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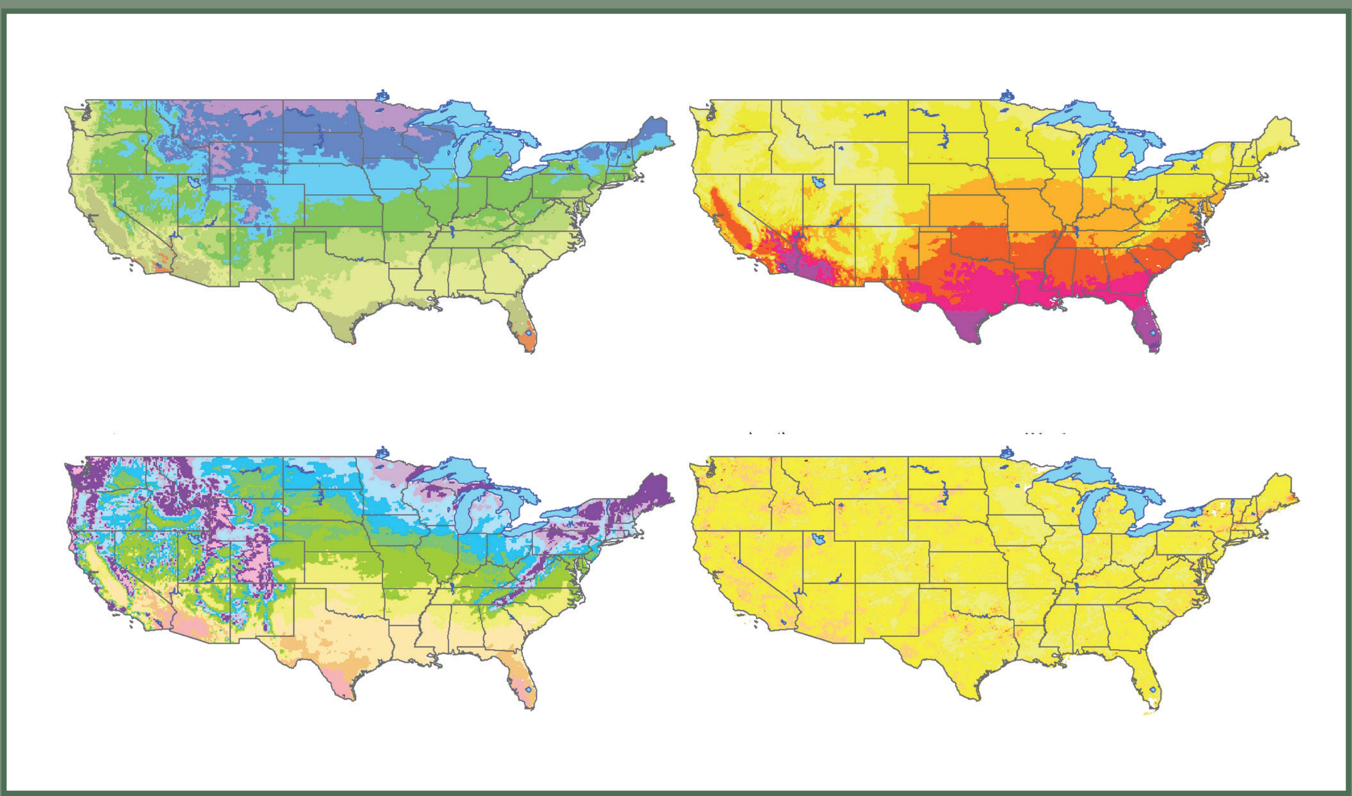
# Assessing Potential Climate Change Pressures across the Conterminous United States: Mapping Plant Hardiness Zones, Heat Zones, Growing Degree Days, and Cumulative Drought Severity throughout this Century



Forest Service

Northern Research Station

Research Map NRS-9

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## Abstract

The maps and tables presented here represent potential variability of projected climate change across the conterminous United States during three 30-year periods in this century and emphasizes the importance of evaluating multiple signals of change across large spatial domains. Maps of growing degree days, plant hardiness zones, heat zones, and cumulative drought severity depict the potential for markedly shifting conditions and highlight regions where changes may be multifaceted across these metrics. In addition to the maps, the potential change in these climate variables are summarized in tables according to the seven regions of the fourth National Climate Assessment to provide additional regional context. Viewing these data collectively further emphasizes the potential for novel climatic space under future projections of climate change and signals the wide disparity in these conditions based on relatively near-term human decisions of curtailing (or not) greenhouse gas emissions.

## Cover Image

A collage of four maps depicting the baseline conditions for plant hardiness zones (clockwise from top left), growing degree days, cumulative drought severity index, and heat zones. See text for full explanation of each.

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# Assessing Potential Climate Change Pressures across the Conterminous United States: Mapping Plant Hardiness Zones, Heat Zones, Growing Degree Days, and Cumulative Drought Severity throughout this Century

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## Disclaimer

## Introduction

In the era of persistent climate change, it is important that we consider how continued perturbations to our climate system may intensify through the end of the century (U.S. Global Change Research Program [USGCRP] 2017). Further, it is important to evaluate these potential changes under alternative scenarios to gauge the potential magnitude of these changes. By focusing on four key metrics related to plant growth and survival, but also of key interest to human well-being, we map and summarize projections of growing degree days, plant hardiness zones, heat zones, and cumulative drought severity across the conterminous United States throughout this century. Each map series captures the potential shifting conditions and collectively, the maps can highlight broad hotspot regions for change across the variables. To evaluate how these combined projected pathways may influence ecological systems, detailed modeling is needed to capture the multidimensional influences. In addition, the visual contrasts between two scenarios of the IPCC 5th assessment (Representative Concentration Pathway [RCP] 4.5, a low storyline; and RCP 8.5, a high storyline) emphasize the variation of possible climate outcomes as a result of human decisions driving emission trajectories through this century (van Vuuren et al. 2011).

## Data Sources

Data used for the production of growing degree days, plant hardiness zones, and heat zones were projected daily values of minimum and maximum temperature for the period 1980–2099, downscaled by Maurer et al. (2007), and were compiled here to address key variables related to plant growth and survival. To explore the potential variation in projected changes of these climate patterns, we evaluated each metric under two RCPs, thus representing "bookends" of a range of possibilities of projected climate change. We used the Community Climate System Model (CCSM4) (Gent et al. 2011), a general circulation model (GCM) with relatively low sensitivity to $CO_2$, and with the RCP 4.5 storyline of relatively rapid reduction of greenhouse gases so that emissions peak ~2040 (Moss et al. 2008). As a result, CCSM4 RCP 4.5 represents the low end of model outputs and a "low" amount of future climate change. For the higher end of potential change, we used the Geophysical Fluid Dynamics Laboratory (GFDL) CM3 model (Donner et al. 2011) with the RCP 8.5 storyline of continuing our current emissions path for much of this century, thus representing a relatively "high" projection of changes by century's end. In this report, we will refer to these two scenarios as “low” and “high”. Global $CO_2$ levels have been tracking much more closely with high than low levels in the time since these scenarios were generated in 2008 (Peters et al. 2013).

These data were statistically downscaled via asynchronous regional regression modeling, to a resolution of one-eighth degree (~13.875 × 13.875 km) (Maurer et al. 2007), but, as with any downscaled data, there are uncertainties and the uncertainty associated with daily data will be greater than that associated with long-term means. To address the accumulation of these daily errors, we report on projected change in each metric at the 30-year average resolution for three time periods: 2010–2039, 2040–2069, and 2070–2099 and represented in this document as early century, mid-century, and late century, respectively. These data sets were also used to prepare difference maps for each time period based on the modeled baseline conditions (1980–2009) from each climate model. These difference maps provide a spatial indication of where and when change is projected.

Additional data were required for the calculation of a cumulative drought severity Index (CDSI) (Peters et al. 2014), as it was performed on monthly projections of precipitation and temperature that were obtained from the National Aeronautics and Space Administration’s (NASA) Earth Exchange Downscaled Climate Projections (NEX-DCP30) dataset (Thrasher et al. 2013). GCMs within the NEX-DCP30 dataset were downscaled to a common grid corresponding to interpolated climate observation derived from the PRISM (Parameter-elevation Regressions on Independent Slopes Model) dataset (Daly et al. 2008) using the bias-correction and spatial disaggregation method (Maurer and Hildago 2008; Wood et al. 2002, 2004). Both the PRISM data and the NEX-DCP30 downscaled GCMs have a spatial resolution of 30 arc-seconds (~800 m) across the conterminous United States. To remove any bias from the GCMs, mean PRISM values for the period 1981–2010 were adjusted using the delta method where the change between monthly GCM values were subtracted from the mean period 1981–2010 from the GCM, providing the predicted change in monthly precipitation and temperature.

Monthly values from the PRISM and GCM datasets were aggregated to 10 × 10 km grids to calculate a self-calibrated Palmer Drought Severity Index (scPDSI) using an algorithm developed by Wells et al. (2004). The scPDSI algorithm requires latitude, available water supply (AWS) of the soil, which was derived from 10-m gridded county soil survey geographic database (gSSURGO) (Natural Resources Conservation Service 2016), monthly climate normals (e.g., mean temperature of calibration period), monthly precipitation, and mean monthly temperature. A snowmelt function (Yan et al. 2014) that accumulates a snowpack when monthly temperatures ≤0 °C and precipitation >0 mm, and then releases a portion of the snowpack when monthly temperatures are above freezing, was used to alter monthly precipitation values. Precipitation stored in the snowpack is released by 20 percent in months when the mean monthly temperature is between

0 and 5 °C; when the monthly temperature exceeds the 5 °C threshold, the remaining snowpack is added to the monthly precipitation. The calibration period was set to the baseline period 1981–2010, and monthly scPDSI values for the period 1980 to 2099 were calculated.

Across all of the variables presented here, the climate metrics capture unique areas spatially and temporally and show areas with the projected greatest and least change under the two climate scenarios. To facilitate regional comparisons, we summarized the climate variables by regions (Figure 1), based on the fourth National Climate Assessment (U.S. Global Change Research Program 2017) by presenting the mean conditions for each region for the baseline period and the three time periods for the low and high scenarios. In addition, we calculated the percent change in area for each climate variable by region to capture both the distributional shift (i.e., the range of projected change to capture the overall magnitude of shift) as well as a means to facilitate comparisons of change across these unique geographic regions.

## Map Projections

All maps in this report are displayed using a geographic coordinate system with an angular unit in degrees and the North American Datum of 1983. Data for growing degree days, heat zones, and plant hardiness zones spanned 25.125° N to 52.875° N and -124.625° E to -67.000° E, including parts of Mexico and Canada, while the cumulative drought severity index spanned 24.062° N to 49.937° N and -125.021° E to -66.479° E, including only the United States.

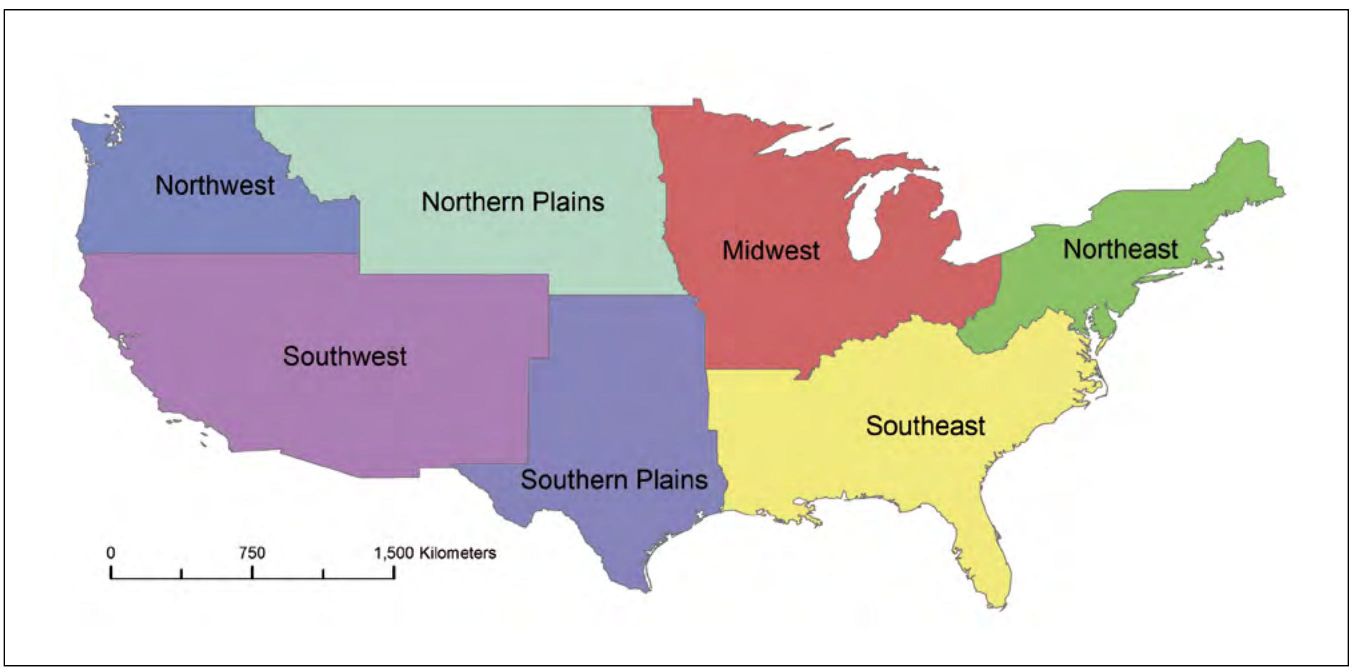


Figure 1.—Regions of the conterminous United States as defined in the National Climate Assessment (USGCRP 2017) and used in this study.

