Future Climate Projections
Wallowa County, Oregon

April 2022

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

Report to the Oregon Department of Land Conservation and Development

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Executive Summary

Climate change is expected to increase the occurrence of many climate-related natural hazards. 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 theoretical principles underlying increasing temperatures in response to ongoing emissions of greenhouse gases. 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, yet these risks are influenced by multiple secondary factors in addition to increasing temperatures. Confidence in projections of changes in risks is indicated as low if projections suggest relatively few to no changes or evidence is limited.

Table 1. Projected direction and level of confidence in changes in the risks of climate-related natural hazards. 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 there is moderate evidence in the peer-reviewed literature and that the direction of change is consistent among more than half of models. Low confidence means 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>Reduced Air Quality</td>
<td>Drought</td>
<td>Heavy Rains</td>
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<td>Expansion of Pests, Pathogens, &amp; Non-native Invasive Species</td>
<td>Flooding</td>
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<td>Wildfire</td>
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<td>Loss of Wetlands</td>
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<td></td>
<td>Heat Waves</td>
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<tr>
<td>Risk Unchanging</td>
<td>Windstorms</td>
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<td></td>
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<tr>
<td>Risk Decreasing</td>
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<td></td>
<td>Cold Waves</td>
</tr>
</tbody>
</table>
This report presents future climate projections for Wallowa County relevant to specific natural hazards for the 2020s (2010–2039) and 2050s (2040–2069) relative to the 1971–2000 historical baseline. The projections are presented for a lower greenhouse gas emissions scenario (RCP 4.5) as well as a higher greenhouse gas emissions scenario (RCP 8.5), with multiple global climate models. 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 are included in the main report.

Heat Waves

The number, duration, and intensity of extreme heat events is expected to increase as temperatures continue to warm.

In Wallowa County, the number of extremely hot days (days on which the temperature in 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 (RCP 4.5) and higher (RCP 8.5) emissions scenarios.

In Wallowa County, the number of days per year with temperatures 90°F or higher is projected to increase by an average of 25 days (range 7–35 days) by the 2050s relative to the 1971–2000 historical baselines, under the higher emissions scenario.

In Wallowa County, the temperature on the hottest day of the year is projected to increase by an average of nearly 8°F (range 3–10°F) by the 2050s, relative to the 1971–2000 historical baselines, under the higher emissions scenario.

Cold Waves

Cold extremes will become less frequent and intense as the climate warms.

In Wallowa County, the temperature on the coldest night of the year is projected to increase by an average of 10°F (range 1–18°F) by the 2050s, relative to the 1971–2000 historical baselines, under the higher emissions scenario.

In Wallowa County, the number of cold days (maximum temperature 32°F or lower) per year is projected to decrease by an average of 19 days (range -11–-27 days) by the 2050s, relative to the 1971–2000 historical baselines, under the higher emissions scenario.

Heavy Rains

The intensity of extreme precipitation is expected to increase as the atmosphere warms and holds more water vapor.

In Wallowa County, the number of days per year with at least 0.75 inches of precipitation is projected to increase by about 1 day 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 16% (range 6–26%) and 11% (range 1–20%), respectively, by the 2050s, relative to the 1971–2000 historical baselines, under the higher emissions scenario.

In Wallowa County, the number of days per year on which a threshold for landslide risk, which is based on 3-day and prior 15-day precipitation accumulation, is exceeded is projected to increase by 1 day (range 0–3 days) by the 2050s, relative to the 1971–2000
historical baselines, under the higher emissions scenario. 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 Wallowa County’s Blue Mountains, 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 Wallowa County by the 2050s.

**Wildfire**
Wildfire risk, expressed as the average number of days per year on which fire danger is very high, is projected to increase in Wallowa County by 16 days (range -4 – 38) by the 2050s, compared to the historical baseline, under the higher emissions scenario.

In Wallowa County, the average number of days per year on which vapor pressure deficit is extreme is projected to increase by 31 days (range 12 – 44) by the 2050s, compared to the historical baseline, under the higher emissions scenario.

**Reduced Air Quality**
The risk of exposure to wildfire smoke in Wallowa County is projected to increase.

In Wallowa County, the number of days per year on which the concentration of wildfire-derived fine particulate matter results in poor air quality is projected to increase by 150%, and the concentration of fine particulate matter is projected to increase by 73%, from 2004–2009 to 2046–2051 under a medium emissions scenario.

**Loss of Wetlands**
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.

**Windstorms**
Limited research suggests little if any change in the frequency and intensity of windstorms in the Northwest as a result of climate change.

**Expansion of Pests, Pathogens, and Non-native Invasive Species**
In general, invasive and pest species in Wallowa County are likely to become more prevalent in response to projected increases in temperature, especially minimum winter temperature, and increases in 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). Climate change is expected to increase the likelihood of natural hazards such as heavy rains, river flooding, drought, heat waves, wildfires, episodes of poor air quality, and to decrease the likelihood of cold waves.

Oregon’s Department of Land Conservation and Development (DLCD) contracted with the Oregon Climate Change Research Institute (OCCRI) to analyze the influence of climate change on natural hazards. The scope of the analysis that yielded this report is limited to the geographic area encompassed by Coos, Curry, and Wallowa Counties, Oregon, which are the focus of the Pre-Disaster Mitigation (PDM) 18 grants that DLCD received from the Federal Emergency Management Agency. Products of this 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 Natural Hazards Mitigation Plan (NHMP) updates for the three counties, and can be used in other county plans, policies, and programs. In addition to the county reports, OCCRI will share data and provide other technical assistance to the counties. This report covers climate change projections related to natural hazards relevant to Wallowa County.

Table 2. Selected natural hazards and related climate metrics.

<table>
<thead>
<tr>
<th>Heat Waves</th>
<th>Cold Waves</th>
</tr>
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<tbody>
<tr>
<td>Hottest Day, Warmest Night</td>
<td>Coldest Day, Coldest Night</td>
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<tr>
<td>Hot Days, Warm Nights</td>
<td>Cold Days, Cold Nights</td>
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<table>
<thead>
<tr>
<th>Heavy Rains</th>
<th>River Flooding</th>
</tr>
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<tbody>
<tr>
<td>Wet Days, Landslide Risk Days</td>
<td>Atmospheric Rivers</td>
</tr>
<tr>
<td></td>
<td>Rain-on-Snow Events</td>
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<table>
<thead>
<tr>
<th>Drought</th>
<th>Wildfire</th>
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<tbody>
<tr>
<td>Summer Flow, Spring Snow</td>
<td>Fire Danger Days</td>
</tr>
<tr>
<td>Summer Soil Moisture</td>
<td>Extremely Dry Air Days</td>
</tr>
<tr>
<td>Summer Precipitation</td>
<td></td>
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<table>
<thead>
<tr>
<th>Reduced Air Quality</th>
<th>Loss of Wetlands</th>
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<tbody>
<tr>
<td>Days with Unhealthy Smoke Levels</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Windstorms</th>
<th>Expansion of Pests, Pathogens, and Non-native Invasive Species</th>
</tr>
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</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 resolution of projections from global climate models have been refined 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 (GCMs) are computer models of Earth's atmosphere, water, and land and their interactions over time and space. The models are grounded in the fundamental laws of physics (Figure 1). The most recent set of GCMs are those that were included in the sixth phase of the Coupled Model Intercomparison Project (CMIP6), the climate modeling foundation for the Intergovernmental Panel on Climate Change's Sixth Assessment Report, which was released in August 2021. Compared with previous generations of GCMs, the CMIP6 models generally have higher resolution, better represent Earth system processes, and improve simulation of recent mean values of climate change indicators (IPCC, 2021).

However, the GCMs used in this report were from the fifth phase of the Coupled Model Intercomparison Project (CMIP5) because downscaled data from CMIP6 are not yet widely available.

Differences in simulations of Oregon’s projected average temperature between CMIP5 and CMIP6 were estimated in the Fifth Oregon Climate Assessment (Dalton and Fleishman, 2021). The CMIP6 models generally projected greater warming over Oregon than the CMIP5 models, largely because temperature in the CMIP6 models was more sensitive to a doubling of atmospheric carbon dioxide. The latter outcome reflected a larger amplification of temperature increases by clouds within the CMIP6 models (Dalton and Fleishman, 2021; IPCC, 2021). Therefore, the CMIP5-based results in this report based on CMIP5 may underestimate increases in temperature if the CMIP6 models’ higher sensitivity to increases in atmospheric carbon dioxide is accurate.

