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Arch Rock, Anacapa Island, Channel Islands National Park (photo P. Gonzalez)

Anthropogenic Climate Change in Channel Islands National Park, California, USA

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Abstract

Greenhouse gas emissions from cars, power plants, deforestation, and other human sources have caused anthropogenic climate change and impacts to ecosystems and human well-being. To assist Channel Islands National Park, California, to effectively manage natural and cultural resources under climate change, this climate change assessment presents park-specific scientific information on climate trends, historical impacts, future risks, and carbon stocks and emissions. The annual average temperature of the area within park boundaries increased at a statistically significant rate of 1ºC ± 0.2ºC (1.8 ± 0.4ºF.) per century from 1895 to 2017. Annual precipitation showed no statistically significant trend. Historical changes detected in the region and attributed by published scientific analyses mainly to anthropogenic climate change include sea level rise of 10 ± 0.5 cm (4 ± 0.2 in.) at Los Angeles from 1924 to 2019, sea surface temperature increase of 1.4 ± 0.2ºC (2.5 ± 0.4ºF.) at Scripps Pier from 1916 to 2019, acidity increase of 40% (-0.15 pH) in ocean waters off the Pacific coast since ca.1750, and dissolved oxygen reduction of 4 ± 1% in the northern Pacific Ocean from 1960 to 2010. Under the highest greenhouse gas emissions scenario of the Intergovernmental Panel on Climate Change (Representative Concentration Pathway [RCP] 8.5), thirty-three climate models project an annual average temperature increase in the park of 3.5 ± 0.8ºC (6.3 ± 1.4ºF.) from 2000 to 2100. Cutting emissions from human activities (RCP2.6) to meet the Paris Agreement goal could reduce projected heating by two-thirds. Two-thirds of climate models project increases in total annual precipitation and one-third project decreases, although higher temperatures would tend to increase aridity. A combination of projected sea level rise, daily tidal range, and storm surge could raise sea level during the worst storms to 3.5 m above the 2000 level by 2100. Continued climate change could increase numerous risks to park resources, including increased wildfire frequency, tree mortality, and growth of invasive plant species, damage to marine life from hotter temperatures, and damage to cultural resources from erosion. Vegetation in the park stores 220 000 ± 160 000 tons of carbon in aboveground biomass, equivalent to the annual emissions of 24 000 ± 17 000 Americans. Conservation of vegetation prevents the carbon from contributing to climate change. From 2001 to 2010, ecosystem carbon increased on one-third of the area of Santa Rosa Island and the eastern end of Santa Cruz Island, coinciding with ecosystem restoration. Motor vehicles and boats of the park and visitors generate 80% of the 350 tons per year of park carbon emissions, pointing to local ways to help reduce the human cause of climate change.

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Introduction

Greenhouse gas emissions from cars, power plants, deforestation, and other human activities have caused climate change (IPCC 2013, USGCRP 2017). Field research shows that human-caused climate change is altering ecosystems and affecting the well-being of people by melting glaciers, raising sea level, exacerbating wildfire, increasing tree death, contributing to animal species extinctions, and causing other impacts globally (IPCC 2014), across the United States (USGCRP 2018), and in United States national parks (Gonzalez 2017).

In response, national parks are developing resource management strategies for conservation under climate change. The objective of this report is to assist Channel Islands National Park to effectively manage natural and cultural resources under climate change. This report is a park-specific climate change science assessment. It presents published results of spatial analyses of historical and projected climate change (Gonzalez et al. 2018) and ecosystem carbon (Gonzalez et al. 2015) and an assessment of published scientific research on historical impacts of climate change and future risks to resources in the Channel Islands, California (Figure 1).

Methods

Historical climate This assessment presents results of spatial analyses of historical climate trends (Gonzalez et al. 2018) from published climate data layers at a spatial resolution of 800 meters, derived from point weather station measurements using the Parameter-elevation Relationships on Independent Slopes Model (PRISM; Daly et al. 2008). PRISM uses elevation and topography to interpolate climate values in the spaces among weather stations. This assessment summarizes results by giving trends for the area within park boundaries as a whole and maps of the spatial patterns of climate trends across the park and surrounding area.

Linear regression of temperature and precipitation time series, corrected for temporal autocorrelation, gives the historical climate trends, standard errors, and statistical probabilities. Analyses of monthly, seasonal, and annual climate were originally run for the periods 1895-2010 and 1950-2010, the data available at the time of the original research. Additional analyses of annual trends were later run for the period 1895-2017. The time periods starting in 1895 provide the longest available weather station-based trends for the area of the park. The configuration of the United States (U.S.) weather station network stabilized in the 1950s (Vose et al. 2014), so the period starting in 1950 gives a trend based on a more consistent set of stations.

Projected climate This assessment presents spatial analyses of future projections of climate (Gonzalez et al. 2018) that use output of all available general circulation models (GCMs) in the Coupled Model Intercomparison Project Phase 5 dataset developed for the most recent Intergovernmental Panel on Climate Change (IPCC) assessment report (IPCC 2013). Each GCM uses different methods to represent atmospheric processes. The coarse-scale GCM output, at spatial resolutions of up to 200 km, has been downscaled to 800 m spatial resolution using the bias correction and spatial disaggregation method (Wood et al. 2004) and the PRISM historical climate time series as a base layer (Daly et al. 2008). Future projected changes are expressed as the change from the standard 1971-2000 historical baseline.

IPCC has coordinated research groups to project possible future climates under four defined greenhouse gas emissions scenarios, called representative concentration pathways (RCPs; Moss et al. 2010). The four emissions scenarios are RCP2.6 (reduced emissions from energy efficiency and renewable energy, achieving the goals of the Paris Agreement (UNFCCC 2015)), RCP4.5 (low emissions), RCP6.0 (high emissions, somewhat lower than continued current practices), and RCP8.5 (highest emissions, no emissions reductions). Climate under each of the four scenarios was projected by up to 33 GCMs. The four emissions scenarios determine the overall range of potential futures. Within each scenario, the spread of projections of the GCMs generates a range of potential futures, characterized here by the average and standard deviation of the GCM ensemble for each scenario.

Historical impacts and future risks This assessment also synthesizes published scientific information on historical impacts of climate change, future risks, and carbon. The impacts and risk information come from a search of the Clarivate Analytics Web of Science <http://www.webofknowledge.com>, the authoritative database of scientific literature, for published research that used field data from the park or surrounding region or that examined the climate sensitivity of species, ecosystems, or other resources found in the park.

Carbon Data on carbon in forests, woodlands, and other ecosystems come from a published statewide analysis of remote sensing and field data (Gonzalez et al. 2015). Analyses of Landsat remote sensing and field measurements of biomass across the state of California produced estimates of the carbon in aboveground vegetation for the forests, woodlands, grasslands, and other non-agricultural and non-urban areas of the state at 30 m spatial resolution. Monte Carlo analyses of error in tree measurements, remote sensing, and the carbon fraction of biomass quantified the uncertainty of carbon stock change estimates. Validation of the carbon stock estimates by independent estimates derived from field measurements found that the new results were close to field-derived estimates.

Historical Climate Trends

Temperature Average annual temperature increased at a statistically significant rate of 1ºC ± 0.2ºC (1.8 ± 0.4ºF.) per century (mean ± standard error) from 1895 to 2017 for the area within park boundaries (Figure 2) (Gonzalez et al. 2018). Seasonally, temperatures increased at the highest rate in autumn, for the period starting in 1895, and in spring, for the period starting in 1950 (Table 1). Monthly temperatures increased at statistically significant rates for six months since 1895 and for five months since 1950 (Table 1). From 1895 to 2010, the period of temperatures above 16ºC (61ºF.) increased from zero to four months (Figure 3). Spatially, temperature increases were highest on Santa Barbara Island and on the south shore of Santa Cruz island (Figure 4). The lowest temperature increases were at higher elevations of San Miguel Island and Santa Rosa Island.

Precipitation Historical annual and seasonal precipitation showed no statistically significant trends for the area within park boundaries (Table 2, Figure 5) (Gonzalez et al. 2018). This is due to the high inter-annual variability of rainfall in coastal southern California and lack of a directional change in annual precipitation (Hall et al. 2018). Spatially, annual precipitation showed decreases on Santa Barbara Island, although the changes were not statistically significant, and statistically significant increases on San Miguel Island (Figure 6).

For the southwestern U.S. as a whole, extreme storms have increased in the past half-century, with the amount of precipitation in 20-year events (a day with more precipitation than any other day in 20 years) increasing in all four seasons from 1948 to 2015, a trend attributable in part to anthropogenic climate change (Easterling et al. 2017).

Drought A severe drought struck most of California, including the Channel Islands, from 2012 to 2016, with the lowest 12-month precipitation totals combining with the hottest annual average temperatures in the period 2012-2014 (Diffenbaugh et al. 2015). Analyses of the Palmer Drought Severity Index (PDSI), an indicator of near-surface soil moisture, for the periods 1895-2014 and 1901-2014 indicate that 2014 was the driest year in the instrumental record for the southern California coast (Robeson 2015, Williams et al. 2015). The 2012-2015 drought was more severe than any other four-year drought in the past 1200 years, based on a PDSI time series reconstructed from tree ring analyses (Robeson 2015). Climate water deficit, the difference between potential and actual evapotranspiration, had already increased by 130 mm (5 in.) per year between the periods 1900-1939 and 1970-2009, indicating that conditions became more arid (Rapacciuolo et al. 2014).

Analyses of PDSI for the period 1896-2014 showed that, while the probability of low precipitation years has not increased, the hotter temperatures of anthropogenic climate change have increased the probability of drought by increasing the probability of high temperature and low precipitation occurring at the same time (Diffenbaugh et al. 2015). Furthermore, the hotter temperatures of anthropogenic climate change reduced snowpack in the period 2011-2015 one-quarter below the 1980-2015 average (Berg and Hall 2015). For the State of California as a whole, the high temperatures of anthropogenic climate change accounted for one-tenth to one-fifth of the 2012-2014 period of the drought (Williams et al. 2015).

The California drought was part of a drought across the southwestern US from 2000 to the present that has been intensified by the increased heat and aridity of anthropogenic climate change (Williams et al. 2020). The drought has been the most severe for the southwestern US as a whole since the 1500s, reducing soil moisture to its lowest levels since that time. The increased heat and aridity of anthropogenic climate change account for half the magnitude of the drought (Williams et al. 2020).

El Niño-Southern Oscillation (ENSO) ENSO is a recurring natural climate pattern across the tropical Pacific that causes relatively predictable changes in temperature and precipitation during the warm phases (El Niño) and the cold phases (La Niña), every two to seven years. El Niño causes warmer than average ocean water temperatures off the southern California coast and more winter rain. Conversely, La Niña causes cooler than average ocean water temperatures and less winter rain. Time series analyses have not determined the contribution of historical climate change to changes in ENSO (IPCC 2013, Timmermann et al. 2018, Yeh et al. 2018).

Santa Ana winds In autumn and winter, a temperature difference between cooler air over interior California and southwest U.S. deserts and warmer air over the Pacific Ocean creates a pressure gradient that produces the hot and dry Santa Ana winds, which blow from the east and down the coastal mountain ranges (Conil and Hall 2006, Hughes and Hall 2010). Analyses of Santa Ana wind events from 1948 to 2012 found no statistically significant change in frequency or average intensity but did find an increase in intensity of the most extreme events (Guzman-Morales et al. 2016). No analyses have attributed the change to climate change.

Historical Impacts

Changes detected in the region and attributed to anthropogenic climate change

Published research that includes data from southern California or the Pacific Ocean off the southern California coast has detected changes that are statistically significantly different from natural variation and attributed the cause of those changes to anthropogenic climate change more than other factors.

Sea level rise At the National Oceanic and Atmospheric Administration (NOAA) tidal gauge at the Port of Los Angeles, the tidal gauge closest to Channel Islands National Park with a continuous time series, sea level increased 10 ± 0.5 cm (4 ± 0.2 in.) (mean ± standard error) from 1924 to 2019 (NOAA 2019) (Figure 7). This tidal gauge has contributed to global analyses that have detected a statistically significant rise in global sea level from 1901 to 2012 (Church and White 2011, IPCC 2013, Dangendorf et al. 2017). Analyses of potential causal factors attribute global sea level rise to anthropogenic climate change through runoff from the melting of glaciers and ice on land and the expansion of ocean water when it warms (IPCC 2013, Slangen et al. 2016).

Ocean warming Measurements from buoys and ships off the California coast and around the world, combined with remote sensing data, have found that the average sea surface temperature of the California Current of the Pacific Ocean increased 0.8 ± 0.2ºC from 1920 to 2016 (Rayner et al. 2003, Jacox et al. 2018) and analyses of casual factors attributed this increase to anthropogenic climate change (IPCC 2013). Temperature measurements at the pier of the Scripps Institution of Oceanography, San Diego, which extends 330 m (1100 ft.) from shore, showed an increase of sea surface temperature of 1.4 ± 0.2ºC (2.5 ± 0.4ºF.) from 1916 to 2019 (Scripps Institution 2019). The record maximum temperature at the pier of 27ºC (81ºF.) was recorded on August 6, 2018. Anthropogenic climate change has also caused substantial ocean warming to a depth of 2000 m (Levitus et al. 2012, Abraham et al. 2013, IPCC 2013, Cheng et al. 2017, Ishii et al. 2017, Resplandy et al. 2018, Cheng et al. 2019).

Ocean acidification Increased atmospheric carbon dioxide (CO_2) concentrations from human sources are increasing the acidity of ocean water globally as the CO_2 dissolves in water and forms carbonic acid. Analyses of ocean water samples off the southern California coast show that anthropogenic CO_2 has increased Pacific Ocean water acidity 25% to 40% (-0.10 to -0.15 pH) from the preindustrial era (ca. 1750) to the early 2000s (Gruber et al. 2012, IPCC 2013, Feely et al. 2016, Carter et al. 2017). Ocean upwelling along the Pacific coast can produce acidification episodes of more than a doubling of acidity (-0.4 pH) within 10 km of the shore at Lompoc, California, north of the park (Chan et al. 2017).

Measurements of pH at three sites in the park from February 2012 to May 2015 characterized ocean acidity variation (Kapsenberg and Hofmann 2016). At Anacapa Island landing cove pier, average pH was 8.01 ± 0.04 (mean ± standard deviation) with 99% of observations in the range 7.88-8.12. The pH results at Santa Cruz Island Prisoner's Harbor pier were 8.00 ± 0.06 and 7.81-8.16. The pH results at San Miguel Island northern subtidal mooring were 8.05 ± 0.05 and 7.92-8.16. Maximum 24-hour and upwelling event pH changes were 0.2. Compared to coastal sites, island sites experienced few acidification events (Kapsenberg and Hofmann 2016). Models estimate that water around the northern Channel Islands at 60 m depth acidified -0.05 pH to -0.08 pH from 1979 to 2012, less than in waters off the coasts of northern California and the northwestern U.S. (Turi et al. 2016).

Globally, ocean acidification has caused mortality in mollusks, reduced calcification in corals, coccolithophores (a type of phytoplankton), and mollusks, and reduced growth in mollusks, echinoderms, and crustaceans (Kroeker et al. 2013). Along the California coast, ocean acidity has increased more rapidly than the natural rate at which some small planktonic sea snails (pteropods) can increase their shell calcification, leading to dissolving of their shells and death (Bednaršek et al. 2014, Busch et al. 2014, Bednaršek et al. 2017). Ocean acidification has damaged shells of young Dungeness crabs (*Metacarcinus magister*) in acidified waters off the coasts of British Columbia and Washington (Bednaršek et al. 2020).

Ocean deoxygenation Dissolved oxygen is essential for the survival of marine mammals and other marine life. The solubility of oxygen decreases as the temperature of water increases. As a result, ocean warming has reduced oxygen concentrations in the Santa Barbara Channel 20% from 1984 to 2012 (Bograd et al. 2015, Ito et al. 2017, Schmidtko et al. 2017).

Wildfire increase, western U.S. Wildfire is an essential part of many forest, shrubland, and grassland ecosystems, reducing understory overgrowth, facilitating germination of new seedlings, killing pests, and serving other critical functions. Across western U.S. continental forests, increases in vegetation aridity due to the hotter temperatures of anthropogenic climate change doubled burned area from 1984 to 2015, compared to what would have burned without climate change (Abatzoglou and Williams 2016). In addition, the hotter temperatures of anthropogenic climate change combined with statistically significant decreases of summer rainfall from 1979 to 2016 to increase burned area across the western U.S. (Holden et al. 2018). For California as a whole, burned area increased ~500% annually and ~800% in summer from 1972 to 2018, increases that statistical analyses find most closely related to increases in temperature and aridity due to anthropogenic climate change (Williams et al. 2019). These analyses included forests on the mainland but not on the Channel Islands.

Across national parks and protected areas of Canada and the U.S., climate factors explained the majority of burned area from 1984 to 2014, with climate factors (temperature, precipitation, relative humidity, evapotranspiration) outweighing local human factors (population density, roads, and built area) (Mansuy et al. 2019). Multivariate analyses of historical wildfires across the western U.S. from 1916 to 2003, including wildfires in

California chaparral, indicated that climate was the dominant factor controlling the extent of burned area, even during periods of active fire suppression (Littell et al. 2009).

Changes consistent with, but not formally attributed to human-caused climate change

Other research has found changes consistent with human-caused climate change, but either has not detected changes that are statistically significantly different than historical variability or has not analyzed potential causal factors to formally attribute the cause of the change.

Marine heat waves From 1982 to 2016, marine heat waves (periods in which sea surface temperature of a local area was hotter than temperatures in 99% of the time series) doubled globally (Frölicher et al. 2018), consistent with higher sea surface temperatures due to climate change. The marine heat wave along the Pacific Coast from 2014 to 2016 was partly due to climate change, but the relative contributions of natural variability and climate change are unresolved (Jacox et al. 2018). That episode led to mass stranding of sick or starving birds and sea lions, reduced salmon survival, and increases in harmful algal blooms (Cavole et al. 2016).

Harmful algal blooms Warmer water temperatures can contribute to formation of harmful algal blooms (O'Neil et al. 2012). Harmful algal blooms along the U.S. Pacific coast have increased in the past decade (Lewitus et al. 2012, Gobler et al. 2017). Harmful algal blooms can produce domoic acid, which can kill people who eat tainted shellfish (Moore et al. 2008, McKibben et al. 2017) and can kill California sea lions (*Zalophus californianus*) (Scholin et al. 2000, McCabe et al. 2016, McKibben et al. 2017). Ocean warming off southern California in 2003 and 2004 caused harmful algae blooms and domoic acid contamination in phytoplankton and fish caught off Scripps Pier in San Diego (Busse et al. 2006).

Ocean upwelling increase A meta-analysis of published research on eastern ocean boundary current systems found intensification of winds in three of five systems, including the California Current, in the last half of the 20th century (Sydeman et al. 2014). This is consistent with steeper ocean-continent temperature and pressure gradients that would occur under climate change (Bakun 1990) but the changes are inconsistent globally and have not been attributed to anthropogenic climate change.

Intertidal invertebrate changes Resurveys in 2002 of mussel bed communities at eight sites in Channel Islands National Park, two sites on Catalina Island, and other sites along the California coast, first surveyed in the 1960s and 1970s, found significant declines in species richness (Smith et al. 2006). In the ten Channel Islands sites, species richness showed a statistically significant 70% decline, from 116 ± 12 species to 34 ± 2 species. This is consistent with, but not attributed to, ocean warming. In Monterey Bay, California, intertidal pool invertebrates, including mollusks and snails, similar to those found in Channel Islands National Park, showed signs of a northern range shift with increasing water temperatures from 1931 to 1996 (Barry et al. 1995, Sagarin et al. 1999).

Seabird decline Ocean temperature and seabird surveys from 1987 to 1998 in the Channel Islands and California Current waters to the west found an overall decline in seabird abundance, a decline in cold-water species, including the sooty shearwater (*Puffinus griseus*), and an increase in warm-water species, including the pink-footed shearwater (*Puffinus creatopus*), consistent with increasing sea surface temperatures during the period (Veit et al. 1996, Hyrenbach and Veit 2003).

Fog reduction Summer fog (marine layer stratus cloudiness) in the Channel Islands cools summer heat and provides moisture for plants and wildlife. Coastal sage scrub vegetation requires the moisture provided by summer fog (Emery et al. 2018). Analyses of stratus clouds at southern California airports found that the number of summer fog days showed a statistically significant decrease of 38% at Santa Monica Airport, east of the park, and cloud ceiling height showed a statistically significant increase of 61 m from 1973 to 2017 (Williams et al. 2018). Fog at airports along the Pacific coast of North America decreased from 1950 to 2012 (Schwartz et al. 2014). While a decline in fog is consistent with anthropogenic climate change, reduced atmospheric particulates, increased sea surface temperatures, and increased night temperatures, partly from the urban heat island of Los Angeles and San Diego, contribute to the fog decline in southern California (LaDochy and Witiw 2012, Williams et al. 2015). No analyses have examined the relative importance of different causes of southern California fog changes.

Wildfire increase, southern California It is possible that people have used fire to manage vegetation in the Channel Islands since the first humans arrived 13 000 years ago

(Hardiman et al. 2016) and during recent Chumash inhabitation of the islands (Timbrook et al. 1982). Chaparral evergreen shrubland has a natural fire return interval of 70 years or more (Keeley and Fothringham 2001, Keeley et al. 2005b). Chaparral naturally burns at high severity, most often during the autumn season of Santa Ana winds, with fires completely burning aboveground vegetation, which re-sprouts from root crowns after sufficient winter rains (Keeley and Fothringham 2001, Keeley et al. 2005a).