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## Growing degree days

Growing degree days (GDD) address an important component to general patterns of plant growth by accumulating the degree days across the growing season. This metric provides a level of detail related to defining the growing season potential. Here, we evaluate the accumulation of growing degree days at or above 5 °C (41 °F), assuming that limited growth occurs below 5 °C (Franklin et al. 2013, Rehfeldt et al. 2006, Sork et al. 2010). Specifically, we calculate growing degree days by first calculating the average daily temperature, based on the maximum and minimum projected daily temperature. We then subtract 5 °C from each mean value and then accumulate the positive difference values for all days within each year. The mean GDD values for the conterminous United States during the baseline period ranged from <100 to over 7,000 degree days, increasing from north to south with highest values in the Florida panhandle, southern Texas, southwestern Arizona, and southeastern California (Figure 2). GDD projections throughout the century suggest a ubiquitous increase across the United States with slightly less change in the Northeast and much greater increases throughout the southern United States under the high scenario (Figure 2 mean GDD and Figure 3 change in GDD).

By region, the mean GDD (Table 1) for the baseline period is greatest in the Southern Plains (4,584 degree days) and least in the Northwest (1,689 degree days) under the high scenario. Though the Southwest has the highest values, the large, cold Rocky Mountains reduces its mean to 2,884 degree days. Each future period increased GDD across the map (Figure 2) with an acceleration of change apparent starting about mid-century. For example, under the high scenario, the late century period showed GDD mean values of 6,272 for the Southeast (a gain of 1,827) and 3,053 for the Northwest (a gain of 1,364; Table 1). There is also a large differential between the low and high scenarios especially by century's end, with a difference between scenarios of at least 1,000 degree days for each of the regions (Table 1).

Table 2 shows the percentage of each region within each GDD 100-degree-day change category and also clearly illustrates the aforementioned trends: the large change occurring, especially by mid-century, the large differential between scenarios, and the large geographical variation. Some locations in the Southeast and Southwest regions of the United States are projected to increase more than 2,000 GDD by the end of the century under the high scenario (Figure 3). Though some plants may benefit from increased GDD, this measure does not incorporate estimates of precipitation, which have greater uncertainties in climate change modeling. Many models suggest precipitation will occur in the form of larger extreme events (including greater drought in between heavy rainfall events) and with more unevenness in seasonality (lower proportion of rainfall in late summer—autumn). Moisture stress added to more heat will likely increase stress among plants and contribute to greater mortality ("hot droughts") (Allen et al. 2015). The CDSI, which considers precipitation and temperature, captures some aspects of water deficits that can lead to plant stress.

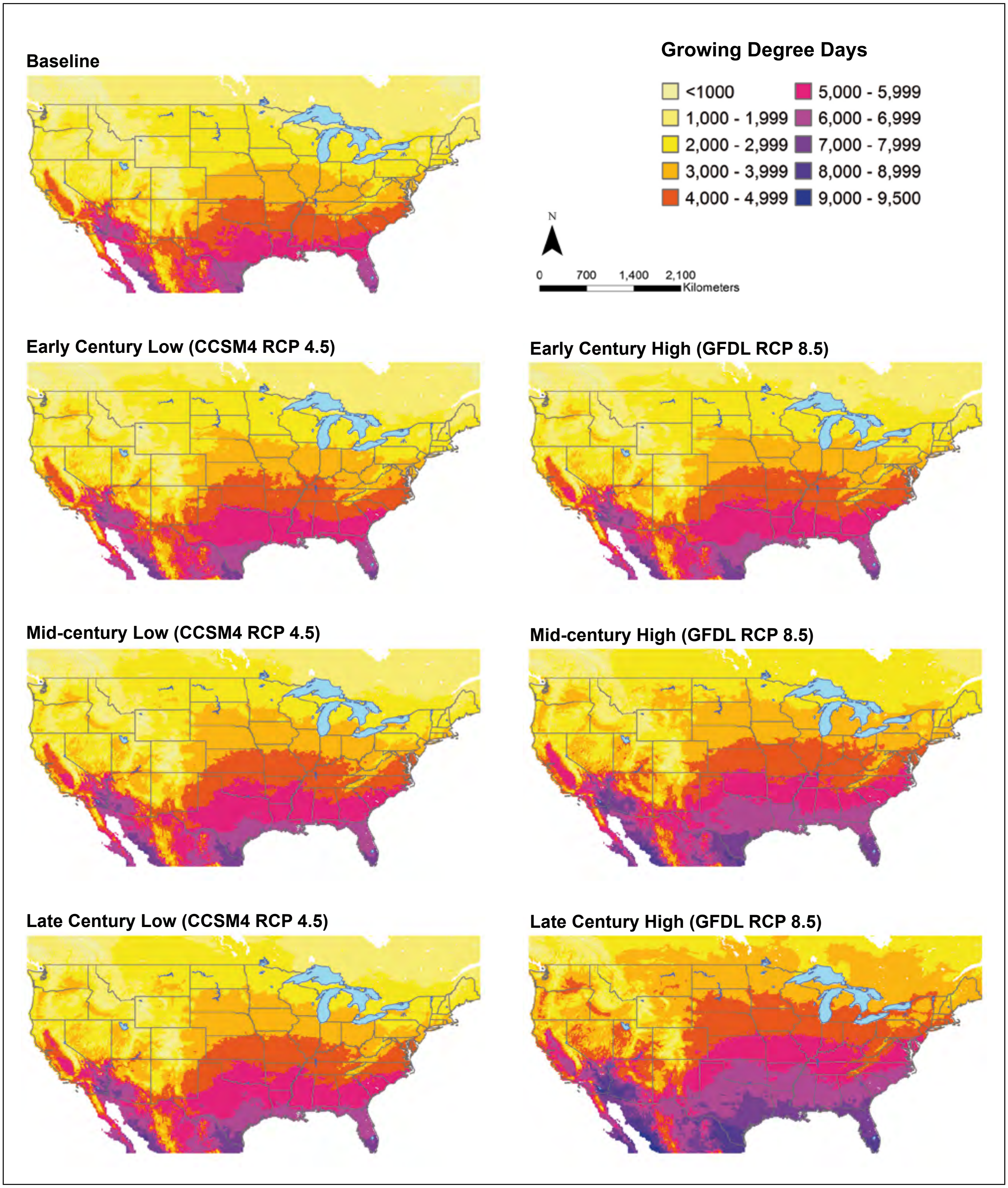


Figure 2.—Maps of baseline and projections of mean growing degree days for conterminous United States by 30-year time period using a low (RCP 4.5; see text for explanation) or high (RCP 8.5; see text for explanation) climate scenario. The maps show an accumulation of growing degree days. Time periods: baseline (1980–2009); early century (2010–2039); mid-century (2040–2069); late century (2070–2099).

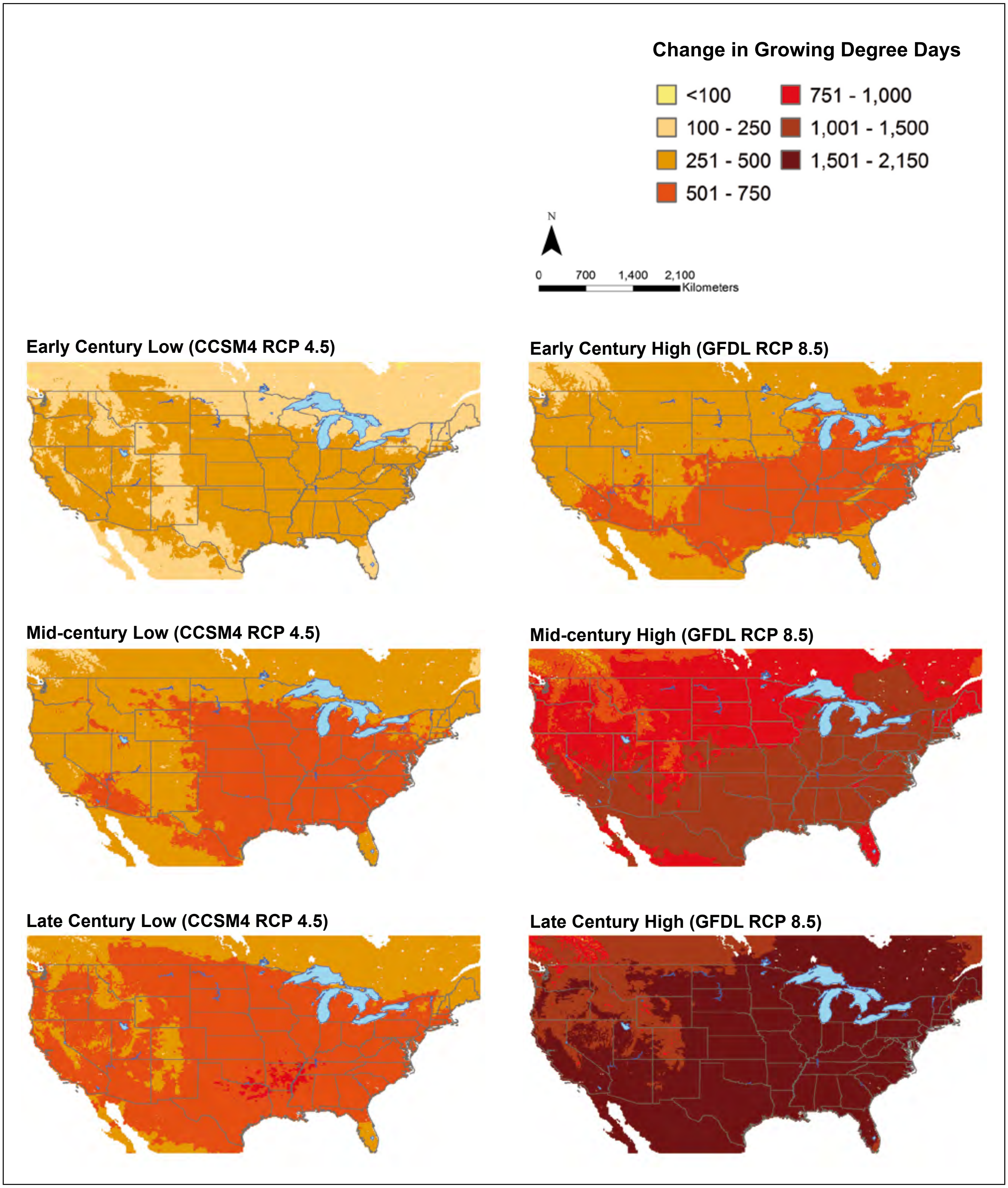


Figure 3.—Mapped projections of increase in growing degree days for conterminous United States by 30-year time period and climate scenario. Projections suggest a ubiquitous increase across the United States, with slightly less change in the Northeast and much greater increases in the Southwest under the high scenario. Time periods: early century (2010–2039); mid-century (2040–2069); late century (2070–2099).

