Future Climate Projections
Polk County, Oregon

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Oregon Climate Change Research Institute
Future Climate Projections: Polk County, Oregon

Meghan Dalton, Erica Fleishman, Dominique Bachelet, and David Rupp
Oregon Climate Change Research Institute
College of Earth, Ocean, and Atmospheric Sciences
104 CEOAS Administration Building
Oregon State University
Corvallis, OR 97331

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Cover Photograph: The Willamette River at Independence, Polk County, Oregon
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Executive Summary

Climate change is expected to increase the occurrence of many climate-related natural hazards and to increase climate-related risks to assets, such as people, buildings, and other infrastructure. Confidence that the risk of heat waves will increase is very high (Table 1) given strong evidence in the peer-reviewed literature, consistency among the projections of different global climate models, and robust scientific principles that explain why temperatures increase in response to ongoing emissions of greenhouse gases. In areas where the human population is growing, and especially where it is aging, both the absolute number and the proportion of people at risk of negative health outcomes from heat exposure is increasing. Confidence that the risk of many other natural hazards will increase as climate changes is high or medium (Table 1), reflecting moderate to strong evidence and consistency among models. The latter risks are influenced by multiple factors in addition to increasing temperatures. Confidence that the risk of windstorms will change is low given that projections suggest relatively few to no changes and evidence is limited.

Table 1. Projected direction and level of confidence in changes in the risks of climate-related natural hazards and associated risks to assets. Very high confidence means that the direction of change is consistent among nearly all global climate models and there is robust evidence in the peer-reviewed literature. High confidence means that the direction of change is consistent among more than half of models and there is moderate to robust evidence in the peer-reviewed literature. Medium confidence means that the direction of change is consistent among more than half of models and there is moderate evidence in the peer-reviewed literature. Low confidence means that the direction of change is small compared to the range of model responses or there is limited evidence in the peer-reviewed literature.

<table>
<thead>
<tr>
<th>Low Confidence</th>
<th>Medium Confidence</th>
<th>High Confidence</th>
<th>Very High Confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Risk Increasing</td>
<td>Drought</td>
<td>Heavy Precipitation</td>
<td>Heat Waves</td>
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<tr>
<td></td>
<td>Expansion of Non-native Invasive Species</td>
<td>Flooding</td>
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<td>Reduced Air Quality</td>
<td>Wildfire</td>
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<td></td>
<td>Loss of Wetlands</td>
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<tr>
<td>Risk Unchanging</td>
<td>Windstorms</td>
<td></td>
<td></td>
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<tr>
<td>Risk Decreasing</td>
<td></td>
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<td>Cold Waves</td>
</tr>
</tbody>
</table>
In this report, we present future climate projections for Polk County relevant to specified natural hazards for the 2020s (2010–2039) and 2050s (2040–2069) relative to the 1971–2000 historical baseline. We present projections that are based on multiple global climate models for both a lower greenhouse gas emissions scenario (RCP 4.5) and a higher emissions scenario (RCP 8.5). Unless otherwise noted, all projections in this executive summary refer to the 2050s, relative to the historical baseline, under the higher emissions scenario. Projections for both time periods and emissions scenarios, and potential consequences for assets given current demographic data and projected population trends, are included in the main report.

**Heat Waves**
The number, duration, and intensity of extreme heat events will increase as temperatures continue to warm. In Polk County, the number of extremely hot days (those on which the temperature is 90°F or higher) and the temperature on the hottest day of the year are projected to increase by the 2020s and 2050s under both the lower and higher emissions scenarios. The number of days per year with temperatures 90°F or higher is projected to increase by an average of 17 (range 6–30) by the 2050s, relative to the 1971–2000 historical baselines, under the higher emissions scenario. The temperature on the hottest day of the year is projected to increase by an average of about 6°F (range 1–9°F) by the 2050s. Projected demographic changes in Polk County, such as an increase in the proportion of older adults and the absolute number of children, will increase the number of people in some of the populations that are vulnerable to extreme heat.

**Cold Waves**
Cold extremes will become less frequent and intense as the climate warms. The number of cold days (maximum temperature 32°F or lower) per year in Polk County is projected to decrease by an average of 1 (range -1.4–0.3). The temperature on the coldest night of the year is projected to increase by an average of 5°F (range 0–10°F). The number of county residents vulnerable to extreme cold is likely to grow, although this increase may be offset somewhat by the decrease in incidence of cold extremes.

**Heavy Precipitation**
The intensity of extreme precipitation is expected to increase as the atmosphere warms and holds more water vapor. In Polk County, the number of days per year with at least 0.75 inches of precipitation is not projected to change substantially. Nevertheless, the amount of precipitation on the wettest day and wettest consecutive five days per year is projected to increase by an average of 14% (range 2–33%) and 11% (range 2–22%), respectively. The number of days per year that exceed a threshold for landslide risk, which is based on prior 18-day precipitation accumulation, is not projected to change substantially. However, landslide risk depends on multiple factors, and this metric does not reflect all aspects of the hazard.
River Flooding
Winter flood risk at mid- to low elevations in Polk County, where temperatures are near freezing during winter and precipitation is a mix of rain and snow, is projected to increase as winter temperatures increase. The temperature increase will lead to an increase in the percentage of precipitation falling as rain rather than snow.

Drought
Drought, as represented by low summer soil moisture, low spring snowpack, low summer runoff, and low summer precipitation, is projected to become more frequent in Polk County. The incidence of related negative physical and mental health outcomes, especially among low income, tribal, rural, and agricultural communities, is likely to increase.

Wildfire
Wildfire frequency, intensity, and area burned are projected to continue increasing in the Northwest. Wildfire risk, expressed as the average number of days per year on which fire danger is very high, is projected to increase in Polk County by 11 days (range -7–28). The average number of days per year on which vapor pressure deficit is extreme is projected to increase by 25 (range 8–42).

Reduction Air Quality
Climate change is expected to reduce outdoor air quality. The risks to human health from wildfire smoke in Polk County are projected to increase. Although the number of days per year on which the concentration of wildfire-derived fine particulate matter results in poor air quality is projected to decrease by 10%, the concentration of fine particulate matter is projected to increase by 162% from 2004–2009 to 2046–2051 under a moderate emissions scenario.

Loss of Wetlands
Losses of wetlands in Polk County in recent decades largely were caused by their conversion to agriculture. Projected effects of climate change on wetlands in the Northwest include reductions in water levels and hydroperiod duration. If withdrawals of ground water do not increase, then wetlands that are fed by ground water rather than surface water may be more resilient to climate change.

Windstorms
Wind patterns affect provision of electricity, transportation safety, and the spread of wildfires and pollutants. Mean wind speeds in Oregon are projected to decrease slightly, but extreme winter wind speeds may increase, especially in western Oregon. The frequency of strong easterly winds during summer and autumn, however, is projected to decrease slightly.

Expansion of Non-native Invasive Species
Expansion of most of the non-native invasive species of aquatic animals that are high priorities in Polk County may become somewhat more likely as climate
changes. Nevertheless, many of these species tolerate a wide range of environmental conditions, and climate change may not be a primary driver of their distribution and abundance. In general, non-native invasive plants in Polk County are likely to become more prevalent in response to projected increases in temperature and the frequency, duration, and severity of drought. However, many of these responses are uncertain, are likely to vary locally, and may change over time.
Introduction

Industrialization has increased the amount of greenhouse gases emitted worldwide, which is causing Earth’s atmosphere, oceans, and lands to warm (IPCC, 2021). Climate change and its effects already are apparent in Oregon (Dalton et al., 2017; Mote et al., 2019; Dalton and Fleishman, 2021; Fleishman, 2023). Climate change is expected to increase the likelihood of natural hazards such as heavy precipitation, flooding of rivers and streams, drought, heat waves, wildfires, and episodes of poor air quality, and to decrease the likelihood of cold waves.

We analyzed the influence of climate change on natural hazards in Polk County, Oregon, and explored potential effects of those natural hazards on the county’s assets. Products of our analysis include county-specific data, graphics, and narrative summaries of climate projections related to ten climate-related natural hazards (Table 2). This information will be integrated into the county’s Natural Hazards Mitigation Plan and can be used in other county plans, policies, and programs.

Table 2. Selected natural hazards and related climate metrics.

<table>
<thead>
<tr>
<th>Heat Waves</th>
<th>Cold Waves</th>
<th>River Flooding</th>
<th>Wildfire</th>
<th>Reduced Air Quality</th>
<th>Loss of Wetlands</th>
<th>Expansion of Non-native Invasive Species</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot Days, Warm Nights</td>
<td>Cold Days, Cold Nights</td>
<td>Atmospheric Rivers</td>
<td>Extremely Dry Air Days</td>
<td>Levels</td>
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<tr>
<td>Heavy Precipitation</td>
<td></td>
<td>Rain-on-Snow Events</td>
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<tr>
<td>Wettest Day, Wettest Five Days</td>
<td>Wet Days, Landslide Risk Days</td>
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<td>Drought</td>
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<tr>
<td>Summer Flow, Spring Snow</td>
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<tr>
<td>Summer Soil Moisture</td>
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<tr>
<td>Summer Precipitation</td>
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<tr>
<td>Reduced Air Quality</td>
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<tr>
<td>Days with Unhealthy Smoke</td>
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<tr>
<td>Levels</td>
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<tr>
<td>Wildfire</td>
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<tr>
<td>Fire Danger Days</td>
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<tr>
<td>Extremely Dry Air Days</td>
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<tr>
<td>Reduced Air Quality</td>
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<tr>
<td>Days with Unhealthy Smoke</td>
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<td>Levels</td>
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<td>Loss of Wetlands</td>
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<tr>
<td>Expansion of Non-native Invasive Species</td>
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As of 2022, an estimated 90,600 people lived in Polk County (PRC, 2023a). The county’s population is projected to increase by 32% by 2040, and by another 59% (or 109% relative to 2022) by 2070 (PRC, 2023b). Social factors affect the probability that natural hazards will negatively affect individuals and communities. For example, inequities in housing, education, income, and transportation access affect how different populations respond to heat, drought, and other climate extremes (Ho et al., 2021). The U.S. Centers for Disease Control and Prevention developed and maintains a social vulnerability index for use in planning for and response to hazardous events (Flanagan et al., 2011; ATSDR, 2022). The index encompasses 16 variables, which are aggregated into four themes: socioeconomic
status, household characteristics, racial and ethnic minority status, and housing type and transportation. No variable value in Polk County (Table 3) was among the highest 10% relative to other counties in Oregon; higher values indicate higher vulnerability (ATSDR, 2022).

Table 3. Measures of social vulnerability in Polk County, Oregon, as estimated on the basis of the 2016–2020 American Community Survey (ATSDR, 2022). Housing cost burden is defined as an occupied housing unit with a household annual income below $75,000 and monthly housing costs that equal or exceed 30 percent of annual income. Single-parent households include one or more children under the age of 18. Racial and ethnic minority status includes individuals who identify as Hispanic, Latino (of any race), Black, African American, American Indian, Alaska Native, Asian, Native Hawaiian, Pacific Islander, two or more races, and other non-White races. Multiple-unit housing refers to housing structures with ten or more units. Crowded housing is defined as an occupied housing unit with more people than rooms. Number of households without a broadband internet subscription is not included in the calculation of the overall social vulnerability index. CI, confidence interval. Percentage, percentage of population or number. Percentages for some variables do not correspond exactly to raw values.

<table>
<thead>
<tr>
<th>Social vulnerability metric</th>
<th>Population or number</th>
<th>CI</th>
<th>Percentage</th>
<th>CI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total population</strong></td>
<td>84,730</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Number of housing units</strong></td>
<td>32,572</td>
<td>32,458–32,686</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Number of households</strong></td>
<td>30,726</td>
<td>30,265–31,187</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Socioeconomic status</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Below 150% poverty</td>
<td>15,874</td>
<td>14,390–17,358</td>
<td>19.2</td>
<td>17.4–21.0</td>
</tr>
<tr>
<td>Unemployed</td>
<td>2290</td>
<td>1822–2758</td>
<td>5.6</td>
<td>4.5–6.7</td>
</tr>
<tr>
<td>Number of cost-burdened housing units</td>
<td>8779</td>
<td>8062–9496</td>
<td>28.6</td>
<td>26.3–30.9</td>
</tr>
<tr>
<td>No high school diploma</td>
<td>4603</td>
<td>4015–5191</td>
<td>8.5</td>
<td>7.4–9.6</td>
</tr>
<tr>
<td>No health insurance</td>
<td>4700</td>
<td>3871–5529</td>
<td>5.6</td>
<td>4.6–6.6</td>
</tr>
<tr>
<td><strong>Household characteristics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aged 65 or older</td>
<td>15,121</td>
<td>15,038–15,204</td>
<td>17.8</td>
<td>17.7–17.9</td>
</tr>
<tr>
<td>Aged 17 or younger</td>
<td>19,150</td>
<td></td>
<td>22.6</td>
<td></td>
</tr>
<tr>
<td>Civilian with a disability</td>
<td>11,674</td>
<td>10,858–12,490</td>
<td>13.9</td>
<td>12.9–14.9</td>
</tr>
<tr>
<td>Single-parent household</td>
<td>1744</td>
<td>1360–2128</td>
<td>5.7</td>
<td>4.5–6.9</td>
</tr>
<tr>
<td>Speaks English less than well</td>
<td>1693</td>
<td>1265–2121</td>
<td>2.1</td>
<td>1.6–2.6</td>
</tr>
<tr>
<td><strong>Racial and ethnic minority status</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minority</td>
<td>19,026</td>
<td>17,542–20,510</td>
<td>22.5</td>
<td>20.7–24.3</td>
</tr>
<tr>
<td><strong>Housing type and transportation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of multiple-unit homes</td>
<td>2599</td>
<td>2166–3032</td>
<td>8</td>
<td>6.7–9.3</td>
</tr>
<tr>
<td>Number of mobile homes</td>
<td>2345</td>
<td>2001–2689</td>
<td>7.2</td>
<td>6.1–8.3</td>
</tr>
<tr>
<td>Number of crowded housing units</td>
<td>551</td>
<td>391–711</td>
<td>1.8</td>
<td>1.3–2.3</td>
</tr>
<tr>
<td>Number of households with no vehicle</td>
<td>1449</td>
<td>1157–1741</td>
<td>4.7</td>
<td>3.7–5.7</td>
</tr>
<tr>
<td>People in group quarters</td>
<td>1687</td>
<td>1391–1983</td>
<td>2.0</td>
<td>1.7–2.3</td>
</tr>
<tr>
<td>People in households without a broadband internet subscription</td>
<td>6562</td>
<td>5537–7587</td>
<td>7.9</td>
<td>6.5–9.0</td>
</tr>
</tbody>
</table>
Future Climate Projections Background

Introduction

The county-specific future climate projections presented here are derived from 10–20 global climate models and two scenarios of future global emissions of greenhouse gases. The spatial resolution of projections from global climate models has been increased to better represent local conditions. County-level summaries of changes in climate metrics (Table 2) are projected to the beginning and middle of the twenty-first century relative to a historical baseline. More information about the data sources is in the appendix.

Global Climate Models

Global climate models are computer models of Earth’s atmosphere, ocean, and land and their interactions over time and space. Climate models generally refer to both general circulation models (GCMs) and Earth system models (ESMs). GCMs simulate the dynamics of interactions between the atmosphere and the land and ocean, whereas ESMs also simulate more-detailed chemical and biological processes that interact with the physical climate. The models are grounded in the fundamental laws of physics and are the most sophisticated tools for understanding Earth’s climate. However, they still necessarily simplify the climate system. Because there are several ways to simplify climate in a global model, different climate models yield somewhat different projections. Accordingly, it is best practice to analyze and present an average and range of projections from at least ten global climate models.

