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Anthropogenic Climate Change in Farallon Islands National Wildlife Refuge, California, USA

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Summary

The world today is warming at a faster rate than at any point in recorded history due to increased greenhouse gas emissions from human activities. As the climate changes, organisms are searching for new habitats, adapting to existing conditions, or in more dire cases, dying. Together, the world's marine, freshwater, and terrestrial ecosystems cradle an abundance of life, provide essential services to humans, hold cultural and spiritual significance, and naturally mitigate the effects of climate change through carbon sequestration, yet are degrading. To assist the Farallon Islands National Wildlife Refuge to effectively manage natural resources and protect biodiversity, this climate change assessment presents scientific information on observed climate trends, ecological changes and impacts, projected climate trends, future risks, and carbon solutions. In the region of the Farallon Islands, sea levels have risen approximately 23 centimeters (NOAA 2023a) and ocean waters have increased in acidity by about 60% since the 19th century (Osborne et al. 2020). Sea surface temperatures in California have increased by 1.2 ± 0.1°C between 1916 to 2018 due to climate change, exacerbating ocean deoxygenation while increasing the demand for oxygen among marine organisms (Rasmussen et al. 2020, IPCC 2021). Anomalously high sea surface temperatures have fueled marine heatwaves, which have doubled globally between 1982 to 2016 (Frölicher et al. 2018) and fueled harmful algal blooms off the coast of California (Gentemann et al. 2017). As global mean air temperatures have increased by 1.1 ± 0.1°C between the period of 1850-1900 to 2011-2020 (IPCC 2021), drought events across the southwestern United States have become more intense (Trenberth 2011, Williams et al. 2022). At the same time, rising temperatures are in part driving stronger tropical cyclones in the Pacific Ocean (Graham and Diaz 2001, IPCC 2021). In the future, this could wash away coastal habitat in the Farallon Islands that species of pinnipeds and seabirds depend on to breed and forage (Graham and Diaz 2001, Allen et al. 2011, Funayama et al. 2013). Hosting the largest breeding colony of seabirds in the continental United States, the Farallon Islands are experiencing declines in the abundance of Cassin's auklets, pigeon guillemots, common murres, and Brandt's cormorants due to altered food web dynamics that climate change might be influencing (Johns and Warzybok 2019, Elliott et al. 2015). If greenhouse gas emissions continue unabated, increases in sea surface temperature and upwelling intensity in the California Current ecosystem may cause a substantial decline in the population growth rate of Cassin's auklet, placing the species at risk of extinction (Wolf et al. 2010). While climate change is directly and indirectly transforming the Farallon Islands, placing flora and fauna in peril, protecting the blue carbon ecosystems in this refuge may help to mitigate greenhouse gas emissions. As a sanctuary for kelp and home to eelgrass and salt marsh grasses, plants in the Farallon Islands can sequester carbon for thousands of years, thus conserving this region may provide co-benefits for wildlife and humans (Duarte 2017, Krause-Jensen and Duarte 2016).

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Introduction

The nature and pace of anthropogenic activities have caused significant greenhouse gas emissions globally, with many downstream consequences to humans. Driven primarily by the burning of fossil fuels in the energy, industry, transportation, and agriculture sectors, greenhouse gas concentrations are at their highest levels in two million years, resulting in a planet that is approximately 1.1°C warmer than it was in the late 1800s (IPCC 2021). Climate change has caused adverse impacts and losses in marine, freshwater, and terrestrial ecosystems, as well as disproportionately altered the livelihoods and vulnerability to future risks of the world's most marginalized populations (IPCC 2022a). Living in an interconnected system where the atmosphere flows into rivers with no demarcation, changes in one area can influence fluxes elsewhere, no impact siloed from another. Global warming is thus shifting atmospheric and ocean circulation patterns, acidifying and deoxygenating oceans, and causing fundamental ecological changes in the most remote regions on Earth (IPCC 2022a).

Preserving the world's protected areas helps to mitigate the effects of climate change, yet these areas are facing conditions that are unprecedented over millennia (IPCC 2022a). Protected areas were originally conceived to safeguard pristine environments, and later used as a tool to conserve biodiversity and maintain populations of endangered species. Today, these areas are increasingly being recognized for their ability to sequester and store large amounts of atmospheric carbon dioxide (CO_2) – a potent greenhouse gas – and as natural buffers to protect species and ecological processes from the most severe impacts of climate change (IPCC 2022a). By providing safe refugia for species and supplying key ecosystem services to support human health and well-being, protected areas offer a means to achieve biodiversity and climate change goals simultaneously.

The objective of this report is to assist the Farallon Islands National Wildlife Refuge to effectively manage and conserve its biodiversity and natural resources under climate change. As the refuge is jointly managed by Point Blue Conservation Science and the U.S. Fish and Wildlife Service (USFWS), this report presents research and surveys conducted by the two entities, along with an assessment of published scientific research on observed impacts of climate change in the Farallon Islands. It culminates in a synthesis of the future risks to the Farallon Islands under various climate change emissions scenarios, assessing blue carbon solutions to sequester CO_2 from the atmosphere that can be combined with concerted global action to assuage the effects of climate change.

Location Description

Located approximately 48 kilometers off the coast of San Francisco in the Pacific Ocean, the Farallon Islands are a group of rocky islands totaling about 0.85 square kilometers that host globally significant wildlife populations. Beyond harboring the largest seabird nesting colony south of Alaska and the largest colony of western gulls in the world, the Farallon Islands and surrounding waters provide feeding and breeding grounds to an amalgam of marine mammals including humpback whales and elephant seals, over a quarter-million seabirds, and hundreds of invertebrate species (USFWS 2023). The Farallon Islands ecosystem supports at least 25 endangered or threatened species and is a place where thousands of endangered California brown pelicans flock to and threatened Steller's sea lions migrate to (USFWS 2023).

In 1909, several of the islands were designated as the Farallon Refuge by President Theodore Roosevelt to protect seabirds and marine mammals, a designation that now includes all of the islands and has benefitted additional species including native salamanders, insects, and plants. Owing to the bountiful marine life found in the surrounding waters of the islands, the Greater Farallones were later designated as a National Marine Sanctuary, receiving federal-level conservation protected by the National Oceanic and Atmospheric Administration (NOAA).

While the islands are not open to the public and only accessed by a small number of biologists due to sensitivity of wildlife, they are nonetheless affected by anthropogenic activities. Over the past five decades, USFWS, Point Blue Conservation Science, and their partners have worked to restore both the damaged ecosystem and historical abundance of wildlife that existed prior to human exploitation and disturbance.

Observed Climate Trends

Changes detected and attributed to anthropogenic climate change

Sea Surface Temperature Comprising over 70% of the Earth's surface, oceans play an essential role in regulating the global climate system by absorbing and redistributing heat and CO_2. As atmospheric greenhouse gas levels continue rising, the world's oceans are absorbing the excess heat caused by emissions, making them warmer and transforming global and regional climate feedbacks. Between 1971 to 2018, oceans absorbed over 90% of the excess heat of climate change (IPCC 2021). As a result, climate change has increased global sea surface temperature by 0.9 ± 0.1°C from 1900 to 2020 (IPCC 2021, Kennedy et al. 2019, Gleckler et al. 2012) (Figure 1).

According to daily temperature measurements taken from the Scripps Institution of Oceanography Pier located in Southern California, climate change has increased sea surface temperature by 1.2 ± 0.1°C between 1916 to 2018 (Rasmussen et al. 2020, IPCC 2021). This time series represents the longest continuous record of temperature in the Pacific Rim (Rasmussen et al. 2020).

Marine Heatwaves Between 1982 to 2016, marine heatwaves – periods of anomalously high sea surface temperature at a particular location that last for at least 5 days – doubled globally (Frölicher et al. 2018). Compared to the pre-industrial climate, the duration and intensity of marine heatwaves have increased 20-fold in the historical period (1982-2017) (Laufkoetter et al. 2020) (Figure 2). The occurrence of a multiyear persistent 2019-2021 marine heatwave is attributable more to anthropogenic than natural forcings, with event-attribution results revealing that greenhouse gas forcing is necessary for these events to occur (less than 1% occurrence probability under no-greenhouse gas effect) (Barkhordarian et al. 2022).

Ocean Acidification As the world's oceans continue to take up CO_2 from human-caused emissions, ocean acidification is increasing globally (IPCC 2021). The surface ocean has absorbed a quarter of all anthropogenic CO_2 emissions largely due to physical-chemical processes (McKinley et al. 2016, Friedlingstein et al. 2020). In the Pacific Ocean, climate change has acidified waters up to 40% between 1750 to 2014 (Carter et al. 2019, IPCC 2021). California waters have increased in acidity by about 60% since 1895 (Osborne et al. 2020), experiencing conditions that impair biological functioning for up to 55% of the year (Gruber et al. 2012).

Ocean Deoxygenation Ocean oxygen decline is driven by changes in ocean ventilation and solubility, and it occurs when oxygen consumption (e.g. from respiration) is greater than oxygen replenishment (from photosynthesis, ventilation, and mixing) (Helm et al. 2011). Climate change has reduced ocean oxygen levels by 2 ± 1% globally between 1960 to 2010 (Schmidtko et al. 2017, IPCC 2021). Ocean warming driven substantially by anthropogenic forcing contributes to about 15% of the dissolved oxygen decrease in the world's oceans by reducing oxygen solubility (IPCC 2021). Oxygen decline is also driven by reduced ventilation of deeper water from enhanced upper-ocean stratification (Long et al. 2016). From 1998 to 2013, dissolved oxygen decreased by 40% in the Central California Current region system (Ren et al. 2018).

Air Temperature Global mean surface temperature has increased by 1.1 ± 0.1°C between the period of 1850-1900 to 2011-2020 (IPCC 2021) (Figure 3). Human activities are responsible for over 99% of the increased heat of climate change that has occurred from 1850 to 2019 (IPCC 2021). In the region of the Farallon Islands, the air and sea surface temperature anomaly in 2022 was 0.24°C with respect to the 1991-2020 average (NOAA 2023b) (Figure 4). Temperature anomalies peaked in 2015 reaching 1.39°C above the 1991-2020 average (NOAA 2023b) (Figure 4).

Precipitation Climate change is altering patterns of precipitation as global warming strengthens evaporation and surface drying, thereby increasing the intensity and duration of drought (Trenberth 2011). For every 1°C increase in temperature, the water holding capacity of air increases by about 7%, leading to more intense precipitation events due to increased water vapor in the atmosphere (Trenberth 2011). In the North Pacific Ocean, extreme cyclones have increased in frequency and intensity since 1950, attributable in part to increases in sea surface temperature (Graham and Diaz 2001). From 1901 to 2019, precipitation in the region of the Farallon Islands increased by between 0-10 mm yr^{-1} per decade (IPCC 2021). Models of observed precipitation for the period from 1980 to 2019 reveal a decrease in precipitation in the region by between 0-25 mm yr^{-1} per decade (IPCC 2021)

Drought Extreme dry conditions in part attributable to anthropogenic climate change have caused a drought in the southwestern United States since 2000 that is the most severe drought since the 1500s (Williams et al. 2022). California experienced the most severe drought period on record between 2012 to 2016, coinciding with the lowest 12-month precipitation totals and hottest annual average temperatures in the period 2012-2014 (Diffenbaugh et al. 2015). By the end of the 2021 water year (October-September), drought conditions in California were comparable to the 2012-2016 drought (OEHHA 2022). Increasing temperatures driven by human activities can greatly amplify evaporation, culminating in more intense droughts (Dai 2013, Dai et al. 2004).