Table 1. The mean number of growing degree days (based on 5 ºC, or 41 ºF) by region for baseline (1980–2009), early (2010–2039), mid (2040–2069), and late century (2070–2099) climate conditions. Data are presented separately for low (CCSM4 RCP 4.5) and high (GFDL CM3 RCP 8.5) scenarios.

| | Growing Degree Days | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Low Scenario | | | | High Scenario | | | |
| | Baseline | Early Century | Mid-century | Late Century | Baseline | Early Century | Mid-century | Late Century |
| Midwest | 2,760 | 3,031 | 3,320 | 3,378 | 2,681 | 3,191 | 3,703 | 4,432 |
| Northeast | 2,363 | 2,607 | 2,854 | 2,908 | 2,324 | 2,812 | 3,382 | 4,075 |
| Northern Plains | 2,143 | 2,403 | 2,622 | 2,724 | 2,036 | 2,456 | 2,907 | 3,574 |
| Northwest | 1,730 | 1,999 | 2,140 | 2,268 | 1,689 | 2,034 | 2,495 | 3,053 |
| Southeast | 4,505 | 4,810 | 5,126 | 5,177 | 4,445 | 4,973 | 5,565 | 6,272 |
| Southern Plains | 4,646 | 4,927 | 5,221 | 5,324 | 4,584 | 5,135 | 5,717 | 6,453 |
| Southwest | 2,920 | 3,198 | 3,366 | 3,479 | 2,884 | 3,349 | 3,879 | 4,537 |

Table 2. The projected increase in mean growing degree days (GDD) are presented as a percentage of land area within each region, by time period. For instance, 67.4 percent of the land area in the Midwest is projected to have an increase of 500 growing degree days during the early century under the high scenario, and during the mid-century, 25.5 percent of the Midwest land area is projected to have an increase of 900 growing degree days. Data are presented separately for low (CCSM4 RCP 4.5) and high (GFDL CM3 RCP 8.5) scenarios.

| | Midwest | | | Northeast | | | Southeast | | | Northern Plains | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Change | Early Century | Mid-century | Late Century | Early Century | Mid-century | Late Century | Early Century | Mid-century | Late Century | Early Century | Mid-century | Late Century |
| **GDD (Low)** | | | | | | | | | | | | |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0 | 0 |
| 200 | 29.6 | 0 | 0 | 51.0 | 0 | 0 | 6.0 | 0 | 0 | 31.1 | 0.1 | 0 |
| 300 | 70.3 | 0 | 0 | 49.0 | 0.9 | 0 | 94.0 | 0.2 | 0 | 68.4 | 4.6 | 0.6 |
| 400 | 0 | 1.9 | 0 | 0 | 25.7 | 14.8 | 0 | 3.9 | 2.8 | 0 | 19.4 | 5.5 |
| 500 | 0 | 42.2 | 16.5 | 0 | 48.7 | 28.2 | 0 | 5.6 | 4.1 | 0 | 67.7 | 17.9 |
| 600 | 0 | 50.3 | 51.0 | 0 | 24.6 | 50.3 | 0 | 56.3 | 19.9 | 0 | 8.2 | 68.5 |
| 700 | 0 | 5.5 | 31.9 | 0 | 0.1 | 6.7 | 0 | 34.0 | 65.8 | 0 | 0 | 7.4 |
| 800 | 0 | 0 | 0.6 | 0 | 0 | 0 | 0 | 0 | 7.4 | 0 | 0 | 0 |
| 900 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **GDD (High)** | | | | | | | | | | | | |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.8 | 0 | 0 |
| 300 | 0 | 0 | 0 | 0.3 | 0 | 0 | 2.0 | 0 | 0 | 10.5 | 0 | 0 |
| 400 | 8.8 | 0 | 0 | 20.6 | 0 | 0 | 5.8 | 0 | 0 | 57.0 | 0 | 0 |
| 500 | 67.4 | 0 | 0 | 70.1 | 0 | 0 | 55.0 | 0 | 0 | 31.5 | 0.7 | 0 |
| 600 | 23.8 | 0 | 0 | 9.0 | 0 | 0 | 37.1 | 0 | 0 | 0.1 | 3.9 | 0 |
| 700 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6.8 | 0 |
| 800 | 0 | 0.1 | 0 | 0 | 0.1 | 0 | 0 | 1.6 | 0 | 0 | 19.9 | 0 |
| 900 | 0 | 25.5 | 0 | 0 | 15.4 | 0 | 0 | 4.1 | 0 | 0 | 48.8 | 0.3 |
| 1,000 | 0 | 32.4 | 0 | 0 | 21.7 | 0 | 0 | 6.1 | 0 | 0 | 19.8 | 1.1 |
| 1,100 | 0 | 37.8 | 0 | 0 | 50.1 | 0 | 0 | 50.5 | 0 | 0 | 0.1 | 3.3 |
| 1,200 | 0 | 4.2 | 0 | 0 | 12.5 | 0 | 0 | 37.7 | 0 | 0 | 0 | 4.0 |
| 1,300 | 0 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 4.9 |
| 1,400 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0.1 | 0 | 0 | 6.7 |
| 1,500 | 0 | 0 | 0.3 | 0 | 0 | 5.3 | 0 | 0 | 3.3 | 0 | 0 | 20.7 |
| 1,600 | 0 | 0 | 9.6 | 0 | 0 | 16.5 | 0 | 0 | 3.6 | 0 | 0 | 34.7 |
| 1,700 | 0 | 0 | 39.2 | 0 | 0 | 21.2 | 0 | 0 | 6.7 | 0 | 0 | 20.7 |
| 1,800 | 0 | 0 | 35.3 | 0 | 0 | 34.0 | 0 | 0 | 38.7 | 0 | 0 | 3.6 |
| 1,900 | 0 | 0 | 15.5 | 0 | 0 | 20.5 | 0 | 0 | 46.0 | 0 | 0 | 0 |
| 2,000 | 0 | 0 | 0 | 0 | 0 | 2.2 | 0 | 0 | 1.6 | 0 | 0 | 0 |
| 2,100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2,200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 2 (continued).

| Change | Southern Plains | | | Northwest | | | Southwest | | |
|---|---|---|---|---|---|---|---|---|---|
| | Early Century | Mid-century | Late Century | Early Century | Mid-century | Late Century | Early Century | Mid-century | Late Century |
| **GDD (Low)** | | | | | | | | | |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 100 | 0 | 0 | 0 | 0.7 | 0 | 0 | 1.2 | 0 | 0 |
| 200 | 21.4 | 0 | 0 | 30.3 | 1.0 | 0.1 | 25.9 | 0.4 | 0.1 |
| 300 | 78.6 | 0 | 0 | 68.1 | 14.0 | 1.7 | 64.5 | 7.7 | 1.7 |
| 400 | 0 | 1.8 | 0 | 0.9 | 55.2 | 12.1 | 8.4 | 42.1 | 8.5 |
| 500 | 0 | 30.1 | 1.3 | 0 | 29.7 | 37.0 | 0 | 49.0 | 32.0 |
| 600 | 0 | 64.7 | 28.3 | 0 | 0.1 | 42.5 | 0 | 0.8 | 44.1 |
| 700 | 0 | 3.4 | 65.0 | 0 | 0 | 6.6 | 0 | 0 | 13.6 |
| 800 | 0 | 0 | 5.4 | 0 | 0 | 0 | 0 | 0 | 0 |
| 900 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **GDD (High)** | | | | | | | | | |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 200 | 0 | 0 | 0 | 4.8 | 0 | 0 | 0.2 | 0 | 0 |
| 300 | 0 | 0 | 0 | 43.1 | 0 | 0 | 6.4 | 0 | 0 |
| 400 | 0.3 | 0 | 0 | 51.4 | 0.1 | 0 | 32.5 | 0 | 0 |
| 500 | 45.3 | 0 | 0 | 0.7 | 1.9 | 0 | 47.6 | 0.2 | 0 |
| 600 | 54.4 | 0 | 0 | 0 | 7.8 | 0 | 13.3 | 1.4 | 0 |
| 700 | 0 | 0 | 0 | 0 | 16.7 | 0 | 0 | 4.0 | 0 |
| 800 | 0 | 0 | 0 | 0 | 30.7 | 0.3 | 0 | 11.3 | 0 |
| 900 | 0 | 0 | 0 | 0 | 36.2 | 1.3 | 0 | 18.7 | 0.1 |
| 1,000 | 0 | 9.1 | 0 | 0 | 6.6 | 2.7 | 0 | 28.4 | 0.6 |
| 1,100 | 0 | 47.0 | 0 | 0 | 0 | 7.2 | 0 | 17.6 | 1.3 |
| 1,200 | 0 | 43.3 | 0 | 0 | 0 | 10.6 | 0 | 15.2 | 2.5 |
| 1,300 | 0 | 0.6 | 0 | 0 | 0 | 15.7 | 0 | 3.3 | 4.5 |
| 1,400 | 0 | 0 | 0 | 0 | 0 | 24.3 | 0 | 0 | 8.9 |
| 1,500 | 0 | 0 | 0 | 0 | 0 | 27.7 | 0 | 0 | 11.8 |
| 1,600 | 0 | 0 | 0 | 0 | 0 | 9.9 | 0 | 0 | 14.5 |
| 1,700 | 0 | 0 | 2.8 | 0 | 0 | 0.4 | 0 | 0 | 20.9 |
| 1,800 | 0 | 0 | 30.4 | 0 | 0 | 0 | 0 | 0 | 13.4 |
| 1,900 | 0 | 0 | 59.7 | 0 | 0 | 0 | 0 | 0 | 12.1 |
| 2,000 | 0 | 0 | 7.0 | 0 | 0 | 0 | 0 | 0 | 8.6 |
| 2,100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.8 |
| 2,200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

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## Plant hardiness zones

Plant hardiness zones (PHZ) provide a general indication of the extent of overwinter stress experienced by plants. PHZ are based on the average annual extreme minimum temperatures and have been used by horticulturists to evaluate the cold hardiness of plants. Specifically, the value used here is the absolute minimum temperature achieved for each year and reported as the 30-year mean (Cathey 1990, Daly et al. 2012). Because they reflect cold tolerance for many plant species, including woody ones, hardiness zones are most likely to reflect plant range limits. The zonal variations caused by warming temperatures in the future will therefore be useful to approximately delineate niche constraints of many plant species and hence their future range potential. Plant hardiness zones and subzones were delineated according to the USDA definitions (Cathey 1990), which break the geography into zones by 10 °F (5.56 °C) increments from zone 1 (-55 to -45.6 °C) to zone 13 (15.7 to 22 °C) of annual extreme minimum temperature. To define the coldest day per year, daily minimum temperatures were identified within the period July 1 to June 30, with the nominal year assigned to the first 6 months of the 12-month period.

The high scenario captures the potential for dramatic changes in PHZ, evident by the mid-century time period onward (Figure 4). All regions could see high rates of warming, with the mean minimum temperature increasing (Table 3). For example, under the high scenario, mean minimum temperature is projected to increase by at least 5 °C in four of the regions by the end of the century (Table 3). This shift is illustrated in Table 4 and Figure 5 across the regions. For example, most of the Northeast and Midwest regions are projected to experience an increase in minimum temperature of at least 8–9 °C with the entire distribution shifting toward warmer conditions. Likewise, Table 4 captures the progression of the temperature distributions across the time periods, with rapidly increasing minimum temperatures projected for the Northeast, Midwest, Northwest, and Northern Plains (Table 4). However, the low scenario is the more conservative in showing change from the baseline to the future. For example, though the minimum temperature changes are sizable for the Midwest (from -26.0 baseline to -21.7 °C by late century), these changes are less than 2 °C in the Northwest (Table 3). Thus under the low scenario, the projections show mostly a reshuffling of minimum temperatures within regions and a limited expansion of larger changes (Table 4).

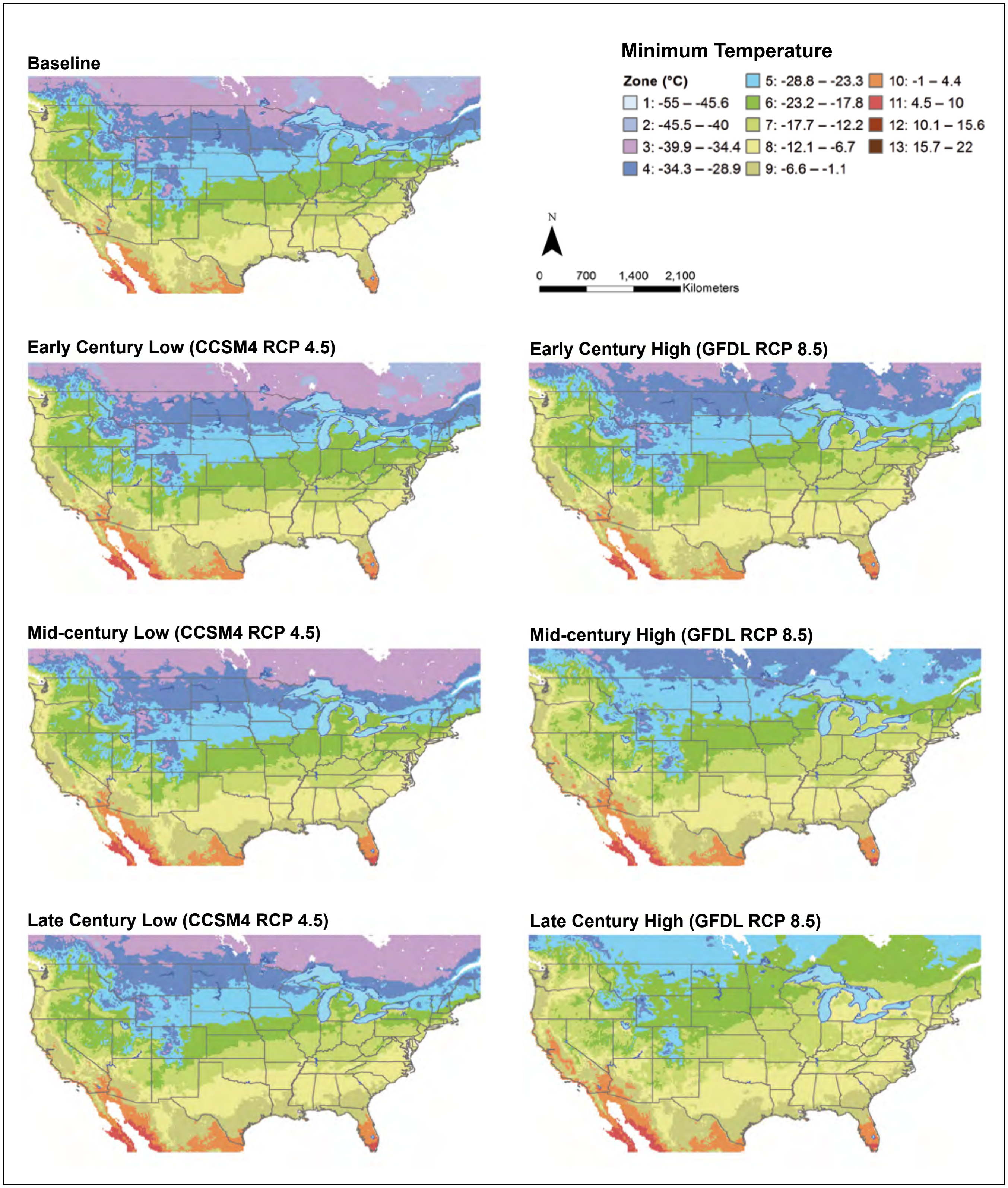


Figure 4.—Maps of baseline and projections of mean absolute minimum temperature (reflecting the plant hardiness zone metric) for conterminous United States by 30-year time period using a low (RCP 4.5; see text for explanation) or high (RCP 8.5; see text for explanation) climate scenario. To define the coldest day per year, daily minimum temperatures were identified within the period July 1 to June 30, with the year assigned to the first 6 months of the 12-month period. Zone categories follow the USDA definitions (Cathey 1990). Time periods: baseline (1980–2009); early century (2010–2039); mid-century (2040–2069); late century (2070–2099).

