

CITY OF ASHLAND, OREGON

# Climate Trends & Projections

FINAL REPORT

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Prepared by:

Meghan M. Dalton Oregon Climate Change Research Institute

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This report presents future climate projections for Ashland for the 2050s and 2080s compared to the 1950-2005 average historical baseline. The projections were analyzed for a low greenhouse gas emissions scenario as well as a high greenhouse gas emissions scenario, using multiple models. This summary lists only the mean projections for the 2050s and 2080s under the high emissions scenario. Projections for both time periods and both emissions scenarios are listed in Table 2 of the report.

## **Summary of Key Findings**



**Temperature.** Ashland has experienced significant warming over the last 120 years. Going forward, the temperature is projected to increase by 5°F on average by the 2050s and 8°F by the 2080s under the high emissions scenario. Warming may be more pronounced in the summer.



**Extreme Heat.** The hottest day of the year in Ashland is projected to increase by about 7°F by the 2050s and 12°F by the 2080s under the high emissions scenario. Warm spells are projected to comprise about 40 more days of the year by the 2050s and 90 more days of the year by the 2080s compared to the historical baseline. The number of daytime high temperatures reaching 100°F or more is projected to increase by 11 days by the 2050s and 27 days by the 2080s. The number of nighttime low temperatures staying above 60°F is projected to increase by 15 days by the 2050s and by 38 days by the 2080s.

**Cold Extremes.** The coldest night of the year in Ashland is projected to increase by about 5°F by the 2050s and by about 8°F by the 2080s under the high emissions scenario. The number of days in which the temperature drops below freezing are projected to decline by about 50 days by the 2050s and by about 80 days by the 2080s compared to the historical baseline.



**Degree Days.** Degree days measure how much heating or air conditioning is required for buildings to maintain a comfortable temperature. With projected increasing temperatures, the need for heating will decrease, with projected declines in heating degree days of about 1240 °F-days by the 2050s and about 2,000 °F-days by the 2080s under the high emissions scenario. Meanwhile, the need for air conditioning will increase, with projected increases in cooling degree days of about 530 °F-days by the 2050s and about 1,000 °F-days by the 2080s.



**Precipitation.** There was no significant change in total precipitation in Ashland over the last 120 years. Future projections are split: some models project an increase in total annual precipitation and others project decreases. Cool season precipitation may increase and warm season precipitation may decrease in the future. Changes in precipitation have been and will continue to be dominated by natural variability, rather than climate change.



**Extreme Precipitation.** It is generally expected that heavy precipitation events will become more common. Under the high emissions scenario, the number of days with more than 20 mm of precipitation is projected to increase by 0.3 days by the 2050s and 0.7 days by the 2080s. Meanwhile, the total amount of rainfall during the year that falls during the heaviest 5% of days is projected to increase by more than half an inch by the 2050s and more than an inch by the 2080s for the multi-model mean. In addition, the longest dry spell in a year is projected to increase by 5 days on average by the 2050s and by 6 days by the 2080s. While the majority of models project increases in these extreme precipitation measures, some project decreases.



**Snowpack.** With warmer temperatures, precipitation is more likely to fall as rain rather than snow at mid-elevations. April 1 snow water equivalent (SWE) on the western flank of the Cascades in the Rogue Basin has mostly declined over the past 50 years. By the 2050s under the high emissions scenario, April 1 SWE in the Middle Rogue basin is projected to decline by 66%. By the 2080s, April 1 SWE is projected to decline by 86% compared to the historical baseline.



**Streamflow.** As expected with future warming and declining snowpack, monthly total runoff averaged over the Middle Rogue basin is projected to shift toward earlier spring melt, higher winter flows, and lower summer flows.



**Wildfire.** Over the past century, warmer and drier conditions contributed to more frequent large fires, which in turn resulted in increased burned acreage across the western U.S. Such trends are expected to continue under future climate change.



## Introduction

The global climate is warming primarily due to the accumulation of greenhouse gases in the atmosphere from human activities like burning fossil fuels. Future climate conditions will depend on the amount of future greenhouse gas emissions and how sensitive the climate is to those emissions (IPCC, 2013).

To support the development of the City of Ashland's Climate and Energy Action Plan, this document presents historical trends in Ashland's temperature and precipitation alongside future projections related to both average and extreme temperature and precipitation. Later sections analyze historical trends in Rogue Basin snowpack and future projections in snowpack and streamflow, as well as historical trends and future projections of wildfire in the western U.S.

## **Data & Methods**

This section summarizes data sources and methods of analysis used in this project. A detailed description of the data and methods is included at the end of the document.

#### **Historical Trends**

The Oregon Climate Change Research Institute analyzed observed trends in annual and seasonal temperature and precipitation from 1893 to 2014 using Ashland data from version 2.5 of the United States Historical Climate Network (Menne, Williams, & Vose, 2009). The team analyzed observed trends in April 1 snow water equivalent (SWE) from 1960 to 2014 using SNOTEL and Snow Course data in the Rogue Basin collected by the Natural Resources Conservation Service. Trends were estimated using standard least squares linear regression.

#### **Future Projections**

-5 <del>-</del> 2000

2020

2040

2060

Year

2080

2100

The future climate projections for Ashland are based on the latest generation of global climate models (GCMs) from the Coupled Model Intercomparison Project phase 5 (CMIP5) (Taylor, Stouffer, & Meehl, 2012) that were used in the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2013). CMIP5 simulations of the 21<sup>st</sup> century were driven by representative concentration pathways (RCPs) that define concentrations of greenhouse gases, aerosols, and chemically active gases leading to a set amount of radiative forcing—or extra energy trapped in the earth-atmosphere system—by the year 2100 (van Vuuren et al., 2011). This project considers two of the four RCPs: RCP4.5 ("low") representing moderate efforts to mitigate emissions, and RCP8.5 ("high") representing a business as usual scenario (see Figure 1). It is important to note that RCP2.6, which attains negative greenhouse gas emissions by 2100, is the only RCP scenario to keep global temperature likely below 2°C (IPCC, 2013). Inherent in GCM projections is uncertainty due to emissions scenario, internal variability, and modeling physics and resolution, which combined yield a range of plausible future climate projections rather than a single precise prediction.

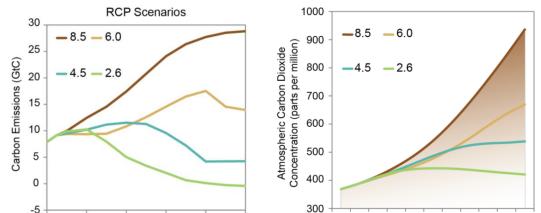


Figure 1. Carbon emissions and atmospheric carbon dioxide concentrations for RCP scenarios (Walsh et al., 2014a).

In a project called "Integrated Scenarios of the Future Northwest Environment," the coarse resolution (100-300 km) of the CMIP5 GCM output was statistically downscaled to a resolution of about 6 km, which was then used as an input to hydrology and vegetation models. Modeled historical and future climate data was analyzed for the 6-km grid cell containing the city of Ashland from 1950 to 2099 for 18 CMIP5 GCMs as well as RCP4.5 and RCP8.5. Historical and future April 1 SWE and total runoff data from the hydrology model were averaged over the Middle Rogue basin.

2000

2020

2040

Year

2060

2080

2100

## **Overview**

Temperature in Ashland increased significantly over the historical period while trends in precipitation were less clear. All models agree that temperature will continue to increase in the future. However, future projections of annual precipitation have less confidence: some models project increases while other models project decreases. Because precipitation is highly variable from year to year, the future direction of change in precipitation and precipitation-derived metrics is less certain than for temperature metrics.

Measures of extreme precipitation and extreme temperature were also analyzed. In general, warm temperature extremes are projected to increase. Extreme cold measures are projected to change in a manner consistent with overall warming: increases in the coldest night of the year and decreases in the number of days below freezing. In terms of possible increases or decreases in precipitation extremes, the sign of change depended on the model.

Snow water equivalent (SWE) in the Rogue Basin—a metric that indicates the amount of water contained within the snowpack—decreased over the historical period. SWE is influenced by both temperature and precipitation changes, but the influence of temperature dominates in future projections. All models agree that SWE will decrease in the future.

Table 1 lists all of the variables that are reported in this document.

Table 1. Description of variables.

| Variable                        | Description   |
|---------------------------------|---|
| Average Temperature             | Daily mean temperature averaged over the year   |
| Hottest Day of Year             | Yearly maximum of daily maximum temperature   |
| Warm Spell Duration Index       | Number of days in the year in which maximum temperature is of the highest 10% for that day in the historical baseline |
| Days above 100°F                | Number of days in the year with maximum temperature equal to or greater than 100°F                                    |
| Days above 110°F                | Number of days in the year with maximum temperature equal to or greater than 110°F                                    |
| Nights above 60°F               | Number of days in the year with minimum temperature equal to or greater than $60^{\circ}F$                            |
| Heating Degree Days             | Annual accumulation of days and degrees below 65°F  |
| Cooling Degree Days             | Annual accumulation of days and degrees above 65°F  |
| Coldest Night of Year           | Yearly minimum of daily minimum temperature   |
| Frost Days                      | Number of days in a year with minimum temperature below 32°F  |
| Precipitation                   | Total water year precipitation  |
| Extreme Precipitation Frequency | Number of days in the year with precipitation equal to or greater than 20 mm ( $^{\sim}3/4$ ")                        |
| Consecutive Dry Days            | Maximum run in a year of consecutive days with less than 1 mm precipitation   |
| Extreme Precipitation Amount    | Total annual precipitation on days with greater than 95th percentile precipitation                                    |
| Snow Water Equivalent           | The amount of water contained within the snowpack   |

Table 2 presents the multi-model mean change and the range of changes across all models for each metric considered in Table 1 for the 2050s (2040-2069 average) and 2080s (2070-2099 average) under the low

(RCP4.5) and high (RCP8.5) emissions scenarios. Projections for each metric are discussed further in the following sections with a focus on the high emissions scenario for the 2080s. Future projections for streamflow and wildfire are also discussed.