GCMs are the most sophisticated tools for understanding Earth’s climate, but they still simplify the climate system. There are several ways to implement such simplifications in a GCM. As a result, different GCMs yield projections that are at least slightly different. Accordingly, it is best practice to average and report the range of projections from at least ten GCMs. More information about GCMs and uncertainty is in the Appendix.
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 calculations and, eventually, models. Various processes and components of the climate system became regularly included in scientific understanding of global climate calculations and, over the second half of the century as computing resources became available, formalized in global climate models. (Source: science2017.globalchange.gov)

Figure 2. Future scenarios of atmospheric carbon dioxide concentrations (left) and global temperature change (right) resulting from several different emissions pathways, called Representative Concentration Pathways (RCPs), which are considered in the fourth and most recent National Climate Assessment. (Source: science2017.globalchange.gov)

**Greenhouse Gas Emissions**

When scientists use GCMs to project future climate, they make an assumption about the quantity of global emissions of greenhouse gases. The GCMs then simulate the effects of those emissions on the air, water, and land over the next century. Because the precise amount of greenhouse gases that will be emitted over the next century is unknown, scientists use multiple scenarios of greenhouse gas emissions that correspond to plausible societal trajectories. The future climate projections in this report, which are based on CMIP5 models, use emissions scenarios called Representative Concentration Pathways...
(RCPs). The higher the volume of global emissions, the greater the projected increase in global temperature (Figure 2).

Projections in this report assume a lower emissions scenario (RCP 4.5) and a higher emissions scenario (RCP 8.5). These are the most commonly used scenarios in the peer-reviewed literature, and downscaled data representing the effects of these scenarios on local climate are available. The emissions scenarios for CMIP6 correspond to emissions scenarios for CMIP5. For CMIP6, the RCPs were augmented by shared socioeconomic pathways that describe more explicitly the social and economic scenarios corresponding to each RCP (Dalton and Fleishman, 2021; IPCC, 2021). More information about emissions scenarios is in the Appendix.

**Downscaling**

Global climate models simulate the climate across contiguous grid cells of about 60 by 60 miles each. To make these coarse-resolution simulations more locally relevant, GCM outputs are combined 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 GCM 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 past years. The average over the 30 past simulated 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 3).

Because each of the 20 GCMs is based on slightly different assumptions, each yields a slightly different value for the historical baseline. Therefore, this report presents the average and range of projected *changes* in values of climate variables relative to each model’s historical baseline rather than presenting the average and range of projected absolute values of variables. The average of the 20 historical baselines, called the *average historical baseline*, is also presented to aid in understanding the relative magnitude of projected changes. The average historical baseline and average projected future change can be used to infer the average projected future absolute value of a given variable. However, the average historical baseline and range of projected future changes cannot be used to infer the range of projected future absolute values.

**Table 3. Historical and future time periods averaged for projections.**

<table>
<thead>
<tr>
<th>Historical Baseline</th>
<th>2020s</th>
<th>2050s</th>
</tr>
</thead>
</table>
**How to Use the Information in this Report**

Because many ongoing and projected changes in climate are not well represented in the observational record, 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 considered as predictions of the weather on a specified date, but rather as projections of the long-term statistical aggregate of weather, or in other words, climate.\(^1\)

The projected direction and magnitude of change in values of climate variables in this report are best interpreted relative to the historical climate conditions under which a particular asset or system was designed to operate. For this reason, considering the projected changes between the historical and future periods allows one to envision how current natural and human systems of interest will 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 this report.

The information in this report can be used to

- Explore a range of plausible future outcomes that take into consideration the climate system’s complex response to increasing concentrations of greenhouse gases
- Envision how current systems may respond under climate conditions different from those under which the systems were designed to operate under
- Inform evaluation of potential mitigation actions within hazard mitigation plans to accommodate future conditions
- 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 2019 (Dalton and Fleishman, 2021). 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 of 1.8°F–5.4°F) under a lower emissions scenario (RCP 4.5) and by 5.0°F (range of 2.9°F–6.9°F) under a higher emissions scenario (RCP 8.5) (Dalton et al., 2017; Dalton and Fleishman, 2021). Furthermore, summers are projected to warm more than other seasons (Dalton et al., 2017; Dalton and Fleishman, 2021).

During the twenty-first century, average temperature in Wallowa County is projected to warm at a rate similar to that of Oregon as a whole (Figure 3). Projected increases in average temperature in Wallowa County relative to each GCM’s 1971–2000 historical baseline range from 1.2–4.1°F by the 2020s (2010–2039) to 2.2–7.8°F by the 2050s (2040–2069), depending on the emissions scenario and GCM (Table 4).

**Figure 3.** Projected annual average temperature in Wallowa 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 multi-model mean differences for the 2020s (2010–2039 average) and the 2050s (2040–2069 average) relative to the average historical baseline (1971–2000 average) are shown.

**Table 4.** Average (and range) of projected future changes in Wallowa County’s annual temperature relative to the historical baselines (1971–2000 average) of each of 20 global climate models under two emissions scenarios.
Heat Waves

Extreme heat has become more frequent and intense worldwide since the 1950s, largely due to human-caused climate change (IPCC, 2021). The number, duration, and intensity of extreme heat events in Oregon is projected to increase due to continued warming temperatures. In fact, the temperature on the hottest days in summer are projected to increase even more than the mean summer temperature in the Northwest (Dalton et al., 2017). Heat waves occur periodically as a result of natural variability, but human-caused climate change is increasing their severity (Vose et al., 2017). In addition, evidence of increases in summer extreme heat events defined by nighttime minimum temperatures is stronger than evidence of increases in extreme heat events based on maximum temperatures (Dalton and Fleishman, 2021).

Extreme heat can refer to days on which maximum or minimum temperatures are over a threshold, seasons in which temperatures are well above average, and heat waves, or multiple days on which temperature are above a threshold. This report presents projected changes in three metrics of extremes daytime heat (maximum temperature) and nighttime heat (minimum temperature) (Table 5).

Table 5. 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 Wallowa County, the number of hot days and warm nights, and the temperatures 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 6, 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 7–35. The average number of hot days per year is projected to be 25 more than the average historical baseline of 10 days. The average
The number of warm nights per year is projected to be 8 more than the average historical baseline of virtually zero days.

Similarly, under the higher emissions scenario the temperature on the hottest day of the year is projected to increase by 2.7–10.4°F by the 2050s relative to the GCMs’ historical baselines. The average projected increase in temperature on the hottest day is 7.8°F above the average historical baseline of 92.6°F. The average projected increase in temperature on the warmest night is 6.7°F above the average historical baseline of 60.8°F.

Under the higher emissions scenario, the numbers of daytime and nighttime heat waves are projected to increase by 1.0–3.8 and 0.1–2.2 events, respectively, by the 2050s relative to the GCMs’ historical baselines. The average number of daytime and nighttime heat waves is projected to increase by 2.6 and 1.1 events, respectively, above the average historical baseline of 1.3 and zero events (Table 6, Figure 6).

Table 6 Mean (and range) of projected future changes in extreme heat metrics in Wallowa County by the 2020s (2010–2039 average) and 2050s (2040–2069 average), relative to the historical baseline (1971–2000 average) of each of 20 global climate models (GCMs), under a lower (RCP 4.5) and higher (RCP 8.5) emissions scenario. The average historical baseline across the 20 GCMs and the average projected future change can be used to infer the average projected future absolute value of a given variable. However, the average historical baseline and the range of projected future changes cannot be used to infer the range of projected future absolute values.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Average Historical Baseline</th>
<th>2020s</th>
<th>2050s</th>
<th>2020s</th>
<th>2050s</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Lower</td>
<td>Higher</td>
<td>Lower</td>
<td>Higher</td>
</tr>
<tr>
<td>Hot Days</td>
<td>9.6 days</td>
<td>8.5 days</td>
<td>10.1 days</td>
<td>17.1 days</td>
<td>25 days</td>
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<tr>
<td></td>
<td></td>
<td>(1.9–12.7)</td>
<td>(2.9–14.1)</td>
<td>(4.8–25.5)</td>
<td>(6.9–35.3)</td>
</tr>
<tr>
<td>Warm Nights</td>
<td>0.4 days</td>
<td>1.6 days</td>
<td>1.8 days</td>
<td>4.2 days</td>
<td>8.3 days</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.4–3.7)</td>
<td>(0.9–3.7)</td>
<td>(0.8–9.7)</td>
<td>(1.9–19.3)</td>
</tr>
<tr>
<td>Hottest Day</td>
<td>92.6°F</td>
<td>3.3°F</td>
<td>3.7°F</td>
<td>5.7°F</td>
<td>7.8°F</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.6–4.8)</td>
<td>(0.9–5.2)</td>
<td>(1.7–7.7)</td>
<td>(2.7–10.4)</td>
</tr>
<tr>
<td>Warmest Night</td>
<td>60.8°F</td>
<td>2.8°F</td>
<td>3.1°F</td>
<td>4.8°F</td>
<td>6.7°F</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1.1–4.6)</td>
<td>(2.1–4.5)</td>
<td>(1.9–7.8)</td>
<td>(3.6–9.5)</td>
</tr>
<tr>
<td>Daytime Heat Waves</td>
<td>1.3 events</td>
<td>1.1 events</td>
<td>1.3 events</td>
<td>2 events</td>
<td>2.6 events</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.3–1.7)</td>
<td>(0.5–1.8)</td>
<td>(0.8–3.2)</td>
<td>(1–3.8)</td>
</tr>
<tr>
<td>Nighttime Heat Waves</td>
<td>0 events</td>
<td>0.2 events</td>
<td>0.2 events</td>
<td>0.5 events</td>
<td>1.1 events</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0–0.4)</td>
<td>(0.1–0.4)</td>
<td>(0–1.2)</td>
<td>(0.1–2.2)</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 Wallowa County by the 2020s (2010–2039 average) and 2050s (2040–2069 average), relative to the historical baseline (1971–2000 average), under two emissions scenarios. The bars and whiskers represent the mean and range, respectively, of changes across 20 global climate models relative to each model’s historical baseline. 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 Wallowa County by the 2020s (2010–2039 average) and 2050s (2040–2069 average), relative to the historical baseline (1971–2000 average), under two emissions scenarios. The bars and whiskers represent the mean and range, respectively, of changes across 20 global climate models relative to each model’s historical baseline.
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) heat waves in Wallowa County by the 2020s (2010–2039 average) and 2050s (2040–2069 average), relative to the historical baseline (1971–2000 average) under two emissions scenarios. The bars and whiskers represent the mean and range, respectively, of changes across 20 global climate models relative to each model’s historical baseline. 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.