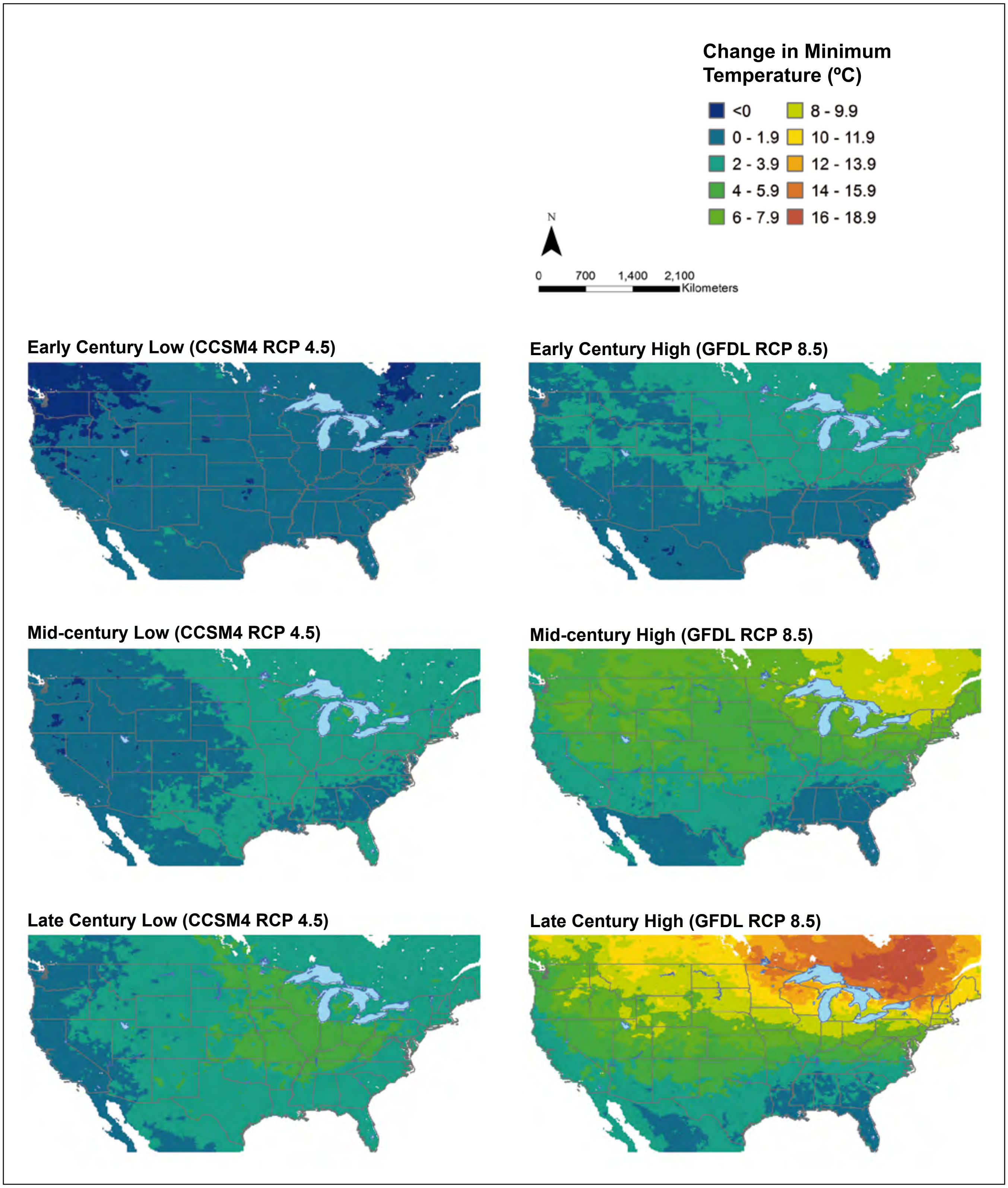


Figure 5.—Mapped projections of changes in minimum temperature for conterminous United States by 30-year time period and climate scenario. Plant hardiness zones are projected to have the greatest changes in the Northeast and Northern Plains. Time periods: early century (2010–2039); mid-century (2040–2069); late century (2070–2099).

Table 3. The mean minimum temperature (plant hardiness zone metric) in degrees Celsius, by region for baseline (1980–2009), early (2010–2039), mid (2040–2069), and late century (2070–2099) climate conditions. Data are presented separately for low (CCSM4 RCP 4.5) and high (GFDL CM3 RCP 8.5) scenarios.

| | Minimum Temperature | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Low Scenario | | | | High Scenario | | | |
| | Baseline | Early Century | Mid-century | Late Century | Baseline | Early Century | Mid-century | Late Century |
| Midwest | -26.0 | -24.8 | -23.0 | -21.7 | -24.6 | -21.7 | -19.2 | -15.4 |
| Northeast | -22.8 | -22.6 | -20.3 | -19.6 | -21.7 | -18.6 | -15.3 | -12.4 |
| Northern Plains | -31.2 | -30.5 | -29.5 | -28.1 | -30.6 | -28.4 | -25.1 | -21.9 |
| Northwest | -20.0 | -20.2 | -19.5 | -18.3 | -20.8 | -18.9 | -15.5 | -14.3 |
| Southeast | -11.7 | -11.1 | -9.6 | -8.4 | -10.7 | -9.8 | -8.7 | -8.1 |
| Southern Plains | -14.3 | -13.4 | -12.2 | -10.8 | -13.5 | -11.9 | -10.3 | -9.6 |
| Southwest | -17.2 | -16.6 | -16.6 | -15.0 | -17.3 | -15.9 | -13.7 | -12.7 |

Table 4. The projected changes in minimum temperature, in degrees Celsius, are presented as a percentage of land area within each region, by time period. For instance, 22.3 percent of the land area in the Midwest is projected to have a 2-degree (Celsius) increase in minimum temperature during the early century under the high scenario, and during mid-century 25.7 percent of the Midwest land area is projected to have a minimum temperature increase of 6 °C. Data are presented separately for low (CCSM4 RCP 4.5) and high (GFDL CM3 RCP 8.5) scenarios.

| | Midwest | | | Northeast | | | Southeast | | | Northern Plains | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Change | Early Century | Mid-century | Late Century | Early Century | Mid-century | Late Century | Early Century | Mid-century | Late Century | Early Century | Mid-century | Late Century |
| **Min Temp (Low)** | | | | | | | | | | | | |
| -3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| -2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| -1 | 0 | 0 | 0 | 0.8 | 0 | 0 | 0 | 0 | 0 | 2.0 | 0 | 0 |
| 0 | 7.0 | 0 | 0 | 79.3 | 0 | 0 | 46.5 | 0 | 0 | 29.9 | 2.0 | 0 |
| 1 | 77.1 | 0 | 0 | 19.9 | 0.2 | 0 | 53.2 | 4.3 | 0 | 66.1 | 42.8 | 0.5 |
| 2 | 16.0 | 13.3 | 0.2 | 0 | 55.7 | 7.8 | 0.3 | 77.7 | 10.8 | 1.9 | 45.4 | 20.2 |
| 3 | 0 | 75.4 | 5.0 | 0 | 41.4 | 54.5 | 0 | 18.0 | 55.5 | 0 | 9.6 | 52.0 |
| 4 | 0 | 10.9 | 60.8 | 0 | 2.6 | 34.4 | 0 | 0 | 30.7 | 0 | 0.1 | 26.4 |
| 5 | 0 | 0.4 | 34.0 | 0 | 0 | 3.3 | 0 | 0 | 3.1 | 0 | 0 | 0.9 |
| 6 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Min Temp (High)** | | | | | | | | | | | | |
| -3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| -2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| -1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 40.3 | 0.9 | 0.1 | 0 | 0 | 0 |
| 1 | 0.2 | 0 | 0 | 0.2 | 0 | 0 | 42.8 | 32.8 | 16.8 | 11.6 | 0 | 0 |
| 2 | 22.3 | 0.3 | 0 | 9.2 | 0 | 0 | 13.6 | 43.4 | 42.7 | 63.9 | 0 | 0 |
| 3 | 65.7 | 6.7 | 1.1 | 78.2 | 0.6 | 0 | 3.3 | 16.2 | 19.9 | 24.4 | 0.3 | 0 |
| 4 | 11.7 | 21.6 | 2.5 | 12.3 | 8.0 | 0.4 | 0 | 5.8 | 11.2 | 0.1 | 7.7 | 0 |
| 5 | 0 | 23.6 | 5.3 | 0 | 18.5 | 3.6 | 0 | 0.9 | 6.9 | 0 | 42.3 | 0.4 |
| 6 | 0 | 25.7 | 9.3 | 0 | 31.9 | 9.4 | 0 | 0 | 2.3 | 0 | 43.2 | 6.1 |
| 7 | 0 | 16.8 | 11.4 | 0 | 23.0 | 17.6 | 0 | 0 | 0.1 | 0 | 6.5 | 13.8 |
| 8 | 0 | 5.1 | 14.7 | 0 | 11.6 | 14.7 | 0 | 0 | 0 | 0 | 0 | 21.9 |
| 9 | 0 | 0.2 | 13.4 | 0 | 5.9 | 12.2 | 0 | 0 | 0 | 0 | 0 | 33.7 |
| 10 | 0 | 0 | 9.8 | 0 | 0.4 | 11.4 | 0 | 0 | 0 | 0 | 0 | 21.3 |
| 11 | 0 | 0 | 8.9 | 0 | 0 | 13.6 | 0 | 0 | 0 | 0 | 0 | 2.7 |
| 12 | 0 | 0 | 10.1 | 0 | 0 | 7.5 | 0 | 0 | 0 | 0 | 0 | 0.1 |
| 13 | 0 | 0 | 7.3 | 0 | 0 | 4.2 | 0 | 0 | 0 | 0 | 0 | 0 |
| 14 | 0 | 0 | 5.2 | 0 | 0 | 2.9 | 0 | 0 | 0 | 0 | 0 | 0 |
| 15 | 0 | 0 | 1.0 | 0 | 0 | 2.4 | 0 | 0 | 0 | 0 | 0 | 0 |
| 16 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 4 (continued).

| | Southern Plains | | | Northwest | | | Southwest | | |
|---|---|---|---|---|---|---|---|---|---|
| **Change** | **Early Century** | **Mid-century** | **Late Century** | **Early Century** | **Mid-century** | **Late Century** | **Early Century** | **Mid-century** | **Late Century** |
| **Min Temp (Low)** | | | | | | | | | |
| -3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| -2 | 0 | 0 | 0 | 0.3 | 0 | 0 | 0 | 0 | 0 |
| -1 | 0 | 0 | 0 | 30.3 | 0.2 | 0 | 0.6 | 0.1 | 0 |
| 0 | 19.9 | 0 | 0 | 59.9 | 46.8 | 0.5 | 35.7 | 17.8 | 0.5 |
| 1 | 73.4 | 4.2 | 0 | 9.5 | 52.1 | 45.0 | 60.6 | 59.7 | 22.5 |
| 2 | 6.7 | 87.4 | 0.1 | 0 | 1.0 | 38.3 | 3.2 | 20.7 | 37.6 |
| 3 | 0 | 8.4 | 53.7 | 0 | 0 | 15.8 | 0 | 1.7 | 32.4 |
| 4 | 0 | 0 | 45.5 | 0 | 0 | 0.3 | 0 | 0 | 6.9 |
| 5 | 0 | 0 | 0.8 | 0 | 0 | 0 | 0 | 0 | 0.1 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Min Temp (High)** | | | | | | | | | |
| -3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| -2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| -1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 4.4 | 0 | 0 | 0.1 | 0 | 0 | 1.8 | 0 | 0 |
| 1 | 46.7 | 0.3 | 0.6 | 25.8 | 0 | 0 | 57.6 | 0 | 0 |
| 2 | 41.9 | 27.8 | 19.2 | 59.7 | 0.5 | 0 | 37.4 | 19.8 | 3.7 |
| 3 | 7.0 | 36.3 | 26.5 | 14.3 | 6.3 | 2.8 | 3.0 | 31.1 | 23.5 |
| 4 | 0 | 29.9 | 20.7 | 0 | 19.3 | 5.5 | 0.1 | 28.2 | 23.7 |
| 5 | 0 | 5.7 | 18.4 | 0 | 28.8 | 14.8 | 0 | 16.5 | 24.1 |
| 6 | 0 | 0 | 11.5 | 0 | 35.1 | 20.1 | 0 | 3.4 | 16.3 |
| 7 | 0 | 0 | 3.0 | 0 | 9.6 | 33.5 | 0 | 0.9 | 5.7 |
| 8 | 0 | 0 | 0 | 0 | 0.4 | 19.8 | 0 | 0.1 | 2.1 |
| 9 | 0 | 0 | 0 | 0 | 0 | 3.5 | 0 | 0 | 0.7 |
| 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 11 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 13 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

