Observed and Projected Changes in Idaho's Climate

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Current climatic setting of Idaho

Idaho's climate varies substantially from the dry rangelands of southern Idaho to the temperate wet forests of the panhandle. The mid-latitude setting of Idaho and topographic patterns both upwind and within the state dictate much of the seasonal and geographic variability in climate. Mid-latitude storms from the Pacific Ocean deliver semi-frequent widespread precipitation during the cool season (November-May), while the poleward retraction of the jet stream in summer leads to generally drier conditions. Large mountain barriers both west (Cascades) and east (Rockies) of Idaho limit both the intrusion of maritime airmasses that moderate temperatures and the intrusion of cold continental airmasses that promote extreme cold air outbreaks.

Substantial geographic variability in temperature and precipitation is evident across the state. The warmest average annual temperatures are found at lower elevations, including near Lewiston (*ca.* 745 ft above sea level) and the broader Treasure Valley near Boise (Figure 1a). Locations in the Treasure Valley experience several days per year of temperatures exceeding 100˚F, with Swan Falls averaging upwards of 20 such days per year during the period 1981-2010. The length of the freeze-free season (the period between the last day in spring with sub-freezing temperatures and the first day in autumn with sub-freezing temperatures) tops more than 200 days in Lewiston. By contrast, the high-elevation mountain peaks and valleys in central Idaho are home to the state's coldest temperatures. The weather station in Stanley, Idaho is frequently the coldest reporting station in the contiguous U.S. during summer and averages nearly 300 days per year of below-freezing temperatures.

Precipitation differences are very pronounced across the state (Figure 1b). Portions of southwestern Idaho near Bruneau received an average of 7 inches of precipitation a year during 1981-2010, while the higher-elevation western slopes of the Bitterroot Range in north-central Idaho averaged more than 70 inches of precipitation a year. Nearly the entire extent of the Snake River Plain, which comprises almost all of the state's agricultural lands and a vast majority of the population, receives less than 14 inches of precipitation a year on average. Thus, much of the water used for irrigation is dependent on water that falls in mountain headwaters and is delivered downstream. Approximately three-quarters of Idaho's annual precipitation is received from November-May as a result of Pacific storms. Precipitation and cloud cover are more plentiful in the northern half of the state than in southern Idaho as moisture-laden airmasses from the Pacific pass through the Cascade Range via the Columbia River Gorge. Summers (June-August) are generally dry. However, thunderstorm activity tied with the strong surface heating and moisture pulses, including from the North American monsoon, can produce local intense precipitation in parts of the state. This is most evident in eastern Idaho, which experiences a more continental climate receiving less precipitation directly from Pacific storms in winter and relatively more precipitation in the spring and summer, with convective activity.

Much of the winter precipitation that falls as snow in Idaho's mountains is stored seasonally as snowpack. The amount of water stored in mountain snowpack (called snow water equivalent; SWE) on April 1 (Figure 1c), a date that often serves as a bellwether for seasonal water availability, averaged approximately 36 million acre-feet over the late 20th century (data from hydrologic simulations, Figure 1c). Idaho's dry, warm summers necessitate water storage to sustain water for multiple needs. Snow delays the release of mountain moisture and serves as a natural reservoir, with snowmelt in the spring and early summer providing a buffer to compensate for the seasonal mismatch in water demands (Li et al., 2017).

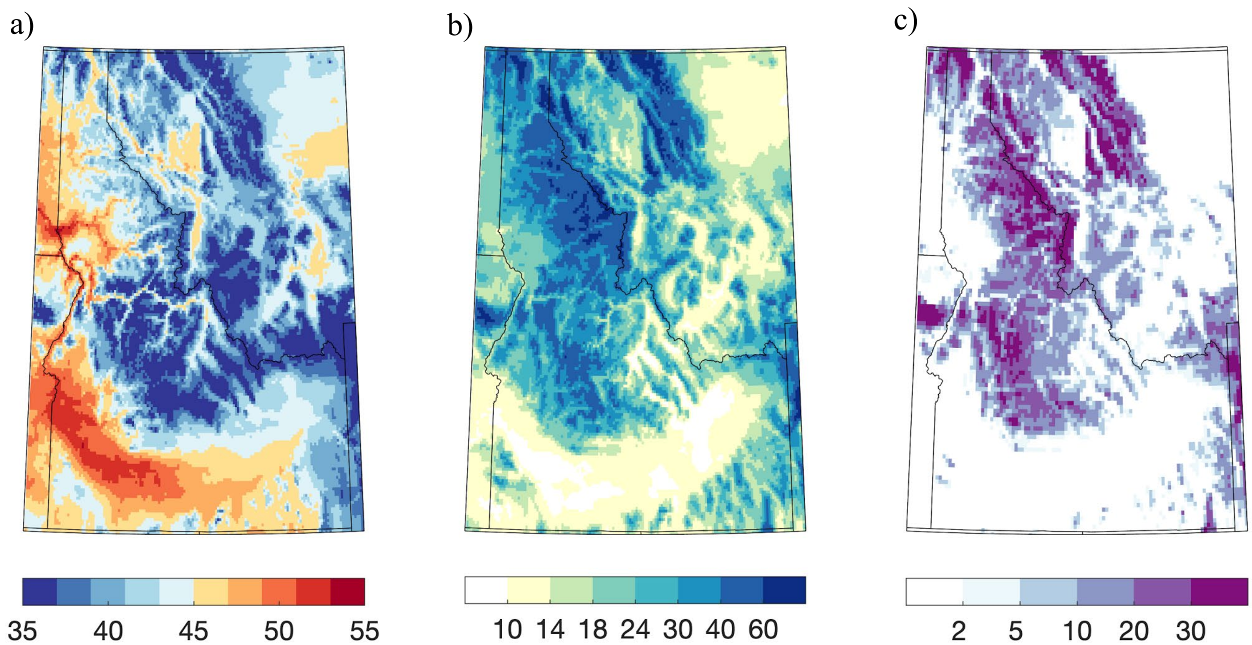


Figure 1: Maps show (a) mean annual daily temperature (degrees F), (b) annual total precipitation (inches), (c) April 1 snow water equivalent (SWE) (inches) averaged for the period 1971-2000. Data source: PRISM gridded data from Oregon State University and VIC hydrologic simulations from the University of Washington.

The diverse climate across the state shapes many of the natural resources that, in turn, shape Idaho's economic sectors and culture. Abundant water from mountain snowmelt flows into the tributaries of the Snake River and supports the vast agricultural lands that require irrigation. These same cool waters provide habitat for trophy fisheries, recreation for whitewater enthusiasts, and the region with abundant, low-carbon hydropower energy. Mountain snowpack yields opportunities for winter recreation, like skiing, snowboarding, and snowmobiling, as well as associated businesses. Idaho is shaped by the vast tracts of forests, waterways, agricultural potential, and recreational opportunities, such as hiking, fishing, hunting, and skiing.

