for (F) 2016−2030 and (G) 2046−2060. [Bias-corrected spatial disaggegation data, 12 kilometer (7.5-mile) resolution]

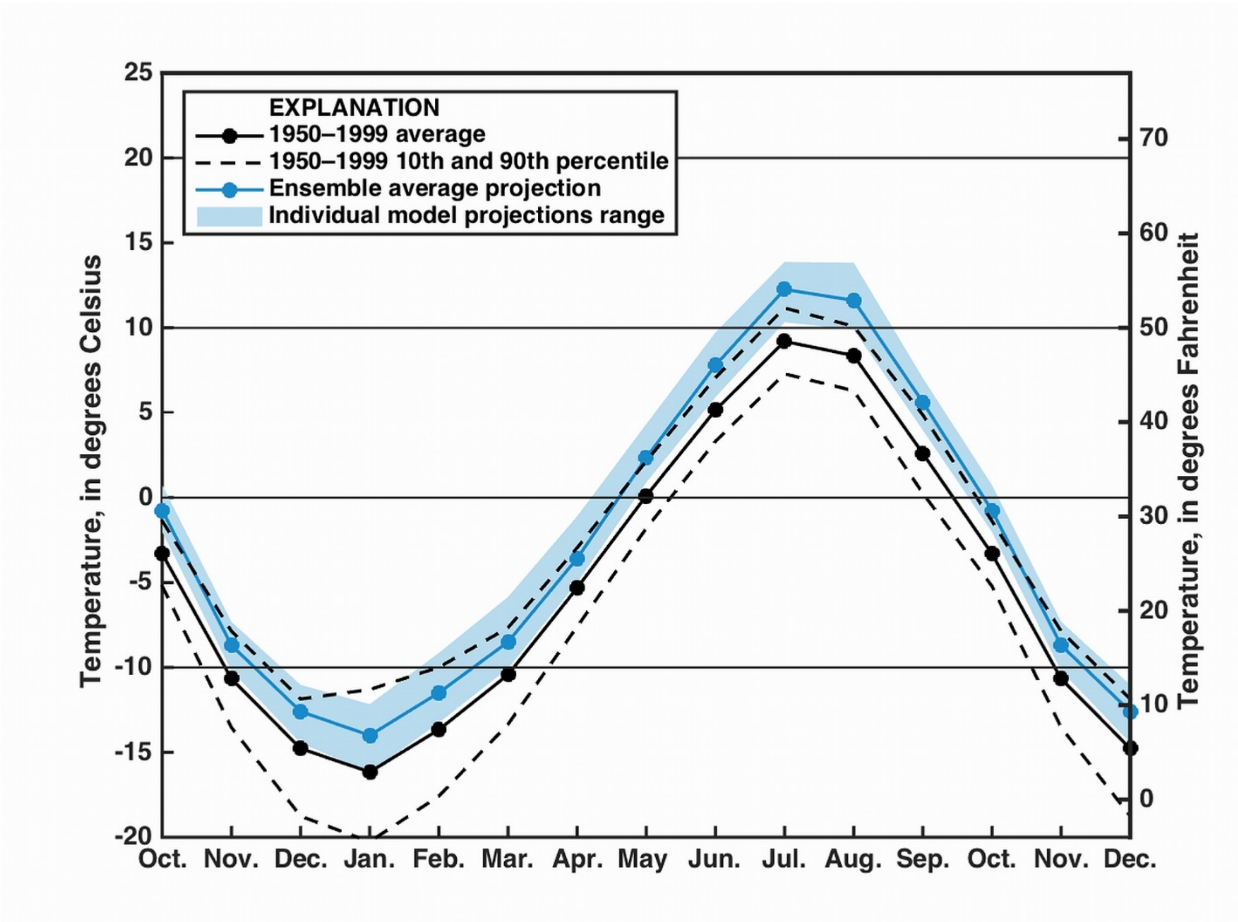

Figure 7–9. Projected changes in the seasonal cycle of temperature. Observed monthly average temperature compared with projections for 2050 over a 48- × 64-kilometer (km) (30- × 40-mile [mi]) region in the Bighorn Mountains. The monthly average (solid black) and 10th and 90th percentile values (dashed black lines) are derived from observations over the period 1950–1999. Projected monthly temperatures (blue shading) are the multi-model ensemble average for the 20-year period centered on 2050 forced by the A1B scenario, which is similar in range to the A2 scenario until mid-century. Ensemble average of the projections is shown as a heavy blue line. [Bias-corrected spatial disaggegation data, 12 kilometer (7.5-mile) resolution]

Precipitation Projections

Precipitation projections for the Wyoming basin (figs. 7–10 to 7–12) are small and subtle compared to the natural variation in the 1960−1990 climatology. The projected change in total annual precipitation, however, varies between about ±10 percent among the climate scenarios, although the multi-model mean shows a slight (<2 percent, not significant) shift towards wetter conditions for the central valley. Nineteen of the 36 model runs are within the ±5 percent variability from 1961–1990, and models show a small change towards conditions wetter than the current natural variability (fig. 7–5*A*). Precipitation is a more difficult variable to project than temperature, in part due to the large natural variability in the observed record of precipitation: the typical year-to year variations that occur are similar in spread to the range of projections.

