Chapter 2
Projected Changes in Future Climate

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2.1 Methods for Projecting Future Climate

Most of the climate projections used to describe future climatic conditions in this book are based on model "ensembles," which are syntheses of the output of various global climate models (GCMs). The book also includes output from four GCMs:

- **CCSM2 (Community Climate System Model, version 2)—**U.S. National Center for Atmospheric Research (http://www.CESM.NCAR.edu).
- **CSIRO Mk3—**Australian Commonwealth Scientific Industrial Research Organisation (Gordon et al. 2002).
- **Hadley (versions 1–3)—**United Kingdom Hadley Center (Burke et al. 2006).
- **PCM (Parallel Climate Model)—**U.S. National Center for Atmospheric Research (Washington et al. 2000).

The book also uses terminology that refers to standard greenhouse gas (GHG) emission scenarios as described by the Intergovernmental Panel on Climate Change (IPCC). Emission scenarios cited in the book are described below, in which A scenarios have higher GHG emissions and higher projected temperature increases than B scenarios.

- **A2—**A2 scenarios represent a more divided world, characterized by independently operating, self-reliant nations; continuously increasing population, and regionally oriented economic development.

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- **A1F1—**A1 scenarios represent a more integrated world, characterized by rapid economic growth, a global population that reaches nine billion in 2050 and then gradually declines, quick spread of new and efficient technologies, a world in which income and way of life converge between regions, and extensive social and cultural interactions worldwide. A1F1 emphasizes the use of fossil fuels.
- **A1B—**Same as A1F1, except it emphasizes a balance of energy sources.
- **B1—**B1 scenarios represent a more integrated, ecologically friendly world, characterized by rapid economic growth as in A1, but with rapid changes toward a service and information economy, population rising to nine billion in 2050 and then declining as in A1, reductions in material intensity and the introduction of clean and resource efficient technologies, and an emphasis on global solutions to economic, social, and environmental instability.
- **B2—**B2 scenarios represent a more divided but more ecologically friendly world, characterized by continuously increasing population but at a slower rate than in A2; emphasis on local rather than global solutions to economic, social, and environmental instability; intermediate levels of economic development; and less rapid and more fragmented technological change than in A1 and B1.

The forthcoming Fifth IPCC Assessment, scheduled for publication in 2014, will use representative concentration pathways (RCPs) rather than the emission scenarios that were used in the Fourth Assessment (Solomon et al. 2007). The RCPs are four GHG concentrations (not emissions), named after a possible range of radiative forcing (increased irradiance caused by GHGs) values at the earth's surface in the year 2100: RCP2.6, RCP4.5, RCP6, and RCP8.5, which represent 2.6, 4.5, 6.0 and 8.5 W m^{-2}, respectively (Moss et al. 2008). Current radiative forcing is approximately 1.6 W m^{-2}, which is equivalent to a global-scale warming effect of 800 terawatts (8×10^{14} W).

2.2 Projected Future Climate in the United States

2.2.1 Temperature

Trends in temperature and precipitation from weather stations show that the United States has warmed over the past 100 years, but the trends differ by region (Backlund et al. 2008). The southeastern United States has cooled slightly (<0.7 °C), and Alaska has warmed the most (~4.5 °C); other northern and western U.S. regions also show a warming trend (~1.5 °C). Here we discuss projected changes in future climate based on output from an ensemble of 15 global climate models (GCMs) (Kunkel et al. 2013). All model runs used future scenarios of economic growth, population growth, and greenhouse gas emissions scenarios that were intended to represent the high (A2) and low (B1) ends of future emissions (see Sect. 2.1).

Average annual air temperatures across the continental United States are likely to steadily increase over the next century under the two emission scenarios (Fig. 2.1).