Over time, the spatial resolution of GCMs has increased and more physical, chemical, and biological processes, such as wildfire emissions and dynamic vegetation change, have been included (Figure 1). The climate models from the sixth phase of the Coupled Model Intercomparison Project (CMIP6), the climate modeling foundation of the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), generally have higher resolution, better represent Earth system processes, and improve simulation of recent mean values of climate change indicators relative to climate models from fifth phase of the Coupled Model Intercomparison Project (CMIP5) (IPCC, 2021). However, some CMIP6 models overestimate observed temperatures in the twentieth century, likely because they yielded a greater increase in temperature in response to modeled changes in cloud patterns (Dalton et al., 2021; IPCC, 2021). The latter increase may not be realistic (Hausfather et al., 2022). Consequently, the IPCC ranked climate models on the basis of their ability to reproduce twentieth-century temperatures, and used only the most accurate models to project warming given different scenarios of fossil fuel emissions (Hausfather et al., 2022).
Figure 1. As scientific understanding of climate has evolved over the last 120 years, increasing amounts of physics, chemistry, and biology have been incorporated into global climate calculations. Over the second half of the twentieth century, as computing resources became available, such knowledge also was incorporated into global climate models. (Source: science2017.globalchange.gov)

Differences in simulations of Oregon’s projected average temperature between CMIP5 and CMIP6 were estimated in the fifth Oregon Climate Assessment (Dalton et al., 2021). The group of CMIP6 models generally projected greater warming over Oregon than the group of CMIP5 models. This outcome was due to the inclusion of several of the CMIP6 models that produce greater warming than most models given the same concentration of greenhouse gases.

One measure of climate sensitivity, the equilibrium climate sensitivity (ECS), is an estimate of the increase in global temperature after it stabilizes over hundreds to thousands of years following a doubling of carbon dioxide concentrations. On the basis of observations, paleoclimate data, and other evidence, the ECS of Earth was estimated to be within 2.5–4.0°C (4.5–7.2°F) (66 percent likelihood) or 2.0–5.0°C (3.6–9.0°F) (90 percent likelihood) (Forster et al., 2021). The scientific community typically evaluates climate model outputs on the basis of how close they are to this range of ECS. ECS in all CMIP5 models was less than 5°C (9°F), whereas about one-fifth of the CMIP6 models had an ECS above 5°C (Hausfather et al., 2022). Although there is a 5 percent likelihood that Earth’s ECS is above 5°C, the CMIP6 climate models with ECS >5°C overestimate the observed warming and therefore are considered less valid and reliable than those with ECS ≤5°C. Consequently, use of the average and range of the CMIP6 model ensemble likely will yield inaccurate projections of future climate (Hausfather et al., 2022).

It is best practice to analyze and present an average and range of projections from at least ten global climate models with realistic climate sensitivity that simulate the historical climate well (Mote et al., 2011; Hausfather et al., 2022; Dalton and Bachelet, 2023). In this report, we rely on projections from 10–20 CMIP5 models (see Appendix), all of which have realistic climate sensitivities and are still considered valid and useful in evaluating future climate (Dalton and Bachelet, 2023). Additionally, locally relevant, high-resolution projections from these models are readily available. It will be advantageous to consider CMIP6 climate projections after the scientific community has further evaluated the
projections and associated impacts and high-resolution projections become more widely available and vetted (Dalton and Bachelet, 2023).

**Greenhouse Gas Emissions**

When scientists use global climate models to project climate, they make assumptions about the future volume of global emissions of greenhouse gases. The models then simulate the effects of those emissions on the air, ocean, and land over the coming centuries. Because the precise amount of greenhouse gases that will be emitted in the future is unknown, scientists use multiple scenarios of greenhouse gas emissions that correspond to plausible societal trajectories.

The CMIP5 models used scenarios called Representative Concentration Pathways (RCPs), which describe concentrations of greenhouse gases, aerosols, and other factors through the year 2100. These concentrations affect the level of outgoing long-wave radiation from Earth’s surface, thus radiative forcing. Radiative forcing is the total amount of energy retained in the atmosphere after absorption of incoming solar radiation, which is affected by the reflectivity of Earth’s surface, and emission of outgoing long-wave radiation. The higher the volume of global emissions, the greater the radiative forcing and projected increase in global temperature (Figure 2).

![Figure 2. Future scenarios of atmospheric carbon dioxide concentrations (left) and projections of global temperature change (right) resulting from several different emissions scenarios, called Representative Concentration Pathways (RCPs), that were considered in the fourth National Climate Assessment. In the left plot, the gray line represents a scenario in which atmospheric carbon dioxide concentrations remain constant upon reaching 400 parts per million. In the right plot, the solid line and shading represent the mean and range of simulations from global climate models included in CMIP5. (Source: science2017.globalchange.gov)](image)

CMIP6 models used scenarios called Shared Socio-economic Pathways (SSPs). The SSPs reflect assumptions about future population, technological, and economic growth that were paired with the different levels of emissions associated with the CMIP5 RCPs (IPCC, 2021).
Projections in this report are based on both a lower emissions pathway (RCP 4.5) and a higher emissions pathway (RCP 8.5) that are often described as representing moderate reductions and business-as-usual increases in greenhouse gas emissions, respectively (Hayhoe et al., 2017). These two RCPs are the most common scenarios in the peer-reviewed literature, and high-resolution data representing the effects of these scenarios on local climate are available.

**Downscaling**

Global climate models simulate the climate across large, contiguous grid cells. One to three grid cells cover the state of Oregon. To make these coarse-resolution simulations more locally relevant, outputs are combined statistically with historical observations, yielding higher-resolution projections. This process is called statistical downscaling. The future climate projections in this report were statistically downscaled to a resolution of about 2.5 by 2.5 miles (Abatzoglou and Brown, 2012). More information about downscaling is in the appendix.

**Future Time Periods**

When analyzing global climate model projections, it is best practice to compare the average of simulations across at least 30 future years to the average of simulations across at least 30 recent past years. The average over those 30 past years is called the *historical baseline*. This report presents projections averaged over two future 30-year periods, 2010–2039 (2020s) and 2040–2069 (2050s), relative to the historical baseline from 1971–2000 (Table 4).

<table>
<thead>
<tr>
<th>Historical Baseline</th>
<th>2020s</th>
<th>2050s</th>
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</thead>
</table>

Because each of the 20 CMIP5 models from which we obtained projections is based on slightly different assumptions, each yields a slightly different value for the historical baseline. Therefore, we do not present the average and range of projected absolute values of variables. Instead, we present the average and range of projected changes in values of climate variables relative to each model's historical baseline. We also present the average of the 20 historical baselines to aid in understanding the relative magnitude of projected changes. The average projected change can be added to the average historical baseline to infer the average future value of a given variable. The average projected change and historical baseline are included in the tables.

**How to Use the Information in this Report**

Because the observational record may not include plausible future values of some climate variables or the plausible future frequency of some climate extremes, one cannot reliably
anticipate future climate by considering only past climate. Future projections from GCMs enable exploration of a range of plausible outcomes given the climate system’s complex response to increasing atmospheric concentrations of greenhouse gases. Projections from GCMs should not be interpreted as predictions of the weather on a given date, but rather as projections of climate, which is the long-term statistical aggregate of weather (Walsh et al., 2014).

The projected direction and magnitude of change in values of climate variables in this report are best interpreted relative to the historical climate under which a particular system or asset evolved or was designed to operate. For this reason, considering the projected changes between the historical and future periods allows one to envision how natural and human systems may respond to future climate conditions that are different from past conditions. In some cases, the projected change may be small enough for the existing system to accommodate. In other cases, the projected change may be large enough to require adjustments, or adaptations, to the existing system. However, engineering or design projects would require an analysis that is more detailed than we present in this report.

The information in this report can be used to

- Explore a range of plausible future outcomes that reflect the climate system’s complex response to increasing concentrations of greenhouse gases
- Envision how current systems may respond to climate conditions different from those under which the systems evolved or were designed to operate
- Inform evaluation of potential mitigation actions within hazard mitigation plans
- Inform a risk assessment in terms of the likelihood of occurrence of a particular climate-related hazard
Average Temperature

Oregon’s average temperature warmed at a rate of 2.2°F per century from 1895 through 2021 (Fleishman, 2023). Average temperature is expected to continue increasing during the twenty-first century if global emissions of greenhouse gases continue; the rate of warming depends on the level of emissions (IPCC, 2021). By the 2050s (2040–2069), relative to the 1970–1999 historical baseline, Oregon’s average temperature is projected to increase by 3.6°F (range 1.8–5.4°F) under a lower emissions scenario (RCP 4.5) and by 5.0°F (range 2.9–6.9°F) under a higher emissions scenario (RCP 8.5) (Dalton et al., 2017, 2021; Fleishman, 2023). Furthermore, summers are projected to warm more than other seasons (Dalton et al., 2017, 2021; Fleishman, 2023).

During the twenty-first century, average temperature in Polk County is projected to warm at a rate similar to that of Oregon as a whole (Figure 3). Projected increases in average temperature in the county, relative to the 1971–2000 historical baseline in each global climate model (GCM), range from 0.9–3.4°F by the 2020s (2010–2039) and 1.4–6.4°F by the 2050s, depending on emissions scenario and GCM (Table 5).

Figure 3. Projected annual average temperature in Polk County as simulated by 20 downscaled global climate models under a lower (RCP 4.5) and a higher (RCP 8.5) greenhouse gas emissions scenario. Solid lines and shading represent the 20-model mean and range, respectively. The figure shows the multiple-model mean differences between the average historical (1971–2000) baseline and the 2020s (2010–2039 average) and 2050s (2040–2069 average).
Table 5. Projected changes in annual temperature in Polk County between the 1971–2000 baseline period and future periods. Values are averages across 20 global climate models (range in parentheses).

<table>
<thead>
<tr>
<th>Emissions Scenario</th>
<th>Future Period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2020s (2010–2039 average)</td>
</tr>
<tr>
<td>Lower (RCP 4.5)</td>
<td>+1.8°F (0.9–3.0)</td>
</tr>
<tr>
<td>Higher (RCP 8.5)</td>
<td>+2.1°F (1.3–3.4)</td>
</tr>
</tbody>
</table>
Heat Waves

Heat is the leading cause of weather-related deaths in the United States (Khatana et al., 2022). Extreme heat and home air conditioning are less common in Oregon than in many other parts of the country, leaving residents more vulnerable when extreme heat occurs. For example, record-breaking heat in June 2021 caused more than 100 deaths in Oregon, mostly inside homes without air conditioning (O’Neill et al., 2023). Dangerous heat is almost always associated with a weather event called a heat wave (O’Neill et al., 2023). Heat waves occur periodically as a result of natural variability in temperature, but human-caused climate change is increasing their frequency and intensity (Vose et al., 2017; IPCC, 2021). In the absence of human-caused climate change, the intensity of the June 2021 heat wave would have been virtually impossible (Philip et al., 2022).

Extreme heat can refer to extremely warm daytime highs or overnight lows (days on which maximum or minimum temperatures are above a threshold), seasons in which temperatures are well above average, and heat waves, or multiple consecutive days on which maximum or minimum temperatures are above a threshold. In the Pacific Northwest, a day on which the maximum temperature is at least 90°F (32°C) is considered an extremely warm day. The number of such days increased significantly across Oregon since 1951 (O’Neill et al., 2023). The heat index is a measure of perceived heat that reflects both temperature and relative humidity and is more relevant to human health impacts. As relative humidity increases, a given temperature can feel hotter. The National Weather Service issues heat warnings when the heat index exceeds given local thresholds. Across Oregon, heat waves rarely are humid (Rastogi et al., 2020), and the heat index generally is similar to the actual temperature. Nevertheless, the average number of hours per year that Oregonians experience a heat index of at least 90°F increased significantly since 1981 (O’Neill et al., 2023).

The number of extremely warm nights is also increasing. In western Oregon, nights on which the minimum temperature was at least 65°F (18°C) were rare before 1990, but the number of such nights has increased significantly in some areas of Oregon during the past two decades (O’Neill et al., 2023). In addition, evidence of increases in the number of summer extreme heat events that are defined by nighttime minimum temperatures is stronger than evidence of increases in the number of those defined by maximum temperatures (Dalton and Loikith, 2021).

The number, duration, and intensity of extreme heat events in Oregon is projected to increase due to continued increases in mean temperatures (Dalton and Loikith, 2021; O’Neill et al., 2023). Climate models generally agree that changes in temperature extremes largely are linearly correlated with changes in the mean temperature. However, some mechanisms, which are the subject of active research, might cause a more substantial increase in extreme temperature than mean temperature (O’Neill et al., 2023). For example, Arctic amplification (the decrease in the equator-to-pole temperature gradient, caused in part by the melting of Arctic sea ice) may alter the shape and position of the midlatitude jet stream, thereby contributing to an increase in the number of summer heat waves in Oregon (O’Neill et al., 2023; Rupp and Schmittner, 2023). In addition, dry soils can
amplify extreme heat events through their relative lack of evaporative cooling (O'Neill et al., 2023).

Here, we present projected changes in three metrics of extreme daytime heat (maximum temperature) and nighttime heat (minimum temperature) (Table 6).

Table 6. Metrics and definitions of heat extremes.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot Days</td>
<td>Number of days per year on which maximum temperature is 90°F or higher</td>
</tr>
<tr>
<td>Warm Nights</td>
<td>Number of days per year on which minimum temperature is 65°F or higher</td>
</tr>
<tr>
<td>Hottest Day</td>
<td>Highest value of maximum temperature per year</td>
</tr>
<tr>
<td>Warmest Night</td>
<td>Highest value of minimum temperature per year</td>
</tr>
<tr>
<td>Daytime Heat Waves</td>
<td>Number of events per year in which the maximum temperature on at least three consecutive days is 90°F or higher</td>
</tr>
<tr>
<td>Nighttime Heat Waves</td>
<td>Number of events per year in which the minimum temperature on at least three consecutive days is 65°F or higher</td>
</tr>
</tbody>
</table>

In Polk County, the number of hot days and warm nights, and the temperature on the hottest day and warmest night, are projected to increase by the 2020s (2010–2039) and 2050s (2040–2069) under both the lower (RCP 4.5) and higher (RCP 8.5) emissions scenarios (Table 7, Figure 4, Figure 5). For example, by the 2050s under the higher emissions scenario, the number of hot days, relative to each GCM’s 1971–2000 historical baseline, is projected to increase by 6–30. The average number of hot days per year is projected to be 17 more than the average historical baseline of 5 days. The average number of days per year with a heat index of 90°F or higher is projected to be 19 more than the average historical baseline of 4 days (Dalton and Loikith, 2021). The average number of warm nights per year is projected to be 3 more than the average historical baseline of less than 1.

Under the higher emissions scenario, the temperature on the hottest day of the year is projected to increase by 1.2–8.9°F by the 2050s relative to the GCMs’ historical baselines. The average projected increase in temperature on the hottest day is 5.9°F above the average historical baseline of 92.6°F. The average projected increase in temperature on the warmest night is 5.2°F above the average historical baseline of 61.7°F.

Under the higher emissions scenario, the numbers of daytime and nighttime heat waves are projected to increase by 1.0–3.5 and 0.0–1.1, respectively, by the 2050s relative to the
GCMs’ historical baselines. The average number of daytime and nighttime heat waves is projected to increase by 2.4 and 0.4, respectively, above the average historical baselines of 0.8 and 0 (Table 7, Figure 6).