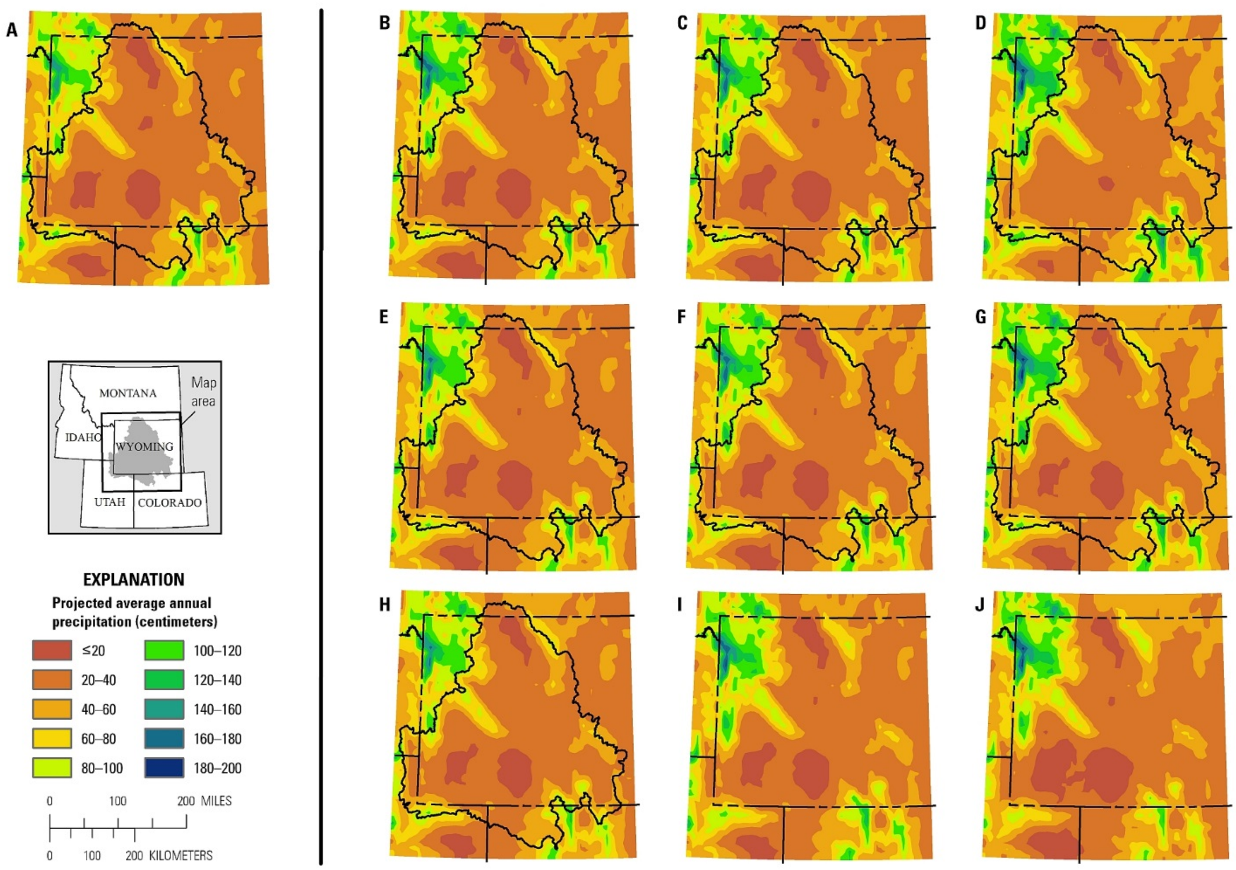

Figure 7–10. Historical and projected average annual precipitation in the Wyoming Basin Ecoregional Assessment project area. (A) Average annual precipitation during the historical period (1961−1990); ECHAM5 model projections for (B)) 2016−2030, (C) 2046− 2060, and (D) 2076−2090; ensemble mean projections for (E) 2016−2030, (F) 2046− 2060, and (G) 2076−2090; and GFDL2.1 model projections for (H) 2016−2030, (I) 2046−2060, and (J) 2076−2090. [Bias-corrected spatial disaggegation data, 12 kilometer (7.5-mile) resolution]

In contrast, analysis by season projects wetter winters and drier summers (fig. 7–13), a pattern that could become more distinct by 2060. These results are consistent with those derived from the National Climate Assessment’s dynamically downscaled GCMs (fig. 25 in Kunkel and others, 2013); although not statistically significant, winters are projected to be ≥9 percent wetter over much of the Wyoming Basin, and summers >5 percent drier. Kunkel and others (2013) also suggests that the current regional trends of a drier southern Basin and a wetter north are projected to become more pronounced compared to the observed 1971−2000 period. Multi-model statistical downscaling (A2 scenario) for the Great Plains NCA shows a similar result: a slight (0−3 percent) increase in precipitation for the Wyoming Basin north of about I-80 out to 2021−2050, 2041−2070, and 2070−2099, and a slight (–3 to 0 percent) decrease in precipitation south of that line, although results are only significant for the 2070−2099 period (fig. 24 in Kunkel and others, 2013).

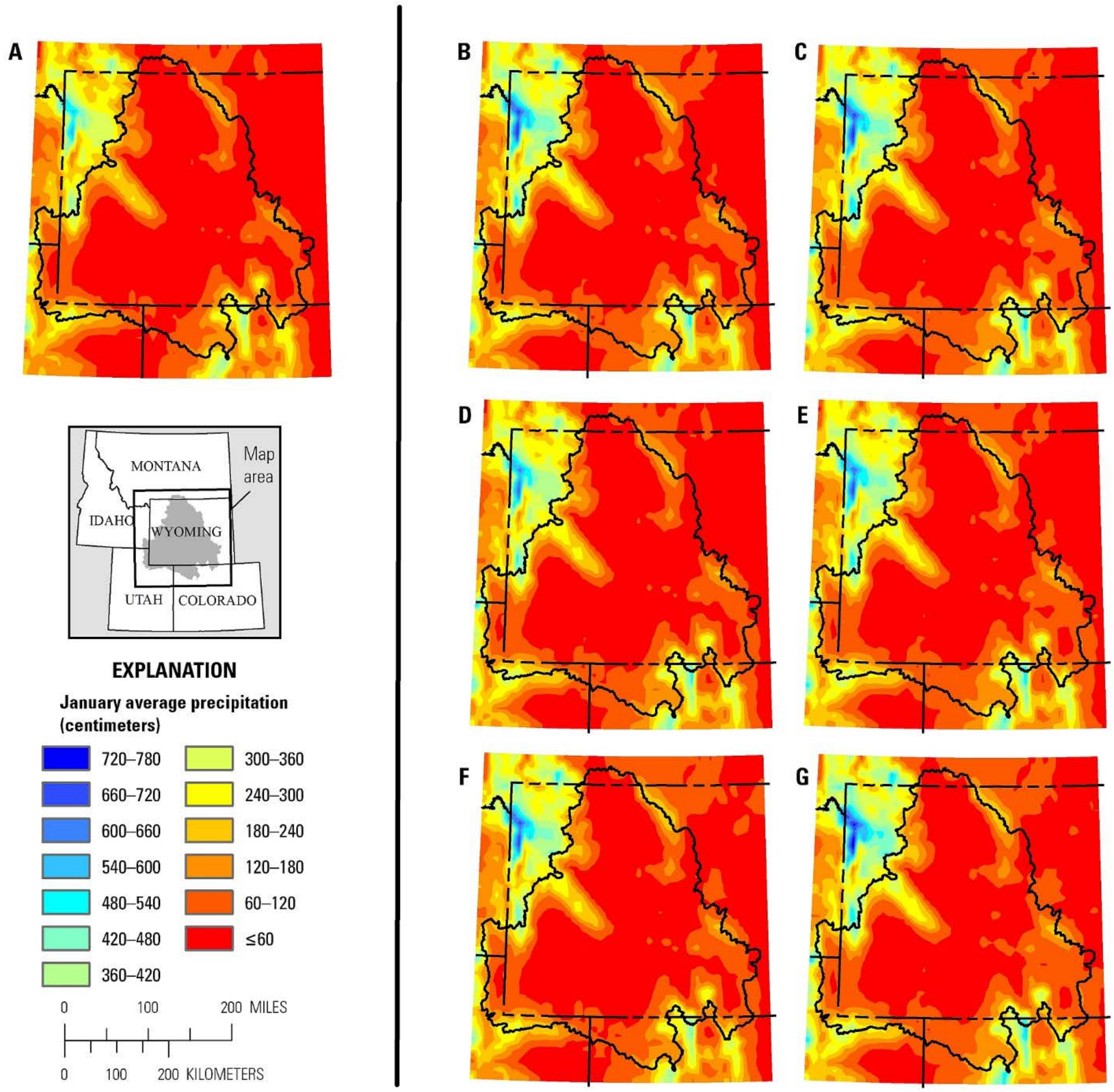

Figure 7–11. Historical and projected average January precipitation in the Wyoming Basin Ecoregional Assessment project area. (A) Average January precipitation during the historical period (1961−1990); ECHAM5 model projections for (B)) 2016−2030 and (C) 2046− 2060; ensemble mean projections for (D) 2016−2030 and (E) 2046− 2060; and GFDL2.1 model projections for (F) 2016−2030 and (G) 2046−2060. [Bias-corrected spatial disaggegation data, 12 kilometer (7.5-mile) resolution]

