Future Climate Projections
Clatsop County

February 2020

A Report to the Oregon Department of Land Conservation and Development

Prepared by
The Oregon Climate Change Research Institute

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OCCRI DLCD

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A 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 most climate-related risks considered in this report. The risks of heat waves are projected to increase with very high confidence due to strong evidence in published literature, model consensus, and robust theoretical principles for continued increasing temperatures. The majority of risks expected to increase with climate change have high or medium confidence due to moderate to strong evidence and consensus yet they are influenced by multiple secondary factors in addition to increasing temperatures. Risks with low confidence, while important, show relatively little to no changes due to climate change or the level of evidence is limited. The projected direction of change along with the level of confidence in the direction of change for each climate change-related risk is summarized in Table 1.

Table 1 Summary of projected direction of change along with the level of confidence in climate change-related risk of natural hazard occurrence. Very high confidence means all models agree on the direction of change and there is strong evidence in the published literature. High confidence means most models agree on the direction of change and there is strong to medium evidence in the published literature. Medium confidence means that there is medium evidence and consensus on the direction of change with some caveats. Low confidence means the direction of change is small compared to the range of model responses or there is limited evidence in the published literature.

	Low Confidence	Medium Confidence	High Confidence	Very High Confidence
Risk Increasing ↑	Poor Air Quality	Drought Increased Invasive Species Risk	Heavy Rains Flooding Wildfire Loss of Wetland Ecosystems Ocean Temp & Chemistry Changes Coastal Hazards	Heat Waves
Risk Unchanging =	Windstorms			
Risk Decreasing ↓				Cold Waves

This report presents future climate projections for Clatsop County relevant to specific natural hazards for the 2020s (2010–2039 average) and 2050s (2040–2069 average) relative to the 1971–2000 average historical baseline. The projections were analyzed for a lower greenhouse gas emissions scenario as well as a higher greenhouse gas emissions scenario, using multiple global climate models. This summary lists only the projections for the 2050s under the higher emissions scenario. Projections for both time periods and both emissions scenarios can be found within relevant sections of the main report.

Heat Waves

Extreme heat events are expected to increase in frequency, duration, and intensity due to continued warming temperatures.

In Clatsop County, the frequency of hot days per year with temperatures at or above 90°F is projected to increase on average by 3 days, with a range of 0 to 7 days, by the 2050s under the higher emissions scenario relative to the historical baselines.

In Clatsop County, the temperature of the hottest day of the year is projected to increase on average by about 6°F, with a range of about 1 to 9°F, by the 2050s under the higher emissions scenario relative to the historical baselines.

Cold Waves

Cold extremes are still expected to occur from time to time, but with less frequency and intensity as the climate warms.

In Clatsop County, the frequency of days at or below freezing is projected to decline by about one day on average by the 2050s under the higher emissions scenario relative to the historical baselines.

In Clatsop County, the temperature of the coldest night of the year is projected to increase on average by about 6°F, with a range of about 0 to 10°F, by the 2050s under the higher emissions scenario relative to the historical baselines.

Heavy Rains

The intensity of extreme precipitation events is expected to increase in the future as the atmosphere warms and is able to hold more water vapor.

In Clatsop County, the frequency of days with at least ¾" of precipitation is not projected to change substantially. However, the magnitude of precipitation on the wettest day and wettest consecutive five days per year is projected to increase on average by about 16% (with a range of about 2% to 32%) and 11% (with a range of about -2% to 24%), respectively, by the 2050s under the higher emissions scenario relative to the historical baselines.

In Clatsop County, the frequency of days exceeding a threshold for landslide risk, based on 3-day and 15-day precipitation accumulation, is not projected to change substantially. However, landslide risk depends on a variety of factors and this metric may not reflect all aspects of the hazard.

River Flooding

Coastal rain-dominated watersheds, such as the Nehalem River, may experience an increase in winter flood risk due to projected greater winter precipitation and warmer winter temperatures causing precipitation to fall more as rain and less as snow, in addition to increases in the frequency and intensity of flood-producing atmospheric river events.

Drought

Drought conditions, as represented by low summer soil moisture, low spring snowpack, low summer runoff, low summer precipitation, and high summer evaporation are projected to become more frequent in Clatsop County by the 2050s.

Wildfire

Wildfire risk, as expressed through the frequency of very high fire danger days, is projected to increase under future climate change. In Clatsop County, the frequency of very high fire danger days per year is projected to increase on average by about 27% (with a range of -9 to +76%) by the 2050s under the higher emissions scenario compared to the historical baseline.

Air Quality

Under future climate change, the risk of wildfire smoke exposure is projected to increase in Clatsop County. The number days with high concentrations of wildfire-specific particulate matter is projected to increase by 32% while the intensity of particulate matter concentrations is projected to increase by 63% by 2046–2051 under a medium emissions scenario compared with 2004–2009.

Coastal Erosion & Flooding

The risk of coastal erosion and flooding hazards on the Oregon coast is expected to increase with climate change due to sea level rise and changing wave dynamics. In Clatsop County, local sea level is projected to rise by 0.8 to 4.8 feet by 2100. These projections include vertical land movement trend estimates meaning that the future sea level rise projections are expected to outpace the current rate of uplifting. At these levels, the multi-year likelihood of a flood event reaching four feet above mean high tide is virtually certain to occur by 2100.

Ocean Temperature & Chemistry

Ocean warming, ocean acidification, and decreasing dissolved oxygen levels are leading to alterations in marine ecosystems affecting coastal communities. The chemistry of the waters off the Oregon coast has already reached a threshold harmful to calcifying organisms and negative impacts are already evident. Reductions in calcifying organisms at the base of the marine food web could have cascading effects on higher trophic marine fish, birds, mammals, and the people who rely on this resource. In addition, warming ocean waters have altered marine species composition with greater prevalence of warm-water species expected during marine heat waves.

Windstorms

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

Increased Invasive Species Risk

Warming temperatures, altered precipitation patterns, and increasing atmospheric carbon dioxide levels increase the risk for invasive species establishment, insect and plant pests and diseases for forests and cropping systems. Invasive species populations are expected to expand in extent (northward in latitude, higher in elevation) with warmer temperatures.

Loss of Coastal Wetland Ecosystems

Coastal wetland ecosystems are sensitive to rising sea levels, increases in coastal storms and wave height, warming air and water temperatures, changing precipitation patterns and freshwater runoff, saltwater intrusion, and ocean acidification, which can lead to changes in biological, chemical, and physical processes; shifts in species and biodiversity loss; and altered location and spatial extent of tidal wetlands.

Introduction

Industrialization has given rise to increasing amounts of greenhouse gas emissions worldwide, which is causing the Earth's climate to warm (IPCC, 2013). The effects of which are already apparent here in Oregon (Dalton *et al.*, 2017; Mote *et al.*, 2019). Climate change is expected to influence the likelihood of occurrence of existing natural hazard events such as heavy rains, river flooding, drought, heat waves, cold waves, wildfire, air quality, and coastal erosion and flooding.

Oregon's Department of Land Conservation and Development (DLCD) contracted with the Oregon Climate Change Research Institute (OCCRI) to perform and provide analysis of the influence of climate change on natural hazards. The scope of this analysis is limited to the geographic area encompassed by the four Oregon counties that are part of the Pre-Disaster Mitigation (PDM) 17 grants DLCD received from FEMA. Those counties include: Lincoln, Clatsop, Baker, and Grant. Outcomes of this analysis include county-specific data, graphics, and text summarizing climate change projections for climate metrics related to each of the natural hazards listed in Table 2. This information will be integrated into the Natural Hazards Mitigation Plan (NHMP) updates for the four counties, and can be used in other county plans, policies, and programs. In addition to the county reports, sharing of data, and other technical assistance will be provided to the counties. This report covers climate change projections related to natural hazards relevant to Clatsop County.

Table 2 Natural hazards and related climate metrics evaluated in this project.

Heavy Rains Wettest Day ◆ Wettest Five Days Landslide Threshold Exceedance	**Heat Waves** Hottest Day ◆ Warmest Night "Hot" Days ◆ "Warm" Nights
River Flooding Annual maximum daily flows Atmospheric Rivers Rain-on-Snow Events	**Cold Waves** Coldest Day ◆ Coldest Night "Cold" Days ◆ "Cold" Nights
Drought Summer Flow ◆ Spring Snow Summer Soil Moisture Summer Precipitation	**Air Quality** Unhealthy Smoke Days
Wildfire Fire Danger Days	**Coastal Erosion & Flooding** Sea Level Rise ◆ Waves
Windstorms	**Ocean Temperature & Chemistry**
Increased Invasive Species Risk	**Loss of Wetland Ecosystems**

Future Climate Projections Background

Introduction

The county-specific future climate projections prepared by OCCRI are derived from 10–20 global climate models (GCM) and two scenarios of future global greenhouse gas emissions. Future climate projections have been "downscaled"—that is, made locally relevant—and summaries of projected changes in the climate metrics in Table 2 are presented for an early 21st century period and a mid 21st century period relative to a historical baseline. (Read more about the data sources in the Appendix.)

Global Climate Models

Global climate models are sophisticated computer models of the Earth's atmosphere, water, and land and how these components interact over time and space according to the fundamental laws of physics (Figure 1). GCMs are the most sophisticated tools for understanding the climate system, but while highly complex and built on solid physical principles, they are still simplifications of the actual climate system. There are several ways to implement such simplifications into a GCM, which results in each one giving a slightly different answer. As such, it is best practice to use at least ten GCMs and look at the average and range of projections across all of them. (Read more about GCMs and uncertainty in the Appendix.)

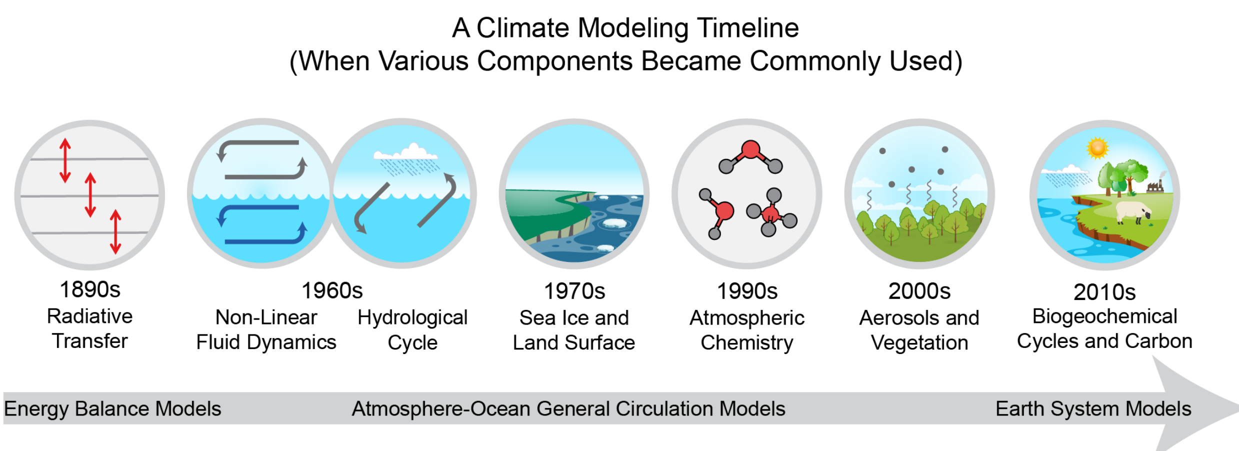

Figure 1 As scientific understanding of climate has evolved over the last 120 years, increasing amounts of physics, chemistry, and biology have been incorporated into calculations and, eventually, models. This figure shows when various processes and components of the climate system became regularly included 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)

Greenhouse Gas Emissions

When used to project future climate, scientists give the GCMs information about the quantity of greenhouse gases that the world would emit, then the GCMs run simulations of what would happen to the air, water, and land over the next century. Since the precise amount of greenhouse gases the world will emit over the next century is unknown, scientists use several scenarios of different amounts of greenhouse gas emissions based on plausible societal trajectories. The future climate projections prepared by OCCRI uses emissions pathways called Representative Concentration Pathways (RCPs). There are several RCPs and the higher global emissions are, the greater the expected increase in global temperature (Figure 2). OCCRI considers a lower emissions scenario (RCP 4.5) and a higher emissions scenario (RCP 8.5) because they are the most commonly used scenarios in published literature and the downscaled data is available for these scenarios. (Read more about emissions scenarios in the Appendix.)

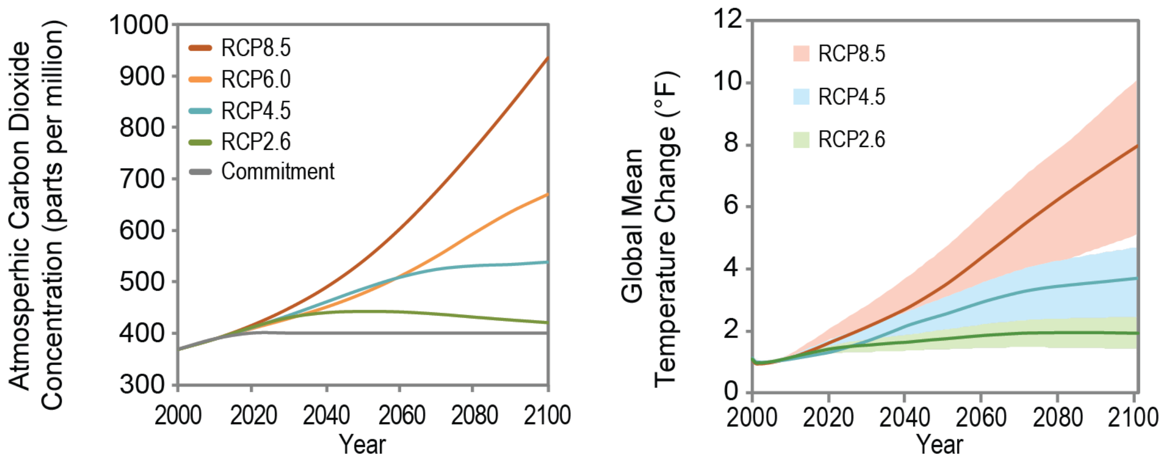

Figure 2 Future scenarios of atmospheric carbon dioxide concentrations (left) and global temperature change (right) resulting from several different emissions pathways, called Representative Concentration Pathways (RCPs), which are considered in the fourth and most recent National Climate Assessment.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

Downscaling

Global climate models simulate the climate across adjacent grid boxes the size of about 60 by 60 miles. To make this coarse resolution information locally relevant, GCM outputs have been combined with historical observations to translate large-scale patterns into high-resolution projections. This process is called statistical downscaling. The future climate projections produced by OCCRI were statistically downscaled to a resolution with grid boxes the size of about 2.5 by 2.5 miles (Abatzoglou and Brown, 2012). (Read more about downscaling in the Appendix.)

Future Time Periods

When analyzing global climate model projections of future climate, it is best practice to compare the average across at least a 30-year period in the future simulations to an average across at least a 30-year period in the historical simulations. The average over a 30-year period in the historical simulations is called the *historical baseline*. For the future climate projections in this report, two 30-year future periods are analyzed in comparison with a 30-year historical baseline (Table 3).

Each of the twenty global climate models simulates historical and future climate slightly differently. Thus, each global climate model has a different historical baseline from which future projections are compared. Because each climate model's historical baseline is slightly different, this report presents the average and range of projected *changes* in the variables relative to each model's own historical baseline (rather than the average and range of future projected absolute values). The average of the twenty historical baselines, called the *average historical baseline*, is also presented to aid in understanding the relative magnitude of projected changes. The average historical baseline can be combined with the average projected future change to infer the average projected future absolute value of a given variable. However, the average historical baseline cannot be combined with the range of projected future changes to infer the range of projected future absolute values.

Table 3 Historical and future time periods for presentation of future climate projections

Historical Baseline	Early 21st Century "2020s"	Mid 21st Century "2050s"
1971–2000	2010–2039	2040–2069

How to Use the Information in this Report

Given the changing climate, anticipating future outcomes by considering only past trends may become increasingly unreliable. Future projections from GCMs provide an opportunity to explore a range of plausible outcomes taking into consideration the climate system's complex response to increasing concentrations of greenhouse gases. It is important to be aware that GCM projections should not be thought of as predictions of what the weather will be like at some specified date in the future, but rather viewed as projections of the long-term statistical aggregate of weather, in other words, "climate", if greenhouse gas concentrations follow some specified trajectory.[1]

The projections of climate variables in this report, both in the direction and magnitude of change, are best used in reference to the historical climate conditions under which a particular asset or system is designed to operate. For this reason, considering the projected changes between the historical and future periods allows one to envision how current systems of interest would respond to climate conditions that are different from what they have been. In some cases, the projected change may be small enough to be accommodated within the existing system. 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 a more detailed analysis than what is available in this report.

The information in this report can be used to:

- Explore a range of plausible future outcomes taking into considering the climate system's complex response to increasing greenhouse gases
- Envision how current systems may respond under climate conditions different from those the systems were designed to operate under
- Evaluate potential mitigation actions to accommodate future conditions
- Influence the risk assessment in terms of the likelihood of a particular climate-related hazard occurring.

[1] Read more: https://nca2014.globalchange.gov/report/appendices/faqs#narrative-page-38784

Average Temperature

Oregon's average temperature warmed at a rate of 2.2°F per century during 1895–2015. Average temperature is expected to continue warming during the 21st century under scenarios of continued global greenhouse gas emissions; the rate of warming depends on the particular emissions scenario (Dalton *et al.*, 2017). By the 2050s (2040–2069) relative to the 1970–1999 historical baseline, Oregon's average temperature is projected to increase by 3.6 °F with a range of 1.8°–5.4°F under a lower emissions scenario (RCP 4.5) and by 5.0°F with a range of 2.9°F–6.9°F under a higher emissions scenario (RCP 8.5) (Dalton *et al.*, 2017). Furthermore, summers are projected to warm more than other seasons (Dalton *et al.*, 2017).

Average temperature in Clatsop County is projected to warm during the 21st century at a similar rate to Oregon as a whole (Figure 3). Projected increases in average temperature in Clatsop County relative to each global climate model's 1971–2000 historical baseline range from 0.9–3.5°F by the 2020s (2010–2039) and 1.4–6.5°F by the 2050s (2040–2069), depending on emissions scenario and climate model (Table 4).

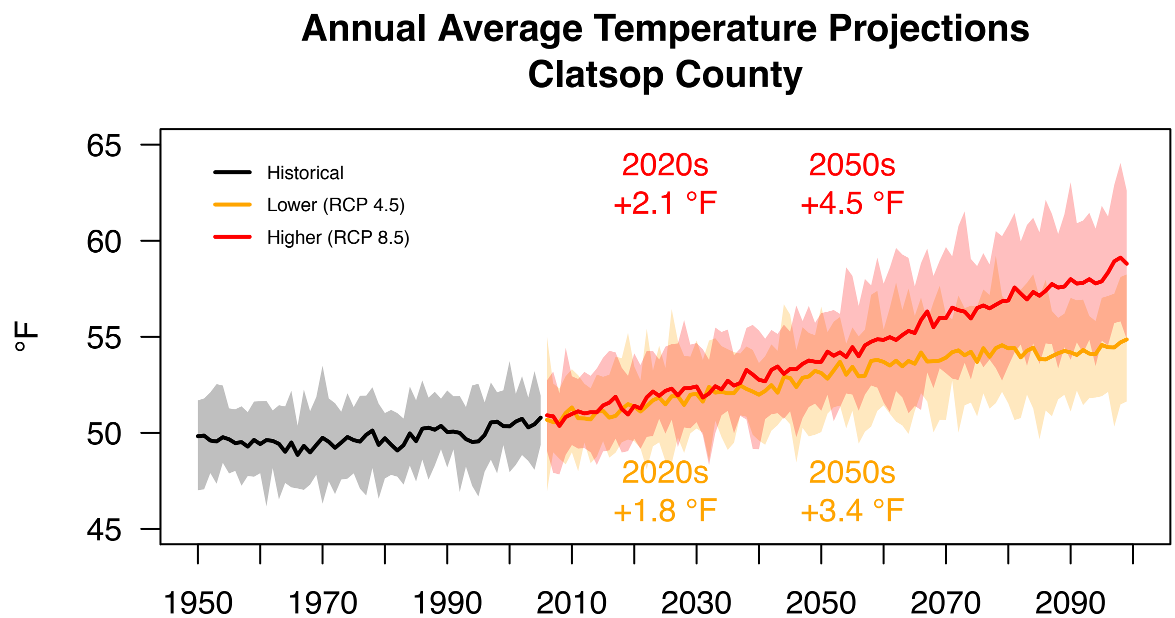

Figure 3 Annual average temperature projections for Clatsop County as simulated by 20 downscaled global climate models under a lower (RCP 4.5) and a higher (RCP 8.5) greenhouse gas emissions scenario. Solid line and shading depicts the 20-model mean and range, respectively. The multi-model mean differences 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 Clatsop County's average temperature relative to each global climate model's (GCM) historical baseline (1971–2000 average) for the 2020s (2010–2039 average) and 2050s (2040–2069 average) under a lower (RCP 4.5) and higher (RCP 8.5) emissions scenario based on 20 GCMs.