Table 7. Projected future changes in extreme heat metrics in Polk County. Changes from the 1971–2000 baseline were calculated for each of 20 global climate models and averaged across the 20 models (range in parentheses) for a lower (RCP 4.5) and higher (RCP 8.5) emissions scenario and for the 2020s (2010–2039 average) and 2050s (2040–2069 average). The average projected change can be added to the average historical baseline to infer the average projected future value of a given variable.

<table>
<thead>
<tr>
<th></th>
<th>Average Historical Baseline</th>
<th>2020s</th>
<th>2050s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2020s Lower</td>
<td>2020s Higher</td>
<td>2050s Lower</td>
</tr>
<tr>
<td>Hot Days</td>
<td>5.2 days</td>
<td>4.3 days (1.7-8.6)</td>
<td>5.8 days (2.8-8)</td>
</tr>
<tr>
<td>Warm Nights</td>
<td>0.3 days</td>
<td>0.3 days (-0.1-1.1)</td>
<td>0.5 days (0-1.6)</td>
</tr>
<tr>
<td>Hottest Day</td>
<td>92.6°F</td>
<td>1.9°F (-0.2-3.1)</td>
<td>2.6°F (1.1-4.7)</td>
</tr>
<tr>
<td>Warmest Night</td>
<td>61.7°F</td>
<td>1.6°F (-0.3-3.5)</td>
<td>2.1°F (0.3-3.8)</td>
</tr>
<tr>
<td>Daytime Heat Waves</td>
<td>0.8 events</td>
<td>0.7 events (0.2-1.4)</td>
<td>0.9 events (0.4-1.4)</td>
</tr>
<tr>
<td>Nighttime Heat Waves</td>
<td>0 events</td>
<td>0 events (0-0.2)</td>
<td>0.1 events (0-0.2)</td>
</tr>
</tbody>
</table>
Figure 4. Projected changes in the number of hot days (left two sets of bars) and warm nights (right two sets of bars) in Polk County by the 2020s (2010–2039 average) and 2050s (2040–2069 average), relative to the historical baseline (1971–2000 average), under two emissions scenarios. Changes were calculated for each of 20 global climate models relative to each model’s historical baseline, then averaged. Whiskers represent the range of changes across the 20 models. Hot days are those on which the maximum temperature is 90°F or higher; warm nights are those on which the minimum temperature is 65°F or higher.
Figure 5. Projected changes in the temperature on the hottest day of the year (left two sets of bars) and warmest night of the year (right two sets of bars) in Polk County by the 2020s (2010–2039 average) and 2050s (2040–2069 average), relative to the historical baseline (1971–2000 average), under two emissions scenarios. Changes were calculated for each of 20 global climate models relative to each model's historical baseline, then averaged. Whiskers represent the range of changes across the 20 models.
Figure 6. Projected changes in the number of daytime heat waves (left two sets of bars) and nighttime heat waves (right two sets of bars) in Polk County by the 2020s (2010–2039 average) and 2050s (2040–2069 average), relative to the historical baseline (1971–2000 average), under two emissions scenarios. Changes were calculated for each of 20 global climate models relative to each model’s historical baseline, then averaged. Whiskers represent the range of changes across the 20 models. Daytime heat waves are defined as three or more consecutive days on which the maximum temperature is 90°F or higher; nighttime heat waves are three or more consecutive days on which the minimum temperature is 65°F or higher.

**Potential Effects of Extreme Heat on People**

Certain populations are considered especially vulnerable to heat-related illness and death; extreme heat also exacerbates interpersonal violence (Miles-Novelo and Anderson, 2019; Stechemesser *et al.*, 2022). These populations include agricultural, forestry, and other outdoor workers; residents of urban heat islands; people with preexisting conditions or without air conditioning or housing; pregnant women; older adults; children; low-income communities; and communities of color (York *et al.*, 2020; Ho *et al.*, 2021).

**Outdoor workers.** The U.S. Bureau of Labor Statistics does not track occupational employment in Polk County. The Oregon Employment Department includes Polk, Linn, Marion, and Yamhill Counties in its Mid Valley employment data and projections (OED, 2023). Within the Mid Valley in 2021, an estimated 11,115 individuals were employed in farming, fishing, and forestry and 17,216 were employed in construction and extraction.
Employment in those two sets of occupations is projected to increase by 4.8% and 14.8%, respectively, by 2031. As of 2018, an estimated 3330 migrant and seasonal farmworkers were employed in Polk County (Rahe, 2018). Employment is not necessarily correlated with residence.

**Urban areas.** As of 2020, about 82% of Polk County's population (about 68,750 people) lived within the urban growth boundaries of Dallas, Falls City, Independence, Monmouth, Salem (within county lines), and Willamina (PRC, 2023b). A projected 84% and 86% of the county’s residents will live within urban growth boundaries by 2040 and 2070, respectively (PRC, 2023b). Nevertheless, population and housing density in Polk County’s cities does not tend to be extremely high, and therefore the number of individuals living in urban heat islands likely will remain relatively low.

**Preexisting conditions.** From 2014–2017, an estimated 3.1% of adults in Polk County had heart disease, 3.7% had chronic obstructive pulmonary disease, 12.9% had asthma, and 57% had any chronic physical or mental condition (Marion and Polk Counties, 2021). Chronic disease was more prevalent among community members below the federal poverty level and among those living outside urban areas.

**Without housing or air conditioning.** As of 2017, the unhoused population in Polk County was estimated to be 1.2 people per 1000 residents, or roughly 100 people (OHA, 2019). A separate estimate indicated that 38.4 per 1000 students enrolled in kindergarten through grade 12, or about 270 children, were unhoused (OHA, 2019). Statewide, an estimated 34% of housing units did not have air conditioning in 2020 (EIA, 2022).

**Vulnerable life stage or age class.** The percentage of Oregon residents of reproductive age (15–44) is projected to decrease from an estimated 39% in 2020 to 36% in 2045 (PRC, 2023c). If 51% of Polk County’s population in that age range is female (U.S. Census Bureau, 2023), and about 5% of women of reproductive age are pregnant at any given time (CDC, n.d.), then the estimated number of pregnant women in Polk County will increase by about 346 (41%) from 2020 to 2045 (PRC, 2023b).

If trends in Polk County mirror statewide projections, then the percentage of county residents aged 65 and older will increase from an estimated 19% in 2020 to 23% in 2045, an increase of 14,063 people (PRC, 2023b, 2023c). The percentage of Oregon’s population that is under the age of 15 is projected to decrease from 17% in 2020 to 14% in 2045 (PRC, 2023c). Accordingly, the projected number of residents under age 15 in Polk County will increase by 4220 (30%) from 2020 to 2045 (PRC, 2023b).

**Low income and communities of color.** An estimated 19.2% of the county's population is low-income, and 22.5% identify as non-White (Table 3).
**Summary**

The number, duration, and intensity of extreme heat events will increase as temperatures continue to warm. In Polk County, the number of extremely hot days (those on which the temperature is 90°F or higher) and the temperature on the hottest day of the year are projected to increase by the 2020s and 2050s under both the lower and higher emissions scenarios. The number of days per year with temperatures 90°F or higher is projected to increase by an average of 17 (range 6–30) by the 2050s, relative to the 1971–2000 historical baselines, under the higher emissions scenario. The temperature on the hottest day of the year is projected to increase by an average of about 6°F (range 1–9°F) by the 2050s. Projected demographic changes in Polk County, such as an increase in the proportion of older adults and the absolute number of children, will increase the number of people in some of the populations that are vulnerable to extreme heat.
Cold Waves

Extremely cold temperatures in Oregon generally occur when Arctic air moves into the state from the north and east (O’Neill et al., 2023). As a result of human-caused climate change, Arctic air is warming more rapidly than the global mean temperature. This has led to a decrease in the intensity and frequency of cold extremes in the Northwest and worldwide over the past century (Vose et al., 2017; IPCC, 2021; O’Neill et al., 2023). At many locations across Oregon, the annual number of days on which the minimum temperature is below freezing has decreased significantly since 1940 (O’Neill et al., 2023).

The frequency of cold extremes is expected to continue decreasing (Vose et al., 2017; IPCC, 2021), although more slowly than the frequency of heat extremes will increase (O’Neill et al., 2023). Extreme cold will still be possible during the next several decades, but will become increasingly rare as winter temperatures warm and become less variable (O’Neill et al., 2023; Rupp and Schmittner, 2023).

Older adults, infants and children, rural residents, unhoused individuals, and people with preexisting cardiovascular or respiratory conditions are considered most susceptible to extreme cold (Conlon et al., 2011; NCHH, 2022). Recent and projected estimates of these populations are summarized in Heat Waves.

Here, we present projected changes in three metrics of extreme daytime cold (maximum temperature) and nighttime cold (minimum temperature) (Table 8).

**Table 8. Metrics and definitions of cold extremes.**

<table>
<thead>
<tr>
<th>Metric</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold Days</td>
<td>Number of days per year on which the maximum temperature is 32°F or lower</td>
</tr>
<tr>
<td>Cold Nights</td>
<td>Number of days per year on which the minimum temperature is 0°F or lower</td>
</tr>
<tr>
<td>Coldest Day</td>
<td>Lowest value of maximum temperature per year</td>
</tr>
<tr>
<td>Coldest Night</td>
<td>Lowest value of minimum temperature per year</td>
</tr>
<tr>
<td>Daytime Cold Waves</td>
<td>Number of events per year in which maximum temperature on at least three consecutive days is 32°F or lower</td>
</tr>
<tr>
<td>Nighttime Cold Waves</td>
<td>Number of events per year in which minimum temperature on at least three consecutive days is 0°F or lower</td>
</tr>
</tbody>
</table>

In Polk County, the number of cold days and nights is projected to decrease by the 2020s (2010–2039) and 2050s (2040–2069) under both the lower (RCP 4.5) and higher (RCP 8.5) emissions scenarios (Table 9, Figure 7). For example, climate models projected that by the 2050s under the higher emissions scenario, the number of cold days will change by -1.4–0.3 relative to each GCM’s 1971–2000 historical baseline. The average projected number of cold days per year is 0.8 less than the average historical baseline of 1.3 days. Nighttime temperatures in Polk County rarely are lower than 0°F.
Similarly, the temperatures on the coldest day and night are projected to increase by the 2020s and 2050s under both emissions scenarios (Table 9, Figure 8). For example, by the 2050s under the higher emissions scenario, the temperature on the coldest night of the year is projected to increase by 0.2–10.1°F relative to the GCMs’ historical baselines. The average projected increase in the temperature on the coldest night is 5.4°F above the average historical baseline of 17.1°F. The average projected increase in the temperature on the coldest day is 4.9°F above the average historical baseline of 31.7°F. Daytime and nighttime cold waves are rare in Polk County (Table 9, Figure 7, Figure 9).

Table 9. Projected future changes in extreme cold metrics in Polk County. Changes from the 1971–2000 baseline were calculated for each of 20 global climate models and averaged across the 20 models (range in parentheses) for a lower (RCP 4.5) and higher (RCP 8.5) emissions scenario and for the 2020s (2010–2039 average) and 2050s (2040–2069 average). The average projected change can be added to the average historical baseline to infer the average projected future value of a given variable.

<table>
<thead>
<tr>
<th></th>
<th>Average Historical Baseline</th>
<th>2020s</th>
<th>2050s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Lower</td>
<td>Higher</td>
</tr>
<tr>
<td>Cold Days</td>
<td>1.3 days</td>
<td>-0.2 days (-1 - 1.2)</td>
<td>-0.5 days (-1.1 - 0.3)</td>
</tr>
<tr>
<td>Cold Nights</td>
<td>0 days</td>
<td>0 days (0 - 0.2)</td>
<td>0 days (0 - 0.2)</td>
</tr>
<tr>
<td>Coldest Day</td>
<td>31.7°F</td>
<td>1.1°F (-2.9 - 3.5)</td>
<td>2.4°F (-1.4 - 5)</td>
</tr>
<tr>
<td>Coldest Night</td>
<td>17.1°F</td>
<td>1.2°F (-2.6 - 3.9)</td>
<td>2.5°F (-0.6 - 5.3)</td>
</tr>
<tr>
<td>Daytime Cold Waves</td>
<td>0.2 events</td>
<td>0 events (-0.2 - 0.2)</td>
<td>-0.1 events (-0.2 - 0.1)</td>
</tr>
<tr>
<td>Nighttime Cold Waves</td>
<td>0 events</td>
<td>0 events (0 - 0)</td>
<td>0 events (0 - 0)</td>
</tr>
</tbody>
</table>
Figure 7. Projected changes in the number of cold days (left two sets of bars) and cold nights (right two sets of bars) in Polk County by the 2020s (2010–2039 average) and 2050s (2040–2069 average), relative to the historical baseline (1971–2000 average), under two emissions scenarios. Changes were calculated for each of 20 global climate models relative to each model’s historical baseline, then averaged. Whiskers represent the range of changes across the 20 models. Cold days are those on which the maximum temperature is 32°F or lower; cold nights are those on which the minimum temperature is 0°F or lower.
Figure 8. Projected changes in the temperature on the coldest day of the year (left two sets of bars) and coldest night of the year (right two sets of bars) in Polk County by the 2020s (2010–2039 average) and 2050s (2040–2069 average), relative to the historical baseline (1971–2000 average), under two emissions scenarios. Changes were calculated for each of 20 global climate models relative to each model’s historical baseline, then averaged. Whiskers represent the range of changes across the 20 models.
Figure 9. Projected changes in the number of daytime cold waves (left two sets of bars) and nighttime cold waves (right two sets of bars) in Polk County by the 2020s (2010–2039 average) and 2050s (2040–2069 average), relative to the historical baseline (1971–2000 average), under two emissions scenarios. Changes were calculated for each of 20 global climate models relative to each model’s historical baseline, then averaged. Whiskers represent the range of changes across the 20 models. Daytime cold waves are defined as three or more consecutive days on which the maximum temperature is 32°F or lower; nighttime cold waves are three or more consecutive days on which the minimum temperature is 0°F or lower.

**Freezing Rain and Ice Accretion**

Freezing rain forms in two ways (Degelia et al., 2016). The first requires a layer of warm air (> 32°F or 0°C) above a subfreezing layer adjacent to the surface. Falling ice particles melt in the warm layer, become super-cooled liquid droplets in the subfreezing layer, and freeze on contact with the surface. Second, freezing rain can form without this warm layer when super-cooled droplets form in subfreezing air and then freeze on contact with the surface.

Ice accretion refers to the process by which a layer of ice accumulates on solid objects that are exposed to freezing rain, drizzle or fog; fog at temperatures below freezing; or extremely small droplets of water in clouds. Because freezing rain intensities tend to be low, only long-duration events typically lead to appreciable ice accretion on surfaces (McCray et al., 2019).
Published observations of ice loads from freezing rain on structures are rare (Changnon and Creech, 2003). The frequency of freezing rain is projected to increase over most of Canada and decrease over the southeastern and southcentral United States during the twenty-first century (Lambert and Hansen, 2011; Klima and Morgan, 2015; Jeong and Sushama, 2018; McCray et al., 2022). The location of the contour line dividing positive and negative change depends on the magnitude of increase in global temperature, but generally moves southward from east to west across the United States. Little change or some increase in the frequency of freezing rain, even under high warming scenarios, is projected in the Intermountain West. Near the Pacific Coast, however, the zero-change contour moves north, and the projected frequency of freezing rain in western Oregon and Washington declines in the future (Jeong et al., 2018; McCray et al., 2022). An analysis of atmospheric rivers projected a decrease in the mean atmospheric river-related freezing rain intensity over western Oregon and Washington, whereas the proportion of atmospheric river-related freezing rain relative to the total amount of freezing rain was largely unchanged (Liang and Sushama, 2019).