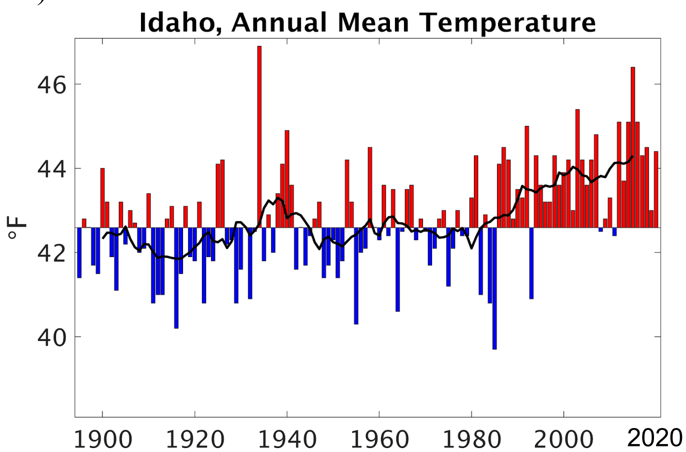
Observed changes in Idaho's climate

Global air temperatures have warmed by 1.8˚F over the past 200 years, a vast majority of which occurred during the past 50 years (Hawkins et al., 2017). Twenty of the warmest 21 years in the instrumental record from 1880 to 2020 have occurred since 2000 (NOAA, 2021). Warming is evident in documented increases in global mean sea level and declines in glacier mass balance and Arctic sea ice extent. The northwestern U.S. and western U.S. have experienced warming trends similar to those seen globally over the past 125 years (1895-2020) (Abatzoglou et al., 2014; Melillo et al., 2014; U.S. Global Change Research Program (USGCRP), 2018). From 1895 to 2020, the northwestern U.S., including Idaho, Washington, and Oregon, experienced an increase in temperature of approximately 2˚F (NOAA, 2021).

Statewide warming trends in Idaho mirror those of the northwestern U.S., featuring a long-term warming of 1.8˚F since 1895 (Figure 2a). While the warmest year in Idaho was 1934 during the Dust Bowl, 7 of the 10 warmest years during 1895-2020 have occurred since 1990, whereas only 1 of the coldest 10 years has occurred since 1990. Moreover, warming trends are evident in all seasons over the past five decades. In addition, observations show approximately a two-week lengthening in the freeze-free season for lower elevation weather stations across in Idaho during the period 1918-2010 (Klos et al., 2015).

Observed statewide precipitation in Idaho has varied, with no significant trends over the 1895-2020 period (Figure 2b; USGCRP, 2018). Rather, statewide precipitation records reflect substantial interannual to decadal variability, including the chronic Dust Bowl (1920s to early 1940s) and a persistent wet epoch (1960s to early 1980s). Records of precipitation across Idaho's mountainous regions are sparse and short in duration. However, declines in westerly wind speed at 10,000 feet in elevation during the winter months across the northwestern U.S., including Idaho, since 1950 are hypothesized to have reduced orographic uplift and mountain precipitation over the past 70 years (Luce et al., 2013). Precipitation intensity has increased across the Northwest, with a 22% increase in the amount of precipitation falling in the wettest 1% of wet days for the 1986-2016 period versus the 1901-1960 period (USGCRP, 2018). Similarly, Klos et al. (2015) showed an increase in maximum daily precipitation accumulation in spring (March-May) in Idaho from 1919 to 2011.

a)



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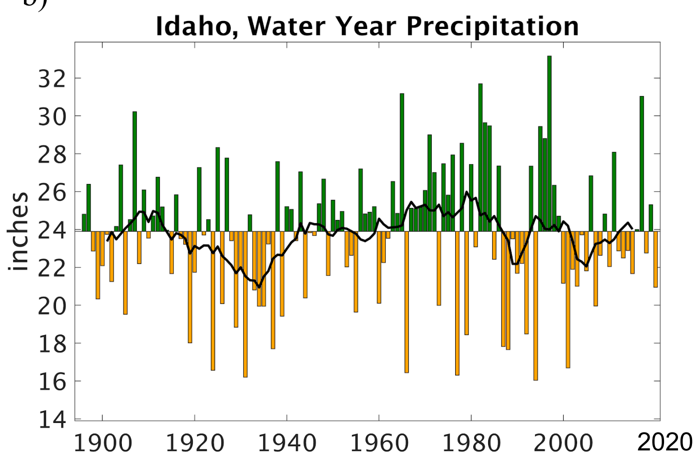
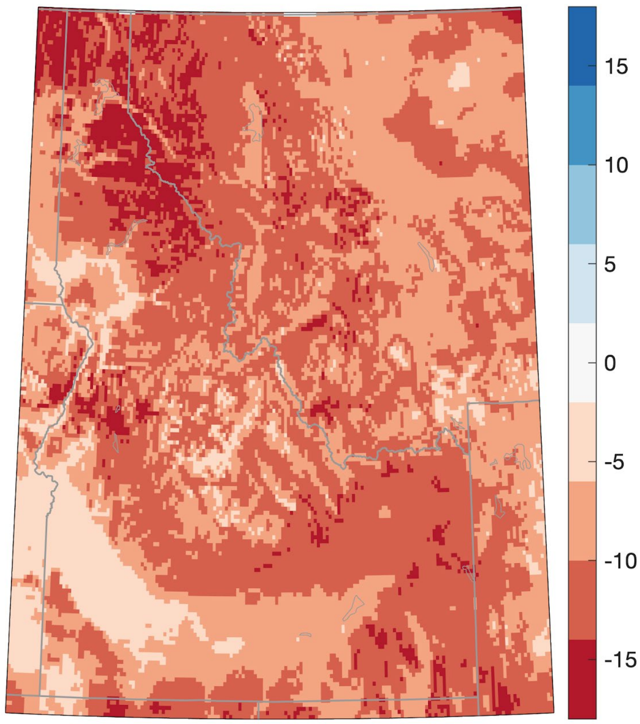


Figure 2: Multipanel time series showing (a) mean annual temperature, (b) total water year precipitation (Oct. 1-Sept. 30). The black line shows an 11-year centered moving mean. For reference, data are plotted relative to the 1901-2000 average. Data source: NOAA National Centers for Environmental Information Climate at a Glance: https://www.ncdc.noaa.gov/cag/statewide/time-series/10/

Observed warming has contributed to declines in April 1 snowpack in Idaho and the western U.S. as a whole since the 1950s, particularly in areas that lie close to the rain-snow transition (Mote et al., 2018). The elevation of the freezing level in Idaho and the broader Northwest has increased over 500 feet during November-April since 1950, commensurate with warming trends, leading to a reduction in the fraction of cool season precipitation falling as snow (e.g., Nayak et al., 2010; Abatzoglou, 2011). As a result, widespread reductions in snowfall are evident across the state, with reductions of up to 15% in snowfall in the Bitterroot Mountains during the period 1950-2020 (Figure 3; Lynn et al., 2020).

a)