	Change by Early 21st Century "2020s"	Change by Mid 21st Century "2050s"
Higher (RCP 8.5)	+2.1°F (1.3 to 3.5)	+4.5°F (2.7 to 6.5)
Lower (RCP 4.5)	+1.8°F (0.9 to 3.1)	+3.4°F (1.4 to 4.9)

Heat Waves

Extreme heat events are expected to increase in frequency, duration, and intensity in Oregon due to continued warming temperatures. In fact, the hottest days in summer are projected to warm more than the change in mean temperature over the Pacific Northwest (Dalton *et al.*, 2017). This report presents projected changes for three metrics of heat extremes for both daytime (maximum temperature) and nighttime (minimum temperature) (Table 5).

Table 5 Heat extreme metrics and definitions

Metric	Definition
Hot Days	Number of days per year maximum temperature is greater than or equal to 90°F
Warm Nights	Number of days per year minimum temperature is greater than or equal to 65°F
Hottest Day	Annual maximum of maximum temperature
Warmest Night	Annual maximum of minimum temperature
Daytime Heat Waves	Number of events per year with at least 3 consecutive days with maximum temperature greater than or equal to 90°F
Nighttime Heat Waves	Number of events per year with at least 3 consecutive days with minimum temperature greater than or equal to 65°F

In Clatsop County, the frequency of extreme heat days (i.e., Hot Days and Warm Nights) and magnitude of extreme heat (i.e., 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). For example, for the 2050s under the higher emissions scenario climate models project that the number of hot days greater than or equal to 90°F per year, relative to each model's 1971–2000 historical baseline, would increase by as much as 7 days. The average projected increase in number of hot days per year is 3 days above the average historical baseline of virtually zero days.

Likewise, the temperature of the hottest day of the year is projected to increase by as little as 0.7°F to as much as 8.6°F by the 2050s under the higher emissions scenario relative to the models' historical baselines. The average projected increase is 5.6°F above the average historical baseline of 85.6°F. In other words, hot days are projected to become more frequent and the hottest days are projected to become even hotter.

Projected changes in the frequency of extreme heat days (i.e., Hot Days and Warm Nights) are shown in Figure 4. Projected changes in the magnitude of heat records (i.e., Hottest Day and Warmest Night) are shown in Figure 5. Projected changes in the frequency of extreme heat events (i.e., Daytime Heat Waves and Nighttime Heat Waves) are shown in Figure 6.

Table 6 Mean and range of projected future changes in extreme heat metrics for Clatsop County relative to each global climate model's (GCM) historical baseline (1971–2000 average) for the 2020s (2010–2039 average) and 2050s (2040–2069 average) under a lower (RCP 4.5) and higher (RCP 8.5) emissions scenario based on 20 GCMs. The average historical baseline across the 20 GCMs is also presented and can be combined with the average projected future change to infer the average projected future absolute value of a given variable. However, the average historical baseline cannot be combined with the range of projected future changes to infer the range of projected future absolute values.

		Change by Early 21st Century "2020s"		Change by Mid 21st Century "2050s"	
	Average Historical Baseline	**Lower**	**Higher**	**Lower**	**Higher**
Hot Days	0.5 days	+0.6 days (0.0–1.3)	+0.8 days (0.3–1.8)	+1.9 days (0.5–4.0)	+3.3 days (0.4–7.0)
Warm Nights	0.2 days	+0.2 days (-0.1–0.5)	+0.3 days (0.0–1.1)	+0.9 days (0.1–2.9)	+1.8 days (0.2–5.2)
Hottest Day	85.6°F	+1.9°F (-0.0–3.6)	+2.6°F (0.6–4.9)	+4.2°F (1.3–6.6)	+5.6°F (0.7–8.6)
Warmest Night	60.1°F	+1.6°F (-0.6–4.1)	+2.1°F (0.3–3.8)	+3.7°F (1.8–6.7)	+5.2°F (2.2–8.8)
Daytime Heat Waves	0.1 events	+0.1 events (0.0–0.2)	+0.1 events (0.0–0.3)	+0.3 events (0.1–0.6)	+0.5 events (0.1–1.1)
Nighttime Heat Waves	0.0 events	+0.0 events (-0.0–0.1)	+0.0 events (-0.0–0.2)	+0.1 events (-0.0–0.4)	+0.2 events (-0.0–0.6)

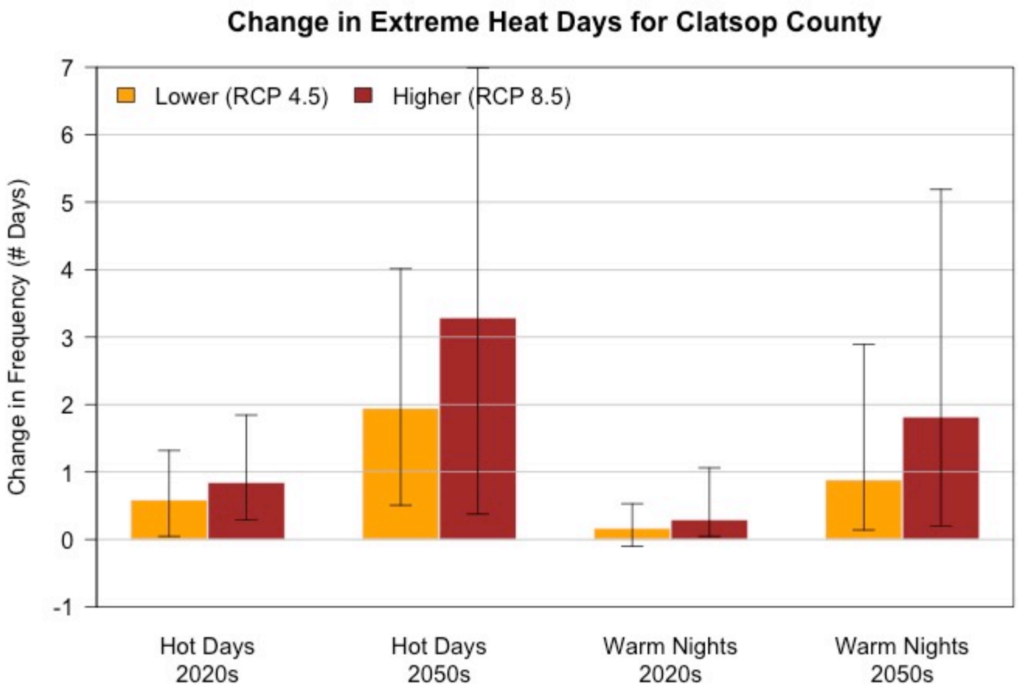

Figure 4 Projected future changes in the number of hot days (left two sets of bars) and number of warm nights (right two sets of bars) for Clatsop County relative to the historical baseline (1971–2000 average) for the 2020s (2010–2039 average) and 2050s (2040–2069 average) under a lower (RCP 4.5) and higher (RCP 8.5) emissions scenario based on 20 global climate models (GCMs). The bars and whiskers display the mean and range, respectively, of changes across the 20 GCMs relative to each GCM's historical baseline. Hot days are defined as days with maximum temperature of at least 90°F; warm nights are defined as days with minimum temperature of at least 65°F.

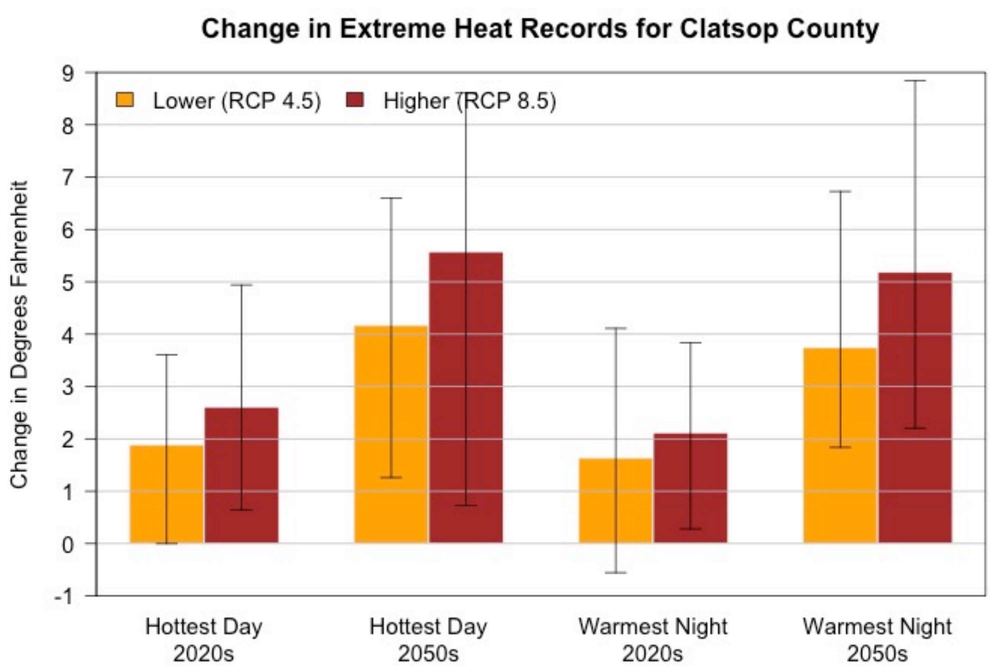

Figure 5 Projected future changes in the hottest day of the year (left two sets of bars) and warmest night of the year (right two sets of bars) for Clatsop County relative to the historical baseline (1971–2000 average) for the 2020s (2010–2039 average) and 2050s (2040–2069 average) under a lower (RCP 4.5) and higher (RCP 8.5) emissions scenario based on 20 global climate models (GCMs). The bars and whiskers display the mean and range, respectively, of changes across the 20 GCMs relative to each GCM's historical baseline.

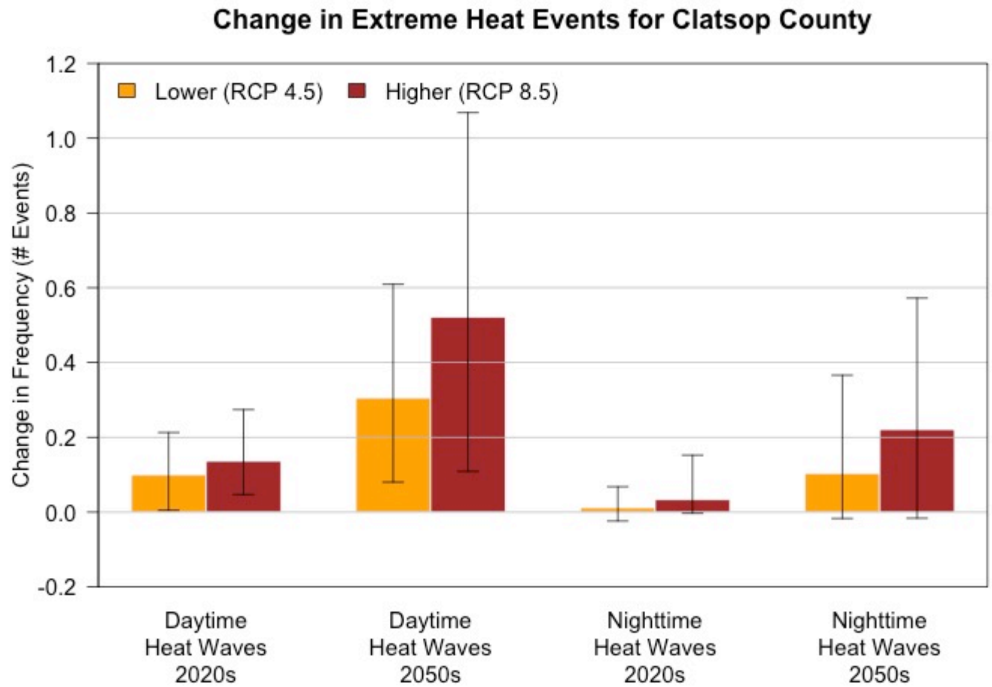

Figure 6 Projected future changes in the number of daytime heat waves (left two sets of bars) and number of nighttime heat waves (right two sets of bars) for Clatsop County relative to the historical baseline (1971–2000 average) for the 2020s (2010–2039 average) and 2050s (2040–2069 average) under a lower (RCP 4.5) and higher (RCP 8.5) emissions scenario based on 20 global climate models (GCMs). The bars and whiskers display the mean and range, respectively, of changes across the 20 GCMs relative to each GCM's historical baseline. Daytime heat waves are defined as events with three or more consecutive days with maximum temperature of at least 90°F; nighttime heat waves are defined as events with three or more consecutive days with minimum temperature of at least 65°F.

Key Messages:

⇒ Extreme heat events are expected to increase in frequency, duration, and intensity due to continued warming temperatures.

⇒ In Clatsop County, the frequency of extreme heat days and magnitude of extreme heat metrics are projected to increase by the 2020s and 2050s under both the lower (RCP 4.5) and higher (RCP 8.5) emissions scenarios (Table 6).

⇒ In Clatsop County, the frequency of hot days per year with temperatures at or above 90°F is projected to increase on average by 3 days, with a range of 0 to 7 days, by the 2050s under the higher emissions scenario relative to the historical baselines.

⇒ In Clatsop County, the temperature of the hottest day of the year is projected to increase on average by about 6°F, with a range of about 1 to 9°F, by the 2050s under the higher emissions scenario relative to the historical baselines.

Cold Waves

Over the past century, cold extremes have become less frequent and severe in the Northwest; this trend is expected to continue under future global warming of the climate system (Vose *et al.*, 2017). This report presents projected changes for three metrics of cold extremes for both daytime (maximum temperature) and nighttime (minimum temperature) (Table 7).

Table 7 Cold extreme metrics and definitions

Metric	Definition
Cold Days	Number of days per year maximum temperature is less than or equal to 32°F
Cold Nights	Number of days per year minimum temperature is less than or equal to 0°F
Coldest Day	Annual minimum of maximum temperature
Coldest Night	Annual minimum of minimum temperature
Daytime Cold Waves	Number of events per year with at least 3 consecutive days with maximum temperature less than or equal to 32°F
Nighttime Cold Waves	Number of events per year with at least 3 consecutive days with minimum temperature less than or equal to 0°F

In Clatsop County, the coldest days and nights are projected to become less cold 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). For example, by the 2050s under the higher emissions scenario the temperature of the coldest night of the year is projected to increase by as little as 0°F to as much as 10.4°F relative to the models' historical baselines. The average projected increase is 5.5°F above the average historical baseline of 17.5°F. However, the frequency of cold days and nights and cold wave events defined in (Table 7) is not projected to change very much given that such days are rare in Clatsop County (Table 8). By the 2050s under the higher emissions scenario, the number of cold days less than or equal to 32°F is projected to decrease by about one day on average.

Projected changes in the frequency of extreme cold days (i.e., Cold Days and Cold Nights) are shown in Figure 7. Projected changes in the magnitude of cold records (i.e., Coldest Day and Coldest Night) are shown in Figure 8. Projected changes in the frequency of extreme cold events (i.e., Daytime Cold Waves and Nighttime Cold Waves) are shown in Figure 9.

Table 8 Mean and range of projected future changes in extreme cold metrics for Clatsop County relative to each global climate model's (GCM) historical baseline (1971–2000 average) for the 2020s (2010–2039 average) and 2050s (2040–2069 average) under a lower (RCP 4.5) and higher (RCP 8.5) emissions scenario based on 20 GCMs. The average historical baseline across the 20 GCMs is also presented and can be combined with the average projected future change to infer the average projected future absolute value of a given variable. However, the average historical baseline cannot be combined with the range of projected future changes to infer the range of projected future absolute values.

		Change by Early 21st Century "2020s"		Change by Mid 21st Century "2050s"	
	Average Historical Baseline	**Lower**	**Higher**	**Lower**	**Higher**
Cold Days	1.7 days	-0.3 days (-1.2 to 1.0)	-0.7 days (-1.3 to 0.1)	-1.0 days (-1.8 to 0.1)	-1.1 days (-1.8 to 0.1)
Cold Nights	0.0 days	0.0 days (-0.0 to 0.1)	0.0 days (-0.0 to 0.2)	0.0 days (-0.0 to 0.0)	0.0 days (-0.0 to 0.1)
Coldest Day	31.5°F	+1.2°F (-2.7 to 4.0)	+2.4°F (-1.5 to 4.8)	+3.9°F (-0.3 to 7.4)	+5.1°F (-0.4 to 8.6)
Coldest Night	17.5°F	+1.3°F (-2.4 to 4.1)	+2.6°F (0.1 to 5.8)	+4.4°F (1.0 to 7.8)	+5.5°F (-0.0 to 10.4)
Daytime Cold Waves	0.2 events	-0.0 events (-0.2 to 0.1)	-0.1 events (-0.2 to 0.0)	-0.1 events (-0.2 to 0.0)	-0.1 events (-0.3 to 0.0)
Nighttime Cold Waves	0.0 events	0.0 events (0.0 to 0.0)	0.0 events (0.0 to 0.0)	0.0 events (0.0 to 0.0)	0.0 events (0.0 to 0.0)

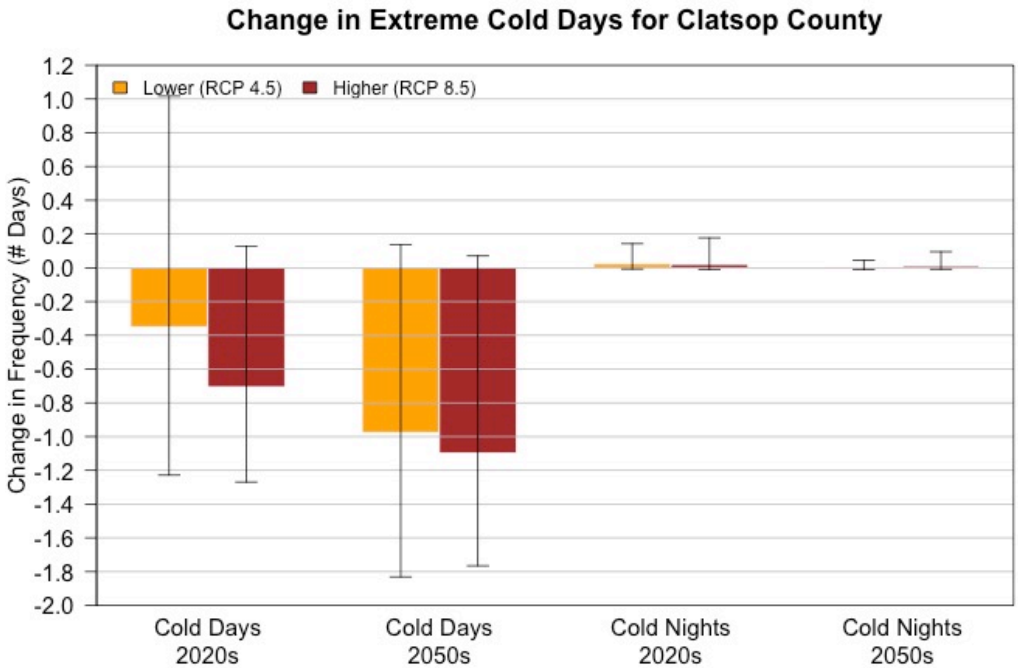

Figure 7 Projected future changes in the number of cold days (left two sets of bars) and number of cold nights (right two sets of bars) for Clatsop County relative to the historical baseline (1971–2000 average) for the 2020s (2010–2039 average) and 2050s (2040–2069 average) under a lower (RCP 4.5) and higher (RCP 8.5) emissions scenario based on 20 global climate models (GCMs). The bars and whiskers display the mean and range, respectively, of changes across the 20 GCMs relative to each GCM's historical baseline. Cold days are defined as days with maximum temperature at or below 32°F; cold nights are defined as days with minimum temperature at or below 0°F.