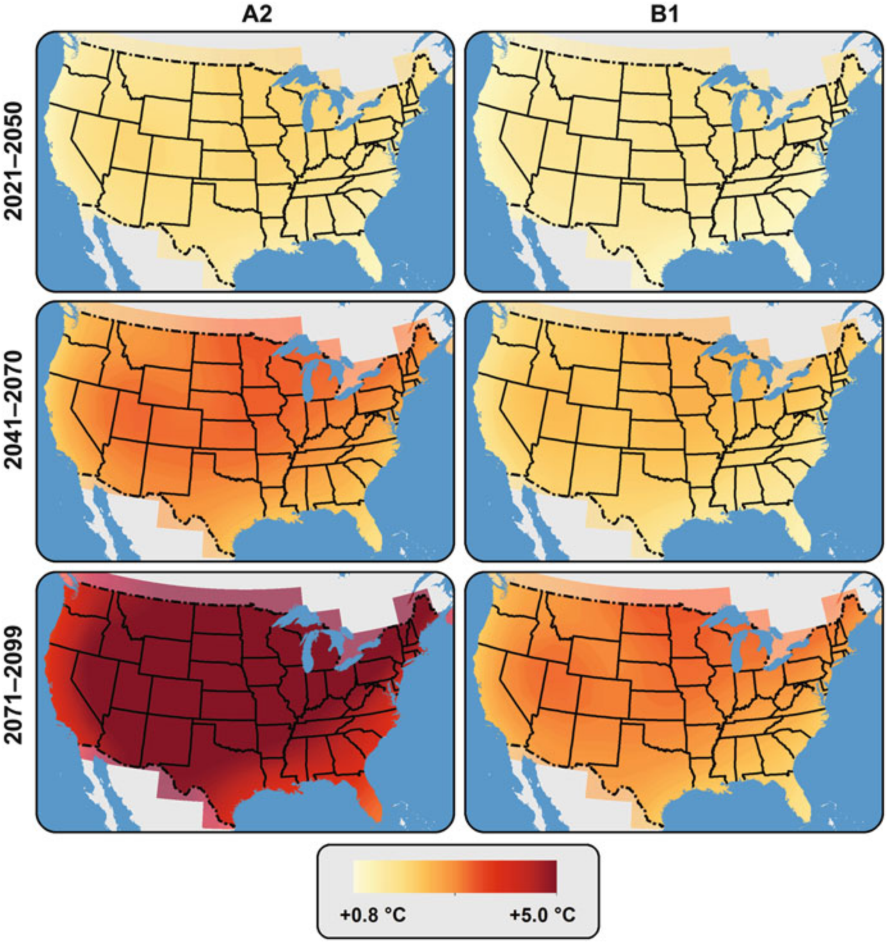

Fig. 2.1 Multi-model mean annual differences in temperature between three future periods compared to 1971–2000, from 15 GCMs using two emission scenarios (*A2* and *B1*). The A2 scenario is for higher emissions than for B1 (see text). For most interior states, models project a 1.4–1.9 °C temperature increase, rising to 2.5–3.6 °C for 2051–2071, and to greater than 4.2 °C for 2071–2099, depending on the emission scenario. Data from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset

Compared to 1971 through 2000, average annual air temperature will likely increase from 0.8 to 1.9 °C by 2050, from 1.4 to 3.1 °C by 2070, and from 2.5 to 5.3 °C by 2099. The range of these estimated temperatures is bounded by the B1 and A2 emission scenarios. Within each scenario, the magnitude of increase depends on latitude and proximity to coastal areas. More warming is projected in northern and interior areas; the largest temperature increases are projected for the upper Midwest, and the smallest increases are projected for peninsular Florida. The magnitude of annual warming is modified by differences in seasonal temperature increases. For the A2 scenario, winter is projected to have the most pronounced warming across the United States, with increases up to 3.6 °C in the northern United States and smaller increases in the South. During the summer, greater warming is projected for more interior locations (up to 3.6 °C warming across the central United States from Kentucky to Nevada). The least amount of warming is expected for autumn (1.9–3.1 °C) and spring (1.4–2.5 °C).

In addition to overall warming during the twenty-first century, both the number of days when maximum temperatures exceed 35 °C and when heat waves occur (defined as the number of consecutive days with maximum temperatures exceeding 35 °C) will increase (Fig. 2.2). For the A2 scenario, the Southeast will likely experience an additional month of days with maximum temperatures exceeding 35 °C, and the Pacific Northwest and Northeast will experience 10 more of these days per year. In addition, the United States will likely experience longer heat waves. In the Southwest, the average length of the annual longest heat wave is projected to increase by 20 days or more. Little or no change is predicted for this metric of heat waves in the Northwest, Northeast, and northern parts of the Great Plains and Midwest, but increases in less extreme levels of heat waves are projected for these regions. Most other areas will likely see heat waves of 2–20 additional days.