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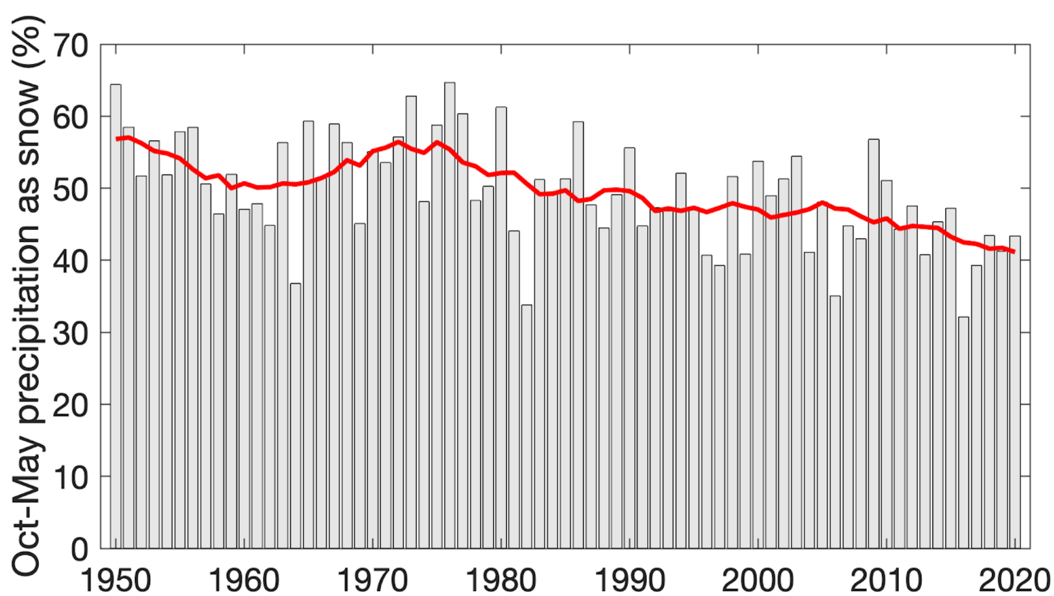

Figure 3: (a) Trends in the modeled percent of October-May precipitation falling as snow during the period 1950-2020 across the state from Lynn et al. (2020). (b) Time series of annual percent of October-May precipitation falling as snow for Idaho. Data source: Lynn et al. (2020)

Changes in streamflow in unregulated basins in Idaho, as measured by U.S. Geological Survey streamgage data, reflect four changes that are related to climate. First, observations show a reduction in total annual streamflow, particularly in the driest quarter of years since 1950 (Luce and Holden, 2009; Clark 2010; Luce et al., 2013). Second, in snowmelt-dominated regions, peak streamflow has occurred 1-2 weeks earlier in the year, tracking the reduction in spring snowpack and a greater portion of runoff occurring in the cool season since 1950 (Stewart et al., 2005; Clark, 2010; Klos et al. 2015). Third, streamgage measurements show decreases in minimum annual streamflow (Kormos et al., 2016). Finally, summer stream temperatures have warmed by an average of 1.5˚F during 1975-2015 (Isaak et al., 2018).

Conceptually, drought is defined as water demand exceeding water supply (Redmond, 2002). This definition thus yields numerous ways to monitor drought and track its impacts, given the variety of users and uses of water and different timescales that dictate imbalances in supply and demand. Drought trends in Idaho are nuanced. Although streamflow records suggest a trend toward more low flow conditions that comprise drought, observations using other measures suggest a different view of changes in drought. The most pronounced multidecadal drought characterized by chronically low cool season precipitation in Idaho's observational record occurred during the Dust Bowl period during the 1920s and 1930s (e.g., Wise 2010). In contrast, there has been a notable trend toward warmer and drier summers over the past five decades that have increased atmospheric water demand and dryness (Abatzoglou et al., 2014). Such changes have contributed to a substantial decrease in fuel moisture (Abatzoglou and Williams, 2016), contributing to escalating fire potential, as well as reduced water availability for many species that have limited post-fire tree establishment at low elevations (Stevens-Rumann et al., 2018).

Box 1: ***Why is the climate changing?***

Long-term records of climate, including those developed from ice cores, ocean records, fossil records, and pollen studies around the globe provide evidence that climate change has occurred throughout Earth's history. The processes governing changes in climate globally over the past several thousand to several hundreds of millions of years are generally well-known. Ongoing cyclical changes in Earth's orbit and axial tilt have largely been responsible for oscillations in global temperature between cold glacial periods (last one ending 18,000 years ago) and warm interglacial periods (like the last 11,700 years). These glacial-interglacial cycles have occurred nearly every 100,000 years during the last 800,000 years. What is known about orbital parameters and their effect on Earth's climate suggest that the present interglacial period is coming to an end. Indeed, long-term records show that most of the North Hemisphere has steadily cooled over the past 3000 years prior to the Industrial Revolution, starting in the late 19th century (Masson-Delmotte et al., 2013). On longer timescales of millions of years, paleoclimate data show that the planet has been substantially warmer than present-day throughout much of Earth's history, corresponding with much higher concentrations of greenhouse gases (Masson-Delmotte et al., 2013).

What is responsible for the changes in global climate that we've seen over the past century? Through the study of past climates and our understanding of the climate system today, the answer comes down to three possible factors: i) the amount of shortwave radiation received from the Sun, ii) the amount of shortwave radiation reflected back from the Earth's atmosphere and surface, and iii) the amount of longwave radiation emitted from the Earth's surface that is trapped by greenhouse gases in Earth's atmosphere.

Regarding the first possible factor, the amount of shortwave radiation that the Sun emits varies on 11-year and longer cycles and there is some evidence to suggest a slight increase in the amount of solar radiation the Earth has received over the past three centuries. However, there has not been significant change in incoming solar radiation for the past 70 years, during which the Earth's climate has changed most rapidly (Myhre et al., 2013).

As for the second possible factor, changes in the amount of cloud cover and the reflectivity of the planet's surface can also contribute to changes in global temperature. There is limited information about long-term changes in global cloud cover. However, increases in fine particles suspended in air or liquid droplets, called aerosols, have been observed since the 1950s as a byproduct of air pollution, which has the effect of cooling the planet by reducing the amount of sunlight reaching the Earth's surface (Myhre et al., 2013). Finally, competing effects with land-cover change have occurred: increased urbanization has darkened the planet, increasing the amount of solar radiation absorbed, while widespread deforestation has brightened the planet – albeit also contributing to carbon emissions.

The third possible factor is important. While water vapor is the dominant greenhouse gas in terms of trapping heat, the addition of carbon dioxide, methane, and other human-caused greenhouse gases to the atmosphere has strengthened the greenhouse effect and allows the Earth-atmosphere system to better retain heat. Globally, carbon dioxide concentrations in the atmosphere over last 800,000 years have fluctuated between 180 parts per million during glacial periods and 280 parts per million during interglacial periods. In the spring of 2021, global carbon dioxide concentrations reached 420 parts per million, 50% higher than recent 'warm' interglacial periods on Earth. These levels of atmospheric carbon dioxide are higher than levels seen in at least the last two million years of the Earth's history. The story is similar for methane, another important greenhouse gas.

The amount of shortwave radiation absorbed by the Earth and its atmosphere versus the energy radiated back to space is termed *radiative forcing*. Recent estimates suggest that collective addition of greenhouse gases and aerosols in the atmosphere has contributed to an additional 2.3 Watts per square meter (W/m^2) of energy trapped in the Earth-atmosphere system during the period 2005-2015 relative to the late 1800s (Andrews and Forester, 2020).