Despite the expected decrease in the frequency of freezing rain events over western Oregon, the projected direction (increase or decrease) of changes in extreme freezing rain amounts is unclear, and varies among climate models, emissions scenarios, and temporal extents (Jeong et al., 2018). One analysis projected decreases in the amount of ice accretion with a 50-year return period (a 2% probability of occurring in any given year) over southwestern and central-western Oregon, but no change in northern Oregon (Jeong et al., 2019). Moreover, published projections of freezing rain trends usually have been provided as maps covering extensive areas (e.g., the conterminous United States or Canada, United States, and northern Mexico), making it difficult to quantify county-level average projections.

<table>
<thead>
<tr>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold extremes will become less frequent and intense as the climate warms. The number of cold days (maximum temperature 32°F or lower) per year in Polk County is projected to decrease by an average of 1 (range -1.4–0.3) by the 2050s, relative to the 1971–2000 historical baselines, under the higher emissions scenario. The temperature on the coldest night of the year is projected to increase by an average of 5°F (range 0–10°F) by the 2050s. The number of county residents vulnerable to extreme cold is likely to grow, although this increase may be offset somewhat by the decrease in incidence of cold extremes.</td>
</tr>
</tbody>
</table>
There is greater uncertainty in projections of future precipitation than projections of future temperature. Precipitation has high natural variability, and the atmospheric patterns that influence precipitation are represented differently among GCMs. Globally, mean precipitation is likely to decrease in many dry regions in the subtropics and mid-latitudes and to increase in many mid-latitude wet regions (IPCC, 2013; Stevenson et al., 2022). Because the location of the boundary between mid-latitude increases and decreases in precipitation varies among GCMs, some models project increases and others decreases in precipitation in Oregon (Mote et al., 2013).

Observed annual precipitation in Oregon has high year-to-year variability and has not changed significantly over the period of record. Annual precipitation in Oregon is projected to increase somewhat over the twenty-first century, although natural variability will continue to dominate this trend (Dalton et al., 2017, 2021; Fleishman, 2023). On average, summers in Oregon are projected to become drier and other seasons to become wetter. However, some models project increases and others decreases in each season (Dalton et al., 2017, 2021; Fleishman, 2023). In addition, regional climate models project larger increases in winter precipitation east of the Cascade Range than west of the Cascade Range, which suggests a weakened rain shadow effect in winter (Mote et al., 2019).

Extreme precipitation in the Northwest is governed by atmospheric circulation and its interaction with complex topography (Parker and Abatzoglou, 2016). Atmospheric rivers—long, narrow swaths of warm, moist air that carry large amounts of water vapor from the tropics to mid-latitudes—generally result in extreme precipitation across large areas west of the Cascade Range, and are associated with the majority of fall and winter extreme precipitation events in Oregon. By contrast, low pressure systems that are not driven by westerly flows from offshore often lead to locally extreme precipitation east of the Cascade Range (Parker and Abatzoglou, 2016).

The frequency and intensity of heavy precipitation has increased across most land areas worldwide since the 1950s (IPCC, 2021). Observed trends in the frequency of extreme precipitation across Oregon vary among locations, time periods, and metrics, but overall, the frequency has not changed substantially. As the atmosphere warms, it holds more water vapor. As a result, the frequency and intensity of extreme precipitation is expected to increase (Dalton et al., 2017, 2021; Kossin et al., 2017). Regional climate models project a larger percentage increase in precipitation extremes east of the Cascade Range than west of the Cascade Range (Mote et al., 2019; Rupp et al., 2022). Additionally, the projected percentage increase in extreme precipitation tends to be larger on the leeward side of the Coast and Cascade Ranges than on the windward side (Rupp et al., 2022). Climate models also project an increase in the number of days on which an atmospheric river is present, and that atmospheric rivers will account for an increasing proportion of total annual precipitation across the Northwest (Dalton et al., 2021).

Here, we present projected changes in four metrics of precipitation extremes (Table 10).
Table 10. Metrics and definitions of precipitation extremes.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wettest Day</td>
<td>Highest one-day precipitation total per water year (1 October–30 September)</td>
</tr>
<tr>
<td>Wettest Five Days</td>
<td>Highest consecutive five-day precipitation total per water year</td>
</tr>
<tr>
<td>Wet Days</td>
<td>Number of days per water year on which precipitation exceeds 0.75 inches</td>
</tr>
</tbody>
</table>
| Landslide Risk Days| Number of days per water year that exceed the landslide threshold developed by the US Geological Survey for Seattle, Washington (see https://pubs.er.usgs.gov/publication/ofr20061064). $P_3/(3.5-.67*P_{15})>1$, where  
  - $P_3 =$ Precipitation accumulation on prior days 1–3  
  - $P_{15} =$ Precipitation accumulation on prior days 4–18 |

In Polk County, the amount of precipitation on the wettest day and wettest consecutive five days is projected to increase on average by the 2020s (2010–2039) and 2050s (2040–2069), relative to the 1971–2000 historical baseline, under both the lower (RCP 4.5) and higher (RCP 8.5) emissions scenarios (Table 11, Figure 10). Some models project decreases in these metrics for certain time periods and scenarios.

Climate models project that by the 2050s under the higher emissions scenario, the amount of precipitation on the wettest day of the year, relative to each GCM’s 1971–2000 historical baseline, will increase by 2.2–32.7% (Figure 10). The average projected amount of precipitation on the wettest day of the year is 13.5% greater than the average historical baseline of 2.8 inches.

Climate models project that by the 2050s under the higher emissions scenario, the amount of precipitation on the wettest consecutive five days of the year will increase by 2.1–21.5% (Figure 10). The average projected amount of precipitation on the wettest consecutive five days is 10.6% above the average historical baseline of 7.1 inches.
Table 11. Projected future changes in extreme precipitation metrics in Polk County. Changes from the 1971–2000 baseline were calculated for each of 20 global climate models and averaged across the 20 models (range in parentheses) for a lower (RCP 4.5) and higher (RCP 8.5) emissions scenario and for the 2020s (2010–2039 average) and 2050s (2040–2069 average). The average projected change can be added to the average historical baseline to infer the average projected future value of a given variable.

<table>
<thead>
<tr>
<th></th>
<th>Average Historical Baseline</th>
<th>2020s</th>
<th>2050s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Lower</td>
<td>Higher</td>
</tr>
<tr>
<td>Wettest Day</td>
<td>2.8 inches</td>
<td>6.6%</td>
<td>7.6%</td>
</tr>
<tr>
<td></td>
<td>(-5.6–14.4)</td>
<td>(-3.3–27.1)</td>
<td>(4.3–19.4)</td>
</tr>
<tr>
<td>Wettest Five-Days</td>
<td>7.1 inches</td>
<td>5.4%</td>
<td>4.8%</td>
</tr>
<tr>
<td></td>
<td>(-2.1–18.7)</td>
<td>(-4.9–25)</td>
<td>(-2.6–19.3)</td>
</tr>
<tr>
<td>Wet Days</td>
<td>27.4 days</td>
<td>0.3 days</td>
<td>-0.1 days</td>
</tr>
<tr>
<td></td>
<td>(-1.3–2.3)</td>
<td>(-3.1–2)</td>
<td>(-2.2–2.9)</td>
</tr>
<tr>
<td>Landslide Risk Days</td>
<td>25.9 days</td>
<td>-0.2 days</td>
<td>-0.5 days</td>
</tr>
<tr>
<td></td>
<td>(-2.2–1.9)</td>
<td>(-3.1–1.3)</td>
<td>(-2.9–2.1)</td>
</tr>
</tbody>
</table>
Figure 10. Projected percent changes in the amount of precipitation on the wettest day of the year (left two sets of bars) and wettest consecutive five days of the year (right two sets of bars) in Polk County by the 2020s (2010–2039 average) and 2050s (2040–2069 average), relative to the historical baseline (1971–2000 average), under two emissions scenarios. Changes were calculated for each of 20 global climate models relative to each model’s historical baseline, then averaged. Whiskers represent the range of changes across the 20 models.

The average number of days per year on which precipitation exceeds 0.75 inches is not projected to change substantially (Figure 11). For example, by the 2050s under the higher emissions scenario, the number of wet days per year is projected to increase by 0.6 (range -3.3–3.5). The historical baseline is an average of 27.4 days per year.

Landslides are often triggered by rainfall when the soil becomes saturated. As a surrogate measure of landslide risk, we present a threshold that is based on recent precipitation (cumulative precipitation over the previous 3 days) and antecedent precipitation (cumulative precipitation on the 15 days prior to the previous 3 days). By the 2050s under the higher emissions scenario, the average number of days per year in Polk County on which the landslide risk threshold is exceeded is projected to remain about the same, with a change of -0.3 (range -2.6–3.2) (Figure 11). The historical baseline is an average of 25.9 days per year. Landslide risk depends on multiple site-specific factors, and this metric does not reflect all aspects of the hazard. Also, the landslide risk threshold was developed for Seattle, Washington, and may be less applicable to other locations.
Figure 11. Projected changes in the number of wet days (left two sets of bars) and landslide risk days (right two sets of bars) in Polk County by the 2020s (2010–2039 average) and 2050s (2040–2069 average), relative to the historical baseline (1971–2000 average), under two emissions scenarios. Changes were calculated for each of 20 global climate models relative to each model’s historical baseline, then averaged. Whiskers represent the range of changes across the 20 models.

The occurrence and magnitude of landslides in western Oregon is largely influenced by past clearcutting and construction of logging roads. In the Lookout Creek watershed in the Willamette National Forest, the major floods of 1964–1965, which occurred during the peak of logging, produced more and larger landslides than major floods in 1996 and 2011, decades after logging in the area ended (Goodman et al., 2023). Landslide risk also can become high when heavy rain falls on an area that burned within approximately the past five to ten years. The probability that extreme rainfall will occur within one year after an extreme fire-weather event in Oregon or Washington was projected to increase by 700% from 1980–2005 to 2100 under the higher emissions scenario (Touma et al., 2022). Similarly, projections suggested that by 2100, 90% of extreme fire-weather events across Oregon and Washington are likely to be succeeded within five years by three or more extreme rainfall events (Touma et al., 2022). Although fire weather is not synonymous with wildfire, these results highlight the increasing likelihood of compounded climate extremes that elevate the risk of natural hazards.
Populations considered particularly vulnerable to the direct and indirect effects of extreme precipitation, from the storms themselves to floods and landslides, include people dependent on medical equipment that requires electricity, older adults, and children and pregnant women (York et al., 2020; Ho et al., 2021). Recent and projected estimates of populations that are older, younger, and of childbearing age are included in previous sections. Some utility companies, such as Pacific Power, provide consultation and additional outreach to individuals who are dependent on electricity for a medical device. Among the diverse health risks associated with extreme precipitation are injuries, toxic exposures, displacement, disruptions in medical care, and negative mental health outcomes (York et al., 2020; Ho et al., 2021).

Summary

The intensity of extreme precipitation is expected to increase as the atmosphere warms and holds more water vapor. In Polk County, the number of days per year with at least 0.75 inches of precipitation is not projected to change substantially. Nevertheless, by the 2050s, the amount of precipitation on the wettest day and wettest consecutive five days per year is projected to increase by an average of 14% (range 2–33%) and 11% (range 2–22%), respectively, relative to the 1971–2000 historical baselines, under the higher emissions scenario. The number of days per year that exceeded a threshold for landslide risk, which is based on prior 18-day precipitation accumulation, is not projected to change substantially. However, landslide risk depends on multiple factors, and this metric does not reflect all aspects of the hazard.
Streams in the Northwest are projected to shift toward higher winter runoff, lower summer and fall runoff, and earlier peak runoff, particularly in snow-dominated regions (Raymondi et al., 2013; Naz et al., 2016). These changes are expected to result from increases in the intensity of heavy precipitation; warmer temperatures that cause more precipitation to fall as rain and less as snow, and snow to melt earlier in spring; and increasing winter precipitation and decreasing summer precipitation (Dalton et al., 2017, 2021; Mote et al., 2019).

Warming temperatures and increasing winter precipitation are expected to increase flood risk in many basins in the Northwest, particularly mid- to low-elevation, mixed rain-and-snow basins in which winter temperatures are near freezing (Tohver et al., 2014). The greatest projected changes in peak streamflow magnitudes are at intermediate elevations in the Cascade Range and Blue Mountains (Safeeq et al., 2015). Recent regional hydroclimate models project increases in extreme high flows throughout most of the Northwest, especially west of the Cascade crest (Salathé et al., 2014; Najafi and Moradkhani, 2015; Naz et al., 2016). One study that used a single climate model projected an increase in flood risk in fall due to earlier, more extreme storms, including atmospheric rivers; and an increase in the proportion of precipitation falling as rain rather than snow (Salathé et al., 2014). Rainfall-driven floods are more sensitive to increases in precipitation than snowmelt-driven floods. Therefore, the projected increases in total precipitation, and in rain relative to snow, likely will increase flood magnitudes in the region (Chegwidden et al., 2020).

The Willamette River at Salem is within a rain-dominated basin with peak flow during winter (Figure 12). By the 2050s (2040–2069), under both emissions scenarios, winter streamflow in the Willamette River at Salem is projected to increase due to increased winter precipitation. Mean monthly flows do not translate directly to flood risk because floods occur over shorter periods of time. Nevertheless, increases in monthly flow may imply increases in flood likelihood, particularly if increases are projected to occur during months in which flood occurrence historically has been high.
Figure 12. Simulated monthly, bias-corrected, non-regulated streamflow at the Willamette River at Salem in 2040–2069 compared to 1971–2000. Solid lines and shading represent the mean and range across ten global climate models. (Data source: Integrated Scenarios of the Future Northwest Environment, [https://climatetoolbox.org/tool/future-streamflows](https://climatetoolbox.org/tool/future-streamflows))

Averaged across the western United States, the magnitudes of major floods are projected to increase by 14–19% by 2010–2039, 21–30% by 2040–2069, and 31–43% by 2070–2099, compared to the 1971–2000 historical baseline, under the higher emissions scenario (Maurer et al., 2018). Major floods are defined as daily peak flow magnitudes that are associated with 100-year to 10-year return periods (1–10% probability that this daily flow magnitude will be exceeded in a given year). Likewise, within the Columbia River basin, projected major flood magnitudes increased nearly everywhere and varied by the dominant precipitation type (Queen et al., 2021). On the Willamette River at Salem, flood levels with 10-year and 100-year return periods were projected to increase by 37% and 43%, respectively, from 1950–1999 to 2050–2099 under the higher emissions scenario (Queen et al., 2021) (Table 12).

We estimated projected changes in the average magnitude of single-day flood levels with 2-year, 10-year, and 25-year return periods (50%, 10%, and 4% probability, respectively, that this daily flow magnitude will be exceeded in a given year) along the Willamette River
at Salem (Table 12). We then compared flood magnitudes between 1961–2010 and 2031–2080 under the lower and higher emissions scenarios. Under the higher emissions scenario, the average magnitudes of single-day floods with 2-year, 10-year, and 25-year return periods were projected to increase by 10%, 23%, and 29%, respectively (Table 12, Figure 13). Some models projected no change or decreases in the magnitude of maximum daily flows for each return period. These results can be interpreted as either an increase in flood magnitude given a flood frequency, or an increase in flood frequency given a flood magnitude. These analyses were exploratory and should not be applied to engineering or design.

Table 12. Percentage change in peak flow associated with multiple return periods for the Willamette River at Salem in Polk County under the higher emissions scenario.