2.2.2 Precipitation

Much of the eastern and southern United States now receives more precipitation than 100 years ago, whereas other areas, especially in the Southwest, now receive less (Backlund et al. 2008). Precipitation differs even more than temperature across the United States and through seasons and years. As a result, long-term trends in precipitation are less apparent. Observed data from the past century across the United States show that mean annual precipitation has significant interannual variability, with two particularly dry decades (1930s and 1950s) followed by a few relatively wet decades (1970–1999); the overall result is a century-long trend of increasing precipitation (Groisman et al. 2004).

Using the same multi-model approach as for temperature (see Sect. 2.2.1), projections for the twenty-first century across the entire United States indicate little or no change in precipitation, although variance among models is high. Some models predict a significantly drier future (at least in some regions), and others a significantly wetter future. Agreement among projections for precipitation is high for some models (Solomon et al. 2007). For example, general consensus exists that annual precipitation in the Southwest will decrease by 6–12 % (Fig. 2.3), whereas precipitation in the northern states will increase by 6–10 % (Easterling et al. 2000a, b; Groisman et al. 2004; Huntington 2006; Pachuri and Reisinger 2007; Solomon et al. 2007).

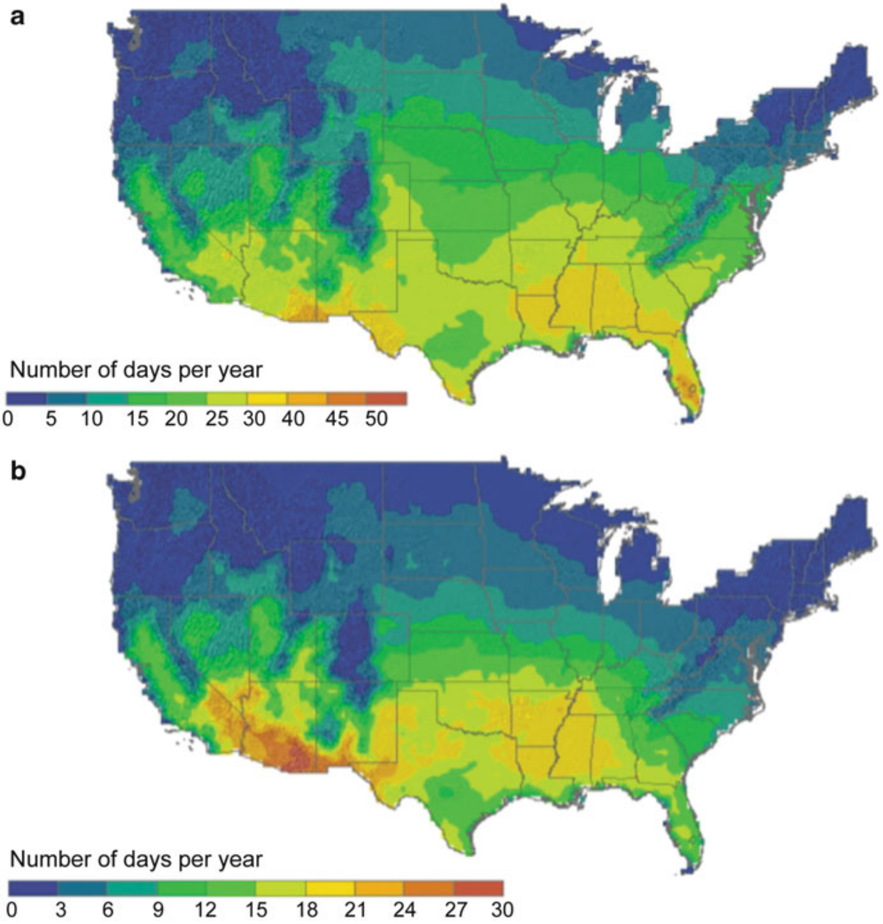

Fig. 2.2 Spatial distribution of the mean change in the annual number of days with a maximum temperature above 35 °C (**a**), and in the annual number of consecutive days with a maximum temperature above 35 °C (**b**) between 1971 and 2000 and 2041–2070. Models project that much of the southeastern and southwestern United States will experience more days with maximum temperature above 35 °C, and more consecutive days above that temperature. Results are for the high (A2) emission scenario only, from the North American Regional Climate Change Assessment Program multi-model means (n = 9 GCMs) (From 2012 draft version of Kunkel et al. (2013). On file with: Ken Kunkel, NOAA's National Climate Center, 151 Patton Avenue, Asheville, NC (USA) 28801)