To better understand how natural and anthropogenic factors have contributed to observed changes in global climate, scientists use numerical models based in physics that describe the climate system. Different research groups around the world use climate models (Box 2) to examine the influence of known natural changes in solar activity and volcanic eruptions, as well as experiments that additionally include changes in aerosols, land-use, and greenhouse gases due to human activity on Earth's climate. Model experiments that consider changes in solar activity and volcanic eruptions show a small amount of warming globally from 1850 to 1950 (0.2°F), but with no change in global temperature over the most recent 70 years (Bindoff et al., 2013). By contrast, experiments that include anthropogenic increases in greenhouse gases largely capture the observed increase in global temperature (Bindoff et al., 2013). These experiments, along with other lines of scientific evidence allowed the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) to conclude that effectively all of the observed warming of global-mean surface air temperature since the late 19th century can be accounted for by human influences on the climate system (IPCC, 2021).

Understanding the causes of regional climate change is more nuanced. Regional changes in climate are influenced by changes in atmospheric circulation that occur in the absence of humans. Several modes of atmosphere-ocean variability influence temperature and precipitation patterns across much of the western U.S., including Idaho, namely the Pacific Decadal Oscillation, the El Niño-Southern Oscillation, and the Pacific North American Pattern (e.g., Redmond and Koch, 1991). Some regional attribution efforts have been undertaken to understand the fractional contribution of changes to a variety of factors. While natural factors, including modes of climate variability, solar activity, and volcanic activity, can help resolve year-to-year fluctuations in regional climate, they alone are inadequate for explaining observed warming across the northwestern U.S. (Abatzoglou et al., 2014). In contrast, regional warming trends in the northwestern U.S. are well-explained when anthropogenic factors were included (Abatzoglou et al., 2014). Barnett et al. (2008) showed that a majority of observed changes in snowpack, winter temperature, and streamflow across the western U.S. are likely influenced by human-induced changes in climate.

A longer view of Idaho's climate

One of the ways to assess long-term trends in climate, including the period before formal weather monitoring records were kept, is by using natural archives of environmental change. Tree rings are a widely used natural archive. Most trees produce a growth ring; the width of each year's ring is controlled by the temperature and precipitation conditions during that year (Fritts, 1976). The science of dendrochronology (tree ring science) allows researchers to use tree rings to view climate conditions that existed before the instrumental record (e.g., late 19th century), which facilitated recording temperature and precipitation with thermometers and rain gauges.

Idaho's large expanse of forests make the state an excellent place to use old trees to better understand past climate conditions of the region. Using tree rings as a predictor of drought, Cook et al. (1999) produced a multi-millennial length dataset of reconstructed summertime (June, July, August) Palmer Drought Severity Index (PDSI) for North America to assess the historical variability of drought conditions (Figure 4). Over the past *ca.* 1000 years, the Idaho region experienced droughts that were more prolonged and severe than those in the instrumental period. A prolonged and severe drought that occurred during the 12th century (*ca.* 1130-1200) appears to be the longest and most severe drought over the past *ca.* 1000 years and exceeds the most noteworthy droughts of the 20th century, such as the Dust Bowl of the 1920s-1940s. The 12th century drought highlights the magnitude and duration of drought potential in Idaho, the likes of which would create major problems for water resource managers should it recur in the contemporary world.

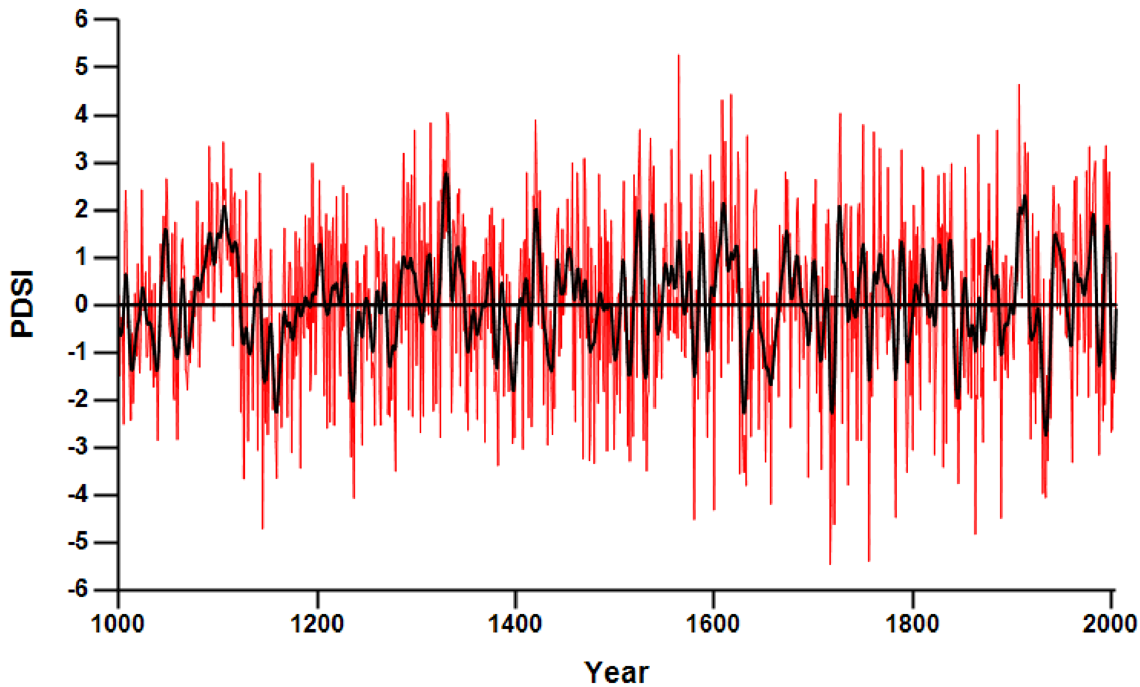

Figure 4: Tree ring-reconstructed June-August drought (Palmer Drought Severity Index; PDSI) for the Idaho region (42-49°N, 111-118°W) during the period 1000-2005. Data source: Cook et al. 1999 (figure adapted from drought.memphis.edu).

While tree rings provide important information about drought, temperature reconstructions for the Idaho region are scarce (e.g., Biondi et al., 1999). However, data from temperature-sensitive trees growing at Big Fisher Lake and Moscow Mountain were used to develop a model for reconstructing April-September maximum temperature (T_{max}) for Idaho. The regression model explains 42% of the annual variability during the period 1905-2019 (Figure 5A-B). The Idaho temperature reconstruction shows that temperature conditions recorded during the instrumental period (*ca.* 1905-2019) are unprecedented within the context of the past *ca.* 200 years (Figure 5C). Temperatures during the Dust Bowl were some of the hottest in the past 200 years, although most of the warmest summers on record have occurred since the year 2000.