Table 2. Future projected changes from the historical baseline (1950-2005) for mid- and late- 21st century under low and high future emissions scenarios in the City of Ashland. Given are the mean differences and range across an ensemble of 18 downscaled global climate models.

|                                 | 2050s         |               | 2080s         |                |
|---------------------------------|---------------|---------------|---------------|----------------|
|                                 | RCP4.5        | RCP8.5        | RCP4.5        | RCP8.5         |
|                                 | (low)         | (high)        | (low)         | (high)         |
| Average Temperature             | 4             | 5             | 5             | 8              |
| (°F)                            | (2, 5)        | (3, 6)        | (3, 7)        | (6, 11)        |
| Hottest Day of Year             | 6             | 7             | 7             | 12             |
| (°F)                            | (4, 8)        | (4, 10)       | (5, 9)        | (8, 14)        |
| Warm Spell Duration Index       | 27            | 39            | 39            | 89             |
| (Days)                          | (11, 42)      | (11, 66)      | (18, 66)      | (36, 136)      |
| Days above 100°F                | 6             | 11            | 10            | 27             |
| .,                              | (3, 10)       | (3, 19)       | (5, 16)       | (13, 40)       |
| Days above 110°F                | 0             | 0             | 0             | 3              |
|                                 | (0, 1)        | (0, 1)        | (0, 1)        | (0, 6)         |
| Nights above 60°F               | 8             | 15            | 13            | 38             |
|                                 | (2, 15)       | (5, 27)       | (3, 24)       | (11, 68)       |
| Heating Degree Days             | -976          | -1240         | -1256         | -2008          |
| (°F-Days)                       | (-473, -1256) | (-717, -1600) | (-641, -1649) | (-1319, -2455) |
| Cooling Degree Days             | 368           | 526           | 506           | 994            |
| (°F-Days)                       | (200, 541)    | (279, 762)    | (279, 753)    | (634, 1455)    |
| Coldest Night of Year (°F)      | 3             | 5             | 4             | 8              |
|                                 | (1, 7)        | (2, 8)        | (0, 8)        | (4, 11)        |
| Frost Days (Days)               | -41           | -52           | -53           | -80            |
|                                 | (-19, -54)    | (-30, -68)    | (-25, -72)    | (-52, -99)     |
| Precipitation                   | -0.2          | -0.2          | 0.0           | 0.4            |
| (Inches)                        | (-2.2, 2.4)   | (-2.4, 2.3)   | (-1.8, 2.2)   | (-2.7, 3.9)    |
| Extreme Precipitation Frequency | 0.2           | 0.3           | 0.4           | 0.7            |
| (Days)                          | (-0.4, 0.8)   | (-0.3, 1.1)   | (-0.4, 1.2)   | (-0.5, 2.2)    |
| Extreme Precipitation Amount    | 0.5           | 0.6           | 0.8           | 1.3            |
| (Inches)                        | (-0.5, 1.4)   | (-0.4, 2.1)   | (-0.2, 2.0)   | (-0.2, 3.4)    |
| Consecutive Dry Days            | 5             | 5             | 4             | 6              |
| (Days)                          | (-2, 17)      | (-2, 13)      | (-2, 10)      | (-8, 21)       |
| Snow water equivalent           | -60           | -66           | -71           | -86            |
| (%)                             | (-69, -41)    | (-83, -47)    | (-81, -58)    | (-93, -70)     |

## **Implications**

**Human Health:** Increases in temperatures and extreme heat elevates the risk of heat-related illnesses (Crimmins et al., 2016). Increasing wildfire occurrence leading to elevated particulate matter exacerbate respiratory and cardiovascular illnesses (Crimmins et al., 2016). Vector-borne diseases, such as Lyme disease, may emerge earlier in the season and expand in range with warmer temperatures (Crimmins et al., 2016). Rising temperatures also increase the risk of exposure to food-related infections such as Salmonella (Crimmins et al., 2016). Certain segments of the populations may be more vulnerable to climate impacts, such as heat extremes. These include: people with low income, immigrants, limited English proficiency

groups, indigenous peoples, children and pregnant women, older adults, outdoor workers, persons with disabilities, and persons with chronic medical conditions (Crimmins et al., 2016).

**Built Infrastructure:** Urban infrastructure and transportation systems will be increasingly compromised by climate change impacts (Cutter et al., 2014; Schwartz et al., 2014). Infrastructure that is past its design age and interdependent on other systems is particularly vulnerable to climate extreme events (Cutter et al., 2014). A warming climate can accelerate asphalt deterioration, cause pavement and rail line buckling, and stress expansion joints on bridges and highways (Schwartz et al., 2014).

**Forest Ecosystems:** The combined impact of increasing wildfire, insect outbreaks, and tree diseases are already causing widespread tree die-off and are likely to cause additional forest mortality and long-term transformation of the forest landscape (Mote et al., 2014). Forest vegetation changes, such as a shift from conifer to mixed forests (Sheehan et al., 2015), could affect the local timber economy (Mote et al., 2014).

Water-Related Challenges: Changes in streamflow timing and amount related to changing snowmelt will reduce the supply of water for many competing demands, such as irrigation, municipal and industrial use, hydropower production, and aquatic habitat preservation, potentially causing ecological and socioeconomic consequences such as water shortages, complex tradeoffs in water allocations, and threatening of salmon and other freshwater species (Mote et al., 2014). In addition, warming, increasing winter precipitation, and more extreme precipitation will likely increase flood risk (Mote et al., 2014).

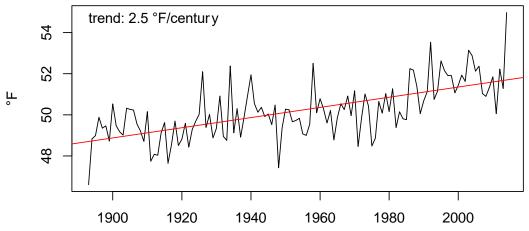
## **Average Temperature**

#### **Historical Trends**

The annual mean temperature in Ashland warmed at a rate of 2.5°F per century between 1893 and 2014 (see Figure 2). This local warming is greater than the observed warming averaged over the Pacific Northwest (PNW), which was about 1.0°F to 1.4°F per century over the period 1901-2012 (Abatzoglou, Rupp, & Mote, 2014). It has been shown that the rise in greenhouse gases was largely responsible for this PNW temperature trend (Abatzoglou et al., 2014). Globally, the Earth's surface warmed about 1.5°F between 1880 and 2012 (IPCC, 2013).

Figure 2. Annual mean temperature in Ashland has increased from 1893 to 2014 at a rate of 2.5°F per century.

## Ashland Annual Mean Temperature



In Ashland, the mean, minimum, and maximum temperature increased year-round with significant (>95%) trends, except for the maximum temperature trend in spring (see Table 3). Minimum temperatures in Ashland have increased faster than maximum temperatures, as was the case for most stations in the PNW. Warming was most pronounced in Ashland during winter, with a 3.9°F per century rate of increase in minimum temperature. Average PNW warming was also largest in winter (Abatzoglou et al., 2014).

Table 3. Annual and seasonal trends in maximum, minimum, and mean temperature and precipitation from 1893 to 2014 for Ashland. An asterisk denotes a statistically significant trend at the 95% level.

|        | Maximum<br>Temperature | Minimum<br>Temperature | Mean Temperature<br>(°F per century) | Precipitation<br>(Inches per |
|--------|------------------------|------------------------|--------------------------------------|------------------------------|
|        | (°F per century)       | (°F per century)       | (                                    | century)                     |
| Annual | 1.4*                   | 3.6*                   | 2.5*                                 | -0.9                         |
| Winter | 2.1*                   | 3.9*                   | 3.0*                                 | -0.9                         |
| Spring | 0.7                    | 3.5*                   | 2.1*                                 | 0.5                          |
| Summer | 1.3*                   | 3.9*                   | 2.6*                                 | 0.03                         |
| Fall   | 1.1*                   | 3.0*                   | 2.1*                                 | -0.4                         |

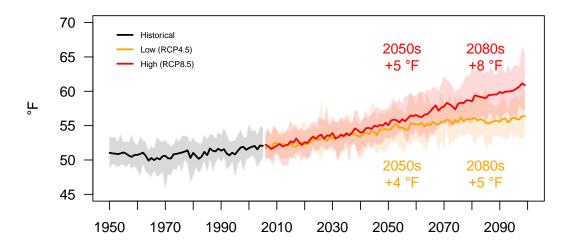
#### **Future Projections**

The range of future changes in annual average temperature in Ashland is 2°F to 6°F for the 2050s and 3°F to 11°F for the 2080s, using all models and both emissions scenarios (see Table 2). The multi-model mean projects an increase of about 8°F by the 2080s under the high emissions scenario compared to the historic baseline (1950-2005) (see Figure 3). Warming occurs year round and is more pronounced during the summer months of July, August, and September (Figure 3).

