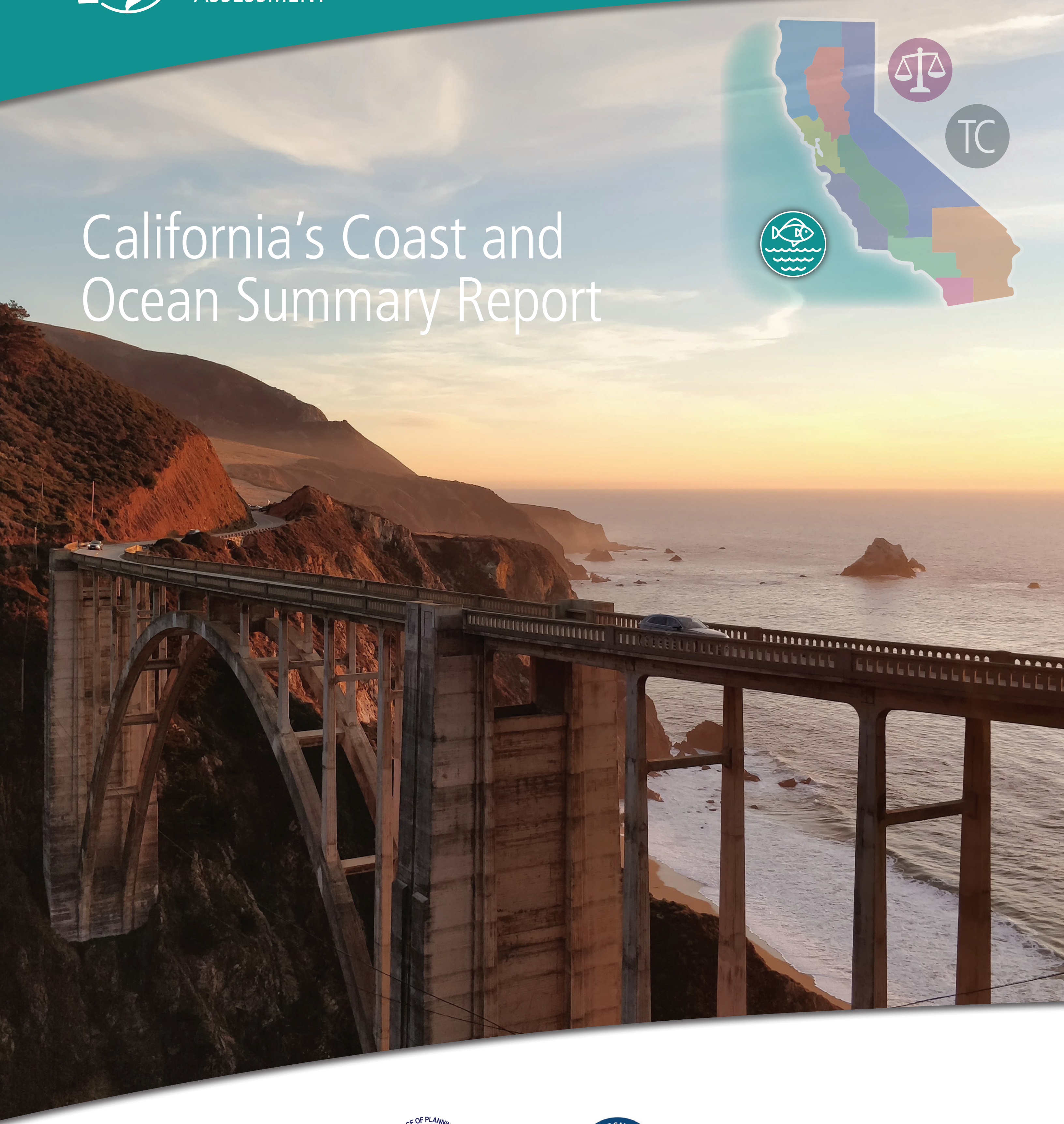
CALIFORNIA'S FOURTH
CLIMATE CHANGE
ASSESSMENT

California's Coast and Ocean Summary Report

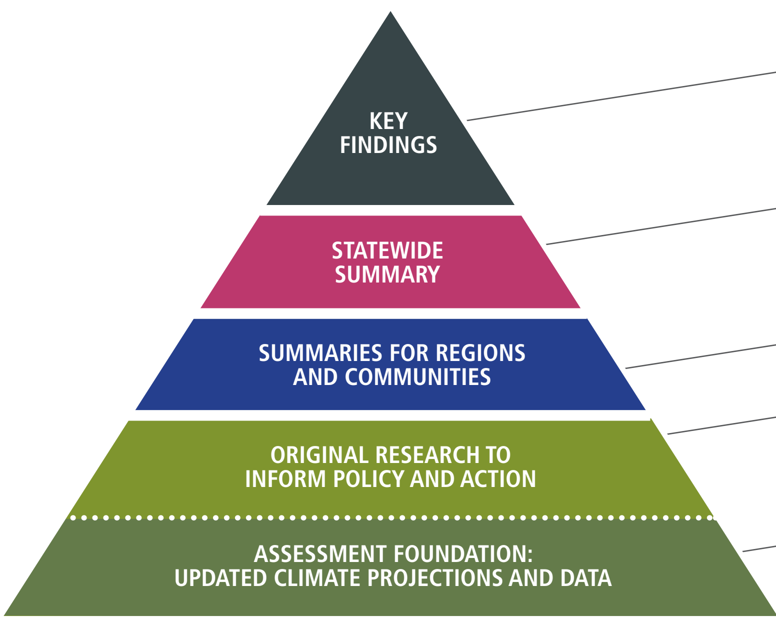


Coordinating Agencies:

Introduction to California's Fourth Climate Change Assessment

California is a global leader in using, investing in, and advancing research to set proactive climate change policy, and its Climate Change Assessments provide the scientific foundation for understanding climate-related vulnerability at the local scale and informing resilience actions. The Climate Change Assessments directly inform State policies, plans, programs, and guidance to promote effective and integrated action to safeguard California from climate change.

California's Fourth Climate Change Assessment (Fourth Assessment) advances actionable science that serves the growing needs of state and local-level decision-makers from a variety of sectors. This cutting-edge research initiative is comprised of a wide-ranging body of technical reports, including rigorous, comprehensive climate change scenarios at a scale suitable for illuminating regional vulnerabilities and localized adaptation strategies in California; datasets and tools that improve integration of observed and projected knowledge about climate change into decision-making; and recommendations and information to directly inform vulnerability assessments and adaptation strategies for California's energy sector, water resources and management, oceans and coasts, forests, wildfires, agriculture, biodiversity and habitat, and public health. In addition, these technical reports have been distilled into summary reports and a brochure, allowing the public and decision-makers to easily access relevant findings from the Fourth Assessment.



- A concise summary of the Fourth Assessment's most important findings and conclusions.
- An in-depth report on how California's people, built environment, and ecosystems will be impacted by climate change and how we can proactively adapt, based on the Fourth Assessment's findings.
- Reports summarizing Fourth Assessment findings to provide a state of the science for nine regions, the coast and ocean, tribal communities, and climate justice in California.
- Academic research that provides robust and detailed results on resilience and vulnerability to climate change.
- A shared foundation of updated climate change projections, data and ecosystem models developed for use by Assessment authors to permit cross-comparability of results and ensure the findings consider a robust range of future climate conditions. These data are available to the public via Cal-Adapt.org.

All research contributing to the Fourth Assessment was peer-reviewed to ensure scientific rigor as well as, where applicable, appropriate representation of the practitioners and stakeholders to whom each report applies.

For the full suite of Fourth Assessment research products, please visit: www.ClimateAssessment.ca.gov

California's Coast and Ocean Report

The Ocean and Coast Communities Summary Report is part of a series of 12 assessments to support climate action by providing an overview of climate-related risks and adaptation strategies tailored to specific regions and themes. Produced as part of California's Fourth Climate Change Assessment and as part of a pro bono initiative by leading climate experts, these summary reports translate the state of climate science into useful information for decision-makers and practitioners to catalyze action that will benefit regions, the coast and ocean frontline communities, and tribal communities.

The Coast and Ocean Report presents an overview of climate science, specific strategies to adapt to climate impacts, and key research gaps needed to spur additional progress on safeguarding Coastal and Ocean Communities from climate change.

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About This Report

This report synthesizes current scientific understanding about the impacts of climate change on California's coast and ocean and presents a forward-looking summary of challenges and opportunities for the future. It is one component of California's Fourth Climate Change Assessment (Fourth Assessment). To prepare this report, the state called upon the California Ocean Protection Council (OPC) and California Ocean Science Trust (OST) to convene an Ocean Protection Council Science Advisory Team (OPC-SAT) working group composed of science and policy leaders. Similar to other components of the Fourth Assessment, the 12-member working group was guided by an Advisory Group of end users and high-level decision-makers.

This report is intended to provide accessible scientific information that is relevant for policy and decision-makers, build a foundation for policy to address climate change impacts through adaptation and mitigation, highlight best practices and models for coastal adaptation to climate change along the coast, and inform interested members of the public on the impacts of climate change on California's coast and ocean waters and potential approaches for adaptation and mitigation. It will also inform the next update of the *Safeguarding California* plan, a policy document serving as California's climate adaptation strategy, by presenting a scientific grounding to help focus and prioritize future state adaptation efforts.

(Photo Source: Ocean Science Trust)

Highlights and Major Findings

In recent years, Californians have witnessed unprecedented events in the ocean and along the coast. There is increasing concern that coastal and marine ecosystems in California are being transformed, degraded, or lost due to climate change impacts, particularly sea-level rise, ocean acidification, and warming. Scientific assessments are an important way for state and local leaders to better understand how climate change has affected Californians, what might be expected in the future, and what can be done now. Greenhouse gas emissions from human activities are the most significant driver of climate change impacts to California's coast. This report synthesizes the current scientific understanding of ocean changes resulting from greenhouse gas emissions, consequences for the things that Californians care about, and the research and actions necessary to build resilience and adapt to potential impacts.

Major Findings

Our analysis resulted in the following findings, elaborated upon in the report:

1. The ocean has significantly limited terrestrial climate change impacts by absorbing excess atmospheric heat and carbon dioxide, but the ocean's capacity to buffer rising greenhouse gas concentrations in the atmosphere (and climate warming) will be progressively diminished in the future. Reducing greenhouse gas emissions is the most effective long-term solution to anthropogenic climate change and ocean acidification.
2. As a result of past and ongoing levels of greenhouse gas emissions, California can anticipate a significant increment of ocean change, and thus it is essential to support adaptation in addition to mitigation. For example, stored carbon in deep ocean waters is expected to return to the surface in the coming several decades and will lead to increased ocean acidification and related impacts. A substantial fraction of the carbon dioxide in the atmosphere today will remain there for centuries, and the associated climate change will likely lead to a sea level in 2050 that will be at least 12 inches (30 centimeters) higher than sea level during the period 1991-2009.
3. Coastal climate impacts are not limited to the shoreline, but will have significant and wide-ranging implications for inland communities and economies. For instance, sea-level rise induced flooding of coastal roadways and railways may impact the movement of goods from coastal ports to inland areas, as well as the rest of the U.S. As beaches narrow, and ultimately disappear in some locations, inland communities will have fewer coastal access locations to which they can escape extreme heat days. Thus, mitigation and adaptation strategies developed for the coast and ocean can benefit inland communities and economies as well.
4. Human well-being is directly affected by impaired water quality related to climate change, including harmful algal blooms, and indirectly by ocean acidification and rising ocean temperatures.
5. Sea-level rise is already affecting the coast; the greatest impacts at present are from extreme events, such as king tides, and large storms associated with El Niño events. Over time, continued sea-level rise will increase the frequency and extent of coastal flooding and cliff and bluff erosion from these and other extreme events.