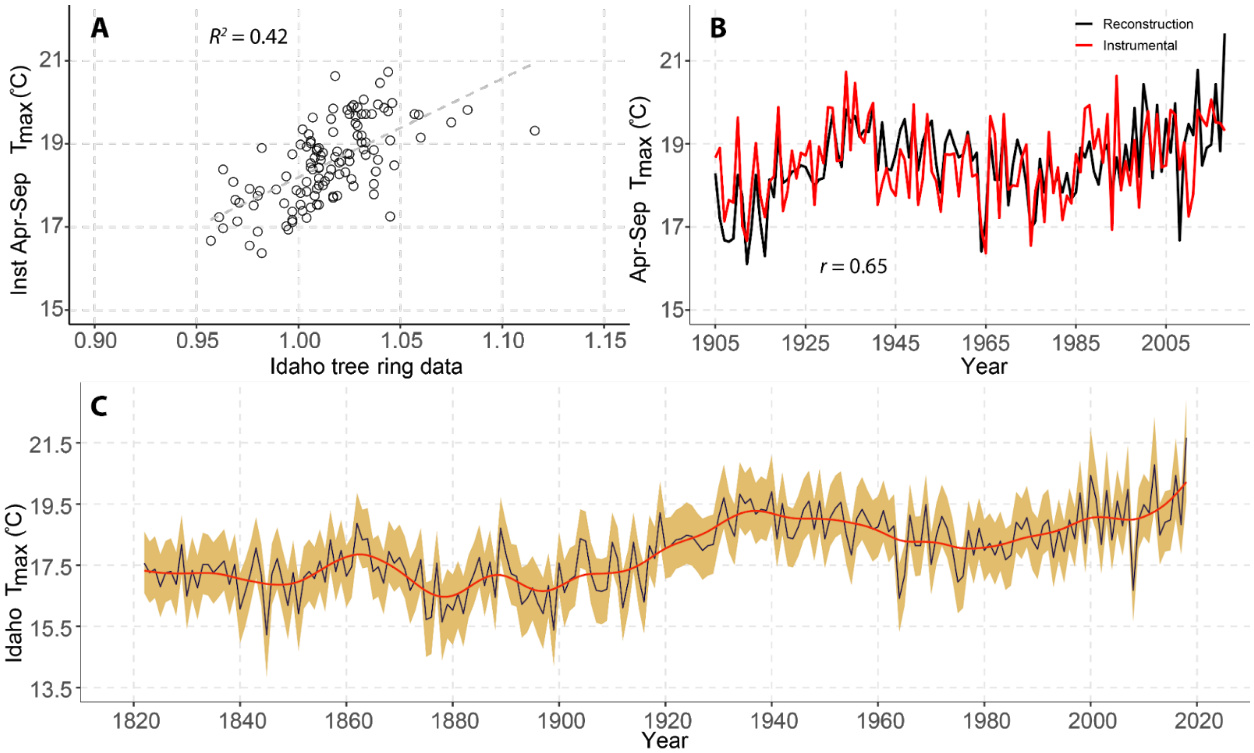

Figure 5: Tree ring-reconstructed April-September maximum temperature (T_{max}) for the Idaho region (42-49°N, 111-118°W) during the period 1822-2019.

Box 2: ***Modeling the future***

Models are physical, mathematical, or conceptual representations of a system used both to better understand how a complex system works and to provide prognostic information to help guide decisions. Models are used in many facets of day-to-day life, are continuously used in the business world, and have become increasingly integrated in our world. Perhaps the most common recognized model outputs we hear about come in the form of weather forecasts. These forecasts use observations and numerical models based on the laws of physics to resolve the evolution of weather over the next several days. Actionable information provided through weather forecasts has been valued at $20 billion dollars net value annually in the U.S. – including efforts to mitigate weather-related hazards and improve overall decision making (Katz et al., 2010).

Climate models are mathematical models that have been used by researchers for decades to better understand the climate system and how it responds to everything from El Niño events, to volcanic eruptions, to changes in greenhouse gas concentrations. Climate models are continuously improving through advances in scientific understanding about the physics and feedbacks of the climate system and increased computational capability. Despite these improvements, state-of-the-art climate models depict a very similar global temperature response to changes in human-caused emissions as some of the original climate models from a half-century ago, suggesting high consistency in our fundamental understanding of the climate system. This report primarily focuses on climate model experiments run for the 21st century that are based on different scenarios of anthropogenic greenhouse gas emissions, based on economic, social, technological, and environmental conditions (Box 3).

Climate models are developed by numerous international research groups. This allows the scientific community to evaluate the results and underlying model assumptions results across models, rather than to rely on the results of a single model. There have been several organized model comparison projects in which all modeling groups run the same experiments and share their results with the broader scientific community. These model comparisons provide an opportunity to improve knowledge on climate system processes, as well as information on future climate that informs climate impacts, adaptation, and mitigation efforts. The Fifth Coupled Model Intercomparison Project (CMIP5) brought together output from over 40 climate models and has provided a rich set of information for scientific studies, including those highlighted in the Fifth Assessment Report of the IPCC (IPCC, 2014). A new suite of modeling efforts is now being compared in Coupled Model Intercomparison Project Phase 6 (CMIP6), although the general projections for climate change globally and in Idaho are largely unchanged from the previous generations of models.

While climate models have improved, they are still unable to resolve fine spatial features and processes that characterize the climate of mountainous regions like Idaho. Additional efforts have been developed to downscale the coarse spatial output of climate models to scales more appropriate for informing state-level climate impacts. This includes statistical approaches based on observed relationships between variables (e.g., precipitation) at local scales that climate models may not directly resolve and larger-scale predictors that climate models can resolve. Several statistical downscaling approaches have been used, including the Multivariate Adaptive Constructed Analogs (MACA; Abatzoglou and Brown, 2012) method that is used in some examples within this report. A more sophisticated, but computationally intensive, approach for downscaling climate models is called dynamical downscaling. Dynamical downscaling runs higher-resolution physics-based climate models at regional scales using the coarse resolution output from climate models.

Uncertainty in the climate experiments is evaluated based on the range of model outcomes. First, most climate models are run multiple times using slightly different initial conditions (e.g., realistic, but random differences in ocean surface temperature patterns when the model commences its experiment). This bit of randomness can lead to slightly different trajectories that arise through modes of climate variability internal to the model. Likewise, the community effort of running the same experiments across different climate models provides another way to evaluate uncertainty, as some models are more sensitive to increased concentrations of greenhouse gases than others. Rather than focus on a deterministic future, which offers a single answer, these models can provide a probabilistic view of the future, which may be more useful in planning and adaptation.

Box 3: ***Future scenarios***

Projected changes in climate in the 21st century are a response to changes in greenhouse gas concentrations in the atmosphere. Increased concentrations of greenhouse gases enhance the amount of longwave radiation the Earth's atmosphere retains. Net changes in energy, termed *radiative forcing*, provide one approach for contextualizing socioeconomic pathways that are used to drive climate modeling experiments.

In this report, we adopt the Representative Concentration Pathways (RCP) convention used by the Fifth Assessment Report of the IPCC (IPCC, 2014). RCPs are meant to capture potential scenarios that may play out under a variety of changes in population, energy choices, and policies. In brief, we focus primarily on two pathways: (i) RCP4.5, which results in 4.5 W/m^2 of energy trapped (above pre-industrial levels, mid-1800s) through changes in greenhouse gases and aerosols by 2100 and (ii) RCP8.5, which results in 8.5 W/m^2 of energy trapped through changes in greenhouse gases and aerosols by 2100. For reference, an additional 2.3 W/m^2 of energy trapped has been trapped in the Earth-atmosphere system during the period 2005-2015 relative to the late 1800s (Andrews and Forster, 2020). Herein, we refer to RCP4.5 as a moderate-warming scenario and RCP8.5 as a high-warming scenario. Mid-century projections are less sensitive to choice of RCP; differences between RCP4.5 and RCP8.5 are most important for late century projections.