Changes consistent with, but not formally attributed to anthropogenic climate change

Fog Fog (formally defined as a cloud whose base touches the ground) and low clouds strongly affect the water, energy, and nutrient flux of coastal ecosystems (Torregrosa et al. 2016). Fog and low clouds of marine origin are the most common cloud type occurring during California's hot and dry Mediterranean climate summers (Torregrosa et al. 2016). Coastal fog over the ocean forms as a result of temperature differences between air and water (Weathers et al. 2020). Analyses of summer fog frequency in the redwood region along the Pacific coast of California revealed a 33% reduction in fog frequency since the early 20th century (Johnstone and Dawson 2010). A decline in fog is consistent with anthropogenic climate change as summer fog in northern California is significantly connected to sea surface temperature anomalies over the Pacific Ocean where fog enhancement is positively correlated with cool ocean conditions (Johnstone and Dawson 2010). In addition, coastal fog in northern California is associated with upwelling-favorable conditions over the California Current (Johnstone and Dawson 2010).

El Niño-Southern Oscillation The El Niño-Southern Oscillation (ENSO) is a recurring natural climate cycle observed across the tropical Pacific. Every two to seven years, the pattern shifts back and forth between El Niño and La Niña, warm and cool periods that affect ocean surface temperature and both wind and rainfall patterns across the tropics.

Past El Niño events have brought dramatic and widespread changes to the physical, chemical, and biological state of the California Current System (Jacox et al. 2016). The 2015-2016 El Niño is considered one of the strongest on record, comparable to earlier events in the late 1900s that caused significant floods, droughts, wildfires, and coral bleaching events. According to the Niño 3.4 Index, the warmest tropical Pacific sea surface temperature anomalies on record occurred in November 2015 (Jacox et al. 2016) (Figure 5). While stronger and more frequent ENSO events over the past 20-30 years have been associated with temperature changes, large variations in the ENSO system may be due to the nature of the climate system rather than human-caused climate change (IPCC 2021).

Observed Ecological Changes and Impacts

Changes detected and attributed to anthropogenic climate change

Sea Level Rise Global mean sea level has increased at a faster rate in the 20th century compared to any previous century over the past three millennia (IPCC 2021). From 1901 to 2018, global mean sea level rose by 0.20 meters mainly due to ocean thermal expansion and mass loss from glaciers and ice sheets (IPCC 2021). At the tidal gauge in San Francisco, sea level has risen by about 33 centimeters since 1854 (NOAA 2023a, NOAA 2020) (Figure 6). Anthropogenic forcing is the dominant cause of global mean sea level increase since 1970, though regional anomalies may be due to a combination of anthropogenic greenhouse gas emissions and internal variability (IPCC 2021).

Intertidal Habitat and Species Ocean acidification is slowing growth rates, decreasing fitness, or causing mortality among organisms with calcium carbonate shells and stony skeletons, altering ecosystem dynamics (Kroeker et al. 2013). In some areas in the Farallon Islands, ocean acidification has already reached a level high enough to impair the growth of shell-forming animals (Chan et al. 2017). Many intertidal species such as barnacles, mussels, and calcium carbonate-forming algae have been negatively affected (NOAA 2020).

Corals Globally, increased greenhouse gas emissions have threatened coral reef ecosystems through thermal stress, ocean acidity, and declining carbonate ion concentrations (Hoegh-Guldberg 2011). Observed impacts include increased mass coral bleaching, declining calcification rates, and other physiological and ecological effects that are not yet well understood (Hoegh-Guldberg 2011). At least two episodes of coral bleaching have been documented in the gulf of California, which are attributable to climate change and strongly associated with ENSO events (Hoegh-Guldberg et al. 2007, Baker et al. 2008, Paez-Osuna et al. 2016). No corals have been recorded in the Farallon Islands Wildlife Refuge, although coral species may exist in offshore waters.

Changes consistent with, but not formally attributed to anthropogenic climate change

Pinnipeds As amphibious animals, pinnipeds (seals and sea lions) face unique challenges because they haul out on land and ice but forage at sea for most of the year (Allen et al. 2011). Sea level rise of more than 20 centimeters over the past century in California coupled with storm surge may be altering pinniped habitat in the Farallon Islands and along the coast by inundating low-lying areas and eroding shorelines (Allen et al. 2011). It is possible that more intense storms due to climate change may be washing away the sandy beaches and rocky material that seals use to access breeding sites in the Farallon Islands, coinciding in time with decreases in breeding populations over the past 25 years (Duncan 2019). Past El Niño events have resulted in a decline in pinniped productivity and survival in California due to reduced prey availability and storm-driven tidal inundation (Trillmich and Ono 1991, Sydeman and Allen 1999). Therefore, the changes in breeding populations are due more to the natural El Niño inter-decadal variability than to anthropogenic climate change.

Cetaceans Marine mammal stranding records may be used as bioindicators of prevailing environmental conditions due to animals' sensitivity to changes in oceanographic and climatic patterns (Moore 2008). An analysis of stranding records from 2000 to 2019 in the Pacific Northwest revealed that strandings of harbor porpoises, gray whales, humpback whales, Dall's porpoises, and striped dolphins are correlated with environmental variables including sea surface temperature, chlorophyll concentration (as a proxy for primary production), and the Pacific Decadal Oscillation (Warlick et al. 2022). While cetacean strandings may be caused by a combination of both natural and anthropogenic factors, anomalous temperature events due to climate change may affect cold-water species in the Pacific Ocean including harbor and Dall's porpoise by shifting their ranges (MacLeod 2009, Warlick et al. 2022). Cetaceans that remain in warming waters due to reduced ability to shift their distribution may experience adverse outcomes such as changes in prey availability or increased exposure to anthropogenic contaminants that may impair fecundity and survival (Cavole et al. 2016). Blue whales that feed off of the California coast have begun arriving at their feeding grounds over one month earlier in 2018 and 2017 compared to 1988 and 2008, respectively, due to increasing sea surface temperatures that influence species phenology (van Weelden et al. 2021). These changes may be consistent with, but have not been robustly attributed to anthropogenic climate change.

Seabirds The multi-year persistent 2019-2021 marine heatwave caused by climate change resulted in low breeding success for most species in the region, less than favorable foraging conditions for seabirds, and delayed reproductive timing for all species (Johns and Warzybok 2019, Barkhordarian et al. 2022). Substantial declines in the number of breeding birds was found for Cassin's auklets, pigeon guillemots, and common murres (Johns and Warzybok 2019). From 2015 to 2017 in Southeast Farallon Island, 25% more western gull foraging trips visited land than in previous years, which coincided with high compression of coastally upwelled waters (Cimino et al. 2022). Southeast Farallon Island's population of Brandt's cormorant has declined since the 1970s and experienced anomalously low breeding productivity in recent years due to shifts in prey community structure (Elliott et al. 2015). These changes are not formally attributed to anthropogenic climate change but rather associated with changes in ocean conditions and overexploitation of prey species (i.e. rockfish), which are driven by human activities (Elliott et al. 2015).

Intertidal Habitat and Species Data collected over an 18-year period (1993-2011) on the South Farallon Islands revealed a gradual decline in overall mussel and algal abundance and an increase in bare substrate cover and crustose algal cover (Roletto et al. 2014). The causes of the long-term declines remain unknown, though sea surface temperatures are known to affect the composition and abundance of intertidal species, larval distribution, predation, grazing, and vulnerability to disease (Roletto et al. 2014). Increased trampling from pinnipeds and waste from wildlife may also explain some of the decline (Roletto et al. 2014).

Harmful Algal Blooms During the 2014-2016 marine heatwave known as "The Blob," water temperatures off of Southern California reached a maximum sea surface temperature anomaly of 6.2°C, pushing species to move north, fueling harmful algal blooms, and causing declines in subtidal kelp beds (Sanford et al. 2019, Gentemann et al. 2017). The Blob caused mass mortalities of seabirds and marine mammals, as well as changes in primary productivity, fish spawning, larval abundance, and marine wildlife health (Cavole et al. 2016, Bond et al. 2015, Di Lorenzo and Mantua 2016). This anomalous warm water event also caused reductions in phytoplankton availability which, combined with elevated sea surface temperatures, resulted in significant changes in zooplankton and marine invertebrate abundance and diversity in California (Cavole et al.

2016, Peterson et al. 2017). Toxic blooms of diatoms due to elevated sea surface temperatures produce the neurotoxin domoic acid, which has been associated with sea lion strandings along the northern California coast (Bargu et al. 2010).

Marine Food Web Dynamics Large-scale climate processes including the natural ENSO pattern have profound effects on the food webs of the California Current ecosystems (Hickey and Banas 2003, Chavez et al. 2003). Decreased upwelling and warming water associated with anthropogenic forcings observed in the California Current after the 1970s resulted in declines in primary productivity, zooplankton, pelagic fish, and seabirds (Warlick et al. 2022). In the Gulf of the Farallones region, predator productivity and population variation is indirectly affected by seasonal variation in upwelling through intermediate trophic levels (Thompson et al. 2012). Food web indicators and path analysis from 1997 to 2006 revealed that Cassin's auklet phenology (timing of egg-laying) was indirectly affected by winter and summer upwelling through zooplankton and chlorophyll-a, and reproductive success was directly affected by winter upwelling (Thompson et al. 2012). Common murre phenology was indirectly affected by winter upwelling through zooplankton, and reproductive success was directly affected by winter upwelling (Thompson et al. 2012). Humpback whale abundance in the region of the Farallon Islands was indirectly affected by summer upwelling through forage fish and directly affected by winter upwelling (Thompson et al. 2012).

Invasive Species Southeast Farallon Island is characterized by a high percentage of non-native (80%) and invasive (25%) plant species (Hawk 2015). Factors that may affect island invasibility include anthropogenic history, disturbance, environmental heterogeneity, community structure, species traits (invasiveness), and stress (Hawk 2015). Elimination of native endemic plants by human settlers in prior centuries may have contributed to the lack of diversity in native plant communities on Southeast Farallon Island, suggesting a high susceptibility to invasion by non-native plants amid climate change (Hawk 2015).

Extinctions Extinctions have occurred at higher rates in recent centuries due to an amalgam of anthropogenic causes including climate change (Groom et al. 2006). Zooplankton abundance has declined by 80% off the California coast, attributed in part to increasing sea surface temperatures (Roemmich and McGowan 1995). As a major food source for oceanic wildlife, the zooplankton decline has caused cascading effects for species in the Farallon Islands. The Cassin's auklet colony in Southeast Farallon Island preys directly on zooplankton and species that eat zooplankton, and has declined substantially off the central California coast since 1987 (Oedekoven et al. 2001). The common murre, whose major breeding population off the California coast is located in the Farallon Islands, has experienced more moderate declines, underscoring the individualistic responses of species to climate change impacts due to differences in life histories, foraging behavior, and habitat preferences (Groom et al. 2006, Oedekoven et al. 2001).

Projected Climate Trends

Sea Surface Temperature Future global mean sea surface temperature for the period 1995-2014 to 2081-2100 is projected to increase by 0.86°C under SSP1-2.6 (temperature increase stabilized at around 1.8°C by the end of the century) and 2.89°C under SSP5-8.5 (worst case scenario; average temperature increase by 4.4°C by the end of the century) (IPCC 2021). In the California Current region, sea surface temperatures are projected to increase by about 0.3°C per decade during the period of 1976 to 2099 (Alexander et al. 2018) (Figure 7). While nearshore waters have cooled slightly due to upwelling of cold deep water, they are also projected to become warmer in the coming decades (Xiu et al. 2018).

Marine Heatwaves On a global scale, the frequency of marine heatwaves is projected to increase this century (Frölicher et al. 2018). For a 2°C increase in global warming, the number of marine heatwave days is projected to increase an average by a factor of 16 (Frölicher et al. 2018). However, a 3.5°C increase in temperature by the end of this century could cause the probability of marine heat waves to increase by a factor of 41 (Frölicher et al. 2018). The biggest changes are projected to occur in the western tropical Pacific and Arctic Oceans (Frölicher et al. 2018).