**Key Messages**

⇒ The number, duration, and intensity of extreme heat events is expected to increase as temperatures continue to warm.

⇒ In Wallowa County, the number of extremely hot days (days on which the temperature in 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 (RCP 4.5) and higher (RCP 8.5) emissions scenarios.

⇒ In Wallowa County, the number of days per year with temperatures 90°F or higher is projected to increase by an average of 25 days (range 7–35 days) by the 2050s relative to the 1971–2000 historical baselines, under the higher emissions scenario.

⇒ In Wallowa County, the temperature on the hottest day of the year is projected to increase by an average of nearly 8°F (range 3–10°F) by the 2050s, relative to the 1971–2000 historical baselines, under the higher emissions scenario.
cold waves

Over the past century, cold extremes have become less frequent and severe in the Northwest and worldwide. This trend is driven by human-caused climate change and is expected to continue (Vose et al., 2017; IPCC, 2021). This report presents projected changes in three metrics of extreme daytime cold (maximum temperature) and nighttime cold (minimum temperature) (Table 7).

Table 7. 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 Wallowa 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 8, Figure 7). For example, climate models projected that by the 2050s under the higher emissions scenario, the number of cold days will decrease by 11–27 relative to each GCM’s 1971–2000 historical baseline. The average projected number of cold days per year is 19 less than the average historical baseline of 31 days. The average projected number of cold nights per year is 2 less than the average historical baseline of 3 nights.

Similarly, the temperatures on the coldest day and night are projected to increase by the 2020s and 2050s under both emissions scenarios (Table 8, 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 0.8–18.1°F relative to the GCMs’ historical baselines. The average projected increase in the temperature on the coldest night is 9.9°F above the average historical baseline of -3.3°F. The average projected increase in the temperature on the coldest day is 6.7°F above the average historical baseline of 15.9°F.

Under the higher emissions scenario, the number of daytime and nighttime cold waves is projected to decrease by 1.3–3.5 and 0.0–0.4 events, respectively, by the 2050s relative to the GCMs’ historical baselines. The average number of daytime and nighttime cold waves is projected to be 2.4 and 0.2 events, respectively, less than the average historical baseline of 3.9 and 0.3 events (Table 8, Figure 9).
Table 8. Mean (and range) of projected future changes in extreme cold metrics in Wallowa County by the 2020s (2010–2039 average) and 2050s (2040–2069 average), relative to the historical baseline (1971–2000 average) of each of 20 global climate models (GCMs), under a lower (RCP 4.5) and higher (RCP 8.5) emissions scenario. The average historical baseline across the 20 GCMs and the average projected future change can be used to infer the average projected future absolute value of a given variable. However, the average historical baseline and the range of projected future changes cannot be used to infer the range of projected future absolute values.

<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>30.7 days</td>
<td>-9.5 days (-17.4 - -0.9)</td>
<td>-11.4 days (-18.1 - -2.8)</td>
</tr>
<tr>
<td>Cold Nights</td>
<td>2.7 days</td>
<td>-1 days (-2 - 0.3)</td>
<td>-1.4 days (-2.6 - -0.3)</td>
</tr>
<tr>
<td>Coldest Day</td>
<td>15.9°F</td>
<td>2.1°F (2.1 - 6.2)</td>
<td>3.5°F (0 - 9.4)</td>
</tr>
<tr>
<td>Coldest Night</td>
<td>-3.3°F</td>
<td>3.4°F (-2.1 - 8.7)</td>
<td>5.3°F (0.4 - 13)</td>
</tr>
<tr>
<td>Daytime Cold Waves</td>
<td>3.9 events</td>
<td>-1.2 events (-2.3 - -0.1)</td>
<td>-1.4 events (-2.3 - -0.5)</td>
</tr>
<tr>
<td>Nighttime Cold Waves</td>
<td>0.3 events</td>
<td>-0.1 events (-0.3 - 0.1)</td>
<td>-0.2 events (-0.3 - 0.1)</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 Wallowa County by the 2020s (2010–2039 average) and 2050s (2040–2069 average), relative to the historical baseline (1971–2000 average) under two emissions scenarios. The bars and whiskers represent the mean and range, respectively, of changes across 20 global climate models relative to each model’s historical baseline. 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 Wallowa County by the 2020s (2010–2039 average) and 2050s (2040–2069 average), relative to the historical baseline (1971–2000 average) under two emissions scenarios. The bars and whiskers represent the mean and range, respectively, of changes across 20 global climate models relative to each model’s historical baseline.
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 Wallowa County by the 2020s (2010–2039 average) and 2050s (2040–2069 average), relative to the historical baseline (1971–2000 average), under two emissions scenarios. The bars and whiskers represent the mean and range, respectively, of changes across 20 global climate models relative to each model’s historical baseline. 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.

**Key Messages**

- Cold extremes will become less frequent and intense as the climate warms.
- In Wallowa County, the temperature on the coldest night of the year is projected to increase by an average of 10°F (range 1–18°F) by the 2050s, relative to the 1971–2000 historical baselines, under the higher emissions scenario.
- In Wallowa County, the number of cold days (maximum temperature 32°F or lower) per year is projected to decrease by an average of 19 days (range -11–-27 days) by the 2050s, relative to the 1971–2000 historical baselines, under the higher emissions scenario.
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. Global 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; future trends in annual precipitation are expected to be dominated by natural variability (Dalton et al., 2017; Dalton and Fleishman, 2021). On average, summers in Oregon are projected to become drier and other seasons to become wetter, resulting in a slight increase in annual precipitation by the 2050s. However, some models project increases and others decreases in each season (Dalton et al., 2017).

Extreme precipitation events in the Northwest are 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 events across large areas west of the Cascade Range. 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 events 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, including atmospheric rivers, is expected to increase (Dalton et al., 2017; Kossin et al., 2017; Dalton and Fleishman, 2021). Atmospheric rivers are associated with the majority of fall and winter extreme precipitation events in Oregon. Climate models project an increase in the number of days on which an atmospheric river is present, and they project that atmospheric rivers will account for an increasing proportion of total annual precipitation across the Northwest (Dalton and Fleishman, 2021).

In addition, regional climate models project that the rain shadow effect over the Cascade Range in winter will weaken, resulting in relatively larger increases in seasonal precipitation and precipitation extremes east of the Cascade Range and smaller increases west of the Cascade Range (Mote et al., 2019).

This report presents projected changes in four metrics of precipitation extremes (Table 9).
Table 9. 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>
<tr>
<td>Landslide Risk Days</td>
<td>Number of days per water year that exceed the landslide threshold developed by the US Geological Survey for Seattle, Washington (see <a href="https://pubs.er.usgs.gov/publication/ofr20061064">https://pubs.er.usgs.gov/publication/ofr20061064</a>).&lt;br&gt;P3/(3.5–67*P15)&gt;1, where&lt;br&gt;P3 = Precipitation accumulation on prior days 1–3&lt;br&gt;P15 = Precipitation accumulation on prior days 4–18</td>
</tr>
</tbody>
</table>

In Wallowa 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 10, Figure 10). However, 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 6.1–26% (Figure 10). The average projected amount of precipitation on the wettest day of the year is 15.6% greater than the average historical baseline of 1 inch.

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 0.8–20.1% (Figure 10). The average projected amount of precipitation on the wettest consecutive five days is 10.7% above the average historical baseline of 2.4 inches.

The average number of days per year on which precipitation exceeds 0.75 inches is projected to increase slightly (Figure 11). For example, by the 2050s under the higher emissions scenario, the number of wet days per year is projected to increase by 0.8 (range 0.3–1.3). The historical baseline is an average of 3 days per year.