<table>
<thead>
<tr>
<th>Return Period (Probability that this level will be exceeded in a given year)</th>
<th>Average Percentage Change in Flow</th>
<th>Time Periods Compared</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-year (50%)</td>
<td>10</td>
<td>2031–2080 vs. 1961–2010</td>
<td>This report</td>
</tr>
<tr>
<td>10-year (10%)</td>
<td>37</td>
<td>2050-2099 vs. 1950-1999</td>
<td>Queen et al. (2021)</td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>2031–2080 vs. 1961–2010</td>
<td>This report</td>
</tr>
<tr>
<td>25-Year (4%)</td>
<td>29</td>
<td>2031–2080 vs. 1961–2010</td>
<td>This report</td>
</tr>
<tr>
<td>100-Year (1%)</td>
<td>43</td>
<td>2050-2099 vs. 1950-1999</td>
<td>Queen et al. (2021)</td>
</tr>
</tbody>
</table>
Figure 13. Projected change in water-year maximum daily, non-regulated streamflows with 2-year, 10-year, and 25-year return periods along the Willamette River at Salem from 1961–2010 to 2031–2080 under lower (RCP 4.5) and higher (RCP 8.5) emissions scenarios. Larger blue and red dots and bars represent the mean and two standard errors across ten global climate models. Only ten of the full set of 20 models that were used to project temperature and precipitation simulated future hydrology (see Appendix). Smaller light blue and light red dots represent projections from individual models. (Data source: Integrated Scenarios of the Future Northwest Environment, https://climate.northwestknowledge.net/IntegratedScenarios/)

Some of the Northwest’s highest floods occur when large volumes of warm rain from atmospheric rivers fall on a deep snowpack (Safeeq et al., 2015). The frequency and amount of moisture transported by atmospheric rivers is projected to increase along the West Coast in response to increases in air temperature (Kossin et al., 2017), which in turn increases the likelihood of flooding (Konrad and Dettinger, 2017).
Future changes in the frequency of rain-on-snow events likely will vary along elevational gradients. At lower elevations, the frequency is projected to decrease due to decreasing snowpack, whereas at higher elevations the frequency is projected to increase due to the shift from snow to rain (Surfleet and Tullos, 2013; Safeeq et al., 2015; Musselman et al., 2018). The likely effects on streamflow of such changes in frequency of rain-on-snow events vary. For example, projections for the Santiam River, Oregon, indicated an increase in annual peak daily flows with return intervals less than 10 years, but a decrease in annual peak daily flows with return intervals of 10 or more years (Surfleet and Tullos, 2013). Average runoff from rain-on-snow events in watersheds in northern coastal Oregon was projected to decline due to depletion of the snowpack (Musselman et al., 2018), which may imply that the driver of floods in these areas shifts from rain-on-snow events to rainfall that exceeds soil capacity (Berghuijs et al., 2016; Musselman et al., 2018). Wildfires and shifts in vegetation that affect soil properties also will likely affect water transport, but hydrological models generally have not accounted for these processes (Bai et al., 2018; Wang et al., 2020; Williams et al., 2022).

An estimated 5791 properties in Polk County (21%) have a ≥26% probability of being severely affected by flooding by 2050 (First Street Foundation, 2023) (Table 13). Among the structures that may be affected by flooding are 4623 residences (19%) at moderate risk, 387 commercial properties (42%) at major risk, 19 critical infrastructure facilities (e.g., hospitals; police, fire, and power stations; and water treatment facilities) (35%) at moderate risk, and 27 (26%) of social facilities (schools, houses of worship, museums, and government or historic buildings) at moderate risk. More than 820 of the 2550 miles of roads in Polk County (32%) were estimated to be at severe risk of flooding and rendered impassable (First Street Foundation, 2023).

Table 13. 30-year cumulative probability of flooding to different depths and First Street Foundation’s associated risk characterizations.

<table>
<thead>
<tr>
<th>Depth of flooding</th>
<th>≤0.06</th>
<th>&gt;0.06–0.12</th>
<th>&gt;0.12–0.27</th>
<th>&gt;0.27–0.47</th>
<th>&gt;0.47–0.96</th>
<th>&gt;0.96</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–3”</td>
<td>Low</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Major</td>
<td>Major</td>
<td>Severe</td>
</tr>
<tr>
<td>&gt;3–6”</td>
<td>Low</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Major</td>
<td>Major</td>
<td>Severe</td>
</tr>
<tr>
<td>&gt;6–9”</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Major</td>
<td>Major</td>
<td>Severe</td>
<td>Extreme</td>
</tr>
<tr>
<td>&gt;9–12”</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Major</td>
<td>Severe</td>
<td>Severe</td>
<td>Extreme</td>
</tr>
<tr>
<td>&gt;12–24”</td>
<td>Moderate</td>
<td>Major</td>
<td>Major</td>
<td>Severe</td>
<td>Extreme</td>
<td>Extreme</td>
</tr>
<tr>
<td>≥24”</td>
<td>Major</td>
<td>Major</td>
<td>Severe</td>
<td>Extreme</td>
<td>Extreme</td>
<td>Extreme</td>
</tr>
</tbody>
</table>
Summary

Winter flood risk at mid- to low elevations in Polk County, where temperatures are near freezing during winter and precipitation is a mix of rain and snow, is projected to increase as winter temperatures increase. The temperature increase will lead to an increase in the percentage of precipitation falling as rain rather than snow.
Drought can be defined in many ways (Table 14), but most fundamentally is insufficient water to meet needs (Redmond, 2002; O’Neill et al., 2021; O’Neill and Siler, 2023). Drought is common in the Northwest, particularly because seasonal precipitation is lowest during the warmest season (O’Neill and Siler, 2023). The incidence, extent, and severity of drought has increased over the last 20 years relative to the twentieth century, and this trend is expected to continue (O’Neill et al., 2021; O’Neill and Siler, 2023).

Table 14. Definitions and characteristics of various drought classes. (Sources: O’Neill et al., 2021; O’Neill and Siler, 2023; Fleishman et al., unpublished)

<table>
<thead>
<tr>
<th>Drought Class</th>
<th>Definition and Characteristics</th>
</tr>
</thead>
</table>
| Meteorological| • lack of precipitation  
• evaporative demand that exceeds precipitation over a prolonged period (at least about 90 days)                                                                                                                                  |
| Hydrological  | • extended periods of meteorological drought affect surface or subsurface water supply, such as streamflow, reservoir and lake levels, or ground water levels  
• tends to evolve more slowly than meteorological drought, with extents longer than six months                                                                            |
| Agricultural  | • occurs when lack of surface or subsurface water supply adversely affects agricultural production  
• reflects precipitation shortages, differences between actual and potential evapotranspiration, soil water deficits, and reduced availability of irrigation water                                                                 |
| Socioeconomic | • occurs when meteorological, hydrological, or agricultural drought reduces the supply of an economic or social good or service  
• often affects state and federal drought declarations                                                                                                                                  |
| Ecological    | • undesirable changes in ecological state caused by deficits in water availability  
• usually caused by meteorological or hydrological drought  
• sensitivity to water limitation varies among species and life stages                                                                                                                     |
| Flash         | • rapid-onset periods of elevated surface temperatures, low relative humidities, precipitation deficits, and a rapid decline in soil moisture  
• tends to develop and intensify rapidly within a few weeks, and may be generated or magnified by prolonged heat waves                                                              |
| Snow          | • snowpack—or snow water equivalent (SWE)—is below average for a given point in the water year, traditionally 1 April  
• often presage hydrological drought conditions during the ensuing spring and summer in snowmelt-dominated watersheds  
• warm snow drought—below-average snowpack resulting primarily from above-average winter temperatures  
• dry snow drought—below-average snowpack resulting primarily from below-average winter precipitation                                                                 |
Drought often affects human health indirectly, such as through food scarcity and the increased incidence of infectious, chronic, and vector-borne diseases. Moreover, drought affects both physical and mental health (Vins et al., 2015). Low income, tribal, rural, and farming and farmworker communities are especially susceptible to negative health effects as a result of drought and associated water scarcity and poor water quality (York et al., 2020; Ho et al., 2021). Recent and projected estimates of low income, rural, and some farmworker populations are presented in previous sections. As of 2022, an estimated 2.7% of Polk County residents identified as one race and as American Indian or Alaska Native (U.S. Census Bureau, 2023).

By 2100, annual mean precipitation in Oregon is projected to increase by 5–10% (O’Neill and Siler, 2023). However, summers in the state are expected to become drier and warmer (Dalton et al., 2021; Fleishman, 2023). As winters become warmer, snowpack across Oregon is projected to decline by approximately 25% by 2050 relative to 1950–2000 (Siirila-Woodburn et al., 2021). The decline in snowpack across the western United States is projected to reduce summer soil moisture in the mountains (Gergel et al., 2017). Climate change is also expected to reduce summer streamflows in snow-dominated and mixed rain and snow basins across the Northwest as snowpack melts earlier and summer precipitation decreases (Dalton et al., 2017; Mote et al., 2019). For example, summer flow is projected to decrease in the Willamette River (Figure 12) by the 2050s (2040–2069). As mountain snowpack declines, seasonal drought will become less predictable and snow droughts will increase the likelihood of hydrological and agricultural drought during the following spring and summer (Dalton and Fleishman, 2021; Fleishman, 2023).

We present projected changes in four variables indicative of drought: low spring (April 1) snowpack (snow drought), low summer (June–August) soil moisture from the surface to 55 inches below the surface (agricultural drought), low summer runoff (hydrological drought), and low summer precipitation (meteorological drought). We present drought in terms of a change in the probability of exceeding the magnitude of seasonal drought conditions for which the historical annual probability of exceedance was 20% (5-year return period) (Figure 14).

In Polk County, summer soil moisture, spring snowpack, summer runoff, and summer precipitation are projected to decline by the 2050s under both lower (RCP 4.5) and higher (RCP 8.5) emissions scenarios. Therefore, seasonal drought conditions will occur more frequently by the 2050s (Figure 14). By the 2050s under the higher emissions scenario, the annual probability of low summer soil moisture is projected to be about 33% (3-year return period). The annual probabilities of low spring snowpack, low summer runoff, and low summer precipitation are projected to be about 37% (2.7-year return period), 45% (2.2-year return interval), and 34% (2.9-year return interval), respectively. We did not evaluate drought projections for the 2020s due to data limitations, but drought magnitudes in the 2020s likely will be smaller than those in the 2050s.
Figure 14. Projected probability of exceeding the magnitude of seasonal drought conditions for which the historical annual probability of exceedance was 20% (50% for spring snowpack). Projections are for the 2050s (2040–2069), relative to the historical baseline (1971–2000), under two emissions scenarios. Seasonal drought conditions include low summer soil moisture (average from June through August), low spring snowpack (April 1 snow water equivalent), low summer runoff (total from June through August), and low summer precipitation (total from June through August). The bars and whiskers represent the mean and range across ten global climate models. (Data source: Integrated Scenarios of the Future Northwest Environment, climate.northwestknowledge.net/IntegratedScenarios/)

Summary

Drought, as represented by low summer soil moisture, low spring snowpack, low summer runoff, and low summer precipitation, is projected to become more frequent in Polk County by the 2050s. The incidence of related negative physical and mental health outcomes, especially among low income, tribal, rural, and agricultural communities, is likely to increase.
Projection of contemporary wildfire risk requires an understanding of interactions among plant physiology, climate, and human activities.

**Aridity, Heat, and Wildfire Risk**

Drought conditions across the western United States have been exacerbated by warmer winters and springs, which drive an overall decline in mountain snowpack and earlier snowmelt (Westerling, 2016), and by longer summers. High temperatures are a major contributor to desiccation of dead vegetation, whereas dry air (in western Oregon, more so than dry soil; Jarecke *et al.*, 2023) reduces moisture in live vegetation. The drier the air, the more plants transpire and lose water. Dry dead or living vegetation is more likely to burn than wet vegetation. If tall trees cannot draw enough water from the soil, they may be at risk of embolism (Olson *et al.*, 2018; Anfodillo and Olson, 2021) and more likely to die. Because concurrent heat and drought are becoming more common (Alizadeh *et al.*, 2020), the volume of stressed or dead vegetation and wildfire risk are increasing.

Trees that become drought-stressed generally are more vulnerable to outbreaks of native and non-native insects and pathogens. For example, Swiss needle cast (*Phaeocryptopus gaeumannii*), a native fungus, killed substantial numbers of Douglas fir (*Pseudotsuga menziesii*) trees in the Tillamook watershed for the first time in 2015. Extreme heat in June 2021 (Heeter *et al.*, 2023) caused mortality of seedlings and saplings in plantations while scorching the canopy of mature trees throughout the Coast Range (Still *et al.*, 2023).

The dryness of the air, also called evaporative demand, is characterized by the vapor pressure deficit (VPD). The VPD is the difference in atmospheric pressure between the current amount of water vapor in the air and the maximum amount of water the air can hold at a given temperature (dew point). VPD is increasing globally, and CMIP6 climate models indicate that human emissions of greenhouse gases explained 68% of the observed VPD increase between 1979 and 2020 (Zhuang *et al.*, 2021). These models also project that across the western United States, given a higher emissions scenario, warm season VPD over the next 30 years will increase at a rate similar to that observed from 1979 through 2020 (Zhuang *et al.*, 2021).

From 1985 through 2017, the annual area burned by high-severity fires across forests in the western United States increased eightfold (Parks and Abatzoglou, 2020). The frequency of large forest fires has also increased: such fires now occur nearly every year in the Northwest (Rupp and Holz, 2023). About half of the observed increase in vegetation dryness in the western United States from 1984 through 2015—again, driven mainly by the dryness of the air—and 16,000 square miles (4.2 million hectares) of burned area were attributable to human-caused climate change (Abatzoglou and Williams, 2016). Area burned is more strongly correlated with VPD than with other drought indices or variables, such as temperature and precipitation (Sedano and Randerson, 2014; Williams *et al.*, 2014; Seager *et al.*, 2015; Rao *et al.*, 2022). CMIP5 models projected that increases in VPD would contribute substantially to wildfire risk in Oregon (Ficklin and Novick, 2017; Chiodi *et al.*, 2021) and across the West (Abatzoglou *et al.*, 2021a; Zhuang *et al.*, 2021; Juang *et al.*, 2022).
Historically, wildfires were less active overnight, and the probability of fire expansion generally was evaluated on the basis of daytime conditions. However, across the western United States, the number of nights during which atmospheric conditions are conducive to burning has increased by 45% since 1979 (Balch et al., 2022). The intensity and duration of wildfires is expected to increase as nights continue to become hotter and drier (Chiodi et al., 2021; Balch et al., 2022).

**Land Use and Wildfire Risk**

Stand-replacing fires, such as the Tillamook series between 1933 and 1951 and the Yaquina and Nestucca fires in the latter half of the nineteenth century, periodically occur in the cool, moist coastal forests of the Northwest. Lightning is rare in this region, however, and the number of large fires historically was low (Holz et al., 2021). Yet projections that include concurrent increases in aridity, temperature, and intensification of land use (which leads to an increase in human ignitions; see below) indicate that area burned and the frequency and intensity of wildfires will continue to increase in the Pacific Northwest, even in relatively wet areas of western Oregon (Sheehan et al., 2015; Dalton et al., 2017; Mote et al., 2019; Dalton and Fleishman, 2021; Rupp and Holz, 2023). The average annual area burned in Oregon’s forests is expected to increase by at least 50% over the next several decades under the lower emissions scenario (Rupp and Holz, 2023). Within national forests in the western Cascade Range, the number of wildfires is projected to increase by 20–140% from 1986–2015 to 2070–2099 under the higher emissions scenario (Heidari et al., 2021). In addition, an increase in the annual average temperature of 2°C (3.6°F) above the 2002–2020 average was projected to double the annual number of extreme, single-day spreading wildfires in the Cascade Range and elsewhere in the western United States (Coop et al., 2022). The interactions among housing development, the growth of tourism in forested areas, and increasing atmospheric dryness suggest that past projections of changing wildfire risk in the West may be underestimates (Rao et al., 2022). For example, neither Heidari et al. (2021) nor Coop et al. (2022) considered the response of Coast Range forests to longer, drier, and hotter summers.