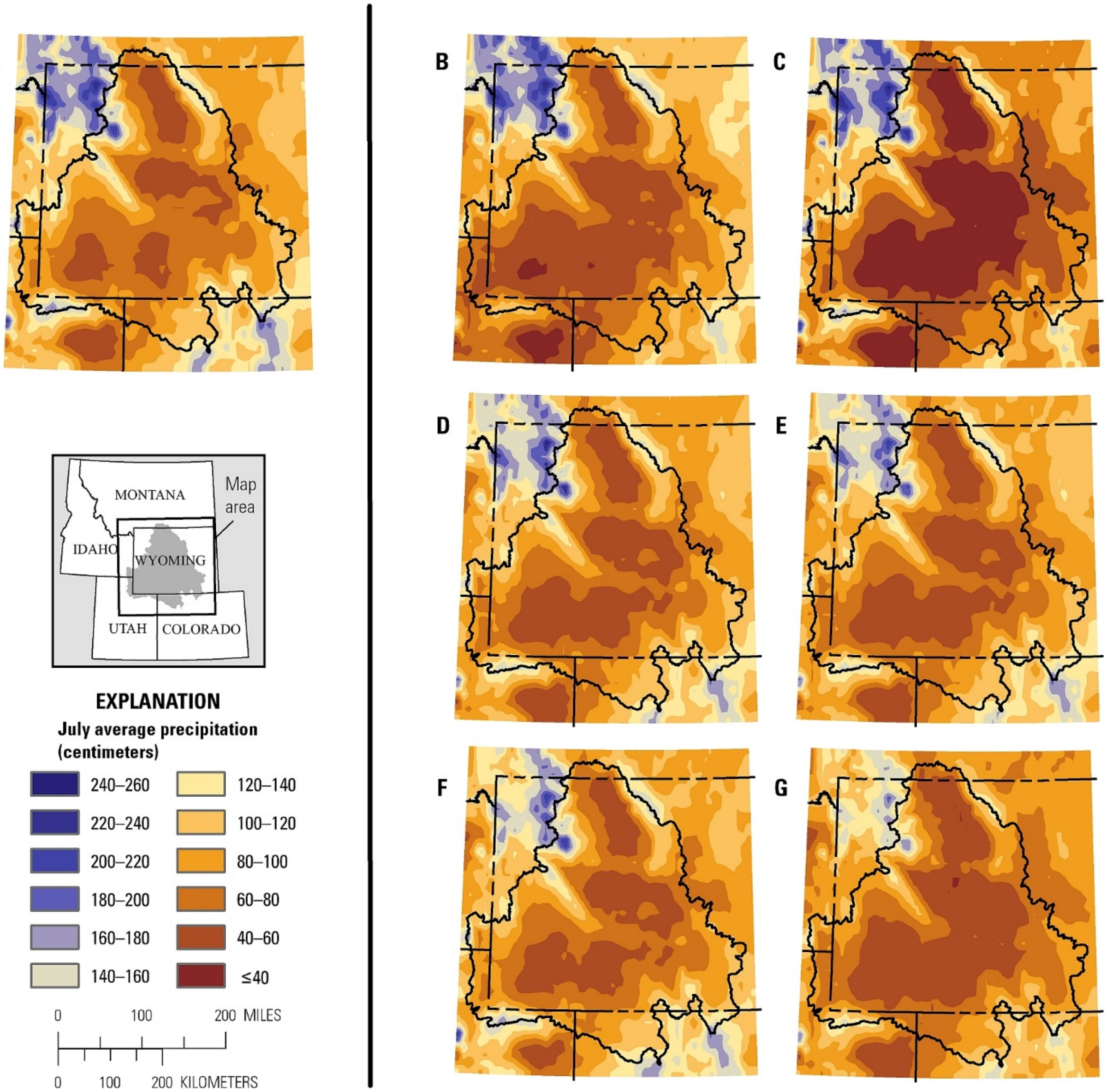

Figure 7–12. Historical and projected average July precipitation in the Wyoming Basin Ecoregional Assessment project area. (A) Average July precipitation during the historical period (1961−1990); ECHAM5 model projections for (B)) 2016−2030 and (C) 2046− 2060; ensemble mean projections for (D) 2016−2030 and (E) 2046− 2060; and GFDL2.1 model projections for (F) 2016−2030 and (G) 2046−2060. [Bias-corrected spatial disaggegation data, 12 kilometer (7.5-mile) resolution]

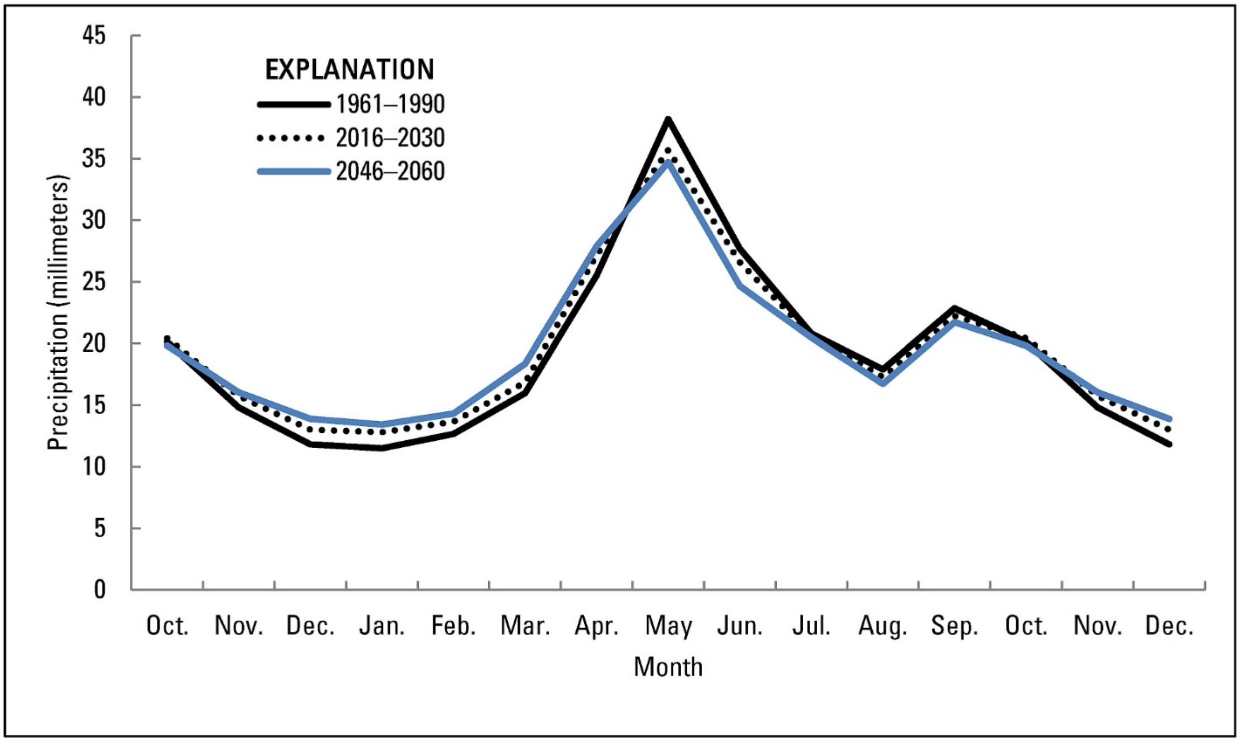

Figure 7–13. Projected annual cycle of precipitation (of an ensemble of global climate models) precipitation for central Wyoming showing potential changes in the monthly average of precipitation. [Bias-corrected spatial disaggegation data, 12 kilometer (7.5-mile) resolution]

Taken together, these results project that the Wyoming Basin is not expected to have a dramatic change in annual precipitation: both somewhat wetter and somewhat drier conditions in the annual average are reasonably foreseeable futures. Although not statistically significant compared to current conditions, the projections suggest a wetter winter and drier spring−fall. The wide variation in model projections for potential changes in the annual total of precipitation (fig. 7–5, especially to 2060) partly reflects the large natural variability in precipitation. The different GCMs show a range of reasonably foreseeable futures of about ±10 percent for precipitation, including natural variability around a mean that has not diverged from the current annual total.