6. Climate extremes and ocean acidification are already impacting fish and shellfish ecosystems and industries in California as well as the people who depend on them, such as sustainable aquaculture growers.
7. Some of California's iconic coastal natural areas and species (such as coastal redwoods, kelp forests, and abalone), may be negatively impacted, displaced, or lost as climate changes, and some new, historically uncommon, or unfamiliar species may become common.
8. Vulnerable communities in coastal areas face increased risks from climate change impacts due to pre-existing socioeconomic inequities, which could result in greater harm or even displacement.
9. Though scientific understanding can continue to advance our knowledge of climate change impacts and adaptation options, we know enough to respond now. The cost of adaptation will be lower if effective mitigation measures are put in place now; inaction today will reduce options and impose higher costs later.
10. Scientific understanding is rapidly increasing but uncertainties and incomplete information will persist. Focused natural and social science research investments can increase our understanding of impacts, illuminate adaptation options, and provide the foundation to evaluate and improve future actions.

In sum, ocean warming, ocean chemistry changes, sea-level rise, and other greenhouse gas-driven changes to California's ocean and coast – those already occurring and projected – will have significant consequences for California's coastal economy, communities, ecosystems, culture, and heritage. These consequences will also have ripple effects in California well beyond the local areas affected, effects that could extend into the U.S. economy. Below and in the complete report, we recommend research priorities and implementation gaps that could be filled to complement existing efforts in California and advance sound adaptation strategies and solutions.

Key research and adaptation needs: problems, opportunities, and benefits

Research Needs:

1. Assessment of the socio-economic consequences of climate change currently relies on syntheses of forecasts of future sea levels and other oceanic changes with data on current socio-economic conditions. Integrating projected future socio-economic conditions (such as changes in the location of population and employment that are incorporated in infrastructure planning) with forecasts of climate change effects can provide predictions and scenarios that can be used to prioritize and select among adaptation options.
2. Changing ocean conditions are already impacting California's marine life and fisheries. Economically and ecologically important marine organisms can be negatively affected by the simultaneous occurrence of different stressors such as increasing temperatures, ocean acidification, and lowered oxygen levels. Improving the current understanding of the combined effects of these ocean changes and whether thresholds exist for potential collapse of ecosystems or fisheries, or significant loss of individual species, can provide guidance for management decisions that can help reduce future losses and impacts.
3. Specific toxins associated with harmful algal blooms (HABs, such as domoic acid and *Pseudo-nitzschia*) can have major effects on both human health and commercial fisheries (such as the delay in the opening of the Dungeness crab fishery in 2015-16). Improving scientific understanding of the environmental conditions or triggers for these harmful algal blooms,

including their interactions with changing ocean temperature and ocean chemistry, and developing early warning systems, can help to ensure the protection of human health. It can also provide guidance for control of terrestrial runoff and wastewater discharge to help reduce the future frequency, duration, and intensity of harmful algal blooms.

4. Sequestration and drawdown of carbon by marine vegetation has the potential to reduce the impact of rising carbon dioxide concentrations and associated ocean chemistry changes. A key need is to understand and quantify the importance of different habitat types and the role that restoration or conservation of these habitats may play in reducing the impact of rising carbon dioxide levels on coastal marine environments.

5. Ocean acidification is already impacting key coastal species throughout the food chain. Maintaining and expanding monitoring of ocean acidification and dissolved oxygen to improve understanding of long-term trends can aid both in developing adaptive responses and in assessing impacts of policy changes. In particular, a clear understanding of the spatial and temporal variability in ocean acidification and declining dissolved oxygen is needed and can be obtained through commitment to statewide monitoring efforts.

6. Reduced dissolved oxygen levels (ultimately leading to hypoxia) in nearshore waters are detrimental to almost all marine animals. A clear understanding of the frequency and extent of low oxygen zones, and the mechanisms causing them, could help inform efforts to reduce these events and their biological impacts.

7. Coastal and ocean monitoring and observation systems have enabled scientists and others to document and quantify individual climate-related changes to the coast and ocean. Continuing to monitor environmental indicators of climate change can expand California's ability to track the extent of climate change effects and respond with appropriate and timely mitigation and adaptation measures.

8. The combination of sea-level rise and extreme water level events (El Niño and king tides, for example) will continue to affect the coast and lead to significant changes to its beaches, dunes, cliffs, and bluffs. These will have important implications and impacts to existing coastal development and infrastructure, as well as coastal habitats and ecosystems. There is a need to continue to improve our understanding of how cliffs, bluffs, dunes, and beaches will erode and change with increased wave impact and extreme water levels. Continuing to monitor both short- and long-term coastal change over time through our existing and developing tools and technologies will allow for more accurate predictions of future change and how the coast will respond to a shifting climate.

Adaptation and Education Needs:

9. Although a variety of strategies have been used historically to address coastal hazards, policies are now being developed and experience is growing in implementing sea-level rise adaptation strategies at state and community-wide scales that attempt to balance environmental and social needs. The longer we wait to adapt, however, the greater the future costs and losses will be. Developing successful approaches to adaptation and publicizing the financial mechanisms for applying them statewide will save money and reduce future risks.

10. Uncertainty remains in the minds of many California residents regarding what they might expect or experience in the future from a changing climate, and how they might better prepare. State efforts to continue to evaluate, assess, and educate all Californians about how climate change is affecting the coastal zone and ocean waters can result in a more informed public and improved decision-making.

11. As communities begin to plan for the impacts of climate change, they should be encouraged to have broad engagement from throughout the community. Social inclusion, in combination with evolving scientific research and understanding, will be critical to advancing coastal adaptation strategies that incorporate all sources of relevant information, are fair and just to all community members, and ultimately have a better chance of adoption and implementation.
12. The roles and responsibilities of multiple public agencies will be impacted by climate change and there are many opportunities for coordination and cooperation between agencies and sectors. Through the engagement of affected stakeholders and the assessment of social and economic costs and benefits, California can develop more transparent and information-based adaptation approaches. Better coordination can promote learning about opportunities for and barriers to working together. New governance structures may be needed to fully address the impacts of climate change.
13. A unique opportunity exists to test and evaluate adaptation strategies in different physical and biological environments as they are implemented, to assess how well they meet different environmental and social needs, and to then export and scale successful adaptation strategies along the coast.

The Western States Water Council visits Goat Rock Beach, located between Goat Rock Point and the Russian River along the Sonoma County shore near the town of Jenner, California. Photo taken June 27, 2017. (Figure Source: California Department of Water Resources)

1. Introduction

In the last three years alone, Californians have witnessed unusual events in the ocean and along the coast, including an unprecedented marine heat wave, a record harmful algal bloom (HAB), the closure of fisheries, a prolonged period of elevated coastal sea levels, and a significant loss of northern kelp forests. There is increasing concern that California's coastal and marine ecosystems are being transformed, degraded, or lost due to ocean acidification and climate change impacts, particularly sea-level rise and ocean warming. Scientific assessments are an important way for state and local leaders to better understand the effect of ocean acidification and climate change, what might be expected in the future, and what the response might be.

In contrast to previous assessments, California's Fourth Climate Change Assessment has incorporated a number of coastal and ocean related issues and projects into its evaluation. Here we present projected climate change impacts to California's coast and ocean, including results from the research projects funded by the Fourth Assessment process, and provide science-based options for mitigating those impacts and adapting to a changing environment. Though the focus is on California, we often expand our scope to include the broader California Current System (CCS) to reflect the scale at which these ecosystems function and how impacts will be felt.

A changed future is certain, so both adaptation and mitigation are essential.

Even in a world that may achieve the Paris Agreement greenhouse gas emission goals, we have already committed to a significant increment of human-caused climate change and ocean acidification, and thus adaptation in addition to mitigation is essential. Interconnected mitigation and adaptation strategies and approaches are required to reduce the likelihood of adverse climate change impacts. Mitigation can reduce exposure by lessening the threat, while adaptation can increase the ability of communities to cope with that threat. As many adaptation actions in California have followed guidance to be local and community-specific, evidence suggests that these actions do not add up to achieve their full potential. To address this gap, coordinated and focused scientifically-informed actions taken today can reduce the costs of adaptation in the future (Risky Business 2014).

We begin the report by describing the importance of the coast and ocean in California and what is at risk. Section 2 then presents current scientific understanding of projected changes to the ocean and coast as a result of greenhouse gas emissions. We focus specifically on changing ocean temperature, sea level, ocean-atmospheric influences, and ocean chemistry. Section 3 describes how these physical changes may impact California, highlighting coastal communities and development, fisheries and aquaculture, human health, economic and social aspects, and natural heritage. Each of these sections present data gaps and ideas for building resilience. Section 4 takes these ideas further by describing the need for cross-sectoral solutions. We conclude the report with a list of research needs necessary to advance adaptation actions.

2. California's Coast and Ocean

2.1 Coastal Economy, Communities, and Heritage

Impacts on ocean ecosystems have significant and wide-ranging implications for coastal and inland communities and economies.

California's coast and ocean supports a large economy and many coastal communities. Although California's 19 coastal counties account for only 22 percent of the state's area, they are home to 68 percent of its people, 80 percent of its wages, and 80 percent of its GDP (ERG 2016). Population density, along with the presence of critical infrastructure and valuable real estate and development along the coast, accentuate the importance of the coastal area to the state's economy. The coast, however, is more than just the shoreline or the beach, and what happens in coastal regions affects far more of the state's population than those who live in coastal counties (Figure 1). Sacramento, for example, while 100 miles inland from the Golden Gate Bridge, is a port for oceangoing ships and cities throughout California, and the nation enjoys and depends on the goods that move through all of the California ports and harbors.

California has the nation's largest ocean-based economy.

California's ocean-based economy is valued at approximately $45 billion annually, and employs over half a million people (ERG 2016). Many of the people who contribute to the largest component of the ocean economy (tourism and recreation) travel to the coast from inland areas, as do many of the workers in ocean industries who can no longer afford to live near the shore. California's ocean also supports a vast diversity of marine life as well as fishing communities that depend on fish, shellfish, and seaweeds for their livelihoods, providing a diverse supply of seafood to the state and for export. In 2012, approximately 1,900 commercial fishing vessels operated in California (Culver and Pomeroy n.d.)

FIGURE 1: WHY THE COAST MATTERS

California ports handle 60 percent of the nation's imports from the Far East and more than 70 percent of California's agricultural export trade; they are at risk from storm impacts and sea level rise.

Agriculture depends on coastal fog; reduced coastal fog and saltwater intrusion threatens some of themost valuable farming areas in the state.

Coast redwoods depend on marine fog; they may become drought-stressed if summer fog declines.

There are a number of locations along the California coast where beaches and other popular shoreline features will be permanently lost to a rising ocean.

Climate change is altering connections between the ocean and the atmosphere, potentially leading to even more severe droughts in our future.