Across southern California, including Channel Islands National Park, the area burned by Santa Ana fires (autumn) and non-Santa Ana fires (summer) increased from 1959 to 2009 (Jin et al. 2014). Temperatures increased significantly during this period, but the relative importance of climate, urbanization, population growth, and other factors have not been determined. Reductions of live fuel moisture and increases of burned area in Southern California were significantly correlated with reduced fog from 1973 to 2017 (Williams et al. 2018). No increase of wildfire has occurred in Channel Islands National Park because the National Park Service (NPS) suppresses all fires, human-ignited and natural.

Tree mortality The California Drought of 2012-2016, caused in part by the increased heat of anthropogenic climate change (Diffenbaugh et al. 2015, Williams et al. 2015), contributed to substantial mortality of bishop pine (*Pinus muricata*) on Santa Cruz Island (Taylor et al. 2019). Other potential factors for tree mortality, however, have not been examined.

Future Climate Projections

Temperature Under the highest emissions scenario (RCP8.5), average annual temperature of the area within park boundaries could increase 1.9 ± 0.5ºC (3.4 ± 0.9ºF.) by 2050 (Table 3) and 3.5 ± 0.8ºC (6.3 ± 1.4ºF.) by 2100, compared to the 1971-2000 baseline (Table 4) (Gonzalez et al. 2018, IPCC 2013). Under the highest emissions scenario, climate change could lengthen the period of temperatures above 18ºC (64º) from zero to four months by 2100, with the current annual maximum temperatures of July occurring as early as May (Figure 3). Cutting greenhouse gas emissions from human activities (emissions scenario RCP2.6) could reduce projected heating by two-thirds (Figure 8). GCMs project the highest temperature increases in autumn (September to November). Projected temperature increases are highest on Anacapa Island and at park headquarters on the mainland in Ventura (Figure 10).

For the area of Ventura, California, models project an increase of the number of days with a maximum temperature greater than 32ºC (90ºF.) of 40 to 60 days per year by 2050 (Vose et al. 2017) and an increase in the hottest day of the year of 5ºC (10ºF.), to as high as 41ºC (105ºF.), by 2100 (Hall et al. 2018) under the highest emissions scenario (RCP8.5).

Precipitation For the area within park boundaries, approximately two-thirds of the GCMs project increases and one-third project decreases (Figure 9). This lack of agreement exists for monthly, seasonal, and annual projections for 2050 (Table 5) and 2100 (Table 6). While the net ensemble average is positive, the projected change is not statistically significant. Even if precipitation increases, increasing temperatures would tend to increase aridity through an increase in evapotranspiration (Byrne and O'Gorman 2015, Jones and Gutzler 2016). Summer fog is controlled by processes that computer modeling currently cannot estimate accurately, so no future projections are available (Clemesha et al. 2016). Spatially, projected precipitation changes are lowest on Santa Barbara Island and highest on San Miguel Island (Figure 11).

For southern California, climate models project increases in precipitation extremes (Polade et al. 2014, 2017). Under the highest emissions scenario, the number of dry days could increase by five to ten days per year (Polade et al. 2014). On the other hand, atmospheric rivers, narrow bands of highly concentrated storms in that move from the Pacific Ocean into California (Warner et al. 2015, Wehner et al. 2017), may increase in frequency and intensity (Jeon et al. 2015, Lavers et al. 2015, Hagos et al. 2016, Kossin et al. 2017). The number of days per year with precipitation may decrease, however, leading to intense wet periods alternating with more intense droughts (Polade et al. 2014, 2017).

For the southwestern U.S. as a whole, models project an increase in five-year storms (a two-day period with more precipitation than any other two-day period in five years) to once every three years (low emissions scenario, RCP4.5) or every two years (highest emissions scenario, RCP8.5) (Easterling et al. 2017). Models project a 20% increase in the amount of precipitation in 20-year storms (a storm with more precipitation than any other storm in 20 years) under the highest emissions scenario (RCP8.5), although a projected increase in downpours does not necessarily increase projected total annual precipitation (Easterling et al. 2017).

Drought Hotter temperatures caused by anthropogenic emissions of greenhouse gases have increased the probability of drought in California by increasing the probability of high temperature and low precipitation occurring at the same time (Diffenbaugh et al. 2015). For the State of California as a whole, under the highest emissions scenario (RCP8.5), climate change increases the probability of a drought as severe as the 2012-2016 drought to ~100% by 2030 (Diffenbaugh et al. 2015).

For the southwestern U.S. as a whole, under the highest emissions scenario (RCP8.5), the severity of drought by 2100 A.D. could increase to a level more severe than any since 1000 A.D. (Cook et al. 2015). Anthropogenic climate change sharply increases the risk of a megadrought, a persistent dry period lasting 10 years or more, with the probability of a megadrought in southern California increasing to 70% to 90% under a temperature increase of 4ºC (Ault et al. 2016). Under the highest emissions scenario, climate models project five to ten more dry days per year in southern California (Polade et al. 2014).

El Niño Southern Oscillation (ENSO) The confidence in any specific projected change in ENSO is low (IPCC 2013, USGCRP 2017). Climate models do not agree on projected changes in the intensity or spatial pattern of ENSO (IPCC 2013, USGCRP 2017, Yeh et al. 2018).

Santa Ana winds For southern California, models project a decrease in the frequency, but not the intensity, of the hot Santa Ana winds (Hughes et al. 2011, Pierce et al. 2018, Guzman-Morales et al. 2019), as much as one-fifth fewer under medium emissions (SRES A1B, IPCC 2007) by 2050 (Hughes et al. 2011). This is due to a potential weakening of the desert air-ocean air temperature gradient (Guzman-Morales et al. 2019).

Future Risks

Without reductions of greenhouse gas emissions from human sources, continued climate change increases risks of ecosystems and other resources to substantial changes (IPCC 2013). Published analyses of projected climate change in southern California or on resources found in Channel Islands National Park has identified numerous risks.

Marine and Coastal Systems

Sea level rise and storm surge Continued climate change under the highest emissions scenario (RCP 8.5) could increase sea level 1.4 m (55 in.) by 2100 at Los Angeles, south of the park (range from 5th to 95th percentile 0.7 m to 2.4 m [28 in. to 94 in.]) (Pierce et al. 2018). A scenario of low emissions (RCP4.5) could limit the increase in sea level to 0.7 cm (30 in.) by 2100 (range from 5th to 95th percentile 0.4 m to 1.4 m [14 in. to 56 in.]) (Pierce et al. 2018). Over and above projected sea level rise, daily high tides and storm surge would increase the potential total sea level rise during the worst storms (Figure 12). The daily tidal range from 1924 to 2019 was 1.7 m (5½ ft.) (NOAA 2019). The storm surge at the Channel Islands from a 100-year storm is approximately 15 cm (6 in.), which is relatively small due to the shallow angle of the islands relative to oncoming storm waves (Bromirski et al. 2017). The worst-case combination of sea level rise under the highest emissions scenario, daily high tide, and storm surge could cause episodes of sea level 3.5 m (11½ ft.) above 2000 sea level by 2100 (Figure 12) (Serafin et al. 2017).

The major future risks of the coast to sea level rise include inundation of land (Pendleton et al. 2010), erosion of coastal cliffs (Young 2018), and inundation of habitat for intertidal species, seabirds, and marine mammals (Funayama et al. 2013). An analysis of the vulnerability of the coasts of Channel Islands National Park to sea level rise analyzed geomorphology, historical shoreline change, regional coastal slope, relative sea level change, mean wave height, and mean tidal range for 1.7 km segments of shoreline (Pendleton et al. 2010). Approximately two-thirds of the San Miguel Island coast and the Sandy Point and Skunk Point sections of Santa Rosa Island are highly vulnerable due to exposed sandy stretches and high waves (Figure 13). Most of the rest of the park shoreline has rock cliffs, steep slopes, and relatively lower wave heights that reduce vulnerability.

Ocean warming Continued climate change could warm California Current waters 2 to 4°C (3.6 to 7.2ºF.) above the 1980–2005 average by 2100 (Alexander et al. 2018). This could contribute to more harmful algal blooms (Gobler et al. 2017, McKibben et al. 2017). Under the highest emissions scenario (RCP8.5), the probability of a marine heat wave off the southern California coast could increase from once every 35 years to once every other year (Frölicher et al. 2018). The 2014-2016 marine heat wave along the Pacific coast demonstrated how warmer ocean waters can increase the mortality of salmon, seabirds, and sea lions (Cavole et al. 2016).

Ocean acidification Ocean acidification dissolves the shells of many marine species and, under high emissions, could deplete near-shore waters of the California Current of calcium carbonate for almost all of the year (Gruber et al. 2012), increasing the vulnerability of many marine species to death. Acidity reduces the water concentrations of calcium carbonate that many marine species, including pteropods, shellfish, and corals, require for building shells for survival. Under a high emissions scenario (SRES A2, IPCC 2007), acidity of California Current waters could increase 40% (-0.15 pH) above 1995 levels by 2050 (Gruber et al. 2012). Under the highest emissions scenario (RCP8.5), acidity of California Current waters could increase 60% (-0.2 pH) above the 2013 level by 2063 (Marshall et al. 2017).

Under continued climate change, ocean upwelling duration in the California Current north of 40ºN latitude could increase by approximately ten days by 2100 A.D. (Wang et al. 2015). Increased upwelling could increase the frequency of incursions of higher-acidity deep ocean water into upper waters.

While analyses project increased acidity in California coastal waters generally, research in the kelp (*Macrocystis pyrifera*) forests of the Channel Islands indicate that photosynthesis uptake of carbon dioxide by kelp and phytoplankton can decrease water acidity (+0.1 to 0.2 pH) (Kapsenberg and Hofmann 2016, Hoshijima and Hofmann 2019). This suggests that the magnitude of acidification in kelp forest waters would be less than in waters outside the kelp forests. This could facilitate limited acclimation of benthic marine invertebrates (Hofmann et al. 2014) and evolutionary adaptation of purple sea urchins (*Strongylocentrotus purpuratus*) (Hoshijima and Hofmann 2019) to acidifying waters.

Ocean deoxygenation Climate change may reduce oxygen in Pacific Ocean waters to levels lower than any naturally occurring levels (dissolved oxygen can vary naturally) as early as 2030 (Long et al. 2016) or 2050 (Henson et al. 2017). Ocean deoxygenation affects fish and marine mammals (sections below). Research in the kelp forests of the Channel Islands found slightly higher dissolved oxygen concentrations in kelp forest waters (Hoshijima and Hofmann 2019).

Intertidal habitat and species Ocean acidification increases the vulnerability of coccolithophores (a type of phytoplankton), mollusks, echinoderms, and crustaceans to mortality and reduced calcification and growth (Kroeker et al. 2013).

Around Santa Cruz Island, sensitivities of sea stars (*Pisaster ochraceus*) and mussels (*Mytilus californianus*) to increases in water temperatures in the intertidal zone and air temperatures at low tide depend on location (Broitman et al. 2009). Body temperatures of sea stars were consistently lower than those of mussels and showed lower daily fluctuations. Body temperatures of the two organisms varied together in warmer southern waters but were less synchronized in cooler northwest waters.

Off-site rearing of the intertidal aquatic crustacean *Tigriopus californicus* taken from Cabrillo National Monument, San Diego (Kelly et al. 2012), Ocean Beach, San Diego (Harada et al. 2019), and other sites along the Pacific coast found that southern populations exhibit more tolerance to warmer water than northern populations, but that the species shows little evolutionary adaptation to temperature increases over time (Kelly et al. 2012).

Ocean warming can shift the ranges of intertidal species from the temperate zone towards the polar zone (Helmuth et al. 2006). In addition, ocean warming can reduce intertidal habitat area when suitable temperatures shift upslope. Research in the intertidal zone on Vancouver Island, Canada, found that 0.4 to 0.6ºC (0.7 to 1.1ºF.) warming of surface waters from 1958 to 2010 reduced the vertical extent of mussel beds by half and contracted predator-free space on rocky shores (Harley 2011). Sea level rise can also inundate intertidal habitat.

Subtidal habitat and species Continued acidification in the California Current could increase mortality of epibenthic invertebrates (crabs, shrimps, benthic grazers, benthic detritivores, bivalves) (Marshall et al. 2017).

Research on the cold-water gorgonian octocoral (*Adelogorgia phyllosclera*) in the waters off Anacapa Island found that the marine heat wave, in 2015 and 2016, increased water temperatures at 20 m depth to 21ºC for up to 14 hours, above the 20ºC thermal limit of the species (Gugliotti et al. 2019).

Warm water temperatures increase the prevalence of the pathogen that causes withering syndrome in black abalone (*Haliotis cracherodii*), which has experienced extirpations across southern California (Neuman et al. 2010, Ben-Horin et al. 2013, Haas et al. 2019). Warm water temperatures also increase the onset of withering syndrome in red abalone (*Haliotis rufescens*) in southern California, halting its growth and reproduction (Vilchis et al. 2005). Reproduction in red abalone declines with increasing water temperatures (Rogers-Bennett et al. 2010) and with acidification (Boch et al. 2017). Comparison of sizes of black abalone from San Miguel Island from 11 000 years ago to the period 1985-2013 showed that larger size was correlated to warmer water temperatures (Haas et al. 2019).

Analyses of benthic water temperatures and abundance of sunflower sea stars (*Pycnopodia helianthoides*) and purple sea urchins (*Strongylocentrotus purpuratus*) in 31 kelp forest monitoring sites in the park from 2006 to 2011 found that, in sites where mean annual temperatures were <14°C, sea stars were common, sea urchins were rare, and kelp was persistent (Bonaviri et al. 2017). At warmer sites, sea stars and kelp were rare but urchins were common.

Reduction of sea star abundance, increase in purple sea urchins, and decrease in kelp, due to grazing by the sea urchins, with increasing waters temperatures observed in the park indicate a risk to kelp forests as climate change continues to warm ocean waters (Bonaviri et al. 2017). While kelp thrives in cooler waters, suggesting a physiological risk under climate change, research at nine kelp forest sites on the mainland coast of the Santa Barbara Channel, north of the park, did not observe reductions in kelp biomass during the marine heat wave years of 2014 and 2015 (Reed et al. 2016).

Marine productivity A projected intensification of upwelling in the California Current system under climate change (Wang et al. 2015) could increase nutrient inputs into surface waters and increase productivity, but potentially disrupt food webs or alter diet composition of marine birds in the park (Sydeman et al. 2001). The reduction of zooplankton with ocean deoxygenation in the Pacific Ocean suggests changes in the food webs that could affect marine mammals (Wishner et al. 2018).

Fish Under a high emissions scenario (SRES A2, IPCC 2007), higher sea surface temperatures in the waters of the Channel Islands could cause northward range shifts of fish species and reduce species richness 5% to 10% by 2050 (Cheung et al. 2015). Reduced oxygen could decrease rockfish habitat off southern California by 20 to 50% (McClatchie et al. 2010). Further deoxygenation may also shrink open-water habitat for hake (*Merluccius productus*) and other fish species in the southern California Current (Koslow et al. 2017). Marine heat waves can cause fish kills, particularly in shallower waters (Cavole et al. 2016).

Seabirds Marine heat waves can cause mortality of seabirds from reduced fish stocks (Cavole et al. 2016). Decreases in seabird populations in the California Current system are related in part to reduced fish stocks (Becker et al. 2006, Ainley and Hyrenbach 2010). Sea level rise could inundate low-lying coastal habitat for Scripps's murrelet (*Synthliboramphus scrippsi*) and other shorebirds in the park (Rick et al. 2014).

Research on Santa Barbara Island found that increased precipitation can increase the population of the Santa Barbara deer mouse (*Peromyscus maniculatus elusus*), which in turn increases the abundance of barn owls (*Tyto alba*), which, when the deer mouse population falls, kills increasing numbers of the Scripps's murrelet (Thomsen et al. 2018). In drought years, the deer mouse feeds on the eggs of the murrelet (Thomsen et al. 2019). These threats to Scripps's murrelet could increase under continued climate change.

Marine mammals Marine heat waves can cause increased mortality of sea lions (Cavole et al. 2016). The reduction of zooplankton with ocean deoxygenation in the Pacific suggests changes in the food webs that could affect marine mammals (Wishner et al. 2018).

Sea level rise could inundate low-lying coastal habitat for seals and other pinnipeds, particularly on San Miguel Island (Rick et al. 2014), analogous to the projected loss of haul-out areas for northern elephant seals (*Mirounga angustirostris*) in Point Reyes National Seashore under continued sea level rise (Funayama et al. 2013).

Gray whales (*Eschrichtius robustus*) and humpback whales (*Megaptera novaeangliae*), which migrate through the park, may spend more time in Arctic waters due to longer and earlier ice-free conditions, delaying their southern migration and changing the duration of their passage through California waters (Moore et al. 2007, Moore and Huntington 2008). One indicator of this has been an increase in gray whale reproduction in the Arctic due to an increase in the ice-free season in the period 1980-2009 (Salvadeo et al. 2015).

Terrestrial Ecosystems

Wildfire The hotter temperatures of anthropogenic climate change and increased aridity of vegetation may increase fire frequency and burned area across much of California (Mann et al. 2016, Westerling 2018). Under high emissions (scenario A2 of IPCC (2007), hotter than RCP6.0 of IPCC (2013)), one fire model projects increased wildfire potential on the northwestern third of Santa Rosa Island and on the eastern third of Santa Cruz Island (Mann et al. 2016). In these areas, the model only provides a rough estimate of a decrease in the fire return interval from an estimated current level of >150 years by approximately 50 years on Santa Cruz Island and 150 years on Santa Rosa Island by 2050. The magnitudes of the projected intervals depend on the current fire interval but the model does not give a more specific estimate of the current interval than >150 years. Under the highest emissions scenario (RCP8.5), another model projects an increase of fire frequency in the central part of Santa Cruz Island from an estimated current level of zero to 3 times per century by 2100 (Westerling 2018). The models project no increase in potential wildfire in the rest of Channel Islands National Park.

Under the highest emissions scenario (RCP8.5), fire frequency could double in forests and shrublands on the mainland north and east of the park (Westerling 2018). Across southern California, increased temperatures and decreased relative humidity could increase probabilities of Santa Ana fires (autumn) and non-Santa Ana fires (summer) (Jin et al. 2014). Analysis of southern California fire records and climate data for the period 1910-2013 indicates that summer and autumn climate conditions are often sufficient for large fires, so that the coincidence of Santa Ana winds and human ignitions would most often determine fire occurrence under climate change (Keeley and Syphard 2017).

Tree mortality Field research in the park shows that fog is important to the survival of bishop pine (*Pinus muricata*) (Fischer et al. 2009, Carbone et al. 2013, Baguskas et al. 2014, 2016, Fischer et al. 2016), Torrey pine (*Pinus torreyana*) (Williams et al. 2008), and island oak (*Quercus tomentella*) (Woolsey et al. 2018), providing essential moisture in the summer. So, any reduction of fog under climate change would increase drought stress and the risk of tree mortality. On Santa Cruz Island, field research found that bishop pine survival in the 2007-2009 drought was highest for trees in areas of more frequent fog (Baguskas et al. 2014). Water from fog and the cooling effect of overcast skies substantially reduces drought stress and seedling mortality in bishop pine (Fischer et al. 2009, Carbone et al. 2013, Baguskas et al. 2016). On Santa Rosa Island, analysis of Torrey pine tree rings and cloud records from 1944 to 2004 at the Oxnard and Santa Barbara airports showed that tree growth was most strongly correlated to summer fog frequency (Williams et al. 2008). Field research in Santa Barbara County indicates that coastal sage scrub also requires summer fog (Emery et al. 2018), so any continued decrease in fog could increase mortality of coastal sage scrub plant species.

Vegetation change Analysis of an indicator of vegetation production derived from remote sensing, the Normalized Difference Vegetation Index, at 250 m spatial resolution, showed no statistically significant change for the park as a whole from 2000 to 2016, with the last three years occurring during the California Drought (Gillespie et al. 2018). This suggests that the drought hindered vegetation recovery that started before the drought in extensive areas of restoration of chaparral and coastal sage scrub vegetation in the park. The section on carbon (below) describes evidence of vegetation and ecosystem carbon recovery using other remote sensing data (Gonzalez et al. 2015).

Increases of fire frequency due to anthropogenic climate change can reduce natural regeneration and increase invasive alien grasses, leading to more fire and conversion of chaparral to coastal sage scrub or grassland (Keeley and Brennan 2012, Lippitt et al. 2013, Rachels et al. 2016, Syphard et al. 2019). For example, after the Cedar Fire east of San Diego in 2003, woolyleaf ceanothus (*Ceanothus tomentosus*) and chamise (*Adenostoma fasciculatum*), both native shrubs, declined in many locations and foxtail chess (*Bromus madritensis*), an invasive alien grass, increased (Keeley and Brennan 2012).

With continued strict fire suppression in Channel Islands National Park, however, the park may not experience such vegetation changes, but perhaps experience increases in the maturity of chaparral stands and in the extent of chaparral, at the expense of coastal sage scrub. For the entire range of white coast ceanothus, fire suppression could cause some biomass accumulation (Uyeda et al. 2016). Post-fire biomass in chaparral showed substantial increases from seven to 28 years, then modest increases from 28 to 68 years (Uyeda et al. 2016).