Extreme wildfires often occur when weather conditions conducive to fire, including high temperatures, aridity, and wind speeds (Reilly et al., 2022), coincide, particularly when vegetation already is dry. These fires can cause widespread loss of structures and the loss of human lives (Abatzoglou et al., 2021b). The 1933 Tillamook fire was enabled in part by a warm and dry summer (as is typical in Oregon), the accumulation of highly flammable vegetation due to logging operations, and strong and dry east winds. Similar conditions facilitated the 2020 Labor Day fires in the western Cascade Range (Higuera and Abatzoglou, 2021). In both cases the dryness of the air was extraordinary and the ignition was human-caused.

Human activities have modified fire dynamics in western forests through fragmentation and exploitation of these ecosystems, suburban population growth and increased recreational activity, introduction of highly flammable, non-native annual grasses, and replacement of indigenous or natural fires by extensive fire suppression and vegetation management. Over half (53%) of Polk County is classified as evergreen forest (Oregon Explorer, 2023). These forests primarily occur on private land; some also occur on federal
land in the Coast Range (Oregon Explorer, 2023). Thirty-four percent of the county is classified as agricultural and six percent as urban.

Over 80% of ignitions in the United States are now human-caused (Balch et al., 2017), and human caused ignitions accounted for 88% of the fire starts in Polk County from 2008 to 2019 (Short, 2022). Most of these ignitions occurred at the interface between the eastern border of forests in western Polk County and agricultural land. Ignition from power generation, transmission, or distribution, often due to high winds, has been identified as the cause of many fires in California and of the Holiday Farm fire in the western Cascade Range. In Oregon’s coastal forests, where the density of housing is low, fire starts seem more likely to be caused by smoking, recreation, fireworks, or equipment and vehicle use. Sparks from logging equipment were responsible for starting the Tillamook fires in the 1930s. The fact that longer summers and human activities have extended the temporal and geographic extent of the fire season (Balch et al., 2017; Bowman et al., 2020; Jones et al., 2022) increases the chances that a late summer fire start could affect large areas of timberland and remnants of old growth.

Management practices likely affected the severity of the 2020 fires in Oregon (Allen et al., 2019; Downing et al., 2022). Uniform canopy structure, which is common in forest plantations and on private lands in the Coast Range, can lead to subcanopy winds that transport moisture out of the watershed (Drake et al., 2022). Crowning and torching associated with dry trees may increase the potential for long-distance spot fires that can cause rapid expansion of the fire front and overwhelm suppression efforts (Rothermel, 1991; Koo et al., 2010; Storey et al., 2020). Firebrands can be carried far by strong winds: in September 2017, embers from the Eagle Creek fire jumped across the Columbia River and started some spot fires on the Washington side.

**Duration and Magnitude of Wildfire Risk**

The duration of the wildfire season is increasing across the western United States (Dennison et al., 2014; Jolly et al., 2015; Westerling, 2016; Williams and Abatzoglou, 2016), and the duration of the fire weather season in forests of the Northwest increased by 43% from 1979 through 2019 (Jones et al., 2022). Anthropogenic emissions increased the likelihood of extreme fire weather during fall by about 40% over the western United States and about 50% over western Oregon, largely through drier vegetation in fall and warmer temperatures during dry wind events (Hawkins et al., 2022). Similarly, the number of days per year on which fire danger was extreme increased by 166% from 1979 through 2019 (Jones et al., 2022). Extreme fire danger was defined as the highest 5% of values of the Canadian Fire Weather Index, which is based on estimates of fuel moisture derived from temperature, precipitation, humidity, and wind (Van Wagner, 1987; Jones et al., 2022).

The Northwest Interagency Coordination Center ([gacc.nifc.gov/nwcc/](http://gacc.nifc.gov/nwcc/)) commonly uses the 100-hour fuel moisture (FM100) index to predict fire danger. FM100 is a measure of the percentage of moisture in the dry weight of dead vegetation with 1–3 inch diameter and is calculated from precipitation, temperature, and relative humidity according to the equations in the National Fire Danger Rating System (Bradshaw et al., 1984). A majority of climate models project that FM100 will decline, resulting in increased fire danger across Oregon by the 2050s (2040–2069) under the higher emissions scenario (Gergel et al., 2018).
2017). Projections of the Keetch–Byram Drought Index, a common fire index that is based on the response of vegetation moisture to precipitation and temperature, suggested that within the Northwest, the area with high fire danger in summer will increase by 345% from 1996–2004 to 2086–2094 under the higher emissions scenario (Brown et al., 2021). All of these methods project that the number of summer days with high fire danger in Oregon will increase through the end of the twenty-first century, particularly in the Cascade Range, Coast Range, and Klamath Mountains (Brown et al., 2021).

Projected Wildfire Risk in Polk County

Here, we estimate the future change in wildfire risk with two metrics, FM100 and VPD, that are proxies for extreme fire danger, or conditions under which wildfire is likely to spread. We present projected changes in the average annual number of days on which FM100 is very high and VPD is extreme for two future periods, both of which we compare to the historical baseline (1971–2000 average), under two emissions scenarios. We define a day with very high fire danger as one on which the FM100 value (moisture on the forest floor) is comparable to the lowest (driest) 10% of values within the historical baseline period (1971–2000). Historically, fire danger in Polk County was very high on 36.5 days per year. By the 2050s under the higher emissions scenario, the average number of days per year on which fire danger is very high is projected to increase by 11 (range -7–28) (Figure 15).

Similarly, we define a day with extreme VPD (dry air) as a day within the warm season (March–October) on which VPD is comparable to the highest (driest) 10% of values within the historical baseline period. Historically, VPD in Polk County was extreme on 24.5 days per year. Under the higher emissions scenario, the average number of days per year on which VPD is extreme is projected to increase by 25 (range 8–42) by the 2050s (Figure 16).
Figure 15. Projected changes by the 2020s (2010–2039 average) and 2050s (2040–2069 average), relative to the 1971–2000 historical baseline and under two emissions scenarios, in the number of days on which fire danger in Polk County is very high. Changes were calculated for each of 18 global climate models relative to each model's historical baseline, then averaged. Whiskers represent the range of changes across the 18 models. Eighteen of the full set of 20 models that were used to project temperature and precipitation included the data necessary to estimate fire danger. (Data source: Climate Toolbox, climatetoolbox.org/tool/Climate-Mapper)
Figure 16. Projected changes by the 2020s (2010–2039 average) and 2050s (2040–2069 average), relative to the 1971–2000 historical baseline and under two emissions scenarios, in the number of days on which vapor pressure deficit in Polk County is extreme. Changes were calculated for each of 20 global climate models relative to each model’s historical baseline, then averaged. Whiskers represent the range of changes across the 20 models. (Data source: Climate Toolbox, climatetoolbox.org/tool/Climate-Mapper)

Summary

Wildfire frequency and intensity and area burned are projected to continue increasing in the Northwest. Wildfire risk, expressed as the average number of days per year on which fire danger is very high, is projected to increase in Polk County by 11 days (range 7–28) by the 2050s, relative to the historical baseline, under the higher emissions scenario. The average number of days per year on which vapor pressure deficit is extreme is projected to increase by 25 (range 8–42) by the 2050s.
Climate change is expected to reduce outdoor air quality. Warmer temperatures may cause an increase in ground-level ozone concentrations, while more numerous and intense wildfires generate higher concentrations of fine particulate matter (particles less than 2.5 micrometers in diameter [PM$_{2.5}$]) and other pollutants (Rohlman *et al.*, 2023). Moreover, increases in pollen abundance and the duration of the pollen season may cause an increase in airborne allergens.

Poor air quality is expected to exacerbate allergy and asthma conditions and increase the incidence of respiratory and cardiovascular illnesses and death (Fann *et al.*, 2016). Excess asthma events due to PM$_{2.5}$ from wildfire smoke are projected to increase in Oregon by about 42 per 10,000 persons, resulting in a projected increase in cost of more than $250,000 per 10,000 persons (Stowell *et al.*, 2021). Those at high risk of adverse health outcomes as a result of wildfire smoke include people with preexisting conditions, outdoor workers, children, pregnant women, older adults, and rural and tribal communities (York *et al.*, 2020; Ho *et al.*, 2021). Poor air quality and increases in airborne allergens are most likely to affect communities with low incomes, high non-White or farmworker populations, or that are near highways and industrial facilities; outdoor workers, especially in urban areas with stagnant air and during harvest season in agricultural areas such as the Willamette Valley; and those with preexisting conditions (York *et al.*, 2020; Ho *et al.*, 2021). Recent and projected estimates of many of these populations are presented in previous sections.

**Wildfire Smoke**

Over the past several decades, the wildfire season has increased in length while the intensity and severity of wildfires have increased. This trend is expected to continue as a result of factors including traditional forest management practices (Downing *et al.*, 2022), increasing human population density in areas with high fire risk (Radeloff *et al.*, 2018), and climate change (Sheehan *et al.*, 2015). Wildfire smoke poses a much greater threat, in terms of deaths and total costs to society, than wildfire flames per se (Fleishman, 2023). Wildfire smoke also impairs visibility near ground level and at altitudes where firefighting aircraft and evacuation helicopters fly (Nolte *et al.*, 2018). Hazardous levels of air pollution are most common near wildfires, but extensive fires in the western United States in recent decades have generated taller plumes of smoke and injected a greater volume of PM$_{2.5}$ at high altitudes, increasing long-range transport of these particulates and posing a health hazard to larger numbers of people both near to and far from those wildfires (Wilmot *et al.*, 2022; Rupp and Holz, 2023).

Wildfires are the primary cause of exceedances of air quality standards for PM$_{2.5}$ in western Oregon and parts of eastern Oregon (Liu *et al.*, 2016), particularly in August and September (Wilmot *et al.*, 2021). Woodstove smoke and diesel emissions also contribute to poor air quality in Oregon (Oregon DEQ, 2016; Liu and Peng, 2019). Fine particulate matter from vehicles, woodstoves, and power plants can be regulated, but it is much more difficult to control wildfires.
Across the western United States, PM$_{2.5}$ concentrations from wildfires are projected to increase 160% by 2046–2051, relative to 2004–2009, under a moderate emissions scenario (SRES A1B) (Liu et al., 2016). The SRES A1B scenario, which is from a generation of emissions scenarios that preceded CMIP5, is most similar to RCP 6.0 (Figure 2). CMIP6 models that were integrated with an empirical statistical model projected that PM$_{2.5}$ concentrations in August and September in the Northwest will double under a lower (SSP5-4.5) emissions scenario and triple under a higher (SSP5-8.5) emissions scenarios by 2080–2100 compared to 1997–2020 (Xie et al., 2022). The Oregon Department of Environmental Quality monitors PM$_{2.5}$ during wildfire seasons with the U.S. Environmental Protection Agency’s Air Quality Index (AQI), which classifies air quality on the basis of potential health effects. In the Willamette Valley, concentrations of PM$_{2.5}$ from wildfire smoke from June 1 through October 20 began to increase and become less healthy around 2012 (Oregon DEQ, 2022).

Exposure to PM$_{2.5}$ aggravates chronic cardiovascular and respiratory illnesses (Cascio, 2018). In addition, because exposure to PM$_{2.5}$ increases susceptibility to viral respiratory infections, exposure to wildfire smoke is likely to increase susceptibility to and the severity of reactions from COVID-19 (Henderson, 2020). During the 2020 wildfires in the western United States, in 18 of 19 Oregon counties analyzed, the number of reported COVID-19 cases increased on days with active wildfire smoke (Zhou et al., 2021). Active wildfire smoke was defined as concentrations of PM$_{2.5}$ that exceeded 21 μg m$^{-3}$, a value within the moderate category of the AQI. Furthermore, wildfire smoke can disrupt outdoor recreational and social activities, in turn affecting physical and mental health (Nolte et al., 2018). For example, on September 11, 2020, Portland’s air quality deteriorated to hazardous and was the worst among major cities worldwide, causing many park closures and halting most outdoor activities (Green, 2020).

The negative effects of wildfire smoke extend beyond human health. For example, during the 2020 wildfire season, 62% of Oregon wineries reported not only unhealthy air that delayed harvest but impacts such as ash on grape skins and reduced sunlight that affected the size of grape clusters (IPRE, 2021). Eighteen percent of Oregon wineries reported smoke damage to their wines, with the majority of red wine grape varieties, particularly Pinot Noir, discarded by producers or not harvested (IPRE, 2021). The thin skin of Pinot Noir, Oregon’s signature grape, makes smoke exceptionally damaging.

Wildfires emit ozone precursors that in hot and sunny conditions react with other pollutants to increase the concentration of ozone. From 2000 through 2020, the frequency, duration, and area of co-occurrence of PM$_{2.5}$ and ozone increased in the western United States (Kalashnikov et al., 2022), including the Pacific Northwest (Buchholz et al., 2022). The population exposed to persistent extreme PM$_{2.5}$ and ozone levels in the West increased by 25 million person-days per year over the period 2001–2020 (Kalashnikov et al., 2022; Rupp and Holz, 2023).

Projected Changes in Air Quality in Polk County

We present projections of future air quality that are based on PM$_{2.5}$ from wildfire smoke. Smoke wave days are defined as two or more consecutive days on which simulated, county-averaged, wildfire-derived PM$_{2.5}$ values are in the highest 2% of simulated daily values.
from 2004 through 2009 (Liu et al., 2016). Smoke wave intensity is defined as the concentration of PM$_{2.5}$ on smoke wave days. Liu et al. (2016) projected mean number of smoke wave days and mean smoke wave intensity for two six-year periods, 2004–2009 and 2046–2051, under a moderate emissions scenario. More information about their methods is in the appendix.

The number of smoke wave days in Polk County is projected to decrease by 10%, but the intensity of smoke on those days is projected to increase by 162% (Figure 17). Polk County is among the 6.8% of counties in the western United States, largely in southwestern Oregon and northern California and Nevada, in which the intensity of the smoke on smoke wave days is projected to increase yet the number of smoke wave days is projected to decrease (Liu et al., 2016). This projected decrease in the number of smoke wave days is inconsistent with projected increases in wildfire occurrence. The apparent underestimation likely reflects that the smoke wave projections did not account for increases in the volume of woody vegetation or the continuity of grasses and forbs (Liu et al., 2016). The volume of woody vegetation is increasing in part as a result of fire suppression and fertilization by increasing atmospheric concentrations of carbon dioxide, and the distribution and density of non-native invasive grasses and forbs is increasing across much of the region. Regardless of how the number of smoke wave days changes, the projected increase in intensity of smoke poses a greater risk to human health.

Figure 17. Simulated present (2004–2009) and future (2046–2051) number (left) and intensity (right) of smoke wave days in Polk County under a moderate emissions scenario. Values represent the average among 15 global climate models. (Data source: Liu et al. 2016, khanotations.github.io/smoke-map/)
**Allergens and Other Airborne Organic Materials**

Plants are responding to changes in climate and atmospheric concentrations of carbon dioxide by producing more pollen, and by producing it earlier in spring and for longer periods of time (Ziska et al., 2009). From 1990 through 2018, pollen seasons increased by about 20 days and pollen concentration increased by 21% in the conterminous United States (Anderegg et al., 2021), including northern California (Paudel et al., 2021).