From shipping to agriculture, ocean change will impact more than just the coast (Figure source: Della Gilleran).

and 7,700 jobs were supported by recreational marine fishing (NMFS 2012). Each of these economic sectors is affected by the changing sea level, temperature, atmospheric processes, and chemistry that are accompanying a changing climate.

Iconic coastal areas and species are critical to state identity and values.

California's coast and ocean represent more than the resources they provide; they are an important part of the state identity and values (Christensen and King 2017; ERG 2016; Raheema et al. 2009). People have long chosen to work, live, and play along the coast and ocean. In 1849, when California's constitution was adopted (before California became a state), it recognized that coastal tidelands belonged to the people (Braje et al. 2017; ERG 2016). The values of the ocean extend well beyond its range and encompass both utilitarian needs and spiritual uses. These values include coastal natural areas, clean water and air, and an extraordinary diversity of wildlife and habitat (Christensen and King 2017; Leeworthy and Schwarzmann 2015). People also value nature for nature's sake (i.e., the inherent or intrinsic value of nature) (Vucetich et al. 2015). A walk along the beach, enjoying a sunset over the ocean, and spending time on or in the water draws people into contact with the natural areas and wildlife of California's coast and ocean and has been demonstrated to have positive physical and mental health benefits (Sandifer 2014; 2015).

People are attracted to living, working, and recreating near the coast and enjoying its natural resources and mild climate. A survey of California voters found that 77 percent visit the coast at least once a year and over 60 percent visit at least several times per year (Christensen and King 2017). California State Parks manages 340 miles of Pacific Ocean shoreline and hosts millions of visitors (ERG 2016). In 2012, sport fishing alone brought 86,000 non-resident anglers to California and 316,000 non-coastal Californians to the coast (ERG 2016).

Many individuals and organizations have fiercely defended public access to the coast as well as conservation of marine and coastal wildlife and habitats. The extensive civic engagement and investment of time and money in policy related to the conservation and sustainable management of California's coast and ocean provides additional strong evidence of the value people place on these natural areas (Box 1). These laws and institutions provide a strong foundation for adaptation action but, in most cases, were established prior to explicit governmental concern about climate change.

BOX 1: COAST AND OCEAN LEGISLATION AND AGENCIES IN CALIFORNIA

Public benefits provided by conservation and sustainable management of the coast and ocean were won over the course of decades through federal and state legislation, the establishment of governmental agencies, and the supportive efforts of private and non-profit groups. Relevant legislation and agencies include:

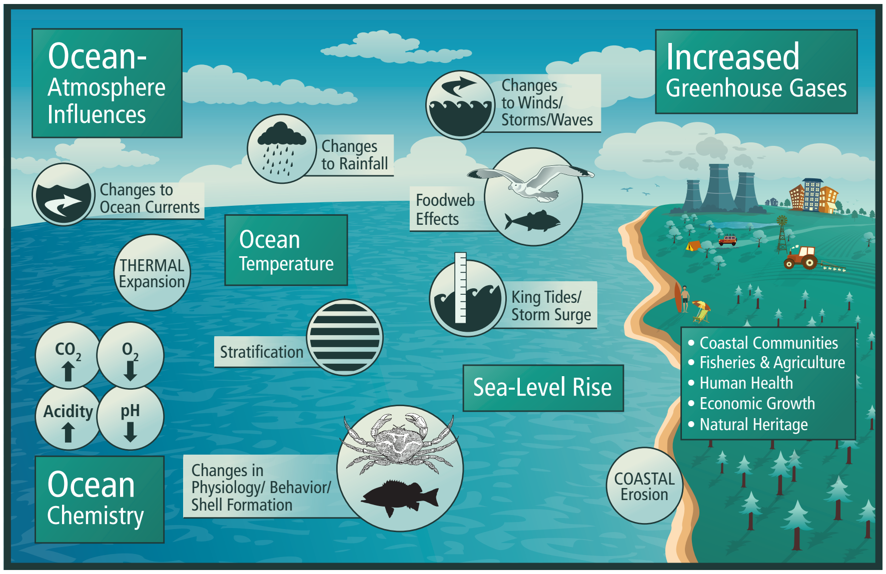
1. The Board of Fish Commissioners, forerunner of the Fish and Game Commission, established in 1870 to provide for the restoration and preservation of fish in California waters
2. The Division of Fish and Game created within the Department of Natural Resources in 1927 (now the Department of Fish and Wildlife)
3. The McAteer-Petris Act (1965) established the Bay Conservation and Development Commission for San Francisco Bay
4. The Coastal Zone Management Act (1972) created the framework for states and federal governments to manage coastal resources, balancing development with conservation and stewardship
5. The California Coastal Zone Conservation Act (1972) established the California Coastal Commission
6. The California Coastal Act (1976) enhanced public access, protects natural resources, and balances coastal development in the public interest
7. The State Coastal Conservancy was established in 1976 to protect California's coastal resources and to promote the public's access and enjoyment
8. The National Marine Sanctuaries Act (1972) authorized the designation and protection of areas of the marine environment with special national significance for conservation, recreational, ecological, historical, scientific, cultural, archeological, educational, or esthetic qualities (California has four)
9. The Marine Mammal Protection Act (1972) protected marine mammals and their ecosystems;
10. The Magnuson-Stevens Fishery Conservation and Management Act (1976) fostered the long-term biological and economic sustainability of national marine fisheries
11. California's Marine Life Management Act (1999) supported sustainable fisheries and their ecosystems in state waters
12. The Marine Life Protection Act (1999) created California's network of state marine protected areas (MPAs)
13. The Ocean Protection Act created the Ocean Protection Council in 2004 to help protect, conserve, and maintain healthy coastal and ocean ecosystems and the economies they support.

2.2 Ocean Changes Caused by Greenhouse Gas Emissions

Greenhouse gas emissions from human activities are the most significant driver of climate change and ocean acidification (Figure 2) (Caldeira and Wickett 2003; IPCC 2007). Annual greenhouse gas emission rates are accelerating, with current trends exceeding those predicted by "worst case" global emissions scenarios (USGCRP 2017). The pace and severity of future change will depend upon when and how rapidly California moves away from a fossil fuel based economy and the success of mitigation and adaptation efforts. California is a recognized leader in efforts to mitigate climate change through emissions reductions and the development of renewable energy. Efforts to aggressively pursue both climate change mitigation and adaptation should be continued as mitigation efforts will have important impacts far beyond California's own borders, in other states, and nations.

Future climate projections in this report are based on the emissions scenarios used by the Intergovernmental Panel on Climate Change's Fifth Assessment Report and are called Representative Concentration Pathways (RCPs). There are four RCPs, named for the associated radiative forcing level in 2100: RCP 2.6, 4.5, 6.0 and 8.5. Each RCP represents a family of possible underlying socioeconomic conditions, policy options, and technological considerations, spanning from a low-end scenario (RCP 2.6) that requires significant emissions reductions to a high-end, "business-as-usual," fossil-fuel-intensive emission scenario (RCP 8.5).

FIGURE 2: OCEAN CHANGES CAUSED BY GREENHOUSE GAS EMISSIONS



Greenhouse gases in the atmosphere are the primary driver of climate change. This affects sea-level rise, increases ocean temperature, alters ocean-atmosphere influences, and affects ocean chemistry with consequences for California's coastal communities, fisheries and aquaculture, human health, economic growth, and natural heritage. (Figure source: Della Gilleran, adapted from QSR 2010 https://qsr2010.ospar.org/en/ch03_01.html).

California's Fourth Climate Change Assessment focuses on medium (RCP 4.5) and high (RCP 8.5) radiative forcing scenarios for years beyond 2060, and RCP 8.5 before 2060 (CO-CAT 2017). RCP 8.5, often referred to as a "business-as-usual" scenario, is consistent with a future where there are few global efforts to limit or reduce emissions. Under RCP 8.5, global carbon dioxide emissions nearly double between years 2015 and 2050. RCP 4.5 is a "medium" emissions scenario that models a future where societies have significantly reduced greenhouse gas emissions (by comparison, RCP 2.6 requires active carbon reduction technologies and corresponds to the goals of the Paris Agreement).

2.2.1 SEA LEVEL

Although sea-level rise is presently occurring at a relatively low rate, this rate is accelerating. It is already affecting the coast and over time it will affect the frequency and extent of coastal flooding and shoreline erosion. Sea-level rise projections under all greenhouse gas emissions scenarios predict accelerating sea-level rise. By 2050 at least 12 inches (30 centimeters) of sea-level rise is projected.

Global sea-level rise is the most well-documented manifestation of climate change along the coast. As the global climate continues to warm, ocean water will warm and expand, and continental glaciers and the ice sheets of Greenland and Antarctica will continue to melt. These ice sheets sequester most of the Earth's terrestrial water that is available to elevate sea level (about 24 feet (7.3 meters) on Greenland and about 187 feet (57 meters) on Antarctica) (Bamber et al. 2013; Fretwell et al. 2013). A suite of observations indicates that sea-level rise contributions from the planet's melting ice have recently eclipsed the contribution due to thermal expansion of seawater, which is believed to have been the primary contributor of sea-level rise during the 19th and 20th centuries. The greatest future contributions to sea-level rise will be from the continued melting of the Greenland and Antarctic ice sheets and evidence indicates that this will happen at an increasing rate (DeConto & Pollard 2016). Very recent analysis of satellite altimeter data has documented an acceleration in the rate of sea-level rise (Nerem et al. 2018).

Sea-level rise has been recorded over most of the California coast south of Cape Mendocino at four to eight inches (10 to 20 centimeters) over the 20th Century (Griggs et al. 2017). As the Earth gradually warms, sea-level rise will continue to threaten coastal communities and infrastructure through more frequent flooding followed by permanent inundation of low-lying areas and increased erosion of cliffs, bluffs, dunes, and beaches (see page 18) (Sweet and Park 2014; Tebaldi et al. 2012; Vitousek et al. 2017b).

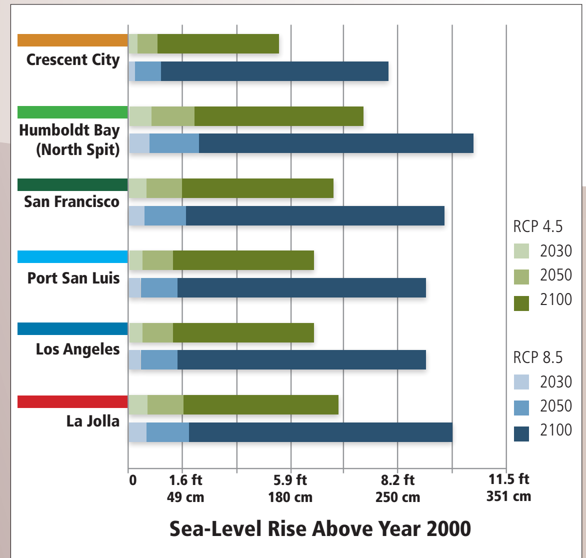
Carbon dioxide and other greenhouse gases from anthropogenic sources that have already been emitted will remain in the atmosphere (and the ocean) for centuries, and will likely lead to a sea level in 2050 that is at least 12 inches (30 centimeters) higher compared to a 1991–2009 baseline (Griggs et al. 2017). Different model projections of sea-level rise between now and 2050 are in general agreement on this value. Beyond 2050, however, there are significant differences in sea-level rise projections that are increasingly dependent on the trajectory of global greenhouse gas emissions, and therefore the extent of additional warming (Box 2). Even under the most optimistic conditions (e.g. a global achievement of the Paris Agreement goals), there will be a substantial rise in sea level over the next several decades and beyond 2050. The science of sea-level rise is evolving rapidly, but current models indicate that significantly reducing carbon dioxide emissions could limit additional sea-level rise to about 2.4 to 4.5 feet (0.7 to 1.4 meters) by 2100 (Cayan et al. 2017). Failure to meet those emission goals, however, could lead to rapid ice sheet loss in Antarctica and potential extreme sea-level rise of as much as eight feet (2.4 meters) by 2100. This is equivalent to a sea-level rise rate about 30-40 times faster than the rate experienced over the last century (Griggs et al. 2017).