Other implications of the projected changes in precipitation include that the number of consecutive "dry" days in which limited precipitation was recorded (≤0.25 cm per 0.1 in) is projected to increase on average 9 days from 1971 to 2000 (Ojima and others, 2013); the maximum consecutive days during which precipitation decreases for most of the Basin is projected to increase by up to 15 days (fig. 29 in Kunkel and others, 2013). For precipitation extremes, the number of days with heavy precipitation >2.5 cm (1 in) is projected to increase by >15 percent by 2041−2070, with higher increases for the western Basin, along the Colorado border, and over the Medicine Bow area; the mean number of days for Wyoming for the 1980−2000 reference period is up to 6 days >2.5 cm (1 in) (fig. 28 in Kunkel and others, 2013). Kharin and others (2013) found a statistically significant increase in the annual extremes of daily precipitation of 5−10 percent for 2046−2065 (fig. 4 in Kharin and others, 2013)—that is, the amount of precipitation with a 20-yr return period is expected to be 5−10 percent higher.

Hydroclimate Projections

A suite of ecologically important variables, including soil moisture, snow water equivalent (SWE), runoff, and actual evapotranspiration, are a function of both temperature and precipitation. As has been found for many places in the west, spring and snowmelt are projected to occur earlier, and soils are projected to dry out earlier in the summer. Several studies provide maps of changes in soil moisture across the western U.S. (fig. 38 in McWethy and others, 2010; fig 5–11 in Ray and others, 2008). These maps show a subtle shift in soil moisture at lower elevations in the basin, and a larger shift at higher elevation. Rather than reproduce maps, we looked in more detail at the time series and seasonal cycle of soil moisture. Figure 7–14 shows time series of soil moisture for two areas in the Wyoming Basin: the lower-elevation valley near Baggs, Wyo., and a higher-elevation area in the Wind River Mountains near Lizardhead Peak (fig. 7–14). Soil moisture varies in all the models used in this report but some models project a decrease over the next century, such that the average future soil moisture in both areas is similar to the drier soil moisture values of the present.

Figures 7–15 and 7–16 show the same data plotted in a different way, to show the normalized change in soil moisture for the current climate and projections for three future periods for an area near Baggs, Wyo. The 1961–1990 period is the simulated soil moisture from the current climate, compared to three future periods for the multi-model ensemble, and the GFDL2.1 GCM. The GFDL2.1 model is chosen for illustration because it has relatively more projected precipitation increase, and thus would be more likely to be able to compensate for the effects of increased temperature on drying out of hydroclimate variables. However, there is still drying out in this model over the century, with the effect most pronounced by 2060 and beyond. Cayan and others (2013) also found that projected future drying of soils in most areas is consistent with the future drought increases using the simpler Palmer Drought Severity Index metric (fig. 22 in Walsh and others, 2014), which is also used in many ecological studies.

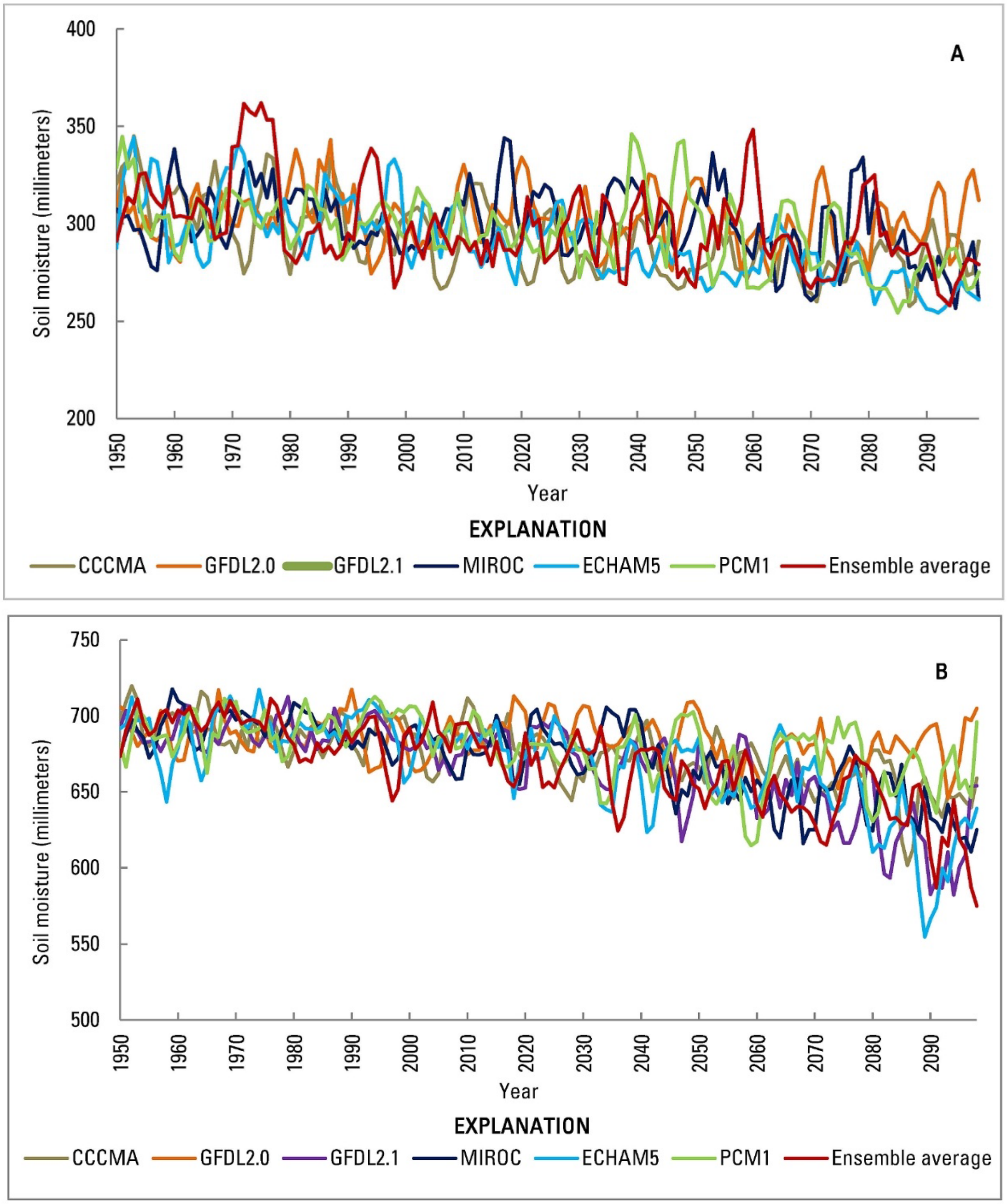

Figure 7–14. Time series of summer soil moisture, 1950−2099. Summer soil moisture (July−September) from 1950−2010 for (*A*), an area near Baggs, Wyo., and (*B*) an area near Lizardhead Peak in the Wind River Range. The times series shows simulated soil moisture data from the current climate (1950−2010), and projected soil moisture for the future (2011−2099) from each of six global climate models used in this report and the multi-model ensemble. [Bias-corrected spatial disaggegation data, 12 kilometer (7.5-mile) resolution]

