Northern California Climate Adaptation Project:

Overview of Climate Trends and Projections

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Further information on the Northern California Climate Adaptation Project is available on the project website (https://tinyurl.com/NorCalAdaptation).

Introduction

This document provides an overview of historical climate trends and future projections for the Northern California Climate Adaptation Project study area. These trends and projections provided the foundation for ranking the climate exposure component of the vulnerability assessment, together with additional literature that provided habitat- and species-specific information related to exposure.

Most climate projections for this project are based on data from the Basin Characterization Model (BCM), which simulates projected changes in hydrologic conditions by using input precipitation and temperature data to model factors that impact landscape-scale water balance, including snowpack, climatic water deficit, groundwater recharge, and surface runoff (Flint et al. 2013; Flint & Flint 2014). We used the BCM to examine changes in precipitation, temperature, climatic water deficit (CWD), and snowpack for each Jepson ecoregion overlapping a portion of the study area (see Figure 1), comparing historical (1951–1980) to late-century (2070–2099) time periods under six different global climate models and three emissions scenarios that span a range of temperature and precipitation possibilities (GFDL-B1, PCM-A2, CCSM4-RCP8.5, GFDL-A2, CNRM-RCP8.5, MIROC-RCP8.5). Projections for other factors within this overview (e.g., water temperature, drought, wildfire) are based on a review of relevant studies in the scientific literature.

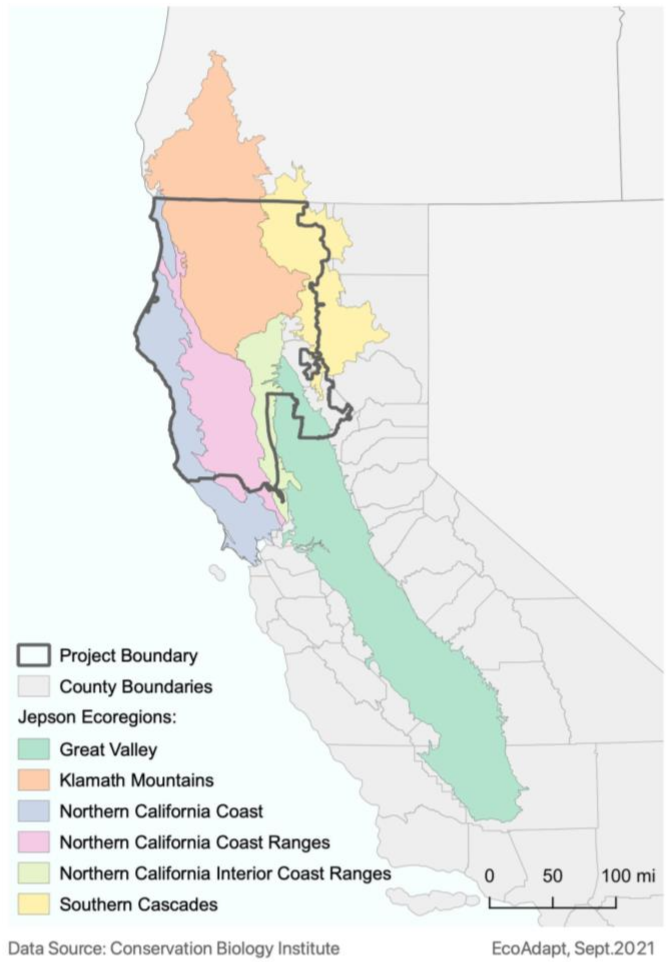

Figure 1. Study area geography and overlapping ecoregions for the Northern California Climate Adaptation Project.

The following table summarizes the trend direction and projected future changes of important climate and climate-driven factors, which are discussed in greater detail in the remaining sections of this report (Table 1).

Table 1. Summary of trend direction and projected future changes for climate and climate-driven factors, extreme events, and major natural disturbance regimes within the Northern California Climate Adaptation Project study area.

Variable	Trend	Projected Future Changes
Climate and climate-driven factors		
Air temperature	↑	• 2.2–6.1°C (4.0–11.0°F) increase in annual mean temperature by 2100
Water temperature	↑	• 0.4–0.8°C (0.8–1.4°F) increase in August stream temperature by the 2080s
Precipitation	↑↓	• -23% to +38% change in mean annual precipitation by 2100 • Shorter, wetter winters and longer, drier summers likely, with higher interannual variability
CWD & Soil moisture	↑ ↓	• 4–43% increase in mean annual climatic water deficit (CWD) by 2100 • Reduced soil moisture due to enhanced evapotranspiration
Snowpack & Snowmelt	↓ ←	• 61–100% decrease in April 1 snow water equivalent (SWE) by 2100 • 5–15-day shift towards earlier timing of snowmelt by 2100
Streamflow	↑↓	• General increase in wet season flows and decrease in dry season flows, with overall increase in flow variability • 30–40% decline in the lowest streamflow per decade by 2100
Coastal fog	↓	• Weak decline in the frequency of days with coastal fog and low clouds
Sea level rise	↑	• High likelihood of 0.03–1.24 m (0.1–4.1 ft) sea level rise by 2100
Extreme events and natural disturbance regimes		
Heat waves	↑	• Significant increase in heat wave frequency and intensity, especially for humid nighttime events and in coastal areas
Storms & Flooding	↑	• Increased storm intensity and duration, resulting in more frequent/intense extreme precipitation events and flooding • 300–400% increase in the frequency of 200-year floods
Drought	↑	• Drought years twice as likely to occur, with significantly increased risk of prolonged and/or severe drought
Wildfire	↑	• 77% increase in mean annual area burned statewide, and up to 400% increase in montane forested areas of northern California • 50% increase in the frequency of extremely large fires (>10k ha) • Significant increases in fire severity are likely due to more extreme fire behavior combined with human activity and fuel buildup

Trends and Projections for Climate and Climate-Driven Factors

Air Temperature

Annual, minimum, and maximum temperatures have increased state-wide over the past century (LaDochy et al. 2007; Cordero et al. 2011; Pierce et al. 2018), with accelerated rates of warming since the 1970s (Cordero et al. 2011). Minimum temperatures (representing nighttime lows) have warmed faster than mean and maximum temperatures in most regions, including northern California (LaDochy et al. 2007; Cordero et al. 2011; Pierce et al. 2018). However, mean annual temperatures have increased less in northern California (+0.6°C [1.0°F]) compared to the state-wide average (+0.8°C [1.5°F]; Grantham 2018; Pierce et al. 2018), and maximum temperatures in the region have exhibited very slight decreases (Rapacciuolo et al. 2014). Within the study area, increases in annual and minimum temperatures over the past century have been greatest in the Great Valley ecoregion; decreases in maximum temperatures are also greatest in this ecoregion (Rapacciuolo et al. 2014).

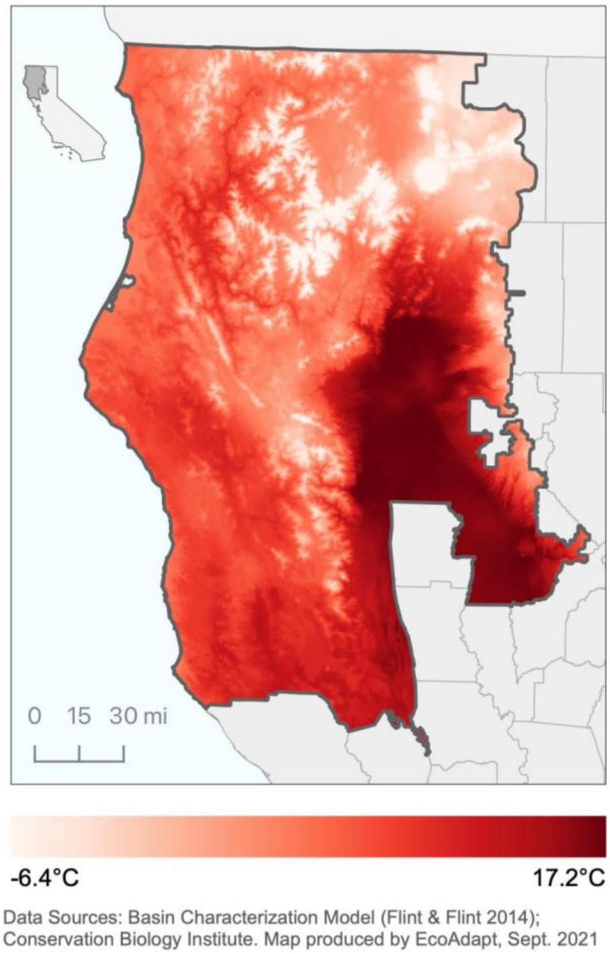

Figure 2. Annual mean temperature in degrees Celsius (°C) for the Northern California Climate Adaptation Project study area between 1951 and 1980.