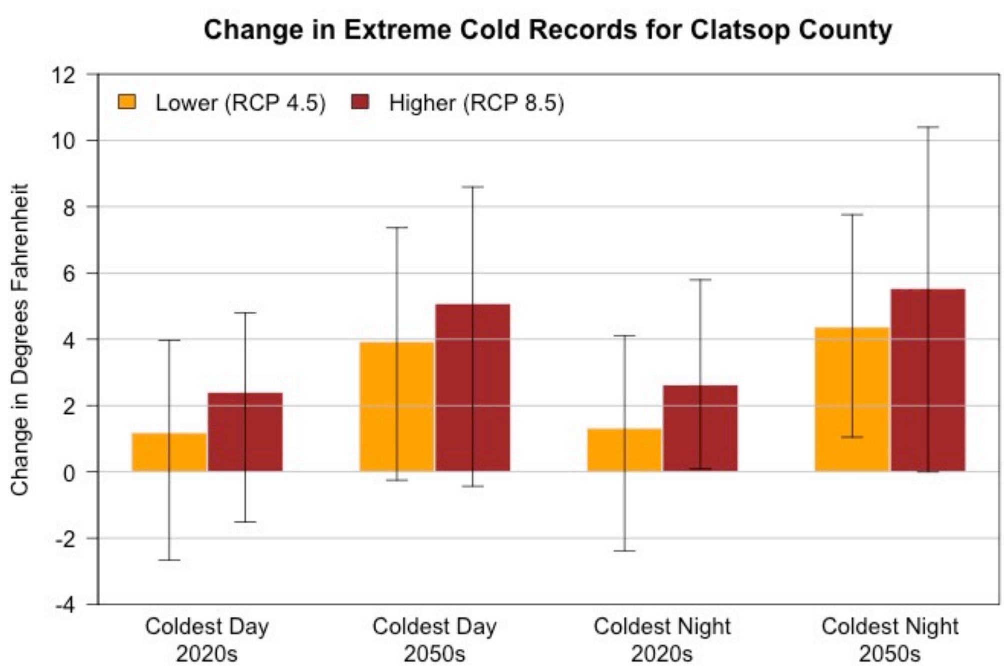

Figure 8 Projected future changes in the coldest day of the year (left two sets of bars) and coldest night of the year (right two sets of bars) for Clatsop County relative to the historical baseline (1971–2000 average) for the 2020s (2010–2039 average) and 2050s (2040–2069 average) under a lower (RCP 4.5) and higher (RCP 8.5) emissions scenario based on 20 global climate models (GCMs). The bars and whiskers display the mean and range, respectively, of changes across the 20 GCMs relative to each GCM's historical baseline.

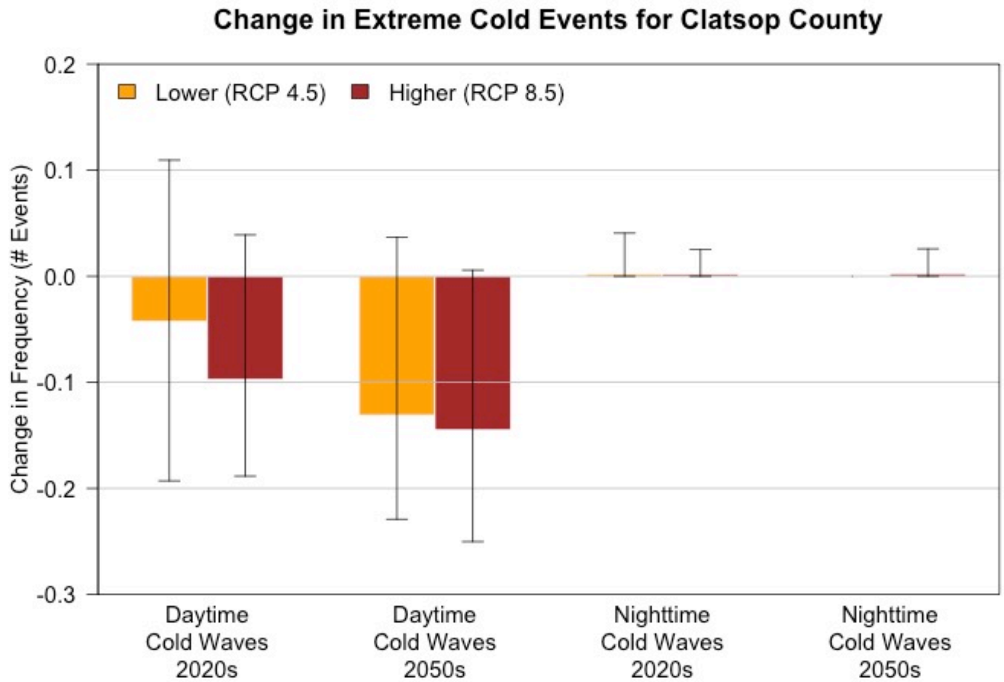

Figure 9 Projected future changes in the number of daytime cold waves (left two sets of bars) and number of nighttime cold waves (right two sets of bars) for Clatsop County relative to the historical baseline (1971–2000 average) for the 2020s (2010–2039 average) and 2050s (2040–2069 average) under a lower (RCP 4.5) and higher (RCP 8.5) emissions scenario based on 20 global climate models (GCMs). The bars and whiskers display the mean and range, respectively, of changes across the 20 GCMs relative to each GCM's historical baseline. Daytime cold waves are defined as events with three or more consecutive days with maximum temperature at or below 32°F; nighttime cold waves are defined as events with three or more consecutive days with minimum temperature at or below 0°F.

Key Messages:

⇒ Cold extremes are still expected to occur from time to time, but with less frequency and intensity as the climate warms.

⇒ In Clatsop County, the frequency of days at or below freezing is projected to decline by about one day on average by the 2050s under the higher emissions scenario relative to the historical baselines.

⇒ In Clatsop County, the temperature of the coldest night of the year is projected to increase on average by about 6°F, with a range of about 0 to 10°F, by the 2050s under the higher emissions scenario relative to the historical baselines.

Heavy Rains

There is greater uncertainty in future projections of precipitation-related metrics than temperature-related metrics. This is because of the large natural variability in precipitation patterns and the fact that the atmospheric patterns that influence precipitation are manifested differently across GCMs. From a global perspective, mean precipitation is likely to decrease in many dry regions in the sub-tropics and mid-latitudes and increase in many mid-latitude wet regions (IPCC, 2013). That boundary between mid-latitude increases and decreases in precipitation is positioned a little differently for each GCM, which results in some models projecting increases and others decreases in Oregon (Mote *et al.*, 2013).

In Oregon, observed precipitation is characterized by high year-to-year variability and future precipitation trends are expected to continue to be dominated by this large natural variability. 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 (2040–2069). However, some models project increases and others decreases in each season (Dalton *et al.*, 2017).

Extreme precipitation events in the Pacific Northwest are governed both by atmospheric circulation and by how it interacts 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 coherent extreme precipitation events west of the Cascade Range, while closed low pressure systems often lead to isolated precipitation extremes east of the Cascade Range (Parker and Abatzoglou, 2016).[2]

Observed trends in the frequency of extreme precipitation events across Oregon have depended on the location, time frame, and metric considered, but overall the frequency has not changed substantially. As the atmosphere warms, it is able to hold more water vapor that is available for precipitation. As a result, the frequency and intensity of extreme precipitation events are expected to increase in the future (Dalton *et al.*, 2017), including atmospheric river events (Kossin *et al.*, 2017). In addition, regional climate modeling results suggest a weakened rain shadow effect in winter projecting relatively larger increases in precipitation east of the Cascades and smaller increases west of the Cascades in terms of both seasonal precipitation totals and precipitation extremes (Mote *et al.*, 2019).

This report presents projected changes for four metrics of precipitation extremes (Table 9).

[2] Verbatim from the Third Oregon Climate Assessment Report (Dalton *et al.*, 2017)

Table 9 Precipitation extreme metrics and definitions

Metric	Definition
Wettest Day	Annual maximum 1-day precipitation per water year
Wettest Five-Days	Annual maximum 5-day precipitation total per water year
Wet Days	Number of days per year with precipitation greater than 0.75 inches
Landslide Risk Days	Number of days per water year exceeding the USGS landslide threshold[3]: https://pubs.er.usgs.gov/publication/ofr20061064 ○ P3/(3.5-.67*P15)>1, where: ▪ P3 = Previous 3-day precipitation accumulation ▪ P15 = 15-day precipitation accumulation prior to P3

In Clatsop County, the magnitude 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) under both the lower and higher emissions scenarios (Table 10). However, some models project decreases in some of these metrics for certain time periods and scenarios.

For the 2050s under the higher emissions scenario, climate models project that the magnitude, or amount, of precipitation on the wettest day of the year, relative to each model's 1971–2000 historical baseline, would increase by as little as 1.6% to as much as 31.5%. The average projected percent increase in the amount of precipitation on the wettest day of the year is 16.1% above the average historical baseline of 3.76 inches.

For the magnitude of precipitation on the wettest consecutive five days of the year, some models project decreases by as much as 2.0% while other models project increases by as much as 24.0% for the 2050s under the higher emissions scenario. The average projected percent change in the amount of precipitation on the wettest consecutive five days is an increase of 10.9% above the average historical baseline of 9.64 inches.

The average number of days per year with precipitation greater than ¾" isn't projected to change substantially. For example, by the 2050s under the higher emissions scenario, climate models project a range of changes in frequency of wet days from four fewer days to six more days per year.

Landslides are often triggered by rainfall when the soil becomes saturated. This report analyzes a cumulative rainfall threshold based on the previous 3-day and 15-day precipitation accumulation as a surrogate for landslide risk. For Clatsop County, the average number of days per year exceeding the landslide risk threshold is projected to remain about the same with a range of four fewer days to two more days by the 2050s under the higher emissions scenario. Landslide risk depends on a variety of site-specific factors and this metric may not reflect all aspects of the hazard. It is important to note that

[3] This threshold was developed for Seattle, Washington and may or may not have similar applicability to other locations.

this particular landslide threshold was developed for Seattle, Washington and may or may not have similar applicability to other locations.

Projected changes in the magnitude of extreme precipitation events (i.e., Wettest Day and Wettest Five-Days) are shown in Figure 10. Projected changes in the frequency of extreme precipitation events (i.e., Wet Days and Landslide Risk Days) are shown in Figure 11.

Table 10 Mean and range of projected future changes in extreme precipitation metrics for Clatsop County relative to each global climate model's (GCM) historical baseline (1971–2000 average) for the 2020s (2010–2039 average) and 2050s (2040–2069 average) under a lower (RCP 4.5) and higher (RCP 8.5) emissions scenario based on 20 GCMs. The average historical baseline across the 20 GCMs is also presented and can be combined with the average projected future change to infer the average projected future absolute value of a given variable. However, the average historical baseline cannot be combined with the range of projected future changes to infer the range of projected future absolute values.

		Change by Early 21st Century "2020s"		Change by Mid 21st Century "2050s"	
	Average Historical Baseline	Lower	Higher	Lower	Higher
Wettest Day	3.76 inches	+7.6% (-8.2 to 16.9)	+9.0% (0.4 to 31.3)	+14.1% (4.8 to 25.2)	+16.1% (1.6 to 31.5)
Wettest Five-Days	9.64 inches	+5.0% (-5.0 to 15.7)	+4.4% (-8.6 to 28.1)	+9.9% (1.1 to 21.8)	+10.9% (-2.0 to 24.0)
Wet Days	46.3 days	+0.4 days (-1.5 to 4.4)	-0.3 days (-4.7 to 2.7)	+0.9 days (-4.6 to 5.2)	+0.7 days (-3.8 to 5.7)
Landslide Risk Days	33.0 days	-0.1 days (-3.8 to 4.2)	-0.2 days (-3.2 to 4.2)	-1.2 days (-4.4 to 1.4)	-0.7 days (-3.9 to 2.0)

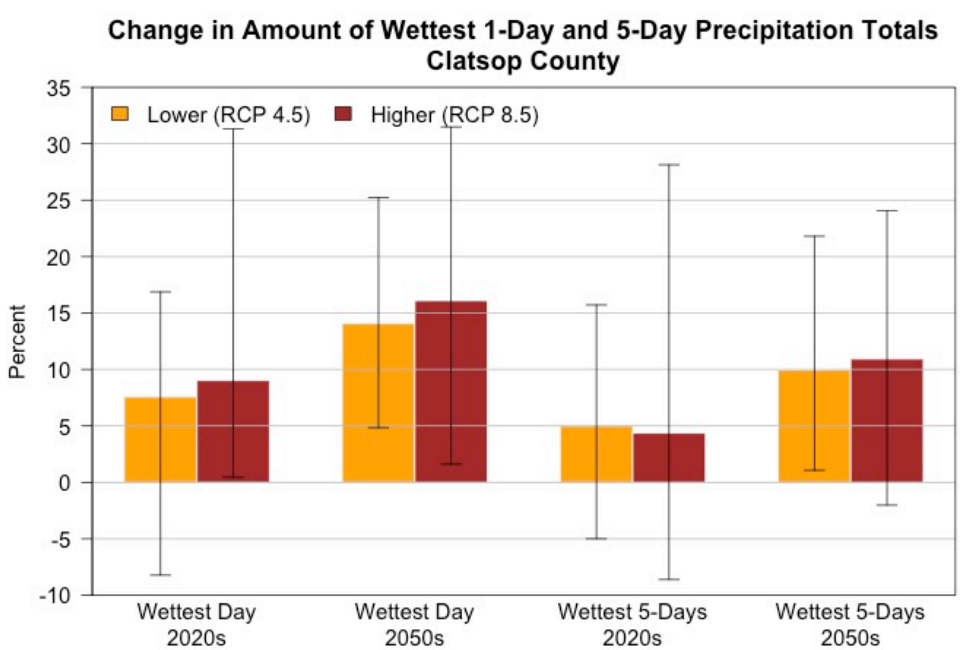

Figure 10 Projected future changes in the wettest day of the year (left two sets of bars) and wettest consecutive five days of the year (right two sets of bars) for Clatsop County relative to the historical baseline (1971–2000 average) for the 2020s (2010–2039 average) and 2050s (2040–2069 average) under a lower (RCP 4.5) and higher (RCP 8.5) emissions scenario based on 20 global climate models (GCMs). The bars and whiskers display the mean and range, respectively, of changes across the 20 GCMs relative to each GCM's historical baseline.

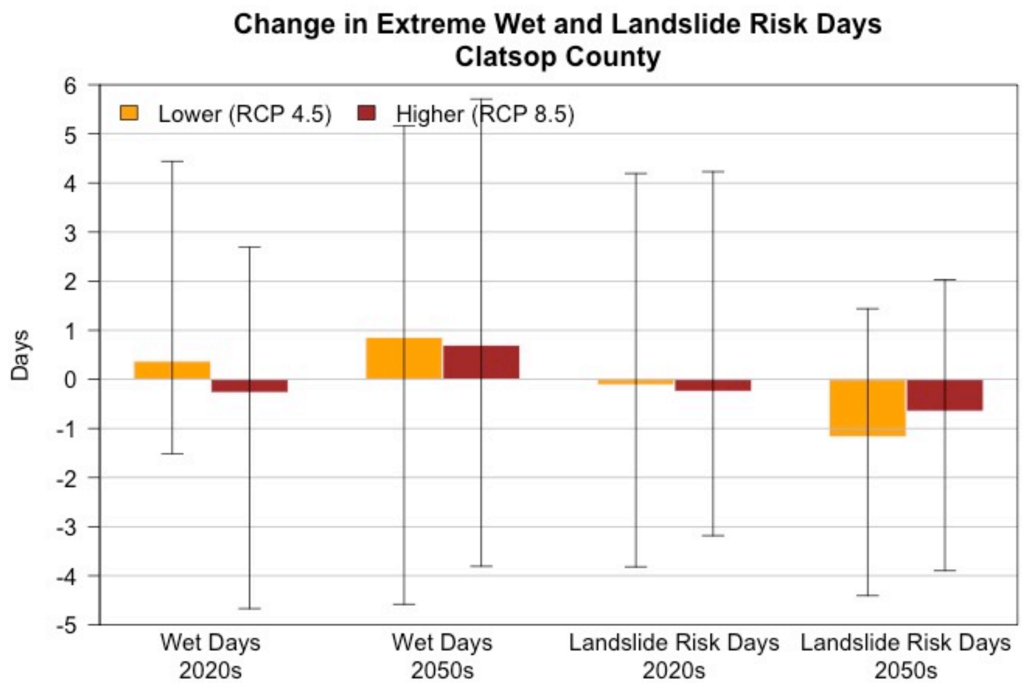

Figure 11 Projected future changes in the frequency of wet days (left two sets of bars) and landslide risk days (right two sets of bars) for Clatsop County relative to the historical baseline (1971–2000 average) for the 2020s (2010–2039 average) and 2050s (2040–2069 average) under a lower (RCP 4.5) and higher (RCP 8.5) emissions scenario based on 20 global climate models (GCMs). The bars and whiskers display the mean and range, respectively, of changes across the 20 GCMs relative to each GCM's historical baseline.

Key Messages:

⇒ The intensity of extreme precipitation events is expected to increase in the future as the atmosphere warms and is able to hold more water vapor.

⇒ In Clatsop County, the frequency of days with at least ¾" of precipitation is not projected to change substantially. However, the magnitude of precipitation on the wettest day and wettest consecutive five days per year is projected to increase on average by about 16% (with a range of about 2% to 32%) and 11% (with a range of about -2% to 24%), respectively, by the 2050s under the higher emissions scenario relative to the historical baselines.

⇒ In Clatsop County, the frequency of days exceeding a threshold for landslide risk, based on 3-day and 15-day precipitation accumulation, is not projected to change substantially. However, landslide risk depends on a variety of factors and this metric may not reflect all aspects of the hazard.

Future streamflow magnitude and timing in the Pacific Northwest is projected to shift toward higher winter runoff, lower summer and fall runoff, and an earlier peak runoff, particularly in snow-dominated regions (Raymondi *et al.*, 2013; Naz *et al.*, 2016).[4] These changes are expected to result from warmer temperatures causing precipitation to fall more as rain and less as snow, in turn causing snow to melt earlier in the spring; and in combination with increasing winter precipitation and decreasing summer precipitation (Dalton *et al.*, 2017; Mote *et al.*, 2019).

Streamflow in rain-dominant watersheds reflects the seasonal pattern of precipitation, with peak flows occurring during the winter and low flows occurring during the summer.[5] Coastal rain-dominated watersheds, like those in Clatsop County, have received very little attention in the published literature in regards to how streamflow is expected to change under future climate. However, the general expectation is for rain-dominated watersheds to experience greater winter flows due to increased winter precipitation and a shift from snowfall to rainfall as winters continue to warm (Dalton *et al.*, 2017; Mote *et al.*, 2019).

Warming temperatures and increased winter precipitation are expected to increase flood risk for many basins in the Pacific Northwest, particularly mid- to low-elevation mixed rain-snow basins with near freezing winter temperatures (Tohver *et al.*, 2014). The greatest changes in peak streamflow magnitudes are projected to occur at intermediate elevations in the Cascade Range and the Blue Mountains (Safeeq *et al.*, 2015). Recent advances in regional hydro-climate modeling support this expectation, projecting increases in extreme high flows for most of the Pacific Northwest, especially west of the Cascade Crest (Salathé *et al.*, 2014; Najafi and Moradkhani, 2015; Naz *et al.*, 2016). One study, using a single climate model, projects flood risk to increase in the fall due to earlier, more extreme storms, including atmospheric river events, and to a shift of precipitation from snow to rain (Salathé *et al.*, 2014).[6]

Some of the Pacific Northwest's largest floods occur when copious warm rainfall from atmospheric rivers combine with a strong snowpack, resulting in rain-on-snow flooding events (Safeeq *et al.*, 2015).[7] The frequency and intensity—amount of transported moisture—of atmospheric river events is projected to increase along the West Coast in response to rising atmospheric temperatures (Kossin *et al.*, 2017). This larger moisture transport of atmospheric rivers would lead to greater likelihoods of flooding along the West Coast (Konrad and Dettinger, 2017).