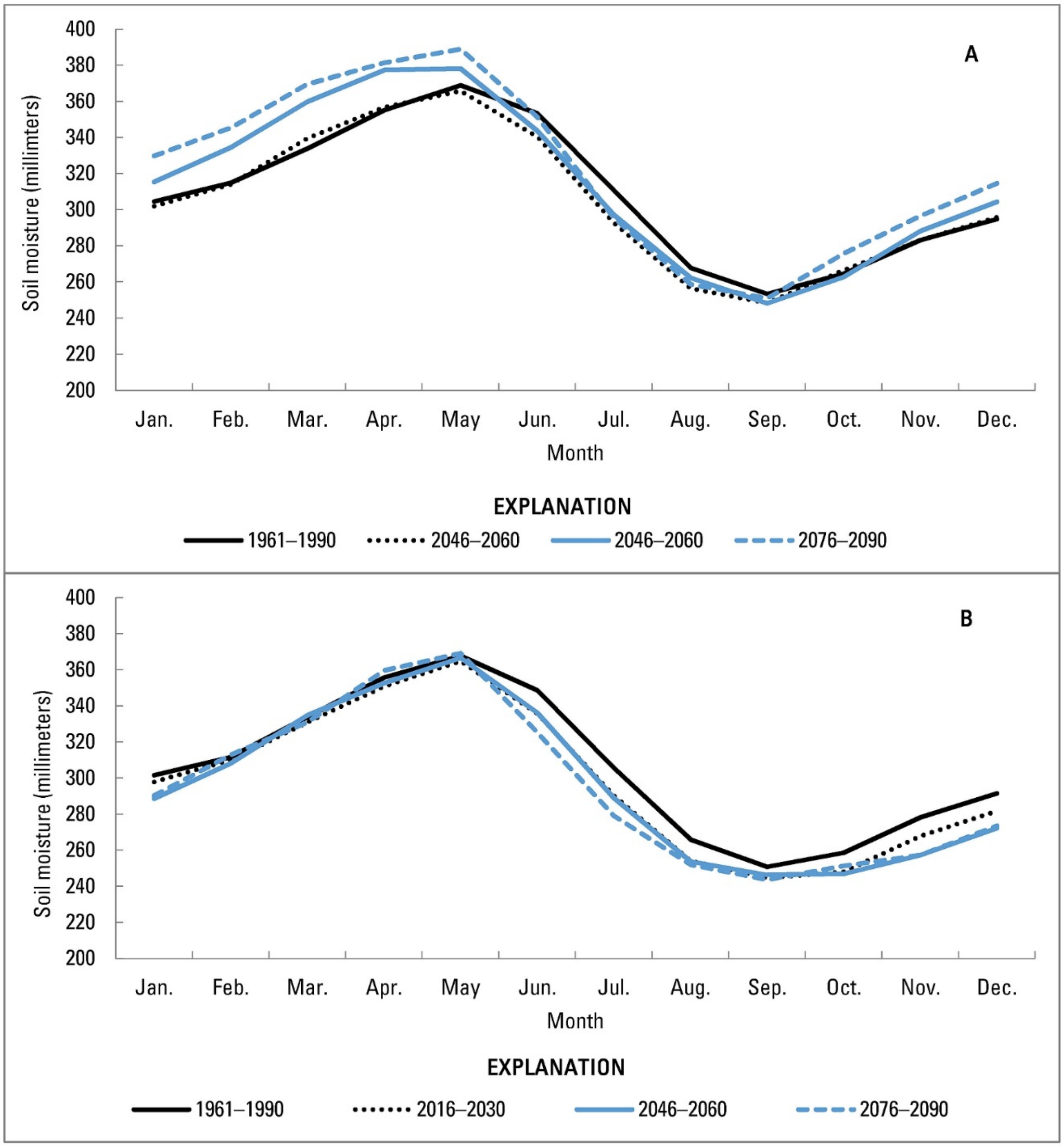

Figure 7–15. Annual cycle of soil moisture in the current climate and three future periods for an area near Baggs, Wyoming. The 1961–1990 period is the simulated soil moisture from the current climate, compared to three future periods for *A*, the multi-model ensemble, and *B*, the GFDL2.1 GCM, which has relatively more projected precipitation increase. [Bias-corrected spatial disaggegation data, 12 kilometer (7.5-mile) resolution]

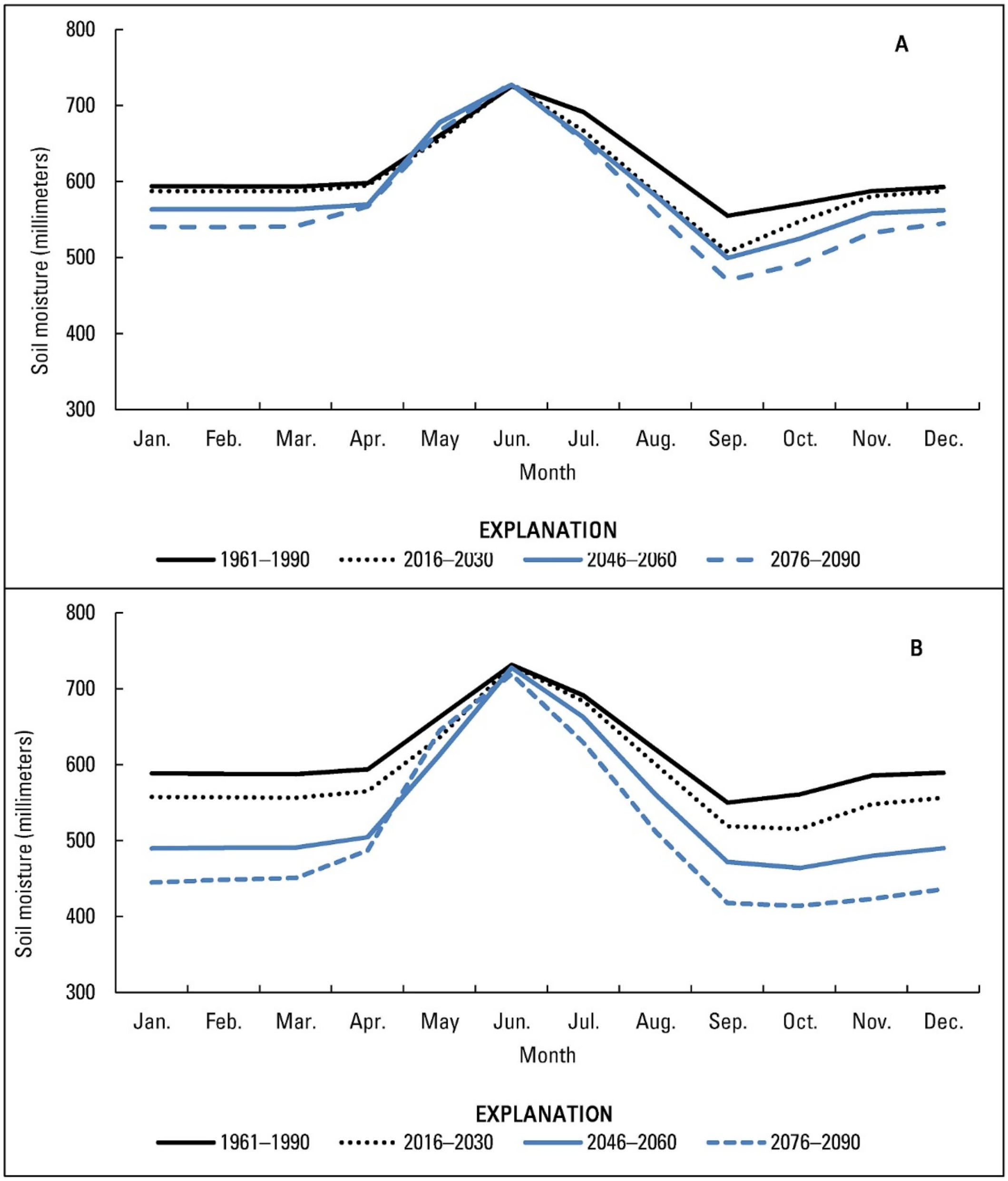

Figure 7–16. Annual cycle of soil moisture in the current climate and three future periods for an area in the Wind River Range near Lizardhead Peak. The 1961–1990 period is the simulated soil moisture from the current climate, compared to three future periods for *A*, the multi-model ensemble, and *B*, the GFDL2.1 GCM, which has relatively more projected precipitation increase. [Bias-corrected spatial disaggegation data, 12 kilometer (7.5-mile) resolution]