Regardless of long-term greenhouse gas emission rates, over the next few decades the greatest coastal impacts associated with sea level will very likely occur when large storms coincide with elevated sea levels during El Niño events or high astronomical tides. Most of California's largest storms occur in winter, although occasionally tropical storms have affected the southern part of the state in late summer and fall. Moreover, El Niño conditions create anomalously high water levels and waves along the West Coast that can lead to increased erosion, which exacerbate damage from coastal impacts (Barnard et al. 2015; Vitousek et al. 2017b; Limber et al. 2018). These short-term or episodic extreme events are common now, have produced significant damage in the past, and will continue into the future (Tebaldi et al. 2012; Griggs et al. 2017).

BOX 2: SEA-LEVEL RISE PROJECTIONS FOR THE FOURTH ASSESSMENT

California's Fourth Climate Change Assessment uses a broader range of sea-level rise projections than the recent report Rising Seas in California: An Update on Sea-Level Rise Science, which was used by OPC in the preparation of State of California Sea-Level Rise Guidance (2018) to provide scientific guidance for state and local decision-makers. The Fourth Assessment sea-level rise projections include the possibility of up to almost 11 feet (3.3 meters) of rise by 2100 only for the RCP 8.5 scenario, while OPC guidance provides an extreme sea-level rise scenario of approximately 10 feet (3 meters), but does not attach this to an individual emissions scenario. Both projections are based on estimates of contributions to sea-level rise from primary sources using different methods, including model projections and expert elicitation. However, the Fourth Assessment used new modeling results that quantified the potential rapid demise of Antarctic land-based ice mass. Because there is still considerable uncertainty in these results, the Fourth Assessment projections are meant for research purposes while the OPC projections are meant for regulatory and planning purposes.

FIGURE 3: LOCAL SEA-LEVEL RISE PROJECTIONS



Due to increasing sea levels in San Francisco, a flood that presently occurs on average about one time every 10 years, will occur 6.8 times per year by 2050 under RCP 4.5. By 2100, under these same emissions conditions, today's 10-year flood will occur 115 times every year, *or nearly every 3 days on average* (Buchanan et al. 2017).

king tide, 2012

SAN FRANCISCO COASTAL FLOOD FREQUENCY AMPLIFICATION

		10-year	10-year	100-year	100-year
Under RCP	Year	2050	2100	2050	2100
	Floods/YR	6.8	115.2	0.8	51.4
Under RCP	Year	2050	2100	2050	2100
	Floods/YR	10.3	155.1	1.24	92.6

Historic sea-level rise values and future projections show a moderate range along California's 1100 mile coastline due to differences in tectonic settings. For example, the difference in projections for future sea levels between Crescent City (Del Norte County) and North Spit (Eureka, Humboldt County) highlight the local importance of tectonic setting as well as the role of extreme events, such as tsunami. Elevated future sea levels, however, will impact the shoreline of the entire state. After 2050, there are significant differences between sea levels resulting from RCP scenarios 4.5 and 8.5. These values for 2100 highlight the need for aggressive adaptation and mitigation efforts. (Figure source: Della Gilleran; Bar chart: Juliette Finzi Hart, data provided by Julie Kalansky).

2.2.2 OCEAN TEMPERATURE

California's coastal ocean warmed by 0.7°C in the last century and is projected to warm by an additional 2–4°C by the end of this century.

Long-term temperature records indicate that the California Current System (CCS) is warming (Alexander et al. 2018). Furthermore, the CCS experienced an unprecedented three-year warming from 2014–2016, leading some to suggest that climate change may be pushing the ecosystem into a state of increased variability (Di Lorenzo and Mantua 2016; Jacox et al. 2018).

The ocean has absorbed about 93 percent of the excess heat trapped by the Earth as a result of increasing greenhouse gas concentrations (USGCRP 2017). From 1900 to 2016, California's coastal ocean warmed by ~ 0.7°C (USGCRP 2017). Model projections suggest that this warming trend will continue; recent climate model simulations under a high-end greenhouse gas emissions scenario (RCP 8.5) indicate California Current waters will be 2 to 4°C above the 1920–2016 average by 2100 (Fig. 4a). These models predict little change for the range in variability such that the rising mean temperature comes with a substantial increase in the frequency of warm extremes (Alexander et al. 2018).

The CCS has historically fluctuated between warmer and cooler periods. In general, cool periods tend to be more biologically productive and warm periods tend to be less productive, as more nutrients are available for phytoplankton growth in cool waters. Under warmer conditions, including those associated with tropical El Niño events, it is largely subtropical species that thrive, including Pacific sardine, California spiny lobster, and California halibut. Under cooler conditions many northern and transitional species, including Dungeness crab, Pacific halibut, and anchovy, are more abundant.

By absorbing so much heat, the ocean serves as a buffer to greenhouse gas-associated warming of the global atmosphere. However, the effects of increasing ocean temperature (rising sea levels, expanded HABs, and enhanced ocean stratification) can impact vulnerable marine and coastal systems. Thus, ocean warming threatens the health and well-being of the human communities that depend on coastal and offshore marine resources, as described in the sections below.

2.2.3 OCEAN-ATMOSPHERE INFLUENCES

Climate change impacts on land and sea are closely linked due to connections between ocean processes, wind, fog, and drought.

California's marine waters, and the coastal climate itself, respond strongly to changes in wind and weather patterns. For California's north and central coast, each spring and summer features persistent northwest winds that cause upwelling of cool waters from depth; the year's coldest ocean temperatures on California's central and north coast occur from April to June. When the upwelled waters contact the overlying atmosphere, they produce a damp and chilly marine layer with persistent coastal fog. California's upwelling and coastal fog season typically continues through September (Johnstone and Dawson 2010). In coastal California, the growing season of economically important crops overlaps with the occurrence of coastal fog, which buffers the summer dry season through shading effects and direct water inputs (Grantham et al. 2018). Iconic species such as coast redwoods also depend on coastal fog. In addition to the marine layer, upwelling brings nutrient rich, oxygen poor, and low pH water to the coastal zone, significantly influencing marine life (Checkley and Barth 2009). In fall and winter, weaker and less persistent north-to-south coastal winds, especially north of the San Francisco Bay Area, mean that upwelling is less frequent and intense, and mostly confined to the southern part of the CCS.

Because wind-driven upwelling affects pH and oxygen levels, changes in local and regional winds also affect the suitability of habitats for various species of marine fish and plankton (Sydeman et al. 2014). Most models predict an intensification of upwelling winds for the CCS in April and May, but a weakening of summertime upwelling winds for the southern half of the CCS (Rykaczewski et al. 2015). A large-ensemble of simulations using the RCP 8.5 emissions scenario predicts that CCS upwelling will intensify in spring but weaken in summer, and that these changes expand beyond the envelope of natural variability primarily in the second half of the 21st century (Brady et al. 2017).

Key water properties in the CCS influenced by broader Pacific Ocean processes are also predicted to change in response to anthropogenic forcing. A northward shift in westerly winds and increased stratification of the upper ocean are projected for the North Pacific, which together increase nutrient and carbon concentrations and reduce dissolved oxygen concentrations of subarctic water entering the CCS (Rykaczewski and Dunne 2010). Such changes in ocean chemistry lead to enhanced primary productivity, but increased acidification and declining dissolved oxygen.

California droughts are also strongly influenced by the Pacific Ocean, with more than 50 percent of the variability associated with El Niño and the Pacific Decadal Oscillation (McCabe et al. 2004). Recent analyses suggest that climate change is altering the hydrologic cycle, potentially leading to even more severe droughts in the future (Mann and Gleick 2015), increasing precipitation extremes (Swain et al. 2018), and enhanced wildfire risk in many parts of the Western U.S. (Westerling et al. 2006).

2.2.4 OCEAN CHEMISTRY

Changes in coastal ocean chemistry threaten California fisheries, aquaculture, and natural environments.

Increases in atmospheric carbon dioxide concentrations are fundamentally changing the chemistry of the ocean (Caldeira and Wickett 2003; Feely et al. 2004). The ocean absorbs approximately 30 percent of the carbon dioxide released into the atmosphere every year (about 1.1 million tons/hour), changing the acidity of the ocean (termed 'ocean acidification'). As the amount of dissolved carbon dioxide increases in the ocean there is a concurrent increase in hydrogen ions (H^+), increasing seawater acidity, and a decreasing amount of carbonate

> "The natural variations in these different dimensions of California's coast and ocean can mask or amplify human-caused changes to carbon chemistry, up to a point. An important research question is to determine when the signal of human-caused changes in carbon inputs will be unmasked or emerge from the envelope (or range) of natural dynamics and processes in the nearshore marine waters of California; we refer to this as the 'time of emergence.'"

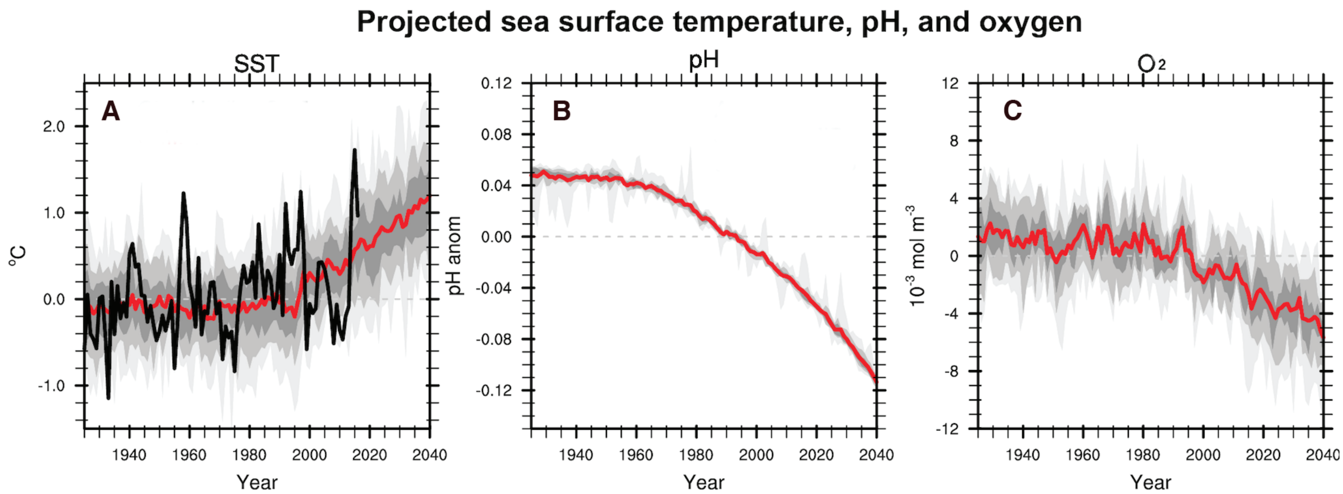
ions (CO_3^{2-}). Carbonate ions are fundamental building blocks used by many marine organisms that form shells and other hard parts out of calcium carbonate. Along the West Coast, models predict the onset of severely acidic conditions for much of the year in nearshore marine environments within as few as 30 years (Gruber et al. 2012).