By the end of the century (2070–2099), annual mean temperatures within the Northern California study area are projected to rise by 2.2–6.1°C (4.0–11.0°F) compared to historical temperatures (1951–1980; Figure 2 and Figure 3), with slightly greater warming projected in summer maximum temperatures (2.0–6.8°C [3.6–12.2°F]) compared to winter minimums (1.9–5.8°C [3.4–10.4°F]; Flint et al. 2013; Flint & Flint 2014; Table 2). Because oceans warm more slowly than land, interior zones are generally projected to experience greater temperature increases than coastal areas ventilated by ocean breezes (Pierce et al. 2018). Other factors associated with landscape-scale temperature variability include elevation and urbanization (LaDochy et al. 2007).

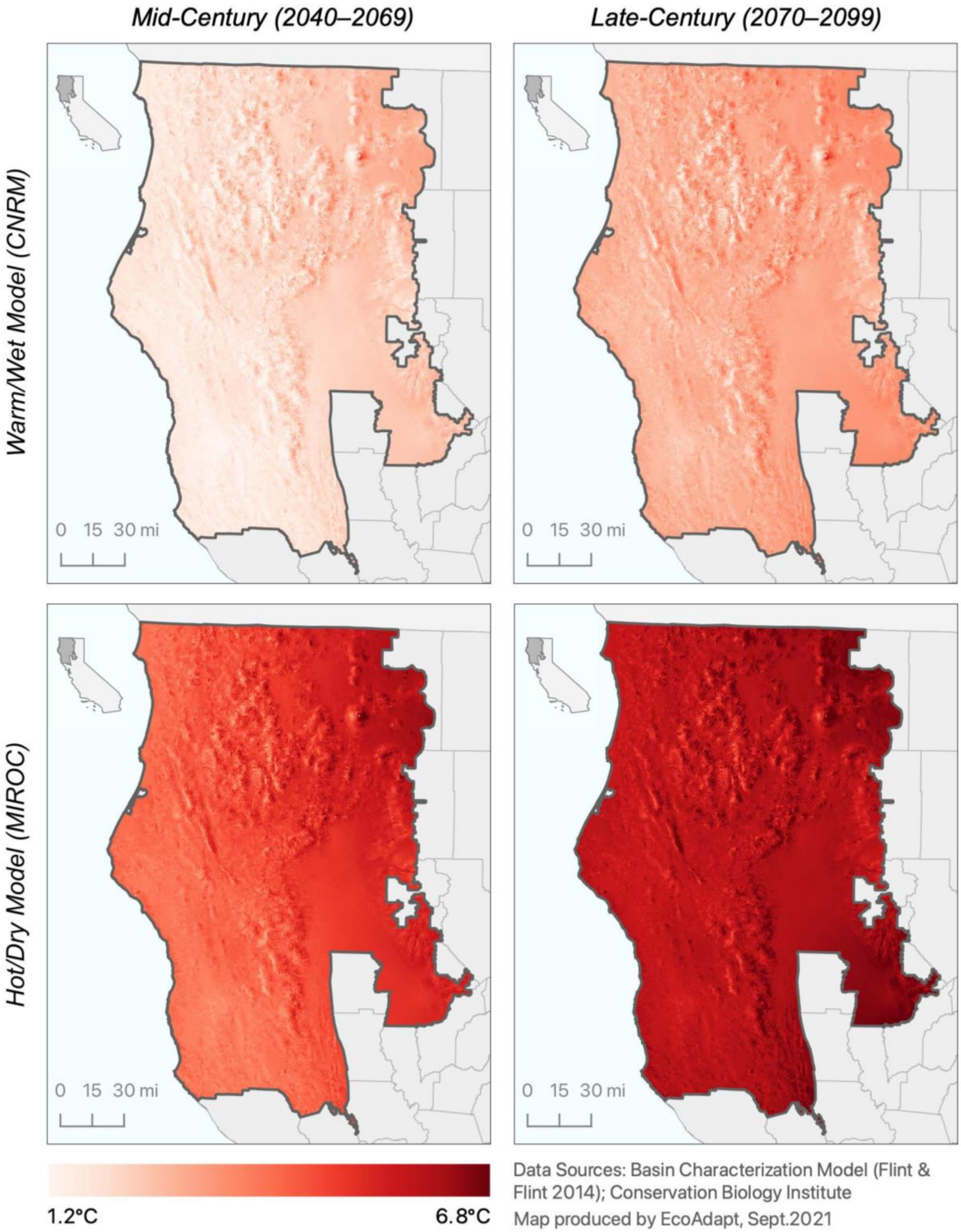

Figure 3. Change in annual mean temperature (°C) in the Northern California Climate Adaptation Project study area, representing the difference between historical average (1951–1980) and projected values for mid-century (2040–2069) and late-century (2070–2099) time frames under two different climate scenarios: CNRM-RCP8.5 (warm/wet future scenario) and MIROC-RCP8.5 (hot/dry future scenario).

Table 2. Projected change in average annual, winter minimum, and summer maximum temperature increases for 2070–2099 compared to 1951–1980 in ecoregions that overlap the Northern California Climate Adaptation Project study area (Flint et al. 2013; Flint & Flint 2014).

Ecoregion		Annual	Winter Minimum	Summer Maximum
North Coast	*Historical*	13.1°C (55.5°F)	3.4°C (38.2°F)	25.6°C (78.2°F)
	Projected	+2.2–5.2°C (+3.9–9.4°F)	+1.9–4.5°C (+3.5–8.1°F)	+2.3–6.1°C (+4.1–11.0°F)
Northern Coast Range	*Historical*	12.8˚C (55.1°F)	1.1˚C (34.0°F)	29.1˚C (84.4°F)
	Projected	+2.2–5.2°C (+4.0–9.4°F)	+2.1–4.2°C (+3.7–8.3°F)	+2.2–5.9°C (+4.0–10.7°F)
Northern Interior Coast Range	*Historical*	16.0°C (60.7°F)	2.7°C (36.8°F)	33.6°C (92.6°F)
	Projected	+2.2–5.4°C (+4.0–9.8°F)	+2.2–4.7°C (+3.9–8.5°F)	+2.3–6.3°C (+4.2–11.4°F)
Klamath Mountains	*Historical*	10.7°C (51.3°F)	-1.0°C (30.1°F)	27.6°C (81.6°F)
	Projected	+2.2–5.2°C (+4.2–9.4°F)	+2.0–4.8°C (+3.6–8.6°F)	+2.8–6.1°C (+5.1–11.1°F)
Southern Cascades	*Historical*	8.3°C (46.9°F)	-4.7°C (23.5°F)	26.1°C (79.0°F)
	Projected	+2.3–5.5°C (+4.1–9.9°F)	+2.0–5.8°C (+3.5–10.5°F)	+3.1–6.7°C (+5.6–12.1°F)
Great Valley	*Historical*	16.6°C (62.0°F)	3.2°C (37.7°F)	34.3°C (93.7°F)
	Projected	+2.5–6.1°C (+4.4–10.9°F)	+2.5–4.9°C (+4.4–8.7°F)	+2.0–6.8°C (3.6–12.3°F)

High confidence in direction of projected trends, moderate confidence in magnitude.

Water Temperature

August stream temperatures in northwestern California (not including the Great Valley ecoregion) increased by roughly 0.1°C (0.2°F) per decade from 1976 to 2015, which corresponded to a 0.4°C (0.7°F) increase in air temperature and 5.3% decrease in stream discharge per decade (Isaak et al. 2017). However, an older study of the Klamath River Basin suggests annual stream temperature increases in the basin could have been as high as 0.5°C [0.9°F] per decade between 1962 and 2001 (Bartholow 2005).

By the 2080s, August stream temperatures in northwestern California are projected to increase 0.4–0.8°C (0.8–1.4°F), corresponding to modeled increases in air temperature of 3.6°C (6.4°F) and a 1.2% decrease in stream discharge (Isaak et al. 2017). These changes reflect a relatively linear trend of a 0.3°C (0.5°F) increase in August stream temperature per 1°C (1.8°F) increase in air temperature, though coldwater streams at high elevations warm at a slower rate compared to those at lower elevations (Isaak et al. 2017). For the Sacramento River, annual water temperatures are projected to increase by 13°C (1.8–5.4°F) by 2100 (Cloern et al. 2011).

High confidence in direction of projected trends, moderate confidence in magnitude.

Precipitation

Mean annual precipitation increased by 263–942 mm (1.0–3.7 in) in northern California between 1900–1939 and 1970–2009 time periods, with the greatest increases occurring in the Cascade Ranges and the least change in the Great Valley (Rapacciuolo et al. 2014). Significant decreases in September precipitation have also been observed across the northern California region between 1953 and 2012 (Asarian & Walker 2016).