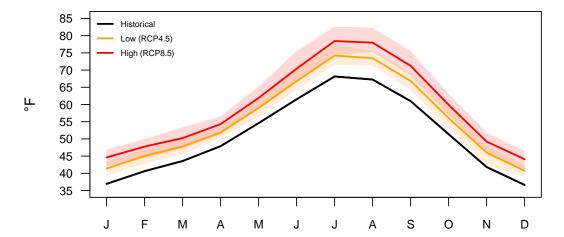
Globally, the Earth's climate will continue to warm with continued greenhouse gas emissions. By the end of the 21<sup>st</sup> century relative to the 1850-1900 average, it is likely that global warming will exceed 2.7°F under RCP4.5 and exceed 3.6°F under RCP8.5. By mid-century (2046-2065 relative to 1986-2005) global warming is "likely" to be in the range of 1.6°F to 3.6°F for RCP4.5 and 2.5°F to 4.7°F for RCP8.5 (IPCC, 2013). It is important to note that the IPCC's "likely" range does not include the full range of models shown for the Ashland projections.

Figure 3. Annual average temperature (top) and monthly average temperature (bottom) projections for Ashland as simulated by 18 downscaled global climate models under a low (RCP4.5) and high (RCP8.5) greenhouse gas emissions scenario. Solid line and shading depicts the 18-model mean and range, respectively. The multi-model mean differences for the 2050s (2040-2069 average) and 2080s (2070-2099 average) compared to the historical baseline (1950-2005) are displayed on the top plot.

## **Ashland Average Temperature Projections**



## **Ashland Monthly Average Temperature Projections** 2080s & Historical



## **Extreme Warm Temperature**

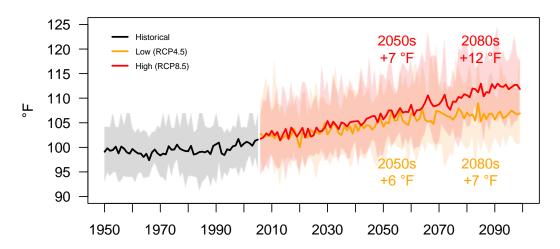
Extreme warm temperature projections are examined using the hottest day of the year, the warm spell duration index, number of days above 100°F, number of days above 110°F, and number of nights above 60°F.

#### **Hottest Day of Year**

The range of future changes in the temperature of the hottest day of the year in Ashland is 4°F to 10°F for the 2050s and 5°F to 14°F for the 2080s (see Table 2); this is the range across all models and both emissions scenarios. The multi-model mean projects an increase of about 12°F by the 2080s under the high emissions scenario compared to the historic baseline (1950-2005) (see Figure 4).

Figure 4. Temperature of the hottest day of year projections for Ashland as simulated by 18 downscaled global climate models for the historical period (1950-2005) and future (2006-2099) under a low (RCP4.5) and high (RCP8.5) greenhouse gas emissions scenario. Solid line and shading depicts the 18-model mean and range, respectively. The multi-model mean differences for the 2050s (2040-2069 average) and 2080s (2070-2099 average) compared to the historical baseline (1950-2005) are displayed.

## **Ashland Hottest Day of Year Projections**

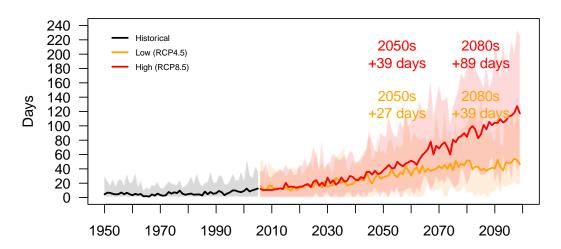


#### Warm Spell Duration Index

A warm spell is defined as at least six consecutive days where each day is above the 90<sup>th</sup> percentile of temperature for that calendar date in the historical baseline (1950-2005 average). Future warm spells are still determined using the 90<sup>th</sup> percentile temperature threshold from the historical baseline. The warm spell duration index counts the number of days per year that occur within such warm spells. Projections indicate the number of warm spell days per year in Ashland is likely to increase by between 11 to 66 days by the 2050s and 18 to 136 days by the 2080s (refer back to Table 2); this is the range of future changes across all models and both emissions scenarios. The multi-model mean projects 89 more warm spell days by the 2080s under the high emissions scenario compared to the historic baseline (1950-2005) (see Figure 5).

Figure 5. Projections of number of days within a warm spell for Ashland as simulated by 18 downscaled global climate models for the historical period (1950-2005) and future (2006-2099) under a low (RCP4.5) and high (RCP8.5) greenhouse gas emissions scenario. Solid line and shading depicts the 18-model mean and range, respectively. The multi-model mean differences for the 2050s (2040-2069 average) and 2080s (2070-2099 average) compared to the historical baseline (1950-2005) are displayed.

## Ashland Warm Spell Days Projections

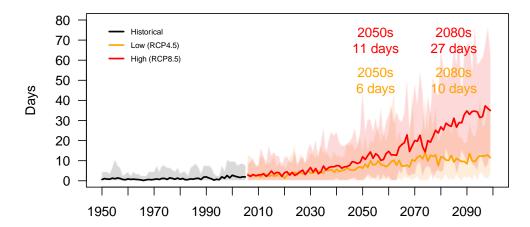


#### Days above 100°F and 110°F

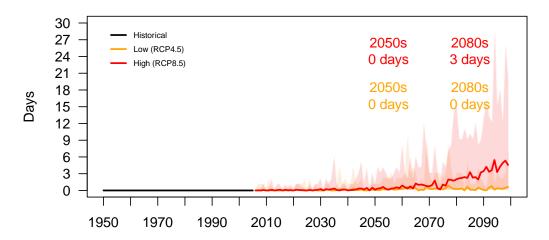
The range of future changes in the number of days at or above 100°F in Ashland is 3 to 19 for the 2050s and 5 to 40 for the 2080s (see Table 2); this is the range across all models and both emissions scenarios. The multimodel mean projects an increase of 27 days by the 2080s under the high emissions scenario compared to the historic baseline (1950-2005) (see Figure 4). The multi-model mean projects an increase of 3 days at or above 110°F for the 2080s under the high emissions scenario with a range of 0 to 6 days.

Figure 6. Projections of number of days over 100°F (top) and 110°F (bottom) for Ashland as simulated by 18 downscaled global climate models for the historical period (1950-2005) and future (2006-2099) under a low (RCP4.5) and high (RCP8.5) greenhouse gas emissions scenario. Solid line and shading depicts the 18-model mean and range, respectively. The multi-model mean differences for the 2050s (2040-2069 average) and 2080s (2070-2099 average) compared to the historical baseline (1950-2005) are displayed.

#### Ashland # Days over 100°F Projections



## Ashland # Days over 110°F Projections

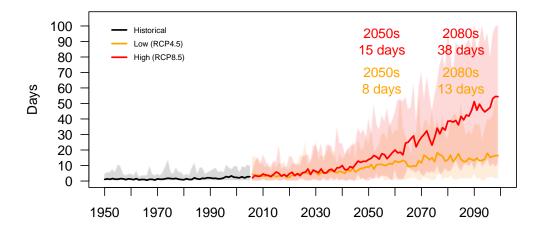


### Nights above 60°F

The range of future changes in the number of nights remaining at or above 60°F in Ashland is 2 to 27 for the 2050s and 3 to 68 for the 2080s (see Table 2); this is the range across all models and both emissions scenarios. The multi-model mean projects an increase of 38 days by the 2080s under the high emissions scenario compared to the historic baseline (1950-2005) (see Figure 4).

Figure 7. Projections of number of nights over 60°F for Ashland as simulated by 18 downscaled global climate models for the historical period (1950-2005) and future (2006-2099) under a low (RCP4.5) and high (RCP8.5) greenhouse gas emissions scenario. Solid line and shading depicts the 18-model mean and range, respectively. The multi-model mean differences for the 2050s (2040-2069 average) and 2080s (2070-2099 average) compared to the historical baseline (1950-2005) are displayed.

## Ashland # Nights above 60°F Projections



## **Extreme Cold Temperature**

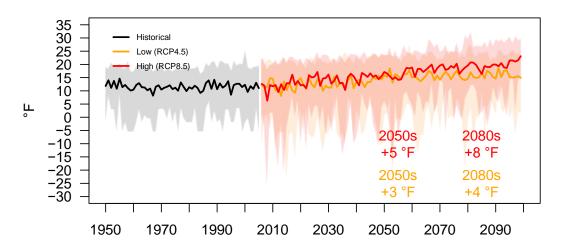
Extreme cold temperature projections are examined using two standard metrics: 1) the coldest night of the year, and 2) number of frost days per year.