There are several plausible ways to achieve any of these scenarios through changes in global population, global economic development, energy sources, and mitigation efforts. Briefly, RCP8.5 is a high-warming scenario, with limited efforts to mitigate greenhouse gas emission, use of fossil fuel reserves (namely coal), and continued growth in global population. Climate models forced by RCP8.5 inputs typically show global warming 8°F or more above pre-industrial levels by 2100. Recent studies have suggested that RCP8.5 may be less likely, given that global coal use peaked in 2013 and slow divergence from continued rapid increases in emissions from the energy sector (Hausfather and Peters, 2020). However, increases in greenhouse gas concentrations may still occur through carbon cycle feedbacks (e.g., carbon uptake by global oceans, permafrost melt) that may not be adequately modeled by current climate models. By contrast, RCP4.5 requires mitigation efforts, including increased use of non-carbon-based energy sources, reduced land-use emissions, and increased carbon capture and storage efforts. Climate models forced by RCP4.5 yield global temperatures that are 4°F above pre-industrial by 2100, with limited additional warming beyond 2060.

The most recent IPCC report uses a slightly different convention for describing these scenarios. The report uses so-called Shared Socioeconomic Pathways (SSP), which prescribe different narratives to the socioeconomic trends that shape future society – and resultant emission trajectories (IPCC, 2021). Notably, SSP2 describes a trajectory of socioeconomic development following historical patterns, including the adoption of moderate mitigation efforts, yielding an emission scenario following RCP4.5. This scenario assumes limited growth in human-caused carbon dioxide emissions through 2050, with emissions falling and reaching net zero by 2100 through the adoption of carbon sequestration and other negative carbon emission technologies. By contrast, SSP5 describes rapid global economic growth driven by carbon-intensive energy sources, yielding an emission scenario following RCP8.5. This scenario assumes carbon dioxide emissions triple by the end of the 21st century. We note that scenario SSP1 (SSP1-2.6) emphasizes sustainability and decarbonization of the economy, yielding limited additional change in radiative forcing beyond current levels. This scenario assumes emissions decline immediately, investment in carbon sequestration solutions, and net-zero carbon emissions for the latter half of the 21st century. Climate models forced by this scenario limit increase in global mean temperature to not less than 2°C (3.8°F) above pre-industrial levels.

Idaho's future climate

Temperature and precipitation

Climate projections from climate models participating in CMIP5 show continued and substantial warming through the 21st century. The magnitude of change in climate through 2050 is largely independent of climate action due to committed warming and inertia in the climate system. In contrast, the trajectories of change for the latter half of the 21st century are strongly influenced by the choice of current emission trajectories (see Box 3). Projected changes in temperature in Idaho largely mirror projected changes for the northwestern U.S. (Rupp et al., 2017; USGCRP, 2018). The annual mean temperature averaged for Idaho is projected to warm 11˚F on average above 1950-1999 values by 2100 under a high-warming scenario (RCP8.5), compared with a warming of 6˚F on average under a moderate-warming scenario (RCP4.5) (Figure 6a). Climate models have also been run using aggressive climate mitigation pathways (RCP2.6), with rapid reductions in emissions and implementation of negative carbon dioxide emission technologies that yield low-warming scenarios. We do not examine these projections here, but note that they tend to show slightly less warming by mid-century compared with a moderate-warming scenario, with nominal additional warming after mid-century. Individual models show varying rates of warming, but all models show faster rates of warming over the 21st century than in the 20th century.

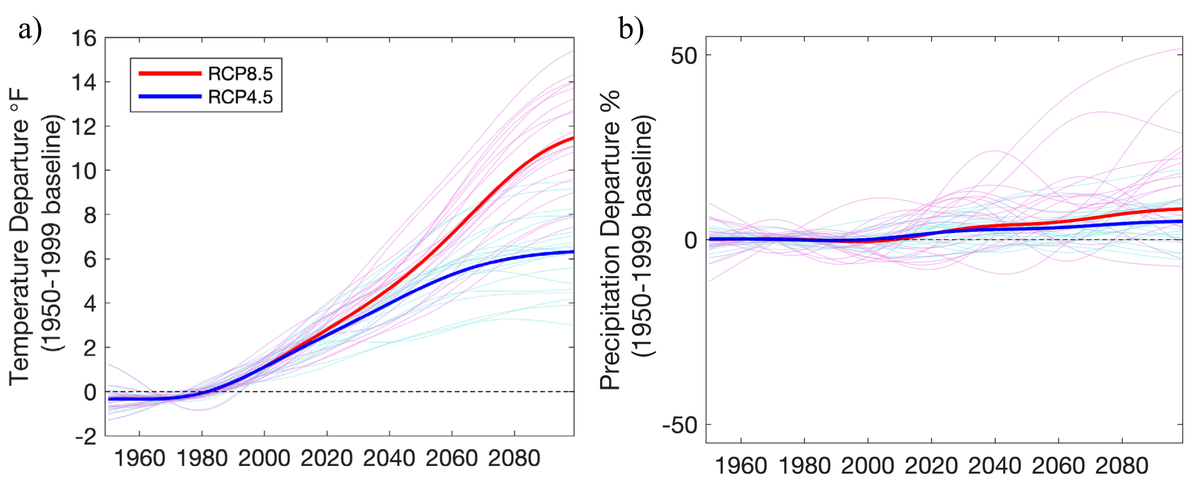

Figure 6: Smoothed traces of (a) annual mean annual temperature anomalies and (b) annual total precipitation departures for the Idaho region averaged over 42-49°N, 110-117°W relative to 1950-1999 averages for two future climate scenarios: moderate-warming scenario (RCP4.5, blue) and high-warming scenario (RCP8.5, red). Individual light traces show results for 20 CMIP5 models, while the thick line (blue and red) shows the CMIP5 multi-model ensemble mean. Data are smoothed using a 50-year low-pass filter to highlight long-term changes. Data source: Direct output from 20 climate models participating in CMIP5.

Accompanying changes in mean annual temperature are changes in seasonal temperatures that have a direct bearing on water resources, agriculture, and human health. The length of the freeze-free season is projected to increase substantially across Idaho (Figure 7a-b). For example, in Nampa, the length of the freeze-free season extends from around 160 days for the late 20th century to 210 days by the mid-21st century under a high-warming scenario. Climate projections also show more acute warming of the coldest temperatures of the year, which limit the severity of extreme cold (Parker and Abatzoglou, 2016), due to the amplified warming of continental Arctic air masses that are host regions for Idaho's cold air outbreaks.

Warming is projected throughout the year, with slightly greater warming in the summer months (Rupp et al., 2016). In addition, summer precipitation and cloud cover are projected to decrease slightly. Despite small decreases in relative humidity, increased temperatures and increased overall atmospheric moisture are projected to dramatically increase the occurrence of days with elevated heat index values across Idaho. The heat index – which incorporates a combination of air temperature and relative humidity – is used by the National Weather Service and health information services across the country to assess heat-related impacts. While Idaho has rarely seen heat indices exceeding 100˚F despite daytime highs topping the century mark, the Snake River Valley could see more frequent days where the heat index exceeds 100˚F by the mid-21st century (Dahl et al., 2019). For example, Boise has seen an average of less than 1 day per year with heat indices over 100˚F during the late 20th century (1971-2000). Model projections suggest the region could see upwards of two weeks of such conditions by the mid-21st century under a high-warming scenario (Figure 7c-d).