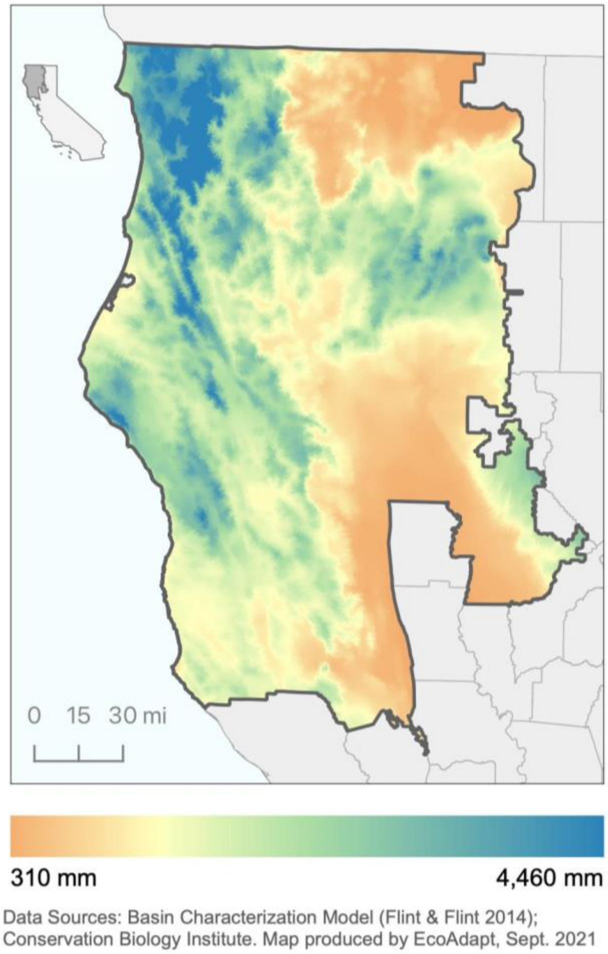

Figure 4. Annual mean precipitation in millimeters (mm) for the Northern California Climate Adaptation Project study area between 1951 and 1980.

Precipitation in California is highly variable on seasonal, annual, decadal, and multidecadal scales, which contributes to a wide range of projections that disagree on both the direction and magnitude of change. By the end of the century (2070–2099), mean annual precipitation within the Northern California study area is projected to change by -23% to +38% compared to historical precipitation (1951–1980; Flint et al. 2013; Flint & Flint 2014; Figure 4 and Figure 5; Table 3). Regardless of whether annual precipitation increases or decreases, it is highly likely that a larger proportion of annual rainfall will occur during a shorter and more intense wet season, with later onset of fall rains and earlier onset of the dry season (Pierce et al. 2018; Swain et al. 2018). Precipitation totals are also expected to become even more variable from year to year (Neelin et al. 2013; Pierce et al. 2018; Swain et al. 2018), and the frequency of both extremely wet years and very dry years are expected to increase, resulting in dramatic swings between periods of drought and flooding (Swain et al. 2018).

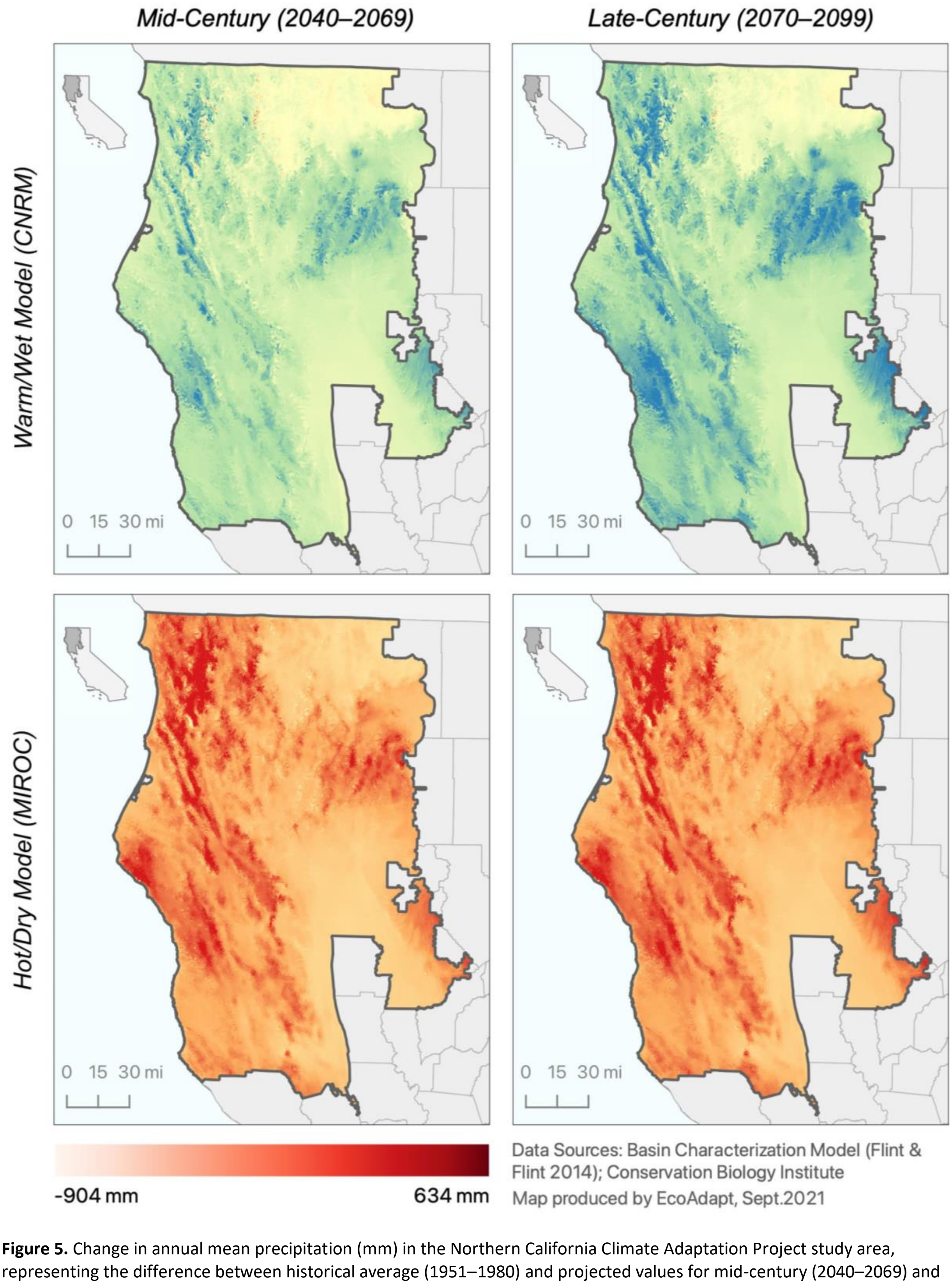

Figure 5. Change in annual mean precipitation (mm) in the Northern California Climate Adaptation Project study area, representing the difference between historical average (1951–1980) and projected values for mid-century (2040–2069) and late-century (2070–2099) time frames under two different climate scenarios: CNRM-RCP8.5 (warm/wet future scenario) and MIROC-RCP8.5 (hot/dry future scenario).

Table 3. Projected percent change in annual and seasonal precipitation for 2070–2099 compared to 1951–1980 in ecoregions that overlap the Northern California Climate Adaptation Project study area (Flint et al. 2013; Flint & Flint 2014).

Ecoregion		Annual	Winter	Spring	Summer	Fall
North Coast	*Historical*	1,474.0 mm (58.0 in)	264.3 mm (10.4 in)	106.4 mm (4.1 in)	9.1 mm (0.3 in)	112.2 mm (4.4 in)
	Projected	-19.8% to +27.2%	-22.8% to +50.7%	-12.2% to +19.1%	-72.2% to +54.3%	-26.2% to +9.3%
Northern Coast Range	*Historical*	1,385.9 mm (54.5 in)	256.5 mm (10.1 in)	96.6 mm (3.8 in)	8.3 mm (0.3 in)	101.5 mm (4.0 in)
	Projected	-20.3% to +27.9%	-23.5% to +49.9%	-12.7% to +20.8%	-92.4% to +49.3%	-25.0% to +10.8%
Northern Interior Coast Range	*Historical*	651.8 mm (25.6 in)	120.8 mm (4.7 in)	45.7 mm (1.8 in)	6.5 mm (0.2 in)	45.4 mm (1.7 in)
	Projected	-17.0% to +34.3%	-19.4% to +55.6%	-8.5% to +37.9%	-57.1% to +38.1%	-23.2% to +16.4%
Klamath Mountains	*Historical*	1,713.7 mm (67.4)	290.9 mm (11.4 in)	122.5 mm (4.8 in)	18.6 mm (0.7 in)	139.9 mm (5.5 in)
	Projected	-16.2% to +18.3%	-18.9% to +35.1%	-11.5% to +23.0%	-22.0% to +41.4%	-24.7% to +7.7%
Southern Cascades	*Historical*	910.5 mm (35.8 in)	147.2 mm (5.8 in)	70.9 mm (2.7 in)	17.0 mm (0.6 in)	68.7 mm (2.7 in)
	Projected	-18.9% to +26.8%	-20.9% to +43.0%	-12.8% to +28.1%	-9.9% to +49.3%	-26.5% to +16.6%
Great Valley	*Historical*	318.5 mm (12.5 in)	57.0 mm (2.2 in)	26.3 mm (1.0 in)	1.7 mm (0.07 in)	21.2 mm (0.8 in)
	Projected	-23.4% to +37.5%	-27.3% to +66.3%	-15.9% to +29.2%	-20.8% to +70.4%	-22.7% to +17.2%

Low confidence in direction and magnitude of projected trends.