#### **Coldest Night of Year**

The range of future changes in the temperature of the coldest night of the year in Ashland is 1°F to 8°F for the 2050s and 0°F to 11°F for the 2080s compared to the historical period (see Table 2); this is the range across all models and both emissions scenarios. The multi-model mean projects an increase of about 8°F by the 2080s under the high emissions scenario compared to the historic baseline (1950-2005) (see Figure 4). Projected increases in the coldest night of the year are smaller than projected increases in the hottest day of the year.

Figure 8. Temperature of the coldest night of year projections for Ashland as simulated by 18 downscaled global climate models for the historical period (1950-2005) and future (2006-2099) under a low (RCP4.5) and high (RCP8.5) greenhouse gas emissions scenario. Solid line and shading depicts the 18-model mean and range, respectively. The multi-model mean differences for the 2050s (2040-2069 average) and 2080s (2070-2099 average) compared to the historical baseline (1950-2005) are displayed.

## Ashland Coldest Night of Year Projections

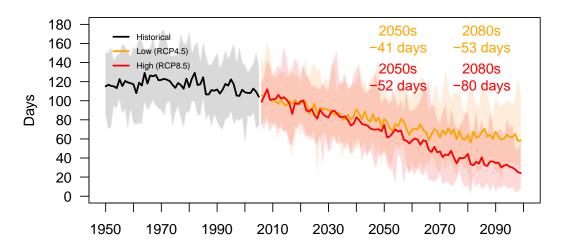


#### **Frost Days**

A frost day is counted when the minimum temperature drops below 32°F. Projections indicate the number of frost days per year in Ashland is likely to decrease by between 19 to 68 days by the 2050s and 25 to 99 days by the 2080s (refer back to Table 2); this is the range of future changes across all models and both emissions scenarios. The multi-model mean projects 80 fewer frost days by the 2080s under the high emissions scenario compared to the historic baseline (1950-2005) (see Figure 5).

Figure 9. Projections of frost days for Ashland as simulated by 18 downscaled global climate models for the historical period (1950-2005) and future (2006-2099) under a low (RCP4.5) and high (RCP8.5) greenhouse gas emissions scenario. Solid line and shading depicts the 18-model mean and range, respectively. The multi-model mean differences for the 2050s (2040-2069 average) and 2080s (2070-2099 average) compared to the historical baseline (1950-2005) are displayed.

## **Ashland Frost Days Projections**



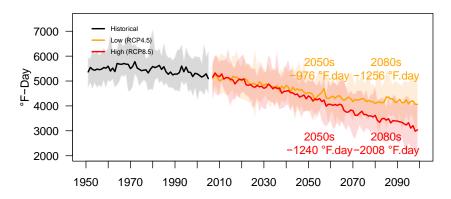
## **Heating & Cooling Degree Days**

The amount of heating or cooling required in buildings is partially determined by how much the air temperature is below or above 65°F, and for how long, defined as heating or cooling degree-days. For example, one day with an average temperature of 64°F counts as one heating degree-day. With projected warming temperatures, the need for heating as expressed by the number of heating degree-days is projected to decline while the need for cooling as expressed by the number of cooling degree-days is projected to increase (see Figure 10).

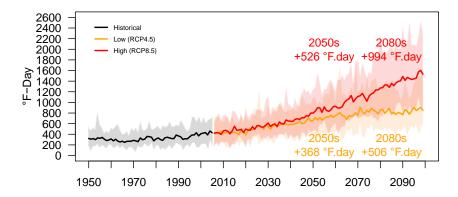
The range across all models and both emissions scenarios of future changes in heating degree-days in Ashland is -473 to -1600 °F-days for the 2050s and -641 to -2455 °F-days for the 2080s (Table 2). For future changes in cooling degree-days in Ashland, the range across all models and both emissions scenarios of future changes is +200 to +762 for the 2050s and +279 to +1455 °F-days for the 2080s (refer to Table 2). The multi-model mean projects a decrease of 2008 heating degree-days, a 37% decrease, and an increase of 994 cooling degree-days, a 303% increase, by the 2080s under the high emissions scenario compared to the historic baseline (1950-2005). Thus, as the climate changes, less heating will be required to heat buildings, but much more air conditioning will be required to cool buildings.

Figure 10. Projections of heating degree days (top) and cooling degree days (bottom) with a base of 65°F for average temperature for Ashland as simulated by 18 downscaled global climate models for the historical period (1950-2005) and future (2006-2099) under a low (RCP4.5) and high (RCP8.5) greenhouse gas emissions scenario. Solid line and shading depicts the 18-model mean and range, respectively. The multi-model mean differences for the 2050s (2040-2069 average) and 2080s (2070-2099 average) compared to the historical baseline (1950-2005) are displayed.

#### Ashland Annual (Jul-Jun) Total Heating Degree Days Base 65°F



#### Ashland Annual (Jan-Dec) Total Cooling Degree Days Base 65°F



## **Total Precipitation**

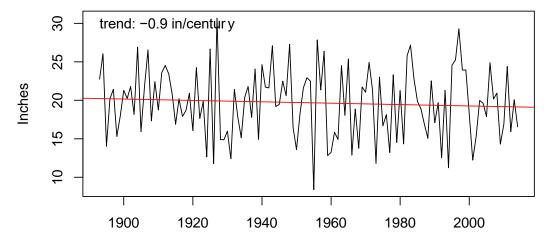
#### **Historical Trends**

Total water year (October-September) precipitation in Ashland decreased at a rate of 0.9 inches per century over the period 1893-2014, but the trend is not significantly different from there being no trend at all (see Figure 11). Likewise, there were no significant trends in precipitation for any season in Ashland (Table 3).

Like Ashland, water year precipitation at the majority of stations in the PNW and averaged over the PNW exhibits considerable variability from year to year and decade to decade with no significant trends from 1901 to 2012 (Abatzoglou et al., 2014). Unlike for temperature trends, increasing greenhouse gases did not contribute significantly to the observed PNW precipitation trends in any season, suggesting that natural variability is larger than any climate change signal over this period (Abatzoglou et al., 2014).

Figure 11. Total water year precipitation in Ashland exhibits large variability and a decreasing trend that is not significantly different from zero during the period 1893-2014.

## Ashland Total Water Year Precipitation



#### **Future Projections**

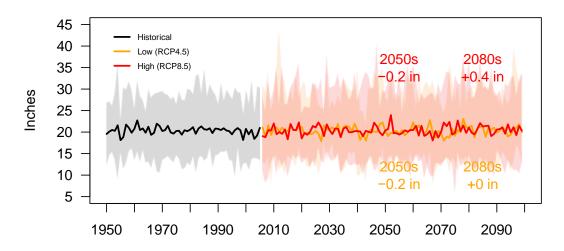
The range of future changes in total precipitation amount in Ashland is -2.4 to +2.4 inches for the 2050s and -2.7 to +3.9 inches for the 2080s across all models and both emissions scenarios (Table 2). The multi-model mean projects an increase of about 0.4 inches by the 2080s under the high emissions scenario compared to the historic baseline (1950-2005) (see Figure 12). In other words, climate models do not agree on whether annual total precipitation will increase or decrease. Seasonally, precipitation is projected to increase during the winter months and remain about the same or decrease at other times of the year. However, in every season, some climate models project increases and others project decreases (Figure 12). Natural variability will continue to play a dominant role in future precipitation through the end of the 21st century.

From a global perspective, changes in precipitation in response to warming will manifest as a larger contrast between wet and dry regions and seasons, although there may be regional exceptions. In the near term, precipitation changes will largely reflect natural internal variability. By the end of the 21<sup>st</sup> century under the highest emissions scenario (RCP8.5), high latitudes and the equatorial Pacific Ocean are likely to experience an increase in annual mean precipitation. Mean precipitation is likely to decrease in many dry regions in the subtropics and mid-latitudes and increase in many mid-latitude wet regions (IPCC 2013). Where exactly that

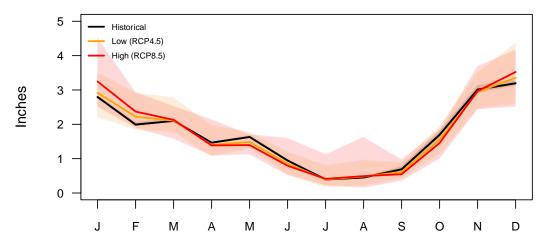
boundary between mid-latitude increases and decreases in precipitation is a little different for each model, which results in some models projecting increases and other decreases in the Pacific Northwest (Mote et al., 2013).

Figure 12. Total annual precipitation projections (top) and monthly total precipitation projections (bottom) for Ashland as simulated by 18 downscaled global climate models under a low (RCP4.5) and high (RCP8.5) greenhouse gas emissions scenario. Solid line and shading depicts the 18-model mean and range, respectively. The multi-model mean differences for the 2050s (2040-2069 average) and 2080s (2070-2099 average) compared to the historical baseline (1950-2005) are displayed on the top plot.