Ocean Acidification Under a low emission scenario (RCP2.6), global mean surface ocean pH is projected to decrease by –0.14 ± 0.001 from 1870-1899 to 2080-2099 (IPCC 2021, Bopp et al. 2013, Hurd et al. 2018). Under a high emissions scenario over the same time period, global mean surface ocean pH is projected to decrease by –0.38 ± 0.005, with substantial regional variability (IPCC 2021, Bopp et al. 2013, Hurd et al. 2018). By the end of this century, open-ocean surface pH is projected to decline from the current average of 8.1 to an average of 7.8 (USGCRP 2017) (Figure 8). Projections in the California Current system indicate a 0.2-unit drop in pH during the summer upwelling season from 2013 to 2063 (Marshall et al. 2017).

Upwelled water that is more acidic than surface water is accelerating acidification in the region of the Farallon Islands, which may become a more imminent threat as upwelling intensity is projected to increase in the coming century (García-Reyes and Largier 2010).

Ocean Deoxygenation Under SSP5-8.5, the global mean change (2080-2099 mean values relative to 1870-1899) in subsurface (100-600 meters) oxygen concentration is projected to be -13.27 ± 5.28 mmol m^{-3} (Kwiatkowski et al. 2020). Under SSP1-2.6, the corresponding change is projected to be -6.36 ± 2.92 mmol m^{-3} (Kwiatkowski et al. 2020). While global mean subsurface deoxygenation is projected under all SSP scenarios, there is substantial variability in projections at regional scales as many oxygen drivers are local, influenced by bathymetry, winds, circulation, and freshwater and nutrient inputs (Kwiatkowski et al. 2020). The largest declines in oxygen are projected at higher latitudes and in the North Pacific Ocean due to increased warming, decreased ventilation, changing productivity, and remineralization patterns (Kwiatkowski et al. 2020, Cocco et al. 2013). Variation in trade winds in the eastern Pacific Ocean surrounding the Farallon Islands affects nutrient inputs, resulting in centennial periods of oxygen decline or increase that do not necessarily follow patterns of global oxygen decline (Deutsch et al. 2014). In the California Current ecosystem, a projected 5% decline in source water oxygen could expand hypoxic area in the region by 12.5% in winter and 22.5% in summer (Dussin et al. 2019).

Air Temperature Under SSP5-8.5, the 20-year average of the global mean surface air temperature would increase by 1.5°C in 2021-2040 relative to the average in 1850-1900 (IPCC 2021). Compared to the period from 1995-2014, the global mean surface air temperature averaged over 2081-2100 could increase by 0.2°C–1.0°C in the low-emissions scenario (SSP1-1.9) and by 2.4°C–4.8°C in the high-emissions scenario (SSP5-8.5) (IPCC 2021). In the region of the Farallon Islands, under SSP5-8.5, mean temperature is projected to increase by approximately 4.5°C relative to 1850-1900 (IPCC 2023).

Precipitation In the region of the Farallon Islands, under SSP5-8.5, total precipitation is projected to increase by approximately 5% relative to 1850-1900, though there is low model agreement (IPCC 2023). Changes to atmospheric circulation are projected to push storms in the region of the Farallon Islands further north, reducing the number of intense storms (Wang et al. 2017). While the frequency of storms is projected to decrease, the strength of each event is projected to increase (USGCRP 2018, Knutson et al. 2019). Furthermore, years characterized by many extreme storms are projected to become more common (Dettinger 2011). Altered patterns of precipitation are projected to exacerbate sea level rise as strong waves produced by intense storms could cause coastal erosion (Erikson et al. 2015).

In the Sierras, snowpack has declined in recent decades, and by 2050 areas historically dominated by snow may receive only rain (Sun et al. 2019). The frequency and intensity of extreme rain and dry events is projected to increase, along with more rapid transitions between wet and dry years (Swain et al. 2018). The increase in extreme wet and dry events and the shift from snowpack to rain may alter the timing and intensity of runoff and sediment into waters surrounding the Farallon Islands (NOAA 2020). The winter and spring seasons are projected to experience a shorter, more intense period of river flow and freshwater discharge, altering coastal stratification and mixing, as well as the seasonal timing of the transport of organisms to the waters surrounding the Farallon Islands (NOAA 2020).

Drought Anthropogenic emissions of greenhouse gases have increased the probability of drought in California by increasing the probability that warm conditions co-occur with precipitation deficits (Diffenbaugh et al. 2015). Evapotranspiration is projected to increase 13-18% by late this century (2070-2099) due to warmer temperatures, with increasing evapotranspiration linked to drought in California (McEvoy et al. 2020). The occurrence of extreme droughts in California is projected to increase 3-15 times by late this century based on the Standardized Precipitation Evapotranspiration Index (McEvoy et al. 2020). Extreme three-year droughts based on precipitation minus evapotranspiration are also projected to increase in frequency in the future (McEvoy et al. 2020).

Fog No published projections of fog under climate change exist for the region of the Farallon Islands. Reductions in fog are projected for both an increase in air temperature and a decrease in the concentration of aerosol particles (Klemm and Lin 2016). A temperature increase of 0.1°C has about the same effect on fog as reducing aerosol concentrations by 10%, though further research is needed to accurately project changes in fog (Klemm and Lin 2016). Both climate change and improvements in air quality contribute to reductions in fog (Klemm and Lin 2016).

El Niño-Southern Oscillation Analysis of climate models reveal there is no robust consensus on changes in the amplitude of ENSO sea surface temperature variability (IPCC 2021). ENSO precipitation variability is projected to intensify in response to climate change during the current century under all SSP scenarios (IPCC 2021). While models indicate that the total number of El Niño events might slightly decrease, the number of extreme events could increase (Cai et al. 2014). Furthermore, extreme El Niño events are projected to double from once every 20 years to once every 10 years amid climate change (Cai et al. 2014). This projected increase in stronger El Niño occurrences would bring more severe weather events to the Farallon Islands.

Future Risks to Ecosystems

Sea Level Rise Global mean sea level is projected to rise between 0.40 (RCP2.6) and 0.81 (RCP8.5) meters by 2100 relative to 1995-2014 (IPCC 2021). Warming produced by climate model simulations reveal that sea level rise along the California coast and estuaries could substantially exceed the rate experienced during modern human development (Cayan et al. 2008). Sea level rise projections for San Francisco indicate a median increase of 74 centimeters (RCP4.5) to 137 centimeters (RCP8.5) by 2100 relative to 2000 (Pierce et al. 2018) (Figure 9). If sea levels rise by up to 0.5 meters, 5% of the Farallon Islands could become permanently inundated, washing away areas that are essential for seabirds and marine mammals (Largier et al. 2010). Under a medium-high greenhouse gas emissions scenario (in which no additional actions are taken to curb emissions), coastal flooding and erosion caused by sea level rise along California's coast is projected to increase areas situated in the coastal floodplain from 1,200 square kilometers (under year-2000 conditions) to 1,500 square kilometers (by year 2100) (Heberger et al. 2011).

Pinnipeds In Point Reyes National Seashore along the coast of northern California, a future sea level rise of 0.5, 1.0, or 1.4 meters in 2050, 2081, and 2099, respectively, would largely inundate most of the current and potential haul-out sites for northern elephant seals by 2050 (Funayama et al. 2013). In the Farallon Islands, sea level rise and coastal erosion may inundate critical pupping and haul-out habitats for northern elephant seals and Steller's sea lions. Climate change altered physical and geomorphic processes including more frequent and intense waves, extreme erosion, increased tidal influence, and severe storms may affect habitat suitability (Funayama et al. 2013). Protection from disturbance and safety from storms and waves will shape future pinniped distributions amid climate change (Funayama et al. 2013).

Cetaceans Rising sea surface temperatures and reducing sea ice extent may alter the distribution, habitat, migration, and interspecific interactions of cetaceans over the next century van (Weelden et al. 2021). Species have shifted to higher latitudes and altered the timing of their migrations, which have unknown effects that may increase risks of extinction (van Weelden et al. 2012).

Seabirds Increasing sea level and coastal erosion in the Farallon Islands may negatively affect the nesting habitats of birds in the Farallon Islands such as American bitterns and threatened western snowy plovers (Largier et al. 2010, NOAA 2020). Species distribution models for western gulls demonstrate less sensitivity to ocean variability compared to other seabird species in the Farallon Islands because they are generalist foragers (McGowan et al. 2013). Common murres may be especially vulnerable to the effects of climate change due to their use of nearshore foraging habitats that are susceptible to sea level rise and coastal erosion (McGowan et al. 2013). By 2030, warmer ocean waters may fall below the range of natural variability in oxygen, altering the habitat of species including rockfish in the Farallon Islands that the common murre and Brandt's cormorant feed on (Hamilton et al. 2017).

Corals Climate change of 1.5°C could bleach 70-90% of coral reef area globally (IPCC 2018). Under the highest anthropogenic carbon dioxide emissions scenario, ocean acidification could cause net dissolving of coral reefs globally before the end of this century (IPCC 2022a, IPCC 2021, Cornwall et al. 2021, Eyre et al. 2018, Langdon et al. 2018).

Intertidal Habitat and Species Projected increases in the intensity of storms and waves may reduce the ability of intertidal species to stay attached to their substrate (NOAA 2020). Rising sea levels and coastal erosion in the Farallon Islands will inundate rocky intertidal habitats and may also increase the exposure of intertidal organisms including mussels, oysters, and algae to predators such as sea stars (NOAA 2020). Ocean acidification may cause reduced larval survival of the Dungeness crab in the Farallon Islands (Bednaršek et al. 2020). Increasing temperatures will push species to move further north or to deeper areas to meet their physiological needs and niche requirements, which could cause population declines (Hobday et al. 2016). For intertidal species, higher air temperatures may limit their ability to move higher in the intertidal zone, constricting their realized niche (NOAA 2020).

Harmful Algal Blooms Warming waters may fuel more frequent and intense harmful algal blooms (Cavole et al. 2016, Gobler et al. 2017). Blooms produce toxins that can harm wildlife, resulting in mass mortalities of animals such as sea lions, whales, and seabirds that could be more severe than those observed during The Blob (McCabe et al. 2016). More frequent harmful algal blooms and anomalous temperature events similar to the Blob may result in extirpations (Cavole et al. 2016).

Invasive Species Through higher CO_2 efficiency and increased warmth, humidity, and disturbance, climate change change favors invasive alien species, posing a high risk to one-sixth of global land under high emissions (Early et al. 2016, Liu et al. 2017, Davidson et al. 2011, Hellman et al. 2008). Island ecosystems are particularly vulnerable to invasive species under climate change due to native evolutionary isolation, low native diversity, and small native populations (Moser et al. 2018, Russell et al. 2017, Harter et al. 2015).

Extinctions The future global extinction risk from climate change is projected to increase and accelerate as global temperatures rise (Urban 2015). For a 2°C post-industrial rise in temperature, global extinction risks increase from 2.8% at present to 5.2% (Urban 2015). If no action is taken to curb greenhouse gas emissions (RCP8.5), climate change threatens one in six species globally (16%) (Urban 2015). Climate change at high emissions could cause the extinction of one-third of marine species, largely avoidable if humans cut carbon pollution to limit heating to 2°C (Penn and Deutsch 2022). Under future climate projections for sea surface temperature (approximate 2°C increase in sea surface temperature year-round) and upwelling intensity in the California Current ecosystem, the population growth rate of the Cassin's auklet at the Farallon Islands is projected to decline 11-45% by the end of the century (Wolf et al. 2010). Such a decrease due to continued anthropogenic emissions of greenhouse gases would lead to rapid population extirpation and may place this species on a trajectory toward extinction (Wolf et al. 2010).

Blue Carbon Solutions

Warming sea surface temperatures, marine heatwaves, ocean acidification, and deoxygenation – threats to the diverse ecosystems in and around the Farallon Islands – can be traced to unfettered carbon emissions. Vegetation naturally removes carbon from the atmosphere through carbon sequestration, which refers to the storage of carbon-containing molecules for over 100 years (Hurd et al. 2022). In the terrestrial world, trees sequester carbon in woody biomass, effectively reducing the magnitude of climate change. In the marine environment, seaweeds and other plants provide an analogous role, underscoring the need to protect marine areas and the treasure trove of life they hold.