Climatic Water Deficit & Soil Moisture

Soil moisture is closely tied to climatic water deficit (CWD), a metric that reflects moisture stress by taking into account the effects of precipitation and local atmospheric conditions (e.g., temperature, humidity) on the ecosystem water balance (Stephenson 1998; Flint et al. 2013). Increases in CWD represent a net loss of water from the ecosystem through reduced water inputs (e.g., less precipitation) and/or increased water loss (e.g., more evapotranspiration, often as a result of warmer temperatures). The balance between water supply and demand in California shifts over the course of the year, with CWD increasing as soil moisture from the winter rains is depleted by late spring and evapotranspiration increases in warmer months. Differences in the drivers of water balance on a particular site (e.g., topographic features that alter evaporative demand, soil properties that affect water-holding capacity) can mediate CWD on a site-level scale (Stephenson 1998; Flint et al. 2013).

Historically, annual CWD within the northern California study area ranged between 0 and 985 mm (average for 1951–1980), with the driest areas occurring in the Great Valley ecoregion (Flint et al. 2013; Flint & Flint 2014; Figure 6). Interannual variability in CWD also varies widely across the region, ranging from very stable conditions up to average swings of 185 mm in the most variable sites in the Klamath Mountains and parts of the Great Valley. Average annual CWD decreased by 112 mm (0.44 in) in the Cascade Ranges between 1900–1939 and 1970–2009 time periods, but increased by 35–43 mm (0.1–0.17 in) in other parts of the study area (Rapacciuolo et al. 2014).

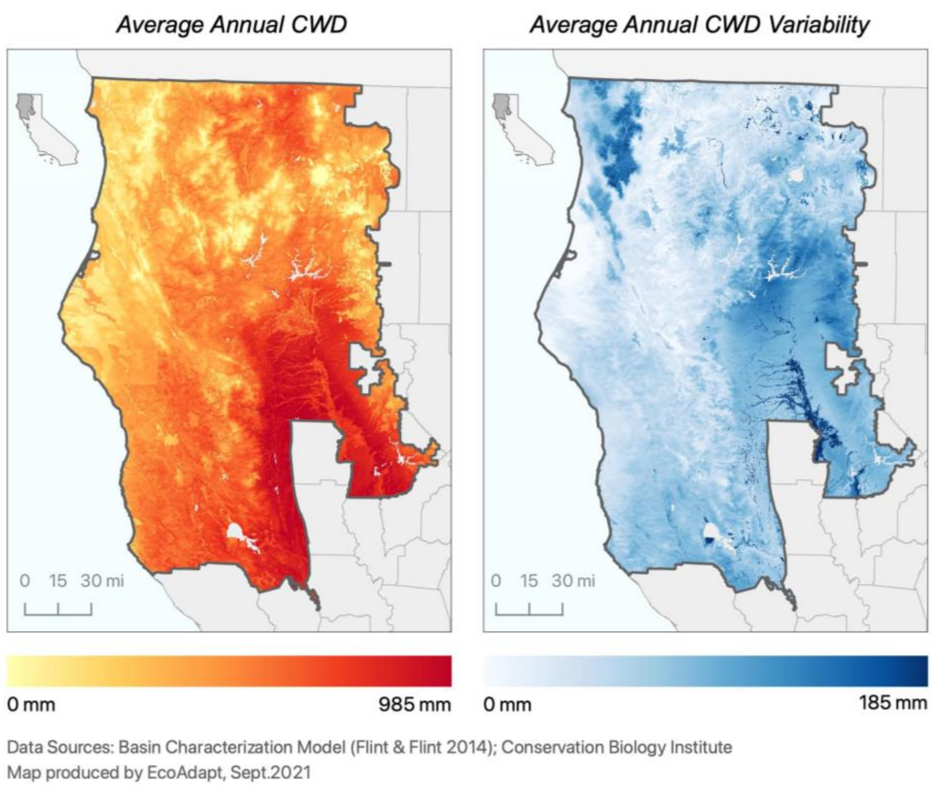

Figure 6. Mean climatic water deficit (CWD) and interannual variability (calculated using the standard deviation of mean annual CWD) in millimeters (mm) for the Northern California Climate Adaptation Project study area between 1951 and 1980.

By the end of the century (2070–2099), average annual CWD within ecoregions overlapping the study area is projected to increase by 4.3% to 43.2% compared to historical conditions (1951–1980; Flint et al. 2013; Flint & Flint 2014; Table 4). The greatest changes are expected to occur in the Southern Cascades ecoregion, where CWD under a hot/dry future scenario may increase by up to 337 mm (13.3 in) on some individual sites (Figure 7). Because increases in evapotranspiration occur as temperatures rise, increased climatic water deficit and decreased soil moisture are expected regardless of the direction of change in precipitation (Flint et al. 2013; Flint & Flint 2014; Micheli et al. 2018; Pierce et al. 2018).

Table 4. Projected percent change in average annual climatic water deficit (CWD) for 2070–2099 compared to 1951–1980 in ecoregions that overlap the Northern California Climate Adaptation Project study area (Flint et al. 2013; Flint & Flint 2014).

Ecoregion	Historical	Projected
North Coast	551.4 mm (21.7 in)	+9% to +28.5%
Northern Coast Range	638.3 mm (25.1 in)	+6.9% to +24.2%
Northern Interior Coast Range	846.9 mm (33.3 in)	+5.2% to +16.1%
Klamath Mountains	486.1 mm (19.1 in)	+10.5% to +31.7%
Southern Cascades	503.4 mm (19.8 in)	+16.3% to +43.2%
Great Valley	1,068.6 mm (42.1 in)	+4.3% to +18.6%

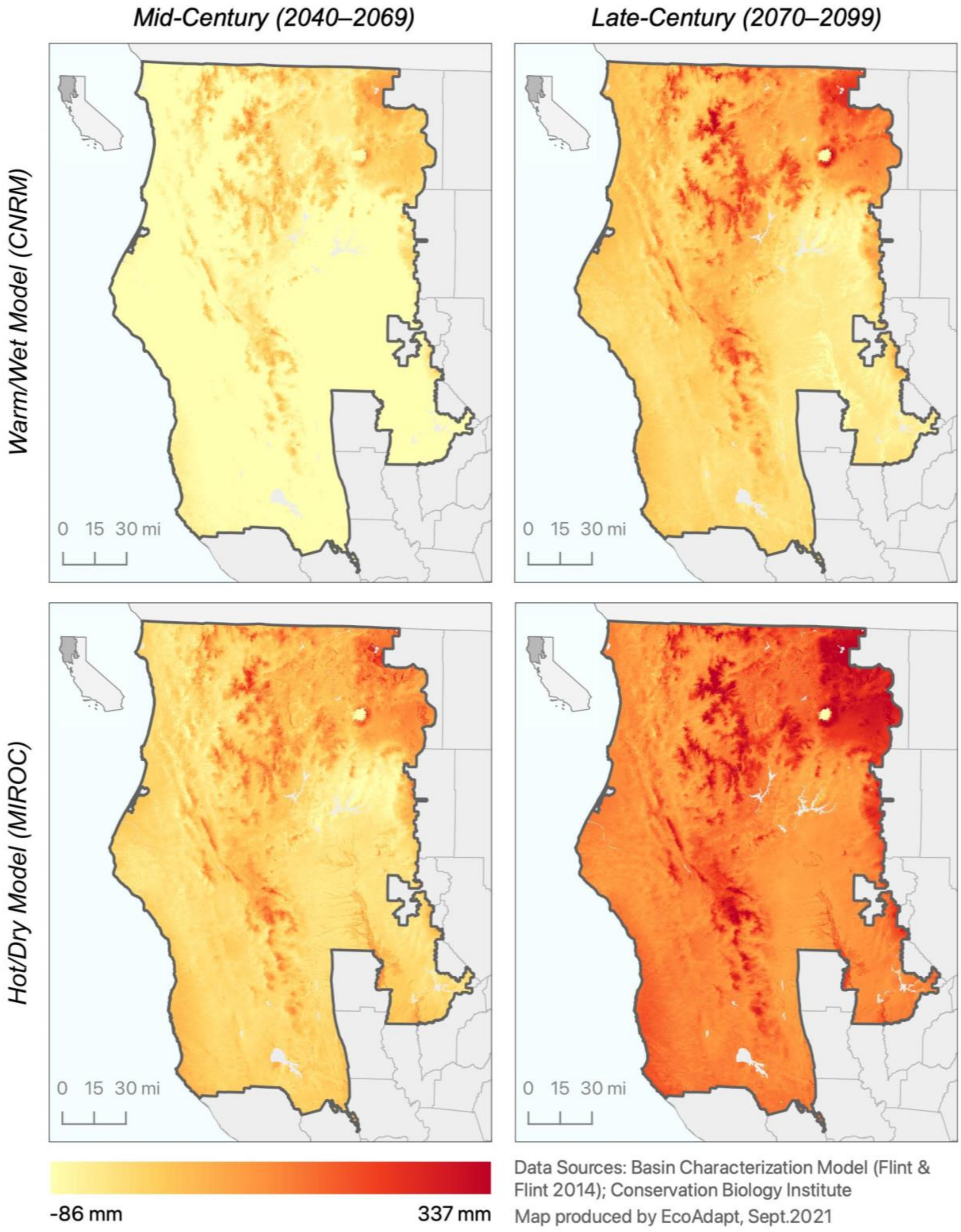

Figure 7. Change in annual CWD (mm) in the Northern California Climate Adaptation Project study area, representing the difference between historical average (1951–1980) and projected values for mid-century (2040–2069) and late-century (2070–2099) time frames under two different climate scenarios: CNRM-RCP8.5 (warm/wet future scenario) and MIROC-RCP8.5 (hot/dry future scenario).