Reasonably Foreseeable Climate Scenarios

As introduced above, the "reasonably foreseeable" concept is modeled after the same concept for "reasonably foreseeable development scenarios" and is intended to reflect a range of potential future conditions due to natural variability and uncertainty in the GCMs. Reasonably foreseeable development scenarios are based on analysis and comparison among the downscaled datasets considered in this report, and bracket futures projected in the suite of GCMs downscaled by Hostetler, Rehfeldt, and a larger suite of GCMs downscaled by Maurer. The characteristics of these reasonably foreseeable development scenarios are as follows.

- By the 2030s, the ensemble average temperature for Wyoming Basin warms about 1.4 ºC (2.5 ºF) with the spread of the GCM ensemble around this mean (which can be thought of as a reasonably foreseeable range) (fig. 7–5). The increase in temperature is consistently higher for the 2060 period, with an ensemble average warming of 2.7 ºC (4.9 ºF). By the 2060s, the ensemble average warming is about 2.6 ºC (4.9ºF), and the spread of the GCM ensemble around this mean is about 1.5−2.7 ºC (2.7‒4.9 ºF).
- The typical summer temperatures of mid-century may be as warm or warmer as the hottest 10 percent of summers in the recent past. There will be fewer extreme cold days, and average minimum temperatures projected to warm, and more and hotter extreme hot days.
- Temperature tends to decrease with elevation, however, at any given elevation, temperatures will be warmer than the recent climatology.
- Warming temperatures may result in earlier snowmelt and runoff, with a later beginning of the snow accumulation season in the fall, and a longer frost free or growing season.
- Variation in temperature and precipitation should be expected around the same range as the current variability and annual average of the recent past (a standard deviation in temperature of about ±0.55 ºC (±1 ºF) and for precipitation ~±5 percent standard deviation).
- A dramatic change in annual average precipitation is not indicated, as the ensemble mean is near zero for the lower elevation valleys and slightly wet (3 percent increase) for the some higher elevation areas, such as the Wind River Range. However, there is a shift in individual seasons, with winter somewhat wetter, and summers drier.

Other precipitation variables also change. Maps of runoff and snow water equivalent (SWE) are provided in figures 6.9–6.11 in Cayan and others (2013) and figure 38 in McWethy and others (2010). Studies for the National Climate Assessment for the southwestern United States included Wyoming and used one of the same downscaling products used for this report, the BCSD downscaling post-processed through a hydrologic model to calculate hydrologic variables. In general, SWE on April 1 is lower by 20 percent or more in much of the Western United States, although the highest mountains are an exception where it may be higher; runoff decreases or remains about the same except in the highest elevation streams (fig. 7–14). In our analysis (not shown), actual evapotranspiration generally increases, but with some offsets for precipitation increases.

Some of the implications of these changes particularly important for ecosystems are listed below.

- Warming temperatures lead to warmer stream temperatures, such as trout streams small enough to equilibrate with air temperature.
- Warmer temperatures may miscue species that cue on temperature as opposed to day length or other climate cues (for example, peak streamflow).

- A longer growing season, with spring arriving earlier and fall somewhat later.
- Shifts in timing in the seasonal hydrograph, which may affect trout, waterfowl, and riparian vegetation.
- Soil moisture drying out earlier. This does not appear to be offset by greater winter precipitation.
- The drier years of the current climate becoming the average years of the future for summer (June‒August) soil moisture. Because of earlier snowmelt and runoff, soil moisture also increases earlier in the spring and dries out earlier in the late summer.
- Temperatures shifting up in elevation, due to the relationship between temperature and elevation, so the temperatures of lower elevation slopes will occur at higher elevations.
- Average minimum temperatures likely to increase; fewer winter cold days for keeping mountain pine beetle population in check; larger areas are above freezing at any point in time.
- Shifts to earlier timing of snowmelt and runoff may influence snow cover as habitat for some land species and streamflow thresholds for riparian species.
- Decrease in spring-summer-fall precipitation and soil moisture drying out earlier in the spring/summer may influence vegetation; potential changes in the timing of fire risk.

References Cited

Beever, Erik A., and Belant, Jerrold L. 2012, Ecological Consequences of Climate Change: Mechanisms, Conservation, and Management: Boca Raton, FL, CRC Press, 342 p.

Benson, M.H., 2010, Adaptive management approaches by resource management agencies in the United States: Implications for Energy Development in the Interior West: Journal of Energy and Natural Resources Law, v. 28, no. 1, p. 87−118.

Bureau of Land Management, 2010, Land use planning handbook, H-1601-1, accessed October 2, 2014, at http://www.blm.gov/wo/st/en/prog/planning/nepa/webguide/document_pages/land_use_planning.html

Cayan, Daniel, Tyree, Mary, Kunkel, K.E., Castro, Chris, Gershunov, Alexander, Barsugli, J.J., Ray, A.J., Overpeck, Jonathan, Anderson, Michael, Russell, Joelen, Rajagopalan, Balaji, Rangwala, Imtaz, and Duffy, Paul, 2013, Future climate—Projected average, *in* Garfin, Greg, Jardine, Angela, Merideth, Robert, Black, Mary, and LeRoy, Sarah, eds., Assessment of climate change in the southwest United States, prepared for the National Climate Assessment by the Southwest Climate Alliance: Washington, D.C., Island Press, p. 101–125.

Chuine, Isabelle, 2000, A unifed model for budburst of trees: Journal of Theoretical Biology, v. 207, p. 337–347, doi:10.1006/jtbi.2000.2178.

Compagnoni, Aldo, and Adler, P.B., 2014, Warming, soil moisture, and loss of snow increase *Bromus tectorum's* population growth rate: Elementia, p. 1–10, doi:10.12952/journal.elementa.000020.

Curtis, Jan, and Grimes, Kate, 2004, Wyoming Climate Atlas: Laramie, Wyo., University of Wyoming, State Climate Office, 328 p., accessed September 16, 2014 at http://www.wrds.uwyo.edu/sco/climateatlas/title_page.html.

Deser, Clara, Phillips, A.S., Alexander, M.A., and Smoliak, B.V., 2014, Projecting North American climate over the next 50 years—Uncertainty due to internal variability: Journal of Climate, v. 27, p. 2271–2296.

Evers, L.B., Miller, R.F., Doescher, P.S., Hemstrom, Miles, and Neilson, R.P. 2013: Simulating current successional trajectories in sagebrush ecosystems with multiple disturbances using a state-and-transition modeling framework: Rangeland Ecology & Management, v. 66, no. 3, p. 313–329. doi: http://dx.doi.org/10.2111/REM-D-11-00220.1.

Di Luzio, Mauro, Johnson, G. L., Daly, Christopher, Eischeid, J.K., and Arnold, J.G., 2008, Constructing retrospective gridded daily precipitation and temperature datasets for the conterminous United States: Journal of Applied Meteorology and Climatology, no. 47, p. 475–497.