In the waters surrounding the Farallon Islands, eelgrass and salt marsh grassess sequester carbon, which becomes buried in the soil for hundreds or thousands of years once these plants die (Duarte 2017). Globally, blue carbon ecosystems could sequester 73 to 866 million tons of carbon per year (Duarte 2017), compared to the annual emissions of California of 100 million tons of carbon per year (California Air Resources Board 2019). The Farallon Islands is also a sanctuary for kelp, which can store carbon for thousands or millions of years (Krause-Jensen and Duarte 2016). Globally, kelp and other macroalgae could sequester 200 million tons of carbon annually, which is over 35 times the annual emissions of San Francisco (Krause-Jensen and Duarte 2016, San Francisco Department of Environment 2018). The Greater Farallones Kelp Restoration Project jointly created by NOAA's Greater Farallones National Marine Sanctuary and the Greater Farallones Association seeks to restore lost kelp forest habitat along northern California's coastline and enhance ecosystem resilience to future climate risks. Over the past decade, kelp forests in northern California have declined by over 90% due to natural processes and anthropogenic climate change (Greater Farallones Association 2023). In particular, stronger El Nino events, marine heatwaves (the Blob), and altered marine food web dynamics due to warmer sea surface temperatures have created conditions that limit essential nutrients for kelp growth (Greater Farallones Association 2023).

In addition to the diverse plant species in the Farallon Islands that have been identified as sources of blue carbon, marine animals play a role in carbon storage and sequestration. Whales that forage near the Farallon Islands directly store carbon in their biomass and sequester carbon in the deep sea through sinking carcasses (Pearson et al. 2023). Whale excreta may fuel phytoplankton growth and capture atmospheric CO_2, which may be the greatest potential for whale-carbon sequestration (Pearson et al. 2023). While the role of marine fauna in carbon sequestration is still an emerging field of research, recovery of whale and other marine animal populations through reduced anthropogenic impacts may contribute to CO_2 removal (Pearson et al. 2023).

Concerted global action to reduce emissions from human activities can protect the Farallon Islands and the blue carbon ecosystems in this region, contributing to climate change mitigation. Without global efforts to reduce anthropogenic emissions, blue carbon ecosystems could become further degraded, resulting in the release of stored carbon (Pendleton et al. 2012). Limiting temperature increase to 1.5-2°C is attainable through collective action by governments, companies, and individuals using existing technologies and behaviors (IPCC 2022b). If this target is achieved, the Farallon Islands ecosystem would benefit from improved ecosystem health that is necessary to preserve the world's biodiversity.

Figure 1. Monthly global average sea surface temperature anomalies (°C) 1850–2018 relative to the bias-adjusted 1961–1990 climatology. The gray line shows the unadjusted data; the black line is the median of the adjusted data. The blue shading represents the 95% range of the ensemble (Kennedy et al. 2019; additional formatting by Patrick Gonzalez).

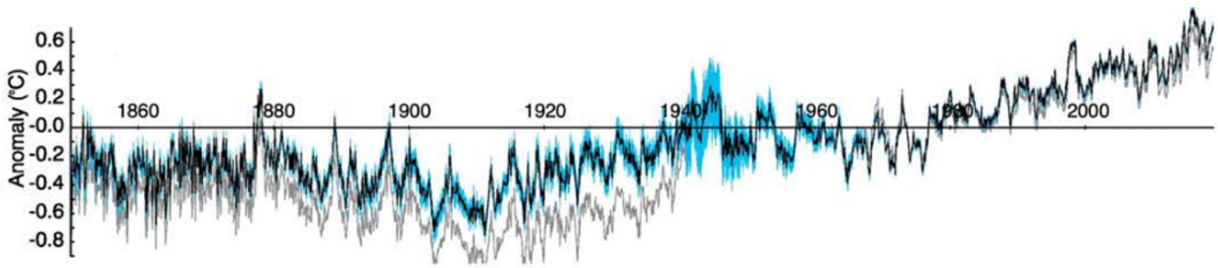


Figure 2. Characteristics of marine heatwaves between 2011-2017. The maps show the duration (upper map), peak temperature anomaly (middle map), and the cumulative intensity (lower map) of the seven prominent recent heatwaves analyzed in this study (Laufkoetter et al. 2020).

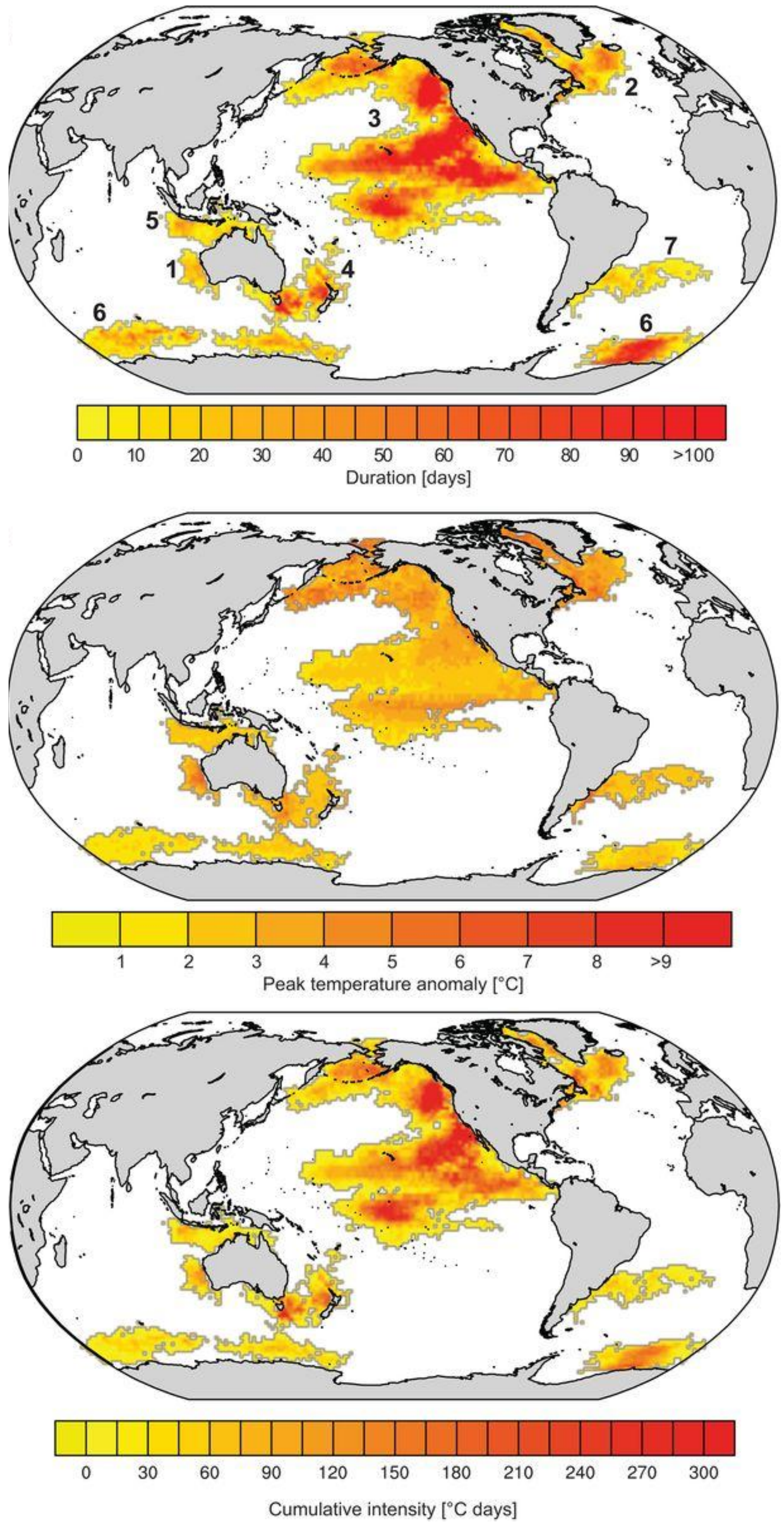


Figure 3. Global surface temperature trends. Spatially resolved trends (°C per decade) for HadCRUTv5 over (upper map) 1900–1980, and (lower map) 1981–2020. '×' marks denote non-significant trends (IPCC 2021).

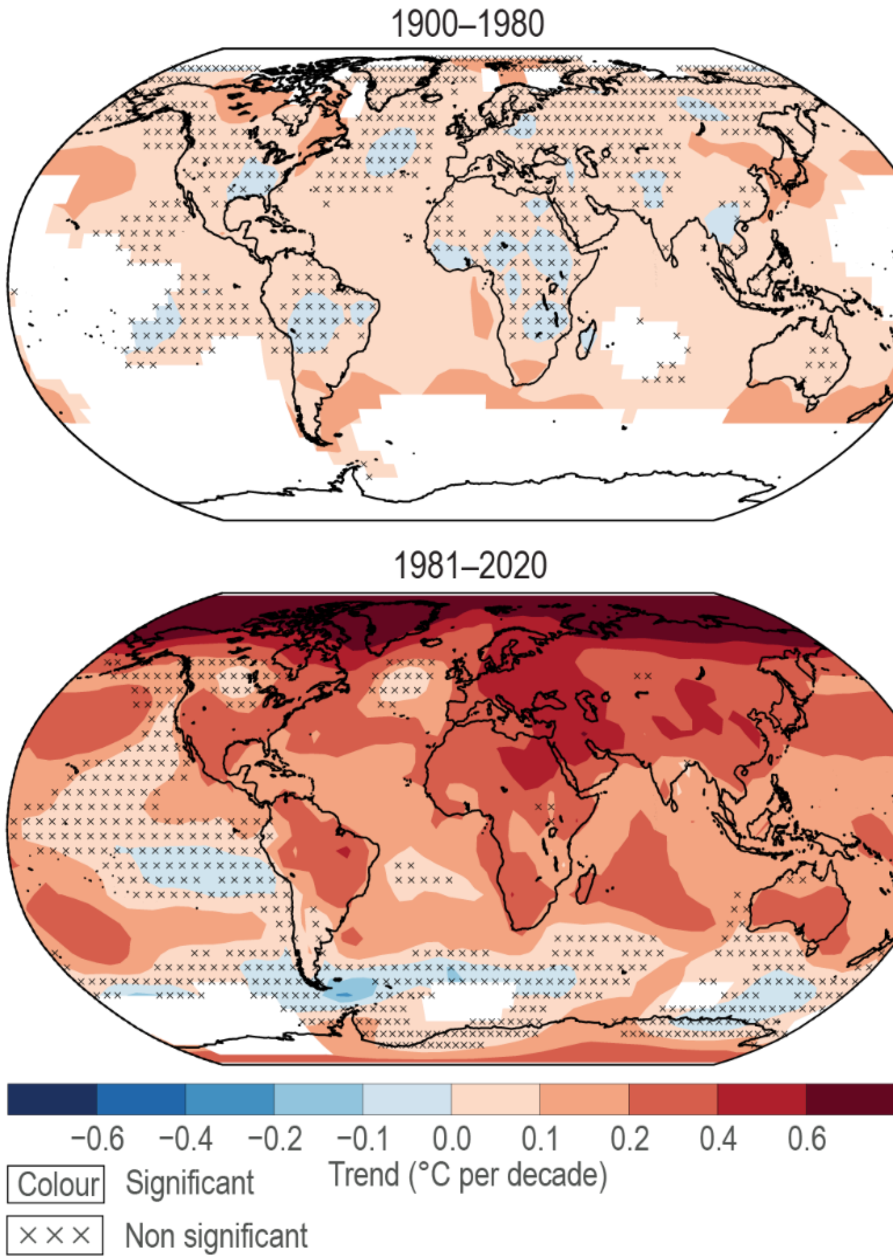


Figure 4. Time series of temperature anomalies in the Farallon Islands with respect to 1991-2020 average (NOAA 2023b).