Invasive plant increase Climate change can favor invasive alien plants in temperate zones, including in the park, for three main reasons:

Carbon dioxide (CO_2) enrichment Invasive alien plants generally exploit atmospheric CO_2 more efficiently than native species, generating higher growth rates (Davidson et al. 2011, Liu et al. 2017). Carbon enrichment experiments on one invasive alien annual found in the park, foxtail chess or Madrid brome (*Bromus madritensis*), indicated that a doubling of atmospheric CO_2 (equivalent to the high emissions scenario, RCP6.0) could lead to a 20% increase in seeds (Huxman et al. 1999). Carbon enrichment experiments on red brome (*Bromus rubens*), an invasive alien annual widespread in the park, indicated that a doubling of atmospheric CO_2 (equivalent to the high emissions scenario, RCP6.0) could lead to a 20% increase in seeds (Huxman et al. 1999) and that a tripling of atmospheric CO_2 (higher than the high emissions scenario, RCP8.5) could increase primary productivity by one-fifth (Yoder et al. 2000).

Warmth and moisture Increasing warmth and moisture due to climate change can increase the suitability of temperate zone ecosystems to plants from tropical zones (Theoharides and Dukes 2007, Hellmann et al. 2008). Exotic grass species are generally annual, taller, with larger leaves, and larger seeds than native species. Across California, these traits are associated with higher temperature, so exotic grass species are more dominant in warmer areas of the state (Sandel and Dangremond 2012).

A rainfall manipulation experiment at the University of California, Irvine, indicated that coastal sage shrub species can outcompete invasive grasses under lower rainfall but that invasive grasses are more competitive under higher rainfall (Goldstein and Suding 2014). In addition, under high emissions (SRES A2, IPCC 2007), species distribution modeling indicates that the park would continue to provide suitable habitat for the invasive yellow starthistle (*Centaurea solstitialis*) (Bradley et al. 2009).

Any future conditions of increasing aridity would be unfavorable to invasive alien plants that thrive in moister conditions. Conversely, any future conditions of increasing moisture could favor invasive alien plants. The chance of increased frequency of extreme storms in the region (Easterling et al. 2017) could lead to episodes of higher moisture, which, if they would happen, would occur in winter (Tables 5, 6). Red brome invasion of native grassland and shrubland increases with higher winter rainfall (Brooks and Berry 2006).

Disturbance Invasive alien plants often proliferate in sites disturbed by physical vegetation removal or by wildfire (Theoharides and Dukes 2007, Hellmann et al. 2008). Anthropogenic climate change causes two disturbances, biome shifts (Gonzalez et al. 2010) and increased wildfire (Abatzoglou and Williams 2016, Littell et al. 2009), that tend to increase the risk of invasive species establishment (Early et al. 2016). As described in the sections above on wildfire and vegetation change, invasive plant species can proliferate after fire in southern California chaparral or coastal scrub (Keeley et al. 2005a, Lippitt et al. 2013). Strict fire suppression in the park would therefore tend to control invasive plant species. Field research in southern California indicates that, in chaparral or coastal scrub, high woody plant cover is the most important element controlling invasive alien plant invasion and persistence (Keeley et al. 2005a).

Furthermore, native plant species on oceanic islands tend to be more vulnerable to invasive non-native plant species due to reduced dispersal capabilities, the lack of adjacent land to shift geographic range, and the small ranges of endemic plant species (Harter et al. 2015).

Rare plant species On Santa Rosa Island, field research examined climate sensitivities of Hoffmann's slender-flowered gilia (*Gilia tenuiflora* ssp. *hoffmannii*), Northern island phacelia (*Phacelia insularis* var. *insularis*), and Santa Cruz Island chicory (*Malacothrix indecora*), three endemic annual plant species listed as endangered under the U.S. Endangered Species Act (Levine et al. 2008, 2011). For these species, population sizes and growth rates are correlated to temperature in the period following the first major storm event of the winter. Under continued climate change, higher temperatures after the first rains may reduce germination. Experiments with the three species did not find any statistically significant effect of competition of the invasive exotic ripgut briome (*Bromus diandrus*) or the native herb California goldfields (*Lasthenia californica*) on the response of the three species to drought or increased rainfall (Levine et al. 2010).

On Santa Rosa Island, hotter growing season temperatures reduce growth of soft-leaved paintbrush (*Castilleja mollis*), a perennial plant listed as endangered under the Endangered Species Act, indicating a sensitivity to continued climate change (McEachern et al. 2009).

An assessment of life history attributes and species distribution models of 156 rare plant species in California identified 42 species as extremely or highly vulnerable to a reduction in population due to climate change (Anacker et al. 2013). Two of these vulnerable species are present in the park: Coulter's saltbush (*Atriplex coulteri*) and Robinson's peppergrass (*Lepidium virginicum* var. *robinsonii*) (NPS 2019).

Surface water Field surveys of surface water features on Santa Rosa Island, including streams, ponds, springs, and seeps, found declines in three of four watersheds, of 10% to 30% from 2014 to 2016, the last three years of the California drought (Power and Rudolph 2018). In these three years, precipitation fell to three-quarters to one-half of the historical average (Figure 5, Table 2), indicating the sensitivity of surface water to future droughts under climate change.

Terrestrial Birds Research on San Clemente Island, south of the park, on the sage sparrow (*Amphispiza belli*), a species listed as present in Channel Islands National Park (NPS 2019), found that drought, which may increase in frequency under climate change, increases the risk of reproductive failure and mortality (Hudgens et al. 2011).

Climate change could continue to shift the ranges of bird species northward across the U.S. (Langham et al. 2015). Modeling of suitable climate for bird species in 2050 indicates that, under the highest emissions scenario (RCP8.5), the park may gain suitable climate for 27 bird species not currently present in winter and 26 species not currently present in summer but lose suitable climate for six species in winter (Wu et al. 2018). Potential colonizers include the bronzed cowbird (*Molothrus aeneus*) and the fish crow (*Corvus ossifragus*). Species vulnerable to extirpation include the pine siskin (*Spinus pinus*) and willow flycatcher (*Empidonax traillii*) (Wu et al. 2018).

While climate change has been invoked as a reason for the managed relocation of the island scrub-jay (*Aphelocoma insularis*) from Santa Cruz Island to Santa Rosa Island, where it has not historically been found (Morrison et al. 2011), no quantitative information on the vulnerability of the species to climate change has been published.

Amphibians, Reptiles An assessment of 358 amphibian, reptile, bird, and mammal species in California listed as species of concern, threatened, or endangered (California Department of Fish and Wildlife 2016) identified species highly vulnerable to drought. None of the 21 highly vulnerable amphibian and reptile species are found in the park (NPS 2019). The loss of surface water observed on Santa Rosa Island during the recent California drought (Power and Rudolph 2018) suggests that amphibians are at risk of losing moist habitat areas if climate change reduces precipitation or fog or increases aridity.

Cultural Resources

Channel Islands National Park protects paleontological, archaeological, and historical artifacts and sites of ancient ecosystems, the indigenous Chumash and Tongva peoples, and more recent fishing people and settlers.

Monitoring of 11 archaeological sites along the coast of Santa Rosa Island from 2013 to 2017 showed that the sites are sensitive to erosion from sea cliff retreat and upland gullies, due to increased precipitation and sea level rise, two hazards exacerbated by climate change (Jazwa and Johnson 2018). During the four-year period, sites experienced erosion of 4% to 56% of their surface area and gully or cliff wall retreat up to 16 cm (6 in.) in a year. Sites on the northwest coast, directly in the path of prevailing winds and winter storms, experienced the most erosion. An analysis of coastal topography, land use, and tides indicated a high vulnerability to erosion of archaeological sites on the northeast, west, and south shores of Santa Rosa Island, the north shore of Santa Cruz Island, and most of the coast of San Miguel Island (Reeder-Myers 2015).

While no other published research has specifically examined cultural resources in Channel Islands National Park, continued climate change could increase the exposure of cultural resources to damage. Sea level rise could inundate some late period and historic Chumash village sites and historic ranch sites, many of which are located in low-lying coastal areas. Any increase in wildfire (Mann et al. 2016, Westerling 2018) could increase the risk of loss of historic wooden structures. Tree mortality and vegetation change could alter the form and character of cultural landscapes, such as the historically significant Monterey cypress trees (*Cupressus macrocarpa*) of Delphine's Grove, in the Santa Cruz Island Historic Ranching District.

Under any climate change scenarios of increased warmth and humidity, research in Europe indicates that museum objects kept in ambient or near-ambient conditions are at risk of increased mold and deterioration (Huijbregts et al. 2012).

Human Health and Public Safety

Extreme heat Exposure to extremely hot temperatures due to anthropogenic climate change in heat waves has killed people in California (Knowlton et al. 2009, Hoshiko et al. 2010, Guirguis et al. 2014) and Arizona (Yip et al. 2008, Putnam et al. 2018). Under continued climate change, models project increases up to 60 more days per year with a maximum temperature >32ºC (90ºF.) in the region around the park under the highest emissions scenario (RCP8.5) (Vose et al. 2017). Increases in hot days and extreme heat will increase the risk of heat-associated deaths (USGCRP 2016).

Smoke from mainland fires Wildfires in mainland forests and shrublands produce smoke plumes that reach the Channel Islands. Projected increases in mainland wildfires under climate change (Mann et al. 2016, Westerling 2018) could increase exposure of staff and visitors in Ventura and the islands to smoke, including fine particulates ($PM_{2.5}$), which can cause severe respiratory problems (Liu et al. 2016). Under a medium emissions scenario (SRES A1B, IPCC (2007), Santa Barbara County as a whole could have one to two more days per year with unhealthy air quality from wildfire smoke ($PM_{2.5}$ > 98^{th} percentile of historical) by 2050 (Liu et al. 2016).

Carbon

Growing vegetation naturally removes carbon from the atmosphere, reducing the magnitude of climate change. Conversely, tree mortality, from deforestation, wildfire, drought, and other causes, emits carbon to the atmosphere, exacerbating climate change. The balance between carbon emissions from vegetation to the atmosphere and removals from the atmosphere into vegetation determines the role of ecosystems in climate change (IPCC 2013).

Analyses of Landsat remote sensing at 30 m spatial resolution, field measurements of biomass, and Monte Carlo analyses of error in tree measurements, remote sensing, and the carbon fraction of biomass determined this balance across the state of California (Gonzalez et al. 2015). In 2010, aboveground live vegetation in Channel Islands National Park contained 220 000 tons ± 160 000 tons of carbon (mean ± 95% confidence interval) (Table 7). This stock is equivalent to the greenhouse gases emitted in one year by 24 000 ± 17 000 Americans, based on 2013 emissions and population. The highest carbon density in the park occurs in the small patches of pine forest in the park (Figure 14). From 2001 to 2010, the carbon stock in the aboveground vegetation of the park showed no statistically significant change (Table 7).

From 2001 to 2010, aboveground vegetation carbon increased on one-third of the land area of Santa Rosa Island and one-tenth of the land area of Santa Cruz Island, primary at its eastern end, exceeding the surface areas of losses (Figure 15, Table 7). The carbon increases result from increased vegetation cover, coinciding with ecosystem recovery in those areas after removal of livestock and feral animals (Summers et al. 2018, Woolsey et al. 2018, Yelenik 2018). Although the total surface area in the national park that experienced carbon increases (green areas in Figure 15) greatly exceeded the surface area that experienced carbon losses (small brown patches in Figure 15), the increases generally involved an increase of grassland cover with only a modest increase in carbon density (carbon per hectare), while the decreases often involved losses of shrub vegetation in chaparral with carbon densities 10-20 times greater than grassland. So, small areas of chaparral loss nullified the grassland gains. The mean change in aboveground carbon stock of the park from 2001 to 2010 showed a slight decrease but the decrease was not statistically significant (Table 7).

Eelgrass (*Zostera marina*) beds and kelp (*Macrocystis pyrifera*) forests in California marine ecosystems also sequester carbon (Nielsen et al. 2018) but no published research has estimated marine carbon stocks in the park.

As part of the NPS Climate Friendly Parks program, Channel Islands National Park has conducted an inventory of greenhouse gas emissions from fossil fuel use in energy, transportation, and waste generation by park operations and visitors (NPS 2010). The analysis estimated total emissions in 2007 of 350 million tons carbon, of which 80% came from cars, boats, and other vehicles, 10% from electricity use, and 10% from solid waste and other sources. The *Channel Islands National Park Action Plan* (NPS 2010) identified energy conservation, renewable energy, recycling, and other actions to cut the emissions that cause climate change.

The Intergovernmental Panel on Climate Change has confirmed that concerted global action can reduce emissions from human activities enough to meet the Paris Agreement goal of limiting the future global temperature increase to 1.5 to 2ºC (IPCC 2018). The difference between the emissions reductions scenario (RCP2.6) and the highest emissions scenario (RCP8.5), as shown in Tables 3 and 4 and much of the research cited in this report, shows that cutting carbon emissions from human activities can substantially reduce future heating and risks to the plants, animals, and unique resources of Channel Islands National Park.

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Figure 1. Real-color image of the northern Channel Islands and mainland California, 11:30 AM, October 18, 2019 (data Landsat, U.S. Geological Survey; analysis P. Gonzalez). Islands, east (right) to west (left): Anacapa, Santa Cruz, Santa Rosa, San Miguel. Cities: Ventura (on coast to the east), Santa Barbara (on coast to the north).

Figure 2. Average annual temperature, 1895-2017, for the area within Channel Islands National Park boundaries, with the trend calculated by linear regression, corrected for temporal autocorrelation (Gonzalez et al. 2018).

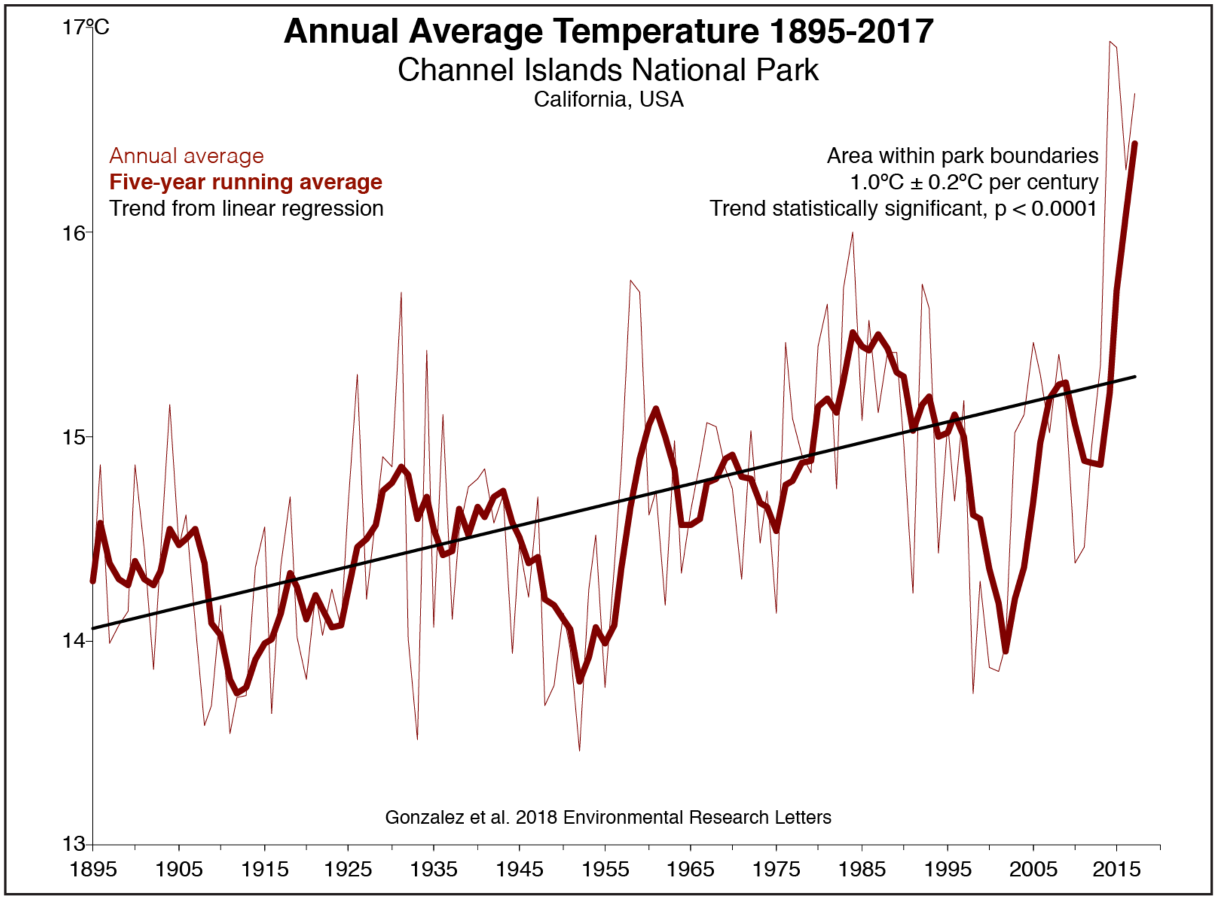

Figure 3. Monthly average temperatures, historical and projected, for the area within Channel Islands National Park boundaries (Gonzalez et al. 2018). From 1895 to 2010, the period of temperatures above 16ºC (61ºF.) increased from zero to four months. Under the highest emissions scenario, climate change could lengthen the period of temperatures above 18ºC (64º) from zero to four months by 2100. Cutting carbon emissions from human activities could reduce the projected increase in heating (RCP8.5) by two-thirds (RCP2.6).

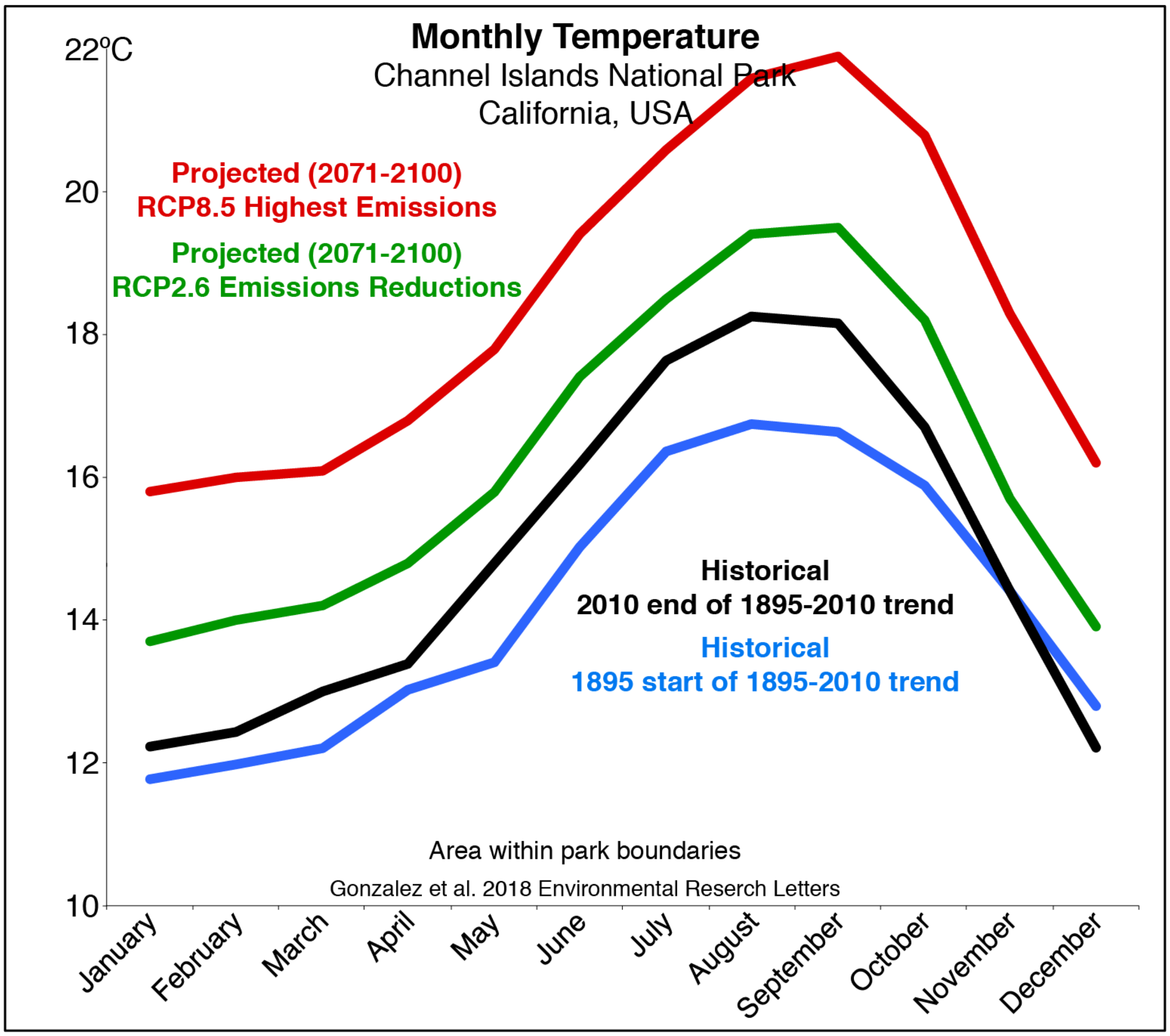

Figure 4. Trend in annual average temperature, 1895-2016, at 800 m spatial resolution, across Channel Islands National Park, from linear regression, corrected for temporal autocorrelation (Gonzalez et al. 2018).