Historical variability in CWD (Figure 2) may be considered together with projected changes in CWD (Figure 3) to better understand areas of the landscape that may be more vulnerable to significant ecosystem changes. Figure 8 contrasts portions of the study area where CWD is projected to increase by the greatest or least amounts by the end of the century (2070–2099 compared to 1951–1980) with areas of greatest and least historical variability in CWD (1951–1980). The areas where these intersect (i.e., historical variability x projected change in CWD; Figure 9) suggest sites where change in CWD is more likely to remain or exceed the historical range of variability, impacting vegetation adapted to either more stable or more variable conditions. For example, areas that have historically had low CWD variability and are expected to undergo significant increases may be more likely to experience type conversion or ecosystem collapse under future conditions, while areas of historically high variability may already support species that are well-suited for periods of extremely dry conditions (Figure 10).

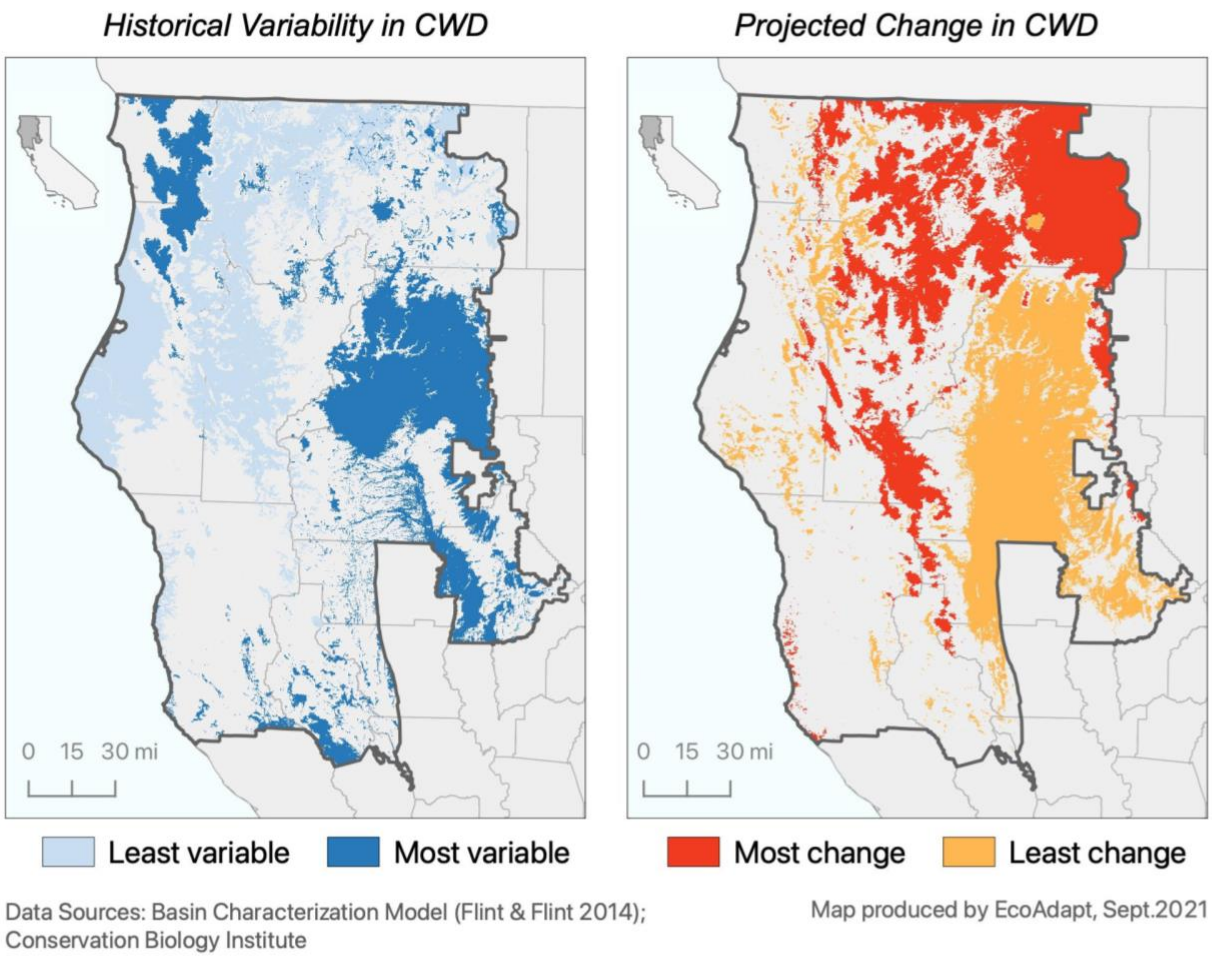

Figure 8. Areas of least and greatest historical CWD variability (average of 1951–1980) and percent projected change in annual CWD (average conditions in 2070–2099 compared to 1951–1980) for the Northern California Climate Adaptation Project study area. Projected future change is calculated using the mean of two climate models (MIROC ESM and CNRM-CM5) under a high-emissions scenario (RCP 8.5). For both historical CWD variability and projected change in CWD, greatest change represents the 80^{th} percentile and least change represents the 20^{th} percentile.