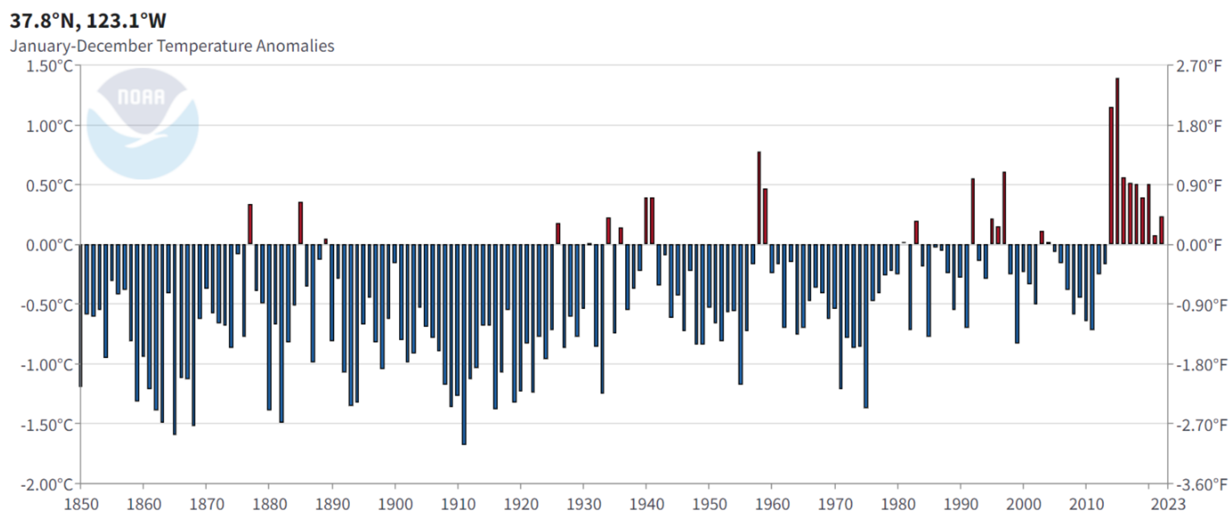


Figure 5. Two-year progression of Niño 3.4 Index for each El Niño since 1950. The circles indicate peak amplitude for each event. The dashed lines mark thresholds used to define El Niño and La Niña events (Jacox et al. 2016).

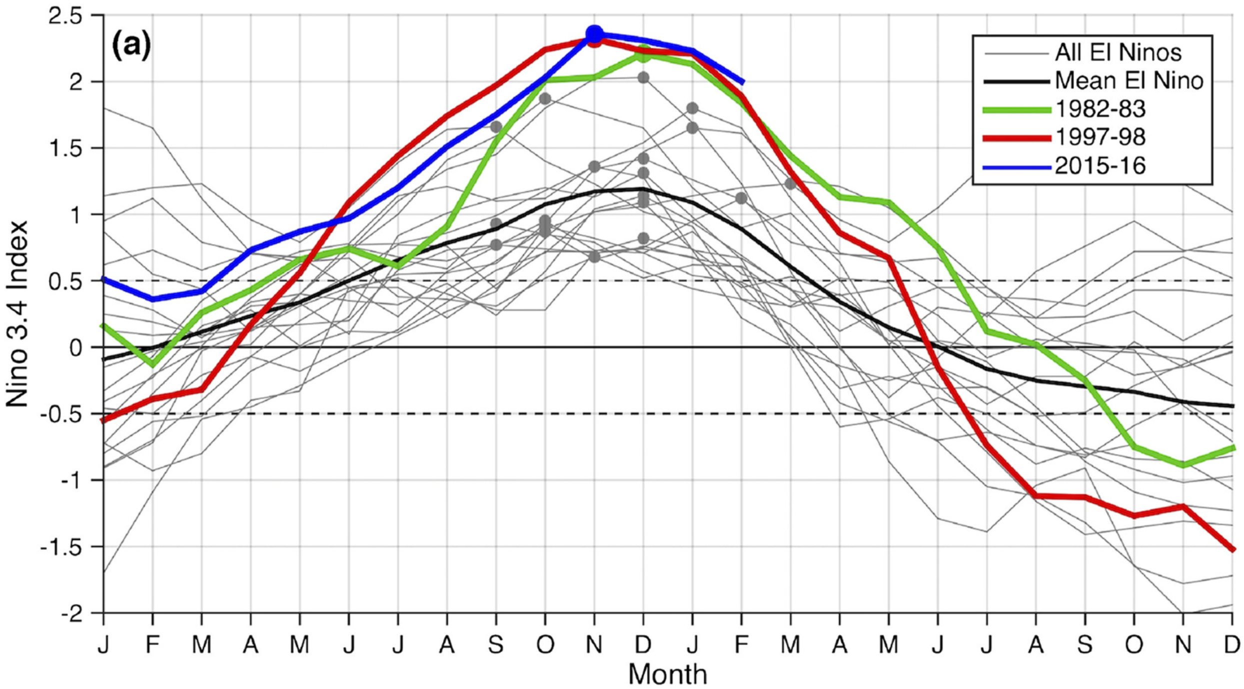


Figure 6. Relative sea level trend in San Francisco, California is 1.97 millimeters/year with a 95% confidence interval of +/- 0.18 mm/year based on monthly mean sea level data from 1897 to 2021 (NOAA 2023a).

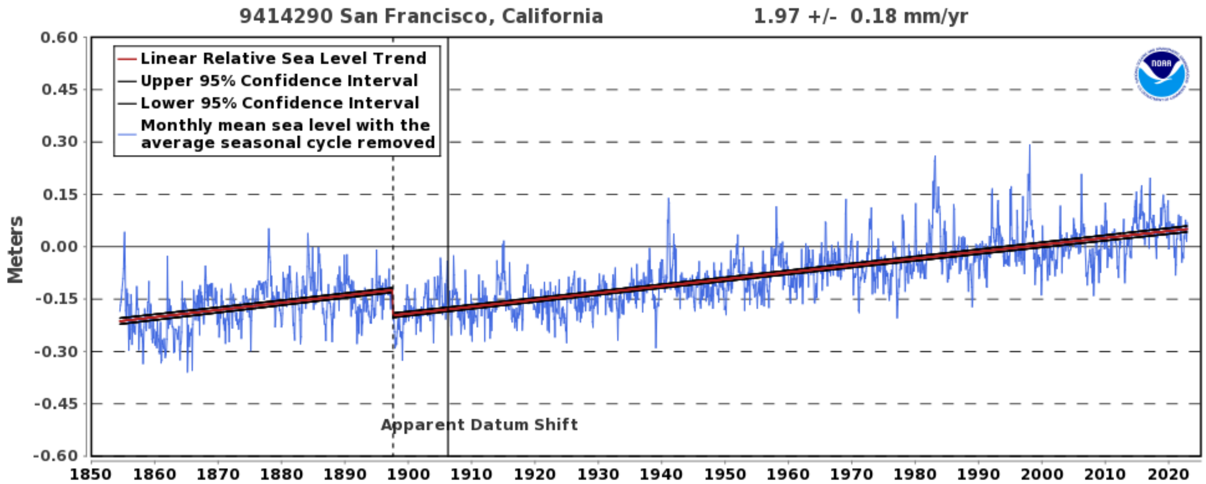


Figure 7. Sea surface temperature trends in large marine ecosystems around the global (3 corresponds to the California Current region). Colors denote the Community Model Intercomparison Project Phase 5 (CMIP5) ensemble mean area-averaged sea surface temperature trends (°C decade^{-1}) during 1976–2099. All trends are significant at the 95% level using a Mann-Kendall test (Alexander et al. 2018).

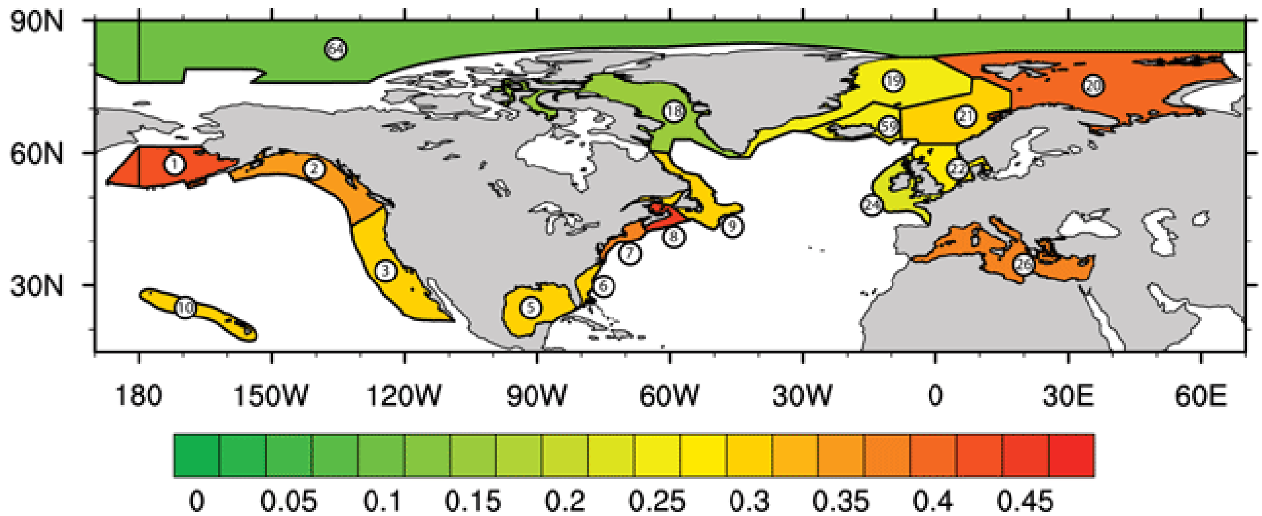


Figure 8. Projected change in sea surface pH in 2090–2099 relative to 1990–1999 under the higher scenario (RCP8.5), based on the Community Earth System Models–Large Ensemble Experiments CMIP5 (USGCRP 2017 adapted from Bopp et al. 2013).