Landslides are often triggered by rainfall when the soil becomes saturated. As a surrogate measure of landslide risk, this report presents a threshold based on recent rainfall (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 on which the landslide risk threshold is exceeded is projected to increase by 1 (range 0–3 days) (Figure 11). The historical baseline is an average of 4 days per year. Landslide risk depends on multiple site-specific factors, and this metric does not reflect all aspects of the hazard. The landslide risk

<table>
<thead>
<tr>
<th>Metric</th>
<th>Definition</th>
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<tbody>
<tr>
<td>Wettest Day</td>
<td>Highest one-day precipitation total per water year (1 October–30 September)</td>
</tr>
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<td>Wettest Five Days</td>
<td>Highest consecutive five-day precipitation total per water year</td>
</tr>
<tr>
<td>Wet Days</td>
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<tr>
<td>Landslide Risk Days</td>
<td>Number of days per water year that exceed the landslide threshold developed by the US Geological Survey for Seattle, Washington (see <a href="https://pubs.er.usgs.gov/publication/ofr20061064">https://pubs.er.usgs.gov/publication/ofr20061064</a>).&lt;br&gt;P3/(3.5–67*P15)&gt;1, where&lt;br&gt;P3 = Precipitation accumulation on prior days 1–3&lt;br&gt;P15 = Precipitation accumulation on prior days 4–18</td>
</tr>
</tbody>
</table>

In Wallowa 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 10, Figure 10). However, 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 6.1–26% (Figure 10). The average projected amount of precipitation on the wettest day of the year is 15.6% greater than the average historical baseline of 1 inch.

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 0.8–20.1% (Figure 10). The average projected amount of precipitation on the wettest consecutive five days is 10.7% above the average historical baseline of 2.4 inches.

The average number of days per year on which precipitation exceeds 0.75 inches is projected to increase slightly (Figure 11). For example, by the 2050s under the higher emissions scenario, the number of wet days per year is projected to increase by 0.8 (range 0.3–1.3). The historical baseline is an average of 3 days per year.

Landslides are often triggered by rainfall when the soil becomes saturated. As a surrogate measure of landslide risk, this report presents a threshold based on recent rainfall (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 on which the landslide risk threshold is exceeded is projected to increase by 1 (range 0–3 days) (Figure 11). The historical baseline is an average of 4 days per year. Landslide risk depends on multiple site-specific factors, and this metric does not reflect all aspects of the hazard. The landslide risk
threshold was developed for Seattle, Washington, and may be less applicable to other locations.

Table 10. Mean (and range) of projected changes in extreme precipitation in Wallowa County by the 2020s (2010–2039 average) and 2050s (2040–2069 average) relative to the historical baseline (1971–2000 average) of each of 20 global climate models (GCMs), under a lower (RCP 4.5) and higher (RCP 8.5) emissions scenario. The average historical baseline across the 20 GCMs and the average projected future change can be used to infer the average projected future absolute value of a given variable. However, the average historical baseline and the range of projected future changes cannot be used to infer the range of projected future absolute values.

<table>
<thead>
<tr>
<th></th>
<th>Average Historical Baseline</th>
<th>2020s</th>
<th></th>
<th>2050s</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Lower</td>
<td>Higher</td>
<td>Lower</td>
<td>Higher</td>
</tr>
<tr>
<td>Wettest Day</td>
<td>1 inches</td>
<td>10.5%</td>
<td>7.9%</td>
<td>11.5%</td>
<td>15.6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(3.6-17.5)</td>
<td>(-1.2-19.6)</td>
<td>(-0.3-22.7)</td>
<td>(6.1-26)</td>
</tr>
<tr>
<td>Wettest Five-Days</td>
<td>2.4 inches</td>
<td>7.2%</td>
<td>4.6%</td>
<td>7.3%</td>
<td>10.7%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(-1.4-17.9)</td>
<td>(-3.7-21)</td>
<td>(-4.8-16.6)</td>
<td>(0.8-20.1)</td>
</tr>
<tr>
<td>Wet Days</td>
<td>3.4 days</td>
<td>0.4 days</td>
<td>0.3 days</td>
<td>0.6 days</td>
<td>0.8 days</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(-0.1-1)</td>
<td>(-0.2-1.1)</td>
<td>(0.1-1.2)</td>
<td>(0.3-1.3)</td>
</tr>
<tr>
<td>Landslide Risk Days</td>
<td>4.2 days</td>
<td>0.5 days</td>
<td>0.4 days</td>
<td>0.6 days</td>
<td>1 days</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(-0.1-1.6)</td>
<td>(-0.4-1.4)</td>
<td>(0-1.4)</td>
<td>(0-3)</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 Wallowa County by the 2020s (2010–2039 average) and 2050s (2040–2069 average), relative to the historical baseline (1971–2000 average), under two emissions scenarios. The bars and whiskers represent the mean and range, respectively, of changes across 20 global climate models relative to each model’s historical baseline.

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 Wallowa County by the 2020s (2010–2039 average) and 2050s (2040–2069 average), relative to the historical baseline (1971–2000 average), under two emissions scenarios. The bars and whiskers represent the mean and range, respectively, of changes across 20 global climate models relative to each model’s historical baseline.
Landslide risk also can become high when heavy precipitation falls on an area that burned within approximately the past five to ten years. By the year 2100, under the higher emissions scenario, the probability that an extreme rainfall event will occur within one year after an extreme fire-weather event in Oregon or Washington was projected to increase by 700% relative to 1980–2005 (Touma et al., 2022). Similarly, projections suggest that by 2100, across Oregon and Washington, 90% of extreme fire-weather events 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.

**Key Messages**

- The intensity of extreme precipitation is expected to increase as the atmosphere warms and holds more water vapor.
- In Wallowa County, the number of days per year with at least 0.75 inches of precipitation is projected to increase by about 1 day 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 16% (range 6–26%) and 11% (range 1–20%), respectively, by the 2050s, relative to the 1971–2000 historical baselines, under the higher emissions scenario.
- In Wallowa County, the number of days per year on which a threshold for landslide risk, which is based on 3-day and prior 15-day precipitation accumulation, is exceeded is projected to increase by 1 day (range 0–3 days) by the 2050s, relative to the 1971–2000 historical baselines, under the higher emissions scenario. However, landslide risk depends on multiple factors and this metric does not reflect all aspects of the hazard.
River Flooding

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, in turn causing snow to melt earlier in spring; and increasing winter precipitation and decreasing summer precipitation (Dalton et al., 2017; Mote et al., 2019; Dalton and Fleishman, 2021).

Warming temperatures and increased 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, which 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 monthly hydrograph of the Grand Ronde River at Troy is characteristic of a snow-dominated basin in which flow peaks during late spring snowmelt (Figure 12). By the 2050s (2040–2069), under both emissions scenarios, streamflow is projected to peak earlier in spring as warmer temperatures cause the snowpack to melt earlier. In addition, winter streamflow is projected to increase due to increased winter precipitation and a greater percentage of precipitation falling as rain rather than snow. Mean monthly flows do not translate directly to flood risk because floods occur over shorter periods of time. However, 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.
This report describes projected changes in single-day flood levels in terms of the magnitude of water-year maximum daily flows with 2-year, 10-year, and 25-year return periods (50%, 10%, and 4% probability, respectively, that this daily flow magnitude would be exceeded in a given year). Flood magnitudes are compared between a historical baseline period (1961–2010) and the 2050s (2031–2080). These longer time periods, necessary for the flood analysis, extend the earliest and latest years of the time periods referenced elsewhere in this report by a decade each. The results of the flood analysis can be interpreted as either an increase in flood magnitude given a flood frequency, or an increase in flood frequency given a flood magnitude. Flood risk projections are not available for the 2020s because the time period necessary for this projection overlapped the historical baseline. These analyses are exploratory and should not be applied to engineering or design.

On the Grand Ronde River at Troy, the average magnitudes of single-day floods with 2-year, 10-year, and 25-year return periods are projected to increase by 17%, 32%, and 37%, respectively, by the 2050s, compared to 1961–2010, under the higher emissions scenarios (RCP 8.5) (Figure 13). However, a few models project decreases in the magnitude of maximum daily flows for each return period.
In parts of the Blue Mountains (Wallowa Mountains, Hells Canyon Wilderness Area, and northeast Wallowa-Whitman National Forest), the magnitude of a flood with a 1.5-year return period (67% probability that this flood level would be exceeded in a given year) is expected to increase by the 2080s (2070–2099), relative to the 1970–1999 historical baseline, under a medium emission scenario (SRES-A1B), particularly at intermediate elevations, as more precipitation falls as rain rather than snow (Clifton et al., 2018) (Figure 14). The SRES-A1B scenario is from an earlier generation of emissions scenarios and is most similar to RCP6.0 (Figure 2). Floods of this magnitude can damage roads. Projections of changes in floods of this magnitude are not available for the 2020s and 2050s in Wallowa County.
Across much of the western United States, major floods—peak flow magnitudes associated with 100-year and 25-year return periods (1% and 4% probability that this daily flow magnitude would be exceeded in a given year)—are projected to increase by 2070–2099, compared to the 1971–2000 historical baseline, under the higher emissions scenario (Maurer et al., 2018). Peak flow magnitudes with 25-year and 100-year return periods along the Grand Ronde River at Troy are projected to increase by about 12% and 17%, respectively, by 2070–2099 relative to the historical baseline (Table 11). In effect, the magnitude of flooding currently corresponding to 25-year and 100-year peak flow events will become magnitudes corresponding to 14-year and 35-year events, respectively (Maurer et al., 2018). Flood levels with 10-year and 100-year return periods (10% and 1% probability that this flood level would be exceeded in a given year) on the Grand Ronde River at Troy were projected to increase by 48% and 68%, respectively, from 1950-1999 to 2050-2099 under the higher emissions scenario (Queen et al., 2021).