Higher precipitation and increased frequency and magnitude of droughts and floods have occurred in some regions of the United States over the last 50 years (Easterling et al. 2000a, b; Groisman et al. 2004; Huntington 2006; Pachuri and Reisinger 2007; Solomon et al. 2007). In most GCMs, as the climate warms, the frequency of extreme precipitation events increases globally, producing an intensification of the hydrologic cycle (Huntington 2006). In fact, the upper 99th

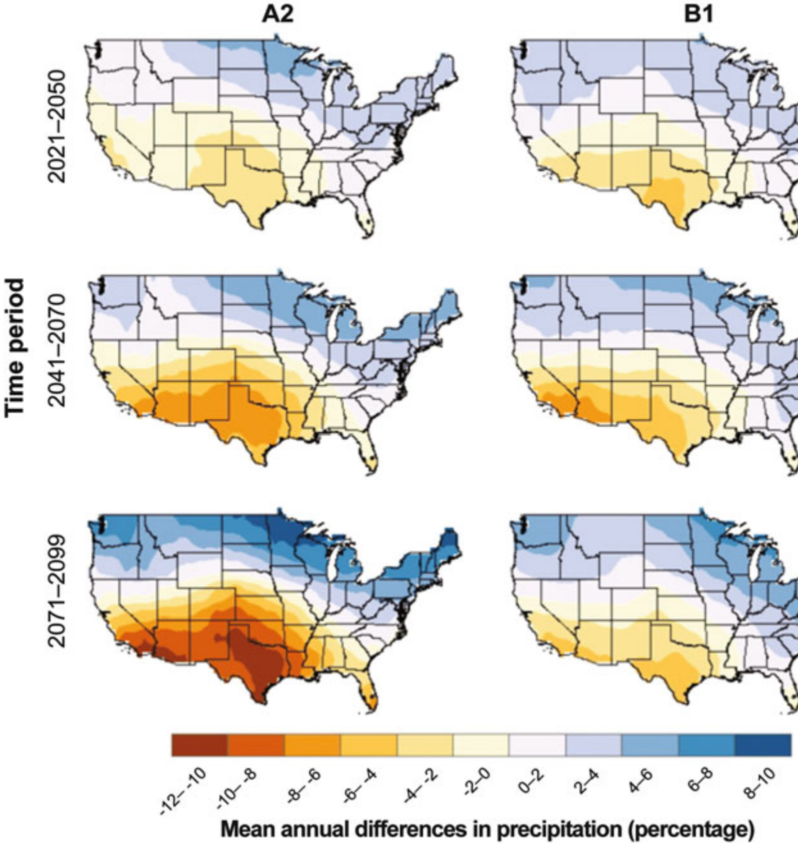

Fig. 2.3 Mean percentage of annual differences in U.S. precipitation between three future periods relative to a 1971–2000 reference period. The Northeast, northern Midwest and Pacific Northwest are projected to have slightly more precipitation, and the Southwest is projected to have 2–12 % less precipitation, depending on the emission scenario, location, and time period. Means are for 15 GCMs (From Kunkel et al. (2013))

percentile of the precipitation distribution is projected to increase by 25 % when atmospheric CO_2 concentration of the Earth reaches around 600 ppm (Allen and Ingram 2002). The timing and spatial distribution of extreme precipitation events are among the most uncertain aspects of future climate scenarios (Karl et al. 1995; Allen and Ingram 2002).