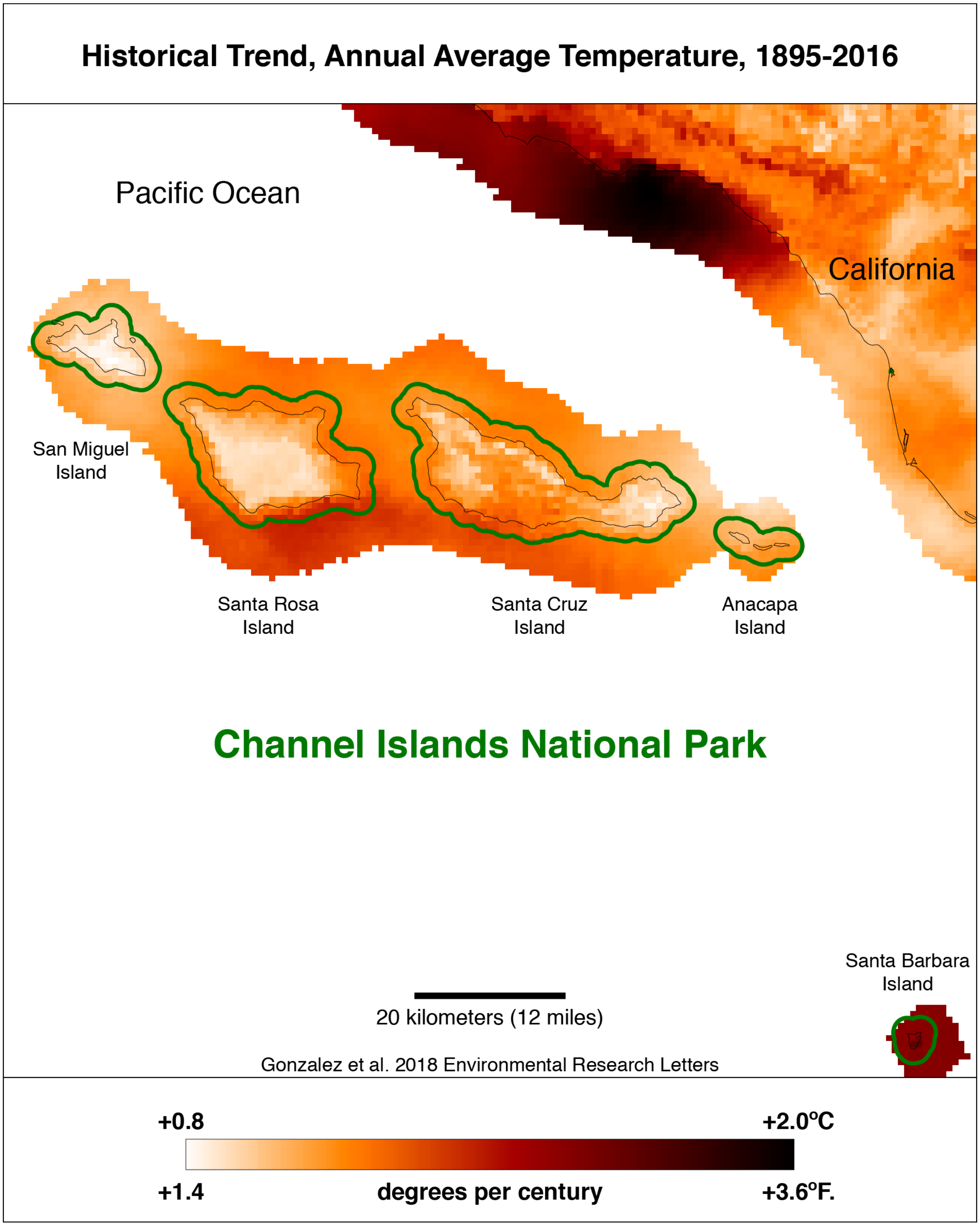

Figure 5. Total annual precipitation, 1895-2017, for the area within Channel Islands National Park boundaries (Gonzalez et al. 2018).

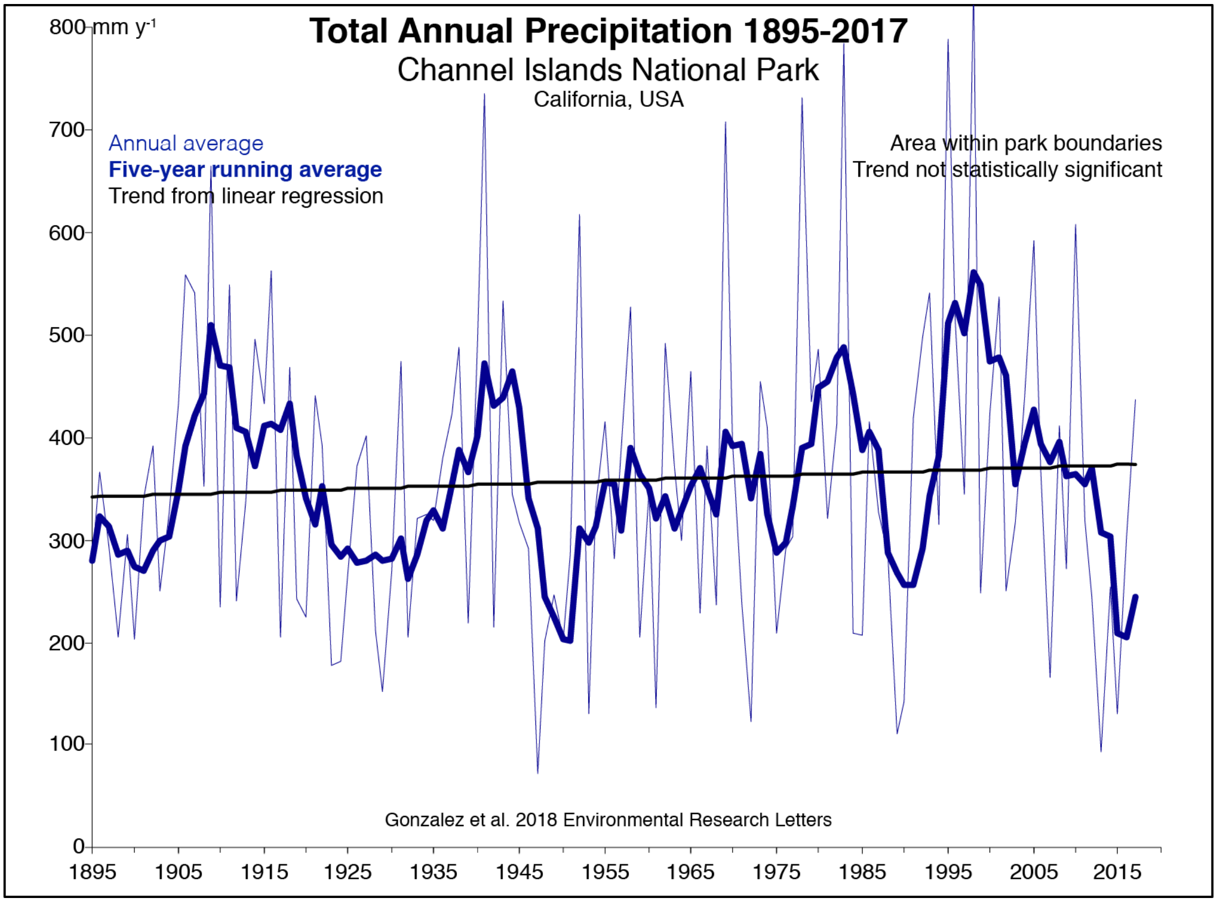

Figure 6. Trend in total annual precipitation, 1895-2016, at 800 m spatial resolution, across Channel Islands National Park, from linear regression, corrected for temporal autocorrelation (Gonzalez et al. 2018).

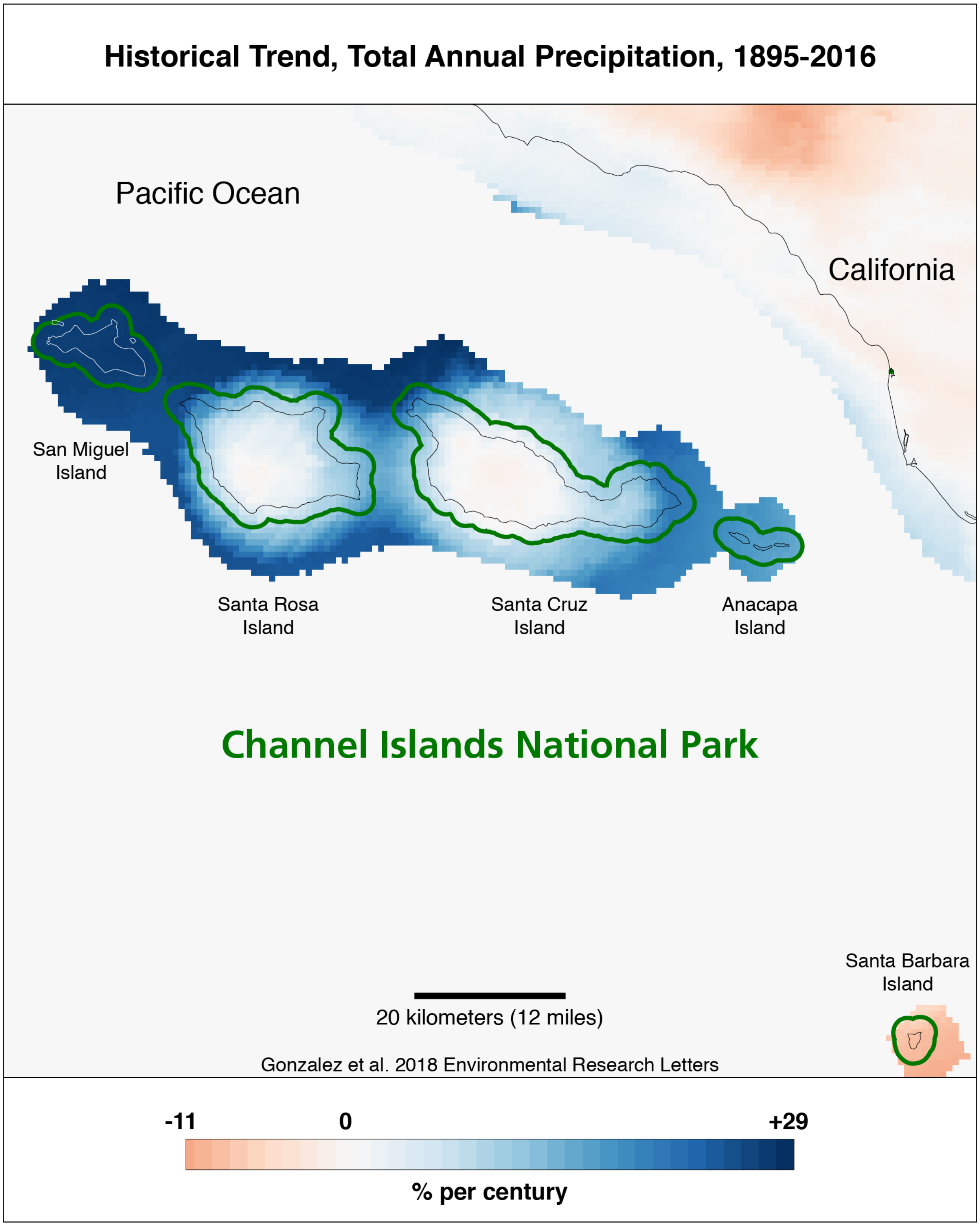

Figure 7. Sea level, 1924-2019, at the tidal gauge at the Port of Los Angeles, California, relative to mean sea level for the period 1983-2001 (the National Tidal Datum Epoch of the U.S. National Ocean Service), with the trend calculated by linear regression, corrected for temporal autocorrelation (NOAA 2019).

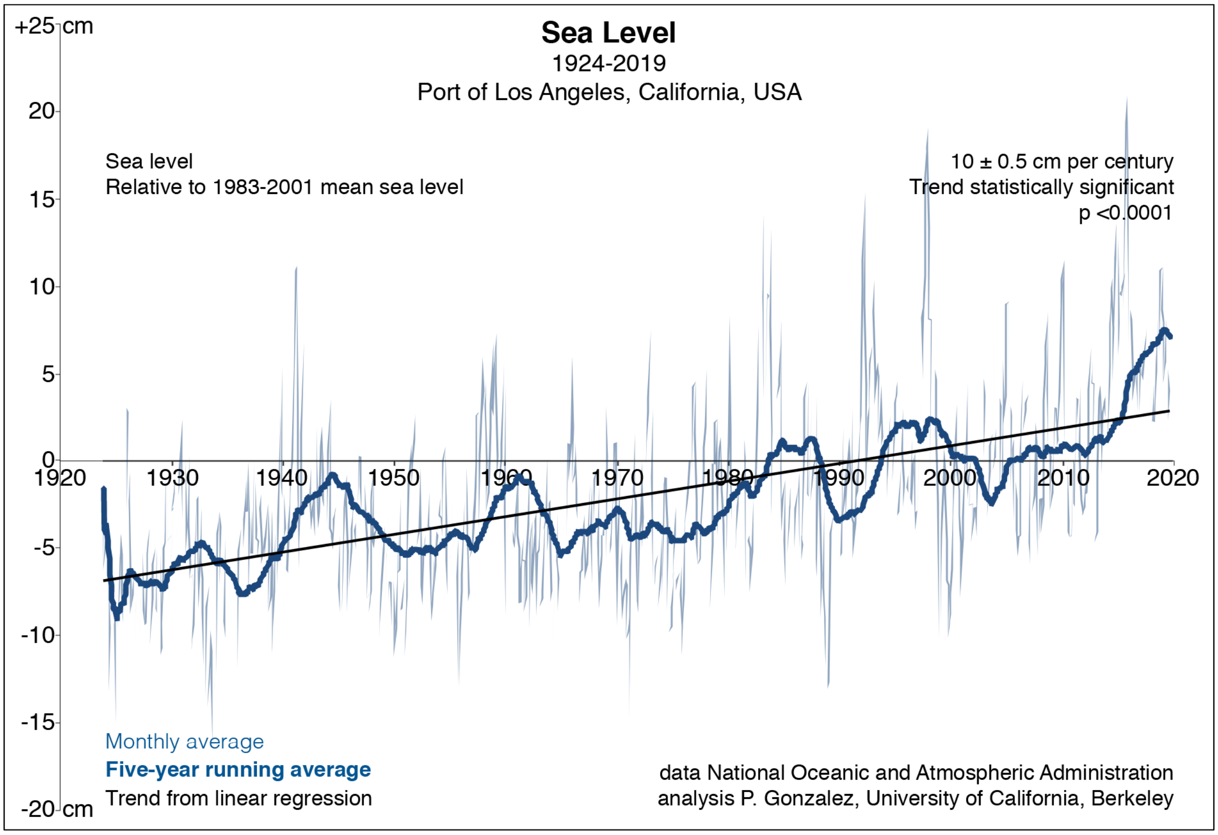

Figure 8. Sea surface temperature, 1924-2019, at Scripps Pier, San Diego, California (Scripps Institution 2019), with the trend calculated by linear regression, corrected for temporal autocorrelation.

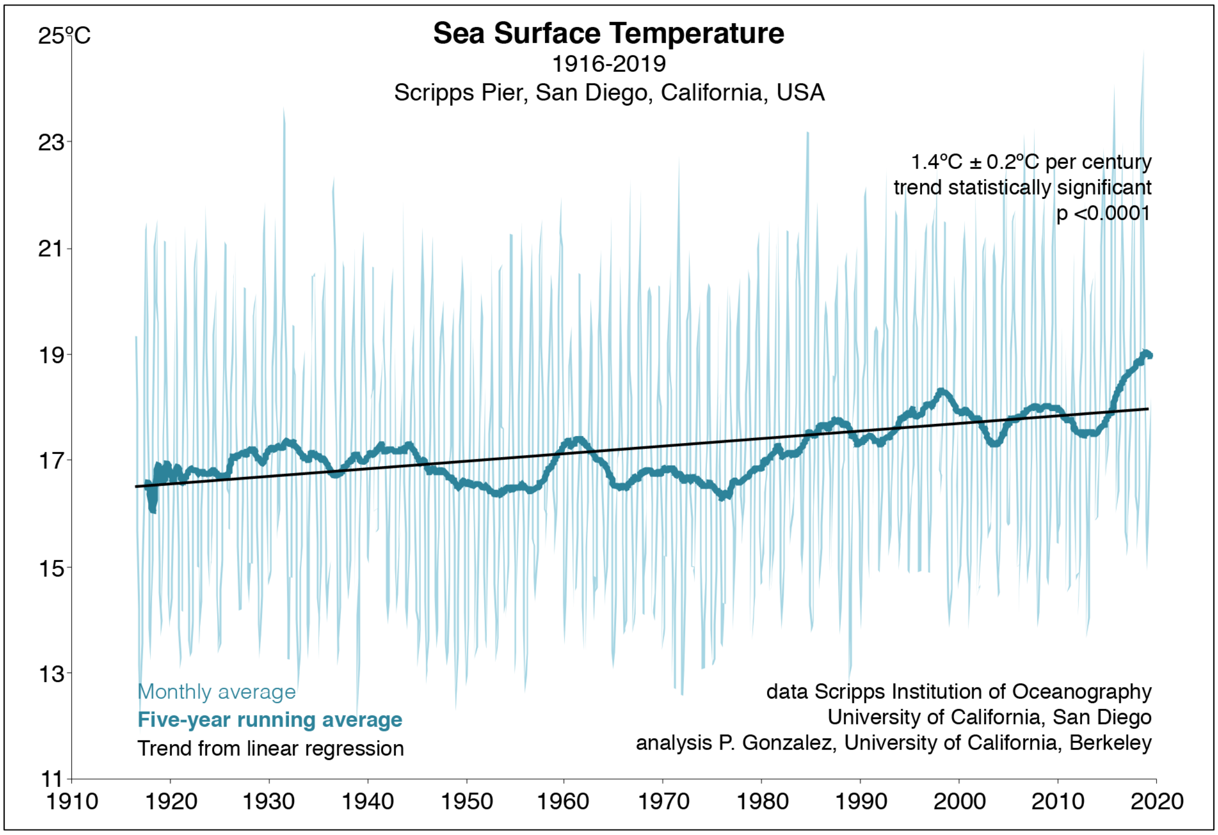

Figure 9. Projections of future climate for the area within park boundaries, relative to 1971-2000 average values (Gonzalez et al. 2018). Each small dot is the output of one of 121 runs of 33 general circulation models. The large color dots are the average values for the four IPCC emissions scenarios. The crosses are the standard deviations of the average values.

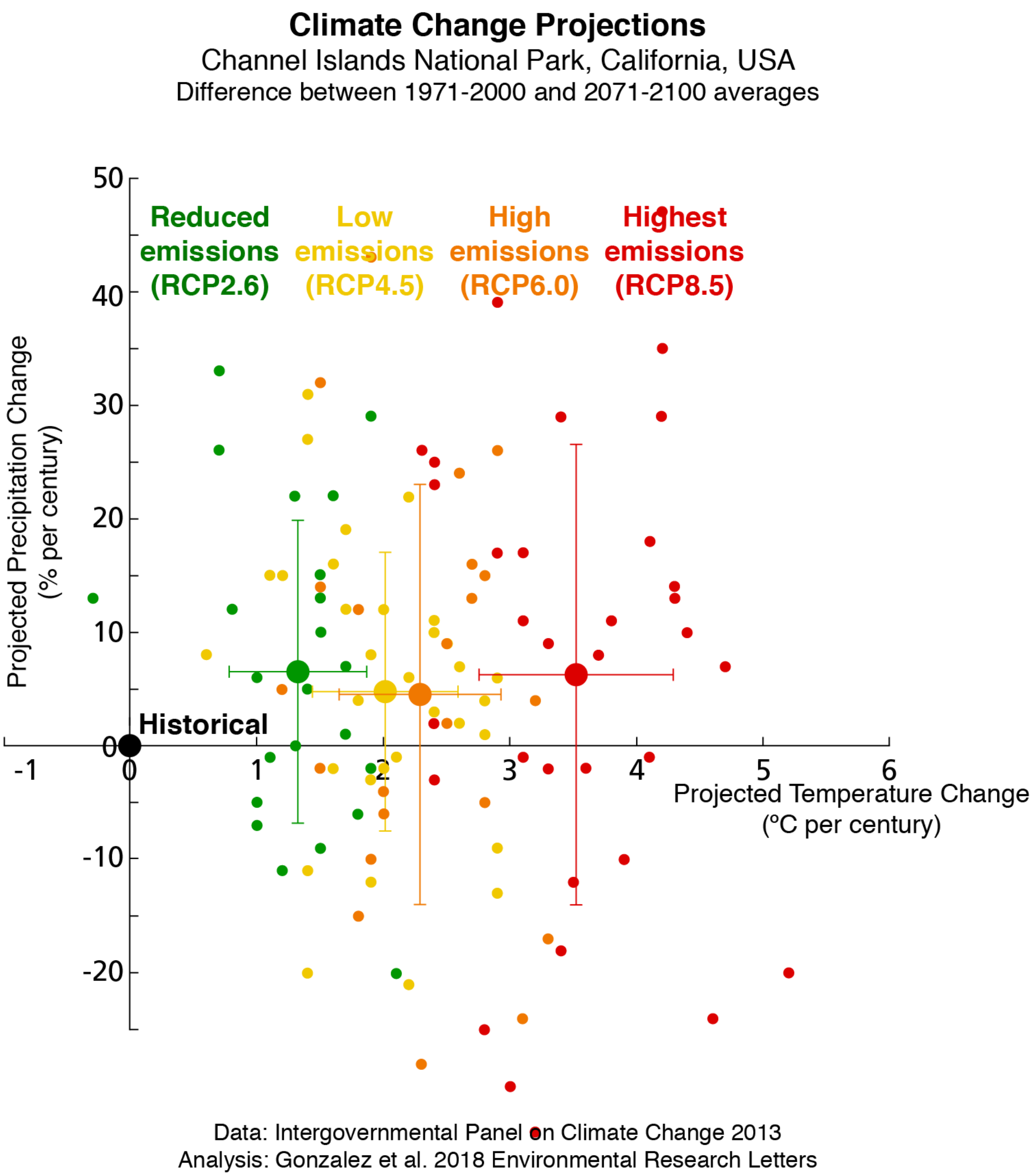

Figure 10. Projected change in annual average temperature, 2000-2100, at 800 m spatial resolution, across Channel Islands National Park, for the highest emissions scenario (RCP8.5) for the average of 33 general circulation models (IPCC 2013, Gonzalez et al. 2018).