The California coast is susceptible to economic impacts from ocean acidification, based upon an assessment of reliance upon income from shellfish fisheries (Ekstrom et al. 2015). Known impacts to species of state interest include decreases in shell size and/or thickness in oysters and mussels, increased mortality in Dungeness crab, and shell dissolution in small plankton (pteropods and foraminifera) that form the base of the food web for many other organisms. Long-term measurements of ocean carbon content at monitoring sites around the globe show consistent increases in the amount of carbon dioxide in the ocean. The long-term change in ocean chemistry in surface waters tracks closely with the rate of carbon dioxide increase in the atmosphere, with a decrease in pH of 0.05 since 1988 (Bates et al. 2014). If actions are taken to limit the global average temperature increase to 2°C during this century, average ocean surface pH may stabilize at 8.01 by 2100 (about 1.5 times more acidic than pre-industrialization). In contrast, under a high emissions scenario, global average ocean pH levels are predicted fall to around 7.7 by 2100 (Bernie et al. 2010; Kennedy 2010).

Just as with sea-level rise and other impacts, local context and conditions matter and the carbonate chemistry of coastal waters can significantly deviate from global averages. Along the California coast, ocean chemistry is monitored and tracked using oceanographic vessels, shore-based instruments, and moorings with carbon dioxide and pH sensors. These monitoring efforts are carried out in collaboration with a wide range of national, regional, and international partners (both public and private). We have learned that variability in ocean and coastal carbon chemistry differs substantially, with coastal ecosystems being much more dynamic (Chan et al. 2017; Feely et al. 2004). Some locations along the coast are exposed more regularly to acidified waters than others, creating a mosaic of coastal conditions (Chan et al. 2017). Despite high levels of variability along the shore and over time, some aspects are predictable and we are learning lessons from investments in long-term monitoring. For example, in coastal ecosystems, daily, tidal, and seasonal cycles in pH are evident and amplified within systems dominated by benthic macrophytes (seagrasses) (Koweek et al. 2017; Nielsen et al. 2018; Silbiger and Sorte 2018). Emerging research suggests these vegetated ecosystems may provide a local refuge from increasingly acidified conditions for some organisms, at least during daytime (photosynthetically active) hours. Additional research and monitoring to fill knowledge gaps can help to make more specific recommendations for how and where to apply the growing scientific understanding to adaptation-related policies.

The natural variations in these different dimensions of California's coast and ocean can mask or amplify human-caused changes to carbon chemistry, up to a point. An important research question is to determine when the signal of human-caused changes in carbon inputs will be unmasked or emerge from the envelope (or range) of natural dynamics and processes in the nearshore marine waters of California; we refer to this as the "time of emergence." For the ocean waters off California and in the CCS, modeling studies predict that time of emergence for human-caused changes beyond the envelope of natural variations comes first for pH (in the mid-to-late 20th century), before other chemical and physical changes (Henson et al. 2017) (Figure 4). For coastal California ecosystems, time of emergence from natural variability is more uncertain because of the greater variability of nearshore and estuarine environments. However, and importantly, species and therefore ecosystems may respond to even small changes in average conditions of pH and CO2, even within the context of a larger range of natural variability.

FIGURE 4: PROJECTED SEA SURFACE TEMPERATURE, pH, AND OXYGEN



Models project rapid future changes in ocean temperature, pH, and dissolved oxygen for the California Current System under a "business as usual" greenhouse gas emissions scenario (RCP 8.5). (A) The observed sea surface temperature is shown in the black line for 1920-2016, while the average of 28 different climate model simulations is shown by the red line. The gray band indicates the full range of temperatures from the 28 different climate model simulations. The projections include a human-caused warming trend of ~0.5 to 1.5 C by 2040, and 2-4C by 2100, with no clear indication of a change in the range of annual variability (Alexander et al. 2018). (B)(C) Historical records for pH anomaly and dissolved oxygen are not as complete as those for ocean temperature so are not shown for these variables. The model projections show rapid declines in California Current pH anomaly and dissolved oxygen concentrations. (Figure source: James Scott, NOAA Earth System Research Lab, Physical Sciences Division, Boulder, CO).

Below the mixed layer, dissolved oxygen concentrations in the southern CCS declined about 20 percent from 1980–2012 (Bograd et al. 2015). Ocean models forced by increasing greenhouse gases predict declines in open ocean dissolved oxygen in response to increased stratification and reduced ventilation. These changes in the CCS are controlled by complex interactions between circulation and biogeochemistry (Crawford and Pena 2016). Between decades, dissolved oxygen variations within 62 miles (100 kilometers) of California's coast have been linked with changing dissolved oxygen concentrations in remote source waters that feed upwelling in the basin-scale gyre circulation (Bograd et al. 2015; Buil and Di Lorenzo 2017). Anthropogenic climate change will drive a sharp decline of dissolved oxygen in the northeastern Pacific Ocean and emerge from the envelope of natural variability roughly in the 2030s (Fig. 4c; also see Long et al. 2016). Declining oxygen concentrations can lead to significant impacts on diversity, abundance, and food webs within marine communities (e.g., Levin et al. 2009; Somero et al. 2015; Stramma et al. 2010). Future reductions in dissolved oxygen are expected to harm bottom-dwelling marine life, shrink open-water habitat for top predators (Koslow et al. 2011), and increase the number of invasions by hypoxia-tolerant species like Humboldt Squid, a species thought to have benefited from an expansion of hypoxic waters and which rapidly expanded its range into the northeast Pacific Ocean in the late 1990s (Gilly et al. 2013; Stewart et al. 2012). It is important to consider that combined anthropogenic stressors (e.g., ocean acidification, hypoxia, temperature change) may interact to generate consequences that are difficult to predict for organisms and ocean environments; investigating the full suite of chemical and physical changes to the ocean is critical to understanding the implications for California.

3. Consequences of Ocean Change

Greenhouse gas emissions drive changes in sea level, ocean temperature, and ocean chemistry, and will individually and in combination have significant consequences for California's coastal ecosystems, economy, communities, culture, and heritage. Below we describe the consequences of the already occurring and projected changes on coastal towns and infrastructure, key fisheries and aquaculture industries, and associated food security, society, ecosystems and economy, and the state's coastal heritage.

In light of these consequences, impacts, and challenges, we also outline key research needs in order to adapt and best respond to impacts to California's coastline, communities, and marine life from climate change.

3.1 Coastal Communities and Development

Sea-level rise is already beginning to affect the coast even though most observed impacts at present are a result of extreme and episodic/short-term events, such as king tides, severe storms, and El Niño events. Even though sea-level rise is currently occurring at a slow rate, over time it will affect the frequency and extent of coastal flooding and the cumulative effects of increases in flood damages will become a significant constraint on economic activity in key parts of the California coast. Vulnerable communities in coastal areas face increased risks from climate change impacts due to pre-existing socioeconomic inequities, which could result in greater harm or even displacement from coastal areas.

Natural processes and human activity have been converging and colliding in the coastal zone for decades and both are changing the coastline in dramatic ways. Much of California's coastal development occurred during 1945–1977, a period with a relatively benign climate. However, in the winter of 1976, the climate over the North Pacific switched to a more than two-decade long warmer, stormier period with increased coastal hazards (Griggs 2017). During this time, several large El Niños and much greater winter storm activity threatened, damaged, and destroyed homes, businesses, and infrastructure from Crescent City to Imperial Beach. Short-term weather and climate events, El Niño events, and storm waves at times of extreme or king tides will very likely continue to have the most damaging effects on coastal development until at least mid-century (Griggs and Johnson 1983; Griggs et al. 2005). Each of these extreme events will be increasingly exacerbated by a persistent and accelerating rise in sea level (Griggs et al. 2017).

COASTAL DEVELOPMENT IS VULNERABLE TO COASTAL FLOODING AND SEA-LEVEL RISE.

All of California's low-lying communities, as well as developments on cliffs, bluffs, dunes, or the beach itself, and their associated infrastructure, are vulnerable to the impacts of a rising sea. King tides, and/or storm events - often accompanied by the simultaneous arrival of large waves - have already impacted many of these areas repeatedly (Barnard et al. 2017). Rates of coastal erosion or shoreline retreat and losses of oceanfront neighborhoods have been well documented for a number of California's coastal areas (Griggs 2015). At a basic physical level, those populations and the infrastructure at the lowest elevations or closest to the shoreline are the most vulnerable and at the greatest future risk for flood damages from higher sea levels (Erikson et al. 2018).

Billions of dollars worth of real estate development (primarily residential properties) line the California shoreline. The total amount and market value of property vulnerable to sea-level rise in California has not been estimated, but property located on beaches and erodible bluffs are at the greatest overall risk. However, local geography will play a large part in shaping future risk. Without advance planning and implementation of adaptation strategies, properties located directly on bluffs or eroding beaches, such as those in Encinitas and Solana Beach (San Diego County), Broad Beach, Malibu (Los Angeles County), and Rio Del Mar (Santa Cruz County), will at some point be claimed by the sea as happened with homes at Gleason Beach in Sonoma County, General Stilwell Hall on the former Fort Ord in Monterey County, or the blufftop apartments in Pacifica (see photographs). Others, such as the properties along Santa Monica or Manhattan Beach (Los Angeles County), have buffers in the form of wide beaches which will provide protection for a longer period (Erikson et al. 2018).

REPETITIVE AND INCREASING DAMAGES FROM FLOODING AND LOSSES TO PROPERTY OWNERS.

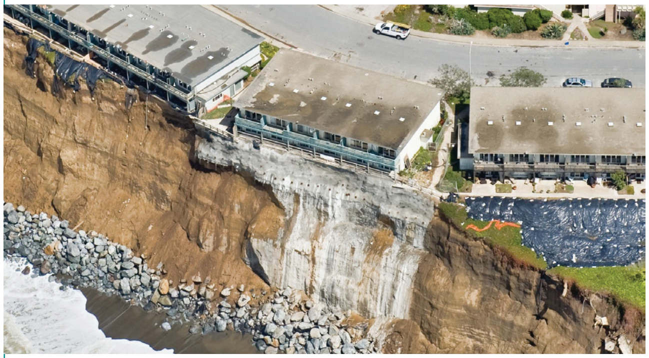
Repetitive and increasing damages from flooding made worse by climate change will have consequences for the California economy that extend well beyond the shoreline or coastal regions. A recent study found that 13,000 properties in the nine Bay Area counties, housing 33,000 people and valued at $8.6 billion in current assessed value, were at risk of chronic inundation by 2100 (UCS 2018). The possibility of losses of billions of dollars in residential properties will realign property tax revenues at city and county levels. There will be a loss of valuation from properties destroyed, yet this loss may be at least partly offset by an increase in surrounding property value. But that increase in value will be shielded from taxes by the 1978 Proposition 13 referendum limiting valuation subject to tax until the property is sold. The net effect over time will be a reduction in property tax revenue from some of the most valuable properties at just the time when local governments will be under stress to respond to flood damages.