Some of the Northwest’s highest floods occur when large volumes of warm rain from atmospheric rivers combine with a deep snowpack, resulting in rain-on-snow floods (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 increase the likelihood of flooding (Konrad and Dettinger, 2017).
Table 11. Percent change in peak flow associated with multiple return periods for the Grand Ronde River at Troy under the higher emissions scenario. The time period of analysis varies among sources.

<table>
<thead>
<tr>
<th>Return Period (Probability that this level would be exceeded in a given year)</th>
<th>Average Percent Change in Flow</th>
<th>Time Periods</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-year (50%)</td>
<td>17%</td>
<td>2031–2080 vs. 1961–2010</td>
<td>David Rupp</td>
</tr>
<tr>
<td>10-year (10%)</td>
<td>48%</td>
<td>2050-2099 vs. 1950-1999</td>
<td>Queen et al. (2021)</td>
</tr>
<tr>
<td></td>
<td>32%</td>
<td>2031–2080 vs. 1961–2010</td>
<td>David Rupp</td>
</tr>
<tr>
<td>25-Year (4%)</td>
<td>12%</td>
<td>2070–2099 vs. 1971–2000</td>
<td>Maurer et al. (2018)</td>
</tr>
<tr>
<td></td>
<td>37%</td>
<td>2031–2080 vs. 1961–2010</td>
<td>David Rupp</td>
</tr>
<tr>
<td>100-Year (1%)</td>
<td>17%</td>
<td>2070–2099 vs. 1971–2000</td>
<td>Maurer et al. (2018)</td>
</tr>
<tr>
<td></td>
<td>68%</td>
<td>2050-2099 vs. 1950-1999</td>
<td>Queen et al. (2021)</td>
</tr>
</tbody>
</table>

Future changes in the frequency of rain-on-snow events likely will vary along an elevational gradient. 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). How such changes in frequency of rain-on-snow events are likely to affect streamflow varies. For example, projections for the Santiam River, Oregon, indicate an increase in annual peak daily flows at return intervals less than 10 years, but a decrease in annual peak daily flows at return intervals greater than or equal to 10-years (Surfleet and Tullos, 2013). Average runoff from rain-on-snow events in watersheds in northern coastal Oregon is 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 extreme rainfall that exceeds soil capacity (Berghuijs et al., 2016; Musselman et al., 2018).

**Key Messages**

⇒ Winter flood risk at mid- to low elevations in Wallowa County’s Blue Mountains, 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 is common in the Northwest. 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 under future climate change (Dalton and Fleishman, 2021). Drought can be defined in many ways (Table 12), but most fundamentally is insufficient water to meet needs (Redmond, 2002; Dalton and Fleishman, 2021).

**Table 12. Definitions and characteristics of various drought classes.** (Source: Dalton and Fleishman, 2021; Fleishman et al., unpublished)

<table>
<thead>
<tr>
<th>Drought Class</th>
<th>Definition &amp; Characteristics</th>
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| Meteorological | • lack of precipitation  
• evaporative demand that exceeds precipitation  
• minimum period of time for consideration operationally is 90 days |
| Hydrological  | • prolonged meteorological drought affects surface or subsurface water supply, such as streamflow, reservoir and lake levels, or groundwater levels  
• tends to evolve more slowly than meteorological drought, with extents longer than six months |
| Agricultural  | • occurs when meteorological and hydrological drought impacts 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 some 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         | • relatively short periods of warm surface temperatures, low relative humidities and precipitation deficits, and rapidly declining soil moisture  
• tend 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 followed by summers with low river and stream flows  
• warm snow drought—low snowpack with above average precipitation and temperature  
• dry snow drought—low snowpack and low precipitation |
Summers in Oregon are expected to become warmer and drier, and mountain snowpack is projected to decline due to warmer winter temperatures (Dalton and Fleishman, 2021). Across the western United States, the decline in mountain snowpack is projected to reduce summer soil moisture in the mountains (Gergel et al., 2017). Climate change is expected to result in lower summer streamflows in snow-dominated basins across the Northwest as snowpack melts earlier due to warmer temperatures and decreases in summer precipitation (Dalton et al., 2017; Mote et al., 2019). For example, a decrease in summer flows is expected for the Grand Ronde River at Troy by the 2050s (2040–2069) (Figure 12). As mountain snowpack declines, seasonal drought will become less predictable and snow droughts will increase the likelihood of meteorological and hydrological drought in subsequent seasons (Dalton and Fleishman, 2021).

This report presents projected changes in four variables indicative of drought: low spring snowpack (snow drought), low summer soil moisture from the surface to 140 cm below the surface (agricultural drought), low summer runoff (hydrological drought), and low summer precipitation (meteorological drought). Drought is presented in terms of a change in the probability of exceeding the magnitude of seasonal drought conditions for which the historical probability of exceedance in a given year was 20% (i.e., 5-year return period) (Figure 15).

In Wallowa County, spring snowpack (snow water equivalent on April 1), summer runoff, summer soil moisture, 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 under both emissions scenarios (Figure 15). By the 2050s under the higher emissions scenario, the annual probability of low spring snowpack, low summer runoff, and low summer soil moisture each is projected to be about 50% (i.e., 2-year return period), and the annual probability of low summer precipitation is projected to be 32% (i.e., about a 3-year return interval). Drought projections for the 2020s were not evaluated due to data limitations, but drought magnitudes in the 2020s likely will be smaller than those in the 2050s.
Figure 15. Projected probability of exceeding the magnitude of seasonal drought conditions for which the historical probability of exceedance in a given year was 20%. 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 bar and whiskers represent the mean and range across ten global climate models. (Data Source: Integrated Scenarios of the Future Northwest Environment, https://climate.northwestknowledge.net/IntegratedScenarios/)

Projected changes in spring snowpack and summer streamflow in northeast Oregon are spatially variable. Within the Blue Mountains, projected declines in spring snowpack generally were greatest at low to mid-elevations, but large declines were also apparent at some higher elevations, such as in the Wenaha-Tucannon Wilderness, and at mid-elevations in the Hells Canyon Wilderness (Clifton et al., 2018). Projected declines in spring snowpack were lowest in Eagle Cap Wilderness, but summer runoff in this area is highly sensitive to late-season snowpack (Clifton et al., 2018). By the 2080s (2070–2099), summer streamflows in about half of the perennial streams in the Blue Mountains are projected to decrease by less than 10%, whereas summer streamflows in the Wallowa Mountains and Wenaha-Tucannon Wilderness are projected to decrease by more than 30% (Clifton et al., 2018) (Figure 16). Although spring snowpack declines were lowest in Eagle Cap in the Wallowa Mountains, the area’s high sensitivity to even small changes in late-season snowpack resulted in large projected decreases in summer runoff (Clifton et al., 2018). The highest risks of summer water shortages associated with low streamflows are in the Burnt, Powder, Upper Grande Ronde, and Wallowa sub-basins (Clifton et al., 2018).
Figure 16. Projected decrease in mean summer streamflow from 1970–1999 to the 2080s (2070–2099) for streams in the Blue Mountains under a medium emissions scenario (SRES-A1B). This scenario is from an earlier generation of emissions scenarios and is most similar to RCP 6.0 (Figure 2). (Source: Clifton et al., 2018)

Key Messages

⇒ 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 Wallowa County by the 2050s.
Human activities have modified fire dynamics in the western United States through clearance of native vegetation for agriculture and urbanization, fragmentation and exploitation of forests and other natural land-cover types, human population growth and increased recreational activities, and replacement of indigenous or no fire management by extensive fire suppression and vegetation management. 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).

Over the last several decades, warmer and drier conditions during summer have contributed to an increase in vegetation dryness and enabled more frequent large wildfires, an increase in the total area burned, and a longer wildfire season across the western United States, particularly in forested ecosystems (Dennison et al., 2014; Jolly et al., 2015; Westerling, 2016; Williams and Abatzoglou, 2016). The lengthening of the wildfire season is largely due to declining mountain snowpack and earlier spring snowmelt (Westerling, 2016).