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## Heat Zones

Heat zones map the distribution of potential heat stress for plants and animals, including humans. We define heat zones as the number of days with maximum daily temperature >30 °C (86 °F) (Cathey 1997). Because species have unique adaptations and abilities to tolerate a wide variety of conditions, this metric is used merely as an indicator of change in “hot” conditions. The 30 °C value is set primarily for agricultural production and is a general temperature threshold at which photosynthesis can be negatively impacted for $C_3$ plants (e.g., most species including trees) (Rennenberg et al. 2006), but it certainly also captures temperatures that induce stress in humans as well (Pal and Eltahir 2015). In addition, increases in temperature above these thresholds for longer periods, especially when accompanied with prolonged dry conditions, are linked to reduced performance and likely mortality of trees (Allen et al. 2015). Each day surpassing the 30 °C threshold was tallied and summed for each year and reported as the mean number of days, per year, over each 30-year period: baseline, early, mid, and late century.

Maps compiling heat zones (Figure 6) show the average number of days per year greater than 30 °C (86 °F) across 30-year intervals. The increase in heat zones is most profound in the Northeast and Midwest and is apparent even by mid-century (Figure 7). Under the high scenario, the Northeast is projected to experience 96 more days by century’s end, while with the low scenario shows the least amount of change among the seven regions with a mean of 29 more days above 30 °C (Table 5). The Midwest is projected to experience the most change under both scenarios with a mean of 95 and 42 (Table 5) additional days, from the high and low scenarios, respectively. Under the high scenario, all regions are projected to have at least a twofold increase in “hot” days, as compared to the low scenario (Table 5). As shown in the other climate metrics, the change tables, Table 6, provides an indication of potential for some regions to enter into novel climate space (climates not now experienced) as the century progresses in regards to hot days, especially under the high scenario. Table 6 also captures a broadening of the distribution shifting toward marked increases. For example in the Southeast, by the end of the century under the high scenario, 86 percent of the land is projected to experience at least an 80-day increase in hot days; this trend is even more extreme in the Midwest and Northeast regions, which all show the potential for more than 50 percent of their landscapes to exceed the 100-day increase threshold. These projected changes are not expected to be consistent across or within regions as evident by the change maps (Figure 7). Locations associated with high elevation (i.e., the Rocky Mountains) may have the least change, while areas of lower latitudes could expect the greatest changes.

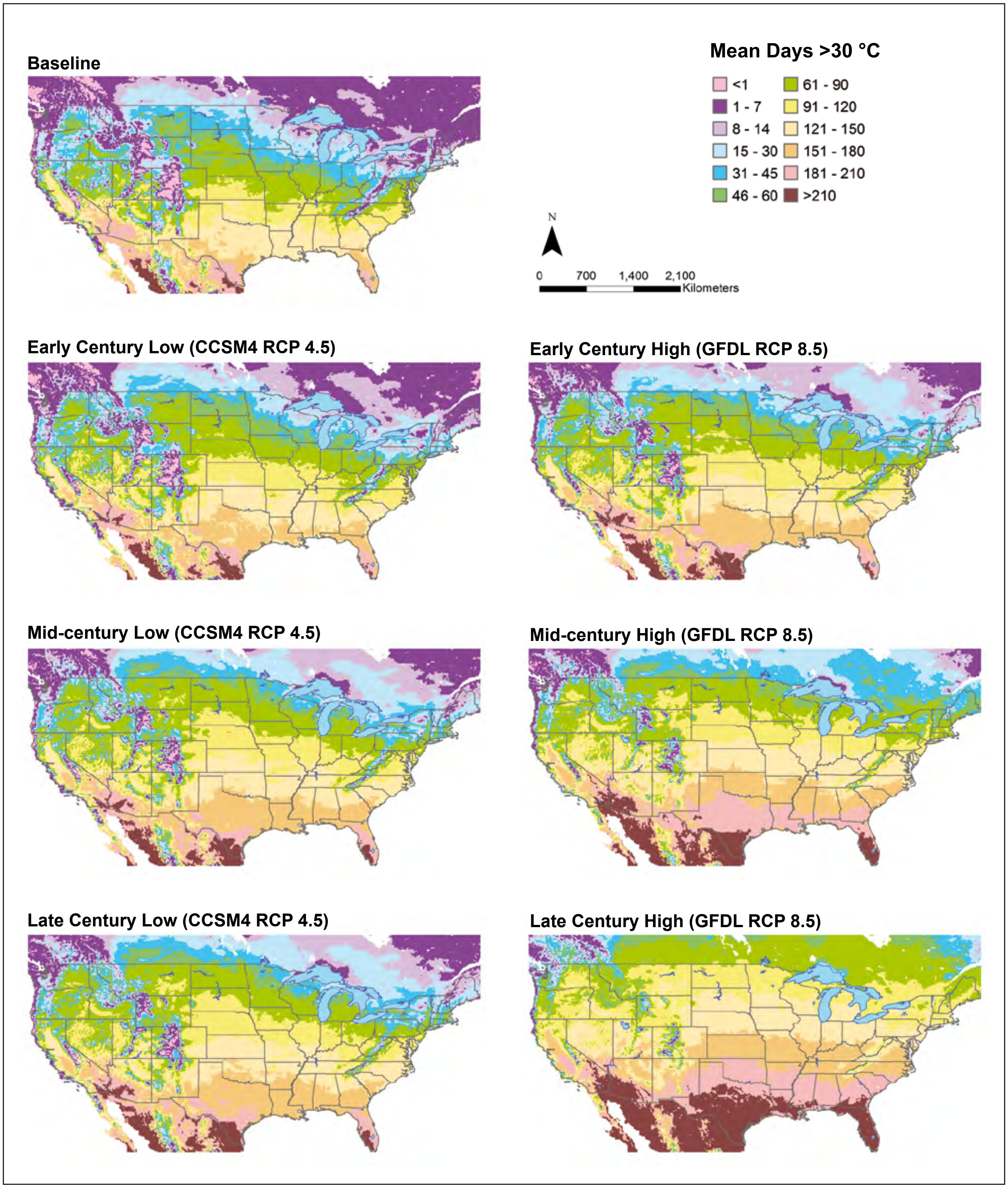


Figure 6.—Maps of baseline and projections of mean number of days per year with temperature above 30 °C (reflecting the heat zone metric) for conterminous United States by 30-year time period using a low (RCP 4.5; see text for explanation) or high (RCP 8.5; see text for explanation) climate scenario. While 30 °C does not represent a species-specific physiological threshold, it is acknowledged that temperatures above this temperature exceed a general optimal threshold for photosynthesis for $C_3$ plants (Rennenberg et al. 2006). Time periods: baseline (1980–2009); early century (2010–2039); mid-century (2040–2069); late century (2070–2099).

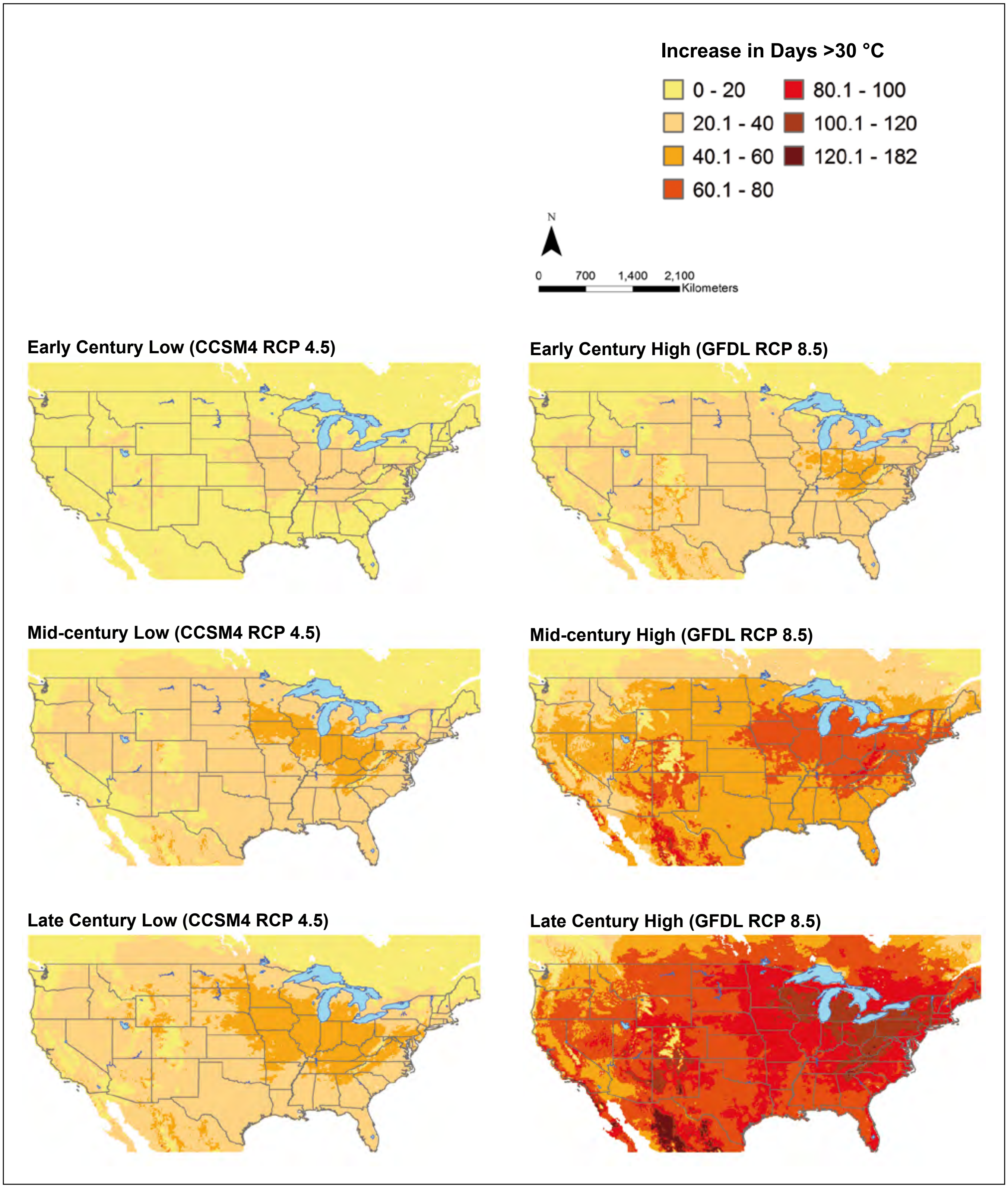


Figure 7.—Mapped projections of changes in number of days per year with temperature above 30 °C for conterminous United States by 30-year time period and climate scenario. Heat zones are projected to expand everywhere, but particularly in the Midwest, parts of the Northeast, and the Rocky Mountains by the end of the century, especially under the high climate scenario. Time periods: early century (2010–2039); mid-century (2040–2069); late century (2070–2099).