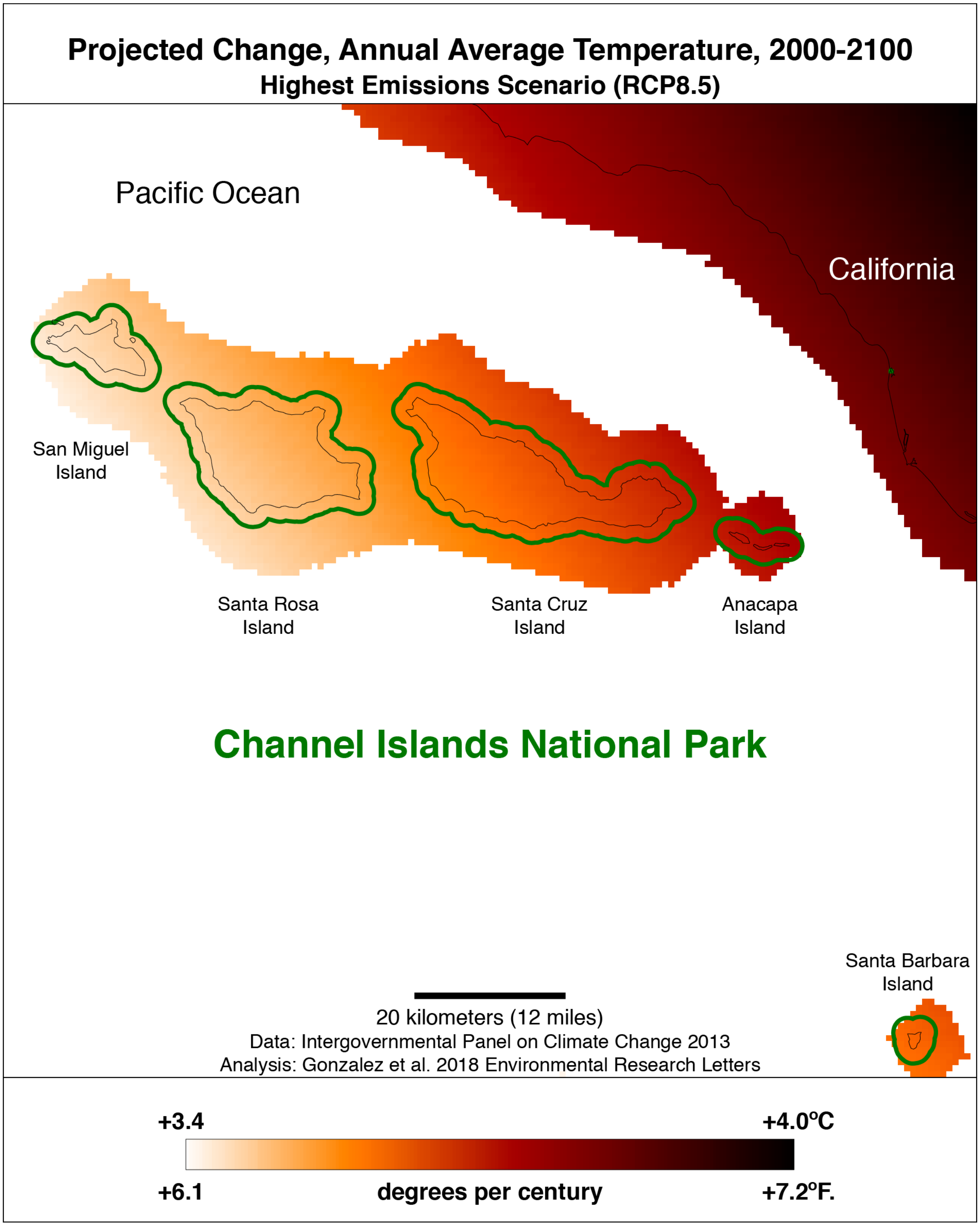

Figure 11. Projected change in total annual precipitation, 2000-2100, at 800 m spatial resolution, across Channel Islands National Park, for the highest emissions scenario (RCP8.5) for the average of 33 general circulation models (IPCC 2013, Gonzalez et al. 2018).

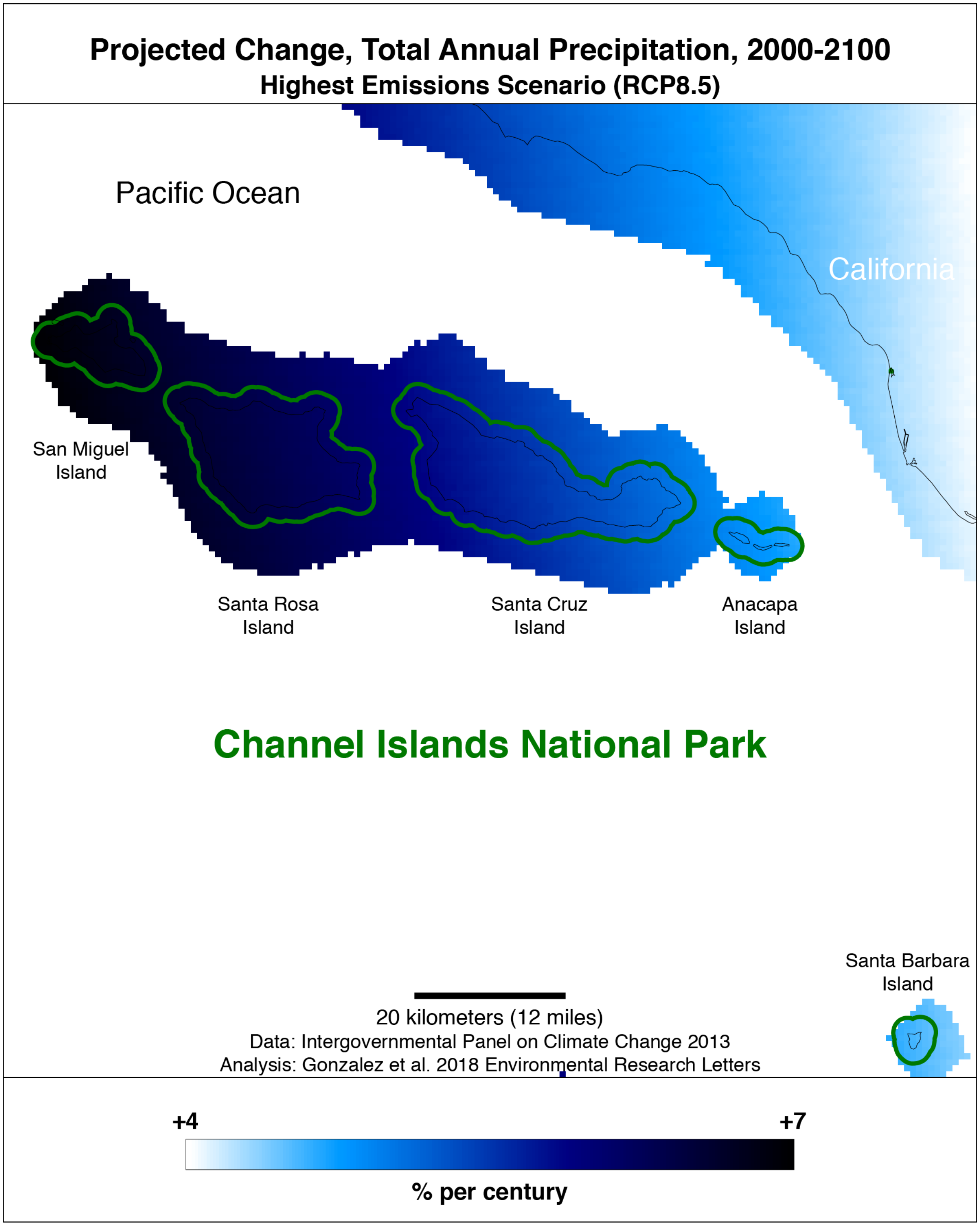

Figure 12. Historical sea level rise (NOAA 2019), projected sea level rise under two emissions scenarios (Pierce et al. 2018), tidal range (NOAA 2019), and storm surge (Bromirski et al. 2017) at the tidal gauge at Los Angeles, California. The combination of past and projected sea level rise, daily tidal range, and storm surge could raise sea level up to 3.5 m above the 2000 level by 2100.

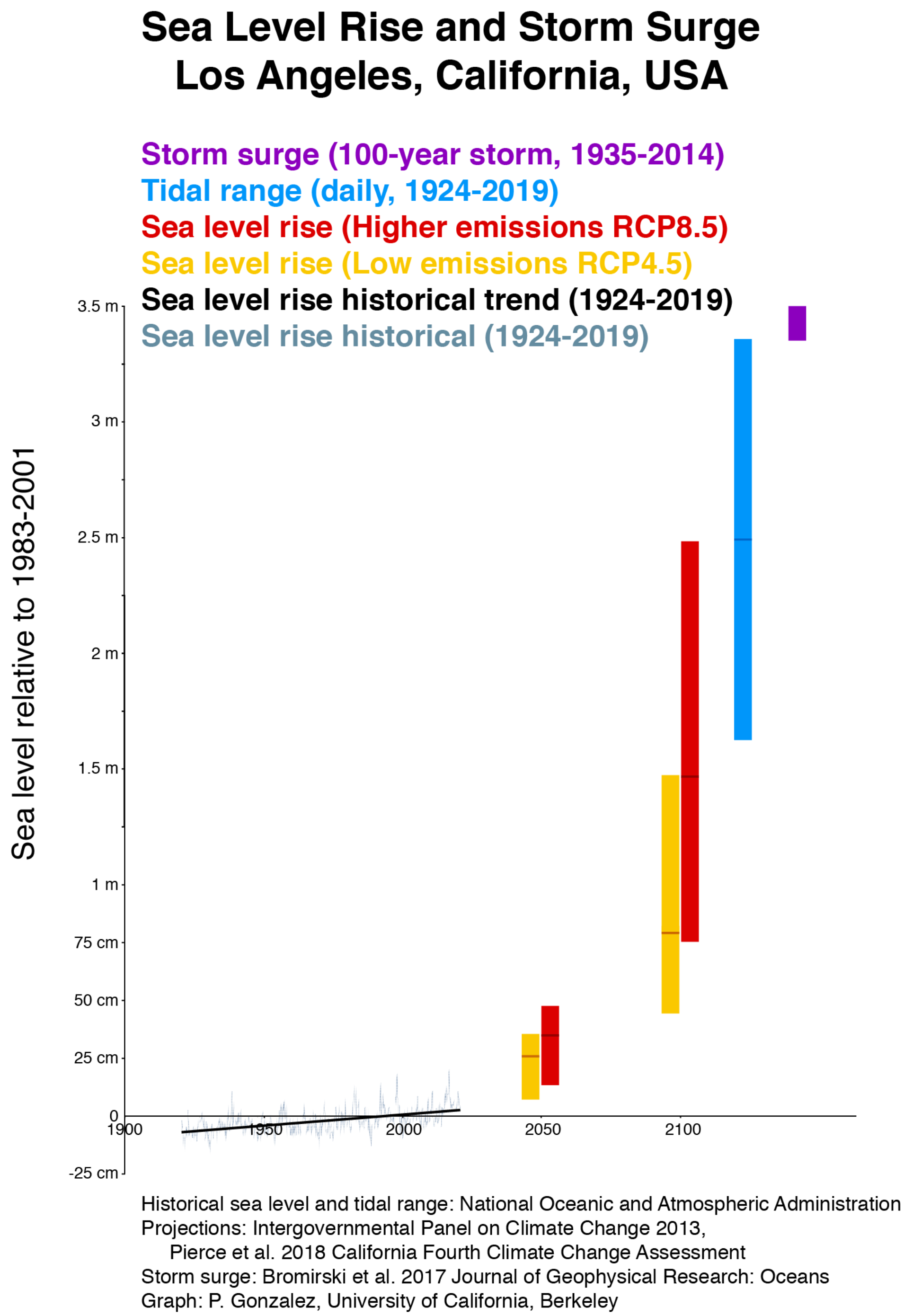

Figure 13. Relative coastal vulnerability across Channel Islands National Park (Pendleton et al. 2010). Shoreline colors show a relative coastal vulnerability index estimated from geomorphology, historical shoreline change, regional coastal slope, relative sea level change, mean wave height, and mean tidal range. Shorelines with rock cliffs, steep slopes, and relatively lower wave heights are least vulnerable. Shorelines with sandy stretches of coast and high waves are most vulnerable.

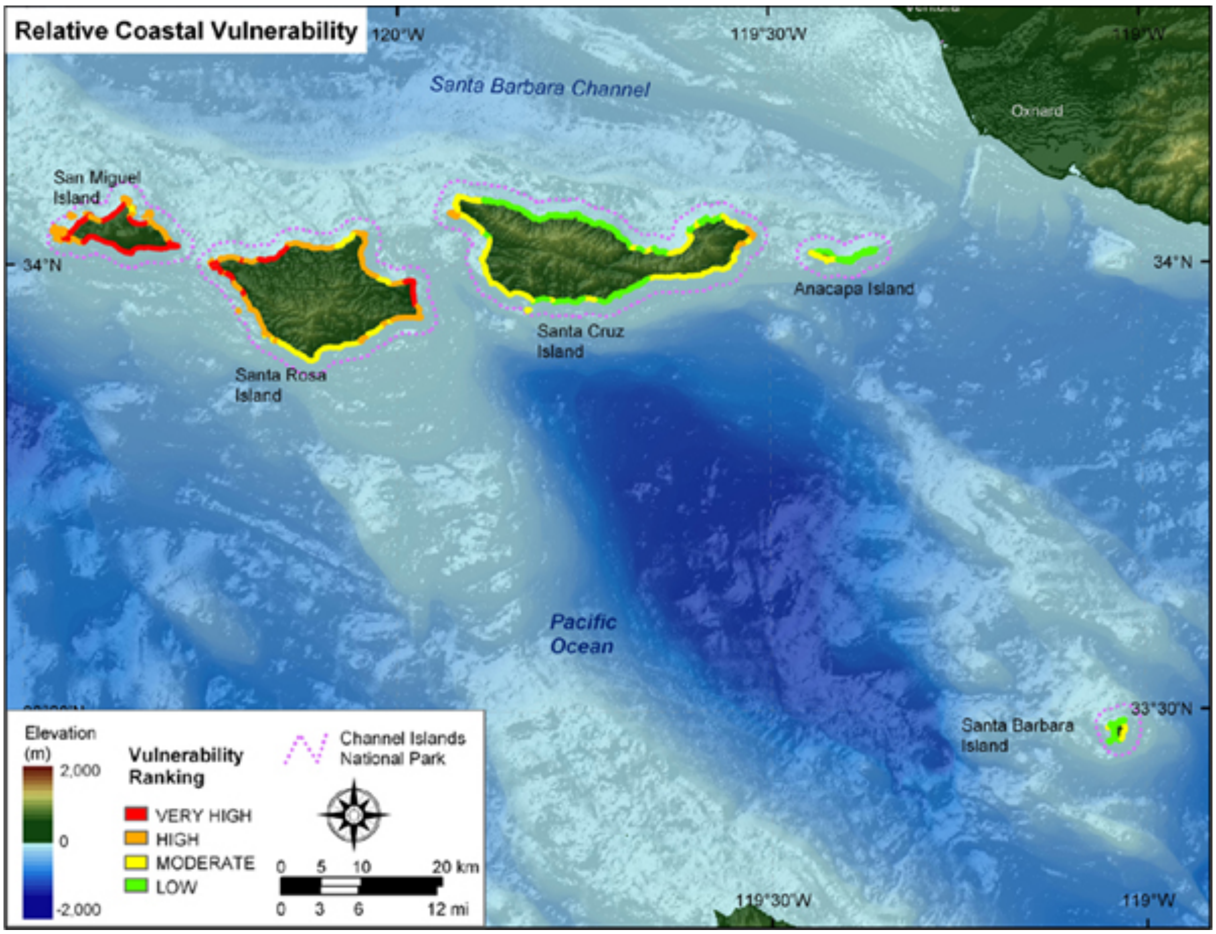

Figure 14. Aboveground vegetation carbon in 2010, across Channel Islands National Park (Gonzalez et al. 2015).

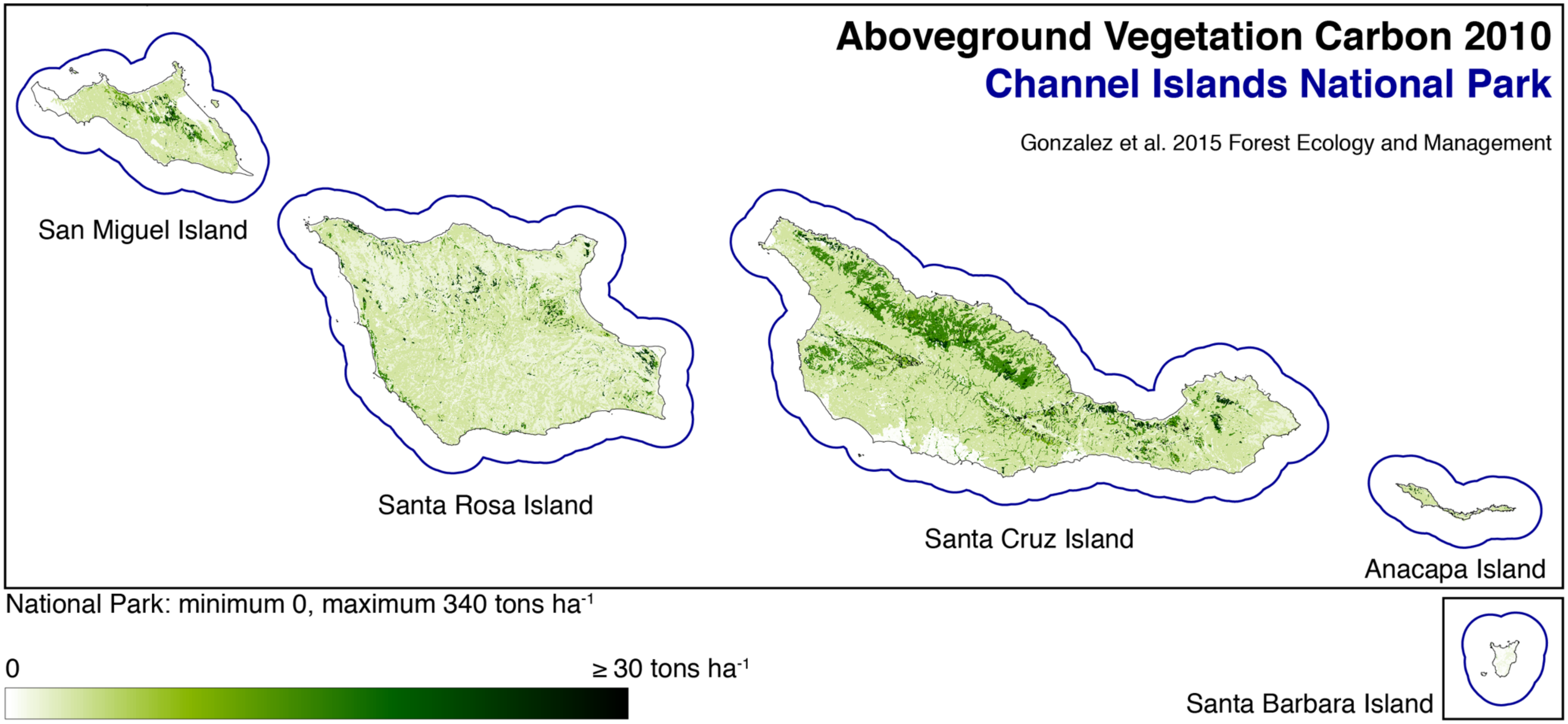

Figure 15. Aboveground vegetation carbon change, 2001-2010, across Channel Islands National Park (Gonzalez et al. 2015).