2.2.3 Drought

As the climate warms from increasing GHGs, both the proportion of land experiencing drought and the duration of drought events will likely increase

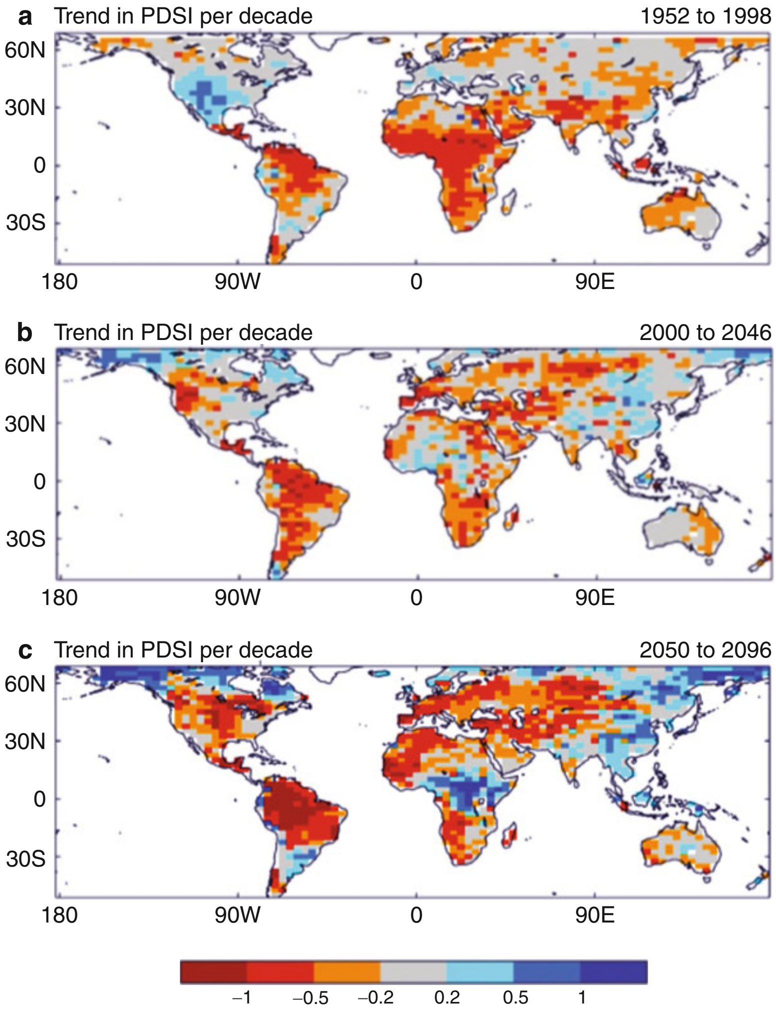

Fig. 2.4 Trend in the Palmer Drought Severity Index (*PDSI*) per decade for (**a**) observed data and the mean of the (**b**) first half and (**c**) second half of the twenty-first century. The PDSI is projected to decrease by 0.5–1 unit per decade for the period 2050–2096. For the PDSI, −1.9 to 1.9 is near normal, −2 to −2.9 is moderate drought, −3 to −3.9 is severe drought and less than −4 is extreme drought. Projections are made by HadCM3 with the A2 emission scenario (Figure from Burke et al. (2006), © British Crown Copyright 2006, Met Office, with permission)

(Burke et al. 2006). Projected spatial distribution of changes in drought over the twenty-first century for the A2 scenario indicates significant drying over the United States (Fig. 2.4). The Palmer Drought Severity Index is projected to decrease by 0.3 per decade (indicating more drought) globally for the first half of the twenty-first century. Relative to historical data, the amount of land surface subject to annual drought is projected to increase in 2010–2020 from 1 to 3 % for extreme droughts,

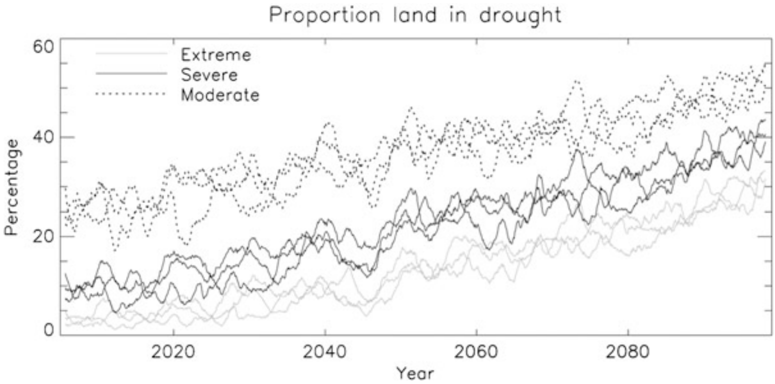

Fig. 2.5 The projected average annual proportion of the global land surface in drought each month shows drought increasing over the current century. Drought is defined as extreme, severe, or moderate, which represents 1, 5 and 20 %, respectively, of the land surface in drought under present-day conditions. Results from the three simulations are from HadCM3 with the A2 emission scenario (Figure from Burke et al. (2006), © British Crown Copyright 2006, Met Office, with permission)