## **Ashland Precipitation Projections**



# Ashland Monthly Precipitation Projections 2080s & Historical



## **Extreme Precipitation**

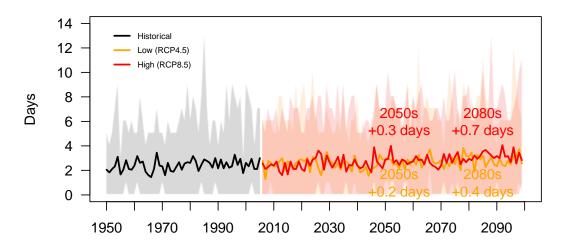
Extreme precipitation projections are examined using three standard metrics: 1) extreme precipitation frequency, as represented by the number of days with more than 20 mm of precipitation, 2) extreme precipitation amount, as represented by the total amount of precipitation falling on days with precipitation above the 95<sup>th</sup> percentile, and 3) maximum length of consecutive dry days, or the longest dry spell.

## **Extreme Precipitation Frequency**

Projections of extreme precipitation frequency are presented as the change in the number of days with more than 20 mm of precipitation (Figure 13). The range of future changes in the number of days with more than 20 mm of precipitation in Ashland is -0.4 to +1.1 days for the 2050s and -0.5 to +2.2 days for the 2080s, using all models and both emissions scenarios (refer to Table 2). The multi-model mean projects that the number of extreme precipitation days will increase by 0.7 days by the 2080s under the high emissions scenario compared to the historic baseline (1950-2005). It is important to note that some models project decreases in extreme precipitation.

Figure 13. Extreme (>20mm) precipitation days projections for Ashland as simulated by 18 downscaled global climate models for the historical period (1950-2005) and future (2006-2099) under a low (RCP4.5) and high (RCP8.5) greenhouse gas emissions scenario. Solid line and shading depicts the 18-model mean and range, respectively. The multi-model mean differences for the 2050s (2040-2069 average) and 2080s (2070-2099 average) compared to the historical baseline (1950-2005) are displayed.

## Ashland >20mm Precipitation Days Projections

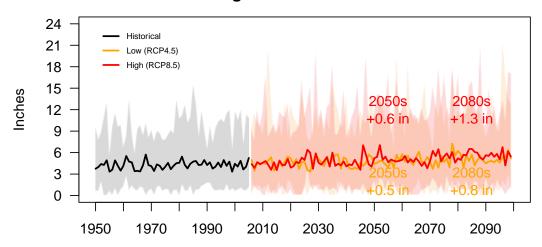


## **Extreme Precipitation Amount**

Extreme precipitation is considered to have occurred on days exceeding the 95<sup>th</sup> percentile of daily precipitation amounts. The total amount of precipitation during the year that falls during such days is projected to increase in Ashland by 1.3 inches for the multi-model average by the 2080s under the high emissions scenario compared to the historic baseline (1950-2005) (see Figure 14). However, some models project decreases in the total amount of precipitation falling on extreme precipitation days. The range across all models and both emissions scenarios of future changes in the amount of precipitation falling on extreme days is -0.5 to +2.1 inches for the 2050s and -0.2 to +3.4 inches for the 2080s (Table 2).

Figure 14. Projections of annual total daily precipitation exceeding the 95th percentile for Ashland as simulated by 18 downscaled global climate models for the historical period (1950-2005) and future (2006-2099) under a low (RCP4.5) and high (RCP8.5) greenhouse gas emissions scenario. Solid line and shading depicts the 18-model mean and range, respectively. The multi-model mean differences for the 2050s (2040-2069 average) and 2080s (2070-2099 average) compared to the historical baseline (1950-2005) are displayed.

# Ashland Annual Total Daily Precipitation Exceeding 95th Percentile Threshold

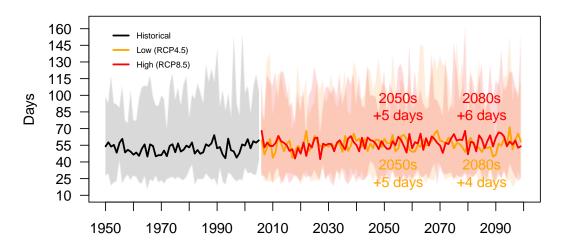


#### Consecutive Dry Days

The annual maximum run of consecutive days without precipitation in Ashland—or longest annual dry spell—is projected to increase by 6 days for the multi-model mean by the 2080s under the high emissions scenario compared to the historic baseline (1950-2005) (Figure 15). The range of future changes in the longest dry spell is -2 to +17 days for the 2050s and -8 to +21 days for the 2080s across all models and both emissions scenarios of future changes (Table 2). It is important to note that some models project a shortening of the longest annual dry spell.

Figure 15. Longest dry spell projections for Ashland as simulated by 18 downscaled global climate models for the historical period (1950-2005) and future (2006-2099) under a low (RCP4.5) and high (RCP8.5) greenhouse gas emissions scenario. Solid line and shading depicts the 18-model mean and range, respectively. The multi-model mean differences for the 2050s (2040-2069 average) and 2080s (2070-2099 average) compared to the historical baseline (1950-2005) are displayed.

## Ashland Longest Dry Spell Projections



## **Snowpack & Streamflow**

In the Pacific Northwest, mountain snowpack serves as a natural water reservoir feeding many rivers and streams during the dry season (April-September). Historical trends and future projections are presented for April 1 snow water equivalent (SWE), a standard measure of snowpack. Future projections in the monthly hydrograph of total runoff are also presented.

#### Historical Trends

Across the western U.S., snowpack declined at about three-fourths of the more than 700 SNOTEL/Snow Course stations. Only about a quarter of all stations exhibited statistically significant trends in April 1 SWE, most being decreases (Mote & Sharp, 2014). The largest decreases in April 1 SWE occurred in Washington, Oregon, and the Northern Rockies; in contrast, the southern Sierra Nevada in California exhibited increases in snowpack. Averaged over all sites, the average change in April 1 SWE over the period 1955-2013 was a 14% decline (Mote & Sharp, 2014).

In the Rogue Basin, almost all stations exhibited decreasing trends in April 1 SWE from 1960 to 2014. The trend was statistically significant at only one site: the Diamond Lake SNOTEL site at an elevation of about 5,300 feet at the northern end of the Upper Rogue sub-basin had a significant trend in which April 1 SWE declined by 59% (see Figure 16). Trends at all other stations, except the Siskiyou Summit Snow Course in the Middle Rogue, were negative, ranging from a decrease of 3% to a decrease of 60% (see Table 4). Siskiyou Summit had a positive, though not significant, trend in April 1 SWE amounting to a 100% increase over the period of record; however, the mean SWE is so small (4 inches) at that location that a small absolute increase resulted in a large relative change.

Figure 16. Trends (cm/year) in April 1 snow water equivalent from 1960 to 2014 at SNOTEL/Snow Course sites in the Upper and Middle Rogue and Applegate sub-basins. The large circle in the northeast corner denotes a statistically significant trend.

## Rogue Basin April 1 Snow Water Equivalent Trends 1960-2014

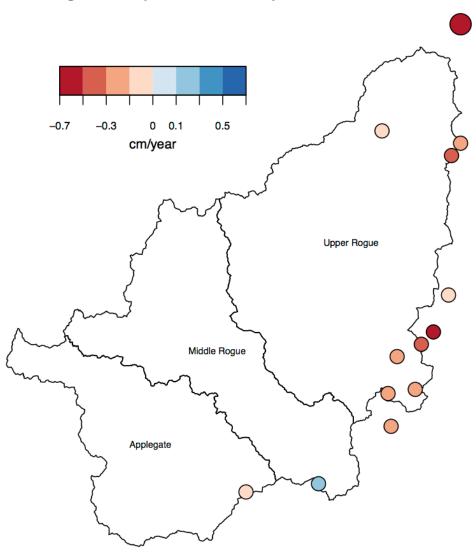


Table 4. SNOTEL (ST) and Snow Course (SC) stations with data beginning at least by 1960 in the Rogue Basin ordered greatest to least percent decline. An asterisk denotes a statistically significant trend at the 95% level.

| Station Name         | Elevation (Feet) | % Change | Trend (cm/yr) | MeanSWE<br>(inches) |
|----------------------|------------------|----------|---------------|---------------------|
| DeadwoodJunction_SC  | 4660             | -60.0    | -0.2          | 5.2                 |
| DiamondLake_ST       | 5280             | -58.5    | -0.6*         | 15.1                |
| HowardPrairie_SC     | 4580             | -38.9    | -0.1          | 5.7                 |
| FishLkST             | 4660             | -32.9    | -0.2          | 8.9                 |
| FourmileLake_ST      | 5970             | -31.2    | -0.5          | 28.7                |
| BillieCreekDivide_ST | 5280             | -25.4    | -0.3          | 21.0                |
| SilverBurn_SC        | 3680             | -20.4    | -0.1          | 8.9                 |
| BeaverDamCreek_SC    | 5120             | -20.3    | -0.1          | 10.1                |
| AnnieSprings_ST      | 6010             | -19.7    | -0.4          | 41.8                |
| ColdSpringsCamp_ST   | 5940             | -7.1     | -0.1          | 27.2                |
| ParkH.q.Rev_SC       | 6570             | -5.1     | -0.1          | 58.7                |
| BigRedMountain_ST    | 6050             | -2.6     | 0.0           | 27.4                |
| SiskiyouSummit_SC    | 4560             | 100.8    | 0.1           | 4.0                 |

#### **Future Projections**

Basins in the Pacific Northwest have been classified into three categories based on the ratio of spring snow water equivalent to wet season (October-March) precipitation (see Figure 17) (Hamlet et al., 2013). Raindominant watersheds, like the Middle and Lower Rogue sub-basins, receive most of their precipitation as rainfall during the winter months and thus have streamflow peaks in winter and low flows in summer. Mixed rain-snow watersheds, like the Upper Rogue sub-basin, tend to have mean temperatures near freezing and therefore receive both rain and snow; this produces a hydrograph with two peak flows, one in winter and one in late spring associated with spring snowmelt. Snow-dominant watersheds receive most of their precipitation as snowfall and thus have their peak streamflow during the late spring (Raymondi et al., 2013). As temperatures warm in the future, precipitation is more likely to fall as rain than as snow, particularly at elevations in which winter temperatures hover near freezing. This will reduce the water supply stored in mountain snowpack (Raymondi et al., 2013).