Future changes in rain-on-snow events as a result of climate warming depend on elevation. At lower elevations, the frequency of rain-on-snow events is projected to decrease due to decreasing snowpack, whereas at high elevations the frequency of rain-on-snow events is projected to increase due to the shift from snowy to rainy days (Surfleet and Tullos, 2013; Safeeq *et al.*, 2015; Musselman *et al.*, 2018). How such changes in rain-on-snow frequency would affect high streamflow events is varied. For example, projections for the Santiam

[4] Verbatim from the Third Oregon Climate Assessment Report (Dalton *et al.*, 2017)

[5] Verbatim from the Third Oregon Climate Assessment Report (Dalton *et al.*, 2017)

[6] Verbatim from the Third Oregon Climate Assessment Report (Dalton *et al.*, 2017)

[7] Verbatim from the Third Oregon Climate Assessment Report (Dalton *et al.*, 2017)

River, OR, show an increase in annual peak daily flows with moderate return intervals (<10 years) but a decrease at higher (> 10-year) return intervals (Surfleet and Tullos, 2013). For northern coastal Oregon watersheds, average runoff from rain-on-snow events is projected to decline in the future due to depletion of snow (Musselman *et al.*, 2018), which may imply that flood potential in these areas shift from being driven by rain-on-snow events to extreme rainfall events that exceed soil capacity (Berghuijs *et al.*, 2016; Musselman *et al.*, 2018).

Across the western US, the 100-year and 25-year peak flow magnitude is projected to increase at a majority of streamflow sites by the 2070–2099 period compared to the 1971–2000 historical baseline under the higher emissions scenario (RCP 8.5) (Maurer *et al.*, 2018). For the Nehalem River, the 25-year and 100-year peak flow magnitudes are projected to increase (Table 11), however, the changes are not considered statistically significant (p-val <0.05) (Maurer *et al.*, 2018).

Along the Columbia River bordering Oregon, peak flows are projected to decrease as a result of the complex interaction between earlier snowmelt and the transition of precipitation falling more as rain and less as snow in this snow-dominated basin (Maurer *et al.*, 2018). The Columbia River with its series of dams is highly managed for flood control and flow regulation can overcome climate signals. Past streamflow trends on the Columbia River at the Dalles display a regulatory signal of declining spring peak flows during 1950–2011 (Hatcher and Jones, 2013).

Table 11 Percent change in the 100-year and 25-year recurrence interval flows for the Nehalem River between 2070–2099 and 1971–2000 and the return period in 2070–2099 of the flow with a magnitude equal to that of the 100-year and 25-year flow as determined fro 1971–2000. (Source: Maurer et al., 2018, personal communication)

Return Period (Probability in a given year)	Percent Change in N-Year Peak Flow 2070–2099 vs. 1971–2000	Return Period of N-Year Peak Flow (2070–2099)
25-Year (4%)	21.38% (p-val=0.792)	10.64-Year (9.4%)
100-Year (1%)	25.96% (p-val=0.4)	29.01-Year (3.4%)

Key Messages:

⇒ Coastal rain-dominated watersheds, such as the Nehalem River, may experience an increase in winter flood risk due to projected greater winter precipitation and warmer winter temperatures causing precipitation to fall more as rain and less as snow, in addition to increases in the frequency and intensity of flood-producing atmospheric river events.

⇒ Flood risk to Clatsop County from the Columbia River is not expected to change substantially based on projected decreases in peak flows and the fact that the Columbia River is highly managed for flood control.

Across the western US, mountain snowpack is projected to decline leading to reduced summer soil moisture in mountainous environments (Gergel *et al.*, 2017). Coastal Oregon is also projected to experience a decrease in summer soil moisture, but to a lesser degree than the Oregon Cascades. Climate change is expected to result in lower summer streamflows in snow-dominated basins across the Pacific Northwest as snowpack melts off earlier due to warmer temperatures and summer precipitation decreases (Dalton *et al.*, 2017; Mote *et al.*, 2019).

Watersheds in Clatsop County are largely rain-dominated systems, meaning the drivers of drought and water scarcity are different than across much of the western US, where mountain snowpack contributes to streamflow (Dalton *et al.*, 2017; Mote *et al.*, 2019). As with the rest of the Pacific Northwest, Clatsop County typically experiences wet winters and dry summers. This seasonal cycle of precipitation means that severe drought is rare during the rainy winters on the Oregon coast, but the region is prone to periods of summertime water scarcity, especially when precipitation is lower than average in the shoulder seasons (e.g., spring, fall). This is exacerbated by the lack of natural storage (e.g., snowpack) and built storage (e.g., reservoirs).

This report presents future changes in five variables indicative of drought conditions—low spring snowpack, low summer soil moisture[8], low summer runoff, low summer precipitation, and high summer evaporation—in terms of a change in the frequency of the historical baseline 1-in-5 year event (that is, an event having a 20% chance of occurrence in any given year). The future projections, displayed in the orange and brown bars of Figure 12, are the frequency in the future period of the magnitude of the event that has a 20% frequency in the historical period.

In Clatsop County, spring snowpack (that is, the snow water equivalent on April 1), summer runoff, summer soil moisture, and summer precipitation are projected to decline while summer evaporation is projected to increase under both lower (RCP 4.5) and higher (RCP 8.5) emissions scenarios by the 2050s (2040–2069). This leads to the magnitude of low summer soil moisture, low spring snowpack, low summer runoff, low summer precipitation, and high summer evaporation expected with a 20% chance in any given year of the historical period being projected to occur much more frequently by the 2050s under both emissions scenarios (Figure 12). The 2020s (2010–2039) were not evaluated in this drought analysis due to data limitations, but can be expected to be similar but of smaller magnitude to the changes for the 2050s.

[8] Soil moisture projections are for the total moisture in the soil column from the surface to 140 cm below the surface.

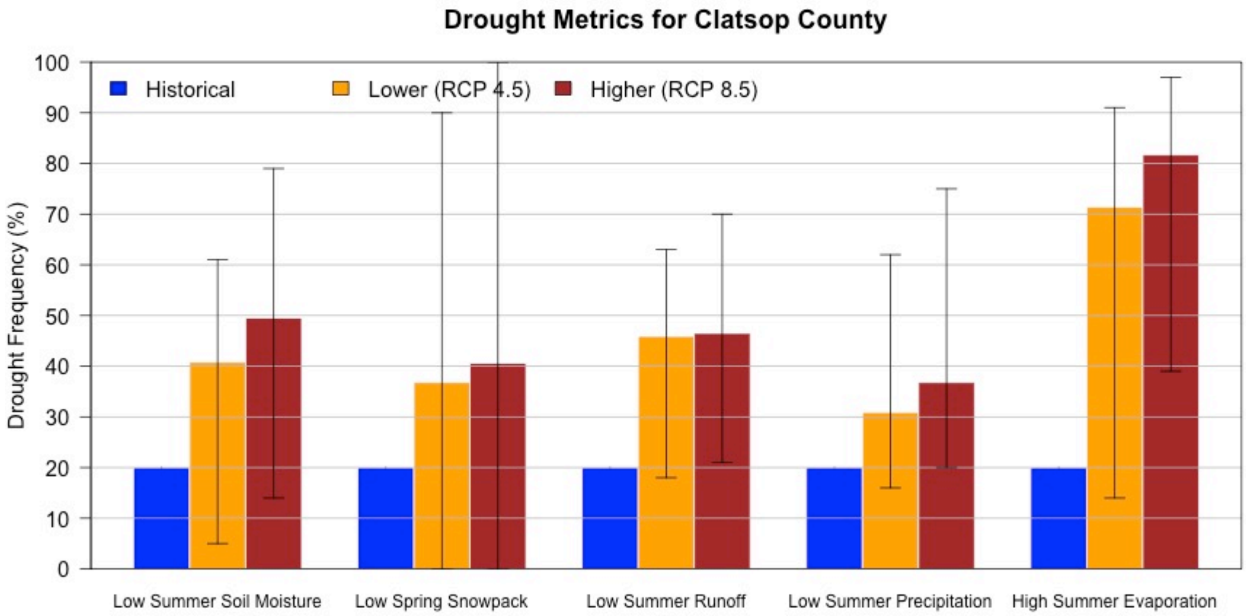

Figure 12 Frequency of the historical baseline (1971–2000) 1-in-5 year event (by definition 20% frequency) of low summer soil moisture (average of June-July-August), low spring snowpack (April 1 snow water equivalent), low summer runoff (total of June-July-August), low summer precipitation (total for June-July-August), high summer evaporation (total for June-July-August) for the future period 2040–2069 for lower (RCP 4.5) and higher (RCP 8.5) emissions scenarios. The bar and whiskers depict the mean and range across ten global climate models. (Data Source: Integrated Scenarios of the Future Northwest Environment, https://climate.northwestknowledge.net/IntegratedScenarios/)

Key Messages:

⇒ Drought conditions, as represented by low summer soil moisture, low spring snowpack, low summer runoff, low summer precipitation, and high summer evaporation are projected to become more frequent in Clatsop County by the 2050s.

Wildfire

Over the last several decades, warmer and drier conditions during the summer months have contributed to an increase in fuel aridity and enabled more frequent large fires, an increase in the total area burned, and a longer fire 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 fire season is largely due to declining mountain snowpack and earlier spring snowmelt (Westerling, 2016). Recent wildfire activity in forested ecosystems is partially attributed to human-caused climate change: during the period 1984–2015, about half of the observed increase in fuel aridity and 4.2 million hectares (or more than 16,000 square miles) of burned area in the western United States were due to human-caused climate change (Abatzoglou and Williams, 2016). Under future climate change, wildfire frequency and area burned are expected to continue increasing in the Pacific Northwest (Barbero *et al.*, 2015; Sheehan *et al.*, 2015),[9] even in the climatologically wet areas in western Oregon (Mote *et al.*, 2019).

As a proxy for wildfire risk, this report considers a fire danger index called 100-hour fuel moisture (FM100), which is a measure of the amount of moisture in dead vegetation in the 1–3 inch diameter class available to a fire. It is expressed as a percent of the dry weight of that specific fuel. FM100 is a common index used by the Northwest Interagency Coordination Center to predict fire danger. A majority of climate models project that FM100 would decline across Oregon by the 2050s (2040–2069) under the higher (RCP 8.5) emissions scenario (Gergel *et al.*, 2017). This drying of vegetation would lead to greater wildfire risk, especially when coupled with projected decreases in summer soil moisture. This report defines a "very high" fire danger day to be a day in which FM100 is lower (i.e., drier) than the historical baseline 10th percentile value. By definition, the historical baseline has 36.5 very high fire danger days annually. The future change in wildfire risk is expressed as the average annual number of additional "very high" fire danger days for two future periods under two emissions scenarios compared with the historical baseline (Figure 13). The impacts of wildfire on air quality are discussed in the following section on Air Quality.

[9] Verbatim from the Third Oregon Climate Assessment Report (Dalton *et al.*, 2017)

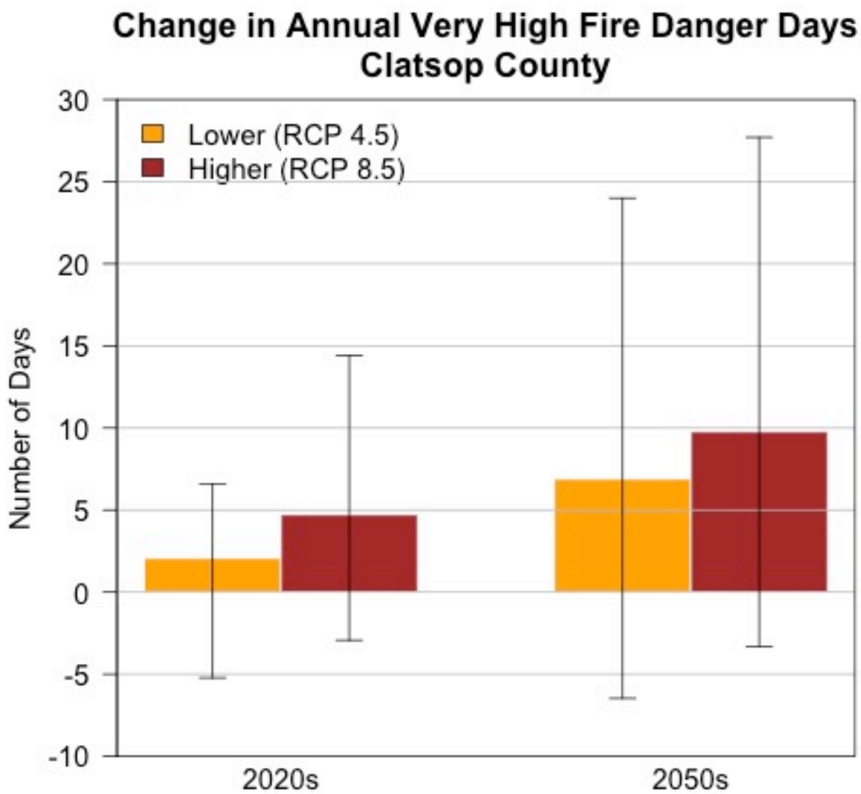

Figure 13 Projected future changes in the frequency of very high fire danger days for Clatsop County from the historical baseline (1971–2000 average) for the 2020s (2010–2039 average) and 2050s (2040–2069 average) under a lower (RCP 4.5) and higher (RCP 8.5) emissions scenario based on 18 global climate models. The bars and whiskers display the mean and range, respectively, of changes across the 18 GCMs. (Data Source: Northwest Climate Toolbox, climatetoolbox.org/tool/Climate-Mapper)

Key Messages:

⇒ Wildfire risk, as expressed through the frequency of very high fire danger days, is projected to increase under future climate change in Clatsop County.

⇒ In Clatsop County, the frequency of very high fire danger days per year is projected to increase on average by about 10 days (with a range of -3 to +28 days) by the 2050s under the higher emissions scenario compared to the historical baseline.

⇒ In Clatsop County, the frequency of very high fire danger days per year is projected to increase on average by about 27% (with a range of -9 to +76%) by the 2050s under the higher emissions scenario compared to the historical baseline.

Air Quality

Climate change is expected to worsen outdoor air quality. Warmer temperatures may increase ground level ozone pollution, more wildfires may increase smoke and particulate matter, and longer, more potent pollen seasons may increase aeroallergens. Such poor air quality is expected to exacerbate allergy and asthma conditions and increase respiratory and cardiovascular illnesses and death (Fann *et al.*, 2016).[10] In addition to increasing health risks, wildfire smoke impairs visibility and disrupts outdoor recreational activities (Nolte *et al.*, 2018). This report presents quantitative projections of future air quality measures related to fine particulate matter (PM2.5) from wildfire smoke.

Climate change is expected to result in a longer wildfire season with more frequent wildfires and greater area burned (Sheehan *et al.*, 2015). Wildfires are primarily responsible for days when air quality standards for PM2.5 are exceeded in western Oregon and parts of eastern Oregon (Liu *et al.*, 2016), although woodstove smoke and diesel emissions are also main contributors (Oregon DEQ, 2016). Across the western United States, PM2.5 levels from wildfires are projected to increase 160% by mid-century under a medium emissions pathway[11] (SRES A1B) (Liu *et al.*, 2016). This translates to a greater risk of wildfire smoke exposure through increasing frequency, length, and intensity of "smoke waves"—that is, two or more consecutive days with high levels of PM2.5 from wildfires (Liu *et al.*, 2016).[11]

The change in risk of poor air quality due to wildfire-specific PM2.5 is expressed as the number of "smoke wave" days within a six-year period and the average intensity—concentration of particulate matter—of smoke wave days in the present (2004–2009) and mid-century (2046–2051) under a medium emissions pathway[12] (Figure 14). See Appendix for description of methodology and access to the Smoke Wave data. In Clatsop County the frequency and intensity of "smoke wave" days is expected to increase.

[10] Verbatim from the Third Oregon Climate Assessment Report (Dalton *et al.*, 2017)

[11] Verbatim from the Third Oregon Climate Assessment Report (Dalton *et al.*, 2017)

[12] The medium emissions pathway used is from an earlier generation of emissions scenarios. Liu et al. (2016) used SRES-A1B, which is most similar to RCP 6.0 from Figure 2.

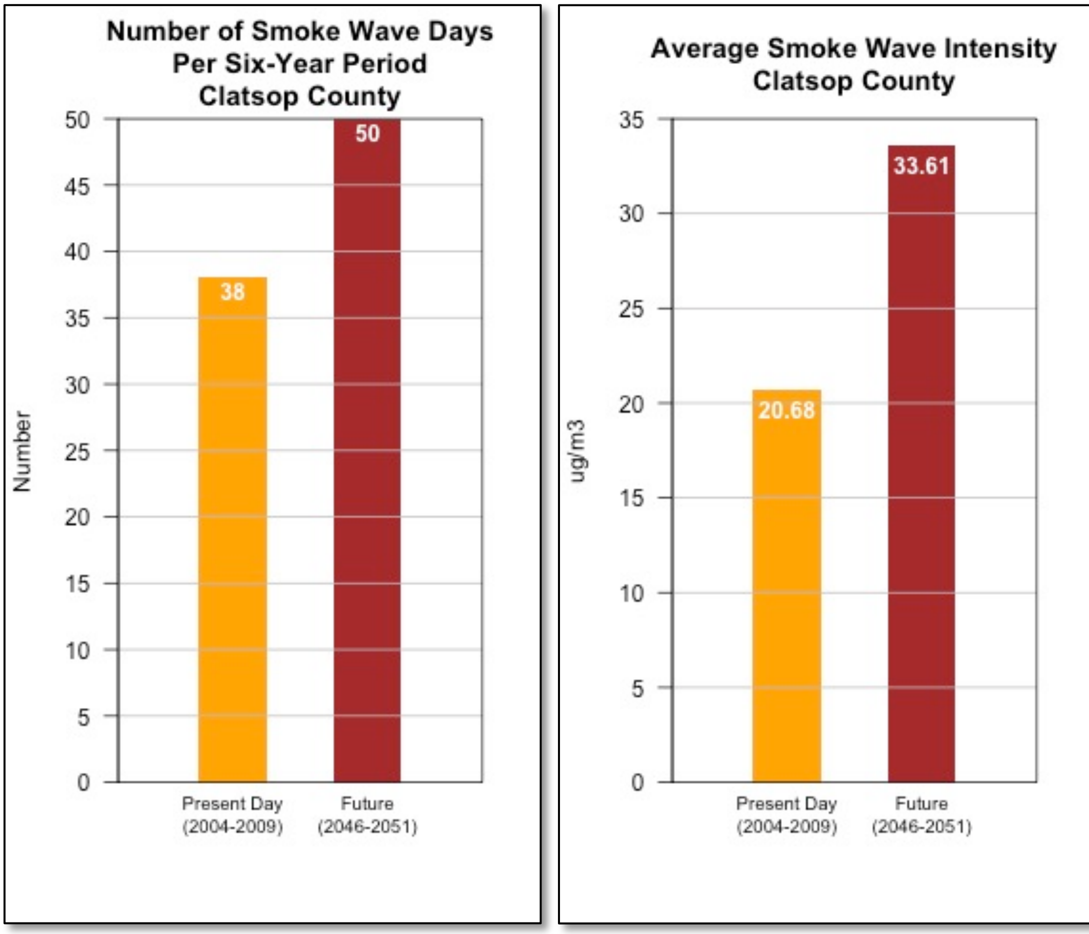

Figure 14 Simulated present day (2004–2009) and future (2046–2051) frequency (left) and intensity (right) of "smoke wave" days for Clatsop County under a medium emissions scenario[11]. The bars display the mean across 15 GCMs. (Data source: Liu et al. 2016, https://khanotations.github.io/smoke-map/)

Key Messages:

⇒ Under future climate change, the risk of wildfire smoke exposure is projected to increase in Clatsop County.