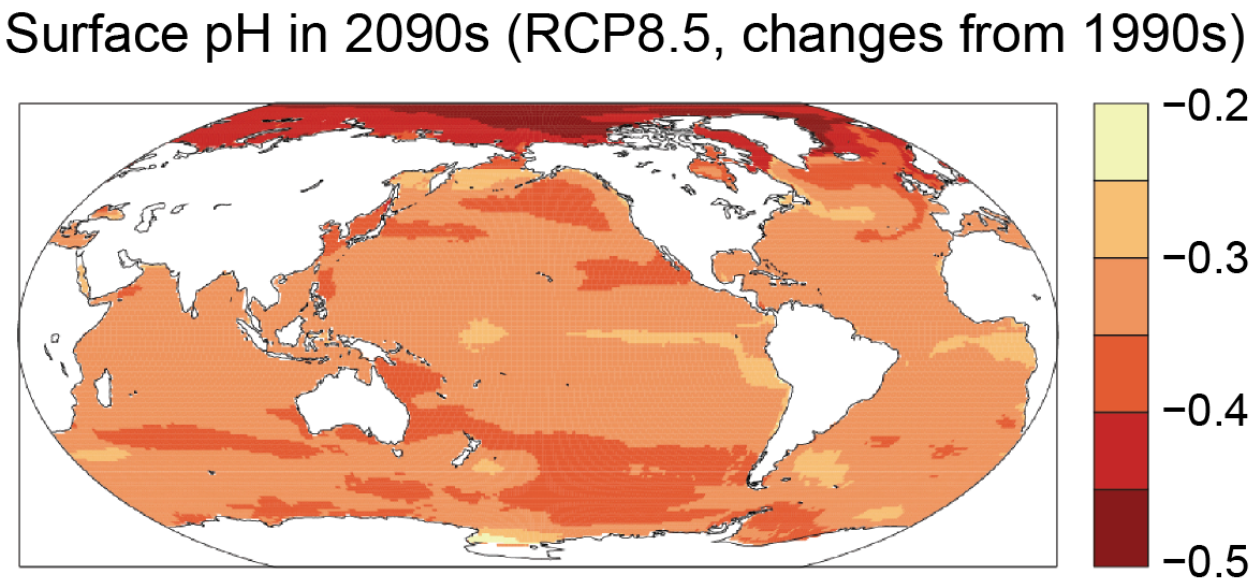
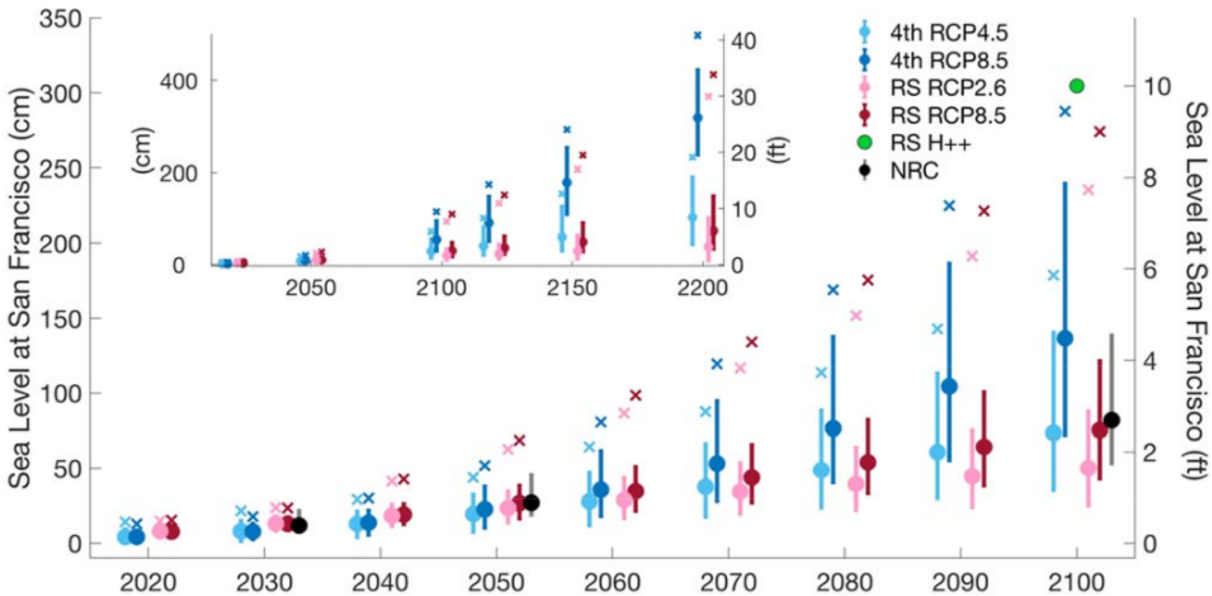


Figure 9. Sea level rise projections for San Francisco for each decade over the 21st century under RCP 4.5 (light blue) and RCP 8.5 (dark blue). The red and pink lines and symbols represent the results from Rising Seas using RCP 2.6 (pink) and RCP 8.5 (red) as well as H++ (large green dot). NRC is represented by the black dots and grey lines. Each decade's estimate is shown as a range from 5th to 95th with circles representing the 50%tile and crosses representing the 99.9th percentile (Pierce et al. 2018).



References

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.

Allen, S., E. Brown, K. Faulkner, S. Gende, and J. Womble. 2011. Conserving pinnipeds in Pacific Ocean parks in response to climate change. National Park Service. Park Science 28:2. https://www.nps.gov/articles/park-science-vol-28-no-2-summer-2011.htm.

Baker, A. C., P. W. Glynn, and B. Riegl. 2008. Climate change and coral reef bleaching: An ecological assessment of long-term impacts, recovery trends and future outlook. Estuarine, Coastal and Shelf Science 80:435–471. doi: 10.1016/j.ecss.2008.09.003.

Bargu, S., M. Silver, T. Goldstein, K. Roberts, and F. Gulland. 2010. Complexity of domoic acid-related sea lion strandings in Monterey Bay, California: foraging patterns, climate events, and toxic blooms. Marine Ecology Progress Series 418:213–222. doi: 10.3354/meps08816.

Barkhordarian, A., D. M. Nielsen, and J. Baehr. 2022. Recent marine heatwaves in the North Pacific warming pool can be attributed to rising atmospheric levels of greenhouse gases. Communications Earth & Environment 3:131. doi: 10.1038/s43247-022-00461-2.

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.

Bond, N. A., M. F. Cronin, H. Freeland, and N. Mantua. 2015. Causes and impacts of the 2014 warm anomaly in the NE Pacific. Geophysical Research Letters 42:3414–3420. doi: 10.1002/2015GL063306.

Bopp, L., L. Resplandy, J. C. Orr, S. C. Doney, J. P. Dunne, M. Gehlen, P. Halloran, C. Heinze, T. Ilyina, R. Séférian, J. Tjiputra, and M. Vichi. 2013. Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. Biogeosciences 10:6225–6245. doi: 10.5194/bg-10-6225-2013.

Cai, W., S. Borlace, M. Lengaigne, P. van Rensch, M. Collins, G. Vecchi, A. Timmermann, A. Santoso, M. J. McPhaden, L. Wu, M. H. England, G. Wang, E. Guilyardi, and F.-F. Jin. 2014. Increasing frequency of extreme El Niño events due to greenhouse warming. Nature Climate Change 4:111–116. doi: 10.1038/nclimate2100.

California Air Resources Board. 2019. California greenhouse gas emissions inventory 2000-2017. 2019 Edition Sacramento, CA.

Carter, B. R., R. A. Feely, R. Wanninkhof, S. Kouketsu, R. E. Sonnerup, P. C. Pardo, C. L. Sabine, G. C. Johnson, B. M. Sloyan, A. Murata, S. Mecking, B. Tilbrook, K. Speer, L. D. Talley, F. J. Millero, S. E. Wijffels, A. M. Macdonald, N. Gruber, and J. L. Bullister.

2019. Pacific Anthropogenic Carbon Between 1991 and 2017. Global Biogeochemical Cycles 33:597–617. doi: 10.1029/2018GB006154.

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. doi: 10.5670/oceanog.2016.32.

Cayan, D. R., E. P. Maurer, M. D. Dettinger, M. Tyree, and K. Hayhoe. 2008. Climate change scenarios for the California region. Climatic Change 87:21–42. doi: 10.1007/s10584-007-9377-6.

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, and 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.

Chavez, F. P., J. Ryan, S. E. Lluch-Cota, and M. Ñiquen C. 2003. From Anchovies to Sardines and Back: Multidecadal Change in the Pacific Ocean. Science 299:217–221. doi: 10.1126/science.1075880.

Cimino, M. A., S. A. Shaffer, H. Welch, J. A. Santora, P. Warzybok, J. Jahncke, I. Schroeder, E. L. Hazen, and S. J. Bograd. 2022. Western Gull Foraging Behavior as an Ecosystem State Indicator in Coastal California. Frontiers in Marine Science 8:790559. doi: 10.3389/fmars.2021.790559.

Cocco, V., F. Joos, M. Steinacher, T. L. Frölicher, L. Bopp, J. Dunne, M. Gehlen, C. Heinze, J. Orr, A. Oschlies, B. Schneider, J. Segschneider, and J. Tjiputra. 2013. Oxygen and indicators of stress for marine life in multi-model global warming projections. Biogeosciences 10:1849–1868. doi: 10.5194/bg-10-1849-2013.

Cornwall, C. E., S. Comeau, N. A. Kornder, C. T. Perry, R. van Hooidonk, T. M. DeCarlo, M. S. Pratchett, K. D. Anderson, N. Browne, R. Carpenter, G. Diaz-Pulido, J. P. D'Olivo, S. S. Doo, J. Figueiredo, S. A. V. Fortunato, E. Kennedy, C. A. Lantz, M. T. McCulloch, M. González-Rivero, V. Schoepf, S. G. Smithers, and R. J. Lowe. 2021. Global declines in coral reef calcium carbonate production under ocean acidification and warming. Proceedings of the National Academy of Sciences 118:e2015265118. doi: 10.1073/pnas.2015265118.

Dai, A. 2013. Increasing drought under global warming in observations and models. Nature Climate Change 3:52–58. doi: 10.1038/nclimate1633.

Dai, A., K. E. Trenberth, and T. Qian. 2004. A Global Dataset of Palmer Drought Severity Index for 1870–2002: Relationship with Soil Moisture and Effects of Surface Warming. Journal of Hydrometeorology 5:1117–1130. doi: 10.1175/JHM-386.1.

Davidson, A. D., A. G. Boyer, H. Kim, S. Pompa-Mansilla, M. J. Hamilton, D. P. Costa, G.

Ceballos, and J. H. Brown. 2012. Drivers and hotspots of extinction risk in marine mammals. Proceedings of the National Academy of Sciences 109:3395–3400. doi: 10.1073/pnas.1121469109.

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. doi: 10.1111/j.1461-0248.2011.01596.x.

Dettinger, M. D. 2011. Climate change, atmospheric rivers, and floods in California - a multimodel analysis of storm frequency and magnitude changes. Journal of the American Water Resources Association 47:514–523. doi: 10.1111/j.1752-1688.2011.00546.x.

Deutsch, C., W. Berelson, R. Thunell, T. Weber, C. Tems, J. McManus, J. Crusius, T. Ito, T. Baumgartner, V. Ferreira, J. Mey, and A. van Geen. 2014. Centennial changes in North Pacific anoxia linked to tropical trade winds. Science 345:665–668. doi: 10.1126/science.1252332.

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 112:3931–3936. doi: 10.1073/pnas.1422385112.

Di Lorenzo, E., and N. Mantua. 2016. Multi-year persistence of the 2014/15 North Pacific marine heatwave. Nature Climate Change 6:1042–1047. doi: 10.1038/nclimate3082.

Duarte, C. M. 2017. Reviews and syntheses: Hidden forests, the role of vegetated coastal habitats in the ocean carbon budget, Biogeosciences 14:301–310. doi: 10.5194/bg-14-301-2017.

Duncan, G.P. 2019. Population size and reproductive performance of pinnipeds on the South Farallon Islands, 2018-2019. Unpublished report to the US Fish and Wildlife Service. Point Blue Conservation Science, Petaluma, California. Point Blue Contribution Number 2329.

Dussin, R., E. N. Curchitser, C. A. Stock, and N. Van Oostende. 2019. Biogeochemical drivers of changing hypoxia in the California Current Ecosystem. Deep Sea Research Part II: Topical Studies in Oceanography 169–170:104590. doi: 10.1016/j.dsr2.2019.05.013.

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.

Elliott, M. L., R. W. Bradley, D. P. Robinette, and J. Jahncke. 2015. Changes in forage fish community indicated by the diet of the Brandt's cormorant (Phalacrocorax penicillatus) in the central California Current. Journal of Marine Systems 146:50–58. doi: 10.1016/j.jmarsys.2014.07.015.

Erikson, L. H., C. A. Hegermiller, P. L. Barnard, P. Ruggiero, and M. van Ormondt. 2015. Projected wave conditions in the Eastern North Pacific under the influence of two CMIP5 climate scenarios. Ocean Modelling 96:171–185. doi: 10.1016/j.ocemod.2015.07.004.

Eyre, B. D., T. Cyronak, P. Drupp, E. H. De Carlo, J. P. Sachs, and A. J. Andersson. 2018. Coral reefs will transition to net dissolving before end of century. Science 359:908–911. doi: 10.1126/science.aao1118.