Widespread declines in April 1 SWE are projected throughout the Columbia River Basin under future climate change (Hamlet et al., 2013). Averaged over the Middle Rogue sub-basin, April 1 SWE is projected to decrease by 86% for the multi-model mean by the 2080s under the high emissions scenario compared to the historical baseline (1950-2005) (see Figure 18). The range across all models and both emissions scenarios of future changes in SWE is -41% to -83% for the 2050s and -58% to -93% for the 2080s (refer back to Table 2).

Across the Pacific Northwest, some of the highest elevation snow-dominant watersheds are likely to remain, but many are likely to trend gradually toward mixed rain-snow watersheds characteristics (see Figure 17). Mixed rain-snow watersheds are likely to trend gradually toward rain-dominant watershed characteristics including earlier spring melt, reduced spring peak flows, increased winter flows, and reduced summer flows (Raymondi et al., 2013). Averaged over the Middle Rogue sub-basin, monthly total runoff is projected to shift toward earlier spring melt, higher winter flows, and lower summer flows (see Figure 19).

Figure 17. The classification of Pacific Northwest watersheds into rain-dominant, mixed rain-snow, and snowmelt-dominant and how these watersheds are expected to changes as a result of climate warming based on a medium emissions scenario (Hamlet et al., 2013; Raymondi et al., 2013).

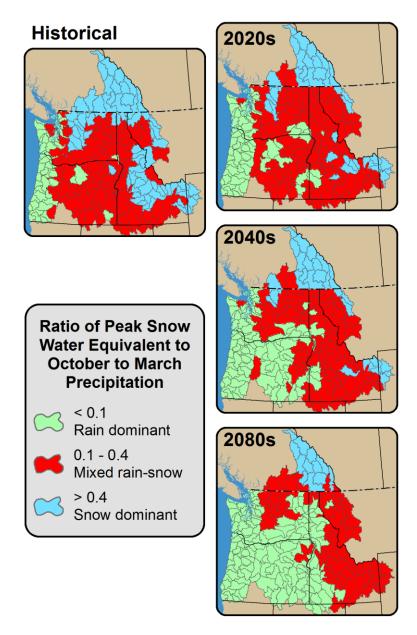


Figure 18. April 1 snow water equivalent projections averaged for the Middle Rogue (USGS17100308) as simulated by 10 downscaled global climate models under a low (RCP4.5) and high (RCP8.5) greenhouse gas emissions scenario. Solid line and shading depict the 10-model mean and range, respectively. The multi-model mean differences for the 2050s (2040-2069 average) and 2080s (2070-2099 average) compared to the historical baseline (1950-2005) are also displayed.

# April 1 Snow Water Equivalent Projections for the Middle Rogue

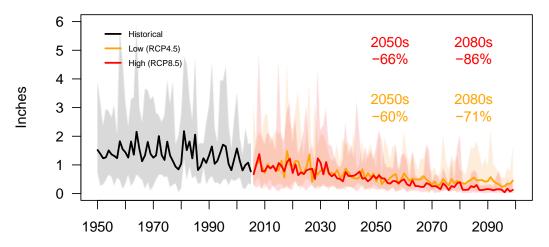
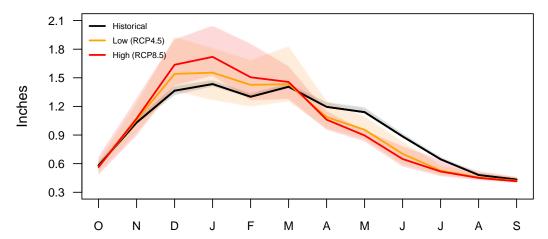


Figure 19. Monthly total runoff projections averaged over the Middle Rogue as simulated by 10 downscaled global climate models and a hydrological model for the historical period (1950-2005) and 2080s (2070-2099) under a low (RCP4.5) and high (RCP8.5) greenhouse gas emissions scenario. Solid line and shading depict the 10-model mean and range, respectively.

# Middle Rogue Monthly Total Runoff Projections 2080s & Historical

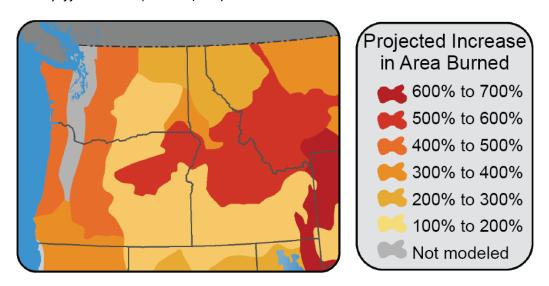


## Wildfire

Warmer and drier conditions have resulted in more frequent large fires and an increase in the total area burned across the western U.S. during the last 30 years (Dennison, Brewer, Arnold, & Moritz, 2014) and over the past century (Littell, McKenzie, Peterson, & Westerling, 2009). The length of the fire season in the western U.S. has also increased due to warmer temperatures and earlier snowmelt (Westerling et al. 2006, Jolly et al., 2015). In the ecoregion encompassing the Cascade, Sierra, and Klamath Mountain ranges, the number of large fires increased at a rate of 0.6 per year and the beginning of the fire season was 1 day earlier per year over the period 1984-2011 (Dennison et al., 2014).

Such trends are expected to continue under future climate change (Figure 20). The probability of very large wildfires is projected to increase by at least 30% by the end of the century in the western U.S. (Stavros, Abatzoglou, Larkin, McKenzie, & Steel, 2014). One study estimated that the Pacific Northwest regional area burned per year would increase by roughly 900 square miles by the 2040s (Littell et al., 2013). In the region west of the Cascades, including the Klamath Mountains, the fire return interval, or average number of years between fires, is projected to decrease by about half from about 80 years in the 20<sup>th</sup> century to about 40 years in the 21<sup>st</sup> century assuming a fire suppression management regime (Sheehan, Bachelet, & Ferschweiler, 2015).

Figure 20. Increases in area burned that would result from the regional temperature and precipitation changes associated with a 2.2°F global warming across areas that share broad climatic and vegetation characteristics. Local impacts will vary greatly within these broad areas with sensitivity of fuels to climate (Mote et al., 2014).



## **Climate Science Overview**

Climate is changing across the globe. This is evident from many different observations. Human activities that release heat-trapping greenhouse gases into the atmosphere are primarily responsible for the past half-century of global warming. Global climate will continue warming throughout the 21<sup>st</sup> century and beyond. How much the Earth's climate will warm in the future depends on the amount of global greenhouse gas emissions, and the sensitivity of the climate to those emissions (NCA, 2014). This section provides additional background on some of these key climate science concepts.

### How do we know the Earth is warming?

Multiple independent observations from weather stations, weather balloons, and satellites concur that the Earth has warmed for the last 150 years. This warming has set into motion many other well-documented changes to the Earth's climate such as melting glaciers and sea ice and increased atmospheric water vapor (see Figure 21). The coherency of changes in all these indicators supports the conclusion that warming of our planet is unequivocal (Walsh et al., 2014b).

Ten Indicators of a Warming World

Air Temperature Near Surface (Troposphere)

Water Vapor

Glaciers and Ice Sheets

Sea Surface Temperature

Sea Level

Sea Level

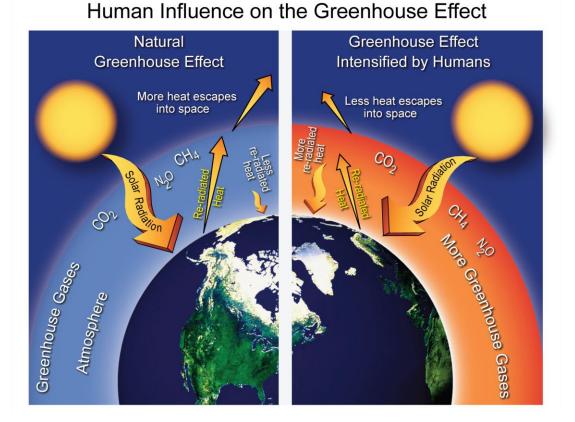
Temperature Over Land

Figure 21. Some of the many long-term global indicators that demonstrate that the Earth's climate is warming (Walsh et al., 2014b).