Vapor pressure deficit (VPD)—atmospheric aridity—is more strongly associated with forest area burned than precipitation, drought indices, or temperature (Sedano and Randerson, 2014; Williams et al., 2014; Seager et al., 2015; Rao et al., 2022). The climate models included in the sixth phase of the Coupled Model Intercomparison Project suggest that human emissions of greenhouse gases explain a large percentage of the observed VPD increase (Zhuang et al., 2021). In the western United States from 1984 through 2015, about half of the observed increase in vegetation dryness—driven mainly by VPD—and 4.2 million hectares (16,000 square miles) of burned area were attributable to human-caused climate change (Abatzoglou and Williams, 2016).

Fire danger is generally evaluated on the basis of daytime conditions that may cause wildfires to spread. Historically, wildfires were less active overnight. However, nights have become hotter and drier, and the temperature and duration of wildfires is expected to increase as a result (Balch et al., 2022). In 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). Vegetation can also amplify or dampen the effect of aridity on wildfires. The geographic co-occurrence of plants with high water sensitivity (e.g., plants that do not close their stomata, shallow-rooted plants on porous soils) and high VPD suggests that the distribution of vegetation in the western United States has amplified the effect of climate change on wildfire hazard (Rao et al., 2022).

High temperatures contribute to the drying of dead vegetation, but high VPD reduces moisture in live vegetation (e.g., the tree canopy), increasing the likelihood that any source of ignition will create a wildfire. The interaction between continued development in areas with flammable vegetation and increases in VPD suggests that projections of changing wildfire risk in the western United States may be conservative (Rao et al., 2022), especially given that over 80% of all ignitions in the United States are now human-caused (Balch et al., 2017) and that human activities have extended both the temporal and geographic extent of the fire season (Balch et al., 2017; Bowman et al., 2020). Furthermore, extreme wildfires may correspond to concurrent extreme weather, including high temperatures,
aridity, and wind speeds, that is becoming more common (Abatzoglou et al., 2021).

Projecting wildfire risk across the western United States in response to changes in climate and land use requires understanding the interactions among biological, climatic, and human factors. The probability of wildfire occurrence in the Cascade Range of Oregon as a function of temperature and precipitation is projected to increase by 63% under the lower emissions scenario (RCP 4.5) to 122% under the higher emissions scenario (RCP 8.5) (Gao et al., 2021). Multiple modeling approaches simulate an increase in forest area burned in the western United States (Abatzoglou et al., 2021). Similarly, model simulations of a common fire index that is based on precipitation and temperature, the Keetch–Byram Drought Index, and a proxy for fuel availability suggests that the number of days on which fire risk is extremely high will increase through the end of the twenty-first century (Brown et al., 2021). Overall, wildfire frequency, intensity, and area burned are projected to continue increasing in the Northwest, even in climatologically wet areas in western Oregon (Dalton et al., 2017; Mote et al., 2019; Dalton and Fleishman, 2021)

This report considers the number of days with extreme values of 100-hour fuel moisture (FM100) and vapor pressure deficit (VPD) as a proxy for wildfire risk. FM100 is a measure of the percentage of moisture in the dry weight of dead vegetation with 1–3 inch diameter, and commonly is used by the Northwest Interagency Coordination Center (https://gacc.nifc.gov/nwcc/) to predict fire danger. A majority of climate models project that fuel moisture will decline across Oregon by the 2050s (2040–2069) under the higher emissions scenario (Gergel et al., 2017). Drying of vegetation leads to greater wildfire risk, especially when coupled with decreases in summer soil moisture and increases in the evaporative demand. VPD is a measure of the dryness of the air; dry air causes live plants to release more water into the air and therefore to become drier and more flammable. CMIP6 model simulations given a higher emissions scenario projected that warm season VPD over the next 30 years will increase at a rate similar to that observed across the western United States from 1980 through 2020 (Zhuang et al., 2021). Increases in VPD also were projected by CMIP5 models to contribute substantially to wildfire risk in eastern Oregon (Ficklin and Novick, 2017; Chiodi et al., 2021). Furthermore, observed increases in nighttime temperatures (Balch et al., 2022) and in nighttime VPD (Chiodi et al., 2021), such as has been observed in the Blue Mountains of eastern Oregon, have been linked to fires burning longer into the night and increases in early morning fire intensity thereby reducing the window of opportunity for suppression. In addition, annual area of forests burned increases exponentially with increases in VPD across the western United States (Zhuang et al., 2021; Juang et al., 2022).

In this report, the future change in wildfire risk is expressed as the increase in the average annual number of days on which fire danger is very high and VPD is extreme. Projections are presented for future periods under two emissions scenarios compared to the historical baseline. A day on which fire danger is very high is defined as a day on which FM100 is lower (i.e., vegetation is drier) than the historical 10th percentile value. Historically, fire danger was very high on 36.5 days per year. A day on which VPD is extreme is defined as a day on which VPD exceeds the historical warm season (March–November) 90th percentile value.
In Wallowa County, the average number of days per year on which fire danger is very high is projected to increase by 16 days (range -4 – 38) by the 2050s, compared to the historical baseline, under the higher emissions scenario (Figure 17). The average number of days per year on which VPD is extreme is projected to increase by 31 days (range 12 – 44) by the 2050s, compared to the historical baseline, under the higher emissions scenario (Figure 18).

The impacts of wildfire on air quality are discussed in the following section on Wildfire risk, expressed as the average number of days per year on which fire danger is very high, is projected to increase in Wallowa County by 16 days (range -4 – 38) by the 2050s, compared to the historical baseline, under the higher emissions scenario.

In Wallowa County, the average number of days per year on which vapor pressure deficit is extreme is projected to increase by 31 days (range 12 – 44) by the 2050s, compared to the historical baseline, under the higher emissions scenario.

Reduced Air Quality.

![Figure 17](https://climatetoolbox.org/tool/Climate-Mapper)

Figure 17. 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 Wallowa County is very high. The bars and whiskers represent the mean and range, respectively, of changes across 18 global climate models. (Data Source: Climate Toolbox, [climatetoolbox.org/tool/Climate-Mapper](http://climatetoolbox.org/tool/Climate-Mapper))
Figure 18. Projected changes by the 2020s (2010–2039 average) and 2050s (2040–2069 average), relative to the 1971–2000 historical baseline under two emissions scenarios, in the number of days on which vapor pressure deficit in Wallowa County is extreme. The bars and whiskers represent the mean and range, respectively, of changes across 20 global climate models. (Data Source: Climate Toolbox, climatetoolbox.org/tool/Climate-Mapper)

**Key Messages**

⇒ Wildfire risk, expressed as the average number of days per year on which fire danger is very high, is projected to increase in Wallowa County by 16 days (range -4 – 38) by the 2050s, compared to the historical baseline, under the higher emissions scenario.

⇒ In Wallowa County, the average number of days per year on which vapor pressure deficit is extreme is projected to increase by 31 days (range 12 – 44) by the 2050s, compared to the historical baseline, under the higher emissions scenario.
Reduced Air Quality

Climate change is expected to reduce outdoor air quality. Warmer temperatures may increase ground-level ozone concentrations, increase the number and size of wildfires, and exacerbate air pollution from other sources. Therefore, the health effects of wildfires are expected to increase in the future.

Wildfires are the primary cause of exceedances of air quality standards in the western United States, although woodsmoke and diesel emissions also contribute. From 2000 through 2020, the frequency, duration, and area of co-occurrence of two air pollutants related to wildfire smoke, PM2.5 and ozone, increased in the western United States (Kalashnikov et al., 2022). Wildfires can create conditions that increase the concentration of ozone, especially in hot and sunny conditions. The area in which PM2.5 and ozone co-occurred more than doubled during this period.

Outdoor recreational and social activities, in turn, affect physical and mental health. Covid-19 (Henderson, 2018) and wildfire smoke also impairs visibility, and can disrupt chronic cardiovascular and respiratory illnesses (Casas, 2018). In addition, because PM2.5 levels increase rapidly, wildfire smoke can pose a health hazard.

This report presents quantitative projections of future air quality reflecting PM2.5 from wildfire smoke. Reduced air quality is expected to exacerbate allergies and asthma conditions and increase the incidence of asthma and respiratory illnesses and death (Fann et al., 2016). Summer smoke wave days are defined as two or more consecutive days with wildfire smoke. Smoke wave days are defined as two or more consecutive days with smoke wave index of 10 or more. The start date for smoke wave days is defined as the day when the smoke wave index is greater than or equal to 10 from 2004 through 2009 (Fann et al., 2016).
mean smoke wave intensity are projected for two six-year periods, 2004–2009 and 2046–2051, under a medium emissions scenario. More information about the methods underlying these projections of future air quality is in the Appendix. In Wallowa County, the number of smoke wave days is projected to increase by 150%, whereas the intensity is projected to increase by 73% (Figure 19).