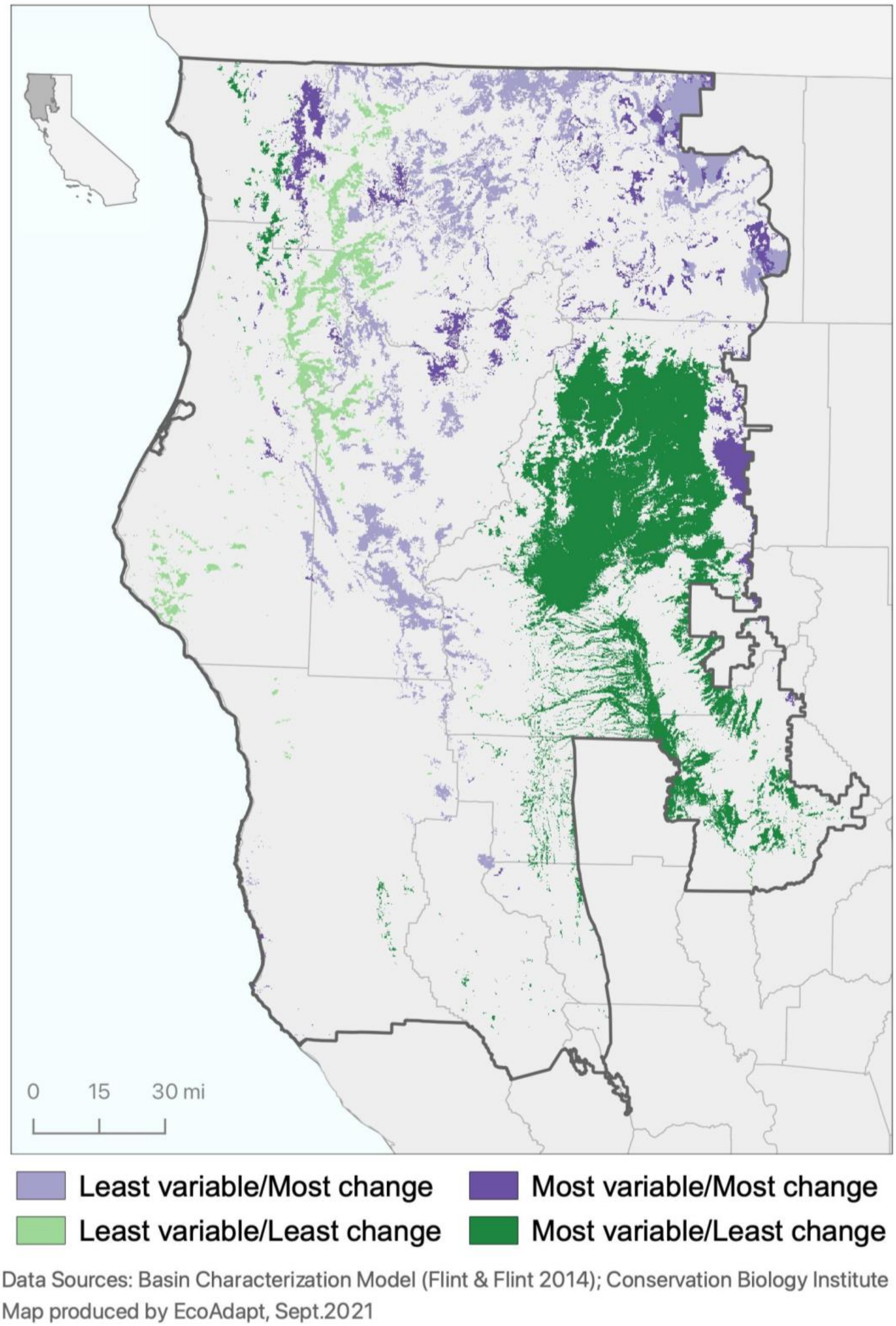

Figure 9. Areas where the least (20th percentile) and most (80th percentile) historical CWD variability (average of 1951–1980) intersect with areas of least and most projected future change in CWD (average conditions in 2070–2099 compared to 1951–1980) for the Northern California Climate Adaptation Project study area. Projected future change is calculated using the mean of two climate models (MIROC ESM and CNRM-CM5) under a high-emissions scenario (RCP 8.5).

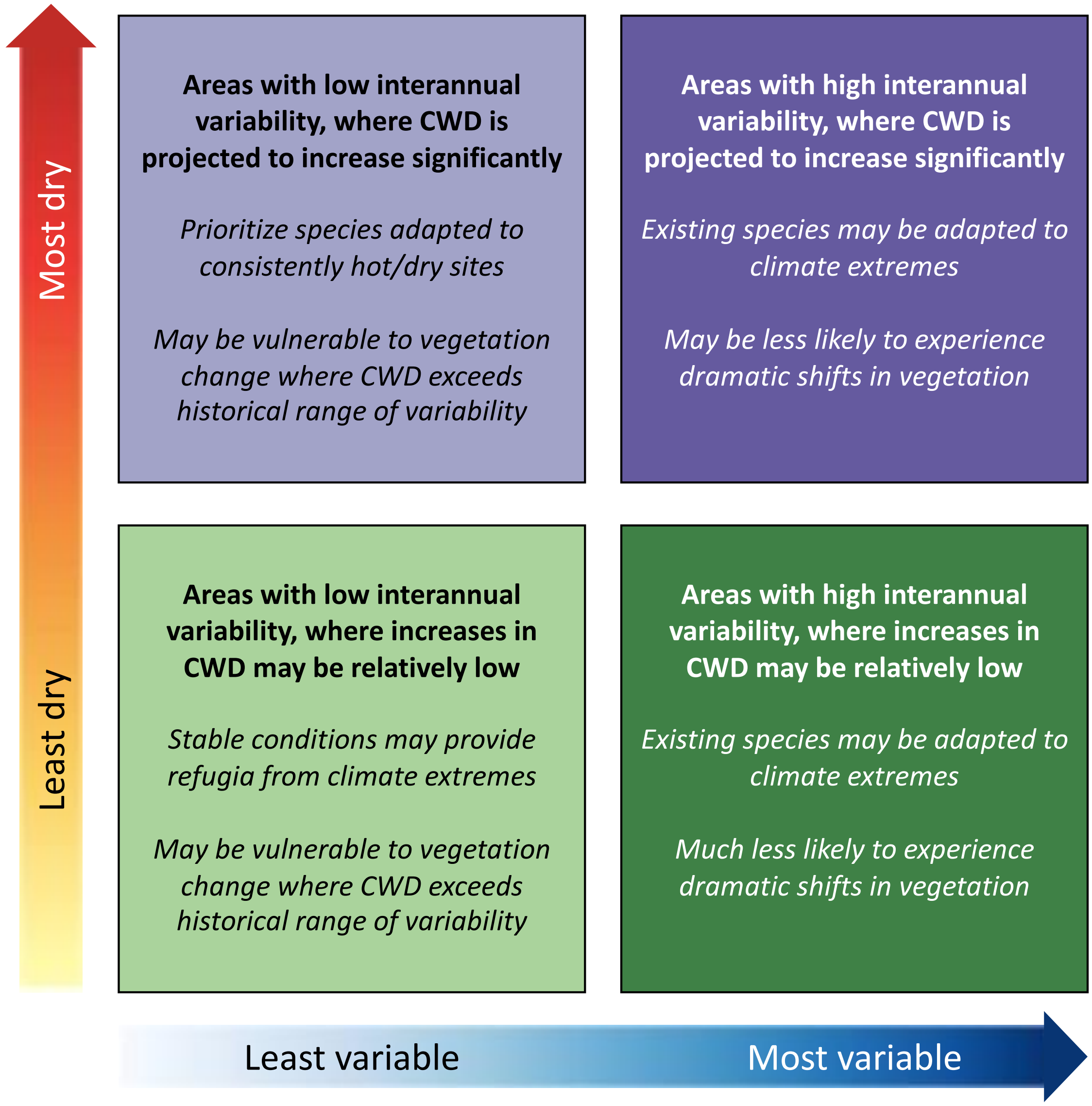

Figure 10. Framework for consideration of intersection between historical CWD variability and projected change in CWD. Figure adapted from Gillogly et al. 2017.

High confidence in trend direction, moderate confidence in trend magnitude.

Snowpack

Between 1900–1939 and 1970–2009 time periods, April 1 snow water equivalent (SWE) decreased by 15–39% across the region, with smaller changes occurring in the Cascade Ranges compared to the Klamath Mountains and coastal areas (Rapacciuolo et al. 2014). Geographic extent of snow on April 1 also declined by 10% in northwestern California between two more recent timeframes (1951–1980 compared to 1981–2010), with the greatest losses occurring in the Klamath Mountains (Micheli et al. 2018).

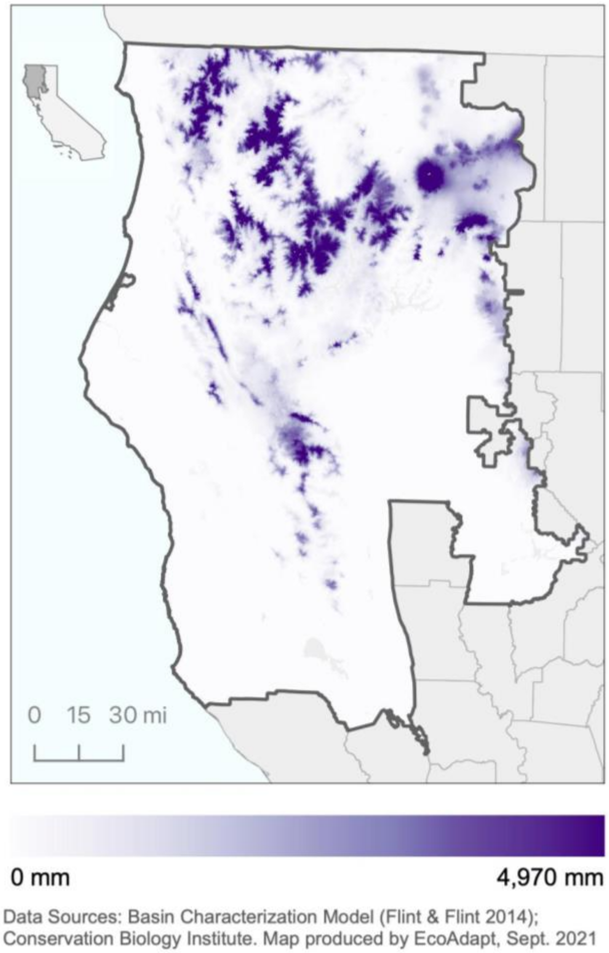

Figure 11. April 1 snow water equivalent (SWE) in millimeters (mm) for the Northern California Climate Adaptation Project study area between 1951 and 1980.

Because snowpack declines are primarily driven by warmer temperatures (Hamlet et al. 2005; Mote 2006), snowpack is projected to decrease in California across all climate models, including those that project increases in precipitation (Flint et al. 2013; Flint & Flint 2014; Micheli et al. 2018). April 1 geographic extent of snow in northwestern California is expected to decline from 60% of the landscape to 30% by 2050 and 11% by 2100, with the greatest losses occurring under warm, dry future scenarios (Micheli et al. 2018). April 1 SWE is also expected to decrease significantly, with losses of 61–100% by 2100 compared to historical SWE (1951–1980; Flint et al. 2013; Flint & Flint 2014; Figure 11 and Figure 12; Table 5). While snowpack is likely to disappear completely in the Northern Interior Coast Range where the historical average is already very low (0.14 mm [0.01 in]), the largest absolute changes are likely to occur in the Klamath Mountains ecoregion, where declines of up to 94.4% may result in April 1 SWE losses of up to 169.8 mm (6.7 in).