Table 5. The mean number of days above 30 °C (heat zone metric) by region for baseline (1980–2009), early (2010–2039), mid (2040–2069), and late century (2070–2099) climate conditions. Data are presented separately for low (CCSM4 RCP 4.5) and high (GFDL CM3 RCP 8.5) scenarios.

| | Heat Zone | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Low Scenario | | | | High Scenario | | | |
| | Baseline | Early Century | Mid-century | Late Century | Baseline | Early Century | Mid-century | Late Century |
| Midwest | 40 | 59 | 78 | 82 | 36 | 69 | 99 | 131 |
| Northeast | 17 | 29 | 43 | 46 | 18 | 42 | 78 | 114 |
| Northern Plains | 38 | 54 | 69 | 73 | 34 | 58 | 80 | 108 |
| Northwest | 24 | 36 | 45 | 49 | 25 | 40 | 58 | 81 |
| Southeast | 106 | 124 | 138 | 143 | 102 | 133 | 160 | 186 |
| Southern Plains | 128 | 142 | 154 | 160 | 123 | 152 | 175 | 200 |
| Southwest | 73 | 87 | 96 | 100 | 73 | 97 | 121 | 145 |

Table 6. The projected increase in days with temperatures above 30 °C is presented as a percentage of land area within each region, by time period. For instance, 31.2 percent of the land area in the Midwest is projected to have 30 additional days with temperatures above 30 °C during the early century under the high scenario, and during mid-century 39.7 percent of the Midwest land area is projected to have 60 more days with temperature above 30 °C. Data are presented separately for low (CCSM4 RCP 4.5) and high (GFDL CM3 RCP 8.5) scenarios.

| | Midwest | | | Northeast | | | Southeast | | | Northern Plains | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Change | Early Century | Mid-century | Late Century | Early Century | Mid-century | Late Century | Early Century | Mid-century | Late Century | Early Century | Mid-century | Late Century |
| **Heat Zone (Low)** | | | | | | | | | | | | |
| 0 | 1.8 | 0.3 | 0.2 | 16.2 | 2.5 | 1.5 | 0.4 | 0.2 | 0.1 | 9.0 | 4.1 | 3.2 |
| 10 | 17.3 | 1.1 | 0.6 | 43.7 | 16.4 | 15.3 | 32.8 | 0.4 | 0.2 | 15.1 | 4.2 | 3.5 |
| 20 | 74.0 | 3.7 | 2.9 | 36.8 | 22.7 | 19.1 | 60.3 | 10.2 | 1.2 | 75.8 | 6.1 | 4.5 |
| 30 | 6.9 | 16.6 | 9.5 | 3.3 | 29.2 | 24.7 | 6.5 | 64.6 | 50.4 | 0 | 53.0 | 12.4 |
| 40 | 0 | 69.8 | 39.8 | 0 | 23.5 | 28.5 | 0 | 18.6 | 34.4 | 0 | 32.6 | 74.9 |
| 50 | 0 | 8.6 | 46.9 | 0 | 5.6 | 10.8 | 0 | 6.0 | 12.1 | 0 | 0 | 1.4 |
| 60 | 0 | 0 | 0.1 | 0 | 0 | 0.1 | 0 | 0 | 1.6 | 0 | 0 | 0 |
| 70 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 80 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 90 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Heat Zone (High)** | | | | | | | | | | | | |
| 0 | 0.4 | 0 | 0 | 2.1 | 0 | 0 | 0.2 | 0 | 0 | 5.3 | 1.6 | 0.1 |
| 10 | 2.4 | 0.2 | 0 | 20.6 | 0.2 | 0 | 0.4 | 0 | 0 | 8.2 | 2.4 | 0.3 |
| 20 | 15.0 | 0.1 | 0 | 24.2 | 1.3 | 0 | 19.8 | 0.1 | 0 | 27.9 | 3.1 | 0.5 |
| 30 | 31.2 | 0.7 | 0 | 31.0 | 4.7 | 0 | 58.1 | 0.1 | 0 | 54.9 | 5.1 | 0.8 |
| 40 | 51.0 | 3.7 | 0.1 | 18.9 | 10.0 | 0.2 | 20.4 | 0.3 | 0 | 3.7 | 22.9 | 1.5 |
| 50 | 0.1 | 13.2 | 0.1 | 3.2 | 12.3 | 0.2 | 1.1 | 49.0 | 0 | 0 | 46.9 | 3.3 |
| 60 | 0 | 39.7 | 0.1 | 0 | 20.4 | 1.1 | 0 | 34.7 | 0 | 0 | 17.9 | 6.7 |
| 70 | 0 | 34.9 | 0.4 | 0 | 37.9 | 4.0 | 0 | 11.0 | 13.7 | 0 | 0.1 | 37.9 |
| 80 | 0 | 7.3 | 10.5 | 0 | 12.9 | 9.4 | 0 | 4.7 | 54.6 | 0 | 0 | 36.5 |
| 90 | 0 | 0 | 34.2 | 0 | 0.2 | 20.4 | 0 | 0.1 | 19.2 | 0 | 0 | 12.3 |
| 100 | 0 | 0 | 49.2 | 0 | 0 | 41.0 | 0 | 0 | 7.2 | 0 | 0 | 0 |
| 110 | 0 | 0 | 5.3 | 0 | 0 | 21.3 | 0 | 0 | 3.6 | 0 | 0 | 0 |
| 120 | 0 | 0 | 0 | 0 | 0 | 2.3 | 0 | 0 | 1.7 | 0 | 0 | 0 |
| 130 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 140 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 6 (continued).

| Change | Southern Plains Early Century | Southern Plains Mid-century | Southern Plains Late Century | Northwest Early Century | Northwest Mid-century | Northwest Late Century | Southwest Early Century | Southwest Mid-century | Southwest Late Century |
|---|---|---|---|---|---|---|---|---|---|
| **Heat Zone (Low)** | | | | | | | | | |
| 0 | 0 | 0 | 0 | 23.6 | 11.9 | 9.4 | 10.7 | 7.3 | 6.6 |
| 10 | 68.2 | 0.1 | 0 | 37.4 | 14.3 | 11.2 | 36.4 | 8.1 | 3.3 |
| 20 | 31.8 | 41.4 | 2.4 | 39.0 | 29.3 | 14.4 | 52.9 | 38.0 | 21.2 |
| 30 | 0 | 56.6 | 77.4 | 0 | 43.6 | 47.1 | 0 | 40.4 | 46.6 |
| 40 | 0 | 2.0 | 20.2 | 0 | 0.9 | 17.9 | 0 | 6.2 | 22.4 |
| 50 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 |
| 60 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 70 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 80 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 90 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Heat Zone (High)** | | | | | | | | | |
| 0 | 0 | 0 | 0 | 13.3 | 7.1 | 1.8 | 6.5 | 2.7 | 0.8 |
| 10 | 0 | 0 | 0 | 26.5 | 6.6 | 3.4 | 3.7 | 1.9 | 0.7 |
| 20 | 12.2 | 0 | 0 | 51.7 | 8.9 | 3.2 | 42.1 | 1.5 | 0.5 |
| 30 | 85.7 | 0.1 | 0 | 8.5 | 15.0 | 2.9 | 34.3 | 8.8 | 0.6 |
| 40 | 2.1 | 4.1 | 0 | 0 | 49.3 | 4.4 | 13.3 | 24.8 | 0.8 |
| 50 | 0 | 69.8 | 0.1 | 0 | 13.1 | 11.3 | 0 | 30.9 | 8.8 |
| 60 | 0 | 25.6 | 1.8 | 0 | 0 | 50.3 | 0 | 17.0 | 23.0 |
| 70 | 0 | 0.3 | 39.3 | 0 | 0 | 19.1 | 0 | 8.3 | 25.0 |
| 80 | 0 | 0.1 | 53.3 | 0 | 0 | 3.5 | 0 | 4.0 | 17.5 |
| 90 | 0 | 0 | 5.2 | 0 | 0 | 0 | 0 | 0.1 | 10.1 |
| 100 | 0 | 0 | 0.2 | 0 | 0 | 0 | 0 | 0 | 6.6 |
| 110 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 | 4.2 |
| 120 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.3 |
| 130 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 |
| 140 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

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## Cumulative drought severity index

Cumulative drought severity index (CDSI) is a weighted value derived from the occurrence and intensity of monthly drought events, where the frequency of moderate (scPDSI -2 to -2.9), severe (scPDSI -3 to -3.9), and extreme (scPDSI ≤ -4) conditions were weighted 1, 2, or 3 times, respectively, and tallied for each year (Peters et al. 2014, 2015). The yearly CDSI values were then accumulated over each of the 30-year periods and mapped. The range of CDSI values for the 360 months in a 30-year period can range from 0 (no months with any drought) to 1080 (every month has an extreme drought, with a weighted score of 12 × 30 × 3 = 1080). The cumulative drought severity index (CDSI) is derived from monthly self-calibrated Palmer Drought Severity Index (scPDSI) values which used the baseline calibration period (1981–2010).

Each future 30-year interval is generally expected to experience more drought events compared to the baseline, according to the two scenarios used in this study (Figure 8). However, as precipitation patterns and temperatures change among the 30-year periods, new normal conditions will be established, influencing the calibration of scPDSI values. Additionally, due to the weighting of drought intensity, regions that generally experience few severe to extreme droughts could see CDSI values increase if many moderate droughts or a few more severe to extreme events are predicted to occur. Under both scenarios, some portions of the regions are predicted to experience fewer drought events or less intense ones than the baseline period (Figure 9); one example is the Southeast during the mid-century period (Table 7). However, most regions are projected to have more frequent or more intense droughts by end of century regardless of scenario (Table 7). Certainly, there are major differences between the low and high scenarios, especially by end of century (Figure 9). Across five of the seven regions (Midwest, Northeast, Southern Plains, Northwest, and Southwest), more than 45 percent of the area in each region is projected to have an increase of at least 700 CDSI under the high scenario (Table 7). These increases have the potential to place additional stress on vegetation leading to increased mortality (Clark et al. 2016).

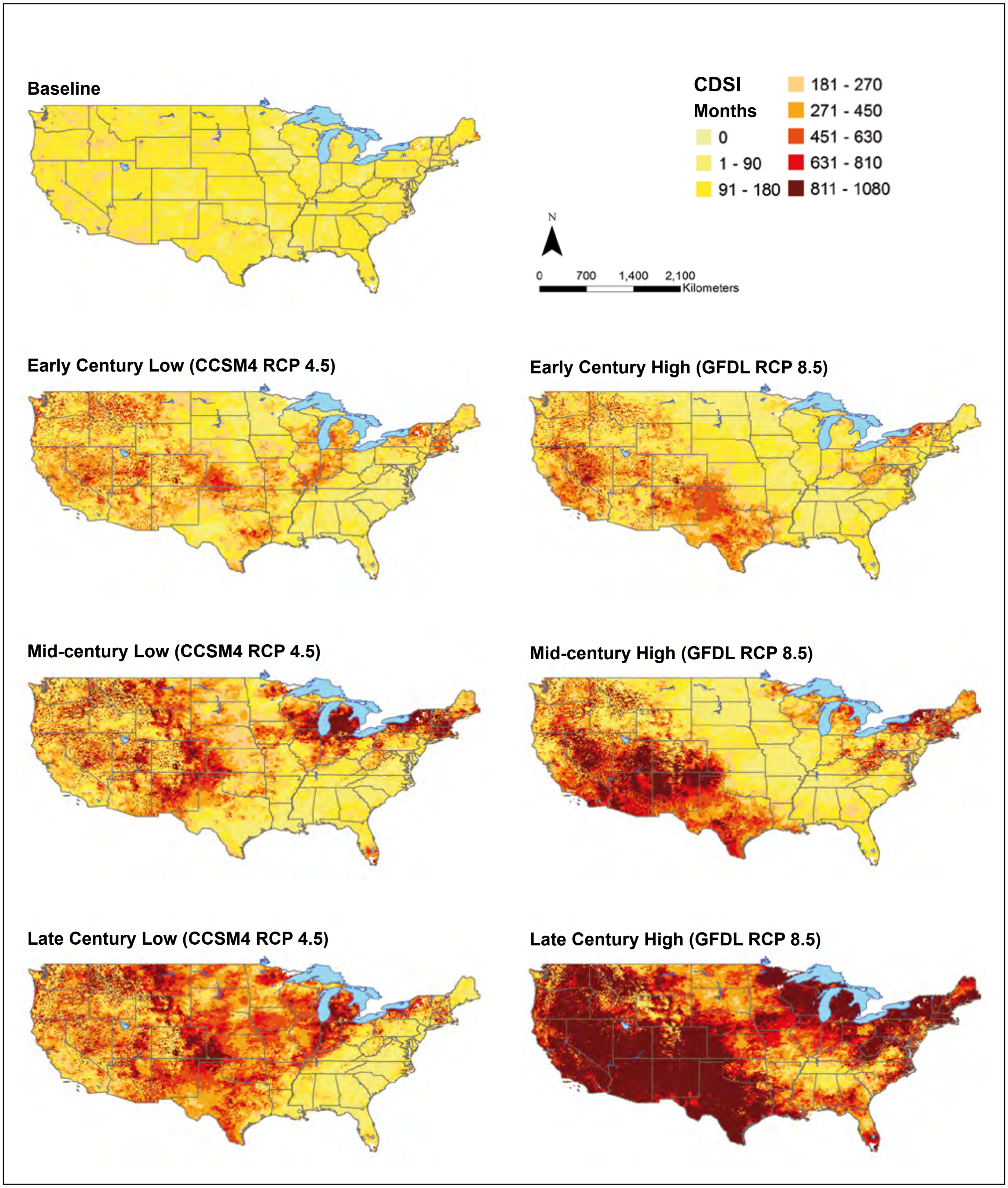


Figure 8.—Maps of baseline and projections of Cumulative Drought Severity Index (CDSI) for conterminous United States by 30-year time period using a low (RCP 4.5; see text for explanation) or high (RCP 8.5; see text for explanation) climate scenario. The yearly CDSI values were accumulated over each of the 30-year periods. The range of CDSI values for the 360 months in a 30-year period can range from 0 (no months with any drought) to 1080 (every month has an extreme drought). Time periods: baseline (1980–2009); early century (2010–2039); mid-century (2040–2069); late century (2070–2099).