⇒ In Clatsop County, the number of "smoke wave" days is projected to increase by 32% and the intensity of "smoke waves" is projected to increase by 63% by 2046–2051 under a medium emissions scenario compared with 2004–2009.

Coastal Erosion & Flooding

The risk of coastal erosion and flooding hazards is expected to increase with climate change due to sea level rise and other factors including changing wave dynamics.

Sea Level Rise

Changes in global sea levels occur due to ocean thermal expansion, glacier and ice sheet mass loss, and land water storage. Regional and local sea levels on the Pacific Northwest's coast are governed by the global mean sea level, but also by natural variability (El Niño–Southern Oscillation affects ocean currents and wind fields), by vertical land motions from subducting ocean plates, and by post-glacial isostatic adjustment (Reeder *et al.*, 2013).[13]

Global average sea level has risen by about 7–8 inches (about 16–21 cm) since 1900, with almost half this rise occurring since 1993 as oceans have warmed and land-based ice has melted. Relative to the year 2000, sea level is very likely to rise 1 to 4 feet (0.3 to 1.3 m) by the end of the 21st century.

Emerging science regarding Antarctic ice sheet stability suggests that, for higher scenarios, a rise exceeding 8 feet (2.4 m) by 2100 is physically possible, although the probability of such an extreme outcome cannot currently be assessed[14] (Hayhoe *et al.*, 2018) (Figure 15). A crucial point about the melting ice sheets in both Greenland and Antarctica is that even after global temperatures are stabilized, melting would continue until a new equilibrium is reached thousands of years later (Mote *et al.*, 2019). This has implications for coastal development in that sea level would continue to rise for millennia after 2100 (Clark *et al.*, 2018; Mote *et al.*, 2019).

Local sea level at Astoria, OR[15] has lowered by about two inches during 1947–2013 (*Coastal Risks for Clatsop County, OR*, 2019) due to the land uplifting at a faster pace than sea level rise over that period. However, the pace of sea level rise is expected to accelerate such that sea level rise over the 21st century would outpace the uplifting land. Local sea level at Astoria is projected to rise by 0.8 to 4.8 feet by 2100 (*Coastal Risks for Clatsop County, OR*, 2019) based on the Intermediate-Low and Intermediate-High global sea level scenarios used in the 2018 U.S. National Climate Assessment (Sweet *et al.*, 2017a). This range of sea level rise scenarios is similar to the *very likely* range projected for the higher emissions scenario, RCP8.5, by 2100 (Figure 15). Table 12 shows the median projected local sea level rise at Astoria, OR for each scenario and decade from 2030 to 2100 relative to the 1992 mean high tide line. These local sea level projections include vertical land movement trend estimates derived from GPS measurements and tide gauge platforms (Sweet *et al.*, 2017b). This means that the future sea level rise projections are relative to the future land position as opposed to the existing land position.

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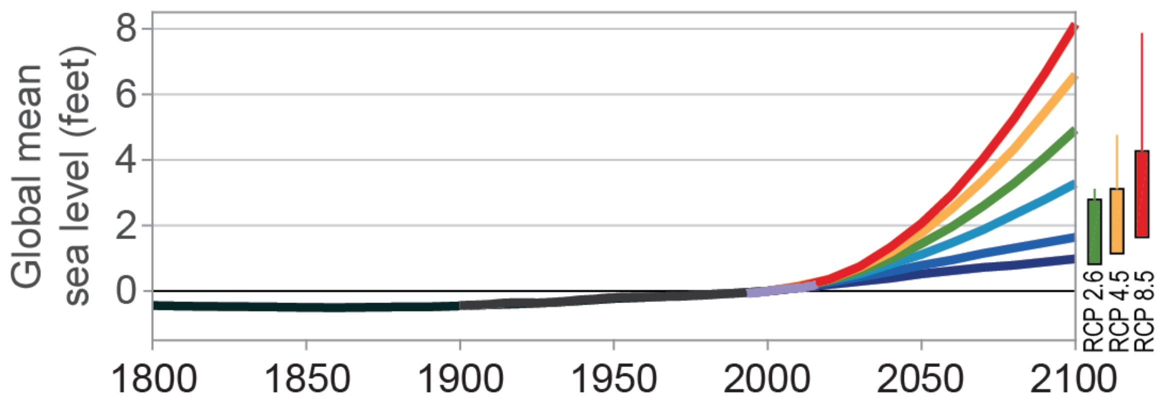
[13] Verbatim from the Third Oregon Climate Assessment Report (Dalton *et al.*, 2017)

[14] Verbatim from the Fourth National Climate Assessment Report (Hayhoe *et al.*, 2018)

[15] NOAA water level station at Astoria–Tongue Point



Scenario	RCP2.6	RCP4.5	RCP8.5
Low (1 ft)	94%	98%	100%
Intermediate-Low (1.6 ft)	49%	73%	96%
Intermediate (3.3 ft)	2%	3%	17%
Intermediate-High (4.9 ft)	0.4%	0.5%	1.3%
High (6.6 ft)	0.1%	0.1%	0.3%
Extreme (8.2 ft)	0.05%	0.05%	0.1%

Figure 15 (Top) Global mean sea level rise from 1800 to 2100 based on tide gauge-based reconstruction (black), satellite-based reconstruction (purple), and six future scenarios (navy blue, royal blue, cyan, green, orange, red) used in the Fourth National Climate Assessment (NCA4). The *very likely* ranges in 2100 for different RCPs (colored boxes), and lines augmenting the very likely ranges by accounting for various estimates of Antarctic contributions. (Bottom) Probability of exceeding each NCA4 global mean sea level scenario in 2100 under three RCPs. New evidence regarding the Antarctic ice sheet, if sustained, may significantly increase the probability of the intermediate-high, high, and extreme scenarios, particularly under the higher emissions scenario (RCP8.5), but these results have not yet been incorporated into a probabilistic analysis (Source: Sweet et al., 2017a, https://science2017.globalchange.gov/chapter/12/)

Table 12 Median local sea level projections for Astoria, OR (NOAA water level station at Astoria–Tongue Point) based on scenarios used in the 2018 U.S. National Climate Assessment. Sea level rise is feet above a 1992 baseline. Projections include vertical land movement trend estimates. (Source: Climate Central Surging Seas Risk Finder, https://riskfinder.climatecentral.org/county/clatsop-county.or.us?comparisonType=place&forecastType=NOAA2017_int_p50&level=4&unit=ft&zillowPlaceType=postal-code)

Scenario	2030	2040	2050	2060	2070	2080	2090	2100
L	0.1	0.1	0.1	0.2	0.3	0.3	0.3	0.3
I-L	0.2	0.2	0.3	0.4	0.5	0.6	0.7	0.8
I	0.3	0.5	0.7	1.0	1.3	1.7	2.1	2.5
I-H	0.6	0.9	1.3	1.8	2.3	3.1	3.8	4.8
H	0.8	1.3	2.0	2.7	3.6	4.8	6.0	7.4
E	1.0	1.6	2.4	3.4	4.7	6.0	7.6	9.3

Wave Climate

Wave heights have increased in the northeast Pacific over the past several decades (Reeder *et al.*, 2013), as have extreme wave events (Bromirski *et al.*, 2013); such waves have been largely responsible for recent increases in coastal flooding and erosion (Ruggiero, 2013). However, attributing increasing wave heights to climate change may not be possible until the second half of the 21st century because natural variability is quite large (Dobrynin *et al.*, 2014). Future projections of average and extreme wave heights along the West Coast are mixed (Wang *et al.*, 2014; Erikson *et al.*, 2015) as they rely on predictions that are difficult to make about extratropical storms and extreme winds (Vose *et al.*, 2014).[16] Coastal water levels and wave heights are also affected by major El Niño-Southern Oscillation (ENSO) events. During El Niño events the Pacific Northwest's coast can experience elevated sea levels, but both the top six El Niño and top five La Niña events during 1979–2016 amplified coastal erosion and wave energy in the Pacific Northwest (Barnard *et al.*, 2015, 2017).[17]

Coastal Erosion & Flooding Hazards

Tall waves, intense storms, and ENSO events can combine with sea level rise to produce coastal erosion and inundation hazards (Reeder *et al.*, 2013).[18] Clatsop County's coastline south of Tillamook Head in the Cannon Beach littoral cell has generally been in an erosional regime with an average shoreline change rate of -0.5 m/yr since the 1960s with 75% of transects eroding and 25% eroding at rates faster than -1 m/yr (Ruggiero *et al.*, 2013) (Figure 16). North of Tillamook Head in the Clatsop Plains subcell of the Columbia River littoral cell has been in an accretion regime with an average shoreline change rate of 3.1 m/yr since the construction of the Columbia River South Jetty in the late 1800s (Ruggiero *et al.*, 2013) (Figure 17).

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[16] Verbatim from the Third Oregon Climate Assessment Report (Dalton *et al.*, 2017)

[17] Verbatim from the Third Oregon Climate Assessment Report (Dalton *et al.*, 2017)

[18] Verbatim from the Third Oregon Climate Assessment Report (Dalton *et al.*, 2017)

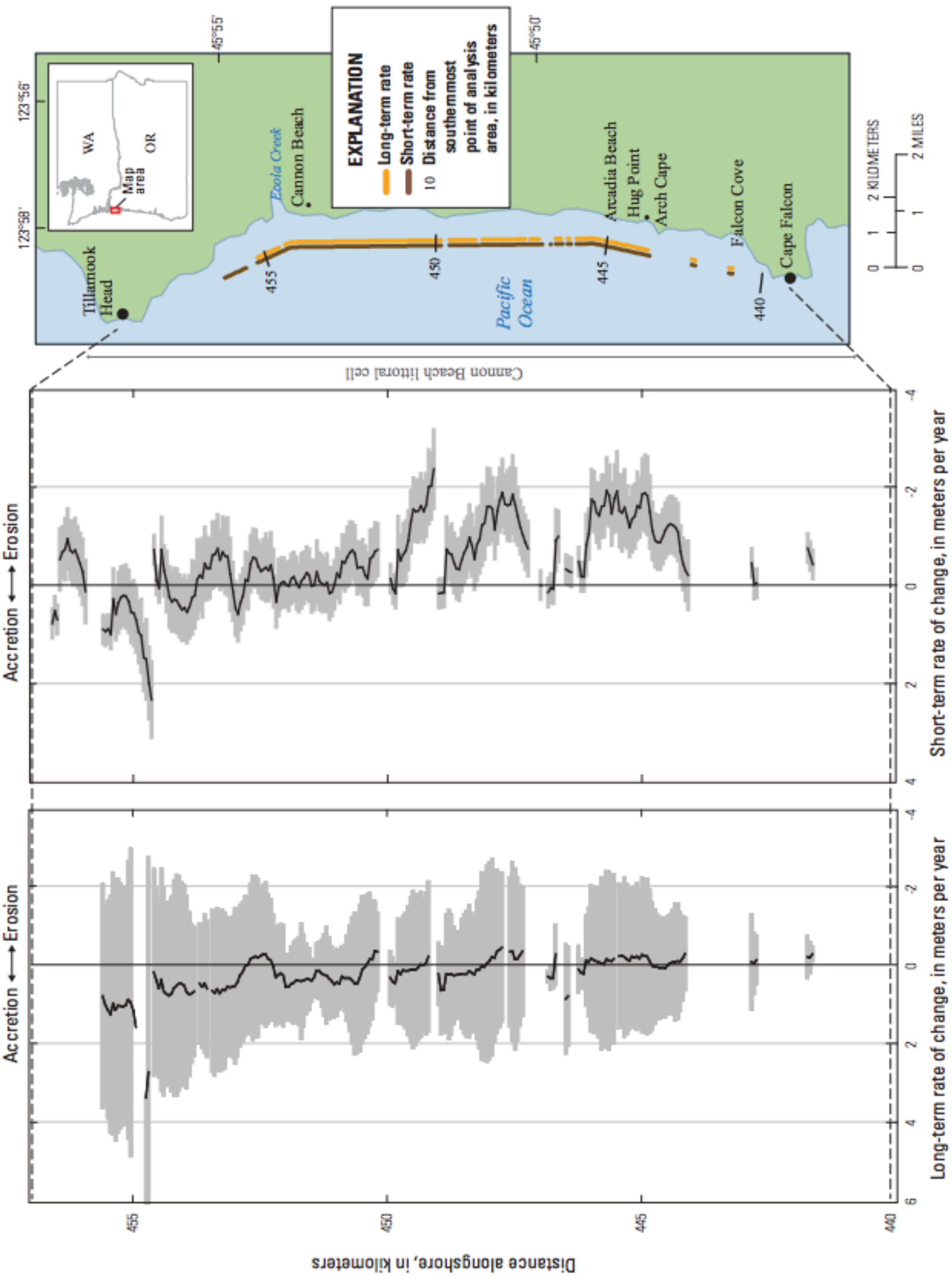

Figure 16 Long- (1800s through 2002) and short-term (1960s through 2002) shoreline change rates (black lines on plots) for the Cannon Beach analysis region in Oregon. The location of the region is shown in figure 1. Shaded gray area behind long- and short-term rates represents uncertainty associated with rate calculation. (Source: Ruggiero et al., 2013)

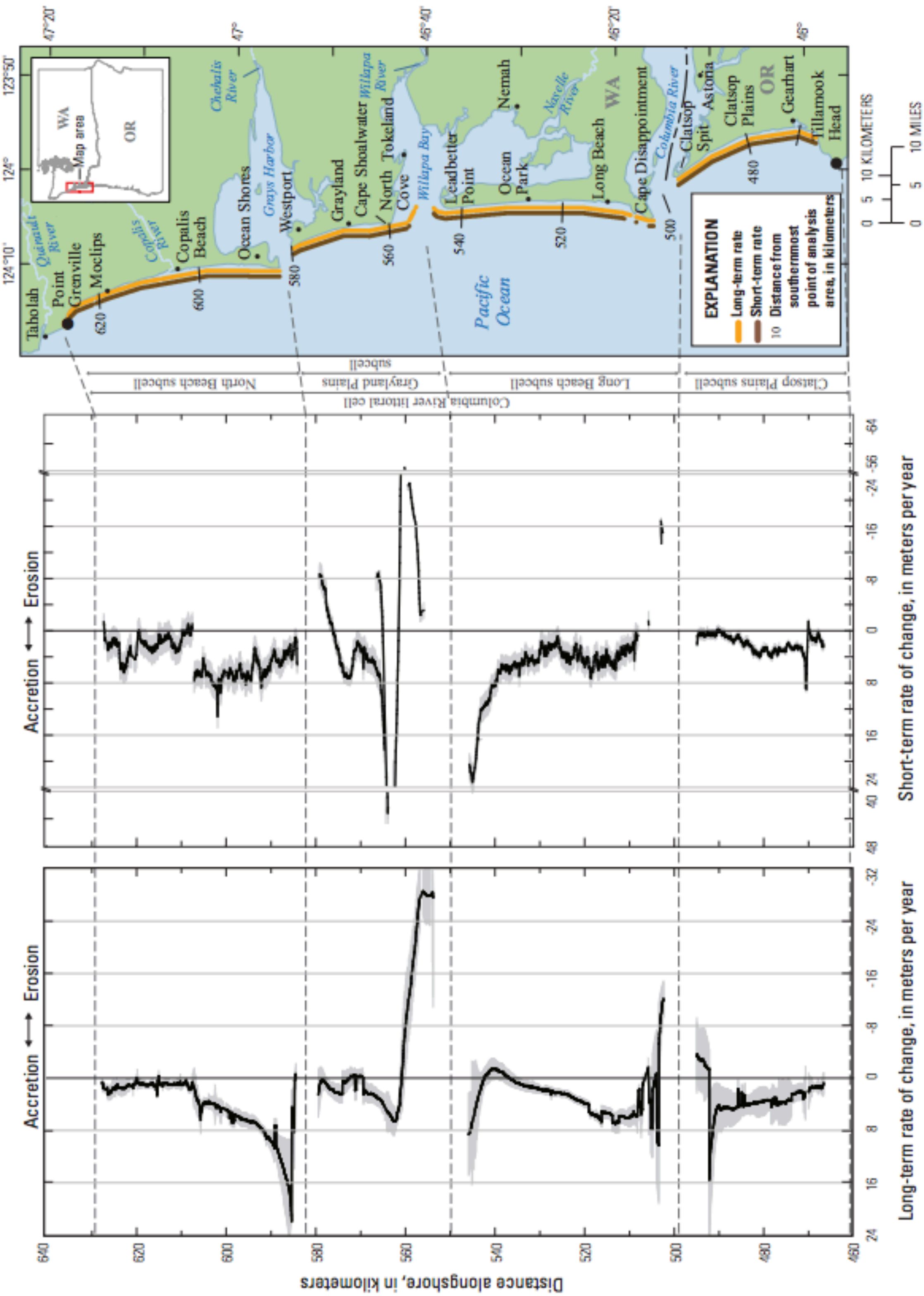

Figure 17 Long- (1800s through 2002) and short-term (1960s or 80s through 2002) shoreline change rates (black lines on plots) for the Columbia River littoral cell in Oregon and Washington. The location of the region is shown in figure 1. Shaded gray area behind long- and short-term rates represents uncertainty associated with rate calculation. (Source: Ruggiero et al., 2013)

The projected increase in local sea levels along the Oregon coast raises the starting point for storm surges and high tides making coastal hazards more severe and more frequent in the future (*Coastal Risks for Clatsop County, OR*, 2019). Assuming the Intermediate-Low to Intermediate-High sea level scenarios for Astoria, OR (Table 12), the multi-year likelihood of a 4-foot flood event—water reaching four feet above mean high tide—ranges from 4%–38% by the 2030s, 19%–100% by the 2050s, and 98%–100% by 2100 (*Coastal Risks for Clatsop County, OR*, 2019). Table 13 shows the multi-year risk of flooding above 4 feet above mean high tide, that is, the risk of at least one such flood from 2016 through each year, for each sea level rise scenario. For historical perspective, the highest observed flood in the area between 1947 and 2013 was 3.8 feet above mean high tide and the statistical 1-in-100 year flood height is 3.7 feet (*Coastal Risks for Clatsop County, OR*, 2019).

These projections represent a real, eventual future flood risk for people and assets within the 4-foot flood area. According to Climate Central's Surging Seas Risk Finder, 3407 people and $138 million in property value are in areas of Clatsop County that are within 4 feet above mean high tide and not potentially protected by levees or other features (Table 14) (*Coastal Risks for Clatsop County, OR*, 2019).

Table 13 Risk (% Likelihood) of at least one flood exceeding 4 feet above mean high tide between 2016 through each year shown based on median local sea level projections for Astoria, OR (Table 12). (Source: Climate Central Surging Seas Risk Finder, https://riskfinder.climatecentral.org/county/clatsop-county.or.us?comparisonType=place&forecastName=Basic&forecastType=NOAA2017_lo_p50&level=4&unit=ft&zillowPlaceType=postal-code)

Scenario	2030	2040	2050	2060	2070	2080	2090	2100
L	1%	1%	3%	6%	13%	23%	33%	43%
I-L	4%	9%	19%	34%	55%	77%	91%	98%
I	14%	37%	75%	98%	100%	100%	100%	100%
I-H	38%	83%	100%	100%	100%	100%	100%	100%
H	69%	100%	100%	100%	100%	100%	100%	100%
E	85%	100%	100%	100%	100%	100%	100%	100%

Table 14 Total population and property value below 4 feet above mean high tide for Clatsop County and select towns. Values exclude sub-4 foot areas potentially protected by levees or other features. (Source: Climate Central Risk Finder, 2019, http://www.riskfinder.org/)

Town	Total Population below 4 feet	Total Property Value below 4 feet
Cannon Beach	5	$1 million
Seaside	101	$11 million
Gearhart	0	$0
Warrenton	2408	$62 million
Jeffers Gardens	331	$18 million
Astoria	105	$20 million
Westport	11	$0
Clatsop County	3407	$138 million

The Oregon Coastal Management Program (OCMP) completed a sea level rise exposure inventory for Oregon's estuaries in 2017, including the Necanicum River in Clatsop County (Sepanik *et al.*, 2017). The Columbia River was excluded from their analysis. The sea level rise and flooding scenarios considered in the OCMP analysis are summarized for Clatsop County and compared with the sea level rise and flooding scenarios from the 2018 NCA and Climate Central in Table 15 in order to place the OCMP analysis in context with the more recent sea level rise scenarios presented earlier in this section. The OCMP sea level rise scenarios are taken from the upper range of projections for Newport, OR in *Sea-Level Rise for Coasts of California, Oregon, and Washington* (National Research Council, 2012). OCMP's scenarios for the 2030s and 2050s most closely align with the 2018 NCA 83rd Percentile of the Intermediate-High Scenario. OCMP's sea level scenario for 2100 most closely aligns with the 2018 NCA Median of the Intermediate-High Scenario (Table 15). The 1% and 50% chance flood levels from Appendix A of OCMP's analysis are 3.95 feet and 2.63 feet, respectively, for Necanicum River in Clatsop County (Sepanik *et al.*, 2017). These levels are analogous to Climate Central's estimates for Astoria's "mild" flood level (2.6 feet) and "major" flood level (3.7 feet) (Table 15).