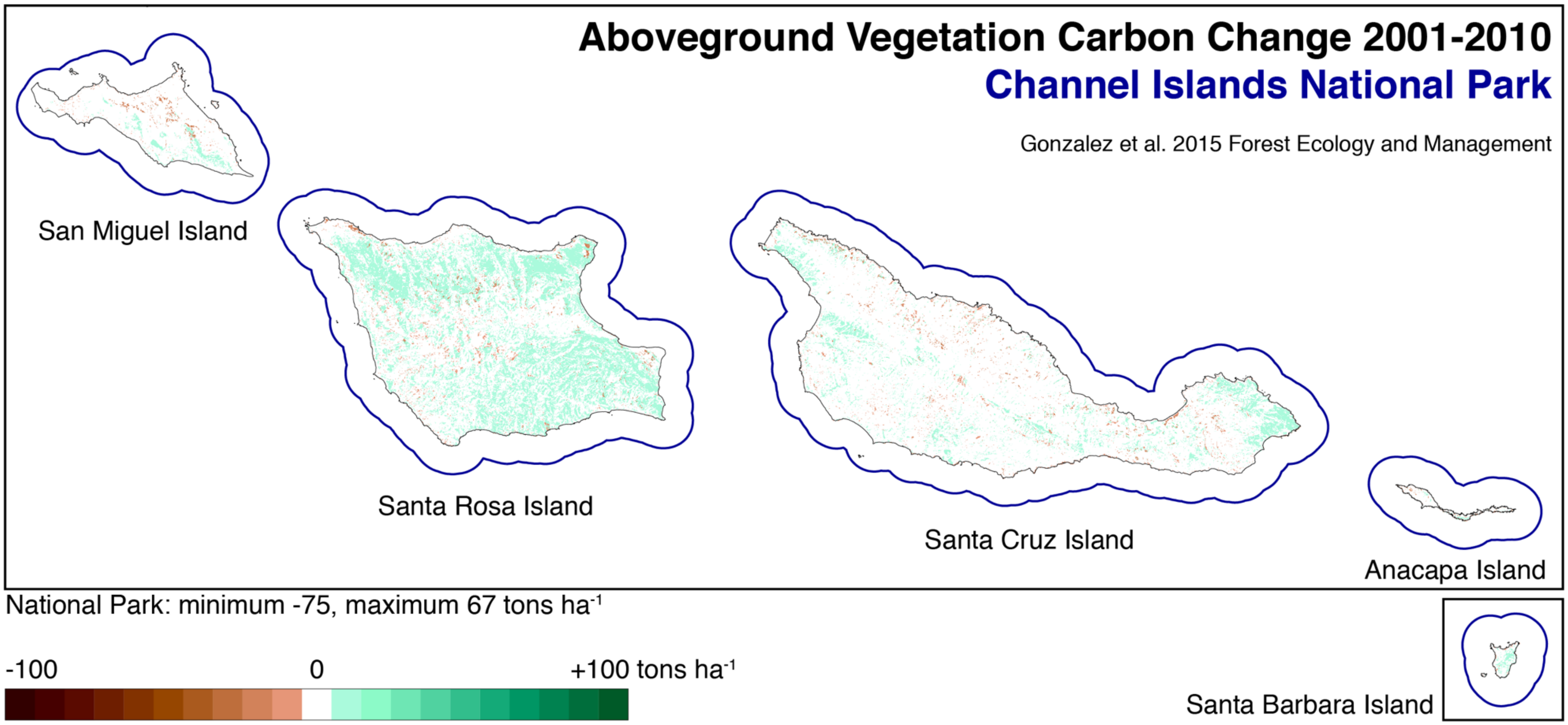

Table 1. **Historical average temperatures** and trends for the area within the boundaries of Channel Islands National Park (Gonzalez et al. 2018). SD = standard deviation, SE = standard error, sig. = statistical significance, * $P \leq 0.05$, ** $P \leq 0.01$, *** $P \leq 0.001$.

	1971-2000		1895-2010			1950-2010		
	mean	SD	trend	SE	sig.	trend	SE	sig.
	ºC		ºC century^{-1}			ºC century^{-1}		
Annual	15	0.5	0.7	0.2	**	1.4	0.6	*
December-February	12.5	0.9	0.1	0.3		0.9	0.6	
March-May	13.7	1	0.7	0.3	*	2.3	0.9	*
June-August	17.3	0.7	1.2	0.3	***	1.7	0.7	*
September-November	16.4	0.7	0.7	0.3	*	0.7	0.6	
January	12.3	1.1	0.4	0.4		2.3	0.8	**
February	12.7	1.1	0.4	0.4		0.9	0.8	
March	12.9	1.3	0.7	0.4		2.6	0.9	**
April	13.6	1.3	0.3	0.4		1.6	1.2	
May	14.6	1.2	1.2	0.3	***	2.8	0.8	**
June	16.2	1	1	0.4	**	2.2	0.8	*
July	17.4	0.8	1.1	0.3	***	1.5	0.7	*
August	18.1	0.9	1.3	0.4	**	1.4	0.9	
September	18	1.3	1.3	0.4	**	1.2	0.9	
October	16.7	0.9	0.7	0.3	*	0.7	0.9	
November	14.3	1.3	0	0.4		0.3	0.8	
December	12.5	1.2	-0.5	0.4		-0.8	1	

Table 2. **Historical average precipitation** totals and trends for the area within the boundaries of Channel Islands National Park (Gonzalez et al. 2018). No trends were statistically significant. SD = standard deviation, SE = standard error.

	1971-2000		1895-2010		1950-2010		
	mean	SD	trend	SE	trend	SE	
	mm y^{-1}		% $century^{-1}$		% $century^{-1}$		
Annual	407	194	11	11	38	28	
December-February	243	146	15	15	58	36	
March-May	111	79	-3	19	-3	51	
June-August	3	5	-24	48	-21	125	
September-November	53	42	14	21	-24	59	
January	85	84	0	24	25	56	
February	98	94	34	23	110	59	
March	83	68	-8	26	32	72	
April	21	25	19	33	-113	76	
May	7	17	-39	51	140	143	
June	1	2	-42	71	51	137	
July	0	1	-52	73	-214	209	
August	2	5	10	84	-24	261	
September	8	19	-60	59	-68	174	
October	13	16	10	34	280	104	**
November	32	32	30	35	-120	91	
December	56	47	19	23	85	65	

Table 3. **Projected temperature increases** (°C), 2000 to 2050, for the area within the boundaries of Channel Islands National Park (Gonzalez et al. 2018), from the average of all available general circulation model projections used for IPCC (2013). RCP = representative concentration pathway, SD = standard deviation.

	Emissions Scenarios							
	Reductions RCP2.6		Low RCP4.5		High RCP6.0		Highest RCP8.5	
	mean	SD	mean	SD	mean	SD	mean	SD
Annual	1.3	0.4	1.5	0.4	1.4	0.3	1.9	0.5
December-February	1.2	0.4	1.5	0.5	1.3	0.4	1.9	0.6
March-May	1.2	0.4	1.4	0.5	1.3	0.4	1.7	0.5
June-August	1.2	0.5	1.4	0.5	1.3	0.3	1.8	0.5
September-November	1.4	0.5	1.7	0.6	1.6	0.4	2.3	0.6
January	1.2	0.5	1.5	0.4	1.4	0.4	1.9	0.6
February	1.2	0.4	1.4	0.5	1.2	0.5	1.7	0.5
March	1.2	0.4	1.4	0.5	1.2	0.5	1.7	0.5
April	1.1	0.5	1.3	0.6	1.3	0.4	1.7	0.5
May	1.2	0.4	1.4	0.6	1.3	0.4	1.7	0.5
June	1.1	0.5	1.3	0.6	1.2	0.4	1.7	0.6
July	1.2	0.6	1.3	0.5	1.3	0.4	1.7	0.6
August	1.4	0.5	1.5	0.6	1.5	0.3	2	0.5
September	1.5	0.5	1.7	0.5	1.6	0.5	2.2	0.6
October	1.4	0.5	1.7	0.6	1.5	0.4	2.3	0.7
November	1.4	0.5	1.7	0.8	1.5	0.4	2.3	0.9
December	1.2	0.5	1.6	0.7	1.4	0.4	2.1	0.8

Table 4. **Projected temperature increases** (°C), 2000 to 2100, for the area within the boundaries of Channel Islands National Park (Gonzalez et al. 2018), from the average of all available general circulation model projections used for IPCC (2013). RCP = representative concentration pathway, SD = standard deviation.

	Emissions Scenarios							
	Reductions RCP2.6		Low RCP4.5		High RCP6.0		Highest RCP8.5	
	mean	SD	mean	SD	mean	SD	mean	SD
Annual	1.3	0.5	2	0.6	2.3	0.6	3.5	0.8
December-February	1.3	0.5	2	0.6	2.3	0.7	3.5	0.9
March-May	1.2	0.5	1.8	0.5	2.1	0.6	3.2	0.7
June-August	1.2	0.6	1.9	0.6	2.2	0.6	3.3	0.8
September-November	1.5	0.6	2.3	0.8	2.5	0.7	4	1
January	1.4	0.5	2	0.6	2.3	0.7	3.5	0.8
February	1.3	0.5	1.9	0.6	2.2	0.7	3.3	0.8
March	1.3	0.6	1.8	0.6	2.2	0.6	3.2	0.8
April	1.2	0.5	1.8	0.6	2.1	0.6	3.2	0.7
May	1.2	0.5	1.9	0.6	2.1	0.6	3.2	0.7
June	1.2	0.6	1.8	0.7	2.1	0.6	3.2	0.8
July	1.1	0.7	1.8	0.7	2.1	0.7	3.2	0.8
August	1.3	0.6	2	0.7	2.4	0.6	3.5	0.8
September	1.5	0.6	2.3	0.7	2.5	0.7	3.9	0.9
October	1.5	0.7	2.4	0.8	2.5	0.8	4.1	1.1
November	1.4	0.6	2.3	1	2.5	0.7	4	1.2
December	1.4	0.5	2.1	0.9	2.3	0.7	3.7	1.2

Table 5. **Projected precipitation changes** (%), 2000 to 2050, for the area within the boundaries of Channel Islands National Park (Gonzalez et al. 2018), from the average of all available general circulation model projections used for IPCC (2013). RCP = representative concentration pathway, SD = standard deviation.

	Emissions Scenarios							
	Reductions RCP2.6		Low RCP4.5		High RCP6.0		Highest RCP8.5	
	mean	SD	mean	SD	mean	SD	mean	SD
Annual	6	12	3	14	5	16	3	16
December-February	8	17	8	21	10	25	10	24
March-May	2	16	-2	19	-5	16	-6	26
June-August	45	73	57	77	35	48	54	99
September-November	4	20	-4	27	5	25	-7	25
January	18	30	10	29	15	35	20	34
February	6	28	10	29	11	35	9	31
March	5	19	-2	23	-1	24	-2	27
April	0	26	-2	28	-14	22	-11	43
May	-3	59	6	96	4	56	1	85
June	23	78	22	64	11	77	14	90
July	92	112	79	147	91	113	79	134
August	71	140	119	193	82	148	114	150
September	43	80	58	128	55	97	41	88
October	18	41	8	53	30	64	13	54
November	-4	22	-13	39	-7	26	-17	28
December	3	23	3	21	3	24	-1	27

Table 6. **Projected precipitation changes** (%), 2000 to 2100, for the area within the boundaries of Channel Islands National Park (Gonzalez et al. 2018), from the average of all available general circulation model projections used for IPCC (2013). RCP = representative concentration pathway, SD = standard deviation.

	Emissions Scenarios							
	Reductions RCP2.6		Low RCP4.5		High RCP6.0		Highest RCP8.5	
	mean	SD	mean	SD	mean	SD	mean	SD
Annual	7	13	5	12	5	18	6	20
December-February	7	16	11	20	10	29	18	32
March-May	8	20	-3	18	-2	20	-11	27
June-August	54	63	55	91	39	79	79	110
September-November	4	19	-3	31	-7	22	-12	22
January	10	23	17	29	16	36	30	44
February	7	27	15	29	13	40	22	42
March	8	27	-2	18	5	26	-4	24
April	9	33	-6	29	-12	29	-20	40
May	27	84	8	96	-8	62	-25	78
June	30	63	18	71	22	83	15	72
July	111	138	83	143	83	145	228	458
August	92	139	122	204	82	147	156	252
September	41	69	32	95	41	83	44	89
October	21	47	3	41	19	50	8	63
November	-4	21	-8	40	-18	24	-22	31
December	3	17	-4	25	2	22	-2	24

Table 7. **Ecosystem Carbon**. Aboveground carbon (mean ± 95% confidence interval) and surface area of changes in Channel Islands National Park (Gonzalez et al. 2015).

		Santa Cruz Island	Santa Rosa Island	Channel Islands NP
Carbon stock 2010	thousand tons	130 ± 91	67 ± 70	220 ± 160
Carbon density 2010	tons per hectare	5.3 ± 3.7	3.1 ± 3.3	4.3 ± 3.2
Change 2001-2010	thousand tons	-1.1 ± 1.6	-1.5 ± 1	-3.9 ± 4.2
Change 2001-2010	% of amount	-1 ± 1	-2 ± 2	-2 ± 2
Carbon increase	% of area	9	34	19
Carbon decrease	% of area	2	2	3

References

Abatzoglou, J.T. and A.P. Williams. 2016. Impact of anthropogenic climate change on wildfire across western US forests. Proceedings of the National Academy of Sciences of the USA 113: 11 770-11 775.

Abraham, J.P., M. Baringer, N.L. Bindoff, T. Boyer, L.J. Cheng, J.A. Church, J.L. Conroy, C.M. Domingues, J.T. Fasullo, J. Gilson, G. Goni, S.A. Good, J.M. Gorman, V. Gouretski, M. Ishii, G.C. Johnson, S. Kizu, J.M. Lyman, A.M. Macdonald, W.J. Minkowycz, S.E. Moffitt, M.D. Palmer, A.R. Piola, F. Reseghetti, K. Schuckmann, K.E. Trenberth, I. Velicogna, and J.K. Willis. 2013. A review of global ocean temperature observations: Implications for ocean heat content estimates and climate change. Reviews of Geophysics 51: 450-483.

Ainley, D.G. and K.D. Hyrenbach. 2010. Top-down and bottom-up factors affecting seabird population trends in the California current system (1985–2006). Progress in Oceanography 84: 242-254.

Alexander, M.A., J.D. Scott, K.D. Friedland, K.E. Mills, J.A. Nye, A.J. Pershing, and A.C. Thomas. 2018. Projected sea surface temperatures over the 21st century: Changes in the mean, variability and extremes for large marine ecosystem regions of Northern Oceans. Elementa: Science of the Anthropocene 6: 9. doi:10.1525/elementa.191.

Anacker, B.L., M. Gogol-Prokurat, K. Leidholm, and S. Schoenig. 2013. Climate change vulnerability assessment of rare plants in California. Madroño 60: 193-210.

Ault, T.R., J.S. Mankin, B.I. Cook, and J.E. Smerdon. 2016. Relative impacts of mitigation, temperature, and precipitation on 21st-century megadrought risk in the American Southwest. Science Advances 2: e1600873. doi:10.1126/sciadv.1600873.

Baguskas, S.A., S.H. Peterson, B. Bookhagen, and C.J. Still. 2014. Evaluating spatial patterns of drought-induced tree mortality in a coastal California pine forest. Forest Ecology and Management 315: 43-53.

Baguskas, S.A., C.J. Still, D.T. Fischer, C.M. D'Antonio, and J.Y. King. 2016. Coastal fog during summer drought improves the water status of sapling trees more than adult trees in a California pine forest. Oecologia 181: 137-148.

Bakun, A. 1990. Global climate change and intensification of coastal ocean upwelling. Science 247: 198-201.

Barry, J.P., C.H. Baxter, R.D. Sagarin, and S.E. Gilman. 1995. Climate-related, long-term faunal changes in a California rocky intertidal community. Science 267: 672-675.

Becker, B.H. and S.R. Beissinger. 2006. Centennial decline in the trophic level of an endangered seabird after fisheries decline. Conservation Biology 20: 470-479.

Bednaršek, N., R.A. Feely, M.W. Beck, S.R. Alin, S.A. Siedlecki, P. Calosi, E.L. Norton, C. Saenger, J. Štrus, D. Greeley, N.P. Nezlin, M. Roethler, and J.I. Spicer. 2020. Exoskeleton dissolution with mechanoreceptor damage in larval Dungeness crab related to severity of present-day ocean acidification vertical gradients. Science of The Total Environment 716: 136610. doi:10.1016/j.scitotenv.2020.136610.

Bednaršek, N., R.A. Feely, J.C.P. Reum, B. Peterson, J. Menkel, S.R. Alin, and B. Hales. 2014. *Limacina helicina* shell dissolution as an indicator of declining habitat suitability owing to ocean acidification in the California Current Ecosystem. Proceedings of the Royal Society B 281: 20140123. doi:10.1098/rspb.2014.0123.

Bednaršek, N., R.A. Feely, N. Tolimieri, A.J. Hermann, S.A. Siedlecki, G.G. Waldbusser, P. McElhany, S.R. Alin, T. Klinger, B. Moore-Maley, and H.O. Pörtner. 2017. Exposure history determines pteropod vulnerability to ocean acidification along the US West Coast. Scientific Reports 7: 4526. doi: 10.1038/s41598-017-03934-z.

Ben-Horin, T., H.S. Lenihan, and K.D. Lafferty. 2013. Variable intertidal temperature explains why disease endangers black abalone. Ecology 94: 161-168.

Berg, N. and A. Hall. 2017. Anthropogenic warming impacts on California snowpack during drought. Geophysical Research Letters 44: 2511-2518.

Boch, C.A., S.Y. Litvin, F. Micheli, G. De Leo, E.A. Aalto, C. Lovera, C.B. Woodson, S. Monismith, and J.P. Barry. 2017. Effects of current and future coastal upwelling conditions on the fertilization success of the red abalone (*Haliotis rufescens*). International Council for the Exploration of the Sea Journal of Marine Science 74: 1125-1134.

Bograd, S.J., M. Pozo Buil, E. Di Lorenzo, C.G. Castro, I.D. Schroeder, R. Goericke, C.R. Anderson, C. Benitez-Nelson, and F.A. Whitney. 2015. Changes in source waters to the Southern California Bight. Deep Sea Research Part II: Topical Studies in Oceanography 112: 42-52.

Bonaviri, C., M. Graham, P. Gianguzza, and N.T. Shears. 2017. Warmer temperatures reduce the influence of an important keystone predator. Journal of Animal Ecology 86: 490-500.

Bradley, B.A., M. Oppenheimer, and D.S. Wilcove. 2009. Climate change and plant invasions: Restoration opportunities ahead? Global Change Biology 15: 1511-1521.

Broitman, B.R., P.L. Szathmary, K.A.S. Mislan, C.A. Blanchette, and B. Helmuth. 2009. Predator–prey interactions under climate change: The importance of habitat vs body temperature. Oikos 118: 219-224.

Bromirski, P.D., R.E. Flick, and A.J. Miller. 2017. Storm surge along the Pacific coast of North America. Journal of Geophysical Research Oceans 122: 441-457.

Brooks, M.L. and K.H. Berry. 2006. Dominance and environmental correlates of alien annual plants in the Mojave Desert, USA. Journal of Arid Environments 67: 100-124.

Busch, D.S., M. Maher, P. Thibodeau, and P. McElhany. 2014. Shell condition and survival of puget sound pteropods are impaired by ocean acidification conditions. PLoS One 9: e105884. doi:10.1371/journal.pone.0105884.

Busse, L.B., E.L. Venrick, R. Antrobus, P.E. Miller, V. Vigilant, M.W. Silver, C. Mengelt, L. Mydlarz, and B.B. Prezelin. 2006. Domoic acid in phytoplankton and fish in San Diego, CA, USA. Harmful Algae 5: 91-101.

Byrne, M.P. and P.A. O'Gorman. 2015. The response of precipitation minus evapotranspiration to climate warming: Why the "wet-get-wetter, dry-get-drier" scaling does not hold over land. Journal of Climate 28: 8078-8092.

California Department of Fish and Wildlife. 2016. A Rapid Assessment of the Vulnerability of Sensitive Wildlife to Extreme Drought. California Department of Fish and Wildlife, Sacramento, CA.

Carbone, M.S., A.P. Williams, A.R. Ambrose, C.M. Boot, E.S. Bradley, T.E. Dawson, S.M. Schaeffer, J.P. Schimel, and C.J. Still. 2013. Cloud shading and fog drip influence the metabolism of a coastal pine ecosystem. Global Change Biology 19: 484-497.

Carter, B.R., R.A. Feely, S. Mecking, J.N. Cross, A.M. Macdonald, S.A. Siedlecki, L.D. Talley, C.L. Sabine, F.J. Millero, J.H. Swift, A.G. Dickson, and K.B. Rodgers. 2017. Two decades of Pacific anthropogenic carbon storage and ocean acidification along Global Ocean Ship-based Hydrographic Investigations Program sections P16 and P02. Global Biogeochemical Cycles 31: 306-327.

Cavole, L.M., A.M. Demko, R.E. Diner, A. Giddings, I. Koester, C.M.L.S. Pagniello, M.L. Paulsen, A. Ramirez-Valdez, S.M. Schwenck, N.K. Yen, M.E. Zill, and P.J.S. Franks. 2016. Biological impacts of the 2013–2015 warm-water anomaly in the Northeast Pacific: Winners, losers, and the future. Oceanography 29: 273-285.

Chan, F., J.A. Barth, C.A. Blanchette, R.H. Byrne, F. Chavez, O. Cheriton, R.A. Feely, G. Friederich, B. Gaylord, T.

Gouhier, S. Hacker, T. Hill, G. Hofmann, M.A. McManus, B.A. Menge, K.J. Nielsen, A. Russell, E. Sanford, J. Sevadjian, L. Washburn. 2017. Persistent spatial structuring of coastal ocean acidification in the California Current System. Scientific Reports 7: 2526. doi:10.1038/s41598-017-02777-y.