Property values in most coastal real estate markets do not currently reflect the risks of rising sea level and more frequent coastal flooding and shoreline erosion. In the decades ahead, the consequences of these impacts will strain local communities, abruptly or gradually, with potential reverberations throughout the state's economy and with staggering financial impacts (UCS, 2018).

A recent study of San Diego County found that the flooding from a 100-year storm could affect between $9 billion and $12 billion in commercial and industrial property valuation depending on whether sea level rises by 3.3 feet (one meter) or 6.5 feet (two meters) (Colgan et al. 2018). The same study also pointed to the widespread economic effects of coastal flooding. Between 15,000 and 50,000 jobs in San Diego could be affected by the same

FIGURE 5: COASTAL INFRASTRUCTURE AT RISK

A. Apartment buildings with some set back from bluffs in Pacifica (1984; Figure source: Gary Griggs).



B. The same apartment buildings in Pacifica shown in Figure 5A in 2011 with failure of protection efforts prior to demolition (Figure source: Joel Avila, Hawkeye Photography).

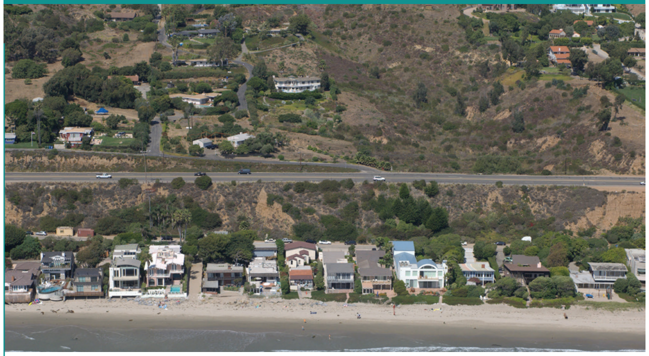
scenarios. Key industries such as tourism, shipbuilding, and professional services would be the most affected. Losses to businesses could exceed $1 billion a day in the extreme case. These effects would ripple through the San Diego County economy with further job and sales losses in firms that sell to those directly affected and to their employees, many of whom work on the coast but live inland.

CRITICAL INFRASTRUCTURE IS AT RISK.

Critical infrastructure located on the shore, such as wastewater treatment plants, power stations, and transportation corridors, will also be affected by energy disruptions that could then lead to cascading impacts of other critical lifeline infrastructure (Moser and Finzi Hart 2018). For instance, there are 35 sewage treatment plants around the margins of San Francisco Bay that treat the wastewater of nearly six million people from the surrounding cities and communities. All of these are exposed to the rising waters of the bay, with several already experiencing flooding with just 13.8 to 19.7 inches (25 to 50 centimeters) of sea-level rise.

Shoreline facilities such as ports and marinas, as well as rail lines and roads, will be subject to significant future disruptions. This will also be a major issue for airports lying at or near current sea level such as San Francisco, Oakland, and San Diego. All of these also have ripple effects in California well beyond the local area affected, effects that could extend into the U.S. economy in the case of key port facilities such as Los Angeles-Long Beach (Grifman et al. 2013; Moser and Finzi Hart 2018). California's ports were the destination for $350 billion in goods imported to the U.S. in 2015, by far the largest of any state. The ports of Los Angeles, Long Beach, and Oakland together are larger than any other port in the U.S. in value of goods moved. Sea-level rise will present clear challenges to these ports, particularly if flooding or inundation affects staging areas next to the docks, as well as the surrounding roadways and railways from which goods are distributed. The size and importance of these ports requires continuing upgrades to infrastructure which present regular opportunities to develop adaptation strategies; this in turn provides the opportunity to develop cross-jurisdictional and cross-sectoral adaptation strategies that bolster both port infrastructure and supporting infrastructure.

FIGURE 6: COASTAL INFRASTRUCTURE AT RISK



A. A section of Broad Beach in Malibu (2006) when a narrow beach still existed. (Figure source: Kenneth and Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org).

B. Broad Beach, Malibu (2008), with temporary sand bags, which didn't last a single winter and were replaced by a rock revetment (Figure source: Deepika Shrestha Ross).

LOCAL ECONOMIES WILL BE AFFECTED BY CHANGING TOURISM AND RECREATION REVENUE.

Nearly 80 percent of the employment (over 400,000 jobs) and 50 percent of the gross domestic product ($19.5 billion) in California's ocean economy was in the coastal tourism and recreation sector in 2014. This sector is likely to be particularly vulnerable to the repeated and increasing disruptions from sea-level rise. There are a number of locations along the California coast where beaches and points of public access to the coast and coastal waters, including small boat launches, picnic areas, coastal trails, and businesses with waterfront viewsheds (e.g., restaurants, hotels, motels) will be permanently lost to a rising ocean (Colgan et al. 2018; Vitousek et al. 2017a). These losses will not eliminate ocean tourism and recreation industries but may result in pressure to relocate facilities inland or to higher ground, which may displace other sectors of the community and disrupt local economies. Planned retreat may be less costly and more adaptive for industry, communities, and individuals than forced, unplanned retreats.

The potential losses to businesses serving the tourism and recreation markets may be significant, but the economic losses to those who enjoy California's unique coastal features will also be considerable. As accelerated erosion and flooding diminish the number and quality of beaches, and people spend more time and money to travel longer distances to more crowded beaches, the number of users and values will decrease. A rough estimate based on studies of specific beaches suggests a total value of beach recreation over and above what is spent to get to the beach of about $8 billion (Colgan and King pers. comm.).

There are a number of other industries that directly or indirectly depend on the ocean and about which relatively little is known concerning their vulnerability (for example, fishing support businesses such as providers of fuel, ice, and fishing gear). The U.S. Navy is a critical part of the economies of San Diego and Ventura counties, with significant vulnerability to sea-level rise, including the General Dynamics shipyard that produces many of their ships.

COASTAL PLANNING DECISIONS ARE BEGINNING TO REFLECT LONG-RANGE IMPACTS AND ASSOCIATED UNCERTAINTIES.

Addressing impacts from rising seas requires a recognition that decision-making processes for California's coast that rely on a relatively stable coastline will not be sufficient for the inevitable increasing rate of future sea-level rise. Coastal planning at the state and local government level has begun to address this reality, with the Coastal Commission and local governments working to complete vulnerability assessments and adaptation plans and making permitting decisions that consider sea-level rise impacts over the life of development. However, there are still significant barriers, including: lack of funding for implementation, lack of staff capacity, lack of leadership from elected officials, lack of public demand, and lack of technical assistance (Moser et al. 2018b).

FIGURE 7: COASTAL INFRASTRUCTURE AT RISK

A. Gleason Beach, Sonoma County, when most of the homes were still intact (1979; Figure source: Kenneth and Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org).

B. Gleason Beach, Sonoma County, where most of the homes have now been destroyed or removed (2009; Figure source: Kenneth and Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org).

State-level coastal planners and managers have also begun to see the benefits of previous investments and coordinated planning (Moser et al. 2018b). While technical assistance and information needs were a primary gap for city or county planners in a 2011 coastal adaptation needs assessment, the recent gap has shifted to requesting more information on solution options and implementation (Moser et al. 2018b). Due to significant investment and action at the local level, as well as state priorities to update Local Coastal Programs (LCPs) and include climate adaptation and resilience strategies in safety elements of general plans (SB 379, 2015), many areas are making progress on understanding threats in their jurisdictions.

Yet additional steps are needed to sustain these actions and achieve the maximum benefits. Many coastal professionals (whether city or county level planners, coastal engineers, or non-governmental organizations (NGOs)) indicate that they have not received any formal training on climate adaptation (Moser et al. 2018b). These coastal professionals are left to understand and digest complicated and ever-evolving scientific information and then make important planning decisions essentially on their own; they are learning these skills "on the job" (Moser et al. 2018b). This same study demonstrated that coastal professionals are in some phase of planning for coastal adaptation, but very few have moved into making decisions and implementing on-the-ground adaptation strategies.

Adaptation actions aimed at reducing threats of sea-level rise to infrastructure and developed property face formidable challenges, including massive costs along the margins of San Francisco Bay and the parts of the southern and central CA coast where development is intensive. For private homes and commercial development, there is little incentive at present to begin a process of relocation when the threat of sea-level rise is still seen as a distant future problem. For public infrastructure and large facilities, such as San Francisco and Oakland International airports, the many sewage treatment facilities and power infrastructure sited along shorelines, the challenges of adaptation are even greater and the costs even larger. There are some examples of successful adaptation that can be used as templates (see Case Study 1). Many instances where structures have been removed from harm's way – the apartments on the bluffs at Pacifica, for example – have been cases of demolition and unplanned retreat, rather than planned retreat (Figure 5).

Tackling this challenge will therefore require a multi-pronged approach. Statelevel investments through sustained funding, staff support, assistance to aid local implementation, and formal technical training will benefit local planners and communities striving to overcome these barriers. Already the state of California has a suite of policy recommendations and guidance documents to help coastal communities plan and ultimately implement new policies (e.g. CCC 2018, OPC Sea-Level Rise Guidance 2018). On a practical level, this guidance shares the common approach of allowing decision-makers and stakeholders at local and regional levels to define their risk strategy and then analyze the risks and suggest options that align with risk tolerances in different circumstances. In this way, specialized technical expertise can support decisions in a specific context, an approach that is demonstrated to facilitate action. However, many legal uncertainties remain, which impede action towards implementation, including the impacts of Takings law, liability concerns, and shifting public trust land jurisdictions under an era of rising seas. Formalized state-level guidance on making multi-scale adaptation decisions in an era of uncertainty would provide local managers with beneficial resources to overcome implementation barriers.

CASE STUDY 1 | Highway 1 Realignment at Piedras Blancas: A Phased Adaptation Success Story

The realignment of an almost three-mile section of Highway 1 north of the Piedras Blancas Light Station in San Luis Obispo County highlights several key components for ensuring successful proactive adaptation to sea-level rise. This roadway experienced decades of erosion from wave action, the fronting beach had disappeared in some areas, and the highway was regularly damaged when waves broke over the highway (Figure 8). Both the California Coastal Commission (Commission) and Caltrans recognized a long-term solution was needed. Through a series of permits in the 1990s, the Commission authorized construction (and interim repair) of a rock revetment to protect the highway with permit conditions that required Caltrans to study the feasibility of relocating the highway inland.

Planning an inland relocation of Highway 1 was a challenge due to the many coastal resources present and because much of the inland area was privately owned. However, after almost two decades of coordination among the Commission, Caltrans, California State Parks, San Luis Obispo County, NGOs, and private landowners, the Commission approved one single permit—thus streamlining regulatory review—in July 2014 that met Coastal Act protection goals for the coastal resources and infrastructure involved. The land between the realigned section of the highway and ocean will be added to Hearst San Simeon State Park and 3.5 new miles of the California Coastal trail will be constructed. Agricultural land and scenic views will be protected through a scenic conservation easement purchased by Caltrans; habitat impacts were mitigated through coastal wetland and prairie restoration projects; and the highway is now set back beyond the projected 100-year erosion line.