Table 15 Key to compare Oregon Coastal Management Program (OCMP) sea level rise (SLR) and flooding scenarios with Climate Central SLR and flooding scenarios based on the 2018 U.S. National Climate Assessment (NCA) SLR scenarios. (Source: Sepanik et al., 2017; Climate Central Surging Seas Risk Finder for Clatsop County, OR, https://riskfinder.climatecentral.org)

OCMP SLR Scenario[19]	2018 NCA SLR Scenario
2030 (0.75 feet)	2030 (0.7 feet)[20]
2050 (1.57 feet)	2050 (1.5 feet)[21]
2100 (4.66 feet)	2100 (4.8 feet)[22]
OCMP Flood Scenario[23]	**Climate Central Flood Scenario[24]**
1% chance (3.95 feet)	"major flood" (3.7 feet)
50% chance (2.63 feet)	"mild flood" (2.6 feet)

[19] The OCMP analysis used the upper end of the range of sea level rise projections for Newport, OR from *Sea-Level Rise for Coasts of California, Oregon, and Washington* (NRC, 2012).

[20] The 2018 NCA sea level rise scenario for Astoria, OR that most closely aligns with the OCMP 2030 sea level rise scenario is the 83rd Percentile of the Intermediate-High scenario.

[21] The 2018 NCA sea level rise scenario for Astoria, OR that most closely aligns with the OCMP 2050 sea level rise scenario is the 83rd Percentile of the Intermediate-High scenario.

[22] The 2018 NCA sea level rise scenario for Astoria, OR that most closely aligns with the OCMP 2100 sea level rise scenario is the Median of the Intermediate-High scenario.

[23] The OCMP analysis used NOAA extreme water levels to calculate the 1% and 50% chance flood levels. Values in the table are for Clatsop County's Necanicum River given in Appendix A of OCMP's report.

[24] Climate Central computed extreme water levels for Astoria water level station to represent Clatsop County

Using the OCMP combined sea level rise and flooding scenarios, we identify an analogous combined scenario from the Climate Central analysis and assign one to each OCMP combined scenario. With these analogs between the two sets of sea level and flooding scenarios, we can assign likelihoods of single and multi-year flood risks from Climate Central's analysis to OCMP's analysis (Table 16). For example, OCMP's "2050 + 50%" scenario has a 70% likelihood of exceeding 4 feet above mean high tide in any single year by the 2050, but has a 100% likelihood of exceeding 4 feet at some point between 2016 and 2050 (Table 16). For OCMP's most extreme scenario considered, "2100 + 1%", the likelihood of exceeding 8 feet above mean high tide in any single year by 2100 is 14% where as the likelihood of exceeding 8 feet at some point between 2016 and 2100 is 36% (Table 16). However, by 2120, there is a 100% likelihood of exceeding 8 feet according to Climate Central's extended analysis.

Table 16 Analogs between the Oregon Coastal Management Program (OCMP) combined sea level rise (SLR) and flooding scenarios and the Climate Central combined SLR and flooding scenarios. The Climate Central Single Year and Flood Risk indicates the likelihood in any single year that water will exceed the floor of the given water level (e.g., the floor is determined by dropping the numbers after the decimal; the flood of 4.4 feet is 4 feet). The Multi-Year Flood Risk indicates the likelihood that water will exceed the floor of the given water level at some point during the given time period. Water levels in columns 2 and 3 are derived by combining the relevant sea level and flood scenarios from Table 15. (Source: Sepanik et al., 2017; Climate Central Surging Seas Risk Finder for Clatsop County, OR, https://riskfinder.climatecentral.org)

OCMP SLR + Flood Scenarios	OCMP SLR + Flood Water Level	Climate Central Equivalent SLR + Flood Water Level	Climate Central Estimated Single Year Flood Risk	Climate Central Estimated Multi-Year Flood Risk
2030 + 50%	3.38 feet	3.3 feet	82%	100%
2030 + 1%	4.71 feet	4.4 feet	12%	60%
2050 + 50%	4.20 feet	4.1 feet	70%	100%
2050 + 1%	5.53 feet	5.3 feet	6%	18%
2100 + 50%	7.29 feet	7.4 feet	84%	100%
2100 + 1%	8.61 feet	8.5 feet	14%	36%

Table 17 summarizes the assets exposed to OCMP's "2050 + 50%" and "2100 + 1%" sea level and flooding scenarios for the Necanicum River in Clatsop County. Under the "2050 + 50%" scenario, which is virtually certain to occur at least once by 2050, total exposed assets in the Necanicum River in Clatsop County include: 0.5 miles of state, county, and local roads, one airport, and 42 buildings (Table 17). Under the "2100 + 1%" scenario, which has a 36% likelihood of occurring at least once by 2100 and is virtually certain to occur at least once by 2120, total exposed assets include: 17.7 miles of state, county, and local roads, one airport, one wastewater treatment plant, and 1469 buildings (Table 17).

Table 17 Assets exposed to OCMP's "2050 + 50%" and "2100 + 1%" sea level and flooding scenarios for the Necanicum River in Clatsop County. The estuaries are color coded based on the combined relative exposure to future flooding based on roads, buildings, and critical facilities as found in OCMP's analysis (Source: Sepanik et al., 2017)

	2050 SLR + 50% Chance Flood (~4.2 feet)									
	SH	R	A	RW	CF	MD	WT	ES	CS	B
Necanicum River	0	0.5	1	0	0	0	0	0	0	42
	2100 SLR + 1% Chance Flood (~8.6 feet)									
	SH	R	A	RW	CF	MD	WT	ES	CS	B
Necanicum River	0.7	17.7	1	0	0	0	1	0	0	1469

SH: State Highways (miles)
R: State, County, & Local Roads (miles)
A: Airports (number)
RW: Railways (miles)
CF: Critical Facilities (number)
MD: Municipal Use Drinking Water (number)
WT: Wastewater Treatment Plant (number)
ES: Electrical Substation (number)
CS: Potential Contaminant Sources (number)
B: Buildings (number)

Key Messages:

⇒ The risk of coastal erosion and flooding hazards on the Oregon coast is expected to increase with climate change due to sea level rise and changing wave dynamics.

⇒ In Clatsop County, local sea level is projected to rise by 0.8 to 4.8 feet by 2100 based on the Intermediate-Low and Intermediate-High global sea level scenarios used in the 2018 U.S. National Climate Assessment. These local sea level projections include vertical land movement trend estimates meaning that the future sea level rise projections are relative to the future land position.

⇒ At these levels, the multi-year likelihood of a 4-foot flood event—water reaching four feet above mean high tide—ranges from 4%–38% by the 2030s, 19%–100% by the 2050s, and 98%–100% by 2100.

⇒ Assets at risk with the 4-foot inundation zone in Clatsop County include 3407 people, $138 million in property value, half a mile of state, county, and local roads,

Ocean Temperature & Chemistry

As a result of increasing human-caused emissions of carbon dioxide (CO_2) in the atmosphere, the world's ocean is warming, acidifying, and deoxygenating. These changes are leading to alterations in marine ecosystems affecting coastal communities across the globe (Pershing *et al.*, 2018).

Warming is the most obvious and well-documented impact of climate change on the ocean. Ocean surface waters have warmed on average 1.3° ± 0.1°F (0.7° ± 0.08°C) per century globally between 1900 and 2016, and more than 90% of the extra heat linked to carbon emissions is contained in the ocean.[25] The coastal waters off the Northwest US have warmed at a rate of 1.15° ± 0.54°F (0.64° ± 0.30°C) per century during the same period (Jewett and Romanou, 2017).

The world's ocean have absorbed 29% of all CO_2 emitted to the atmosphere since the beginning of the Industrial Revolution leading to a fundamental shift in ocean chemistry (Jewett and Romanou, 2017). When CO_2 dissolves in seawater, it changes three aspects of ocean chemistry [collectively referred to as "ocean acidification" (OA)]. First, it increases dissolved CO_2 and bicarbonate ions, which are used by algae and plants as the fuel for photosynthesis, potentially benefiting many of these species. Second, it increases the concentration of hydrogen ions, acidifying the water. Acidity is measured with the pH scale, with lower values indicating more acidic conditions. Third, it reduces the concentration of carbonate ions. Carbonate is a critical component of calcium carbonate, which is used by many marine organisms to form their shells or skeletons.[26]

Increased CO_2 levels in the atmosphere are also causing a decline in ocean oxygen concentrations. Deoxygenation is linked to ocean warming through the direct influence of temperature on oxygen solubility (warm water holds less oxygen). Warming of the ocean surface creates an enhanced vertical density contrast, which reduces the transfer of oxygen below the surface.[27]

These change in ocean temperature and chemistry are already transforming ocean ecosystems and the economy, coastal communities, cultures, and businesses that depend on them (Pershing *et al.*, 2018). Ecosystem disruption will intensify as ocean warming, acidification, deoxygenation, and other aspects of climate change increase. In the absence of significant reductions in carbon emissions, transformative impacts on ocean ecosystems cannot be avoided.[28] Some of the most vulnerable organisms include: clams, oysters, scallops, mussels, corals, starfish, sea urchins, sea butterflies, and shell-forming algae and amoebas. In addition, warming ocean waters and altered ocean chemistry is expected to promote shifts in marine species assemblages along the waters of the West Coast (Somero *et al.*, 2016). Ocean warming over the past half century has contributed to changes in biogeography and community composition of marine species, and altered interactions between species (Bindoff *et al.*, 2019). Fisheries catches since the 1970s have become increasingly dominated by warm-water species (Bindoff *et al.*, 2019). This is exemplified by

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[25] Verbatim from the Fourth National Climate Assessment, Volume 2, Chapter 9 (Pershing *et al.*, 2018)

[26] Verbatim from the Fourth National Climate Assessment, Volume 2, Chapter 9 (Pershing *et al.*, 2018)

[27] Verbatim from the Fourth National Climate Assessment, Volume 2, Chapter 9 (Pershing *et al.*, 2018)

[28] Verbatim from the Fourth National Climate Assessment, Volume 2, Chapter 9 (Pershing *et al.*, 2018)

recent marine heat wave events in which warm-water species, not normally present, were found along the West Coast and Alaska (Bond *et al.*, 2015; Peterson *et al.*, 2017).

Under a higher scenario [RCP8.5], a global increase in average sea surface temperature of 4.9° ± 1.3°F (2.7° ± 0.7°C) by 2100 is projected, with even higher changes in some U.S. coastal regions.[29] Northwest US coastal water are projected to warm by 5.0° ± 1.1°F (2.8° ± 0.6°C) by 2100 under RCP8.5 (Jewett and Romanou, 2017). The marine heat wave in the northeastern Pacific Ocean occurring between 2014 and 2016—coined “the Blob”—produced exceptionally warm waters that were more than 3.6°F above the normal range (Pershing *et al.*, 2018). This event triggered a coast-wide harmful algal bloom that affected commercial, recreation, and tribal subsistence fisheries off the Northwest coast (May *et al.*, 2018). This event provided a glimpse into the conditions and challenges likely to become more commonplace in the future under warmer ocean conditions.

Under a higher scenario [RCP8.5], open-ocean surface pH is projected to decline from 8.1 to 7.8 by 2100, representing a doubling in the ocean’s average acidity (Jewett and Romanou, 2017). Although it negatively affects some physiological processes, pH may not be the most useful number by which to monitor the biological effects of OA, particularly on calcifying organisms (Waldbusser *et al.*, 2015; Chan *et al.*, 2016). Furthermore, biologically-relevant thresholds of mineral carbonate saturation state are expected to be crossed much sooner than pH thresholds for some organisms (Waldbusser *et al.*, 2015). Even before it declines enough to corrode calcium carbonate shells, a lowered carbonate saturation state can “make it more difficult and energetically costly for larval bivalves to build shells” (Waldbusser *et al.*, 2015). Reductions in calcifying organisms at the base of the marine food web could have cascading effects on higher trophic marine fish, birds, mammals, and the people who rely on this resource. In a simple projection of ocean water saturation state changes, the mean annual surface seawater aragonite saturation state off the Oregon coast is projected to reach a threshold known to disrupt calcification and development in larval bivalves by the 2030s (Ekstrom *et al.*, 2015). However, the West Coast has already reached a threshold and negative impacts are already evident, such as dissolved shells in pteropod populations (Feely *et al.*, 2016) and impaired oyster hatchery operations (Barton *et al.*, 2012).[30]

Hypoxic—low oxygen—waters along the West Coast have expanded upward into shallower depths and are already affecting marine ecosystems (Somero *et al.*, 2016). Natural climate variability exercises strong control on dissolved oceanic oxygen levels, but detection of a deoxygenation trend beyond natural variability may be possible by the 2030s and 2040s in the north Pacific Ocean and along the US West Coast according to earth system modeling results (Long *et al.*, 2016).[31] Declines in ocean oxygen concentrations are projected to be about 3.5% on average under RCP8.5 by 2100, but much larger (17%) in the North Pacific Ocean (Jewett and Romanou, 2017).

On the West Coast, OA and hypoxia tend to co-occur as they are both driven by increased atmospheric CO_2 levels and local nutrient and organic carbon inputs and the combined

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[29] Verbatim from the Fourth National Climate Assessment, Volume 1, Chapter 13 (Jewett and Romanou, 2017)

[30] Verbatim from the Third Oregon Climate Assessment Report (Dalton *et al.*, 2017)

[31] Verbatim from the Third Oregon Climate Assessment Report (Dalton *et al.*, 2017)

effects can be worse than the effects either of hypoxia or acidification independently (Chan *et al.*, 2016). The West Coast of North America is one of the first places in the world to experience severe environmental, ecological, and economic consequences of OA and hypoxia largely due to the naturally occurring CO_2-enriched, low-oxygen deep water that wells up along the continental shelf of the West Coast (Chan *et al.*, 2016). How the region manages these ongoing changes will likely influence management choices of other coastal regions of the world. OA is a global problem, and reducing global levels of CO_2 emissions will be the most effective strategy to lessen the effect of OA (Chan *et al.*, 2016). However, better management of local nutrient and organic matter inputs to the coastal environment can lessen exposure to OA where those local stressors are having impacts. Furthermore, managing ecosystems to increase resilience—the ability to withstand impacts—to OA represent an important path for local adaptation actions. Time is of the essence because delayed action will reduce management options in the future and more greatly diminish ecosystem services (Chan *et al.*, 2016). [32]

Key Messages:

⇒ Ocean warming, ocean acidification, and decreasing dissolved oxygen levels are leading to alterations in marine ecosystems affecting coastal communities. The chemistry of the waters off the Oregon coast has already reached a threshold harmful to calcifying organisms and negative impacts are already evident. Reductions in calcifying organisms at the base of the marine food web could have cascading effects on higher trophic marine fish, birds, mammals, and the people who rely on this resource. In addition, warming ocean waters have altered marine species composition with greater prevalence of warm-water species expected during marine heat waves.

[32] Verbatim from the Third Oregon Climate Assessment Report (Dalton *et al.*, 2017)

Loss of Coastal Wetland Ecosystems

Oregon's coastal wetlands play key roles in major ecological processes and provide a number of essential ecosystem services such as providing habitat for fish, wildlife, and aquatic plants; serving as breeding and nursery grounds for rockfish, juvenile salmon, other fish, crustaceans, and mollusks; buffering wave damage during storms; and improving water quality (Oregon Department of Fish and Wildlife, (n.d.)). Climate change stands to affect Oregon coastal estuaries and tidal wetlands through rising sea levels, increases in coastal storms and wave height, warming air and water temperatures, changing precipitation patterns and freshwater runoff, saltwater intrusion, and ocean acidification, which can all act to exacerbate existing threats from human activities and invasive species (Oregon Department of Fish and Wildlife, (n.d.)).

Coastal wetlands may experience changes in biological, chemical, and physical processes as well as shifts in species and biodiversity loss as the climate changes (Oregon Department of Fish and Wildlife, (n.d.)). In addition, sea level rise is likely to alter the location and spatial extent of tidal wetlands. Some tidal wetlands may remain in place if the rate of accretion keeps pace with sea level rise, otherwise wetlands will need to migrate upslope if possible (Brophy *et al.*, 2017).

In a recent study that projected potential tidal wetland area under multiple sea level rise scenarios for 23 estuaries in Oregon, the general pattern across estuaries showed slight rises in potential tidal wetland areas for sea level rise scenarios up to 2.5 feet as tidal inundation spreads onto slightly higher land surfaces (Brophy *et al.*, 2017). However, starting at 4.7 feet of sea level rise, potential tidal wetland area declines sharply with a 21% loss and increases to 45% loss at 8.2 feet and 60% loss at 11.5 feet of sea level rise (Brophy *et al.*, 2017). Two estuaries in Clatsop County were included in the study: Nehalem River and Necanicum River.

The Nehalem River followed the general pattern of slight increases in potential tidal wetland area with up to 2.5 feet of sea level rise and sharper decreases with 4.7 feet of sea level rise and greater (Brophy *et al.*, 2017). These levels of sea level rise corresponds to the upper end of the projected range of sea level rise for 2050 and 2100, respectively, for Newport, Oregon provided by the West Coast Sea Level Rise study (National Research Council, 2012). The 2.5 feet sea level rise scenario is analogous to the relative sea level rise projections in Table 12 for the Intermediate Scenario by the 2080s, the Intermediate-High Scenario by the 2060s, the High Scenario by the 2050s, and the Extreme Scenario by the 2040s to 2050s. The 4.7 feet sea level rise scenario is analogous to the relative sea level rise projections in Table 12 for the Intermediate-High Scenario by the 2090s, the High Scenario by the 2070s to 2080s, and the Extreme Scenario by the 2060s to 2070s. Figure 18 shows the potential future extent of tidal wetlands and areas likely to be lost with sea level rise of 4.7 feet for the Nehalem River Estuary.

The Necanicum River is projected to gain potential tidal wetland, however, much of the added tidal wetland area consists of developed land in Seaside, Oregon (Brophy *et al.*, 2017). Figure 19 shows the potential future extent of tidal wetlands and areas likely to be lost with sea level rise of 4.7 feet for Necanicum River Estuary.