### What causes the Earth's climate to change?

Natural external forcings such as cyclical variations in solar output, episodic volcanic eruptions, and slow changes in the Earth's orbit all affect the Earth's climate to some degree. While natural forcings still affect climate today, the primary cause of the current warming is the accumulation of carbon dioxide and other heat-trapping greenhouse gases in the atmosphere due to human activities. According to Walsh et al. 2014a, "as the sun shines on the Earth, the Earth heats up. The Earth then re-radiates this heat back to space. Some gases, including water vapor ( $H_2O$ ), carbon dioxide ( $CO_2$ ), ozone ( $O_3$ ), methane ( $CH_4$ ), and nitrous oxide ( $N_2O$ ), absorb some of the heat given off by the Earth's surface and lower atmosphere. These heat-trapping gases then radiate energy back toward the surface, effectively trapping some of the heat inside the climate system." Human activities are artificially intensifying this natural greenhouse effect, thereby increasing the amount of heat trapped in the Earth's climate system (see Figure 22).

Figure 22. The natural greenhouse effect intensified by human influence (Walsh et al., 2014a).

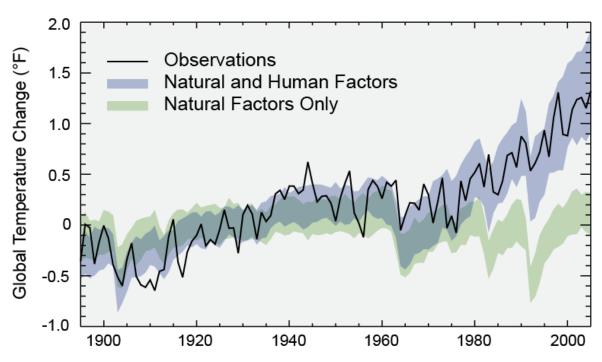


## How do we know the current warming is human-caused?

The basic physics of the atmosphere says that increasing atmospheric CO<sub>2</sub> concentrations will cause climate warming through the intensified greenhouse effect. The observed pattern of warming throughout the atmosphere is consistent with the pattern expected under the intensified greenhouse effect rather than natural changes. Furthermore, patterns of human-induced change have been identified in many other aspects of the climate system, including changes in ocean heat content, precipitation, atmospheric moisture, and Arctic sea ice. In addition, global climate modeling demonstrates that the observed 20<sup>th</sup> century warming can only be replicated when human influences are added to natural factors (see Figure 23) (Walsh et al., 2014a, 2014b).

Figure 23. The green band shows how global average temperature would have changed over the last century due to natural forces alone, as simulated by climate models. The blue band shows model simulations of the effects of human and natural forces (including solar and volcanic activity) combined. The black line shows the actual observed global average temperatures (Walsh et al., 2014b).

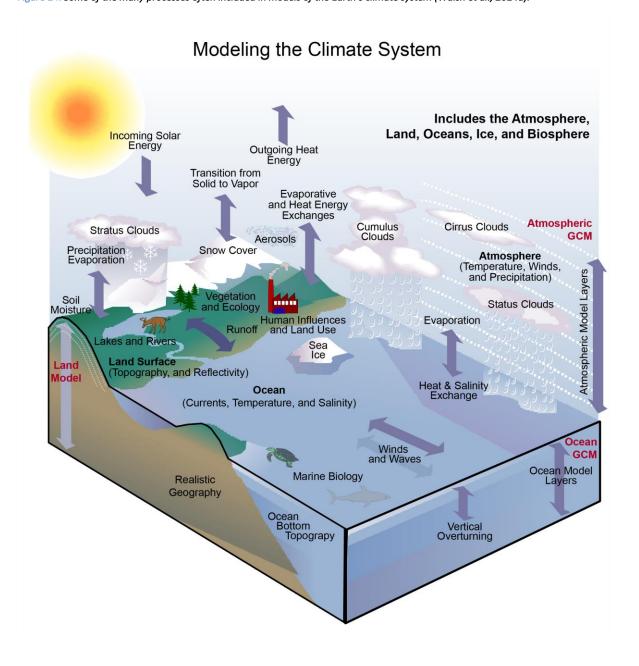
## Separating Human and Natural Influences on Climate



## How do scientists project future climate change?

Climate scientists use global climate models to make projections of how temperature, precipitation, and other climate indicators may change in the future. These models use mathematical and physical equations to represent the fundamental laws of nature and relevant climate processes (see Figure 24). They reproduce well the global features of the current climate and the significant warming trend over the last half-century. Hence, climate models are useful tools for exploring how climate may change in the future in response to increasing heat-trapping gases and other external forcings.

Figure 24. Some of the many processes often included in models of the Earth's climate system (Walsh et al., 2014a).



## Full Description of Data Sources & Analysis Methods

#### **Historic Trends**

Observed trends in annual and seasonal temperature and precipitation were analyzed from 1893 to 2014 using monthly data from the United States Historical Climate Network Version 2.5 (USHCNv2.5) downloaded from the Carbon Dioxide Information Analysis Center website for the station in Ashland (350304) located at 42.2128°N and -122.7144°E at an elevation of 532.2 meters. The USHCN is a subset of the National Weather Service Cooperative Observer Program network. While there are several weather stations in the vicinity of Ashland, the USHCN station was selected for its length of record and data completeness. In addition, the USHCN stations have been quality controlled and bias-corrected to remove non-climatic influences such as site moves, canopy changes, and instrumentation changes (Menne et al., 2009). They provide the best quality data for long-term trend analysis. Monthly data of temperature and precipitation were aggregated for winter (December, January, and February), spring (March, April, and May), summer (June, July, and August), fall (September, October, and November), and annually for the analysis. Annual and seasonal trends in maximum, mean, and minimum temperature and total precipitation were estimated over the period 1893-2014.

Observed trends in April 1 snow water equivalent (SWE) were analyzed using SNOTEL and Snow Course data collected by the Natural Resources Conservation Service. Trends were estimated over the period 1960-2014 (Mote & Sharp, 2014) for 13 stations in the Rogue Basin, mostly located within the Upper Rogue sub-basin along the western slopes of the Cascade Mountains. SNOTEL sites began recording data in the 1980s, so NRCS uses data from existing Snow Course sites to extend the record backward by using statistical relationships between co-located, overlapping SNOTEL and Snow Course data.

For temperature, precipitation, and April 1 SWE, standard least squares linear regression was used to estimate the linear trend (i.e., the slope) and calculate the 2.5%-97.5% confidence interval on the trend to determine statistical significance. A lack of statistical significance was reported if the confidence interval included a trend of zero. Because these estimated confidence intervals assume the observed deviations from the linear trend (i.e., the residuals) are normally distributed, a test to confirm normality was performed. When the residuals were not normally distributed, the Mann-Kendall test, preferred in such cases, was used to assess significance in the trend. Strong autocorrelation in a time series can lead to overly narrow confidence intervals and therefore may lead to an improper conclusion of statistical significance when performing either standard linear regression or the Mann-Kendall test. Therefore, adjustments for autocorrelation were applied when strongly present.

#### **Future Projections**

The future climate projections for Ashland are based on the latest generation of global climate models (GCMs) from the Coupled Model Intercomparison Project phase 5 (CMIP5) (Taylor et al., 2012) that were used in the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2013). CMIP5 simulations of the 21<sup>st</sup> century were driven by representative concentration pathways (RCPs) that define concentrations of greenhouse gases, aerosols, and chemically active gases leading to set amount of radiative forcing, or extra energy trapped in the earth-atmosphere system, by the year 2100 (van Vuuren et al., 2011). We consider two of the four RCPs (Figure 21): RCP4.5 ("low") representing moderate efforts to mitigate emissions, and RCP8.5 ("high") representing a business as usual scenario.

In the RCP4.5 scenario, emissions stabilize by mid-century reaching a peak of about 10 gigatonnes of carbon per year (GtC/yr) and then decline in the decades following resulting in a near stabilization of atmospheric carbon dioxide concentrations at about 500 ppm by the end of the century. The RCP8.5 scenario represents a continuance of our current path of emissions throughout the 21st century that begins to stabilize toward the

end of the century and results in atmospheric carbon dioxide concentrations greater than 900 ppm that will continue to rise beyond 2100. See Figure 25 for a graphic representation of these differences. It is important to note that RCP2.6, which attains negative greenhouse gas emissions by 2100, is the only RCP scenario to keep global temperature likely below 2°C (IPCC, 2013).

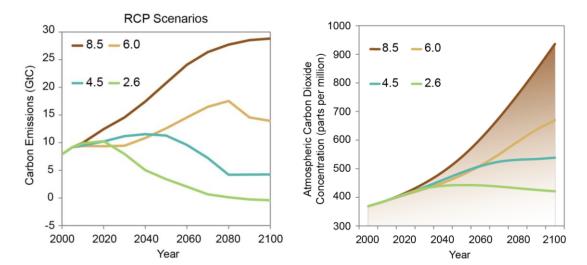


Figure 25. Carbon emissions and atmospheric carbon dioxide concentrations for RCP scenarios (Walsh et al., 2014a).

In an integrated climate-hydrology-vegetation modeling project called "Integrated Scenarios of the Future Northwest Environment," the coarse resolution (100-300 km) of the CMIP5 GCM output was downscaled over the Western United States to a resolution of about 6 km using the Multivariate Adaptive Constructed Analogs (MACA) method (Abatzoglou & 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. The downscaled climate data was then used as an input to hydrology and vegetation models.