Cheng, L., J. Abraham, Z. Hausfather, and K.E. Trenberth. 2019. How fast are the oceans warming? Science 363: 128-129.

Cheng, L., K.E. Trenberth, J. Fasullo, T. Boyer, J. Abraham, and J. Zhu. 2017. Improved estimates of ocean heat content from 1960 to 2015. Science Advances 3: e1601545. doi:10.1126/sciadv.1601545.

Cheung, W.W.L., R.D. Brodeur, T.A. Okey, and D. Pauly. 2015. Projecting future changes in distributions of pelagic fish species of Northeast Pacific shelf seas. Progress in Oceanography 130: 19-31.

Church, J.A. and N.J. White. 2011. Sea-level rise from the late 19th to the early 21st Century. Surveys in Geophysics 32: 585-602.

Clemesha, R.E.S., A. Gershunov, S.F. Iacobellis, A.P. Williams, and D.R. Cayan. 2016. The northward march of summer low cloudiness along the California coast. Geophysical Research Letters 43: 1287-1295.

Conil, S. and A. Hall. 2006. Local regimes of atmospheric variability: A case study of southern California. Journal of Climate 19: 4308-4325.

Cook, B.I., T.R. Ault, J.E. Smerdon. 2015. Unprecedented 21st century drought risk in the American Southwest and Central Plains. Science Advances 1: e1400082. doi:10.1126/sciadv.1400082.

Daly, C., M. Halbleib, J.I. Smith, W.P. Gibson, M.K. Doggett, G.H. Taylor, J. Curtis, and P.P. Pasteris. 2008. Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. International Journal of Climatology 28: 2031-2064.

Dangendorf, S., M. Marcos, G. Wöppelmann, C.P. Conrad, T. Frederikse, and R. Riva. 2017. Reassessment of 20th century global mean sea level rise. Proceedings of the National Academy of Sciences of the USA 2017 114: 5946-5951.

Davidson, A.M., M. Jennions, and A.B. Nicotra. 2011. Do invasive species show higher phenotypic plasticity than native species and, if so, is it adaptive? A meta-analysis. Ecology Letters 14: 419-431.

Diffenbaugh, N.S., D.L. Swain, and D. Touma. 2015. Anthropogenic warming has increased drought risk in California. Proceedings of the National Academy of Sciences of the USA 112: 3931-3936.

Early, R., B.A. Bradley, J.S. Dukes, J.J. Lawler, J.D. Olden, D.M. Blumenthal, P. Gonzalez, E.D. Grosholz, I. Ibañez, L.P. Miller, C.J.B. Sorte, and A.J. Tatem. 2016. Global threats from invasive alien species in the twenty-first century and national response capacities. Nature Communications 7: 12485. doi:10.1038/ncomms12485.

Easterling, D.R., J.R. Arnold, T. Knutson, K.E. Kunkel, A.N. LeGrande, L.R. Leung, R.S. Vose, D.E. Waliser, and M.F. Wehner. 2017. Precipitation change in the United States. In U.S. Global Change Research Program (USGCRP). Climate Science Special Report: Report: Fourth National Climate Assessment, Volume I. [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)] USGCRP, Washington, DC.

Emery, N.C., C.M. D'Antonio, and C.J. Still. 2018. Fog and live fuel moisture in coastal California shrublands. Ecosphere 9: e02167. doi:10.1002/ecs2.2167.

Feely, R.A., S. Alin, B. Carter, N. Bednaršek, B. Hales, F. Chan, T.M. Hill, B. Gaylord, E. Sanford, R.H. Byrne, C.L. Sabine, D. Greeley, and L. Juranek. 2016. Chemical and biological impacts of ocean acidification along the west coast of North America. Estuarine, Coastal, and Shelf Science 183: 260-270.

Fischer, D.T., C.J. Still, C.M. Ebert, S.A. Baguskas, and A.P. Williams. 2016. Fog drip maintains dry season ecological function in a California coastal pine forest. Ecosphere 7: e01364. doi:10.1002/ecs2.1364.

Fischer, D.T., C.J. Still, and A.P. Williams. 2009. Significance of summer fog and overcast for drought stress and ecological functioning of coastal California endemic plant species. Journal of Biogeography 36: 783-799.

Frölicher, T.L., E.M. Fischer, and N. Gruber. 2018. Marine heatwaves under global warming. Nature 560: 360-364.

Funayama, K., E. Hines, J. Davis, and S. Allen. 2013. Effects of sea-level rise on northern elephant seal breeding habitat at Point Reyes Peninsula, California. Aquatic Conservation: Marine and Freshwater Ecosystems 23: 233-245.

Gillespie, T.W., S. Ostermann-Kelm, C. Dong, K.S. Willis, G.S. Okin, and G.M. MacDonald. 2018. Monitoring changes of NDVI in protected areas of southern California. Ecological Indicators 88: 485-494.

Gobler, C.J., O.M. Doherty, T.K. Hattenrath-Lehmann, A.W. Griffith, Y. Kang, and R.W. Litaker. 2017. Ocean warming since 1982 has expanded the niche of toxic algal blooms in the North Atlantic and North Pacific oceans. Proceedings of the National Academy of Sciences of the USA 114: 4975-4980.

Goldstein, L.J. and K.N. Suding 2014. Intra-annual rainfall regime shifts competitive interactions between coastal sage scrub and invasive grasses. Ecology 95: 425-435.

Gonzalez, P. 2017. Climate change trends, impacts, and vulnerabilities in US national parks. In Beissinger, S.R., D.D. Ackerly, H. Doremus, and G.E. Machlis (eds.) Science, Conservation, and National Parks. University of Chicago Press, Chicago, IL.

Gonzalez, P., J.J. Battles, B.M. Collins, T. Robards, and D.S. Saah. 2015. Aboveground live carbon stock changes of California wildland ecosystems, 2001-2010. Forest Ecology and Management 348: 68-77.

Gonzalez, P., R.P. Neilson, J.M. Lenihan, and R.J. Drapek. 2010. Global patterns in the vulnerability of ecosystems to vegetation shifts due to climate change. Global Ecology and Biogeography 19: 755-768.

Gonzalez, P., F. Wang, M. Notaro, D.J. Vimont, and J.W. Williams. 2018. Disproportionate magnitude of climate change in United States national parks. Environmental Research Letters 13: 104001. doi:10.1088/1748-9326/aade09.

Gruber, N., C. Hauri, Z. Lachkar, D. Loher, T.L. Frolicher, and G.K. Plattner. 2012. Rapid progression of ocean acidification in the California Current System. Science 337: 220-223.

Gugliotti, E.F., M.E. DeLorenzo, and P.J. Etnoyer. 2019. Depth-dependent temperature variability in the Southern California bight with implications for the cold-water gorgonian octocoral *Adelogorgia phyllosclera*. Journal of Experimental Marine Biology and Ecology 514-515: 118-126.

Guirguis, K., A. Gershunov, A. Tardy, and R. Basu. 2014. The impact of recent heat waves on human health in California. Journal of Applied Meteorology and Climatology 53: 3-19.

Guzman-Morales, J., A. Gershunov, J. Theiss, H. Li, and D. Cayan. 2016. Santa Ana Winds of Southern California: Their climatology, extremes, and behavior spanning six and a half decades. Geophysical Research Letters 43: 2827–2834.

Haas, H., T.J. Braje, M.S. Edwards, J.M. Erlandson, and S.G. Whitaker. 2019. Black abalone (*Haliotis cracherodii*) population structure shifts through deep time: Management implications for southern California's northern Channel Islands. Ecology and Evolution 9: 4720-4732.

Hagos, S.M., L.R. Leung, J.H. Yoon, J. Lu, and Y. Gao. 2016. A projection of changes in landfalling atmospheric river frequency and extreme precipitation over western North America from the Large Ensemble CESM simulations.

Geophysical Research Letters 43: 1357-1363.

Hall, A., N. Berg, and K. Reich. 2018. Los Angeles Summary Report. California Fourth Climate Change Assessment, Report SUM-CCCA4-2018-007, Sacramento, CA.

Harada, A.E., T.M. Healy, and R.S. Burton. 2019. Variation in thermal tolerance and its relationship to mitochondrial function across populations of *Tigriopus californicus*. Frontiers in Physiology 10: 213. doi:10.3389/fphys.2019.00213

Hardiman, M., A.C. Scott, N. Pinter, R.S. Anderson, A. Ejarque, A. Carter-Champion, and R.A. Staff. 2016. Fire history on the California Channel Islands spanning human arrival in the Americas. Philosophical Transactions of the Royal Society B 371: 20150167. doi:10.1098/rstb.2015.0167.

Harley, C.D.G. 2011. Climate change, keystone predation, and biodiversity loss. Science 334: 1124-1127.

Harrigan, R.J., H.A. Thomassen, W. Buermann, and T.B. Smith. 2014. A continental risk assessment of West Nile virus under climate change. Global Change Biology 20: 2417-2425.

Harter, D.E.V., S.D.H. Irl, B. Seo, M.J. Steinbauer, R. Gillespie, K.A. Triantis, J.M. Fernández-Palacios, and C. Beierkuhnlein. 2015. Impacts of global climate change on the floras of oceanic islands – Projections, implications and current knowledge. Perspectives in Plant Ecology, Evolution, and Systematics 17: 160-183.

Harvell, C.D., D. Montecino-Latorre, J.M. Caldwell, J.M. Burt, K. Bosley, A. Keller, S.F. Heron, A.K. Salomon, L. Lee, O. Pontier, C. Pattengill-Semmens, and J.K. Gaydos. 2019. Disease epidemic and a marine heat wave are associated with the continental-scale collapse of a pivotal predator (*Pycnopodia helianthoides*). Science Advances 5: eaau7042. doi:10.1126/sciadv.aau7042.

Hellmann, J.J., J.E. Byers, B.G. Bierwagen, and J.S. Dukes. 2008. Five potential consequences of climate change for invasive species. Conservation Biology 22: 534-543.

Helmuth, B., N. Mieszkowska, P. Moore, and S.J. Hawkins. 2006. Living on the edge of two changing worlds: Forecasting the responses of rocky intertidal ecosystems to climate change. Annual Review of Ecology, Evolution, and Systematics 37: 373-404.

Henson, S.A., C. Beaulieu, T. Ilyina, J.G. John, M. Long, R. Séférian, J. Tjiputra, and J.L. Sarmiento. 2017. Rapid emergence of climate change in environmental drivers of marine ecosystems. Nature Communications 8: 14682. doi:10.1038/ncomms14682.

Hofmann, G.E., T.G. Evans, M.W. Kelly, J.L. Padilla-Gamiño, C.A. Blanchette, L. Washburn, F. Chan, M.A. McManus, B.A. Menge, B. Gaylord, T.M. Hill, E. Sanford, M. LaVigne, J.M. Rose, L. Kapsenberg, and J.M. Dutton. 2014. Exploring local adaptation and the ocean acidification seascape – studies in the California Current Large Marine Ecosystem. Biogeosciences 11: 1053–1064.

Hoshijima, U. and G.E. Hofmann. 2019. Variability of seawater chemistry in a kelp forest environment is linked to in situ transgenerational effects in the purple sea urchin, Strongylocentrotus purpuratus. Frontiers in Marine Science 6: 62. doi:10.3389/fmars.2019.00062.

Holden, Z.A., A. Swanson, C.H. Luce, W.M. Jolly, M. Maneta, J.W. Oyler, D.A. Warren, R. Parsons, and D. Affleck. 2018. Decreasing fire season precipitation increased recent western US forest wildfire activity. Proceedings of the National Academy of Sciences of the USA 115: E8349-E8357.

Hoshiko, S., P. English, D. Smith, and R. Trent. 2010. A simple method for estimating excess mortality due to heat waves, as applied to the 2006 California heat wave. International Journal of Public Health 55: 133-137.

Hudgens, B., F. Beaudry, T. L. George, S. Kaiser, and N.M. Munkwitz. 2011. Shifting threats faced by the San

Clemente sage sparrow. Journal of Wildlife Management 75: 1350-1360.

Hughes, M. and A. Hall. 2010. Local and synoptic mechanisms causing Southern California's Santa Ana winds. Climate Dynamics 34: 847-857.

Hughes, M., A. Hall, and J. Kim. 2011. Human-induced changes in wind, temperature and relative humidity during Santa Ana events. Climatic Change 109:S119–S132.

Huijbregts, Z., R.P. Kramer, M.H.J. Martens, A.W.M. van Schijndel, and H.L. Schellen. 2012. A proposed method to assess the damage risk of future climate change to museum objects in historic buildings. Building and Environment 55: 43-56.

Huxman, T.E., E.P. Hamerlynck, and S.D. Smith. 1999. Reproductive allocation and seed production in *Bromus madritensis* ssp. *rubens* at elevated atmospheric CO_2. Functional Ecology 13: 769-777.

Hyrenbach, K.D. and R.R. Veit. 2003. Ocean warming and seabird communities of the southern California Current System (1987–98): Response at multiple temporal scales. Deep Sea Research Part II: Topical Studies in Oceanography 50: 2537-2565.

Intergovernmental Panel on Climate Change (IPCC). 2007. Climate Change 2007: The Physical Science Basis. Cambridge University Press, Cambridge, UK.

Intergovernmental Panel on Climate Change (IPCC). 2013. Climate Change 2013: The Physical Science Basis. Cambridge University Press, Cambridge, UK.

Intergovernmental Panel on Climate Change (IPCC). 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Cambridge University Press, Cambridge, UK.

Intergovernmental Panel on Climate Change (IPCC). 2018. Global Warming of 1.5°C. [Masson-Delmotte, V., P. Zhai, H.O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)] IPCC, Geneva, Switzerland.

Ishii, M. Y. Fukuda, S. Hirahara, S. Yasui, T. Suzuki, and K. Sato. 2017. Accuracy of global upper ocean heat content estimation expected from present observational data sets. Science Online Letters on the Atmosphere 13: 163–167.

Ito, T., S. Minobe, M.C. Long, and C. Deutsch. 2017. Upper ocean O_2 trends: 1958–2015. Geophysical Research Letters 44: 4214-4223.

Jacox, M.G., M.A. Alexander, N.J. Mantua, J.D. Scott, G. Hervieux, R.S. Webb, and F.E. Werner. 2018. Forcing of multiyear extreme ocean temperatures that impacted California current living marine resources in 2016. Bulletin of the American Meteorological Society 99: S27-S33.

Jazwa, C.S. and K.N. Johnson. 2018. Erosion of coastal archaeological sites on Santa Rosa Island, California. Western North American Naturalist 78: 302-327.

Jeon, S., Prabhat, S. Byna, J. Gu, W.D. Collins, and M.F. Wehner. 2015. Characterization of extreme precipitation within atmospheric river events over California. Advances in Statistical Climatology, Meteorology, and Oceanography 1: 45-57.

Jin, Y., J.T. Randerson, N. Faivre, S. Capps, A. Hall, and M.L. Goulden. 2014. Contrasting controls on wildland fires in Southern California during periods with and without Santa Ana winds. Journal of Geophysical Research Biogeosciences 119: 432-450.

Jones, S.M. and D.S. Gutzler. 2016. Spatial and seasonal variations in aridification across southwest North America.

Journal of Climate 29: 4637-4649.

Kapsenberg, L. and G.E. Hofmann. 2016. Ocean pH time-series and drivers of variability along the northern Channel Islands, California, USA. Limnology and Oceanography 61: 953-968.

Keeley, J.E., M. Baer-Keeley, and C.J. Fotheringham. 2005a. Alien plant dynamics following fire in Mediterranean-climate California shrublands. Ecological Applications 15: 2109-2125.

Keeley, J.E. and T.J. Brennan. 2012. Fire-driven alien invasion in a fire-adapted ecosystem. Oecologia 169: 1043–1052.

Keeley, J.E. and C.J. Fotheringham. 2001. Historic fire regime in southern California shrublands. Conservation Biology 15: 1536-1548.

Keeley, J.E., C.J. Fotheringham, and M. Baer-Keeley. 2005b. Determinants of postfire recovery and succession in Mediterranean-climate shrublands of California. Ecological Applications 15: 1515-1534.

Kelly, M.W., E. Sanford, and R.K. Grosberg. 2012. Limited potential for adaptation to climate change in a broadly distributed marine crustacean. Proceedings of the Royal Society of London B 279: 349-356.

Keeley, J.E., and A.D. Syphard. 2017. Different historical fire–climate patterns in California. International Journal of Wildland Fire 26: 253-268.

Knowlton, K., M. Rotkin-Ellman, G. King, H.G. Margolis, D. Smith, G. Solomon, R. Trent, and P. English. 2009. The 2006 California heat wave: Impacts on hospitalizations and emergency department visits. Environmental Health Perspectives 117: 61-67.

Koslow, J.A., H. McMonagle, and W. Watson. 2017. Influence of climate on the biodiversity and community structure of fishes in the southern California Current. Marine Ecology Progress Series 571:193-206.

Kossin, J.P., T. Hall, T. Knutson, K.E. Kunkel, R.J. Trapp, D.E. Waliser, and M.F. Wehner. 2017. Extreme storms. In U.S. Global Change Research Program (USGRP). Climate Science Special Report. Fourth National Climate Assessment, Volume I. [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)] USGCRP, Washington, DC.

Kroeker, K.J., R.L. Kordas, R. Crim, I.E. Hendriks, L. Ramajo, G.S. Singh, C.M. Duarte, and J. Gattuso. 2013. Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. Global Change Biology 19: 1884-1896.

LaDochy, S. and M. Witiw. 2012. The continued reduction in dense fog in the southern California region: Possible causes. Pure and Applied Geophysics 169: 1157-1163.

Langham, G.M., J.G. Schuetz, T. Distler, C.U. Soykan, and C. Wilsey. 2015. Conservation status of North American birds in the face of future climate change. PLoS One 10: e0135350. doi:10.1371/journal.pone.0135350.

Lavers, D.A., M.F. Ralph, D.E. Waliser, A. Gershunov, and M.D. Dettinger. 2015. Climate change intensification of horizontal water vapor transport in CMIP5. Geophysical Research Letters 42: 5617-5625.

Levitus, S, J.I. Antonov, T.P. Boyer, O.K. Baranova, H.E. Garcia, R.A. Locarnini, A.V. Mishonov, J.R. Reagan, D. Seidov, E.S. Yarosh, and M.M. Zweng. 2012. World ocean heat content and thermosteric sea level change (0–2000 m), 1955–2010. Geophysical Research Letters 39: L10603. doi:10.1029/2012GL051106.

Lewitus, A.J., R.A. Horner, D.A. Caron, E. Garcia-Mendoza, B.M. Hickey, M. Hunter, D.D. Huppert, R.M. Kudela, G.W. Langlois, J.L. Largier, E.J. Lessard, R. RaLonde, J.E.J. Rensel, P.G. Strutton, V.L. Trainer, J.F. Tweddle. 2012. Harmful algal blooms along the North American west coast region: History, trends, causes, and impacts. Harmful Algae 19: 133-159.

Levine, J.M., A.K. McEachern, and C. Cowan. 2008. Rainfall effects on rare annual plants. Journal of Ecology 96: 795-806.

Levine, J.M., A.K. McEachern, and C. Cowan. 2010. Do competitors modulate rare plant response to precipitation change? Ecology 91: 130–140.

Levine, J.M., A. K. McEachern, and C. Cowan. 2011. Seasonal timing of first rain storms affects rare plant population dynamics. Ecology 92: 2236-2247.

Lippitt,C.L., D.A. Stow, J.F. O'Leary, and J. Franklin. 2012. Influence of short-interval fire occurrence on post-fire recovery of fire-prone shrublands in California, USA. International Journal of Wildland Fire 22: 184-193.

Littell, J.S., D. McKenzie, D.L. Peterson, and A.L. Westerling. 2009. Climate and wildfire area burned in western U.S. ecoprovinces, 1916–2003. Ecological Applications 19: 1003-1021.

Liu, J.C., L.J. Mickley, M.P. Sulprizio, F. Dominici, X. Yue, K. Ebisu, G.B. Anderson, R.F.A. Khan, M.A. Bravo, and M.L. Bell. 2016. Particulate air pollution from wildfires in the Western US under climate change. Climatic Change 138: 655-666.

Liu, Y., A.M.O. Oduor, Z. Zhang, A. Manea, I.M. Tooth, M.R. Leishman, X. Xu, and M. van Kleunen. 2017. Do invasive alien plants benefit more from global environmental change than native plants? Global Change Biology 23: 3363-3370.

Long, M.C., C. Deutsch, and T. Ito. 2016. Finding forced trends in oceanic oxygen. Global Biogeochemical Cycles 30: 381-397.

Mann, M.L., E. Batllori, M.A. Moritz, E.K. Waller, P. Berck, A.L. Flint, L.E. Flint, and E. Dolfi. 2016. Incorporating anthropogenic influences into fire probability models: Effects of human activity and climate change on fire activity in California. PLoS ONE 11: e0153589. doi:10.1371/journal.pone.0153589.

Mansuy, N., C. Miller, M.A. Parisien, S.A. Parks, E. Batllori, and M.A. Moritz. 2019. Contrasting human influences and macro-environmental factors on fire activity inside and outside protected areas of North America. Environmental Research Letters 14: 064007. doi:10.1088/1748-9326/ab1bc5.