Gray, S.T., Lukas, J.J., and Woodhouse, C.A., 2011, Millennial-length records of streamflow from three major upper Colorado River tributaries: Journal of the American Water Resources Association, v. 47, no. 4, p. 704–712, doi:10.1111/j.1752-1688.2011.00535.x.

Groffman, P.M., Kareiva, Peter, Carter, Shawn, N.B. Grimm, Lawler, Josh, Mack, Michelle, Matzek, Virginia, and Tallis, Heather, 2014, Ecosystems, biodiversity, and ecosystem services, chap. 8 *of* Melillo, J.M., Richmond, T.C., and Yohe, G.W., eds., Climate change impacts in the United States, The Third National Climate Assessment: U.S. Global Change Research Program, p. 195–219, doi:10.7930/J0TD9V7H.

Haak, A.L., Williams, J.E., Isaak, Daniel, Todd, A., Muhlfeld, C.C., Kershner, J.L., Gresswell, Robert, Hostetler, S.W., and Neville, H.M., 2010, The potential influence of changing climate on the persistence of salmonids of the inland west: U.S. Geological Survey Open-File Report 2010–1236, 74 p., http://pubs.usgs.gov/of/2010/1236/.

Hayhoe, Katharine, Cayan, Daniel, Field, C.B., Frumhoff, P.C., Maurer, E.P., Miller, N.L., Moser, S.C., Schneider, S.H., Cahill, K.N., Cleland, E.E., Dale, Larry, Drapek, Ray, Hanemann, R.M., Kalkstein, L.S., Lenihan, James, Lunch, C.K., Neilson, R.P., Sheridan, S.C., and Verville, J.H., 2004, Emissions pathways, climate change, and impacts on California: Proceedings of the National Academy of Sciences, v. 101, n. 34, p. 12422–12427.

Hayhoe, Katharine, Wake, C.P., Huntington, T.G., Luo, Lifeng, Schwartz, M.D., Sheffield, Justin, Wood, Eric, Anderson, Bruce, Bradbury, James, DeGaetano, Art, Troy, T.J., and Wolfe, David, 2008, Past and future changes in climate and hydrological indicators in the US Northeast: Climate Dynamics, v. 28, no. 4, p. 381–407.

Hegerl, G.C., Zwiers, F.W., Braconnot, P., Gillett, N.P., Luo, Y., Marengo Orsini, J.A., Nicholls, N., Penner, J.E., and Stott, P.S., 2007, Understanding and attributing climate change, *in* Solomon, S., Qin, Dahe, Manning, Martin, Chen, Zhenlin, Marquis, Melinda, Averyt, K.B., Tignor, Melinda, and Miller, H.L., Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change: Cambridge, United Kingdom, Cambridge University Press, 996 p.

Hostetler, S.W., Alder, J.R., and Allan, A.M., 2011, Dynamically downscaled climate simulations over North America—Methods, evaluation, and supporting documentation for users: U.S. Geological Survey Open-File Report 2011–1238, 64 p., http://pubs.usgs.gov/of/2011/1238/.

Intergovernmental Panel on Climate Change (IPCC), 2013, Climate change 2013—The physical science basis, *in* Stocker, T.F., Qin, Dahe, Plattner, G.-K., Tignor, Melinda, Allen, S.K., Boschung, Judith, Nauels, Alexander, Xia, Yu, Bex, Vincent, and Midgley, P.M., eds., Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change: Cambridge, United Kingdom, Cambridge University Press, 1535 p.

Intergovernmental Panel on Climate Change (IPCC), 2007, Climate change 2007—The physical science basis, *in* Solomon, S., Qin, Dahe, Manning, Martin, Chen, Zhenlin, Marquis, Melinda, Averyt, K.B., Tignor, Melinda, and Miller, H.L., Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change: Cambridge, United Kingdom, Cambridge University Press, 996 p.

Jarnevich, C.S., and Reynolds, L.V., 2011, Challenges of predicting the potential distribution of a slow-spreading invader: a habitat suitability map for an invasive riparian tree: Biological Invasions v.13, p. 153−163.

Karl, T.R., Meehl, G.A., Miller, C.D., Hassol, S.J., Waple, A.M., and Murray, W.L., eds., 2008, Regions of focus—North America, Hawaii, Caribbean, and U.S. Pacific Islands, *in* 3.3 Weather and climate extremes in a changing climate—A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research: Washington, D.C., Department of Commerce, National Oceanic and Atmospheric Administration, National Climatic Data Center, 164 p., accessed September 16, 2014 at http://downloads.globalchange.gov/sap/sap3-3/sap3-3-final-all.pdf.

Kharin, V.V., Zwiers, F.W., Zhang, Xuebin, and Wehner, Michael, 2013, Changes in temperature and precipitation extremes in the CMIP5 ensemble: Climatic Change, no. 119, p. 345–357, doi:10.1007/s10584-013-0705-8.

Kunkel, K.E., Stevens, L.E., Stevens, S.E., Sun, Liqiang, Janssen, Emily, Wuebbles, Donald, Kruk, M.C., Thomas, D.P., Shilski, M.D., Umphlett, N.A., Hubbard, K.G., Robbins, K., Romolo, Luigi, Akuz, Adnan, Pathak, T.B., Bergantino, T.R., and Dobson, J.G., 2013. Climate of the U.S.—Great Plains, National Oceanic and Atmospheric Administration Technical Report NESDIS 142–144, accessed September 16, 2014 at http://www.hprcc.unl.edu/publications/files/NOAA_NESDIS_Tech_Report_142-4-Climate_of_the_U.S.%20Great_Plains.pdf.

Littell, J.S., McKenzie, D.M., Peterson, D.L., and Westerling, A.J., 2009, Climate and wildfire area burned in western U.S. ecoprovinces, 1916–2003: Ecological Applications, v. 19, no. 4, p. 1003–1021.

Littell, J.S., Oneil, E.E., McKenzie, D., Hicke, J.A., Lutz, J.A., Norheim, R.A., Elsner, M.M., 2010, Forest ecosystems, disturbance, and climatic change in Washington State, USA: Climatic Change, v. 102, p. 129–158.

Louisiana State University, 2012, United States climate trends map: Baton Rouge, La., Louisiana State University, accessed Sept 20, 2014 http://charts.srcc.lsu.edu/trends/.

Lukas, Jeff, Barsugli, J.J., Doesken, Nolan, Rangwala, Imtiaz, and Wolter, Klaus, 2014, Climate change in Colorado—A Synthesis to support water resources management and adaptation. Denver, Colo., Colorado Water Conservation Board, accessed October 7, 2014 at http://cwcb.state.co.us/environment/climate-change/Pages/main.aspx.

Maurer, E.P., Hidalgo, H.G., Das, Tapash, Dettinger, M.D., and Cayan, D.R., 2010, Assessing climate change impacts on daily streamflow in California—The utility of daily large-scale climate data: Hydrology Earth System Sciences Discussions, v. 7, p. 1209–1243, doi:10.5194/hessd-7-1209-2010.

Maurer, E.P., Brekke, Levi, Pruitt, Thomas, and Duffy, P.B., 2007, Fine-resolution climate projections enhance regional climate change impact studies: EOS Transactions of the American Geophysical Union, v. 88, no. 47, p. 504.

McWethy D.B., Gray, S.T., Higuera, P.E., Littell, J.S., Pederson, G.T., Ray, A.J., and Whitlock, C., 2010, Climate and terrestrial ecosystem change in the U.S. Rocky Mountains and Upper Columbia Basin—Historical and future perspectives for natural resource management: Fort Collins, Colo., National Park Service, Natural Resource Report NPS/GRYN/NRR—2010/260.