Simulations of historical and future climate for the 6-km grid cell containing the city of Ashland were obtained at the daily time step for the maximum temperature, minimum temperature, and precipitation variables from 1950 to 2099 for 18 CMIP5 GCMs and the two available RCPs (i.e., RCP4.5 and RCP8.5). The selected temperature and precipitation metrics were derived from these variables (see Table 3).

Streamflow and snow dynamics within the Integrated Scenarios project were simulated using the Variable-Infiltration Capacity hydrological model (VIC version 4.1.2.1; (Liang, Lettenmaier, Wood, & Burges, 1994) and updates) run on a 6 km grid. Simulations of streamflow and snow water equivalent (SWE) are only available for 10 GCMs used as inputs to VIC. Future projections for routed streamflow at sites in the Rogue Basin do not yet exist, but are being generated and are anticipated to become available in fall 2016. However, projections of runoff—the amount of water at a particular location before it flows into a stream—are available. Unfortunately, vegetation data are not yet available. For SWE, the value on the first day of April was averaged over the Middle Rogue sub-basin. For streamflow, monthly sums of total daily runoff were averaged over the Middle Rogue.

For each variable except runoff, we generated an annual time series from 1950 to 2099 and computed time period averages for each model and scenario. In Table 4, we present future changes from the historical period (1950-2005 average) to the 2050s (2040-2069 average) and the 2080s (2070-2099 average) as a mean and range of the differences computed for each model for a low (RCP4.5) and a high (RCP8.5) emissions scenario. Changes in monthly hydrology of total runoff are presented for the 2080s under both emissions scenarios. Projections for the 2080s under RCP8.5 for all variables are described in the text.

#### **Uncertainty**

Inherent in GCM projections is uncertainty due to emissions scenario, internal variability, and modeling physics and resolution. Individual GCMs project different magnitudes of warming because the models' "climates" are either more or less sensitive to external radiative forcings (e.g., increasing greenhouse gases). Furthermore, the chaotic nature of the climate system means that even a single climate model, if identical simulations were started on a different day, yields a range of outcomes. In addition, even at 100-mile horizontal resolution most GCMs are still unable to resolve key topographical features that influence western US climate.

Precipitation projections are generally more uncertain than temperature projections. Temperature projections, while models may vary on the magnitude, are highly robust since all models agree on warming under increasing greenhouse gases. Modeling accurate microphysical cloud processes that produce precipitation requires resolutions much finer than current GCMs can attain so most of those processes are estimated (i.e., parameterized), resulting in inherent uncertainty in precipitation projections. There is no consensus among the GCMs on the sign of future precipitation change as some models project increases and others decreases.

## References

- Abatzoglou, J. T., & Brown, T. J. (2012). A comparison of statistical downscaling methods suited for wildfire applications. *International Journal of Climatology*, *32*(5), 772–780. http://doi.org/10.1002/joc.2312
- Abatzoglou, J. T., Rupp, D. E., & Mote, P. W. (2014). Seasonal Climate Variability and Change in the Pacific Northwest of the United States. *Journal of Climate*, *27*(5), 2125–2142. http://doi.org/10.1175/JCLI-D-13-00218.1
- Crimmins, A., J. Balbus, J.L. Gamble, C.B. Beard, J.E. Bell, D. Dodgen, R.J. Eisen, et al. 2016. "The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment." Washington, DC: U.S. Global Change Research Program. http://dx.doi.org/10.7930/J0R49NQX.
- Cutter, S. L., W. Solecki, N. Bragado, J. Carmin, M. Fragkias, M. Ruth, and T. J. Wilbanks, 2014: Ch. 11: Urban Systems, Infrastructure, and Vulnerability. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 282-296. doi:10.7930/ J0F769GR.
- Dennison, P. E., Brewer, S. C., Arnold, J. D., & Moritz, M. A. (2014). Large wildfire trends in the western United States, 1984–2011. *Geophysical Research Letters*, 41(8), 2014GL059576. http://doi.org/10.1002/2014GL059576
- Hamlet, A. F., Elsner, M. M., Mauger, G. S., Lee, S.-Y., Tohver, I., & Norheim, R. A. (2013). An Overview of the Columbia Basin Climate Change Scenarios Project: Approach, Methods, and Summary of Key Results. *Atmosphere-Ocean*, 51(4), 392–415. http://doi.org/10.1080/07055900.2013.819555
- IPCC. (2013). Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge, United Kingdom and New York, NY, USA.: Cambridge University Press.
- Liang, X., Lettenmaier, D. P., Wood, E. F., & Burges, S. J. (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, J. S., Hicke, J. A., Shafer, S. L., Capalbo, S. M., Houston, L. L., & Glick, P. (2013). Forest ecosystems: Vegetation, disturbance, and economics: Chapter 5. In M. M. Dalton, P. W. Mote, & A. K. Snover (Eds.), *Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities* (pp. 110–148). Washington, DC: Island Press. Retrieved from https://pubs.er.usgs.gov/publication/70048492
- Littell, J. S., McKenzie, D., Peterson, D. L., & Westerling, A. L. (2009). Climate and wildfire area burned in western U.S. ecoprovinces, 1916–2003. *Ecological Applications*, 19(4), 1003–1021. http://doi.org/10.1890/07-1183.1
- Menne, M. J., Williams, C. N., & Vose, R. S. (2009). The U.S. Historical Climatology Network Monthly Temperature Data, Version 2. *Bulletin of the American Meteorological Society*, *90*(7), 993–1007. http://doi.org/10.1175/2008BAMS2613.1
- Mote, P. W., & Sharp, D. (2014). 2014 update to data originally published in: Mote, P.W., A.F. Hamlet, M.P. Clark, and D.P. Lettenmaier. 2005. Declining mountain snowpack in Western North America. Bull. Am. Meteorol. Soc. 86(1):39–49.
- Mote, P. W., Snover, A. K., Capalbo, S. M., Eigenbrode, S. D., Glick, P., Littell, J. S., ... Reeder, S. (2014). Ch. 21: Northwest. In J. M. Melillo, T. (T. C. . Richmond, & G. W. Yohe (Eds.), *Climate Change Impacts in the United States: The Third National Climate Assessment* (pp. 487–513). U.S. Global Change Research Program. Retrieved from http://nca2014.globalchange.gov/report/regions/northwest

- Mote, P. W., Abatzoglou, J. T., and Kunkel, K. E. (2013). Chapter 2. Climate Variability and Change in the Past and the Future. In M. M. Dalton, P. W. Mote, and A. K. Snover (Eds.), *Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities.* pp. 25-40. Island Press, Washington, D.C.
- NCA. (2014). Climate Change Impacts in the United States: The Third National Climate Assessment. (J. M. Melillo, T. (T. C. . Richmond, & G. W. Yohe, Eds.). U.S. Global Change Research Program. Retrieved from http://nca2014.globalchange.gov
- Raymondi, R. R., Cuhaciyan, J. E., Glick, P., Capalbo, S. M., Houston, L. L., Shafer, S. L., & Grah, O. (2013). Water Resources: Implications of Changes in Temperature and Precipiptation: Chapter 3. In M. M. Dalton, P. W. Mote, & A. K. Snover (Eds.), Climate Change in the Northwest: Implications for Our Landscapes, Waters, and Communities (pp. 41–66). Washington, DC: Island Press.
- Schwartz, H. G., M. Meyer, C. J. Burbank, M. Kuby, C. Oster, J. Posey, E. J. Russo, and A. Rypinski, 2014: Ch. 5: Transportation. *Climate Change Impacts in the United States: The Third National Climate Assessment,* J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 130-149. doi:10.7930/J06Q1V53.
- 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. http://doi.org/10.1016/j.ecolmodel.2015.08.023
- Stavros, E. N., Abatzoglou, J., Larkin, N. K., McKenzie, D., & Steel, E. A. (2014). Climate and very large wildland fires in the contiguous western USA. *International Journal of Wildland Fire*, *23*(7), 899–914.
- Taylor, K. E., Stouffer, R. J., & Meehl, G. A. (2012). An Overview of CMIP5 and the Experiment Design. *Bulletin of the American Meteorological Society*, *93*(4), 485–498. http://doi.org/10.1175/BAMS-D-11-00094.1
- van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., ... Rose, S. K. (2011). The representative concentration pathways: an overview. *Climatic Change*, *109*(1-2), 5–31. http://doi.org/10.1007/s10584-011-0148-z
- Walsh, J., Wuebbles, D., Hayhoe, K., Kossin, J., Kunkel, K., Stephens, G., ... Somerville, R. (2014a). Appendix 3: Climate Science Supplement. In J. M. Melillo, T. C. Richmond, & G. W. Yohe (Eds.), Climate Change Impacts in the United States: The Third National Climate Assessment (pp. 735–789). U.S. Global Change Research Program. Retrieved from http://nca2014.globalchange.gov/report/appendices/climate-science-supplement
- Walsh, J., Wuebbles, D., Hayhoe, K., Kossin, J., Kunkel, K., Stephens, G., ... Somerville, R. (2014b). Appendix 4: Frequently Asked Questions. In J. M. Melillo, T. C. Richmond, & G. W. Yohe (Eds.), *Climate Change Impacts in the United States: The Third National Climate Assessment* (pp. 790–820). U.S. Global Change Research Program. Retrieved from http://nca2014.globalchange.gov/report/appendices/faqs