Cooperation and comprehensive advanced planning were key to success. By authorizing a permit for armoring but conditioning that permit to require Caltrans to complete a long-term planning process, the Commission and Caltrans set up a phased adaptation approach that ensured protection of an important transportation corridor while a long-term solution that balances protection needs for varying coastal resources was identified and implemented. This approach of combining interim permitting with long-term planning has been used in other transportation corridor projects (e.g. Surfer's Beach in San Mateo County; Highway 101 in Humboldt Bay; Great Highway and the San Francisco Ocean Beach Master Plan). More broadly, collaborative efforts to identify phased adaptation approaches can be useful in a variety of situations to address competing resource needs and to ensure resilience to sea-level rise.

FIGURE 8: HIGH SWELLS OFF HIGHWAY 1

California Highway 1 before realignment, San Piedras. (Figure source: Caltrans).

California Highway 1 before realignment with high swells, San Piedras. (Figure source: Caltrans).

CASE STUDY 2 | Property Acquisition in Pacifica: A Potential Indicator of Future Cliffside Adaptation Issues

With continuing coastal erosion, the City of Pacifica in San Mateo County has had a history of dialogue regarding acquiring and demolishing property at risk of falling into the sea. Following El Niño storm impacts on the cliff-front homes in both the 1982-83 and 1997-98 El Niños, ten cliff-top homes were declared uninhabitable and purchased using $1.2 million from FEMA's Hazard Mitigation Grant Program—covering 75 percent of the costs. During the winter storms of January 2016, a state of emergency was declared, including the designation of residential properties as uninhabitable due to failing infrastructure protection driven by storm events. A group of apartments and homes along Pacifica's Esplanade Avenue have already been demolished and the City's extensive shoreline armoring has exhibited costly structural failures associated with armoring, thus limiting coastal access (Figure 5). With a rapidly eroding but developed cliff, the City of Pacifica is investigating paying for the acquisition and demolition of these properties through a balance of federal and state funding. The consideration of property acquisition in Pacifica can be seen as an indicator of increasingly damaging storm events threatening urban, cliffside settings.

3.2 Fisheries and Aquaculture

Climate change is impacting fish stocks and ecosystems in California as well as the human communities who depend on them, through warmer temperatures, sea-level rise, acidification, extreme events, and changing ocean chemistry.

WARMING, OCEAN ACIDIFICATION, HYPOXIA, AND SEA-LEVEL RISE THREATEN CALIFORNIA FISHERIES AND AQUACULTURE.

Climate extremes are already affecting fish stocks and associated fishing communities in California and will continue to have impacts well into the future. Direct impacts on fishing communities include increased storms, sea-level rise, and associated damage to fishing infrastructure and businesses (Seara et al. 2016). Indirect impacts include those on fished species or food web dynamics as a result of warming ocean temperature, acidification, more extreme or variable conditions, or the crossing of thresholds into new ecological states (Chavez et al. 2017b; Ekstrom et al. 2015).

The ecosystem and fishery impacts of historically warm and cool periods in the CCS have been fairly predictable, but in recent decades, unusual marine heat waves have demonstrated the high vulnerability of marine organisms and ecosystems to extreme climate events (Chavez et al. 2017a; Frölicher and Laufkötte 2018). For example, a marine heat wave from 2014–2016 produced record high ocean temperatures along the Pacific Coast from Baja California, Mexico, to Vancouver Island, Canada (Jacox et al. in 2018). This heat wave in the Northeast Pacific was unprecedented, with record single-year sea surface temperatures in the CCS in 2015 and record 3-year average temperatures in 2014–2016. This led to mass strandings of sick or starving birds and sea lions, northward shifts of pelagic red crabs, tunas, and other sub-tropical fish into coastal waters of California, and closures of commercially-important fisheries (Cavole et al. 2016). It also contributed to substantial reductions in California's salmon catches in 2016, and a salmon fishery closure in Northern California, resulting in limited catch for tribes and sport and commercial fishers in 2017 (PFMC 2018a).

Periods with unusually warm ocean temperatures have also contributed to an increase in Harmful Algal Blooms (HABs) along the Pacific Coast (Gobler et al. 2017; McKibben et al. 2017). HABs and shellfish contamination in 2015 caused an unprecedented 5-month delay in the opening of the commercially important Dungeness crab fishery, which in turn contributed to substantially reduced statewide landings compared to the previous season (Callahan 2016; Chavez et al. 2017b). Although some fishermen caught up on their landings and ex-vessel revenues when the fishery eventually opened, the lapse in income, especially after they had invested considerable time and money gearing up for the season, caused substantial economic hardship, though precise measures of these losses have not been made. The delayed opening of the crab fishery also resulted in increased usage of fishing gear (such as crab pots) in nearshore waters during late spring of 2016 and coincided with a record numbers of humpback whale entanglements. More frequent and widespread HABs may result in increasing economic damages and threats to the health of people, marine mammals, and seabirds (Gobler et al. 2017; McKibben et al. 2017). This may be exacerbated by the combined effects of rising temperatures and ocean acidification. For example, the dinoflagellate *Akashiwo sanguinea*, responsible for massive bird mortality events in 2007 and 2009, may be favored by higher temperatures and lower pH (Ou et al. 2017), while the toxic diatom *Pseudo-nitzschia* may become even more toxic with rising carbon dioxide concentrations and changes in nutrients (Tatters et al. 2012).

CASE STUDY 3 | Impacts from Climate Change Could Mean Hard Times for California's Salmon Fisheries

California's salmon fishery has experienced chronic declines in landings over the 1970–2017 period, with an increased frequency of extremely poor fishery years starting in the mid-1980s. There were 15 federal disaster declarations for California, Oregon, and Washington salmon fisheries between the early 1980s and 2015, with each declaration associated with climate extremes that caused widespread declines in salmon productivity and abundance. A number of factors have affected the availability of salmon for California's salmon fisheries, including forestry practices, dams, water diversions, hatcheries, and other actions that have simplified salmon habitat and reduced the diversity in California's salmon production system (Herbold et al. (in press)). Impacts from climate change compound these threats. Multi-year droughts in the Klamath and Sacramento/San Joaquin watersheds and poor ocean conditions that involved persistently warm ocean temperatures or weak upwelling have been proximate causes for exceptional one to three year declines in California's salmon landings. Over the past 40-year period of declining salmon landings, participation in the commercial ocean troll fishery has declined by ~90 percent, and coastal communities formerly reliant on salmon fishing have experienced substantial economic losses (PFMC 2018a). Because future climate warming will promote an increased frequency and intensity of both drought and marine heat waves, it will likely result in increasingly hard times for California's salmon fisheries unless other habitat restoration and population recovery actions alleviate existing stressors in ways that can effectively mitigate climate change impacts (Herbold et al. (in press)).

Predicted warming of California's marine waters and the broader CCS is also expected to lead to a northward shift in the distribution of marine life (Cheung et al. 2015; Hazen et al. 2012). It is likely that some cool-water species, such as California market squid, anchovy, and Pacific halibut, will become less abundant in California, or even lost from state waters, But there is also potential for increased fishing opportunities for warm-water species such as California spiny lobster, yellowtail, dorado, yellowfin and bluefin tuna, and other species that have been especially abundant during warm ocean years during the past century.

Commercial and recreational fishing infrastructure and businesses are especially vulnerable to impacts from sea-level rise and associated storm surge (Colburn et al. 2016). Fishing community viability depends on functioning infrastructure, which includes ports, docks, fish processing facilities, and fuel docks. The quality of fishing infrastructure varies throughout the state, and there is evidence that extreme events such as the 2006 tsunami can be devastating when communities do not have the revenue to rebuild (Pomeroy et al. 2011).

THE WEST COAST IS PARTICULARLY VULNERABLE TO OCEAN ACIDIFICATION.

Ocean acidification presents a significant and well-established threat to commercial fisheries and farmed shellfish, and therefore human coastal communities (Ekstrom et al. 2015). Ocean acidification impacts many shell-forming species, including oysters, mussels, abalone, crabs, and some of the microscopic plankton that form the base of the oceanic food chain (e.g., Kroeker et al. 2010; 2013). Impacts from ocean acidification are not limited to shell-forming species. Significant changes in behavior and physiology of fish and invertebrates due to rising temperature and decreased pH have now been documented (e.g., Jellison et al. 2017; Munday et al. 2009). Species vulnerable to ocean acidification include economically important species such as Dungeness crab and Olympia oysters (Cooley and Doney 2009; Marshall et al. 2017 Box 3).

BOX 3: OCEAN ACIDIFICATION IMPACTS ON FISHERIES

As pH is projected to decline rapidly over time (increasing ocean acidification), we are still learning about the thresholds of particular organisms to these changes in ocean chemistry. Here we summarize current understanding of the thresholds of Dungeness crab and Olympic oysters, two important fisheries.

- Dungeness crab: only 13-20% larval survival after 45 days at pH below 7.5 (from 58% survival at 8.0). (Miller et al. 2016)
- Olympia oysters: juveniles exhibit a 41% decrease in growth rate at pH 7.8 relative to 8.0 (Hettinger et al. 2012)

CASE STUDY 4 | Planning for Ocean Acidification Impacts with Science Investments, Coordinated Monitoring, and Novel Partnerships

California has been a leader in protecting ocean ecosystems that are important in regulating its climate. The entire West Coast has made significant strides in understanding climate change impacts to the ocean and coast and in taking action to address them. In April 2016, the state released the West Coast Ocean Acidification and Hypoxia (OAH) Science Panel summary recommendations (Chan et al. 2016), which provide the best available science and management options on ocean acidification and hypoxia. In direct response, OPC made critical investments to partners along the length of the coastline to implement those recommendations. In September 2016, California also enacted new state policy addressing ocean acidification and hypoxia (i.e., Senate Bill 1363 and Assembly Bill 2139) largely in response to the Panel's findings and recommendations. This legislation directed state managers to continue to work in close partnership with academic, federal, and NGO colleagues. In December 2016, Governor Brown and West Coast leaders hosted the launch of the International Alliance to Combat Ocean Acidification (OAA 2018), further recognizing that ocean acidification is an environmental challenge that cannot be discussed in isolation and that requires a comprehensive approach.

To plan for ocean acidification and declining dissolved oxygen, progress has been made at the state and federal level to identify indicator species that might be most sensitive to this process. These preliminary indicator species can be employed for biological and chemical monitoring. Potential indicator species have been summarized in the Ocean Indicators Report (Duncan et al. 2013) and have also been reviewed in the *Indicators of Climate Change in California* report initiated by California's Office of Environmental Health and Hazard Assessment (OEHHA 2013). A recent study completed as part of California's Fourth Climate Change Assessment (Gaylord et al. 2018) suggests a promising role for California mussels (*Mytilus californianus*) to serve as bio-indicators of ocean acidification in California's coastal waters. The California mussel is widely distributed across the state, and has been previously identified as a species that may be easily monitored and collected, a key attribute of an effective indicator. This study utilized field collection of juvenile mussels to link patterns of mussel abundance, size, and body condition to climate-related oceanographic drivers.