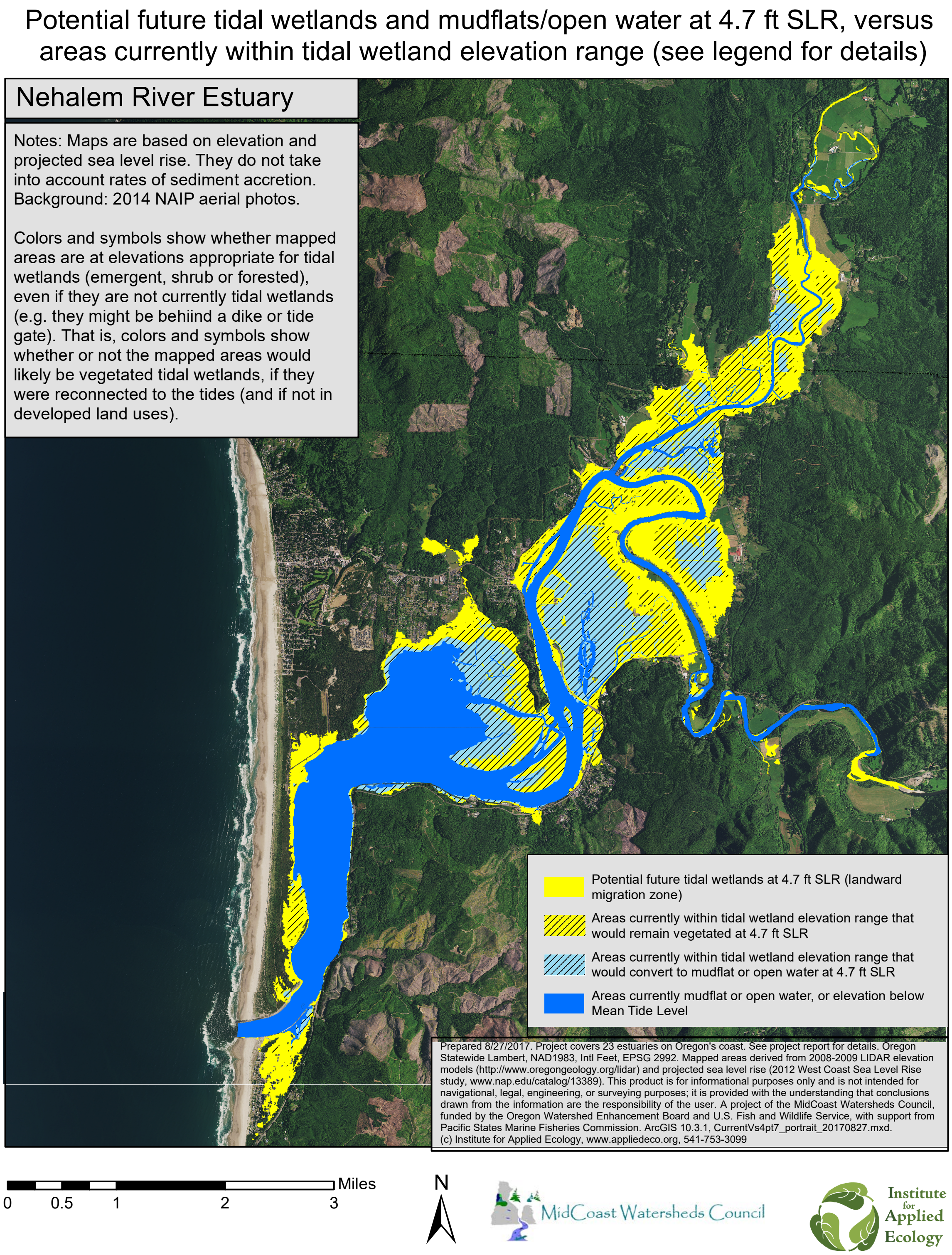

Figure 18 Potential tidal wetlands and mudflats/open water at 4.7 feet sea level rise, versus areas currently within tidal wetland elevation range for the Nehalem River Estuary. Source: Brophy et al., 2017.

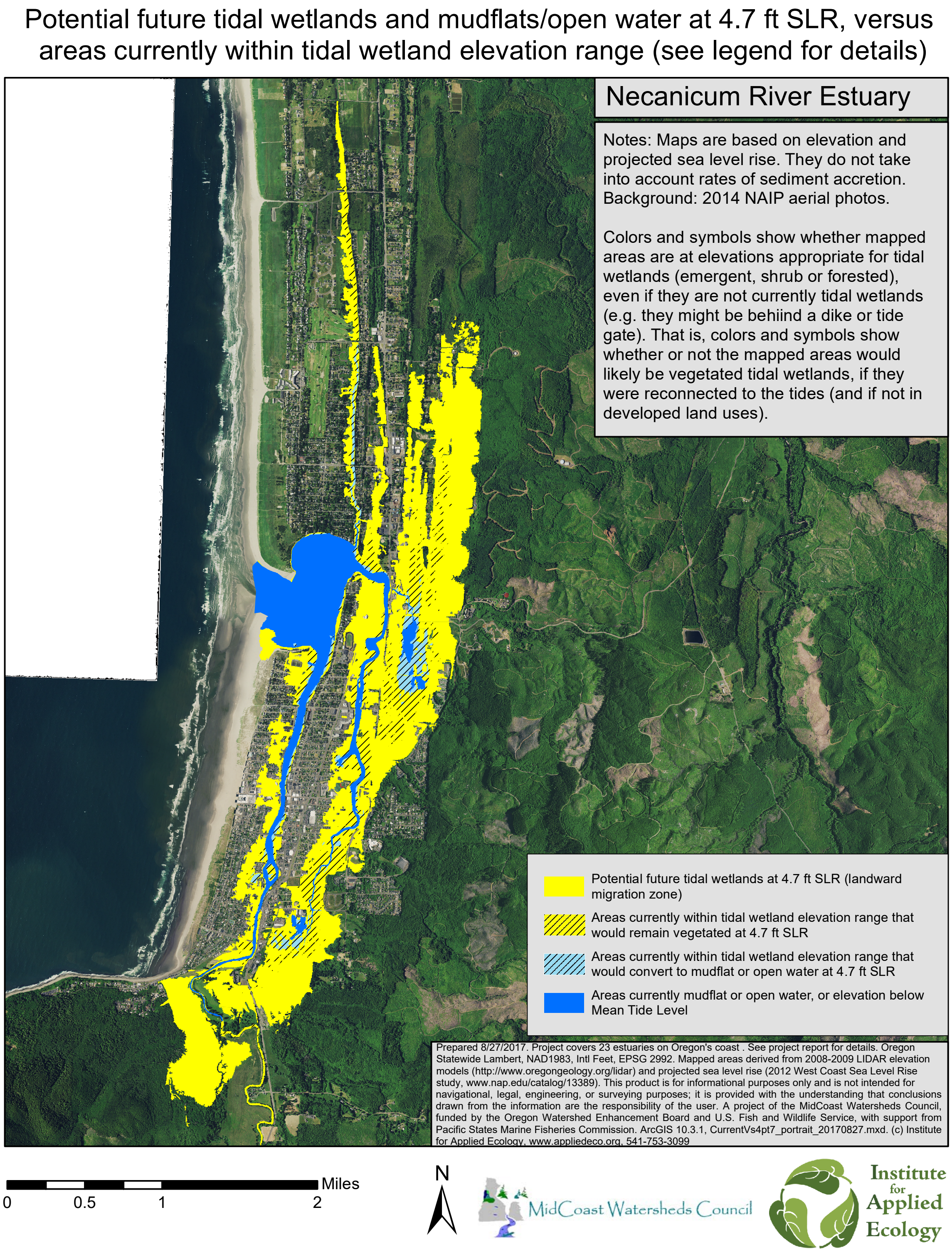

Figure 19 Potential tidal wetlands and mudflats/open water at 4.7 feet sea level rise, versus areas currently within tidal wetland elevation range for the Necanicum River Estuary. Source: Brophy et al., 2017.

Key Messages:

⇒ Coastal wetland ecosystems are sensitive to rising sea levels, increases in coastal storms and wave height, warming air and water temperatures, changing precipitation patterns and freshwater runoff, saltwater intrusion, and ocean acidification, which can lead to changes in biological, chemical, and physical processes; shifts in species and biodiversity loss; and altered location and spatial extent of tidal wetlands.

⇒ The Nehalem River Estuary is projected to experience modest increases (sharp decreases) in potential tidal wetland area under lower (higher) sea level rise projections whereas the Necanicum River Estuary is projected to gain potential tidal wetland area as sea level rises.

Windstorms

Climate change has the potential to alter surface winds through changes in the large-scale free atmospheric circulation and storm systems, and through changes in the connection between the free atmosphere and the surface. West of the Cascade Mountains in the Pacific Northwest, changes in surface wind speeds tend to follow changes in upper atmosphere winds associated with extratropical cyclones (Salathé *et al.*, 2015). Winter extratropical storm frequency in the northeast Pacific exhibited a positive, though statistically not significant, trend since 1950 (Vose *et al.*, 2014). However, there is a high degree of uncertainty in future projections of extratropical cyclone frequency (IPCC, 2013).

Future projections indicate a slight northward shift in the jet stream and extratropical cyclone activity, but there is as yet no consensus on whether or not 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 Therefore, no descriptions of future changing conditions are included in this report.

Key Messages:

⇒ Limited research suggests very little, if any, change in the frequency and intensity of windstorms in the Pacific Northwest as a result of climate change.

Increased Invasive Species Risk

Warming and more frequent drought will likely lead to a greater susceptibility among trees to insects and pathogens, a greater risk of exotic species establishment, more frequent and severe forest insect outbreaks (Halofsky and Peterson, 2016), and increased damage by a number of forest pathogens (Vose *et al.*, 2016).[33]

Certain tree diseases with known climate associations are also expected to increase in the future (Littell *et al.*, 2013). One such disease is Swiss needle cast (*Phaeocryptopus gaeumannii*), which affects Douglas-fir and can have significant economic impacts. In the Oregon Coast Range, warmer temperatures and increasing spring precipitation has contributed to a greater severity and distribution of Swiss needle cast (Littell *et al.*, 2013). The distribution of Swiss needle cast increased from about 205 square miles in 1996 to about 922 square miles of affected trees in 2015 in the Coast Range (Ritóková *et al.*, 2016). Swiss needle cast stunts Douglas-fir growth by 23% on average (Ritóková *et al.*, 2016). Swiss needle cast disease severity is expected to increase with warmer winters at higher elevation coastal sites and at inland sites where fungal growth is currently limited by cold winter temperatures (Lee *et al.*, 2013). The changing incidence of Swiss needle cast can affect mixed-species forest stands by allowing increased western hemlock (*Tsuga heterophylla*) growth in stands where severe Swiss needle cast affects Douglas-fir growth (Zhao *et al.*, 2014).[34]

Climate change—increasing temperature, altered precipitation patterns, increasing atmospheric carbon dioxide—may increase the likelihood of invasion by non-native plant species through increased photosynthesis of weedy plants, climate-facilitated range expansion, and establishment after climate-related disturbances (Kerns and Guo, 2012).

Crop pests and pathogens may continue to migrate poleward under global warming as has been observed globally for several types since the 1960s (Bebber *et al.*, 2013). Much remains to be learned about which pests and pathogens are most likely to affect certain crops as the climate changes, and about which management strategies will be most effective.[35]

Key Messages:

⇒ Warming temperatures, altered precipitation patterns, and increasing atmospheric carbon dioxide levels increase the risk for invasive species establishment, insect and plant pests and diseases for forests and cropping systems. Invasive species populations are expected to expand in extent (northward in latitude, higher in elevation) with warmer temperatures.

[33] Verbatim from the Third Oregon Climate Assessment Report (Dalton *et al.*, 2017), p. 49

[34] Verbatim from the Third Oregon Climate Assessment Report (Dalton *et al.*, 2017), p. 51

[35] Verbatim from the Third Oregon Climate Assessment Report (Dalton *et al.*, 2017), p. 67

Appendix

Future Climate Projections Background

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

Emissions Scenarios: https://science2017.globalchange.gov/chapter/4#section-2

Global Climate Models & Downscaling:
https://science2017.globalchange.gov/chapter/4#section-3

Uncertainty: https://science2017.globalchange.gov/chapter/4#section-4

Climate & Hydrological Data

Statistically downscaled GCM output from the Fifth phase of the Coupled Model Intercomparison Project (CMIP5) served as the basis for future projections of temperature, precipitation, and hydrology variables. The coarse resolution of GCMs output (100–300 km) was downscaled to a resolution of about 6 km using the Multivariate Adaptive Constructed Analogs (MACA) method, which has demonstrated skill in complex topographic terrain (Abatzoglou and Brown, 2012). The MACA approach utilizes a gridded training observation dataset to accomplish the downscaling by applying bias-corrections and spatial pattern matching of observed large-scale to small-scale statistical relationships. (For a detailed description of the MACA method see:
https://climate.northwestknowledge.net/MACA/MACAmethod.php.)
This downscaled gridded meteorological data (i.e., MACA data) is used as the climate inputs to an integrated climate-hydrology-vegetation modeling project called Integrated Scenarios of the Future Northwest Environment
(https://climate.northwestknowledge.net/IntegratedScenarios/). Snow dynamics were simulated using the Variable Infiltration Capacity hydrological model (VIC version 4.1.2.l; (Liang *et al.*, 1994) and updates) run on a $1/16^{th}$ x $1/16^{th}$ (6 km) grid.

Simulations of historical and future climate for the variables maximum temperature (*tasmax*), minimum temperature (*tasmin*), and precipitation (*pr*) are available at the daily time step from 1950 to 2099 for 20 GCMs and 2 RCPs (i.e., RCP4.5 and RCP8.5). Hydrological simulations of snow water equivalent (*SWE*) are only available for the 10 GCMs used as input to VIC. Table 18 lists all 20 CMIP5 GCMs and indicates the subset of 10 used for hydrological simulations. Data for all the models available was obtained for each variable from the Integrated Scenarios data archives in order to get the best uncertainty estimates.

Table 18 The 20 CMIP5 GCMs used in this project. The subset of 10 CMIP5 GCMs used in the Integrated Scenarios: Hydrology dataset are noted with asterisks.

Model Name	Modeling Center
BCC-CSM1-1 BCC-CSM1-1-M*	Beijing Climate Center, China Meteorological Administration
BNU-ESM	College of Global Change and Earth System Science, Beijing Normal University, China
CanESM2*	Canadian Centre for Climate Modeling and Analysis
CCSM4*	National Center for Atmospheric Research, USA
CNRM-CM5*	National Centre of Meteorological Research, France
CSIRO-Mk3-6-0*	Commonwealth Scientific and Industrial Research Organization/Queensland Climate Change Centre of Excellence, Australia
GFDL-ESM2G GFDL-ESM2M	NOAA Geophysical Fluid Dynamics Laboratory, USA
HadGEM2-CC* HadGEM2-ES*	Met Office Hadley Center, UK
INMCM4	Institute for Numerical Mathematics, Russia
IPSL-CM5A-LR IPSL-CM5A-MR* IPSL-CM5B-LR	Institut Pierre Simon Laplace, France
MIROC5* MIROC-ESM MIROC-ESM-CHEM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies
MRI-CGCM3	Meteorological Research Institute, Japan
NorESM1-M*	Norwegian Climate Center, Norway

All simulated climate data and the streamflow data have been bias-corrected using quantile-mapping techniques. Only SWE is presented without bias correction. Quantile mapping adjusts simulated values by creating a one-to-one mapping between the cumulative probability distribution of simulated values and the cumulative probability distribution of observed values. In practice, both the simulated and observed values of a variable (e.g., daily streamflow) over the some historical time period are separately sorted and ranked and the values are assigned their respective probabilities of exceedence. The bias corrected value of a given simulated value is assigned the observed value that has the same probability of exceedence as the simulated value. The historical bias in the simulations is assumed to stay constant into the future; therefore the same mapping relationship developed from the historical period was applied to the future scenarios. For MACA, a separate quantile mapping relationship was made for each non-overlapping 15-day window in the calendar year. For streamflow, a separate quantile mapping relationship was made for each calendar month.

Hydrology was simulated using the Variable Infiltration Capacity hydrological model (VIC; Liang et al. 1994) run on a $1/16^{th}$ x $1/16^{th}$ (6 km) grid. To generate daily streamflow estimates, runoff from VIC grid cells was then routed to selected locations along the stream network using a daily-time-step routing model. Where records of naturalized flow were available, the daily streamflow estimates were then bias-corrected so that their statistical distributions matched those of the naturalized streamflows.

The wildfire danger day metric was computed using the same MACA climate variables to compute the 100-hour fuel moisture content according to the equations in the National Fire Danger Rating System.

Smoke Wave Data

Abstract from Liu et al. (2016):
Wildfire can impose a direct impact on human health under climate change. While the potential impacts of climate change on wildfires and resulting air pollution have been studied, it is not known who will be most affected by the growing threat of wildfires. Identifying communities that will be most affected will inform development of fire management strategies and disaster preparedness programs. We estimate levels of fine particulate matter ($PM_{2.5}$) directly attributable to wildfires in 561 western US counties during fire seasons for the present-day (2004–2009) and future (2046–2051), using a fire prediction model and GEOS-Chem, a 3-D global chemical transport model. Future estimates are obtained under a scenario of moderately increasing greenhouse gases by mid-century. We create a new term "Smoke Wave," defined as ≥2 consecutive days with high wildfire-specific $PM_{2.5}$, to describe episodes of high air pollution from wildfires. We develop an interactive map to demonstrate the counties likely to suffer from future high wildfire pollution events. For 2004–2009, on days exceeding regulatory $PM_{2.5}$ standards, wildfires contributed an average of 71.3 % of total $PM_{2.5}$. Under future climate change, we estimate that more than 82 million individuals will experience a 57 % and 31 % increase in the frequency and intensity, respectively, of Smoke Waves. Northern California, Western Oregon and the Great Plains are likely to suffer the highest exposure to wildfire smoke in the future. Results point to the potential health impacts of increasing wildfire activity on large numbers of people in a warming climate and the need to establish or modify US wildfire management and evacuation programs in high-risk regions. The study also adds to the growing literature arguing that extreme events in a changing climate could have significant consequences for human health.

Data can be accessed here: https://khanotations.github.io/smoke-map/
For the DLCD project, we looked at the variables "Total # of SW days in 6 yrs" and "Average SW Intensity". The first variable tallies all the days within each time period in which the fine particulate matter exceeded the threshold defined as the 98^{th} quantile of the

distribution of daily wildfire-specific $PM_{2.5}$ values in the modeled present-day years, on average across the study area. The second variable computes the average concentration of fine particulate matter across identified "smoke wave" days within each time period. Liu et al. (2016) used 15 GCMs from the Third Phase of the Coupled Model Intercomparison Project (CMIP3) under a medium emissions scenario (SRES-A1B). The data site only offers the multi-model mean value (not the range), which should be understood as the aggregate direction of projected change rather than the actual number expected.

Sea Level Rise & Coastal Flooding Data

For the DLCD project, we used the sea level rise projections for the United States (Sweet *et al.*, 2017b) developed for the 2018 National Climate Assessment (Sweet *et al.*, 2017a) as accessed from Climate Central Surging Seas Risk Finder (riskfinder.climatecentral.org). The amount of global mean sea level rise by 2100 (GMSL) defines each scenario. This tool gives corresponding local projections also provided by NOAA, which vary due to local factors such as rising or sinking land. Low, middle, and high sub-scenarios give a range of possible local outcomes (17th, 50th and 83rd percentiles) given each main scenario. Overall, lower emissions of heat-trapping pollution increase the chances for lower scenarios, and higher emissions point toward higher scenarios. The "Low" scenario assumes that sea level rise rates from the last 30 years continue unchanged, whereas the "Extreme" scenario assumes accelerated ice sheet loss in Antarctica.

Flood likelihoods and assets at risk were based on these sea level change scenarios and accessed directly from the Climate Central Surging Seas Risk Finder data visualization tools (riskfinder.climatecentral.org).

References

Abatzoglou JT, Brown TJ. 2012. A comparison of statistical downscaling methods suited for wildfire applications. *International Journal of Climatology*, 32(5): 772–780. https://doi.org/10.1002/joc.2312.

Abatzoglou JT, Williams AP. 2016. Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences*, 113(42): 11770–11775. https://doi.org/10.1073/pnas.1607171113.

Barbero R, Abatzoglou JT, Larkin NK, Kolden CA, Stocks B. 2015. Climate change presents increased potential for very large fires in the contiguous United States. *International Journal of Wildland Fire*, 24(7): 892–899.

Barnard PL, Hoover D, Hubbard DM, Snyder A, Ludka BC, Allan J, Kaminsky GM, Ruggiero P, Gallien TW, Gabel L, McCandless D, Weiner HM, Cohn N, Anderson DL, Serafin KA. 2017. Extreme oceanographic forcing and coastal response due to the 2015–2016 El Niño. *Nature Communications*, 8: 14365.

Barnard PL, Short AD, Harley MD, Splinter KD, Vitousek S, Turner IL, Allan J, Banno M, Bryan KR, Doria A, Hansen JE, Kato S, Kuriyama Y, Randall-Goodwin E, Ruggiero P, Walker IJ, Heathfield DK. 2015. Coastal vulnerability across the Pacific dominated by El Nino/Southern Oscillation. *Nature Geoscience*, 8(10): 801–807. https://doi.org/10.1038/ngeo2539.