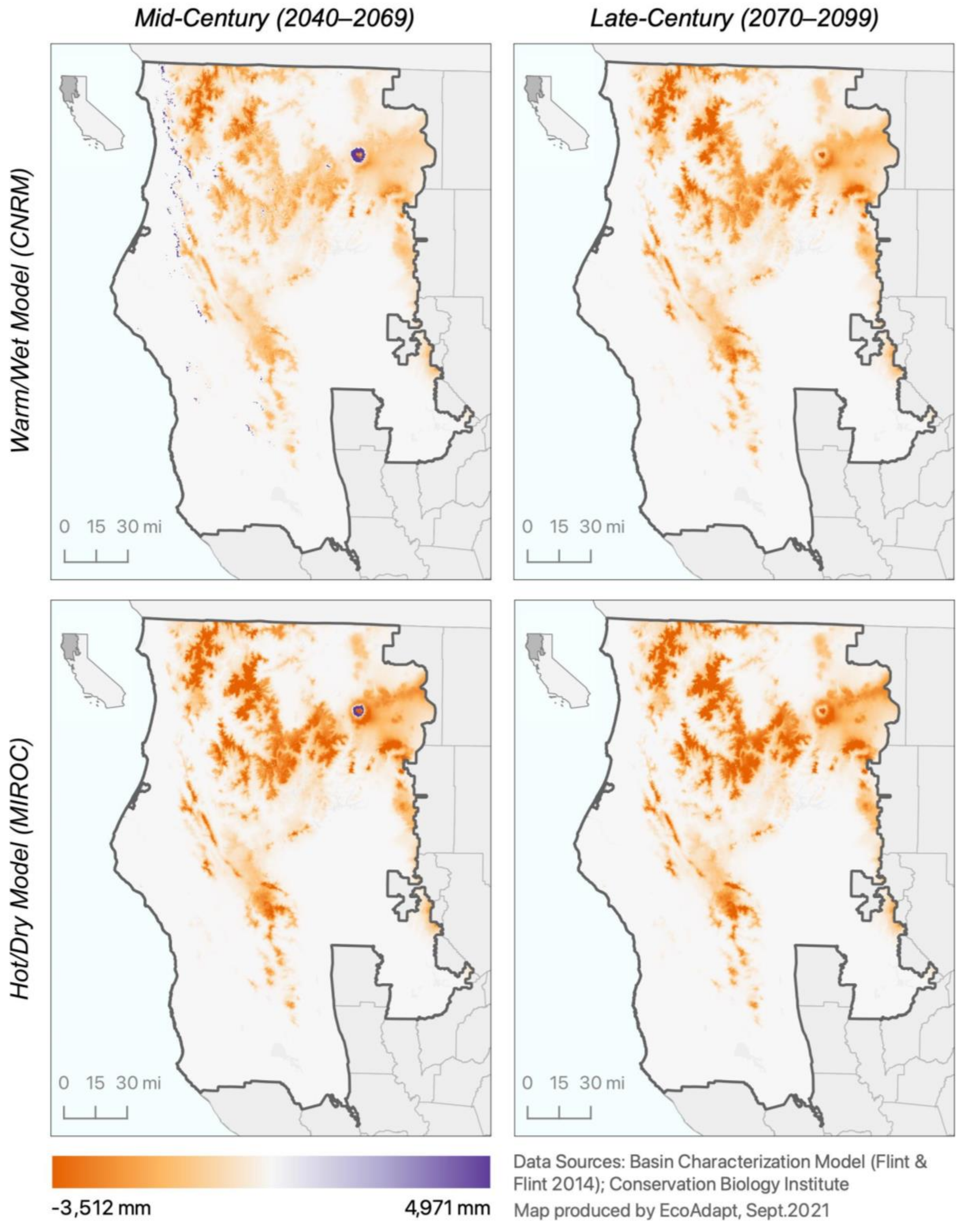

Figure 12. Change in April 1 snow water equivalent (SWE; in mm) in the Northern California Climate Adaptation Project study area, representing the difference between historical average (1951–1980) and projected values for mid-century (2040–2069) and late-century (2070–2099) time frames under two different climate scenarios: CNRM-RCP8.5 (warm/wet future scenario) and MIROC-RCP8.5 (hot/dry future scenario).

Table 5. Projected percent change in average April 1 snow water equivalent (SWE) for 2070–2099 compared to 1951–1980 in ecoregions that overlap the Northern California Climate Adaptation Project study area (Flint et al. 2013; Flint & Flint 2014).

Ecoregion	Historical	Projected
North Coast	3.1 mm (0.1 in)	-86.1% to -99.2%
Northern Coast Range	58.5 mm (2.3 in)	-82.4% to -98.8%
Northern Interior Coast Range	0.14 mm (0.01 in)	-100.0%
Klamath Mountains	235.9 mm (9.3 in)	-72.0% to -94.4%
Southern Cascades	268.6 mm (10.6 in)	-60.8% to -88.7%
Great Valley	3.1 mm (0.1 in)	-86.1% to -99.2%

High confidence in trend direction, moderate confidence in magnitude of change.

Timing of Snowmelt and Runoff

The timing of snowmelt and spring runoff shifted 10–30 days earlier across the western U.S. between 1948 and 2002 (Stewart et al. 2005), and up to 40 days earlier since 1915 (Hamlet et al. 2005). Continued shifts towards earlier timing of snowmelt-driven runoff are expected, with estimates for northern California ranging from 5 to 15 days by 2100 compared to 1948–2000 (Stewart et al. 2005). This represents a smaller change than the western U.S. as a whole, which is projected to see an overall shift of up to 40–60-days earlier (Stewart et al. 2005; Rauscher et al. 2008).

High confidence in trend direction, moderate confidence in magnitude of change.

Streamflow

In rain-dominated coastal rivers of northwestern California, minimum annual flows have decreased and late summer recession rates have increased over the past 40-80 years (Sawaske & Freyberg 2014; Asarian & Walker 2016; Klein et al. 2017). In northwestern California and southwestern Oregon, summer stream flows declined between 1953 and 2012, with the largest decreases occurring in the Upper Klamath Basin (Asarian & Walker 2016). The most consistent declining trends were observed between August and November, and 73% of sites showed declines in September flows. However, changes in precipitation alone do not account for the observed trends, which are likely also driven by water withdrawals and loss of riparian vegetation in the region (Asarian & Walker 2016).

Flow patterns in the western U.S. already exhibit high interannual and spatial variability in streamflow patterns, and flow variability is expected to increase further over the coming century (Stewart et al. 2005). The timing of spring peak flows may also shift earlier by up to 30 days as a result of temperature-driven changes in the timing of snowmelt-driven runoff (Stewart et al. 2005). Overall, wet season flows are projected to increase and dry season flows are projected to decrease (Leng et al. 2016; Naz et al. 2016; Burke & Ficklin 2017; Grantham et al. 2018), with the most significant changes expected in January (25% increase by 2050) and May flows (24% decrease by 2050; Grantham et al. 2018). As a result of more extreme dry conditions, the lowest streamflow per decade is projected to decrease an additional 30–40% by 2100 (compared to 1950–2005; Pierce et al. 2018).

Moderate confidence in trend direction and magnitude of change.

Coastal Fog

Relatively little is known about long-term trends in coastal fog, and potential changes in global circulation patterns (e.g., the jet stream), the timing and strength of upwellings, winds, and other interacting oceanic and atmospheric factors that influence coastal fog are largely unknown (Grantham 2018). A study conducted at two locations on the northern and central California coast found a 33% reduction in the frequency of coastal fog and low clouds under 400 m (1,312 ft) since 1901, though no significant changes occurred after 1951 (Johnstone & Dawson 2010). A modeling study of California coastal fog frequency found similar trends over the same time frames, though the magnitude of declines was less extreme (3–4% decline in frequency from 1920–1950, then 0.5–1% decline from 1950–2008; O'Brien 2011). Modeled future projections suggest weak declines may continue through the end of the century (0.1% per decade), driven primarily by warming sea surface temperatures (O'Brien 2011).

Low confidence in trend direction and magnitude of change.

Sea Level Rise

Globally, sea level rise has been accelerating from a background rate of 1 mm (0.004 in) per year over the last two millennia (National Research Council 2012) to 1.7 mm (0.07 in) per year between 1901 and 2010 (Church & White 2006; Anderson 2018). Relative sea level rise on the U.S. West Coast is 18% higher than the global average, at 2.0 mm (0.08 in) per year between 1901 and 2010, and is 34% higher than global rates within the Cascadia Subduction Zone (includes the Pacific Northwest and northern California), at 2.3 mm (0.09 in) over the same time period (Burgette et al. 2009; Anderson 2018). This difference is due to vertical land motion (VLM), including tectonic land-level changes, sediment compaction, and/or land subsidence, which alters the rate of local sea-level changes relative to background global rates (Burgette et al. 2009; Patton et al. 2017; Anderson 2018). Within the study area, rates of relative sea level rise over the past century range from slight decreases of -0.8 mm (-0.03 in) per year from 1933–2018 recorded at the Crescent City tide gage (due to land uplift; rates equivalent to -0.08 mm [-0.26 ft] in 100 years) to 4.9 mm per year (0.18 in) at the Humboldt Bay (North Spit) tide gage from 1977–2018 (due to land subsidence; rates equivalent to 0.49 m [1.6 ft] in 100 years; Patton et al. 2017; Anderson 2018).