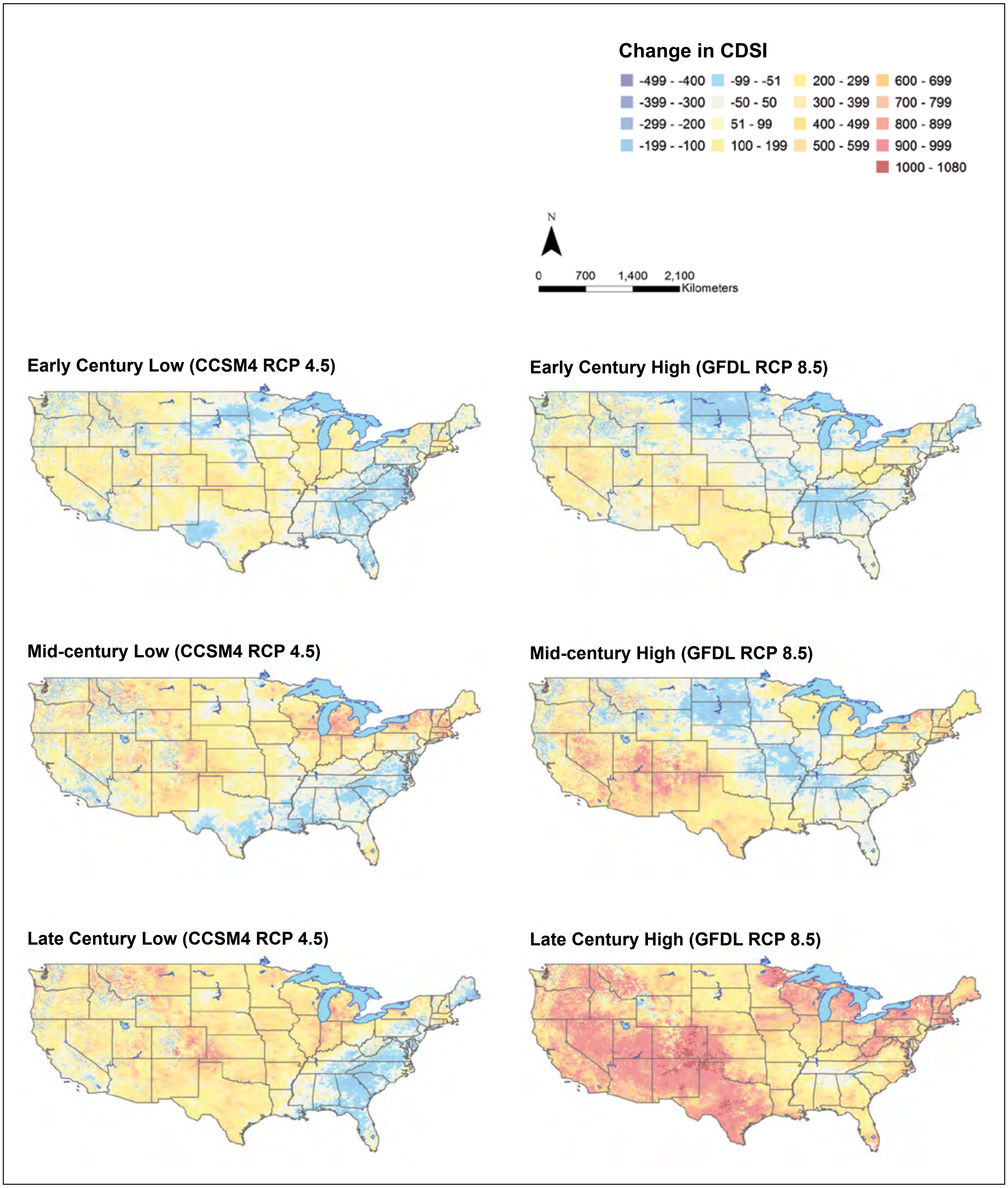


Figure 9.—Mapped projections of changes in CDSI for conterminous United States by 30-year time period and climate scenario. Each future 30-year interval is generally expected to experience more drought events (increased index score), according to the two scenarios used in this study. However, most regions could see more frequent or more intense droughts by end of century, regardless of scenario. More than 45 percent of the area in the Midwest, Northeast, Southern Plains, Northwest, and Southwest regions is projected to see an increase of at least 700 CDSI under the high scenario. Time periods: early century (2010–2039); mid-century (2040–2069); late century (2070–2099).

Table 7. The projected changes in CDSI are presented as a percentage of land area within each region, by time period. For instance, 1.7 percent of the land area in the Midwest is projected to experience an increase of 200 CDSI during the early century under the high scenario, and during the mid-century, 8.9 percent of the Midwest land area is projected to experience an increase of 200 CDSI. CDSI values represent the occurrence of drought conditions weighted by intensity during a 30-year period for each region; a positive change (increase) in CSDI values indicate an increase in droughty conditions. Data are presented separately for low (CCSM4 RCP 4.5) and high (GFDL CM3 RCP 8.5) scenarios.

| | Midwest | | | Northeast | | | Southeast | | | Northern Plains | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Change** | **Early Century** | **Mid-century** | **Late Century** | **Early Century** | **Mid-century** | **Late Century** | **Early Century** | **Mid-century** | **Late Century** | **Early Century** | **Mid-century** | **Late Century** |
| **CDSI (Low)** | | | | | | | | | | | | |
| -400 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 |
| -300 | 0.1 | 0 | 0 | 0.2 | 0 | 0.8 | 0.3 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| -200 | 1.0 | 0.1 | 0 | 5.9 | 1.1 | 6.1 | 9.7 | 6.5 | 10.8 | 5.2 | 1.8 | 0.9 |
| -100 | 8.7 | 1.2 | 0 | 15.9 | 3.2 | 14.5 | 27.5 | 24.1 | 28.9 | 13.8 | 2.2 | 1.2 |
| -50 | 31.5 | 17.2 | 3.5 | 40.2 | 18.0 | 37.0 | 46.0 | 54.2 | 34.5 | 37.6 | 12.0 | 4.7 |
| 50 | 14.1 | 11.4 | 3.5 | 10.1 | 10.0 | 7.5 | 6.9 | 7.1 | 6.7 | 13.7 | 13.4 | 5.0 |
| 100 | 22.5 | 18.1 | 13.1 | 11.0 | 16.1 | 9.7 | 5.8 | 4.4 | 7.0 | 14.7 | 25.3 | 13.7 |
| 200 | 12.8 | 13.1 | 15.5 | 6.9 | 11.2 | 7.4 | 2.5 | 1.9 | 4.6 | 6.5 | 15.8 | 16.1 |
| 300 | 6.9 | 9.4 | 16.3 | 5.1 | 7.8 | 5.4 | 1.0 | 1.0 | 3.7 | 3.5 | 10.8 | 17.8 |
| 400 | 2.4 | 7.8 | 21.1 | 2.9 | 6.2 | 4.1 | 0.2 | 0.4 | 2.0 | 2.2 | 7.1 | 14.8 |
| 500 | 0.1 | 6.0 | 13.0 | 0.9 | 5.4 | 3.2 | 0.1 | 0.2 | 0.9 | 1.5 | 4.4 | 10.3 |
| 600 | 0 | 5.0 | 6.7 | 0.7 | 5.4 | 2.0 | 0 | 0.1 | 0.4 | 0.9 | 2.6 | 6.8 |
| 700 | 0 | 5.7 | 4.5 | 0.2 | 6.3 | 1.1 | 0 | 0 | 0.2 | 0.3 | 1.8 | 4.4 |
| 800 | 0 | 4.0 | 2.1 | 0.1 | 6.2 | 0.6 | 0 | 0 | 0.1 | 0 | 1.3 | 2.5 |
| 900 | 0 | 1.0 | 0.6 | 0 | 2.9 | 0.2 | 0 | 0 | 0 | 0 | 1.2 | 1.6 |
| 1000 | 0 | 0.1 | 0 | 0 | 0.2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1100 | 0 | 0.1 | 0 | 0 | 0.2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **CDSI (High)** | | | | | | | | | | | | |
| -400 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| -300 | 0.1 | 0.1 | 0 | 0.4 | 0.1 | 0 | 0 | 0 | 0 | 0.3 | 0.4 | 0.1 |
| -200 | 1.7 | 3.3 | 0 | 5.0 | 0.4 | 0.1 | 5.7 | 2.2 | 0.1 | 16.2 | 14.8 | 0.7 |
| -100 | 16.4 | 16.6 | 0 | 11.5 | 1.4 | 0 | 23.7 | 14.4 | 0.7 | 24.2 | 25.5 | 1.1 |
| -50 | 61.5 | 38.0 | 1.4 | 31.8 | 12.5 | 0.9 | 50.0 | 53.3 | 11.4 | 36.5 | 31.3 | 2.2 |
| 50 | 11.3 | 10.3 | 0.6 | 12.6 | 9.1 | 0.8 | 10.4 | 15.2 | 8.1 | 7.4 | 8.4 | 2.5 |
| 100 | 7.1 | 14.6 | 3.6 | 16.7 | 18.7 | 2.2 | 6.8 | 8.8 | 18.1 | 7.6 | 8.0 | 15.4 |
| 200 | 1.7 | 8.9 | 7.5 | 11.6 | 15.5 | 3.2 | 2.8 | 2.8 | 16.1 | 3.6 | 4.0 | 16.5 |
| 300 | 0.1 | 4.5 | 10.3 | 5.4 | 11.1 | 5.4 | 0.5 | 1.8 | 11.7 | 1.7 | 2.3 | 13.0 |
| 400 | 0.1 | 1.9 | 9.1 | 2.7 | 9.1 | 7.0 | 0.1 | 0.8 | 11.2 | 1.0 | 1.5 | 10.0 |
| 500 | 0 | 1.2 | 11.0 | 1.4 | 6.8 | 8.4 | 0 | 0.2 | 8.2 | 0.9 | 1.1 | 9.8 |
| 600 | 0 | 0.5 | 14.4 | 0.6 | 7.0 | 9.2 | 0 | 0.2 | 6.5 | 0.6 | 0.8 | 10.0 |
| 700 | 0 | 0.1 | 16.8 | 0.2 | 4.1 | 13.5 | 0 | 0.1 | 4.1 | 0.2 | 0.7 | 7.1 |
| 800 | 0 | 0 | 14.2 | 0.1 | 2.9 | 23.9 | 0 | 0.1 | 2.9 | 0 | 0.6 | 6.0 |
| 900 | 0 | 0 | 10.1 | 0 | 1.3 | 23.6 | 0 | 0.1 | 1.1 | 0 | 0.6 | 5.4 |
| 1000 | 0 | 0 | 1.1 | 0 | 0 | 1.9 | 0 | 0 | 0 | 0 | 0 | 0.2 |
| 1100 | 0 | 0 | 1.0 | 0 | 0 | 1.9 | 0 | 0 | 0 | 0 | 0 | 0.2 |

Table 7 (continued).