Fungal spores could also become more abundant following extreme floods or droughts, which are expected to become more common. The period during which outdoor airborne mold spores are detectable increased in the last 20 years as a result of increasing concentrations of carbon dioxide and changes in climate and land use (Paudel et al., 2021). Furthermore, because both ozone and fine particulate matter affect the sensitivity of respiratory systems to airborne allergens, the combined effects of climate change, air pollution, and changes in vegetation phenology will likely increase the severity of respiratory diseases and allergies (D’Amato et al., 2020).

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**Summary**

Climate change is expected to reduce outdoor air quality. The risks to human health from wildfire smoke in Polk County are projected to increase. Although the number of days per year with poor air quality due to elevated concentrations of wildfire-derived fine particulate matter is projected to decrease by 10%, the concentration of fine particulate matter is projected to increase by 162% from 2004–2009 to 2046–2051 under a moderate emissions scenario.
In the United States, wetlands are defined under the Clean Water Act as “areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas.” Wetlands also may be associated with the edges of lakes and with streams and rivers (Halofsky et al., 2019).

The extent of historic wetlands in the Willamette Valley has been reduced by an estimated 57–95% by agriculture, urbanization, timber harvest, and channelization of the Willamette River (Baker et al., 2004; Christy and Alverson, 2011; Fickas et al., 2016). About 4% of emergent, lacustrine, riparian, and riverine wetland area within the two-year floodplain inundation zone along the main stem Willamette River changed (became larger or smaller or changed among the latter four classes) from 1972 through 2012 (Fickas et al., 2016). The majority of losses resulted from conversion to agriculture (Daggett et al., 1998; Bernert et al., 1999; Fickas et al., 2016), and the greatest proportion of change reflected conversion of riparian to riverine wetland (Fickas et al., 2016). Some of the gains and losses in area related to agriculture may have been prompted by drought—creation of ponds in the former case, and farming of newly dry lands in the latter—and may not be permanent (Bernert et al., 1999).

Wetlands and their associated plants and animals are likely to be affected by increases in air temperature, which generally are correlated with increases in freshwater temperature; decreases in snowpack and summer stream flows; and increases in evapotranspiration (Lee et al., 2015). Projected effects in the Northwest include reductions in water levels and hydroperiod duration, and may be most pronounced in wetlands that become temporary in dry years (Lee et al., 2015). Wetlands along low-gradient, wide valley bottoms that are dominated by riparian trees and understory species may be most susceptible to decreases in flow and water volume, in part because recruitment of some riparian species depends on seasonal flooding (Dwire et al., 2018). Systems that are fed primarily by ground water may have more consistent temperature, water chemistry, and water levels than wetlands that are fed primarily by surface water (Halofsky et al., 2019). However, effects of climate change on ground water aquifers that are recharged by snowpack are uncertain (Dwire et al., 2018). Moreover, where increasing aridity leads to greater demand for ground water, decreases in ground water availability may affect wetlands. Additionally, changes in vegetation at the perimeter of wetlands that result from land use or changes in climate, such as replacement of riparian hardwoods to conifers and shrubs (Dwire et al., 2018), may affect water temperatures (Halofsky et al., 2019), chemistry, and nutrient cycles. If increases in temperature or decreases in water availability increase use of wetlands by domestic livestock, habitat quality for native species likely will decrease.

From 1994 through 1996, The Nature Conservancy of Oregon conducted an inventory of 172 wetlands and stream or river reaches in the Willamette Valley (Titus et al., 1996). Of those 172 locations, the effort identified 21, including the Luckiamute River and Santiam Bar in Polk County, as particularly high priorities for conservation. The inventory highlighted riparian forest at the confluence of the Luckiamute and Little Luckiamute
Rivers that were dominated by bigleaf maple (*Acer macrophyllum*) and Oregon ash (*Fraxinus latifolia*). The Santiam Bar is at the confluence of the Luckiamute and Willamette Rivers and near the confluence of the Santiam and Willamette Rivers. Dominant trees in the Santiam Bar include bigleaf maple, Oregon ash, black cottonwood (*Populus balsamifera ssp. trichocarpa*), and black hawthorn (*Crataegus douglasii*).

The Polk Soil and Water Conservation District encourages landowner participation in the Conservation Reserve Enhancement Program, a component of the U.S. Department of Agriculture Farm Service Agency’s Conservation Reserve Program. This voluntary, public–private partnership provides financial incentives and payments for restoration of wetlands and riparian ecosystems in agricultural areas. The intent of the program is to establish riparian buffers that will shade rivers and streams, protect water quality, provide habitat for riparian- and stream-associated animal species, prevent erosion, and reduce the likelihood of downstream flooding.

The 2016 Oregon Conservation Strategy (www.oregonconservationstrategy.org), developed by the Oregon Department of Fish and Wildlife, includes six conservation opportunity areas in Polk County that can contribute meaningfully to achieving goals for conservation of wetland-associated aquatic and terrestrial animals. These areas are Mill Creek, Rickreal Creek and Little Luckiamute River Headwaters, Red Prairie–Mill Creek–Willamina Oaks South, Baskett Butte, Eola Hills, and Luckiamute River and Tributaries. The eastern border of the county also overlaps with the Middle Willamette River Floodplain conservation opportunity area. Baskett Butte encompasses the 2492-acre (1008-hectare) Basket Slough National Wildlife Refuge.

**Summary**

Losses of wetlands in Polk County in recent decades largely were caused by their conversion to agriculture. Projected effects of climate change on wetlands in the Northwest include reductions in water levels and hydroperiod duration. If withdrawals of ground water do not increase, then wetlands that are fed by ground water rather than surface water may be more resilient to climate change.
Windstorms

Wind patterns in the northwestern United States affect natural disturbances, public health, and multiple sectors. For example, variability in winds affects generation of wind power and, via downed power lines, the reliability of electricity transmission. Changes in winds also affect the safety of transportation by air, land, and sea and the spread of wildfires and pollutants, including wildfire smoke and allergens. In Oregon, average near-surface wind speeds are expected to decrease slightly in the future in response to global climate change (Pryor et al., 2012; Jeong and Sushama, 2019; Chen, 2020; Mass et al., 2022). However, a decrease in the average wind speed may not translate to a decrease in strong winds. Although projections are highly uncertain, climate models tend to agree that the magnitude of extreme wind speed will increase in western Oregon (Pryor et al., 2012; Jeong and Sushama, 2019). Such increases are not projected in eastern Oregon. An extreme wind refers to an annual maximum wind speed with a given average return period, such as 20 or 50 years (annual exceedance probability of 5% or 2%, respectively).

Oregon’s location accounts for some of the uncertainty in the response of strong winds to human-caused emissions of greenhouse gases. The state’s most severe windstorms occur from October through April and are associated with extratropical cyclones (cyclones that occur from 30–60° latitude) (Read, 2003, 2007; Mass and Dotson, 2010). Future changes in wind speeds in extratropical cyclones are expected to be small, but the projected poleward shift in the storm tracks of these cyclones could lead to substantial changes in extreme wind speeds in some regions (Seneviratne et al., 2021). One study indicated that by 2081–2099 relative to 1981–1999, assuming the higher emissions scenario, extratropical cyclones that generate severe winds will shift northward by an average of 2.2° over the North Pacific Ocean (Seiler and Zwiers, 2016). Therefore, these extratropical cyclones will become more frequent north of 45°N and less frequent and weaker south of 45°N. Oregon lies between about 42°N and 46°N. Accordingly, although Seiler and Zwiers (2016) did not examine the landfall location of severe cyclones, it is uncertain whether the frequency of severe landfalling extratropical cyclones and the distribution of wind speeds will change in Oregon.

The intensity of strong offshore (easterly) winds, which are most common in summer and in fall before the onset of the rainy season, typically is lower than that of winter windstorms. Nevertheless, offshore winds play a major role in summer heat waves in Oregon, including the record-breaking June 2021 heat wave (Chang et al., 2021), because they displace cooler marine air west of the Cascade Range (Brewer and Mass, 2016). Projections from global climate models, assuming the higher emissions scenario, suggest a decrease in the frequency of strong offshore winds over western Oregon and Washington in July and August, with about a 50% reduction from 1970–1999 to 2071–2100 in the number of days with easterly wind speeds greater than approximately 11 miles per hour (5 meters per second) measured at approximately 5000 feet (1.5 km or 850-hPa) above Earth’s surface (Brewer and Mass, 2016).

Easterly winds were key drivers of the largest wildfires on record in western Oregon, including the 2020 Labor Days fires (Abatzoglou et al., 2021b; Mass et al., 2021; Reilly et al., 2022). The results of regional climate models that accounted for topographic effects on
wind indicated that from the preindustrial to the current era, the frequency of fall (September through November) easterly winds along the Cascade Range in Oregon decreased by about 2% (Hawkins et al., 2022). The latter research defined easterly winds as those with horizontal speeds of at least 13 meters per second (approximately 29 miles per hour) and downward speeds of at least 0.6 Pascals per second (at 0°C [32°F], approximately 2 inches per second or 10 feet per minute), both measured at 10,000 feet (700 hPa) above Earth’s surface, and near-surface relative humidity no greater than 30%. By the year 2099 relative to 1970, assuming the higher emissions scenario, the frequency of 10-meter (approximately 33 feet) easterly winds with a daily maximum exceeding 3.4 meters per second (7.6 miles per hour), which is one standard deviation above the average wind speed, decreased modestly west of the Cascade Range (Mass et al., 2022). For example, in Alpine, Washington, the annual number of days with such winds decreased from 15 to 11 (Mass et al., 2022).

Understanding of how anthropogenic emissions may affect local winds in Oregon remains limited. Due to their coarse spatial resolution, global climate models and all but the highest-resolution regional climate models cannot adequately simulate mountain slope, valley, and coastal winds, sea breezes, and winds associated with mesoscale convective systems (Doblas-Reyes et al., 2021). Large numbers of simulations from multiple high-resolution (1 to 10 km [0.6 to 6 mi]) regional climate models ultimately will be required to estimate changes in these types of winds across Oregon with high confidence.

**Summary**

Wind patterns affect provision of electricity, transportation safety, and the spread of wildfires and pollutants. Mean wind speeds in Oregon are projected to decrease slightly, but extreme winter wind speeds may increase, especially in western Oregon. The frequency of strong easterly winds during summer and autumn, however, is projected to decrease slightly.
Expansion of Non-native Invasive Species

Changes in climate and atmospheric concentrations of carbon dioxide can affect the distribution and population dynamics of native and non-native species of animals and plants that are considered to be invasive or pests in natural and agricultural systems. Species-environment relations are not static (MacDonald, 2010; Walsworth et al., 2019). Therefore, even when the current ecology of a species is well understood, it often is difficult to predict with confidence how the species will respond to projected changes in climate, especially when climate change interacts with land-use change or other environmental changes. Species adapt not only in response to climate change but in response to all types of environmental change, including management actions (Thomas et al., 1979; Skelly et al., 2007; Winter et al., 2016). These responses may be rapid, on the order of years or decades, especially when organisms have short generation times (Boughton, 1999; MacDonald et al., 2008; Willis and MacDonald, 2011; Singer, 2017). Adaptive capacity also is affected by whether individuals can move freely or whether habitat fragmentation and other barriers impede movement (Thorne et al., 2008; Willis and MacDonald, 2011; Fleishman and Murphy, 2012). Monocultures, dense populations, and even-aged populations of animals or plants generally are more susceptible to pests and pathogens than individuals in areas with higher species richness or populations with greater demographic diversity.

Aquatic Animals

The Polk County Soil and Water Conservation District identifies ten high-priority, non-native invasive species of animals that may pose considerable economic and ecological threats to aquatic systems in Oregon: New Zealand mudsnail (Potamopyrgus antipodarum), quagga mussel (Dreissena rostriformis), zebra mussel (Dreissena polymorpha), Chinese mystery snail (Cipangopaludina chinensis), Asian carp (Cyprinus carpio), mitten crab (Eriocheir sinensis), pond loach or Oriental weatherfish (Misgurnus anguillicaudatus), northern snakehead (Channa argus), red-eared slider (Trachemys scripta elegans), and snapping turtle (Chelydra serpentina). There is evidence or informed speculation about how some of these species may respond to projected changes in climate. Nevertheless, most of these species thrive across a wide range of environmental conditions, and the probability of their future expansion may not be strongly related to climate change.

New Zealand mudsnails can survive weeks of desiccation, and especially where minimum water temperatures are above freezing, the species’ distribution may be relatively independent of climate change. The Oregon Department of Fish and Wildlife notes that expansion of the species in Oregon likely will lead to predation on native invertebrates and competition with native trout. In Idaho, densities of New Zealand mudsnails were highest during summer, whereas near to below-freezing water temperatures were associated with reduction in population size (Moffitt and James, 2012).

Quagga and zebra mussels also compete with native fishes for food. Both occur across a wide gradient of water temperatures. Worldwide, zebra mussels occur in waters with temperatures 10.8–29.4°C (51–85°F) (Feng et al., 2020), and likely can tolerate both higher water temperatures and longer durations of high temperatures than quagga mussels (Thorp et al., 1998). In the eastern United States, growth rates of zebra mussels during fall and early winter, but not during summer and early fall, increased when temperatures were
experimentally increased (Thorp et al., 1998). If higher water temperatures lead to stratification of the water column, the mussels may become food-limited. Exposure of quagga mussel to cyanobacteria associated with harmful algal blooms may inhibit spawning or fertilization, especially if the blooms occur relatively early in the year and overlap with spawning (Boegehold et al., 2018).

Asian carp are highly adaptable and may gain a competitive advantage over quagga and zebra mussels if water columns stratify (Souza et al., 2022). In the laboratory, development of eggs to larvae accelerated as temperatures were increased experimentally from 16°C (61°F) to 24°C (75°F), and larval size increased as temperatures increased (Réalis-Doyelle et al., 2018). Some work suggested that mortality of Asian carp tends to increase, and body size to decrease, as water temperatures increase (Weber et al., 2015). Others found that the species can maintain or even reduce its metabolism and rate of oxygen consumption as it acclimates to warmer temperatures (Opinion et al., 2021). Exposure to nitrate (the main nutrient that causes eutrophication) in addition to warmer temperatures did not increase the metabolic rate or stress tolerance of Asian carp, and in some cases was even associated with a decrease (Opinion et al., 2021).

Mitten crabs prey on native invertebrates and can lead to erosion of stream banks into which they burrow. The species’ distribution may be limited to areas with mean annual temperatures of 10–20°C (50–68°F) (Zhang et al., 2019).

Red-eared sliders generally are believed to compete with western pond turtles (Actinemys marmorata), which are listed as sensitive in Oregon, for basking and nesting sites and food. However, field data are limited (Lambert et al., 2019), and it is possible that as the abundance of western pond turtles decreases for other reasons, the abundance of red-eared sliders increases. Predators of both species include introduced American bullfrogs (Lithobates catesbeianus); centrarchid fishes; raccoons (Procyon lotor), coyotes (Canis latrans), corvids, and other native vertebrates; and domestic dogs and cats. Sparse vegetation cover, often a result of livestock grazing, exposes nesting turtles to predation and can increase the temperatures to which they are exposed. High temperatures skew sex ratios toward females and reduce population growth rates. Some predators of the turtles may tolerate or adapt to increases in temperature, changing the functional form of the interaction between those two stressors.

Snapping turtles also compete with native turtles. Whether snapping turtles will adapt genetically to changes in climate is uncertain. Climate was not significantly associated with variation in either genes with known function that may be affected by selection or genes believed to be neutral (Byer et al., 2021). Furthermore, in a population in Ontario, Canada, primary sex ratios (those at the time of conception) were stable from 1982 to 2020 despite warming. The latter may reflect that nest temperature and development rate were more responsive to maximum daily temperature than minimum daily temperature, and minimum temperature is warming more than maximum temperature (Leivesley et al., 2022).