Friedlingstein, P., M. O'Sullivan, M. W. Jones, R. M. Andrew, J. Hauck, A. Olsen, G. P. Peters, W. Peters, J. Pongratz, S. Sitch, C. Le Quéré, J. G. Canadell, P. Ciais, R. B. Jackson, S. Alin, L. E. O. C. Aragão, A. Arneth, V. Arora, N. R. Bates, M. Becker, A. Benoit-Cattin, H. C. Bittig, L. Bopp, S. Bultan, N. Chandra, F. Chevallier, L. P. Chini, W. Evans, L. Florentie, P. M. Forster, T. Gasser, M. Gehlen, D. Gilfillan, T. Gkritzalis, L. Gregor, N. Gruber, I. Harris, K. Hartung, V. Haverd, R. A. Houghton, T. Ilyina, A. K. Jain, E. Joetzjer, K. Kadono, E. Kato, V. Kitidis, J. I. Korsbakken, P. Landschützer, N. Lefèvre, A. Lenton, S. Lienert, Z. Liu, D. Lombardozzi, G. Marland, N. Metzl, D. R. Munro, J. E. M. S. Nabel, S.-I. Nakaoka, Y. Niwa, K. O'Brien, T. Ono, P. I. Palmer, D. Pierrot, B. Poulter, L. Resplandy, E. Robertson, C. Rödenbeck, J. Schwinger, R. Séférian, I. Skjelvan, A. J. P. Smith, A. J. Sutton, T. Tanhua, P. P. Tans, H. Tian, B. Tilbrook, G. van der Werf, N. Vuichard, A. P. Walker, R. Wanninkhof, A. J. Watson, D. Willis, A. J. Wiltshire, W. Yuan, X. Yue, and S. Zaehle. 2020. Global Carbon Budget 2020. Earth System Science Data 12:3269–3340. doi: 10.5194/essd-12-3269-2020.

Frölicher, T.L., E.M. Fischer, and N. Gruber. 2018. Marine heatwaves under global warming. Nature 560: 360-364. doi: 10.1038/s41586-018-0383-9.

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. doi: 10.1002/aqc.2318.

García-Reyes, M., and J. Largier. 2010. Observations of increased wind-driven coastal upwelling off central California. Journal of Geophysical Research: Oceans 115. doi: 10.1029/2009JC005576.

Gentemann, C. L., M. R. Fewings, and M. García-Reyes. 2017. Satellite sea surface temperatures along the West Coast of the United States during the 2014–2016 northeast Pacific marine heat wave. Geophysical Research Letters 44:312–319. doi:10.1002/2016GL071039.

Gleckler, P. J., B. D. Santer, C. M. Domingues, D. W. Pierce, T. P. Barnett, J. A. Church, K. E. Taylor, K. M. AchutaRao, T. P. Boyer, M. Ishii, and P. M. Caldwell. 2012. Human-induced global ocean warming on multidecadal timescales. Nature Climate Change 2:524–529. doi: 10.1038/nclimate1553.

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 114:4975–4980. doi: 10.1073/pnas.1619575114.

Graham, N. E., and H. F. Diaz. 2001. Evidence for Intensification of North Pacific Winter Cyclones since 1948. Bulletin of the American Meteorological Society 82:1869–1894. doi: 10.1175/1520-0477(2001)082<1869:EFIONP>2.3.CO;2.

Greater Farallones Association. 2023. Kelp Restoration. https://farallones.org/kelp/.

Groom, M. J., G. K. Meffe, and C. R. Carroll. 2006. Principles of Conservation Biology, 3rd

Edition. Chapter 10: Biological Impacts of Climate Change. Sinauer Associates, Sunderland, MA.

Gruber, N., C. Hauri, Z. Lachkar, D. Loher, T. L. Frölicher, and G.-K. Plattner. 2012. Rapid Progression of Ocean Acidification in the California Current System. Science 337:220–223. doi: 10.1126/science.1216773.

Hamilton, S. L., C. A. Logan, H. W. Fennie, S. M. Sogard, J. P. Barry, A. D. Makukhov, L. R. Tobosa, K. Boyer, C. F. Lovera, and G. Bernardi. 2017. Species-Specific Responses of Juvenile Rockfish to Elevated pCO2: From Behavior to Genomics. PLOS ONE 12: e0169670. doi: 10.1371/journal.pone.0169670.

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. doi: 10.1016/j.ppees.2015.01.003.

Hawk, J. L. 2015. Classification, Vegetation-Environment Relationships, and Distribution of Plant Communities in Southeast Farallon Island, California. San Francisco State University.

Heberger, M., H. Cooley, P. Herrera, P. H. Gleick, and E. Moore. 2011. Potential impacts of increased coastal flooding in California due to sea-level rise. Climatic Change 109:229–249. doi: 10.1007/s10584-011-0308-1.

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: The Journal of the Society for Conservation Biology 22:534–543. doi: 10.1111/j.1523-1739.2008.00951.x.

Helm, K. P., N. L. Bindoff, and J. A. Church. 2011. Observed decreases in oxygen content of the global ocean. Geophysical Research Letters 38: L23602. doi: 10.1029/2011GL049513.

Hickey, B. M., and N. S. Banas. 2003. Oceanography of the U.S. Pacific Northwest Coastal Ocean and estuaries with application to coastal ecology. Estuaries 26:1010–1031. doi: 10.1007/BF02803360.

Hobday, A. J., L. V. Alexander, S. E. Perkins, D. A. Smale, S. C. Straub, E. C. J. Oliver, J. A. Benthuysen, M. T. Burrows, M. G. Donat, M. Feng, N. J. Holbrook, P. J. Moore, H. A. Scannell, A. Sen Gupta, and T. Wernberg. 2016. A hierarchical approach to defining marine heatwaves. Progress in Oceanography 141:227–238. doi: 10.1016/j.pocean.2015.12.014.

Hoegh-Guldberg, O. 2011. The Impact of Climate Change on Coral Reef Ecosystems. Pages 391–403 *in* Z. Dubinsky and N. Stambler, editors. Coral Reefs: An Ecosystem in Transition. Netherlands, Dordrecht. doi: 10.1007/978-94-007-0114-4_22.

Hoegh-Guldberg, O., P. J. Mumby, A. J. Hooten, R. S. Steneck, P. Greenfield, E. Gomez, C. D. Harvell, P. F. Sale, A. J. Edwards, K. Caldeira, N. Knowlton, C. M. Eakin, R. Iglesias-Prieto, N. Muthiga, R. H. Bradbury, A. Dubi, and M. E. Hatziolos. 2007. Coral

Reefs Under Rapid Climate Change and Ocean Acidification. Science 318:1737–1742. doi: 10.1126/science.1152509.

Hurd, C. L., A. A. Lenton, B. Tilbrook, and P. W. Boyd. 2018. Current understanding and challenges for oceans in a higher-CO_2 world. Nature Climate Change 8:686–694. doi: 10.1038/s41558-018-0211-0.

Hurd, C. L., C. S. Law, L. T. Bach, D. Britton, M. Hovenden, E. R. Paine, J. A. Raven, V. Tamsitt, and P. W. Boyd. 2022. Forensic carbon accounting: Assessing the role of seaweeds for carbon sequestration. Journal of Phycology 58:347–363. doi: 10.1111/jpy.13249.

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.

Intergovernmental Panel on Climate Change (IPCC). 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Intergovernmental Panel on Climate Change (IPCC). 2022a. Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Intergovernmental Panel on Climate Change (IPCC). 2022b. Climate Change 2022: Mitigation of Climate Change. [Shukla, P.R., J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley (eds.)]. Cambridge University Press, Cambridge, UK.

Intergovernmental Panel on Climate Change (IPCC). 2023. IPCC WG1 Interactive Atlas: Regional Information (Advanced). https://interactive-atlas.ipcc.ch.

Jacox, M. G., E. L. Hazen, K. D. Zaba, D. L. Rudnick, C. A. Edwards, A. M. Moore, and S. J. Bograd. 2016. Impacts of the 2015–2016 El Niño on the California Current System: Early assessment and comparison to past events. Geophysical Research Letters 43:7072–7080. doi: 10.1002/2016GL069716.

Johns, M.E. and P. Warzybok. 2019. Population Size and Reproductive Performance of Seabirds on Southeast Farallon Island, 2019. Unpublished report to the U.S. Fish and Wildlife Service. Point Blue Conservation Science, Petaluma, California. Point Blue Conservation Science Contribution Number 2328.

Johnstone, J. A., and T. E. Dawson. 2010. Climatic context and ecological implications of summer fog decline in the coast redwood region. Proceedings of the National Academy of Sciences 107:4533–4538. doi: 10.1073/pnas.0915062107.

Kennedy, J. J., N. A. Rayner, C. P. Atkinson, and R. E. Killick. 2019. An Ensemble Data Set of Sea Surface Temperature Change From 1850: The Met Office Hadley Centre HadSST.4.0.0.0 Data Set. Journal of Geophysical Research: Atmospheres 124:7719–7763. doi: 10.1029/2018JD029867.

Klemm, O., and N.-H. Lin. 2016. What Causes Observed Fog Trends: Air Quality or Climate Change? Aerosol and Air Quality Research 16:1131–1142. doi: 10.4209/aaqr.2015.05.0353.

Knutson, T., S. J. Camargo, J. C. L. Chan, K. Emanuel, C.-H. Ho, J. Kossin, M. Mohapatra, M. Satoh, M. Sugi, K. Walsh, and L. Wu. 2019. Tropical Cyclones and Climate Change Assessment: Part I: Detection and Attribution. Bulletin of the American Meteorological Society 100:1987–2007. doi: 10.1175/BAMS-D-18-0189.1.

Krause-Jensen, D., and C. M. Duarte. 2016. Substantial role of macroalgae in marine carbon sequestration. Nature Geoscience 9:737–742. doi: 10.1038/ngeo2790.

Kroeker, K. J., R. L. Kordas, R. Crim, I. E. Hendriks, L. Ramajo, G. S. Singh, C. M. Duarte, and J.-P. Gattuso. 2013. Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. Global Change Biology 19:1884–1896. doi: 10.1111/gcb.12179.

Kwiatkowski, L., O. Torres, L. Bopp, O. Aumont, M. Chamberlain, J. R. Christian, J. P. Dunne, M. Gehlen, T. Ilyina, J. G. John, A. Lenton, H. Li, N. S. Lovenduski, J. C. Orr, J. Palmieri, Y. Santana-Falcón, J. Schwinger, R. Séférian, C. A. Stock, A. Tagliabue, Y. Takano, J. Tjiputra, K. Toyama, H. Tsujino, M. Watanabe, A. Yamamoto, A. Yool, and T. Ziehn. 2020. Twenty-first century ocean warming, acidification, deoxygenation, and upper-ocean nutrient and primary production decline from CMIP6 model projections. Biogeosciences 17:3439–3470. doi: 10.5194/bg-17-3439-2020.

Langdon, C., R. Albright, A. C. Baker, and P. Jones. 2018. Two threatened Caribbean coral species have contrasting responses to combined temperature and acidification stress. Limnology and Oceanography 63:2450–2464. doi: 10.1002/lno.10952.

Largier, J.L, Cheng, B.S., and Higgason, K.D., editors. 2010. Climate Change Impacts: Gulf of the Farallones and Cordell Bank National Marine Sanctuaries. Report of a Joint Working Group of the Gulf of the Farallones and Cordell Bank National Marine Sanctuaries Advisory Councils. Marine Sanctuaries Conservation Series ONMS-11-04. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of National Marine Sanctuaries, Silver Spring, MD.

Laufkötter, C., J. Zscheischler, and T. L. Frölicher. 2020. High-impact marine heatwaves attributable to human-induced global warming. Science 369:1621–1625. doi: 10.1126/science.aba069.

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. doi: 10.1111/gcb.13579.

Long, M. C., C. Deutsch, and T. Ito. 2016. Finding forced trends in oceanic oxygen. Global Biogeochemical Cycles 30:381–397. doi: 10.1002/2015GB005310.