![Number of Smoke Wave Days Per Six-Year Period](image1)
![Average Smoke Wave Intensity](image2)

**Figure 19.** Simulated present (2004–2009) and future (2046–2051) number (left) and intensity (right) of smoke wave days in Wallowa County under a medium emissions scenario. Values represent the mean among 15 global climate models. (Data source: Liu et al. 2016, [https://khannotations.github.io/smoke-map/](https://khannotations.github.io/smoke-map/))

Vegetation is also responding to changes in climate and atmospheric concentrations of carbon dioxide by producing more pollen, and by producing pollen earlier in the 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 also could become more abundant following extreme floods or droughts, which are expected to become more common with climate change. 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 particulates 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).

**Key Messages**

- The risk of wildfire smoke in Wallowa County is projected to increase.
- In Wallowa County, the number of days per year on which the concentration of wildfire-derived fine particulate matter results in poor air quality is projected to increase by 150%, and the concentration of fine particulate matter is projected to increase by 73%, from 2004–2009 to 2046–2051 under a medium emissions scenario.
Loss of Wetlands

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). All of these wetland types, some of which are fed by surface water and some by ground water, occur in the Blue Mountains (Dwire et al., 2018).

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, such as those in the Blue Mountains, 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.

At least four populations of Columbia spotted frog (Rana luteiventris), a rare species that was petitioned for listing under the U.S. Endangered Species Act in 1989, occurred in wetlands in Wallowa County as of 2005 (Bull, 2005). If increases in temperature or decreases in water availability increase use of wetlands by domestic cattle, habitat quality for this and other native species likely will decrease (Adams et al., 2018). Populations of Columbia spotted frog also are likely to decline if permanent wetlands occupied by the species become temporary (Hossack et al., 2013; McCaffery et al., 2014; Kissel et al., 2019), and as mean peak snow water equivalent decreases (McCaffery et al., 2012).

**Key Messages**

- 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.
Climate change has the potential to alter surface winds through changes in the global free atmospheric circulation and storm systems, and through changes in the connection between the free atmosphere and Earth’s surface. West of the Cascade Range, changes in surface wind speeds tend to follow changes in upper atmosphere winds associated with extratropical cyclones (Salathé et al., 2015). The trend in winter extratropical storm frequency in the northeast Pacific since 1950 was positive, although not statistically significant (Vose et al., 2014). However, uncertainty in projections of future extratropical cyclone frequency is high (IPCC, 2013).

Future projections indicate a slight northward shift in the jet stream and extratropical cyclone activity in the North Pacific. Over the Northern Hemisphere, the frequency of the most intense extratropical cyclones generally is projected to decrease, although in the northern North Pacific the frequency is projected to increase (IPCC, 2021) Therefore, there is no consensus on whether extratropical storms (Vose et al., 2014; Seiler and Zwiers, 2016; Chang, 2018) and associated extreme winds (Kumar et al., 2015) will intensify or become more frequent along the Northwest coast under a warmer climate.

**Key Messages**

⇒ Limited research suggests little if any change in the frequency and intensity of windstorms in the Northwest as a result of climate change.
Expansion of Pests, Pathogens, and 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 plants and animals that are considered to be invasive or pests in natural and agricultural systems. Increasing concentrations of carbon dioxide not only lead to increases in global temperature, but affect plants’ primary productivity, water-use efficiency, and nutrient content. 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). In general, invasive and pest species in Wallowa County are likely to become more prevalent in response to projected increases in temperature, especially minimum winter temperature, and increases in the frequency, duration, and severity of drought. However, many of these responses are uncertain, and are likely to vary locally. Moreover, the responses may change over time.

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 plants or animals generally are more susceptible to pests and pathogens than individuals in areas with higher species richness or populations with greater demographic diversity.

Many insects that defoliate or otherwise damage or kill conifers in Oregon and elsewhere in the Northwest are native herbivores that are eruptive. For example, densities of native mountain pine beetles (Dendroctonus ponderosae) generally are low, but eruptions can result in 60% stand-level mortality over tens to hundreds of square kilometers (Abrams et al., 2021). Therefore, research often concentrates on the environmental conditions that lead to increases in the size and distribution of insect populations and the susceptibility of trees to predation and mortality. Organisms that are physiologically stressed, especially at intermediate levels of stress, generally are more susceptible to herbivores and pathogens.

Douglas-fir beetle (Dendroctonus pseudotsugae), an insect native to Oregon, can damage both stressed and, especially during their outbreaks, healthy Douglas-fir (Pseudotsuga menziesii) trees. The effects of outbreaks on trees generally are greatest during hot, dry summers when trees may be water-stressed (Agne et al., 2018). Additionally, warm winters may decrease beetle mortality, increasing the likelihood of an eruption (Agne et al., 2018). The effects of Douglas-fir engraver beetles (Scolytus unispinosis) on their host trees also tend to be greater during periods of drought (Agne et al., 2018). However, adults of both species of beetles have an obligate winter diapause, and increases in winter
temperature that interfere with diapause may decrease their effects on conifers (Bentz et al., 2010).

Both water availability and temperature are associated with outbreaks of and mortality from mountain pine beetles, which feed on ponderosa pine (*Pinus ponderosa*), lodgepole pine (*Pinus contorta*), and many other species of *Pinus*. When population sizes of mountain pine beetles are small, the insects tend to inhabit small and stressed trees, which provide limited nutrition (Bone and Nelson, 2019). When their population sizes are large, mountain pine beetles also inhabit larger trees, which provide more nutrition (Bone and Nelson, 2019). Substantial increases in the density of mountain pine beetles may require consecutive warm years (Bone and Nelson, 2019). In Washington and Oregon, outbreaks appear to be most likely when mean August temperature exceeds 15°C (59°F) (Preisler et al., 2012). The probability of considerable mortality increased as minimum winter temperature increased and during or following years with low summer precipitation (Preisler et al., 2012). Furthermore, mountain pine beetles that were acclimated to and relatively tolerant of cold winter temperatures generally caused higher tree mortality (Preisler et al., 2012). However, the magnitude and abruptness of cold spells in spring and the duration of cold spells in midwinter that result in beetle mortality are unknown (Bone and Nelson, 2019). It is possible that mortality is higher following consecutive years with periods of extreme cold than in a single year with a marked cold spell (Bone and Nelson, 2019).

Western spruce budworms (*Choristoneura fremani*) are moths native to Oregon. They feed on the foliage of Douglas-fir, grand fir (*Abies grandis*), white fir (*Abies concolor*), and other conifers, reducing tree growth and increasing trees’ susceptibility to other insects and pathogens and the likelihood of mortality (Flower et al., 2014). Outbreaks can occur over extensive areas and for durations of more than a decade (local mean 8–15 years), and can be synchronous (Flower et al., 2014). Synchrony decreases as the distance between outbreak locations increases, but synchrony increased over the twentieth century, likely reflecting changes in both climate and land use (Flower et al., 2014). Data from dendroclimatological reconstruction and the observational record indicated that outbreaks over the past several centuries were associated with warm and dry conditions during the preceding two to four years (Flower et al., 2014; Xu et al., 2019), perhaps especially one and two years prior to the outbreak (Xu et al., 2019), and cool and wet conditions in the year of the outbreak and the three following years (Flower et al., 2014). Thus, outbreaks typically may begin toward the end of a drought. Heavy precipitation and low temperatures in late spring and early summer can reduce the likelihood of outbreak, perhaps by displacing budworms from trees or via mortality of the insects (Flower et al., 2014). Nevertheless, understanding of relations between outbreaks of western spruce budworm and climate has been characterized as poor, and those relations may differ between the west and east sides of the Cascade Range (Agne et al., 2018). Additionally, relations between seasonal drought and outbreaks of western spruce budworm were stronger in the northwestern than in the southwestern United States (Xu et al., 2019), which raises the possibility that as aridity increases in the Northwest, the insects will become less sensitive to water limitation.

There is some concern that extensive herbivory and mortality increases the likelihood of
wildfires or severe wildfires in coniferous forests. However, there was little evidence that wildfires in Oregon and Washington from 1984–2012 were more likely, larger, or more severe following outbreaks of mountain pine beetles or western spruce budworms (Meigs et al., 2015, 2016). In fact, wildfires were less likely following outbreaks of western spruce budworms (Meigs et al., 2015). Moreover, fire severity following eruptions generally was lower than in areas without such outbreaks, perhaps because herbivory decreased the biomass of live vegetation (Meigs et al., 2016).

Douglas-fir tussock moth (Orgyia pseudotsugata), a native defoliator of Douglas-fir, true firs (Abies spp.), and spruce, may become more abundant and widespread, and its effects on conifers more extensive, as the climate continues to become warmer and drier (Agne et al., 2018). In Oregon, larch casebearer (Coleophora laricella), a non-native moth introduced to the United States from Europe in the late 1800s, feeds on the leaves of western larch (Larix occidentalis). The insects generally require 66 ± 4 (mean ± SE) degree-days above 5°C (41°F) to break winter diapause and become mobile (Ward et al., 2020). Therefore, larch casebearer also may become more prevalent given projected changes in temperature.