In Nebraska, egg mass, clutch size, and clutch mass relative to body size of snapping turtles were positively associated with mean daily maximum temperature in September and October of the year prior to reproduction. Following warm falls, the clutch size of relatively
small turtles increased, whereas egg mass of relatively large turtles increased (Hedrick et al., 2018). Some evidence suggests that sex ratios of snapping turtles are female-biased at temperatures below about 24.5°C (76°F), male-biased from about 24.5–30°C (86°F), and restricted to females above about 30°C (O’Steen, 1998). Morbidity and mortality have been observed when daily maximum soil temperatures exceed about 37.5°C (100°F) and 40°C (104°F), respectively (Ewert et al., 2005).

**Plants**

In Oregon, A listed weeds are species of known economic importance that occur in small enough populations in the state to make eradication or containment possible, or are not known to occur in the state, but are present in neighboring states and likely to colonize Oregon. B listed weeds are species of economic importance that are regionally abundant but have patchy distributions. The Oregon Department of Agriculture’s WeedMapper (www.oregon.gov/oda/programs/weeds/pages/weedmapper.aspx) documents virtually no populations of A listed weeds in Polk County, but more than one or two populations of 19 B listed weeds (Table 15). WeedMapper does not track all of the weeds on either the A or B lists, and almost certainly underestimates species distributions. Although little is known about how many of these species may to respond to climate change, some evidence suggests how others may be affected. In general, non-native invasive plants are likely to become more prevalent in response to projected changes in climate. However, many of these responses are uncertain, and are likely to vary locally. Moreover, the responses may change over time.

Table 15. Oregon B listed weeds with occurrences in Polk County documented by the Oregon Department of Agriculture.

<table>
<thead>
<tr>
<th>Species</th>
<th>Growth form</th>
</tr>
</thead>
<tbody>
<tr>
<td>Armenian blackberry (<em>Rubus armeniacus</em>)</td>
<td>Shrub</td>
</tr>
<tr>
<td>Bohemian knotweed (<em>Fallopia x bohemicum</em>)</td>
<td>Perennial forb</td>
</tr>
<tr>
<td>Bull thistle (<em>Cirsium vulgare</em>)</td>
<td>Annual or biennial forb</td>
</tr>
<tr>
<td>Canada thistle (<em>Cirsium arvense</em>)</td>
<td>Perennial forb</td>
</tr>
<tr>
<td>English hawthorn (<em>Crataegus laevigata</em>)</td>
<td>Tree</td>
</tr>
<tr>
<td>False brome (<em>Brachypodium sylvaticum</em>)</td>
<td>Perennial grass</td>
</tr>
<tr>
<td>Field bindweed (<em>Convolvulus arvensis</em>)</td>
<td>Perennial forb</td>
</tr>
<tr>
<td>Giant knotweed (<em>Fallopia sachalinensis</em>)</td>
<td>Perennial forb</td>
</tr>
<tr>
<td>Herb Robert geranium (<em>Geranium robertianum</em>)</td>
<td>Annual or biennial forb</td>
</tr>
<tr>
<td>Himalayan knotweed (<em>Polygonum polystachyum</em>)</td>
<td>Perennial forb</td>
</tr>
<tr>
<td>Japanese knotweed (<em>Fallopia japonica</em>)</td>
<td>Shrub</td>
</tr>
<tr>
<td>Meadow knapweed (<em>Centaurea pratensis</em>)</td>
<td>Perennial forb</td>
</tr>
<tr>
<td>Perennial peavine (<em>Lathyrus latifolius</em>)</td>
<td>Herbaceous forb</td>
</tr>
<tr>
<td>Purple loosestrife (<em>Lythrum salicaria</em>)</td>
<td>Perennial forb</td>
</tr>
<tr>
<td>Scotch broom (<em>Cytisus scoparius</em>)</td>
<td>Shrub</td>
</tr>
<tr>
<td>Shiny leaf geranium (<em>Geranium lucidum</em>)</td>
<td>Annual or biennial forb</td>
</tr>
<tr>
<td>Spotted knapweed (<em>Centaurea stoebe</em>)</td>
<td>Short-lived perennial forb</td>
</tr>
<tr>
<td>St. Johnswort (<em>Hypericum perforatum</em>)</td>
<td>Shrub</td>
</tr>
</tbody>
</table>
Carbon dioxide, nitrogen, and ozone concentrations. Increasing concentrations of carbon dioxide not only lead to increases in global temperature, but affect some plants' primary productivity, water-use efficiency, and nutrient content. Increases in photosynthesis in response to increases in carbon dioxide are more common in plants with C3 metabolism than in plants with C4 metabolism. C4 metabolism has evolved multiple times, usually as an adaptation to hot, dry climate. Plants with C4 metabolism lose considerably less water per unit of carbon dioxide absorbed, and tend to photosynthesize more efficiently, than plants with C3 metabolism. By contrast, tolerance of the herbicide glyphosate, the active ingredient in Roundup, tends to increase more in C4 than in C3 plants as carbon dioxide increases (Chen et al., 2020). Experiments suggested that the photosynthetic rate and biomass of Canada thistle, and the number and length of the species' spines, are likely to increase as ambient concentrations of carbon dioxide increase throughout the twenty-first century, and may have increased during the previous century (Ziska, 2002). Whether the root biomass of Canada thistle responds positively to increases in carbon dioxide concentrations, especially independent of increases in temperature, is unclear (Ziska et al., 2004; Torresen et al., 2020), and may vary in space. Furthermore, both bull thistle and Canada thistle can establish readily in soils that have been disturbed by high-severity wildfires, which may become more common as climate changes, or by logging (Reilly et al., 2020).

Changes in climate, ongoing human additions of nitrogen to the environment, and their interactions also affect the growth and competitive relations among plant and animal species (Greaver et al., 2016). The competitive advantage of non-native forbs and grasses over native taxa may be strongest in relatively warm and dry microclimates, which often coincide with lower elevations (Dodson and Root, 2015). Moreover, non-native invasive plants generally gain a competitive advantage from nitrogen deposition. For example, Japanese knotweed may be more likely to outcompete native species when nitrogen availability is variable or episodic (Parepa et al., 2013). However, how field experiments with supplemental nitrogen relate to changes in nitrogen deposition or availability as a result of climate change is uncertain. Japanese knotweed also is fairly tolerant of high temperatures, drought, saturated soils, and fire (Clements and DiTommaso, 2012).

As tropospheric concentrations of ozone continue to increase, productivity of native and agricultural plants generally is expected to decrease. However, ozone tolerance in weedy, vegetatively reproducing species may increase relatively quickly, allowing them to gain a competitive advantage over some crops (Grantz and Shrestha, 2006).

Temperature. Responses of non-native invasive plants to increases in temperature are diverse, even within the same species. For example, photosynthesis in Japanese knotweed currently is constrained by temperatures below freezing (Baxendale and Tessier, 2015). The range of Japanese knotweed is expanding northward, perhaps reflecting evolution of frost tolerance (Clements and DiTommaso, 2012), and the species may continue to become more widespread or abundant as minimum temperatures increase. Warming also increased seed mass of diffuse knapweed independent of increases in carbon dioxide (Li et
Scotch broom usually is not highly tolerant of frost in fall, although populations can become more frost-tolerant over time (Strelau et al., 2018; Winde et al., 2020).

The flowering phenology of purple loosestrife, which readily colonizes wetlands, is adapted to the duration of the growing season. At northern latitudes, including Oregon, purple loosestrife flowers early, at a small size; at southern latitudes, it flowers later, at a larger size (Colautti and Barrett, 2013). Early flowering limits reproductive growth of purple loosestrife, and northern plants generally produce fewer seeds and have less population-level genetic variation than southern plants (Colautti et al., 2010). Climate change is expected to prolong the growing season, and therefore to increase the long-term viability of purple loosestrife, although local adaptation may be relatively slow due to genetic constraints of flowering time (Colautti et al., 2010, 2017).

**Precipitation and water availability.** Changes in the amount and timing of precipitation may contribute to expansion or contraction of different non-native invasive plants. Some species that occur in Polk County tend to have high drought tolerance. For example, spotted knapweed may be outcompeted by some native grasses (e.g., bluebunch wheatgrass [*Pseudoroegneria spicata*]) during drought, but may have a competitive advantage when precipitation is closer to average (Pearson et al., 2017). Monocultures of spotted knapweed appear to be less affected by drought (Pearson et al., 2017). Evidence of drought tolerance in Scotch broom is equivocal, especially in the field rather than in greenhouse experiments (Potter et al., 2009; Hogg and Moran, 2020). The growth and survival of Scotch broom in relatively open woodlands and forests may increase as snow depths decrease, especially during the winter after germination (Stevens and Latimer, 2015).

**Wildfire and other disturbances.** The density and distribution of weedy plants tends to increase in response to ground disturbance, whether from wildfire, livestock grazing, recreational activities, or removal of overstory trees and shrubs. Some non-native plants also contribute to a positive feedback cycle by increasing the probability of disturbances that facilitate their population growth. To illustrate, the rapid expansion of non-native invasive grasses has increased fine-fuel biomass and spatial continuity of fuels (Balch et al., 2013; Kerns et al., 2020; Tortorelli et al., 2020).

### Summary

Expansion of most of the non-native invasive species of aquatic animals that are high priorities in Polk County may become somewhat more likely as climate changes. Nevertheless, many of these species tolerate a wide range of environmental conditions, and climate change may not be a primary driver of their distribution and abundance. In general, non-native invasive plants in Polk County are likely to become more prevalent in response to projected increases in temperature and the frequency, duration, and severity of drought. However, many of these responses are uncertain, are likely to vary locally, and may change over time.
Appendix

We projected future climate and hydrology on the basis of outputs from twenty global climate models (GCM) and two emissions scenarios (Representative Concentration Pathway [RCP] 4.5 and RCP 8.5) from the fifth phase of the Coupled Model Intercomparison Project (CMIP5) (Table A1).

Table A1. The 20 global climate models (GCMs) from the fifth phase of the Coupled Model Intercomparison Project (CMIP5) represented in this report. Asterisks (*) indicate the ten GCMs used as inputs to the Variable Infiltration Capacity hydrological model in the Integrated Scenarios of the Future Northwest Environment project. Carets (^) indicate the GCMs that do not include daily relative humidity.

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Modeling Center</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCC-CSM1-1</td>
<td>Beijing Climate Center, China Meteorological Administration</td>
</tr>
<tr>
<td>BCC-CSM1-1-M*</td>
<td>College of Global Change and Earth System Science, Beijing Normal University, China</td>
</tr>
<tr>
<td>BNU-ESM</td>
<td>Canadian Centre for Climate Modeling and Analysis</td>
</tr>
<tr>
<td>CanESM2*</td>
<td>National Centre for Atmospheric Research, USA</td>
</tr>
<tr>
<td>CNRM-CM5*</td>
<td>National Centre of Meteorological Research, France</td>
</tr>
<tr>
<td>CSIRO-Mk3-6-0*</td>
<td>Commonwealth Scientific and Industrial Research Organization/Queensland Climate Change Centre of Excellence, Australia</td>
</tr>
<tr>
<td>GFDL-ESM2G</td>
<td>NOAA Geophysical Fluid Dynamics Laboratory, USA</td>
</tr>
<tr>
<td>GFDL-ESM2M</td>
<td>Met Office Hadley Center, UK</td>
</tr>
<tr>
<td>INMCM4</td>
<td>Institute for Numerical Mathematics, Russia</td>
</tr>
<tr>
<td>IPSL-CM5A-LR</td>
<td>Institut Pierre Simon Laplace, France</td>
</tr>
<tr>
<td>MIROC5*</td>
<td>Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies, Japan</td>
</tr>
<tr>
<td>MIROC-ESM</td>
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<tr>
<td>MIROC-ESM-CHEM</td>
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</tbody>
</table>
MACA Downscaling

The coarse horizontal resolution of the GCM outputs (100–300 km) was statistically downscaled to a resolution of about 6 km with the Multivariate Adaptive Constructed Analogs (MACA) statistical downscaling method, which is skillful in complex terrain (Abatzoglou and Brown, 2012). A detailed description of the MACA method is at climate.northwestknowledge.net/MACA/MACAmethod.php. The MACA method uses gridded observational data to train the downscaling. It applies bias corrections and matches the spatial patterns of observed coarse-resolution to fine-resolution statistical relations. The downscaled variables include daily maximum and minimum temperature, maximum and minimum relative humidity, specific humidity, precipitation, wind, and downward solar radiation at the surface from 1950 through 2099. All simulated climate data were bias-corrected with quantile mapping, which adjusts simulated values by comparing the cumulative probability distributions of simulated and observed values. In practice, the simulated and observed values of a variable over the historical time period are sorted and ranked, and each value is assigned a probability of exceedance. The bias-corrected value of a given simulated value is assigned the observed value that has the same probability of exceedance as the simulated value. The historical bias in the simulations is assumed to be constant. Therefore, the relations between simulated and observed values in the historical period were applied to the future scenarios. Climate data in the MACA outputs reflect quantile mapping relations for each non-overlapping 15-day window in the calendar year.

Climate and Fire Danger Variables

We used MACA-downscaled minimum and maximum temperature and precipitation data to characterize heat waves, cold waves, and heavy precipitation. We characterized wildfire risk on the basis of vapor pressure deficit (VPD) and 100-hour fuel moisture (FM100), which were computed by the Integrated Scenarios of the Future Northwest Environment project (climate.northwestknowledge.net/IntegratedScenarios/) with the MACA climate variables according to the equations in the National Fire Danger Rating System (Bradshaw et al., 1984). FM100 projections are only available for 18 GCMs because two models (CCSM4 and Nor-ESM1-M) do not include relative humidity at a daily time step. Calculation of FM100 requires daily relative humidity data.

Hydrological Simulations and Variables

We used streamflow data from the Integrated Scenarios project to characterize changes in the timing of seasonal streamflow, which affects the likelihood of drought and flooding, and changes in extreme flood magnitudes.

The Integrated Scenarios project used MACA downscaled climate data as the inputs to their simulations of hydrology, which they ran with the Variable Infiltration Capacity (VIC)
hydrological model (VIC version 4.1.2; Liang et al., 1994 and updates). VIC was applied to ten GCMs and run on a 1/16° x 1/16° (6 km) grid (Table A1). We used the hydrological simulations of snow water equivalent (SWE), runoff, and soil moisture to project drought. The Integrated Scenarios project bias-corrected hydrology variables (excepting SWE) for each month with quantile mapping. The project estimated daily streamflow by routing daily runoff from VIC grid cells to selected locations along the stream network. Where records of naturalized flow were available, the daily streamflow estimates were bias-corrected for each month with quantile mapping. As a result, their statistical distributions matched those of the naturalized streamflows.

**Air Quality Data**

Our projections of air quality are based on smoke wave data from Liu et al. (2016), which are available at khannotations.github.io/smoke-map/. We used two variables, “Total # of SW days in 6 yrs” and “Average SW Intensity”. The former is the number of days within each time period on which the concentration of fine particulate matter (PM$_{2.5}$), averaged within the county, exceeded the 98th quantile of the distribution of daily, wildfire-specific PM$_{2.5}$ values from 2004 through 2009 (smoke wave days). The latter is the average concentration of PM$_{2.5}$ across smoke wave days within each time period. Liu et al. (2016) used 15 GCMs from the third phase of the Coupled Model Intercomparison Project under a moderate emissions scenario (SRES-A1B) as inputs to a fire prediction model and the GEOS-Chem three-dimensional global chemical transport model. The available data include only the multiple-model mean value (not the range), which should be interpreted as the direction of projected change rather than the actual expected value.
Literature Cited