Marshall, K.N., I.C. Kaplan, E.E. Hodgson, A. Hermann, D.S. Busch, P. McElhany, T.E. Essington, C.J. Harvey, and E.A. Fulton. 2017. Risks of ocean acidification in the California Current food web and fisheries: ecosystem model projections. Global Change Biology 23: 1525-1539.

McCabe, R.M., B.M. Hickey, R.M. Kudela, K.A. Lefebvre, N.G. Adams, B.D. Bill, F.M.D. Gulland, R.E. Thomson, W.P. Cochlan, and V.L. Trainer. 2016. An unprecedented coastwide toxic algal bloom linked to anomalous ocean conditions. Geophysical Research Letters 43: 10 366-10 376.

McClatchie, S., R. Goericke, R. Cosgrove, G. Auad, and R. Vetter. 2010. Oxygen in the Southern California Bight: Multidecadal trends and implications for demersal fisheries. Geophysical Research Letters 37: L19602. doi:10.1029/2010GL044497.

McEachern, A.K., D.M. Thomson, and K.A. Chess. 2009. Climate alters response of an endemic island plant to removal of invasive herbivores. Ecological Applications 19: 1574-1584.

McKibben, S.M., W. Peterson, A.M. Wood, V.L. Trainer, M. Hunter, and A.E. White. 2017. Climatic regulation of the neurotoxin domoic acid. Proceedings of the National Academy of Sciences 114: 239-244.

Miner, C.M. J.L. Burnaford, R.F. Ambrose, L. Antrim, H. Bohlmann, C.A. Blanchette, J.M. Engle, S.C. Fradkin, R. Gaddam, C.D.G. Harley, B.G. Miner, S.N. Murray, J.R. Smith, S.G. Whitaker, and P.T. Raimondi. 2018. Large-scale impacts of sea star wasting disease (SSWD) on intertidal sea stars and implications for recovery. PLoS

One 13: e0192870. doi:/10.1371/journal.pone.0192870.

Moore, S.E. and H.P. Huntington. 2008. Arctic marine mammals and climate change: Impacts and resilience. Ecological Applications 18: S157-S165.

Moore, S.E., K.M. Wynne, J.C. Kinney, and J.M. Grebmeier. 2007. Gray whale occurrence and forage southeast of Kodiak Island, Alaska. Marine Mammal Science 23: 419-428.

Moore, S.K., V.L. Trainer, N.J. Mantua, M.S. Parker, E.A. Laws, L.C. Backer, and L.E. Fleming. 2008. Impacts of climate variability and future climate change on harmful algal blooms and human health. Environmental Health 7: S4. doi:10.1186/1476-069X-7-S2-S4.

Morrison, S.A., T.S. Sillett, C.K. Ghalambor, J.W. Fitzpatrick, D.M. Graber, V.J. Bakker, R. Bowman, C.T. Collins, P.W. Collins, K.S. Delaney, D.F. Doak, W.D. Koenig, L. Laughrin, A.A. Lieberman, J.M. Marzluff, M.D. Reynolds, J.M. Scott, J.A. Stallcup, W. Vickers, and W.M. Boyce. 2011. Proactive conservation management of an island-endemic bird species in the face of global change. BioScience 61: 1013-1021.

Moss, R.H., J.A. Edmonds, K.A. Hibbard, M.R. Manning, S.K. Rose, D.P. van Vuuren, T.R. Carter, S. Emori, M. Kainuma, T. Kram, G.A. Meehl, J.F.B. Mitchell, N. Nakicenovic, K. Riahi, S.J. Smith, R.J. Stouffer, A.M. Thomson, J.P. Weyant, and T.J. Wilbanks. 2010. The next generation of scenarios for climate change research and assessment. Nature 463: 747-756.

National Oceanic and Atmospheric Administration (NOAA). 2019. Relative Sea Level Trend, 9410660 Los Angeles, California. https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=9410660.

National Park Service (NPS). 2010. Climate Friendly Parks. Channel Islands National Park Action Plan. National Park Service, Washington, DC.

National Park Service (NPS). 2019. NPSpecies, Park Species List, Channel Islands National Park. https://irma.nps.gov/NPSpecies/Search/SpeciesList/CHIS.

Neuman, M., B. Tissot, and G. Vanblaricom. 2010. Overall status and threats assessment of black abalone (*Haliotis cracherodii* Leach, 1814) populations in California. Journal of Shellfish Research 29: 577-586.

Nielsen, K., J. Stachowicz, H. Carter, K. Boyer, M. Bracken, F. Chan, F. Chavez, K. Hovel, M. Kent, K. Nickols, J. Ruesink, J. Tyburczy, and S. Wheeler. 2018. Emerging understanding of the potential role of seagrass and kelp as an ocean acidification management tool in California. California Ocean Science Trust, Oakland, California.

O'Neil, J.M., T.W. Davis, M.A. Burford, and C.J. Gobler. 2012. The rise of harmful cyanobacteria blooms: The potential roles of eutrophication and climate change. Harmful Algae 14: 313-334.

Pendleton, E.A., E.R. Thieler, and S.J. Williams. 2010. Importance of coastal change variables in determining vulnerability to sea- and lake-level change. Journal of Coastal Research 26: 176-183.

Pierce, D.W., J.F. Kalansky, and D.R. Cayan. 2018. Climate, Drought, and Sea Level Rise Scenarios for the Fourth California Climate Assessment. California Fourth Climate Change Assessment, Report CNRA-CEC-2018-006. Scripps Institution of Oceanography, San Diego, CA.

Polade, S.D., A. Gershunov, D.R. Cayan, M.D. Dettinger, and D.W. Pierce. 2017. Precipitation in a warming world: assessing projected hydro-climate changes in California and other Mediterranean climate regions. Scientific Reports 7:10783. doi:10.1038/s41598-017-11285-y.

Polade, S.D., D.W. Pierce, D.R. Cayan, A. Gershunov, and M.D. Dettinger. 2014. The key role of dry days in changing regional climate and precipitation regimes. Scientific Reports 4: 4364. doi:10.1038/srep04364.

Power, P. and R. Rudolph. 2018. Quantifying surface water on Santa Rosa Island, California, following a major five-year drought. Western North American Naturalist 78: 530-539.

Putnam, H., D.M. Hondula, A. Urban, V. Berisha, P. Iñiguez, and M. Roach. 2018. It's not the heat, it's the vulnerability: attribution of the 2016 spike in heat-associated deaths in Maricopa County, Arizona. Environmental Research Letters 13: 094022. doi:10.1088/1748-9326/aadb44.

Rachels, D.H., D.A. Stow, J.F. O'Leary, H.D. Johnson, and P.J. Riggan. 2016. Chaparral recovery following a major fire with variable burn conditions. International Journal of Remote Sensing 37: 3836-3857.

Rapacciuolo, G., S.P. Maher, A.C. Schneider, T.T. Hammond, M.D. Jabis, R.E. Walsh, K.J. Iknayan, G.K. Walden, M.F. Oldfather, D.D. Ackerly, and S.R. Beissinger. 2014. Beyond a warming fingerprint: Individualistic biogeographic responses to heterogeneous climate change in California. Global Change Biology 20: 2841-2855.

Rayner, N.A., D.E. Parker, E.B. Horton, C.K. Folland, L.V. Alexander, D.P. Rowell, E.C. Kent, and A. Kaplan. 2003. Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. Journal of Geophysical Research 108: 4407. doi:10.1029/2002JD002670.

Reed, D., L. Washburn, A. Rassweiler, R. Miller, T. Bell, and S. Harrer. 2016. Extreme warming challenges sentinel status of kelp forests as indicators of climate change. Nature Communications 7: 13757. doi:10.1038/ncomms13757.

Reeder-Myers, L.A. 2015. Cultural heritage at risk in the Twenty-First Century: A vulnerability assessment of coastal archaeological sites in the United States. Journal of Island and Coastal Archaeology 10: 436-445.

Resplandy, L., R.F. Keeling, Y. Eddebbar, M.K. Brooks, R. Wang, L. Bopp, M.C. Long, J.P. Dunne, W. Koeve, and A. Oschlies. 2018. Quantification of ocean heat uptake from changes in atmospheric O_2 and CO_2 composition. Nature 563: 105-108.

Rick, T.C., T.S. Sillett, C.K. Ghalambor, C.A. Hofman, K. Ralls, R.S. Anderson, C.L. Boser, T.J. Braje, D.R. Cayan, R.T. Chesser, P.W. Collins, J.M. Erlandson, K.R. Faulkner, R.Fleischer, W.C. Funk, R. Galipeau, A. Huston, J. King, L. Laughrin, J. Maldonado, K. McEachern, D.R. Muhs, S.D. Newsome, L. Reeder-Myers, C. Still, and S.A. Morrison. 2014. Ecological change on California's Channel Islands from the Pleistocene to the Anthropocene. BioScience 64: 680-692.

Robeson, S.M. 2015. Revisiting the recent California drought as an extreme value. Geophysical Research Letters 42: 6771-6779.

Rogers-Bennett, L., R.F. Dondanville, J.D. Moore, and L.I. Vilchis. 2010. Response of red abalone reproduction to warm water, starvation, and disease stressors: Implications of ocean warming. Journal of Shellfish Research 29: 599-611.

Sagarin, R.D., J.P. Barry, S.E. Gilman, and C.H. Baxter. 1999. Climate-related change in an intertidal community over short and long time scales. Ecological Monographs 69: 465-490.

Salvadeo, C.J., U.A. Gómez-Gallardo, M. Nájera-Caballero, J. Urbán-Ramirez, and D. Lluch-Belda. 2015. The effect of climate variability on gray whales (*Eschrichtius robustus*) within their wintering areas. PLoS One 10: e0134655. doi:10.1371/journal.pone.0134655.

Sandel, B. and E.M. Dangremond. 2012. Climate change and the invasion of California by grasses. Global Change Biology 18: 277-289.

Schmidtko, S., L. Stramma, and M. Visbeck. 2017. Decline in global oceanic oxygen content during the past five decades. Nature 542: 335-339.

Scholin, C.A., F. Gulland, G.J. Doucette, S. Benson, M. Busman, F.P. Chavez, J. Cordaro, R. DeLong, A. De Vogelaere, J. Harvey, M. Haulena, K. Lefebvre, T. Lipscomb, S. Loscutoff, L.J. Lowenstine, R. Marin, P.E. Miller, W.A. McLellan, P.D.R. Moeller, C.L. Powell, T. Rowles, P. Silvagni, M. Silver, T. Spraker, V. Trainer, and F.M. Van Dolah. 2000. Mortality of sea lions along the central California coast linked to a toxic diatom bloom. Nature 403: 80-84.

Schwartz, R.E., A. Gershunov, S.F. Iacobellis, and D.R. Cayan. 2014. North American west coast summer low cloudiness: Broadscale variability associated with sea surface temperature. Geophysical Research Letters 41: 3307-3314.

Scripps Institution of Oceanography, University of California, San Diego. 2019. Surface temperature time series. https://scripps.ucsd.edu/programs/shorestations/shore-stations-data/data-sio.

Serafin, K.A., P. Ruggiero, and H.F. Stockdon. 2017. The relative contribution of waves, tides, and nontidal residuals to extreme total water levels on U.S. West Coast sandy beaches. Geophysical Research Letters 44: 1839-1847.

Slangen, A.B.A, J.A. Church, C. Agosta, X. Fettweis, B. Marzeion, and K. Richter. 2016. Anthropogenic forcing dominates global mean sea-level rise since 1970. Nature Climate Change 6: 701-705.

Smith, J.R., P. Fong, and R.F. Ambrose. 2006. Dramatic declines in mussel bed community diversity: response to climate change? Ecology 87: 1153-1161.

Summers, R., J. Masukawa, and B.D. Hartman. 2018. The influence of slope on vegetation recovery following nonnative grazer removal on Santa Rosa Island, California. Western North American Naturalist 78: 787-798.

Sydeman, W.J., M. García-Reyes, D.S. Schoeman, R.R. Rykaczewski, S.A. Thompson, B.A. Black, and S.J. Bograd. 2014. Climate change and wind intensification in coastal upwelling ecosystems. Science 345: 77-80.

Sydeman, W.J., M.M. Hester, J.A Thayer, F. Gress, P. Martin, and J. Buffa. 2001. Climate change, reproductive performance and diet composition of marine birds in the southern California Current system, 1969–1997. Progress in Oceanography 49: 309-329.

Syphard, A.D., T.J. Brennan, and J.E. Keeley. 2019. Extent and drivers of vegetation type conversion in Southern California chaparral. Ecosphere 10: e02796. doi:10.1002/ecs2.2796.

Taylor, A., T. Biswas, J.M. Randall, K. Klausmeyer, and B. Cohen. 2019. Parched pines: A quantitative comparison of two multi-year droughts and associated mass mortalities of bishop pine (Pinus muricata) on Santa Cruz Island, California. Remote Sensing in Ecology and Conservation. doi:10.1002/rse2.123.

Theoharides, K.A. and J.S. Dukes. 2007. Plant invasion across space and time: Factors affecting nonindigenous species success during four stages of invasion. New Phytologist 176: 256-273.

Thomsen, S.K., D.M. Mazurkiewicz, T.R Stanley, and D.J. Green. 2018 El Niño/Southern Oscillation-driven rainfall pulse amplifies predation by owls on seabirds via apparent competition with mice. Proceedings of the Royal Society of London B 285: 20181161. doi:10.1098/rspb.2018.1161.

Thomsen, S.K. and D.J. Green. 2019. Predator-mediated effects of severe drought associated with poor reproductive success of a seabird in a cross-ecosystem cascade. Global Change Biology 25: 1642-1652.

Timbrook, J., J.R. Johnson, and D.D. Earle. 1982. Vegetation burning by the Chumash. Journal of California and Great Basin Anthropology 4: 163-186.

Timmermann, A., S.I. An, J.S. Kug, F.F. Jin, W. Cai, A. Capotondi, K.M. Cobb, M. Lengaigne, M.J. McPhaden, M.F.

Stuecker, K.Stein, A.T. Wittenberg, K.S. Yun, T. Bayr, H.C. Chen, Y. Chikamoto, B. Dewitte, D. Dommenget, P. Grothe, E. Guilyardi, Y.G. Ham, M. Hayashi, S. Ineson, D. Kang, S. Kim, W. Kim, J.Y. Lee, T. Li, J.J. Luo, S. McGregor, Y. Planton, S. Power, H. Rashid, H.L. Ren, A. Santoso, K. Takahashi, A. Todd, G. Wang, G. Wang, R. Xie, W.H. Yang, S.W. Yeh, J. Yoon, E. Zeller, and X. Zhang. 2018. El Niño–Southern Oscillation complexity. Nature 559: 535-545.

Turi, G., Z. Lachkar, N. Gruber, and M. Münnich. 2016. Climatic modulation of recent trends in ocean acidification in the California Current System. Environmental Research Letters 11: 014007. doi:10.1088/1748-9326/11/1/014007.

United Nations Framework Convention on Climate Change (UNFCCC). 2015. Adoption of the Paris Agreement. Document FCCC/CP/2015/10/Add1, Decision 1/CP21. UNFCCC, Bonn, Germany.

United States Global Change Research Program (USGCRP). 2016. The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment. [Crimmins, A., J. Balbus, J.L. Gamble, C.B. Beard, J.E. Bell, D. Dodgen, R.J. Eisen, N. Fann, M.D. Hawkins, S.C. Herring, L. Jantarasami, D.M. Mills, S. Saha, M.C. Sarofim, J. Trtanj, and L. Ziska (Eds.)] U.S. Global Change Research Program, Washington, DC.

United States Global Change Research Program (USGCRP). 2017. Climate Science Special Report: Fourth National Climate Assessment, Volume I [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. USGCRP, Washington, DC.

United States Global Change Research Program (USGCRP). 2018. Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II. [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)] USGCRP, Washington, DC.

Uyeda, K.A., D.A. Stow, J.F. O'Leary, I.T. Schmidt, P.J. Riggan, and N. Hölzel. 2016. Spatial variation of fuel loading within varying aged stands of chaparral. Applied Vegetation Science 19: 267-279.

Veit, R.R., P. Pyle, and J.A. McGowan. 1996. Ocean warming and long-term change in pelagic bird abundance within the California current system. Marine Ecology Progress Series 139: 11-18.

Vilchis, L.I., M.J. Tegner, J.D. Moore, C.S. Friedman, K.L. Riser, T.T. Robbins, and P.K. Dayton. 2005. Ocean warming effects on growth, reproduction, and survivorship of southern California abalone. Ecological Applications 15: 469-480.

Vose, R.S., S. Applequist, M. Squires, I. Durre, M.J. Menne, C.N. Williams, C. Fenimore, K. Gleason, and D. Arndt. 2014. Improved historical temperature and precipitation time series for U.S. climate divisions. Journal of Applied Meteorology and Climatology 53: 1232-1251.

Vose, R.S., D.R. Easterling, K.E. Kunkel, A.N. LeGrande, and M.F. Wehner. 2017. Temperature changes in the United States. In U.S. Global Change Research Program (USGRP). Climate Science Special Report. Fourth National Climate Assessment, Volume I. [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)] USGCRP, Washington, DC.

Wang, D., T.C. Gouhier, B.A. Menge, and A.R. Ganguly. 2015. Intensification and spatial homogenization of coastal upwelling under climate change. Nature 518: 390-394.

Warner, M.D., C.F. Mass, and E.P. Salathé. 2015. Changes in winter atmospheric rivers along the North American West Coast in CMIP5 climate models. Journal of Hydrometeorology 16: 118–128.

Wehner, M.F., J.R. Arnold, T. Knutson, K.E. Kunkel, and A.N. LeGrande. 2017. Droughts, floods, and hydrology. In U.S. Global Change Research Program (USGCRP). Climate Science Special Report: Report: Fourth National

Climate Assessment, Volume I. [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)] USGCRP, Washington, DC.

Westerling, A.L. 2018. Wildfire Simulations for California's Fourth Climate Change Assessment: Projecting Changes in Extreme Wildfire Events with a Warming Climate. California Fourth Climate Change Assessment, Report CCCA4-CEC-2018-014, Sacramento, CA.

Williams, A P., J.T. Abatzoglou, A. Gershunov, J. Guzman-Morales, D.A. Bishop, J.K. Balch, and D.P. Lettenmaier. 2019. Observed impacts of anthropogenic climate change on wildfire in California. Earth's Future 7: 892-910.

Williams, A.P., E.R. Cook, J.E. Smerdon, B.I. Cook, J.T. Abatzoglou, K. Bolles, S.H. Baek, A.M. Badger, and B. Livneh. 2020. Large contribution from anthropogenic warming to an emerging North American megadrought. Science 368: 314-318. doi:10.1126/science.aaz9600.

Williams, A.P., P. Gentine, M.A. Moritz, D.A. Roberts, and J.T. Abatzoglou. 2018. Effect of reduced summer cloud shading on evaporative demand and wildfire in coastal Southern California. Geophysical Research Letters 45: 5653-5662.

Williams, A.P., R. Seager, J.T. Abatzoglou, B.I. Cook, J.E. Smerdon, and E.R. Cook. 2015. Contribution of anthropogenic warming to California drought during 2012–2014. Geophysical Research Letters 42: 6819-6828.

Williams, A.P., C.J. Still, D.T. Fischer, and S.W. Leavitt. 2008. The influence of summertime fog and overcast clouds on the growth of a coastal Californian pine: a tree-ring study. Oecologia 156: 601-611.

Wishner, K.F., B.A. Seibel, C. Roman, C. Deutsch, D. Outram, C.T. Shaw, M.A. Birk, K.A.S. Mislan, T.J. Adams, D. Moore, and S. Riley. 2018. Ocean deoxygenation and zooplankton: Very small oxygen differences matter. Science Advances 4: eaau5180. doi: 10.1126/sciadv.aau5180.

Wood, A.W., L.R. Leung, V. Sridhar and D.P. Lettenmaier. 2004. Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs. Climatic Change 62: 189-216.

Woolsey, J., C. Hanna, K. McEachern, S. Anderson, and B.D. Hartman. 2018. Regeneration and expansion of *Quercus tomentella* (Island Oak) groves on Santa Rosa Island. Western North American Naturalist 78: 758-767.

Wu, J.X., C.B. Wilsey, L. Taylor, and G.W. Schuurman. 2018. Projected avifaunal responses to climate change across the U.S. National Park System. PLoS ONE 13 e0190557 doi:10.1371/journal.pone.0190557.

Yeh, S.W., W. Cai, S.K. Min, M.J. McPhaden, D. Dommenget, B. Dewitte, M. Collins, K. Ashok, S.I. An, B.Y. Yim, and J.S. Kug. 2018. ENSO atmospheric teleconnections and their response to greenhouse gas forcing. Reviews of Geophysics 56: 185-206.

Yelenik, S.G. 2018. Long-term impacts of exotic grazer removal on native shrub recovery, Santa Cruz Island, California. Western North American Naturalist 78: 777-786.

Yip, F.Y., W.D. Flanders, A. Wolkin, D. Engelthaler, W. Humble, A. Neri, L. Lewis, L. Backer, and C. Rubin. 2008. The impact of excess heat events in Maricopa County, Arizona: 2000–2005. International Journal of Biometeorology 52: 765-772.

Yoder, C., P. Vivin, L. DeFalco, J. Seemann, and R. Nowak. 2000. Root growth and function of three Mojave Desert grasses in response to elevated atmospheric CO_2 concentration. New Phytologist 145: 245-256.

Young, A.P. 2018. Decadal-scale coastal cliff retreat in southern and central California. Geomorphology 300: 164-175.