Balsam woolly adelgid (Adelges piceae) is a non-native aphid that was introduced to the eastern United States from Europe around 1900 and was detected in Oregon around 1930 (apps.fs.usda.gov/r6_decaid/views/balsam_woolly adelgid.html). The adelgid feeds on the sap of fir trees (Abies spp.), which are most common at relatively high elevations. Higher levels of herbivory and tree damage were associated with high minimum temperatures in late summer and early autumn, which may increase survival of overwintering juvenile aphids; and cool, wet conditions in May, which may increase tree growth (Hrinkevich et al., 2016).

Non-native forbs classified as noxious weeds that were recognized as high priorities in the 2021 Wallowa County Multi-Jurisdictional Natural Hazard Mitigation Plan are common bugloss (Anchusa officinalis), leafy spurge (Euphorbia esula), meadow hawkweed (Hieracium pratense), knapweeds (Centaurea spp.) dalmatian toadflax (Linaria dalmatica), sulfur cinquefoil (Potentilla recta), and rush skeletonweed (Chondrilla juncea). In eastern Oregon, the primary knapweeds are spotted knapweed (C. maculosa), diffuse knapweed (C. diffusa), Russian knapweed (C. repens), and yellow starthistle (C. solstitialis). All of these species are perennial with the exception of three of the knapweeds. Spotted knapweed is biennial or a short-lived perennial, diffuse knapweed is annual or biennial, and yellow starthistle is annual. 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. 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). Additionally, non-native invasive plants generally gain a competitive advantage from nitrogen deposition. For example, the size of yellow starthistle plants increased substantially in response to experimentally increased carbon dioxide and nitrogen deposition, whereas co-occurring native plants responded less strongly (Dukes et al., 2011).

The rapid expansion of non-native invasive grasses, such as cheatgrass (Bromus tectorum) and ventenata grass (Ventenata dubia), has increased fine-fuel biomass and spatial
continuity of fuels in sagebrush-dominated ecosystems (Balch et al., 2013; Kerns et al., 2020; Tortorelli et al., 2020). Expansion of cheatgrass leads to a positive feedback loop in which increases in fire frequency and extent facilitate further increases in the distribution and density of cheatgrass.

Cheatgrass currently is most abundant in areas where precipitation is greatest during autumn and spring, which facilitates the species’ germination and growth (Bradley et al., 2016), and with hot, dry summers. Percent cover and biomass of cheatgrass also tends to increase in years with heavy winter and spring precipitation (Knapp, 1998; Garton et al., 2011), and may remain high during the following year (Bradley et al., 2016). Germination, growth, and reproduction of cheatgrass generally are highest at intermediate elevations with moderate temperatures and water availability. At low elevations, cheatgrass is limited by relatively high temperatures and low precipitation, and at high elevations, the species is limited by low soil temperatures (Meyer et al., 2001; Chambers et al., 2007, 2017; Compagnoni and Adler, 2014). Projected increases in temperature at high elevations (as at all elevations) may reduce that constraint on cheatgrass expansion in the future. Furthermore, soil moisture and nutrient levels commonly increase as elevation increases, supporting higher primary productivity and competition between cheatgrass and other species (Chambers et al., 2007; Compagnoni and Adler, 2014), especially perennial grasses, which can reduce the cover and density of cheatgrass (Reisner et al., 2013; Bradley et al., 2016; Larson et al., 2017).

<table>
<thead>
<tr>
<th>Key Messages</th>
</tr>
</thead>
<tbody>
<tr>
<td>⇒ In general, invasive and pest species in Wallowa County are likely to become more prevalent in response to projected increases in temperature, especially minimum winter temperature, and increases in the frequency, duration, and severity of drought. However, many of these responses are uncertain, are likely to vary locally, and may change over time.</td>
</tr>
</tbody>
</table>
Appendix

**Future Climate Projections Background**
Read more about global climate models, emissions scenarios, and uncertainty in the Climate Science Special Report—Volume 1 of the Fourth National Climate Assessment ([https://science2017.globalchange.gov](https://science2017.globalchange.gov)).

Global climate models (GCMs) and downscaling: [https://science2017.globalchange.gov/chapter/4#section-3](https://science2017.globalchange.gov/chapter/4#section-3)

Emissions scenarios: [https://science2017.globalchange.gov/chapter/4#section-2](https://science2017.globalchange.gov/chapter/4#section-2)

Uncertainty: [https://science2017.globalchange.gov/chapter/4#section-4](https://science2017.globalchange.gov/chapter/4#section-4)


**Climate and Hydrological Data**
Statistically downscaled GCM outputs from the fifth phase of the Coupled Model Intercomparison Project (CMIP5) were the basis for projections of future temperature, precipitation, and hydrology in this report. The coarse resolution of the GCMs outputs (100–300 km) was 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). The MACA approach 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 relationships. For a detailed description of the MACA method see: [https://climate.northwestknowledge.net/MACA/MACAmethod.php](https://climate.northwestknowledge.net/MACA/MACAmethod.php).

MACA data are the inputs to integrated models of climate, hydrology, and vegetation run by the Integrated Scenarios of the Future Northwest Environment project ([https://climate.northwestknowledge.net/IntegratedScenarios/](https://climate.northwestknowledge.net/IntegratedScenarios/)). Snow dynamics were simulated by the Integrated Scenarios project, which applied the Variable Infiltration Capacity hydrological model (VIC version 4.1.2; Liang *et al.*, 1994 and updates) to a 1/16 x 1/16 degree (6 km) grid.

Simulations of daily maximum temperature, minimum temperature, and precipitation from 1950 through 2099 for 20 GCMs (Table 13) and two emissions scenarios (RCP 4.5 and RCP 8.5) are available. Hydrological simulations of snow water equivalent (SWE) are available for the 10 GCMs used as input to VIC. All available modeled outputs were obtained from the Integrated Scenarios data archives and included in this report to represent the mean and range of projections among the largest possible ensemble of GCMs.
Table 13. The 20 CMIP5 GCMs represented in this report. Asterisks indicate the ten GCMs used as inputs to the Variable Infiltration Capacity hydrological model.

<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></td>
</tr>
<tr>
<td>BNU-ESM</td>
<td>College of Global Change and Earth System Science, Beijing Normal University, China</td>
</tr>
<tr>
<td>CanESM2*</td>
<td>Canadian Centre for Climate Modeling and Analysis</td>
</tr>
<tr>
<td>CCSM4*</td>
<td>National Center 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></td>
</tr>
<tr>
<td>HadGEM2-CC*</td>
<td>Met Office Hadley Center, UK</td>
</tr>
<tr>
<td>HadGEM2-ES*</td>
<td></td>
</tr>
<tr>
<td>INMCM4</td>
<td>Institute for Numerical Mathematics, Russia</td>
</tr>
<tr>
<td>IPSL-CM5A-LR</td>
<td></td>
</tr>
<tr>
<td>IPSL-CM5A-MR*</td>
<td>Institut Pierre Simon Laplace, France</td>
</tr>
<tr>
<td>IPSL-CM5B-LR</td>
<td></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>
<td></td>
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<tr>
<td>MIROC-ESM-CHEM</td>
<td></td>
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<tr>
<td>MRI-CGCM3</td>
<td>Meteorological Research Institute, Japan</td>
</tr>
<tr>
<td>NorESM1-M*</td>
<td>Norwegian Climate Center, Norway</td>
</tr>
</tbody>
</table>

All simulated climate data and the streamflow data, with the exception of snow water equivalent, were bias-corrected with quantile-mapping by the Integrated Scenarios project. Quantile mapping adjusts simulated values by comparing the cumulative probability distributions of simulated and observed values. In practice, the simulated and observed values of a variable (e.g., daily streamflow) 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 with 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 dataset reflect quantile mapping relationships for each non-overlapping 15-day window in the calendar year. Streamflow data reflect quantile mapping relationships for each calendar month.

The Integrated Scenarios project simulated hydrology with VIC (Liang et al., 1994) run on a 1/16 x 1/16 degree (6 km) grid. To generate daily streamflow estimates, daily runoff from VIC grid cells was routed to selected locations along the stream network. Where records of naturalized flow were available, the daily streamflow estimates were bias-corrected so their statistical distributions matched those of the naturalized streamflows.

Vapor pressure deficit and 100-hour fuel moisture were computed by the Integrated Scenarios project with the same MACA climate variables according to the equations in the National Fire Danger Rating System (NWCG, 2019).

**Smoke Wave Data**
Data from Liu et al. (2016) are available at [https://khanotations.github.io/smoke-map/](https://khanotations.github.io/smoke-map/). Variables used in this report included, “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 each county, exceeded the 98$^{th}$ 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 medium 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 multi-model mean value (not the range), which should be interpreted as the direction of projected change rather than the actual expected value.
References