| Change | Southern Plains Early Century | Southern Plains Mid-century | Southern Plains Late Century | Northwest Early Century | Northwest Mid-century | Northwest Late Century | Southwest Early Century | Southwest Mid-century | Southwest Late Century |
|---|---|---|---|---|---|---|---|---|---|
| **CDSI (Low)** | | | | | | | | | |
| -400 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| -300 | 0 | 0 | 0 | 0.4 | 0.7 | 0.4 | 0 | 0.1 | 0 |
| -200 | 3.3 | 1.9 | 0 | 7.5 | 8.2 | 4.1 | 1.3 | 3.1 | 1.1 |
| -100 | 7.6 | 11.6 | 0 | 10.1 | 8.3 | 4 | 4.2 | 5.4 | 2.4 |
| -50 | 25.1 | 28.4 | 2 | 28.2 | 20.5 | 12.4 | 20.8 | 16.3 | 12.4 |
| 50 | 15.1 | 12.6 | 3.8 | 12.2 | 9.7 | 7.7 | 14.5 | 9.2 | 8.3 |
| 100 | 21.7 | 20.3 | 14.4 | 16.4 | 16.3 | 17.2 | 25.4 | 16.8 | 16.1 |
| 200 | 12.7 | 9.7 | 22.3 | 8.4 | 10.1 | 15 | 15.7 | 12.4 | 15.4 |
| 300 | 6.8 | 4.9 | 22.9 | 6.3 | 7.3 | 11.8 | 8.4 | 10.1 | 13.4 |
| 400 | 3.9 | 3.6 | 15.1 | 3.9 | 4.7 | 8.4 | 4.4 | 8.2 | 10.3 |
| 500 | 3.0 | 3.9 | 8.9 | 3.4 | 3.5 | 5.7 | 2.3 | 6.8 | 7.9 |
| 600 | 0.6 | 2.4 | 4.6 | 2.1 | 3.0 | 4 | 1.6 | 5.3 | 5.7 |
| 700 | 0.1 | 0.5 | 3.2 | 1.0 | 2.7 | 3.9 | 0.9 | 3.6 | 3.5 |
| 800 | 0 | 0.1 | 2.3 | 0 | 3.0 | 3.2 | 0.3 | 1.8 | 2.3 |
| 900 | 0 | 0 | 0.5 | 0 | 1.9 | 2 | 0 | 0.8 | 1.1 |
| 1000 | 0 | 0 | 0 | 0 | 0.1 | 0.1 | 0 | 0.1 | 0.1 |
| 1100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0.1 |
| **CDSI (High)** | | | | | | | | | |
| -400 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| -300 | 0 | 0 | 0 | 0.4 | 0.8 | 0.1 | 0 | 0.1 | 0 |
| -200 | 0.1 | 0.5 | 0 | 7.9 | 8.4 | 0.6 | 0.7 | 0.9 | 0 |
| -100 | 0.7 | 5.2 | 0 | 12.2 | 8.5 | 0.9 | 3.3 | 1.7 | 0.1 |
| -50 | 14.5 | 12.9 | 0.1 | 29.3 | 18.0 | 3.7 | 20.4 | 4.0 | 0.4 |
| 50 | 10.6 | 6.8 | 0.3 | 11.0 | 8.0 | 1.8 | 12.9 | 2.3 | 0.3 |
| 100 | 24.6 | 12.2 | 1.4 | 15.1 | 14.2 | 3.9 | 19.6 | 6.5 | 0.7 |
| 200 | 20.7 | 15.8 | 3.7 | 9.1 | 11.4 | 3.6 | 17.8 | 8.1 | 0.9 |
| 300 | 18.7 | 16.1 | 4.4 | 5.9 | 9.0 | 4.1 | 12.0 | 10.5 | 1.5 |
| 400 | 8.0 | 12.9 | 5.3 | 3.7 | 7.3 | 5.5 | 5.8 | 11.7 | 2.1 |
| 500 | 1.9 | 7.0 | 7.5 | 2.7 | 5.4 | 8.3 | 3.5 | 13.3 | 4.1 |
| 600 | 0.2 | 4.8 | 8.2 | 2.0 | 3.4 | 11.4 | 2.2 | 11.8 | 7.4 |
| 700 | 0 | 3.8 | 10.3 | 0.9 | 2.5 | 13.7 | 1.4 | 10.9 | 12.7 |
| 800 | 0 | 1.8 | 21.6 | 0 | 2.0 | 22.9 | 0.5 | 11.1 | 24.3 |
| 900 | 0 | 0.2 | 33.7 | 0 | 1.1 | 19.3 | 0.1 | 6.9 | 41.6 |
| 1000 | 0 | 0 | 3.7 | 0 | 0 | 0.4 | 0 | 0.2 | 3.9 |
| 1100 | 0 | 0 | 3.5 | 0 | 0 | 0.3 | 0 | 0.2 | 3.8 |

## Conclusions

The maps depict the potential for a changing climate across the conterminous United States by the end of the century. The magnitude of these shifts is strongly influenced by the emissions pathways evaluated, and thus the decisions of the world's policy makers and citizens with regard to its energy future. The combination of climate conditions showing a widening of the range of conditions within each region and a directional shift toward increases in each of the metrics under the higher emissions scenario represents a clear picture of the multifaceted way global climate change can perturb our climate as well as ecological, social, and economic systems. Individually, each of these variables has the potential to influence and reshape competitive interactions of species. Collectively, they further indicate the potential for novel conditions likely to emerge across all regions. Understanding these potential patterns as well as advancing our understanding of how species respond to climate and other global change pressures will be essential to plan for resilience and adaptation in our forests and other aspects of biological conservation and society as a whole.

## Literature Cited


Allen, C.D.; Breshears, D.D.; McDowell, N.G. 2015. **On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene.** Ecosphere. 6(8): art129. https://doi.org/10.1890/ES15-00203.1.

Cathey, H.M. 1990. **USDA plant hardiness zone map.** Misc. Publ. 1475. Washington, DC: U.S. Department of Agriculture, Agriculture Research Service. 20 p. https://archive.org/details/usdaplanthardine1475unit (accessed Jan. 8, 2018).

Cathey, H. M. 1997. **Plant heat zone map.** American Horticultural Society. http://ahsgardening.org/gardening-resources/gardening-maps/heat-zone-map (accessed Oct. 11, 2017).

Clark, J.S.; Iverson, L.; Woodall, C.W.; Allen, C.D.; Bell, D.M. [et al.]. 2016. **The impacts of increasing drought on forest dynamics, structure, and biodiversity in the United States.** Global Change Biology 22(7): 2329-2352. https://doi.org/10.1111/gcb.13160.

Daly, C.; Halbleib, M.; Smith, J.I.; Gibson, W.P.; Doggett, M.K. [et al.]. 2008. **Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States.** International Journal of Climatology. 28(15): 2031-2064. https://doi.org/10.1002/joc.1688.

Daly, C.; Widrlechner, M.P.; Halbleib, M.D.; Smith, J.I.; Gibson, W.P. 2012. **Development of a new USDA plant hardiness zone map for the United States.** Journal of Applied Meteorology and Climatology. 51(2): 242-264. https://doi.org/10.1175/2010JAMC2536.1.

Donner, L.J.; Wyman, B.L., Hemler, R.S.; Horowitz, L.W.; Ming, Y. [et al.]. 2011. **The dynamical core, physical parameterizations, and basic simulation characteristics of the atmospheric component AM3 of the GFDL Global Coupled Model CM3.** Journal of Climate. 24(13): 3484-3519. https://doi.org/10.1175/2011JCLI3955.1.

Gent, P.R.; Danabasoglu, G.; Donner, L.J.; Holland, M.M.; Hunke, E.C. [et al.]. 2011. **The community climate system model version 4.** Journal of Climate. 24(19): 4973-4991. https://doi.org/10.1175/2011JCLI4083.1.

Franklin, J.; Davis, F.W.; Ikegami, M.; Syphard, A.D.; Flint, L.E. [et al.]. 2013. **Modeling plant species distributions under future climates: how fine scale do climate projections need to be?** Global Change Biology. 19(2): 473-483. https://doi.org/10.1111/gcb.12051.

Le Quéré, C.; Peters, G.P.; Andres, R.J.; Andrew, R.M.; Boden, T.A. [et al.]. 2014. **Global carbon budget 2013.** Earth System Science Data. 6: 235-263. https://doi.org/10.5194/essd-6-235-2014.

Melillo, J.M.; Richmond, T.C.; Yohe, G.W., eds. 2014. **Climate change impacts in the United States: the third National Climate Assessment.** Washington, DC: U.S. Global Change Research Program. 841 p. https://doi.org/10.7930/J0Z31WJ2.

Maurer, E.P.; Brekke, L.; Pruitt, T.; Duffy, P.B. 2007. **Fine-resolution climate projections enhance regional climate change impact studies.** Eos. 88(47): 504. https://doi.org/10.1029/2007EO470006.

Maurer, E.P.; Hidalgo, H.G. 2008. **Utility of daily vs. monthly large-scale climate data: an intercomparison of two statistical downscaling methods.** Hydrology and Earth System Sciences. 12: 551-563. https://doi.org/10.5194/hess-12-551-2008.

Moss, R. H.; Babiker, M.; Brinkman, S.; Calvo, E.; Carter, T. [et al.]. 2008. **Towards new scenarios for analysis of emissions, climate change, impacts, and response strategies.** Technical summary. Geneva, Switzerland: Intergovernmental Panel on Climate Change. 25 p. https://www.ipcc.ch/pdf/supporting-material/expert-meeting-ts-scenarios.pdf (accessed Oct. 11, 2017).

Natural Resources Conservation Service [NRCS]. 2016. **Gridded soil survey geographic (gSSURGO) database for conterminous United States.** Washington, DC: U.S. Department of Agriculture, Natural Resources Conservation Service. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcs142p2_053628 (accessed Jan. 8, 2018).

Pal, J.S.; Eltahir, E.A.B. 2015. **Future temperature in southwest Asia projected to exceed a threshold for human adaptability.** Nature Climate Change. 6: 197-200. https://doi.org/10.1038/nclimate2833.

Peters, G.P.; Andrew, R.M.; Boden, T.; Canadell, J.G.; Ciais, P. [et al.]. 2013. **The challenge to keep global warming below 2 °C.** Nature Climate Change. 3(1): 4-6. https://doi.org/10.1038/nclimate1783.

Peters, M.P.; Iverson, L.R.; Matthews, S.N. 2014. **Spatio-temporal trends of drought by forest type in the conterminous United States, 1960-2013.** Res. Map NRS-7. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. [scale: 1:12,000,000]. https://doi.org/10.2737/NRS-RMAP-7.

Peters, M.P.; Iverson, L.R.; Matthews, S.N. 2015. **Long-term droughtiness and drought tolerance of eastern US forests over five decades.** Forest Ecology and Management. 345: 56-64. https://doi.org/10.1016/j.foreco.2015.02.022.

Rehfeldt, G.E.; Crookston, N.L.; Warwell, M.V.; Evans, J.S. 2006. **Empirical analyses of plant-climate relationships for the western United States.** International Journal of Plant Sciences. 167(6): 1123-1150.

Rennenberg, H.; Loreto, F.; Polle, A.; Brilli, F.; Fares, S. [et al.]. 2006. **Physiological responses of forest trees to heat and drought.** Plant Biology. 8: 556-571. https://doi.org/10.1055/s-2006-924084.

Sork, V.L.; Davis, F.W.; Westfall, R.; Flint, A.; Ikegami, M. [et al.]. 2010. **Gene movement and genetic association with regional climate gradients in California valley oak (*Quercus lobata* Née) in the face of climate change.** Molecular Ecology. 19: 3806-3823. https://doi.org/10.1111/j.1365-294X.2010.04726.x.

Thrasher, B.; Xiong, J.; Wang, W.; Melton, F.; Michaelis, A.; Nemani, R. 2013. **Downscaled climate projections suitable for resource management. Eos.** 94(37): 321-323. https://doi.org/10.1002/2013EO370002.

U.S. Global Change Research Program. 2017. **Climate science special report: fourth national climate assessment, volume I.** Washington, DC: U.S. Global Change Research Program: 470 p. https://doi.org/10.7930/J0J964J6.

van Vuuren, D.P.; Edmonds, J.; Kainuma, M.; Riahi, K.; Thomson, A. [et al.]. 2011. **The representative concentration pathways: an overview.** Climatic Change. 109(1): 5-31. https://doi.org/10.1007/s10584-011-0148-z.

Wells, N.; Goddard, S.; Hayes, M.J. 2004. **A self-calibrating Palmer Drought Severity Index.** Journal of Climate. 17(12): 2335-2351. https://doi.org/10.1175/1520-0442(2004)017<2335:ASPDSI>2.0.CO;2.

Wood, A.W.; Leung L.R.; Sridhar, V.; Lettenmaier, D.P. 2004. **Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs.** Climatic Change. 62(1-3): 189-216. https://doi.org/10.1023/B%3ACLIM.0000013685.99609.9e.

Wood, A.W.; Maurer, E.P.; Kumar, A.; Lettenmaier, D.P. 2002: **Long-range experimental hydrologic forecasting for the eastern United States.** Journal of Geophysical Research. 107(D29): 4429. https://doi.org/10.1029/2001JD000659.

Yan, H.; Wang, S.-Q.; Lu, H.-Q.; Yu, Q.; Zhu, Z.-C. [et al.]. 2014. **Development of a remotely sensing seasonal vegetation-based Palmer Drought Severity Index and its application of global drought monitoring over 1982–2011.** Journal of Geophysical Research: Atmospheres. 119(15): 9419-9440. https://doi.org/10.1002/2014JD021673.

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Matthews, Stephen N.; Iverson, Louis R.; Peters, Matthew P.; Prasad, Anantha M. 2018. **Assessing potential climate change pressures across the conterminous United States: mapping plant hardiness zones, heat zones, growing degree days, and cumulative drought severity throughout this century.** RMAP-NRS-9. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 31 p. https://doi.org/10.2737/NRS-RMAP-9.

The maps and tables presented here represent potential variability of projected climate change across the conterminous United States during three 30-year periods in this century and emphasizes the importance of evaluating multiple signals of change across large spatial domains. Maps of growing degree days, plant hardiness zones, heat zones, and cumulative drought severity depict the potential for markedly shifting conditions and highlight regions where changes may be multifaceted across these metrics. In addition to the maps, the potential change in these climate variables are summarized in tables according to the seven regions of the fourth National Climate Assessment to provide additional regional context. Viewing these data collectively further emphasizes the potential for novel climatic space under future projections of climate change and signals the wide disparity in these conditions based on relatively near-term human decisions of curtailing (or not) greenhouse gas emissions.

KEY WORDS: climate change indices, regional change, novel climate conditions

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