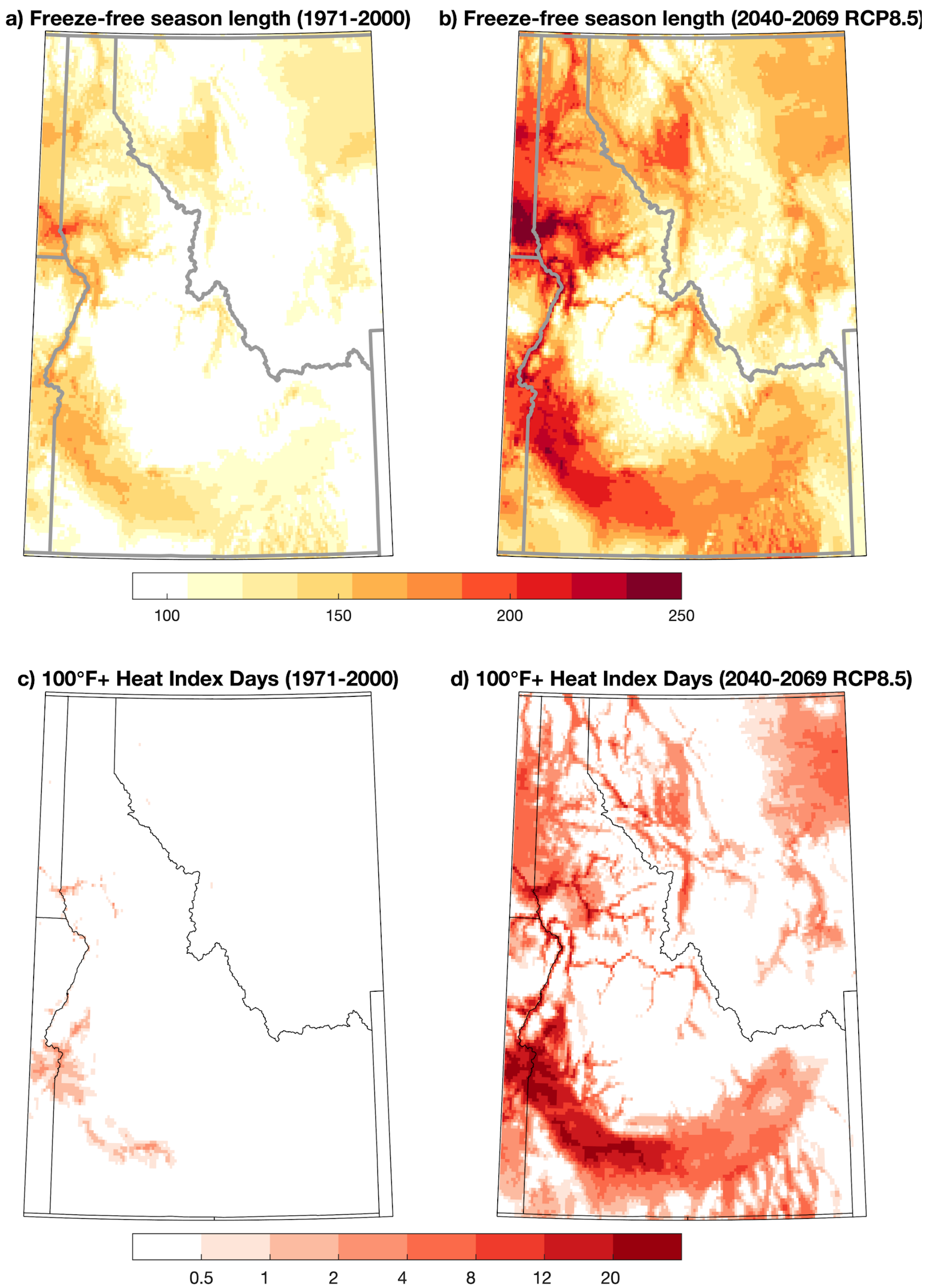

Figure 7: Maps of (a, b) length of the freeze-free season in days and (c, d) number of days with heat index above 100°F for the (a, c) late 20th century and (b, d) mid-21st century under a high-warming scenario (RCP8.5). Data source: MACAv2-gridMET downscaled data.

Projected changes include a slight increase (5-10%) in total annual precipitation by 2100, but there is substantial variability among the climate model projections (Figure 6b). Note that this increase in precipitation is far less than historical interdecadal variability (Figure 2b). This is in contrast to projected changes in temperature that greatly outpace historical interdecadal variability. The projected increase in mean annual precipitation is dominated by increases in winter and spring precipitation, whereas precipitation in summer is projected to slightly decline (Rupp et al., 2017; USGCRP, 2018).

While climate models simulate overall increases in mean annual precipitation across the state, the output from dynamically downscaled climate model output provides additional nuance that may further inform downstream impacts. Climate models suggest a slight decrease in westerly flow near mountain top level across the northwestern U.S. that would weaken upslope flow and orographic precipitation leading to reduced mountain precipitation (and weaker rainshadow-effect) in the cool season across the region (Luce et al., 2013). Similarly, studies have pointed to increases in cool season atmospheric stability that would reduce mountain precipitation relative to lower elevations (Shi and Durran, 2014; Rupp et al., 2017; Grose et al., 2019). As nearly all runoff in Idaho originates from mountain precipitation, mountain precipitation is critically important for many water-dependent sectors of the state.

In addition to changes in cumulative precipitation, models suggest changes in the character of precipitation. Climate models generally project increases in extreme precipitation magnitudes in mid-latitudes, with short-duration precipitation magnitudes increasing approximately 7% for every degree Celsius increase in temperature, substantially more than changes in average precipitation (O'Gorman et al., 2016; Prein et al, 2017). Likewise, the frequency of extremely heavy hourly precipitation during December-February is projected to increase 3-5 fold across Idaho by the end of the 21st century using a high-warming scenario (Prein et al., 2017). Compensatory changes in the frequency of precipitation are also projected for the region, with a few additional days per year without notable precipitation (Polade et al., 2015).

Snowpack

Despite uncertain projected changes in the total amount of precipitation, warming results in decreased snowpack as precipitation falls more as rain and less as snow (Peacock et al., 2011; Ashfaq et al., 2013; Mankin et al., 2015; Fyfe et al., 2017). April 1 volumetric snowpack storage across Idaho is projected to decrease by one-third by the mid-21st century under a high-warming scenario relative to the late 20th century (Gergel et al., 2017) – equivalent to the current potential reservoir storage in Idaho (Figure 8). Substantial reductions in the land area that is snow-dominated (i.e., areas where most precipitation falls as snow in the winter) are anticipated with warming (Klos et al., 2014). In addition, multiple consecutive years of snow drought—years with very low snow or snow that melts very early—are projected to become much more common, particularly in the northern part of the state (Marshall et al., 2019). Across parts of Idaho that averaged of 4 inches or more of annual maximum SWE during the late 20th century, multi-year snow droughts occurred in approximately 7% of these years; multi-year snow droughts are projected to occur 45% of the time by the period 2050-2079 in a high-warming scenario (Marshall et al., 2019).