Mearns, L.O., Gutowski, W.J., Jones, Richard, Leung, Ruby, McGinnis, Seth, Nunes, Ana, and Qian, Yun, 2009, A regional climate change assessment program for North America: EOS Transactions of the American Geophysical Union, v. 90, no. 36, p. 311–312, at http://www.agu.org/pubs/eos/eo0936.shtml.

Mote, Philip, and Redmond, K.T., 2012, Western climate change, *in* Beever, Erik A., and Belant, Jerrold L. eds., Ecological consequences of climate change: Mechanisms, conservation, and management: Boca Raton, Fla., CRC Press: Washington, D.C., Island Press, p. 3–28.

Nakicenovic, Nebojsa, and Swart, Rob, 2000, Special report on emissions scenarios—A special report of Working Group III of the Intergovernmental Panel on Climate Change: Cambridge, United Kingdom, Cambridge University Press, 599 p., accessed October 7, 2014 at http://www.grida.no/climate/ipcc/emission/index.htm.

Ojima, Dennis, Shafer, Mark, Antle, J.M., Kluck, Doug, McPherson, R.A., Petersen, Sascha, Scanlon, Bridget, Sherman, Kathleen, 2013, Great Plains, chap. 19 *of* the Third National Climate Assessment, v. 7, p. 755–789: Globalchange.gov Web site, accessed October 7, 2014 at http://ncadac.globalchange.gov/.

Ray, A.J., Barsugli, J.J., Averyt, K.B., Wolter, K., and Doesken, Nolan, 2008, Colorado climate change—A synthesis to support water resource management and adaptation, a report for the Colorado Water Conservation Board by the NOAA–CU Western Water Assessment: Boulder, Colo., University of Colorado, accessed Oct 7, 2014 at http://cwcb.state.co.us/environment/climate-change/Pages/main.aspx.

Ray, A.J., Barsugli, J.J.,Wolter, K.E., and Eischeid, J.K., 2010, Rapid-response climate assessment to support the FWS status review of the American pika: Boulder, Colo., National Oceanic and Atmospheric Administration Earth Systems Research Laboratory, 47 p., accessed Oct 7, 2014 at http://www.esrl.noaa.gov/psd/news.

Rehfeldt, G.E., 2006, A spline model of climate for the Western United States: Fort Collins, Colo., U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-165, 21 p.

Rehfeldt, G.E., Ferguson, D.E., and Crookston, N.L., 2009, Aspen, climate, and sudden decline in western USA: Forest Ecology and Management, v. 258, p. 2353–2364.

Rehfeldt, G.E., Crookston, N.L., Saenz-Romero, Cuauhtemoc, and Campbell, E.M., 2012, North American vegetation model for land-use planning in a changing climate—A solution to large classification problems: Ecological Applications, v. 22, no. 1, p. 119–141.

Romme, H., Allen, Craig D., Bailey, John D., Baker, William L., Bestelmeyer, Brandon T., Brown, Peter M., Eisenhart, Karen S., Floyd, M. Lisa, Huffman, David W., Jacobs, Brian F., Miller, Richard F., Muldavin, Esteban H., Swetnam, Thomas W., Tausch, Robin J., and Weisberg, Peter J., 2009, Historical and modern disturbance regimes, stand structures, and landscape dynamics in piñon-juniper vegetation of the western United States: Rangeland Ecology and Management v. 62, p. 203-22.

Schlaepfer, D.R., Lauenroth, W.K., and Bradford, J.B., 2012, Effects of ecohydrological variables on current and future ranges, local suitability patterns, and model accuracy in big sagebrush: Ecography, v. 35, p. 374–384.

U.S. Department of Agriculture Forest Service, 2011, Western U.S. stream flow metric dataset—A dataset of modeled flow metrics for streams in major river basins of the Western U.S. for historical and future climate change scenarios: U.S. Department of Agriculture, Forest Service, accessed November 20, 2013 at http://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml. [January 25, 2011 (updated June 27, 2011)]

U.S. Department of the Interior Bureau of Reclamation, 2011a, Reclamation SECURE Water Act Report, Climate Change and Water, Report to Congress: Bureau of Reclamation, accessed October 7, 2014 at http://www.usbr.gov/climate/SECURE/.

U.S. Department of the Interior Bureau of Reclamation, 2011b, West-wide climate risk assessments—Bias-corrected and spatially downscaled surface water projections: Denver, Colo., Bureau of Reclamation, Technical Service Center, Technical Memorandum 86–68210–2011–01 138 p.

U.S. Department of the Interior Bureau of Reclamation, 2013, Downscaled CMIP3 and CMIP5 climate and hydrology projections—Release of downscaled CMIP5 climate projections, comparison with preceding information, and summary of user needs: Denver, Colo., U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center, 47 p.

Vose, J.M., Peterson, D.L., and Patel-Weynand, Toral, eds., 2012, Effects of climatic variability and change on forest ecosystems—A comprehensive science synthesis for the U.S. forest sector: U.S. Department of Agriculture, General Technical Report PNW-GTR-870, accessed October 7, 2014 at http://www.fs.fed.us/pnw/pubs/pnw_gtr870/pnw_gtr870.pdf.

Walsh, John, Wuebbles, Donald, Hayhoe, Katherine, Kossin, James, Kunkel, Kenneth, Stephens, Graeme, Thorne, Peter, Vose, Russell, Wehner, Michael, Willis, Josh, Anderson, David, Feely, R., Hennon, P., Kharin, V., Knutson, Thomas, Landerer, Felix, Lenton, Thomas, Kennedy, John, and Somerville, Richard, 2014, Our changing climate, *in* Melillo, J.M., Richmond, T.C., and Yohe, G.W., eds., Climate change impacts in the United States—The Third National Climate Assessment: U.S. Global Change Research Program, p. 19‑67, *doi:10.7930/J0KW5CXT*.

Watling, J.I., Bucklin, D.N., Speroterra, Carolina, Brandt, L.A., Mazzotti, F.J., and Romañach, S.S., 2013, Validating predictions from climate envelope models: PLoS ONE, v. 8, no. 5, e63600, doi:10.1371/journal.pone.0063600.

Watson, T.A., Barnett, F.A. Gray, S.T., and Tootle, G.A., 2009, Reconstructed streamflows for the headwaters of the Wind River, Wyoming, United States: Journal of the American Water Resources Association, v. 45, no. 1, p. 224−236.

Wenger, S.J., Isaak, D.J., Luce, C.H., Neville, H.M., Fausch, K.D., Dunham, J.B., Dauwalter, D.C., Young, M.K., Elsner, M.M., Rieman, B.E., Hamlet, A.F., and Williams, J.E., 2011, Flow regime, temperature, and biotic interactions drive differential declines of trout under climate change: Proceedings of the National Academy of Sciences, v. 108, p. 14175–14180.

Wenger, S.J., Isaak, D.J., and Luce, C.H., 2010a, Comparison of hydrologic predictions from the Variable Infiltration Capacity (VIC) model and the MC1 model to observed gage data in the region around the Shoshone National Forest: Boise, Idaho, Trout Unlimited and U.S. Department of Agriculture Forest Service Rocky Mountain Research Station.

Wenger, S.J., Luce, C.H., Hamlet, A.F., Isaak, D.J., and Neville, H.M., 2010b, Macroscale hydrologic modeling of ecologically relevant flow metrics: Water Resources Research, v. 46, W09513, doi:10.1029/2009WR008839.

Whitlock, Cathy, Shafer, S.L., and Marlon, Jennifer, 2003, The role of climate and vegetation change in shaping past and future fire regimes in the northwestern US and the implications for ecosystem management: Forest Ecology and Management, v. 178, p. 5−21.