Barton A, Hales B, Waldbusser GG, Langdon C, Feely RA. 2012. The Pacific oyster, Crassostrea gigas, shows negative correlation to naturally elevated carbon dioxide levels: Implications for near-term ocean acidification effects. *Limnology and Oceanography*, 57(3): 698–710. https://doi.org/10.4319/lo.2012.57.3.0698.

Bebber DP, Ramotowski MAT, Gurr SJ. 2013. Crop pests and pathogens move polewards in a warming world. *Nature Climate Change*, 3(11): 985–988. https://doi.org/10.1038/nclimate1990.

Berghuijs WR, Woods RA, Hutton CJ, Sivapalan M. 2016. Dominant flood generating mechanisms across the United States. *Geophysical Research Letters*, 43(9): 4382–4390. https://doi.org/10.1002/2016GL068070.

Bindoff NL, Cheung WWL, Kairo JG. 2019. Chapter 5: Changing Ocean, Marine Ecosystems, and Dependent Communities. *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. In Press.

Bond NA, Cronin MF, Freeland H, Mantua N. 2015. Causes and impacts of the 2014 warm anomaly in the NE Pacific. *Geophysical Research Letters*, 42(9): 2015GL063306. https://doi.org/10.1002/2015GL063306.

Bromirski PD, Cayan DR, Helly J, Wittmann P. 2013. Wave power variability and trends across the North Pacific. *Journal of Geophysical Research: Oceans*, 118(12): 6329–6348. https://doi.org/10.1002/2013JC009189.

Brophy LS, Ewald MJ, Recht F. 2017. *Modeling sea level rise impacts to Oregon's tidal wetlands: Maps and prioritization tools to help plan for habitat conservation into the future. A report to the MidCoast Watersheds Council.* Institute for Applied Ecology: Corvallis, OR.

Chan F, Boehm AB, Barth JA, Chornesky EA, Dickson AG, Feely RA, Hales B, Hill TM, Hofmann G, Ianson D, Klinger T, Largier J, Newton J, Pedersen TF, Somero GN, Sutula M, Wakefield WW, Waldbusser GG, Weisberg SB, Whiteman EA. 2016. *The West Coast Ocean Acidification and Hypoxia Science Panel: Major Findings, Recommendations, and Actions*. California Ocean Science Trust: Oakland, California, USA.

Chang E. 2018. CMIP5 Projected Change in Northern Hemisphere Winter Cyclones with Associated Extreme Winds. *Journal of Climate*, 31(16): 6527–6542. https://doi.org/10.1175/JCLI-D-17-0899.1.

Clark PU, Mix AC, Eby M, Levermann A, Rogelj J, Nauels A, Wrathall DJ. 2018. Sea-level commitment as a gauge for climate policy. *Nature Climate Change*, 8(8): 653. https://doi.org/10.1038/s41558-018-0226-6.

Coastal Risks for Clatsop County, OR. 2019. Climate Central.

Dalton MM, Dello KD, Hawkins L, Mote PW, Rupp DE. 2017. *The Third Oregon Climate Assessment Report*. Oregon Climate Change Research Institute, College of Earth, Ocean and Atmospheric Sciences, Oregon State University: Corvallis, OR, 99.

Dennison PE, Brewer SC, Arnold JD, Moritz MA. 2014. Large wildfire trends in the western United States, 1984–2011. *Geophysical Research Letters*, 41(8): 2014GL059576. https://doi.org/10.1002/2014GL059576.

Dobrynin M, Murawski J, Baehr J, Ilyina T. 2014. Detection and Attribution of Climate Change Signal in Ocean Wind Waves. *Journal of Climate*, 28(4): 1578–1591. https://doi.org/10.1175/JCLI-D-13-00664.1.

Ekstrom JA, Suatoni L, Cooley SR, Pendleton LH, Waldbusser GG, Cinner JE, Ritter J, Langdon C, van Hooidonk R, Gledhill D, Wellman K, Beck MW, Brander LM, Rittschof D, Doherty C, Edwards PET, Portela R. 2015. Vulnerability and adaptation of US shellfisheries to ocean acidification. *Nature Climate Change*, 5(3): 207–214. https://doi.org/10.1038/nclimate2508.

Erikson LH, Hegermiller CA, Barnard PL, Ruggiero P, van Ormondt M. 2015. Projected wave conditions in the Eastern North Pacific under the influence of two CMIP5 climate scenarios. *Ocean Modelling*, 96, Part 1: 171–185. https://doi.org/10.1016/j.ocemod.2015.07.004.

Fann N, Brennan T, Dolwick P, Gamble JL, Ilacqua V, Kolb L, Nolte CG, Spero TL, Ziska L. 2016. Ch. 3: Air Quality Impacts. *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. US Global Change Research Program: Washington, DC, 69–98.

Feely RA, Alin SR, Carter B, Bednaršek N, Hales B, Chan F, Hill TM, Gaylord B, Sanford E, Byrne RH, Sabine CL, Greeley D, Juranek L. 2016. Chemical and biological impacts of ocean acidification along the west coast of North America. *Estuarine, Coastal and Shelf Science*, 183, Part A: 260–270. https://doi.org/10.1016/j.ecss.2016.08.043.

Gergel DR, Nijssen B, Abatzoglou JT, Lettenmaier DP, Stumbaugh MR. 2017. Effects of climate change on snowpack and fire potential in the western USA. *Climatic Change*, 141(2): 287–299. https://doi.org/10.1007/s10584-017-1899-y.

Halofsky JE, Peterson DL. 2016. Climate Change Vulnerabilities and Adaptation Options for Forest Vegetation Management in the Northwestern USA. *Atmosphere*, 7(3): 46. https://doi.org/10.3390/atmos7030046.

Hatcher KL, Jones JA. 2013. Climate and Streamflow Trends in the Columbia River Basin: Evidence for Ecological and Engineering Resilience to Climate Change. *Atmosphere-Ocean*, 51(4). https://doi.org/10.1080/07055900.2013.808167.

Hayhoe K, Wuebbles DJ, Easterling DR, Fahey DW, Doherty S, Kossin J, Sweet W, Vose R, Wehner M. 2018. Chapter 2: Our Changing Climate. *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]*. US Global Change Research Program: Washington, DC, USA, 72–144.

IPCC. 2013. Summary for Policymakers. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA.

Jewett L, Romanou A. 2017. Ocean acidification and other ocean changes. In: Wuebbles DJ, Fahey DW, Hibbard KA, Dokken DJ, Stewart BC and Maycock TK (eds) *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. U.S. Global Change Research Program: Washington, DC, 364–392.

Jolly WM, Cochrane MA, Freeborn PH, Holden ZA, Brown TJ, Williamson GJ, Bowman DMJS. 2015. Climate-induced variations in global wildfire danger from 1979 to 2013. *Nature Communications*, 6: 7537. https://doi.org/10.1038/ncomms8537.

Kerns BK, Guo Q. 2012. Climate Change and Invasive Plants in Forests and Rangelands. *U.S. Department of Agriculture, Forest Service, Climate Change Resource Center*.

Konrad CP, Dettinger MD. 2017. Flood Runoff in Relation to Water Vapor Transport by Atmospheric Rivers Over the Western United States, 1949–2015. *Geophysical Research Letters*, 44(22): 11,456-11,462. https://doi.org/10.1002/2017GL075399.

Kossin JP, Hall T, Knutson T, Kunkel KE, Trapp RJ, Waliser DE, Wehner MF. 2017. Chapter 9: Extreme Storms. *Climate Science Special Report: Fourth National Climate Assessment Volume I [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]*. US Global Change Research Program: Washington, DC, USA, 257–276.

Kumar D, Mishra V, Ganguly AR. 2015. Evaluating wind extremes in CMIP5 climate models. *Climate Dynamics*, 45(1): 441–453. https://doi.org/10.1007/s00382-014-2306-2.

Lee EH, Beedlow PA, Waschmann RS, Burdick CA, Shaw DC. 2013. Tree-ring analysis of the fungal disease Swiss needle cast in western Oregon coastal forests. *Canadian Journal of Forest Research*, 43(8): 677–690. https://doi.org/10.1139/cjfr-2013-0062.

Liang X, Lettenmaier DP, Wood EF, Burges SJ. 1994. A simple hydrologically based model of land surface water and energy fluxes for general circulation models. *Journal of Geophysical Research*, 99(D7): 14415–14428.

Littell JS, Hicke JA, Shafer SL, Capalbo SM, Houston LL, Glick P. 2013. Forest ecosystems: Vegetation, disturbance, and economics: Chapter 5. In: Dalton MM, Mote PW and Snover AK (eds) *Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities*. Island Press: Washington, DC, 110–148.

Liu JC, Mickley LJ, Sulprizio MP, Dominici F, Yue X, Ebisu K, Anderson GB, Khan RFA, Bravo MA, Bell ML. 2016. Particulate air pollution from wildfires in the Western US under climate change. *Climatic Change*, 138(3–4): 655–666. https://doi.org/10.1007/s10584-016-1762-6.

Long MC, Deutsch C, Ito T. 2016. Finding forced trends in oceanic oxygen. *Global Biogeochemical Cycles*, 30(2): 2015GB005310. https://doi.org/10.1002/2015GB005310.

Maurer EP, Kayser G, Gabel L, Wood AW. 2018. Adjusting Flood Peak Frequency Changes to Account for Climate Change Impacts in the Western United States. *Journal of Water Resources Planning and Management*, 144(3): 05017025. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000903.

May C, Luce CH, Casola J, Chang M, Cuhaciyan JE, Dalton MM, Lowe S, Morishima G, Mote PW, Petersen A, Roesch-McNally G, York E. 2018. Northwest. In: Reidmiller DR, Avery CW, Easterling DR, Kunkel KE, Lewis KLM, Maycock TK and Stewart BC (eds) *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. U.S. Global Change Research Program: Washington, DC, USA, 1036–1100.

Mote PW, Abatzoglou JT, Dello KD, Hegewisch K, Rupp DE. 2019. *Fourth Oregon Climate Assessment Report*. Oregon Climate Change Research Institute: Corvallis, OR.

Mote PW, Abatzoglou JT, Kunkel KE. 2013. Climate: Variability and Change in the Past and the Future: Chapter 2. In: Dalton MM, Mote PW and Snover AK (eds) *Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities*. Island Press: Washington, DC, 25–40.

Musselman KN, Lehner F, Ikeda K, Clark MP, Prein AF, Liu C, Barlage M, Rasmussen R. 2018. Projected increases and shifts in rain-on-snow flood risk over western North America. *Nature Climate Change*, 8(9): 808–812. https://doi.org/10.1038/s41558-018-0236-4.

Najafi MR, Moradkhani H. 2015. Multi-model ensemble analysis of runoff extremes for climate change impact assessments. *Journal of Hydrology*, 525: 352–361. https://doi.org/10.1016/j.jhydrol.2015.03.045.

National Research Council. 2012. *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future*. .

Naz BS, Kao S-C, Ashfaq M, Rastogi D, Mei R, Bowling LC. 2016. Regional hydrologic response to climate change in the conterminous United States using high-resolution hydroclimate simulations. *Global and Planetary Change*, 143: 100–117. https://doi.org/10.1016/j.gloplacha.2016.06.003.

Nolte CG, Dolwick PD, Fann N, Horowitz LW, Naik V, Pinder RW, Spero TL, Winner DA, Ziska LH. 2018. Air Quality. In: Reidmiller DR, Avery CW, Easterling DR, Kunkel KE, Lewis KLM, Maycock TK and Stewart BC (eds) *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. U.S. Global Change Research Program: Washington, DC, USA, 512–538.

Oregon Department of Fish and Wildlife. (n.d.). *Oregon Conservation Strategy Fact Sheet: Climate Change and Oregon's Estuaries*. Oregon Department of Fish and Wildlife: Salem, Oregon.

Oregon DEQ. 2016. *2015 Oregon Air Quality Data Summaries*. Oregon Department of Environmental Quality: Portland, OR.

Parker LE, Abatzoglou JT. 2016. Spatial coherence of extreme precipitation events in the Northwestern United States. *International Journal of Climatology*, 36(6): 2451–2460. https://doi.org/10.1002/joc.4504.

Pershing AJ, Griffis RB, Jewett EB, Armstrong CT, Bruno JF, Busch DS, Haynie AC, Siedlecki SA, Tommasi D. 2018. Oceans and Marine Resources. In: Reidmiller DR, Avery CW, Easterling DR, Kunkel KE, Lewis KLM, Maycock TK and Stewart BC (eds) *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. U.S. Global Change Research Program: Washington, DC, USA, 353–390.

Peterson WT, Fisher JL, Strub PT, Du X, Risien C, Peterson J, Shaw CT. 2017. The pelagic ecosystem in the Northern California Current off Oregon during the 2014–2016 warm anomalies within the context of the past 20 years. *Journal of Geophysical Research: Oceans*, 122(9): 7267–7290. https://doi.org/10.1002/2017JC012952.

Raymondi RR, Cuhaciyan JE, Glick P, Capalbo SM, Houston LL, Shafer SL, Grah O. 2013. Water Resources: Implications of Changes in Temperature and Precipiptation: Chapter 3. In: Dalton MM, Mote PW and Snover AK (eds) *Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities*. Island Press: Washington, DC, 41–66.

Reeder WS, Ruggiero P, Shafer SL, Snover AK, Houston LL, Glick P, Newton JA, Capalbo SM. 2013. Coasts: Complex Changes Affecting the Northwest's Diverse Shorelines: Chapter 4. In:

Dalton MM, Mote PW and Snover AK (eds) *Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities*. Island Press: Washington, DC, 67–109.

Ritóková G, Shaw DC, Filip G, Kanaskie A, Browning J, Norlander D. 2016. Swiss Needle Cast in Western Oregon Douglas-Fir Plantations: 20-Year Monitoring Results. *Forests*, 7(8): 155. https://doi.org/10.3390/f7080155.

Ruggiero P. 2013. Is the Intensifying Wave Climate of the U.S. Pacific Northwest Increasing Flooding and Erosion Risk Faster Than Sea-Level Rise? *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 139(2): 88–97. https://doi.org/10.1061/(ASCE)WW.1943-5460.0000172.

Ruggiero P, Kratzmann MG, Himmelstoss EA, Reid D, Allan J, Kaminsky G. 2013. *National assessment of shoreline change—Historical shoreline change along the Pacific Northwest coast: U.S. Geological Survey Open-File Report 2012–1007*. , 62.

Safeeq M, Grant GE, Lewis SL, Staab B. 2015. Predicting landscape sensitivity to present and future floods in the Pacific Northwest, USA. *Hydrological Processes*, 29(26): 5337–5353. https://doi.org/10.1002/hyp.10553.

Salathé E, Mauger G, Steed R, Dotson B. 2015. *Final Project Report: Regional Modeling for Windstorms and Lightning. Prepared for Seattle City Light.* Climate Impacts Group, University of Washington: Seattle, WA.

Salathé EP, Hamlet AF, Mass CF, Lee S-Y, Stumbaugh M, Steed R. 2014. Estimates of Twenty-First-Century Flood Risk in the Pacific Northwest Based on Regional Climate Model Simulations. *Journal of Hydrometeorology*, 15(5): 1881–1899. https://doi.org/10.1175/JHM-D-13-0137.1.

Seiler C, Zwiers FW. 2016. How will climate change affect explosive cyclones in the extratropics of the Northern Hemisphere? *Climate Dynamics*, 46(11): 3633–3644. https://doi.org/10.1007/s00382-015-2791-y.

Sepanik J, Lanier A, Dana R, Haddad T. 2017. *Sea Level Rise Exposure Inventory for Oregon's Estuaries*. Oregon Coastal Management Program, Oregon Department of Land Conservation and Development: Salem, Oregon.

Sheehan T, Bachelet D, Ferschweiler K. 2015. Projected major fire and vegetation changes in the Pacific Northwest of the conterminous United States under selected CMIP5 climate futures. *Ecological Modelling*, 317: 16–29. https://doi.org/10.1016/j.ecolmodel.2015.08.023.

Somero GN, Beers JM, Chan F, Hill TM, Klinger T, Litvin SY. 2016. What Changes in the Carbonate System, Oxygen, and Temperature Portend for the Northeastern Pacific Ocean: A Physiological Perspective. *BioScience*, 66(1): 14–26. https://doi.org/10.1093/biosci/biv162.

Surfleet CG, Tullos D. 2013. Variability in effect of climate change on rain-on-snow peak flow events in a temperate climate. *Journal of Hydrology*, 479: 24–34. https://doi.org/10.1016/j.jhydrol.2012.11.021.

Sweet WV, Horton R, Kopp RE, LeGrande AN, Romanou A. 2017a. Sea level rise. In: Wuebbles DJ, Fahey DW, Hibbard KA, Dokken DJ, Stewart BC and Maycock TK (eds) *Climate Science Special Report: Fourth National Climate Assessment, Volume I*. U.S. Global Change Research Program: Washington, DC, USA, 333–363.

Sweet WV, Kopp RE, Weaver CP, Obeysekera J, Horton RM, Thieler ER, Zervas C. 2017b. *Global and Regional Sea Level Rise Scenarios for the United States*. NOAA Technical Report. NOAA National Ocean Service: Silver Spring, MD, 75.

Tohver IM, Hamlet AF, Lee S-Y. 2014. Impacts of 21st-Century Climate Change on Hydrologic Extremes in the Pacific Northwest Region of North America. *JAWRA Journal of the American Water Resources Association*, 50(6): 1461–1476. https://doi.org/10.1111/jawr.12199.

Vose JM, Clark JS, Luce CH, Patel-Weynand T. 2016. Executive Summary. In: Vose JM, Clark JS, Luce CH and Patel-Weynand T (eds) *Effects of drought on forests and rangelands in the United States: a comprehensive science synthesis. Gen. Tech. Rep. WO-93b*. U.S. Department of Agriculture, Forest Service, Washington Office: Washington, D.C., 289.

Vose RS, Applequist S, Bourassa MA, Pryor SC, Barthelmie RJ, Blanton B, Bromirski PD, Brooks HE, DeGaetano AT, Dole RM, Easterling DR, Jensen RE, Karl TR, Katz RW, Klink K, Kruk MC, Kunkel KE, MacCracken MC, Peterson TC, Shein K, Thomas BR, Walsh JE, Wang XL, Wehner MF, Wuebbles DJ, Young RS. 2014. Monitoring and Understanding Changes in Extremes: Extratropical Storms, Winds, and Waves. *Bulletin of the American Meteorological Society*, 95(3): 377–386. https://doi.org/10.1175/BAMS-D-12-00162.1.

Vose RS, Easterling DR, Kunkel KE, LeGrande AN, Wehner MF. 2017. Temperature changes in the United States. In: Wuebbles DJ, Fahey DW, Hibbard KA, Dokken DJ, Stewart BC and Maycock TK (eds) *Climate Science Special Report: Fourth National Climate Assessment, Volume 1*. U.S. Global Change Research Program: Washington, DC, USA, 185–206.

Waldbusser GG, Hales B, Langdon CJ, Haley BA, Schrader P, Brunner EL, Gray MW, Miller CA, Gimenez I. 2015. Saturation-state sensitivity of marine bivalve larvae to ocean acidification. *Nature Climate Change*, 5(3): 273–280. https://doi.org/10.1038/nclimate2479.

Wang XL, Feng Y, Swail VR. 2014. Changes in global ocean wave heights as projected using multimodel CMIP5 simulations. *Geophysical Research Letters*, 41(3): 1026–1034. https://doi.org/10.1002/2013GL058650.

Westerling AL. 2016. Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. *Phil. Trans. R. Soc. B*, 371(1696): 20150178. https://doi.org/10.1098/rstb.2015.0178.

Williams AP, Abatzoglou JT. 2016. Recent Advances and Remaining Uncertainties in Resolving Past and Future Climate Effects on Global Fire Activity. *Current Climate Change Reports*, 2(1): 1–14. https://doi.org/10.1007/s40641-016-0031-0.

Zhao J, Maguire DA, Mainwaring DB, Kanaskie A. 2014. Western hemlock growth response to increasing intensity of Swiss needle cast on Douglas-fir: changes in the dynamics of mixed-species stands. *Forestry*, 87(5): 697–704. https://doi.org/10.1093/forestry/cpu030.