MacLeod, C. D. 2009. Global climate change, range changes and potential implications for the conservation of marine cetaceans: a review and synthesis. Endangered Species Research 7: 125-136.

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. doi: 10.3354/esr00197.

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 43:10366–10376. doi: 10.1002/2016GL070023.

McEvoy, D. J., D. W. Pierce, J. F. Kalansky, D. R. Cayan, and J. T. Abatzoglou. 2020. Projected Changes in Reference Evapotranspiration in California and Nevada: Implications for Drought and Wildland Fire Danger. Earth's Future 8: e2020EF001736. doi: 10.1029/2020EF001736.

McGowan, J., E. Hines, M. Elliott, J. Howar, A. Dransfield, N. Nur, and J. Jahncke. 2013. Using Seabird Habitat Modeling to Inform Marine Spatial Planning in Central California's National Marine Sanctuaries. PLOS ONE 8:e71406. doi: 10.1371/journal.pone.0071406.

McKinley, G. A., D. J. Pilcher, A. R. Fay, K. Lindsay, M. C. Long, and N. S. Lovenduski. 2016. Timescales for detection of trends in the ocean carbon sink. Nature 530:469–472. doi: 10.1038/nature16958.

Moore, S. E. 2008. Marine Mammals as Ecosystem Sentinels. Journal of Mammalogy 89:534–540. doi: 10.1644/07-MAMM-S-312R1.1.

Moser, D., B. Lenzner, P. Weigelt, W. Dawson, H. Kreft, J. Pergl, P. Pyšek, M. van Kleunen, M. Winter, C. Capinha, P. Cassey, S. Dullinger, E. P. Economo, P. García-Díaz, B. Guénard, F. Hofhansl, T. Mang, H. Seebens, and F. Essl. 2018. Remoteness promotes biological invasions on islands worldwide. Proceedings of the National Academy of Sciences 115:9270–9275. doi: 10.1073/pnas.1804179115.

National Oceanic and Atmospheric Administration (NOAA). 2023a. Relative Sea Level Trend 9414290 San Francisco, California. https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=9414290.

National Oceanic and Atmospheric Administration (NOAA). 2023b. Climate at a glance global time series. https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/global/

time-series.

NOAA Office of National Marine Sanctuaries. 2020. Climate Change Impacts Greater Farallones National Marine Sanctuary. https://nmsfarallones.blob.core.windows.net/farallones-prod/media/docs/2020-climate-change-impacts-profiles-gfnms.pdf.

Oedekoven, C. S., D. G. Ainley, and L. B. Spear. 2001. Variable responses of seabirds to change in marine climate: California Current, 1985-1994. Marine Ecology Progress Series 212:265-281. doi: 10.3354/meps212265.

Office of Environmental Health Hazard Assessment (OEHHA). 2022. Indicators of Climate Change in California, Fourth Edition, California Environmental Protection Agency, OEHHA. https://oehha.ca.gov/media/downloads/climate-change/document/2022 caindicatorsreport.pdf.

Osborne, E. B., R. C. Thunell, N. Gruber, R. A. Feely, and C. R. Benitez-Nelson. 2020. Decadal variability in twentieth-century ocean acidification in the California Current Ecosystem. Nature Geoscience 13:43–49. doi: 10.1038/s41561-019-0499-z.

Paez-Osuna, F., J. Sanchez-Cabeza, A. C. Ruiz-Fernandez, and R. Alonso. 2016. Environmental status of the Gulf of California: A review of responses to climate change and climate variability. Earth-Science Reviews 162:253-268. doi: 10.1016/j.earscirev.2016.09.015.

Pearson, H. C., M. S. Savoca, D. P. Costa, M. W. Lomas, R. Molina, A. J. Pershing, C. R. Smith, J. C. Villaseñor-Derbez, S. R. Wing, and J. Roman. 2023. Whales in the carbon cycle: can recovery remove carbon dioxide? Trends in Ecology & Evolution 38:238–249. doi: 10.1016/j.tree.2022.10.012.

Pendleton, L., D. C. Donato, B. C. Murray, S. Crooks, W. A. Jenkins, S. Sifleet, C. Craft, J. W. Fourqurean, J. B. Kauffman, N. Marbà, P. Megonigal, E. Pidgeon, D. Herr, D. Gordon, and A. Baldera. 2012. Estimating Global "Blue Carbon" Emissions from Conversion and Degradation of Vegetated Coastal Ecosystems. PLOS ONE 7:e43542. doi: 10.1371/journal.pone.0043542.

Penn, J. L., and C. Deutsch. 2022. Avoiding ocean mass extinction from climate warming. Science 376:524–526. doi: 10.1126/science.abe903.

Peterson, W. T., J. L. Fisher, P. T. Strub, X. Du, C. Risien, J. Peterson, and C. T. Shaw. 2017. The pelagic ecosystem in the Northern California Current off Oregon during the 2014–2016 warm anomalies within the context of the past 20 years. Journal of Geophysical Research: Oceans 122:7267–7290. doi: 10.1002/2017JC012952.

Pierce, D. W., J. F. Kalansky, and D. R. Cayan, (Scripps Institution of Oceanography). 2018. Climate, Drought, and Sea Level Rise Scenarios for the Fourth California Climate Assessment. California's Fourth Climate Change Assessment, California Energy Commission. Publication Number: CNRA-CEC-2018-006.

Rasmussen, L. L., M. L. Carter, R. E. Flick, M. Hilbern, J. T. Fumo, B. D. Cornuelle, B. K. Gordon, L. F. Bargatze, R. L. Gordon, and J. A. McGowan. 2020. A Century of Southern California Coastal Ocean Temperature Measurements. Journal of Geophysical Research: Oceans 125:e2019JC015673. doi: 10.1029/2019JC015673.

Ren, A. S., F. Chai, H. Xue, D. M. Anderson, and F. P. Chavez. 2018. A Sixteen-year Decline in Dissolved Oxygen in the Central California Current. Scientific Reports 8:7290. doi: 10.1038/s41598-018-25341-8.

Roemmich, D., and J. McGowan. 1995. Climatic Warming and the Decline of Zooplankton in the California Current. Science 267:1324–1326. doi: 10.1126/science.267.5202.1324.

Roletto, J., S. Kimura, N. Cosentino-Manning, R. Berger, and R. Bradley. 2014. Status and Trends of the Rocky Intertidal Community on the Farallon Islands. Monographs of the Western North American Naturalist 7:260–275. doi: 10.3398/042.007.0120.

Russell, J. C., J.-Y. Meyer, N. D. Holmes, and S. Pagad. 2017. Invasive alien species on islands: impacts, distribution, interactions and management. Environmental Conservation 44:359–370. doi: 10.1017/S0376892917000297.

Sanford, E., J. L. Sones, M. García-Reyes, J. H. R. Goddard, and J. L. Largier. 2019. Widespread shifts in the coastal biota of northern California during the 2014–2016 marine heatwaves. Scientific Reports 9:4216. doi: 10.1038/s41598-019-40784-3.

San Francisco Department of Environment. 2018. 2016 San Francisco geographic greenhouse gas emissions inventory at a glance. San Francisco Department of Environment, Climate Program.

Schmidtko, S., L. Stramma, and M. Visbeck. 2017. Decline in global oceanic oxygen content during the past five decades. Nature 542:335–339. doi: 10.1038/nature21399.

Schroeder, I. D., J. A. Santora, N. Mantua, J. C. Field, B. K. Wells, E. L. Hazen, M. Jacox, and S. J. Bograd. 2022. Habitat compression indices for monitoring ocean conditions and ecosystem impacts within coastal upwelling systems. Ecological Indicators 144:109520. doi: 10.1016/j.ecolind.2022.109520.

Sun, F., N. Berg, A. Hall, M. Schwartz, and D. Walton. 2019. Understanding End-of-Century Snowpack Changes Over California's Sierra Nevada. Geophysical Research Letters 46:933–943. doi: 10.1029/2018GL080362.

Swain, D. L., B. Langenbrunner, J. D. Neelin, and A. Hall. 2018. Increasing precipitation volatility in twenty-first-century California. Nature Climate Change 8:427–433. doi: 10.1038/s41558-018-0140-y.

Sydeman, W. J., and S. G. Allen. 1999. Pinniped Population Dynamics in Central California: Correlations with Sea Surface Temperature and Upwelling Indices. Marine Mammal Science 15:446–461.

Thompson, S. A., W. J. Sydeman, J. A. Santora, B. A. Black, R. M. Suryan, J. Calambokidis, W. T. Peterson, and S. J. Bograd. 2012. Linking predators to seasonality of upwelling: Using food web indicators and path analysis to infer trophic connections. Progress in Oceanography 101:106–120. doi: 10.1016/j.pocean.2012.02.001.

Torregrosa, A., C. Combs, and J. Peters. 2016. GOES-derived fog and low cloud indices for coastal north and central California ecological analyses. Earth and Space Science 3:46–67. doi: 10.1002/2015EA000119.

Trenberth, K. E. 2011. Changes in precipitation with climate change. Climate Research

47:123–138. doi: 10.3354/cr00953.
Trillmich, F. and K. A. Ono. 1991. Pinnipeds and El Niño Responses to Environmental Stress. Springer Berlin, Heidelberg. doi: 10.1007/978-3-642-76398-4.
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.)]. U.S. Global Change Research Program, Washington, DC, USA.
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.)]. U.S. Global Change Research Program, Washington, DC, USA.
Urban, M. C. 2015. Accelerating extinction risk from climate change. Science 348:571–573. doi: 10.1126/science.aaa498.
U.S. Fish & Wildlife Service (USFWS). 2023. Farallon Islands National Wildlife Refuge. Species. https://www.fws.gov/refuge/farallon-islands/species.
van Weelden, C., J. R. Towers, and T. Bosker. 2021. Impacts of climate change on cetacean distribution, habitat and migration. Climate Change Ecology 1:100009. doi: 10.1016/j.ecochg.2021.100009.
Wang, J., H.-M. Kim, and E. K. M. Chang. 2017. Changes in Northern Hemisphere Winter Storm Tracks under the Background of Arctic Amplification. Journal of Climate 30:3705–3724. doi: 10.1175/JCLI-D-16-0650.1.
Warlick, A. J., J. L. Huggins, D. M. Lambourn, D. A. Duffield, D. N. D'Alessandro, J. M. Rice, J. Calambokidis, M. B. Hanson, J. K. Gaydos, S. J. Jeffries, J. K. Olson, J. J. Scordino, A. M. Akmajian, M. Klope, S. Berta, S. Dubpernell, B. Carlson, S. Riemer, J. Hodder, V. Souze, A. Elsby, C. King, K. Wilkinson, T.Boothe, and S. A. Norman. 2022. Cetacean Strandings in the US Pacific Northwest 2000-2019 Reveal Potential Linkages to Oceanographic Variability. Frontiers in Marine Science 9:758812. doi: 10.3389/fmars.2022.758812.
Weathers, K. C., A. G. Ponette-González, and T. E. Dawson. 2020. Medium, Vector, and Connector: Fog and the Maintenance of Ecosystems. Ecosystems 23:217–229. doi: 10.1007/s10021-019-00388-4.
Williams, A. P., B. I. Cook, and J. E. Smerdon. 2022. Rapid intensification of the emerging southwestern North American megadrought in 2020–2021. Nature Climate Change 12:232–234. doi: 10.1038/s41558-022-01290-z.
Wolf, S. G., M. A. Snyder, W. J. Sydeman, D. F. Doak, and D. A. Croll. 2010. Predicting population consequences of ocean climate change for an ecosystem sentinel, the seabird Cassin's auklet. Global Change Biology 16:1923-1935. doi: 10.1111/j.1365-2486.2010.02194.x.
Xiu, P., F. Chai, E. N. Curchitser, and F. S. Castruccio. 2018. Future changes in coastal upwelling

ecosystems with global warming: The case of the California Current System. Scientific Reports 8:2866. doi: 10.1038/s41598-018-21247-7.