from 5 to 10 % for severe droughts, and from 20 to 28 % for moderate droughts (Fig. 2.5). This drying trend continues throughout the twenty-first century, and by the 2090s, the amount of land area in drought is projected to increase for extreme, severe, and moderate droughts to 30, 40 and 50 %, respectively. The number of drought events is projected to double for extreme and severe droughts, but remain stable for moderate drought. The duration of all forms of drought events also increases.

2.3 Sea Level Rise

Global sea level rise results from changing the ocean's water volume because of changes in temperature, salinity, ice melting, and land surface runoff. Global sea level responds to climate cycles of alternating glacial and interglacial conditions over millions of years (Kawamura et al. 2007). Mean sea level rose by 120 m since the most recent ice age, at a rate of about 1 m per century. Sea level has remained relatively stable for the last 6,000 years, and observed data indicate a global mean increase of 0.17 m per century (Grinsted et al. 2010).

Satellite altimetry records show that mean sea level rise since the middle of the nineteenth century has not been uniform. The Pacific Coast of the United States showed little sea level rise, consistent with tide gage records (see discussion in Parris et al. 2011). In contrast, sea level rise in the Gulf of Mexico has averaged 3.2 mm year^{-1} since 1992. The trajectory of spatially explicit trends in the future is a topic of active research. For example, the spatial trend in the Pacific is thought to be a combination of wind stress patterns associated with the Pacific Decadal Oscillation

(PDO) and El Niño-Southern Oscillation (ENSO). Because of regular phase shifts in PDO (20–40 years) and ENSO (3–7 years), it is unlikely that the observed sea level rise trends will continue with the same magnitude and direction.

For various emission scenarios, as temperature increases, several factors (e.g., polar ice sheet melting) contribute to sea level rise (Parris et al. 2011). Different emission scenarios result in disparate projections of sea level rise by 2100, ranging from 0.2 m for the lowest scenario to 2.0 m for the highest scenario. For two intermediate scenarios, sea level is projected to increase from 0.5 m (B1) to 1.2 m (A2). This wide range of projections reflects high uncertainty in how sea level rise may affect coastal forests and terrestrial and aquatic ecosystems in coastal regions.

2.4 Using Climate Projections to Estimate Effects on Forests

No standard approach exists for linking climate projections with potential effects on forest species and ecosystems. Therefore, users of climate information must develop their own approach for accessing that information and applying it to assessments of vulnerability of natural resources to climate change. Different providers of climate information use different GCMs to develop projections of climate, typically at different time increments until 2100, and they often use different emission scenarios (B1, A2, etc.) (see Sect. 2.1). This can make it challenging for resource managers to identify appropriate data for specific applications.

Despite the diversity of GCMs and emission scenarios, most temperature projections are similar until around 2050, so one can have confidence in most model output during this time period. Beyond 2050, model output diverges considerably, especially as a function of emission scenario. All models project significant temperature increases with some confidence, but precipitation projections are more variable (some increase, some decrease) and are less reliable than for temperature projections. Some users select output from a model in which they have confidence. Others select output from multiple models—typically temperature projections that are high, moderate, and low—thus bracketing a range of potential future climates and effects on resources. This latter approach is a reasonable way to project a range of possible futures for natural resources. In addition, the current trajectory of GHG emissions is at the high end of the IPCC emission scenarios, so it may be more realistic to base climate projections on the “A” scenarios. It is always important to document which models and scenarios were used for any particular application and to understand how their basic assumptions affect climate projections.

In recent years, considerable effort has been invested in downscaling GCM output to smaller geographic areas, with the intention of providing more site-specific climate projections. Downscaled climate data may or may not be useful, depending on the spatial scale of interest for different natural resources, and downscaled data do not reduce the uncertainty of climate projections. For example, simply knowing that mean annual temperature will increase 2–4 °C by the year 2060 is probably sufficient for estimating effects on forest growth, wildfire, and insects and for developing appropriate adaptation options.

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