By 2100, it is likely (66% probability) that sea level rise within the study area will occur within a range of 0.03–1.24 m (0.1–4.1 ft) compared to 2000 sea levels, with lower rates likely towards the northern part of the region and higher rates in and around Humboldt Bay (Kopp et al. 2014; Griggs et al. 2017; Sweet et al. 2017; Anderson 2018). Under the most extreme sea level rise scenarios (representing collapse of the Antarctic ice sheet), global sea levels may rise by up to 2.5 m (8.2 ft), and sea levels in northern California may increase by up to 2.8–3.4 m (9.1–11.0

ft). However, it is difficult to model the complex and non-linear impacts of warming temperatures on ice sheets, so the probability of the most extreme scenario occurring is unknown (Kopp et al. 2014; Griggs et al. 2017; Sweet et al. 2017; Anderson 2018).

Table 6. Probabilistic projections of relative sea level rise (SLR) for three tide gages within the Northern California Climate Adaptation Project study area, representing likely (67% probability) and very likely (95% probability) ranges for 2100 (compared to 2000) across three future emissions scenarios (RCP 2.6, RCP 4.5, RCP 8.5). Probability of the extreme scenario, representing collapse of the Antarctic ice sheet, is unknown (Kopp et al. 2014; Griggs et al. 2017; Sweet et al. 2017; Anderson 2018).

	Likely Range	**1-in-200 Chance**	**Extreme Scenario**
Location	*66% probability SLR occurs within range*	*0.5% probability SLR meets or exceeds…*	*Probability uncertain (ice sheet collapse)*
Crescent City	0.03–0.65 m (0.1–2.1 ft)	1.55 m (5.1 ft)	2.79 m (9.1 ft)
Humboldt Bay (North Spit)	0.62–1.24 m (2.0–4.1 ft)	2.15 m (7.0 ft)	3.37 m (11.0 ft)
Arena Cove	0.21–0.94 m (0.7 to 3.1 ft)	2.04 m (6.7 ft)	3.02 m (9.9 ft)

High confidence in trend direction, moderate confidence in magnitude of change.

Trends and Projections for Extreme Events and Natural Disturbance Regimes

Heat Waves

Frequency, intensity, and duration of heat waves have increased over the past few decades, and these changes are projected to continue over the coming century, with the greatest increases likely to occur in humid nighttime heat waves and in coastal areas (Gershunov & Guirguis 2012). State-wide, the maximum temperature on the hottest day of the year is likely to increase by an average of 2–6°C (3.6–10.8°F) by the end of the century, with the greatest increases occurring under high-emissions scenarios (Pierce et al. 2018). For inland regions, the hottest day of the year is expected to exceed 41°C (105°F; Pierce et al. 2018).

High confidence in trend direction and magnitude of change.

Extreme Precipitation, Storms, and Flooding

Both the frequency and intensity of extreme precipitation events declined in northern California from 1950 to 2009 (Mass et al. 2010). However, the intensity and duration of storm events (including atmospheric rivers) are projected to increase over the coming century, resulting in greater maximum precipitation rates and volume (Dettinger 2011; Shields & Kiehl 2016; Prein et al. 2017; Pierce et al. 2018). By 2100, available projections suggest that there may be a 30% increase in the number of days per year with atmospheric river events (Dettinger 2011), and daily rainfall totals during extreme precipitation events may increase by 15–20% under a high-emissions scenario (RCP 8.5; Pierce et al. 2018). However, confidence in projections related to changes in future storms remains low due to complex interactions between large-scale atmospheric patterns (e.g., ENSO, atmospheric rivers), sea level rise, and precipitation, which are all uncertain for northern California.

The projected increases in extreme precipitation events are also expected to cause more frequent and more severe winter flooding (Dettinger 2011; Naz et al. 2016; Burke & Ficklin 2017; AghaKouchak et al. 2018; Swain et al. 2018; Grantham et al. 2018). One study projects that, in California, floods with a current likelihood of occurring once every 200 years will become 50-year floods by the end of the century (Swain et al. 2018). In the Sacramento River Basin, 50-year flood volume is expected to increase by 13% and 50-year floods are projected to become 1.6 times more likely (e.g., a 50-year-flood becomes a 31-year-flood) by 2050 (Pagán et al. 2016).

Moderate confidence in trend direction, low confidence in magnitude of change.

Drought

Drought years occurred twice as often in the most recent two decades as in the previous century (30% of years from 1995–2014 compared to 14% of years from 1896–1994), and are most likely to occur when low-precipitation years and high-temperature years coincide

(Diffenbaugh et al. 2015). The probability of these two anomalies co-occurring doubled within that time period (91% chance of low-precipitation/high-temperature year from 1995–2014 compared to 42% chance from 1896–1994), despite little change in the probability of low-precipitation years. Thus, the observed increase in drought was due largely to an increase in the frequency of high-temperature years (80% over the past two decades compared to 45% in the previous century; Diffenbaugh et al. 2015). Increases have also occurred in extreme drought conditions in California; for instance, the 2012–2016 drought had the lowest precipitation, highest temperatures, and most extreme drought indicators on record (Griffin & Anchukaitis 2014; Diffenbaugh et al. 2015). Paleoclimate reconstructions suggest this was the most severe drought in the last 1,200 years (Griffin & Anchukaitis 2014), with the exceptional severity largely attributed to record high temperatures combined with low levels of precipitation (Griffin & Anchukaitis 2014; Williams et al. 2015).

Over the coming century, warmer temperatures are expected to drive significant increases in drought risk even if precipitation increases (Cook et al. 2015; Diffenbaugh et al. 2015; Pierce et al. 2018). Drought years are projected to be twice as likely to occur in any given year, and under a high-emissions scenario there is a greater than 80% chance of a multi-decadal drought by 2100 (Cook et al. 2015). Severe droughts are also projected to become much more frequent, with those that now occur once every 20 years projected to happen once every 10 years by the end of the century, and once-in-a-century droughts projected to occur once every 20 years by 2100 (Pierce et al. 2018).

High confidence in trend direction and magnitude of change.

Wildfire

Although fire frequency and extent of burning in most areas of California remain well below the levels of activity that occurred prior to Euro-American settlement (Stephens et al. 2007; Safford & Van de Water 2014), more recent trends have shown increases in fire size, frequency, and annual area burned over the last several decades (Miller et al. 2012; Westerling 2016). Both fire size and total area burned increased on U.S. Forest Service lands in northwestern California between 1910 and 2008, with the highest values occurring after 2000 (Miller et al. 2012). Between 1970 and 2012, large fires (>400 ha in size) on public lands in the inland northern California and Sierra Nevada regions have increased in frequency by 184–274% per decade, and total area burned by large fires has increased by 270–492% per decade, with significantly more fire in forested areas occurring in years with early snowmelt (Westerling 2016). The length of the fire season increased by 215% in this region, and the burn time of large fires has increased by 612% (Westerling 2016). No significant trends in the proportion of high-severity fire have been observed between 1984 and 2014 (Miller et al. 2012; Parks et al. 2015; Law & Waring 2015; Keyser & Westerling 2017). However, the relatively short period of record for data on fire severity may obscure longer-term trends, and there are not yet peer-reviewed studies on temporal trends in fire severity that include data from the last several years.

State-wide, mean annual area burned is expected to increase by up to 77%, with a 50% increase in the frequency of extremely large fires (>10,000 ha) by 2100 (Westerling 2018). Within the montane forested areas of northern California, burned areas may increase by up to 400% (Westerling et al. 2011; Westerling 2018). The fire season is also expected to continue getting longer due to warmer temperatures and earlier snowmelt, with the most significant changes occurring at mid- to high elevations (Westerling 2016; Micheli et al. 2018). Fire frequency is projected to increase the most in the North Coast region due to growing human populations that increase the risk of ignitions (Mann et al. 2016; Micheli et al. 2018). Longer fire seasons and more available fuels in the region may also increase the chances of lightning strikes that ignite wildfires (Lutz et al. 2009; Grantham et al. 2018). Although models based solely on historical fire-climate relationships project little change in fire severity for northwestern California by 2050 (Parks et al. 2016), human activity and fuel buildup from decades of fire suppression have altered these historical fire-climate relationships (Taylor et al. 2016; Syphard et al. 2017; Wahl et al. 2019) and projections that incorporate these factors suggest significant increases in fire severity and size in the region (Mann et al. 2016; Wahl et al. 2019). Overall, the majority of impacts to natural and human ecosystems over the coming century are likely to be caused by extreme fire events, which are expected to increase significantly (Westerling 2018) and are already being observed across the region (Goss et al. 2020).

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