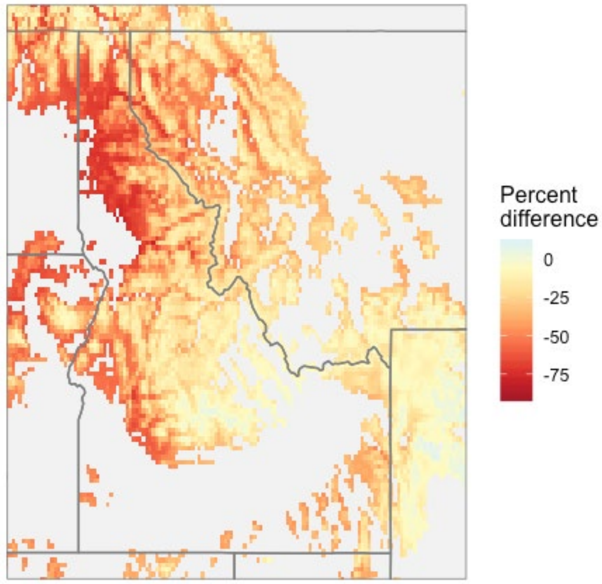

Figure 8. Percent difference in annual maximum snow water equivalent (SWE) from the historic (1970-1999) to future (RCP8.5, 2050-2079) case. Data source: Hydrologic simulations from the VIC model forced by downscaled climate projections from 10 different climate models – MACAv2-Livneh.

In addition to a reduction in total snowpack, several other projected changes to snow accumulation and melt dynamics affect snow-dependent social and ecological systems. A larger fraction of the annual snowpack is projected to come from large storm events (Lute et al., 2015) and snowmelt is projected to occur earlier in the year (Musselman et al., 2017; Marshall et al., 2019). In northern Idaho, rain-on-snow (ROS) events are projected to become less common due to the shorter duration of the snow season, while in the higher elevation regions of southern Idaho where snowpack is expected to persist, ROS events are projected to become more common as a consequence of increased spring rain with warming temperatures (Musselman et al., 2018). Despite more ambiguous changes in snowmelt contributions to flooding, hydrologic simulations suggest increases in annual maximum flows across the region as a result of increased rainfall magnitudes (Chegwidden et al., 2020; Queen et al., 2021). Finally, earlier snowmelt runoff (Parida and Buermann, 2014; Harpold and Molotch, 2015) and increased evapotranspiration in spring and early summer lead to decreased streamflow and heightened stress for water resources (e.g., Hamlet et al., 2010; Xin and Sridhar, 2012; Vano et al., 2015).

Drought

The likelihood, duration, magnitude, and character of drought are also likely to change across the state in the coming decades. As mentioned previously, definitions of drought can vary depending on impacts, but generally refer to water demands exceeding available supplies (Redmond, 2002).

The earlier timing of snowmelt and subsequent earlier drawdown of soil moisture result in decreased soil moisture and increased climatic water deficit (potential evapotranspiration minus actual evapotranspiration). Increased moisture deficits during summer are also expected to increase drought stress and associated disturbances in Idaho forests. For example, fuel moisture – a measure of the water content in vegetation – in Idaho forests is projected to decline substantially by the mid-21st century (Gergel et al., 2017), contributing to the escalating potential for large fires across the region (e.g., Barbero et al., 2015). Paradoxically, increased winter rainfall (rather than snow) in lower elevations of Idaho during periods of low water demand and unfrozen soil allows water to percolate to deeper soil moisture pools, leading to increased soil moisture in winter and spring for deeper soils while surface soil moisture declines (Berg et al., 2017). Meanwhile, increased temperature and evaporative demand increase water demand for irrigated agricultural systems in Idaho.

Warming, associated increased evaporative demand (i.e., evapotranspiration without surface water limitations), and reduced mountain snowpack all favor a future of increased summer drought, particularly in mountainous parts of the state where snowmelt is projected to occur earlier in the year. At larger scales, drought, as quantified through summer soil moisture and related metrics, is projected to increase substantially across much of the western U.S., including Idaho (Cook et al., 2015). However, drought, as viewed through the lens of solely precipitation accumulation, may not exhibit substantial changes, given the weak tendency for increased precipitation. Some studies have suggested that changes in climate will increase the likelihood of multidecadal drought across the west through the 21st century (Ault et al., 2016). The combination of warmer temperatures and changes in seasonal precipitation, superposed with naturally occurring megadrought conditions similar to those seen in the 12th century, would substantially impact water resources in Idaho (Overpeck and Udall, 2010).

An example of changing drought occurrence based on four different indicators averaged over the Upper Snake River Basin is shown in Figure 9. Drought conditions are nominally defined statistically as conditions that occur for 20% of years historically. Model projections for the period 2021-2050 indicate an uptick in drought occurrence based on low summer runoff, low summer soil moisture, and low spring snowpack. For example, models project that low April 1 snowpack that occurred one out of every five years in the late 20th century is projected to occur, on average, in one of every three years during the period 2021-2050. On the other hand, the frequency of low precipitation years is not projected to change significantly.

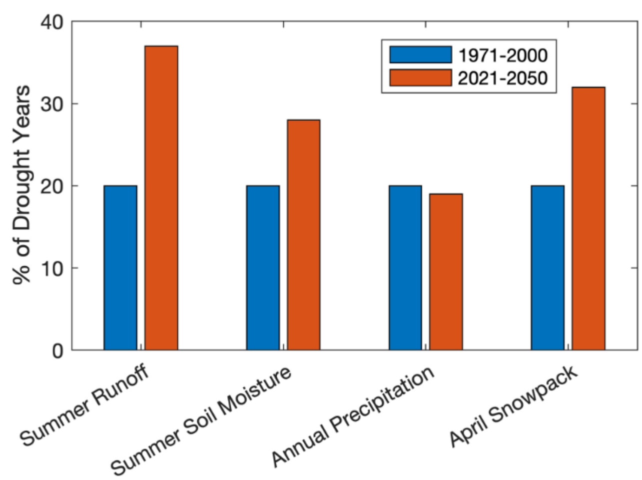

Figure 9: Modeled percent of years in drought for the period 1971-2000 (blue) and 2021-2050 (orange, scenario RCP4.5) in the Upper Snake River Basin averaged from 10 downscaled climate models. Drought conditions were defined as occurring for 20% of the driest years (e.g., driest 20% of years for summer runoff) for the period 1971-2000. Data source: MACAv2-gridMET and MACAv2-Livneh simulations.

Conclusion

Projected changes to Idaho's climate suggest very high confidence in warming trends, limited changes in total annual precipitation albeit a significant reduction in the proportion of precipitation falling as snow, and high potential for increased frequency of certain types of droughts. The magnitude of future changes is a function of global greenhouse gas emissions and sequestration pathways, with global pathways in conjoined climate and energy policies having measurable impact on changes in climate over the latter half of the 21st century. Natural climate variability, such as the El Niño-Southern Oscillation, is projected to continue to exert influence on Idaho's climate through the 21st century. The fusion of natural climate variability with shifting baselines imposed by climate change is likely to yield significant changes in certain climate and meteorological extremes. These changes pose serious challenges for the state's economic and cultural dependence on snow, water resources, forests, agriculture, and outdoor recreation.

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