There are additional steps that could help coastal regions address ocean acidification, for example controlling or reducing nutrient runoff from both sewage disposal and the application and runoff of excess agricultural fertilizers. Excess nutrients can promote algal blooms and subsequent microbial decay that contributes to additional reductions in pH and dissolved oxygen levels. Carbon dioxide is also captured by marine plants and seaweeds in coastal kelp forests, salt marshes, and seagrass meadows. Kelp and seagrass remove carbon dioxide from the water, while salt marshes remove carbon dioxide from the air, through the process of photosynthesis following daily and seasonal cycles. Salt marshes and seagrass meadows can also store carbon over much longer time scales and loss of these ecosystems can result in the release of substantial carbon to the atmosphere (Lovelock et al. 2017). However, it is submerged marine vegetation (seagrasses and kelp forests) that hold the most promise for localized amelioration of acidification because they actively draw down carbon dioxide from the water and can achieve high biomass and cover (Foster & Schiel 1985; Graham 2004; Nielsen et al. 2018). These systems also provide other important habitat functions. Thus protection, preservation, and restoration of marine vegetation remain important goals (Nielsen et al. 2018). However, additional research is needed to understand where carbon storage and ocean acidification amelioration potential may be greatest within the mosaic of physical environments along California's coast.

DECLINING DISSOLVED OXYGEN IS A CONCERN FOR SPECIES IMPORTANT IN RECREATIONAL AND COMMERCIAL FISHERIES.

Declining dissolved oxygen concentrations in ocean waters, and the associated changes in the depth and extent of low oxygen zones, can lead to significant and complex ecological changes in marine ecosystems. There is evidence that decreased oxygen could reduce rockfish habitat off the southern California coast by a fifth to a half (McClatchie et al. 2010). Future reductions in dissolved oxygen are expected to harm bottom-dwelling marine life, shrink open-water habitat for top predators (Koslow et al. 2011), and increase the number of invasions by hypoxia tolerant species like Humboldt Squid, a species thought to have benefited from an expansion of hypoxic waters by rapidly expanding its range into the northeast Pacific Ocean in the late 1990s (Gilly et al. 2013; Stewart et al. 2012). These impacts, considered in concert with changes in temperature and ocean carbon dioxide (and pH), could result in changes in the behavior, biogeography (distribution), and structure of coastal marine ecosystems (Somero et al. 2015), and may drive the need for adaptation within recreational and commercial fisheries.

NOT ALL CALIFORNIA FISHING COMMUNITIES ARE EQUALLY VULNERABLE TO CLIMATE CHANGE IMPACTS.

Assessments of fisheries vulnerability to climate change are at the center of efforts to prioritize adaptation investments from scarce funding in ways that address who needs it most, and have been receiving increasing attention from policy-makers and academics around the world (Metcalf et al. 2015). Vulnerability assessments can incorporate social, ecological, and economic information and measure the propensity of a fishery or community to be harmed. Generally, the vulnerability of fishing communities to climate change is assessed in terms of three components: exposure to change, sensitivity to impacts, and adaptive capacity, or potential to offset impacts (e.g., Colburn et al. 2016).

NOAA's National Marine Fisheries Service (NMFS) has assessed the vulnerability of federally-managed fish stocks and associated human communities to climate change on the East Coast (Colburn et al. 2016; Hare et al. 2016). NMFS is in the process of replicating this effort on the West Coast. The state of California is now considering adapting these methodologies to analyze state-managed fisheries, as recommended by the OPC-SAT Climate Change and California Fisheries Working Group (Chavez et al. 2017b). This would allow for an analysis of vulnerability of the 52 fishing communities in California based on the full suite of commercially valuable fisheries for each community, regardless of management jurisdiction. An initial Development of Community Social Vulnerability Indices suggests that not all fishing communities are equally vulnerable to external shocks, but the integration of climate data would contribute further insights into which communities are most vulnerable (Harvey et al. 2017). Another US-wide assessment specific to ocean acidification highlighted the need for region-level vulnerability assessments that have the potential to generate relevant products for state and local level adaptation planning (Ekstrom et al. 2015).

Following from the agency's work on the East Coast, NMFS is also engaged in developing recreational fishing indices for West Coast communities, including those in California. Indices which link West Coast communities to a reliance on and engagement with recreational fishing will be included in the NMFS social indicators mapping tool subsequent to their review by the Pacific Fishery Management Council's Science and Statistical committee in September of 2018 (PFMC 2018b). As with commercial fishing, these indices would provide metrics of California community vulnerability to changing ocean conditions, whether those changes affect the species targeted in commercial or recreational activities. Similarly, NMFS has developed a HAB impact index for West Coast Communities, applying the same factor analysis methodology used in the community social vulnerability index results (Colburn et al. 2013) to a set of data that link coastal communities to HAB events, including proximity to closure areas and community-level harvest of HAB-impacted Dungeness Crab and shellfish (Moore et al., under review).

FLEXIBLE, ADAPTIVE, AND RESPONSIVE FISHERIES AND AQUACULTURE MANAGEMENT.

Fisheries managers must be able to anticipate and respond to current and future climate impacts on ecosystems and fisheries to reduce impacts and help communities adapt to variability. In California, fisheries are managed by state and federal agencies with well-defined management mechanisms, but nonetheless, hurdles exist that must be addressed in preparing for climate change. The Marine Life Management Act (MLMA) specifies many principles important for addressing climate change (e.g., habitat conservation, collecting and incorporating socioeconomic and ecological information into management, adaptive management, and constituent involvement). As climate change was not evident during the crafting of the MLMA, a recent report by OPC, OST, and the OPC-SAT outlined possible scenarios under climate change and provided management approaches that could help to reduce impacts (Chavez et al. 2017b). This report informed a process that the California Department of Fish and Wildlife (CDFW) is undertaking to amend the MLMA Master Plan for Fisheries which included guidance for adapting fisheries management to climate change impacts such as changing species distribution and abundance, habitat alteration, and impacts to port infrastructure (CDFW 2018). OPC, CDFW, and other partners are also beginning to implement other recommendations from the report. Additionally, California continues to make investments linking climate research to the state's globally significant MPA network in order to better understand the role that a well-implemented, science-based network of MPAs may play in enhancing climate adaptation and resilience (see Case Study 7). This work on fisheries management and MPAs in a changing climate is also being explored in other places and through governmental and non-governmental avenues.

Climate adaptation actions for aquaculture management in California present different hurdles. Marine fish and shellfish are receiving increasing attention as potential sources of ecologically sustainable protein. However, California is known to have some of the strictest aquaculture regulations and permitting processes in the country. Consequently, compared to other states, California has few commercial aquaculture operations and low output from these farms (Bernadette 2014). Ocean acidification poses another challenge to aquaculture. Aquaculturists are working with scientists to understand which species may be more resistant to ocean acidification impacts (Case Study 4) as well as where they might site aquaculture sites to reduce risks.

CASE STUDY 5 | Oyster Farmers Adapt to Ocean Acidification with The Help of Scientists and the State

A NOVEL STRATEGY TO ADDRESS THE IMPACTS OF OCEAN ACIDIFICATION ON SHELLFISH AQUACULTURE IS THE PARTNERSHIP OF INDUSTRY MEMBERS WITH SCIENTISTS TO MONITOR AND INTERPRET COASTAL WATER CHEMISTRY DATA.

AS TOLD FROM THE PERSPECTIVE OF TERRY SAWYER AND JOHN FINGER, CO-OWNERS, HOG ISLAND OYSTER CO:

Hog Island Oyster Company found itself at the center of dramatic impacts of ocean acidification, when we were unable to purchase oysters from hatcheries in Oregon and Washington for several years due to significant mortality events. In 2007 Whiskey Creek Shellfish Hatchery on the Oregon coast noticed a phenomenon within their hatchery - oysters influenced by acidic (low pH) waters were smaller, misshapen, and died more frequently (Barton et al. 2012). As one of the major distributors of young oysters to farms along the West Coast (these are the "seed" for oyster farmers to then put out in estuaries and grow to market size), a mortality event at this location had a huge effect on the industry as a whole. Over the next few years, shellfish farmers along the California, Oregon, and Washington coast began to partner with scientists to understand the impact of ocean acidification on their industry.

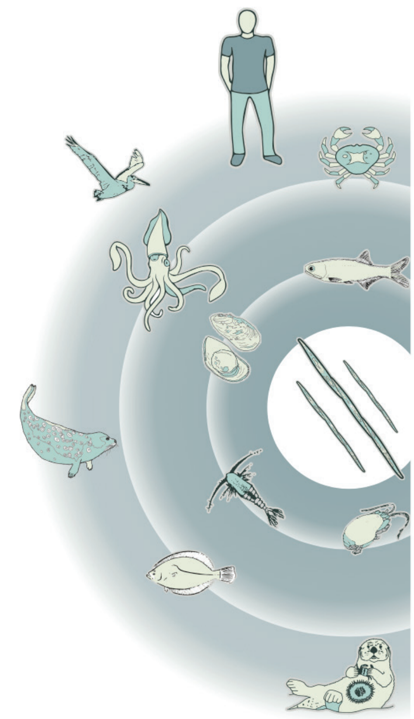
As co-owners of Hog Island Oyster Company, we decided to approach this problem by taking a lead role in understanding the impacts of ocean acidification on our community, and in guiding adaptation strategies that would allow our business to thrive. For example, we collaborated with scientists and the Integrated Ocean Observing Network (IOOS) to develop a monitoring station in Tomales Bay that would publicly provide real time ocean chemistry data so that any business or local management agency could learn more about ocean acidification. We also began to build in strategies for the health of our business, including opening the only oyster hatchery in California in Humboldt Bay in 2018, and expanding ocean chemistry monitoring to that site. Additionally, we actively work with scientists to understand potential solutions to ocean acidification that can be utilized by the state as well as industry members, including the conservation of vegetated habitats (seagrass, kelp forests) that may ameliorate ocean acidification, and the co-location of seaweed and shellfish aquaculture.

3.3 Human Health

HARMFUL ALGAL BLOOMS, SEA-LEVEL RISE, AND FLOODING THREATEN HUMAN HEALTH.

The health and well-being of Californians heavily relies on the state's coastal ecosystems. The ocean provides resources, recreation, and moderates California's Mediterranean climate. To some extent, there is an arbitrary distinction between ecosystem health and human health. Symptoms of an unhealthy ecosystem, such as more frequent, larger, and more toxic HABs, invasive species, and poor water quality caused by nutrient pollution, industrial waste, and high levels of harmful bacteria, affect all organisms, including humans who interact with the ocean (Miller et al. 2012). Continuing climate change will have wide-ranging impacts on a variety of processes that directly influence human (and ecosystem) health, including heat waves and droughts as well as rising ocean temperatures and sea-level rise.

FIGURE 9: DOMOIC ACID IN THE CALIFORNIA MARINE FOOD-WEB



Domoic acid, a toxin produced by the phytoplankton Pseudo-nitzschia, can move through the food web and be fatal for people and animals who eat tainted fish or shellfish. Scientists, other experts, and the State are working to better track, predict, and project future harmful algal bloom events and mitigate impacts with early indicators or advanced warning to prepare the fishing industry and consumers (Figure source: Della Gilleran, adapted from Raphe Kudela).

HARMFUL ALGAL BLOOMS ARE EXPANDING WITH CLIMATE CHANGE.

Rising ocean temperatures will lead to ecological winners and losers. Some of the "winners" are directly detrimental to humans. One well-documented example is the spread of infections caused by the bacteria *Vibrio* from human consumption of shellfish, which now extends as far north as Alaska (Martinez-Urtaza et al. 2010). Pathogenic *Vibrio* pose a significant human health risk, with ~4600 cases per year in the U.S. alone (Burge et al. 2014). A warmer climate is projected to allow pathogenic *Vibrio* to increase its range. Under current conditions, *Vibrio* habitat is largely limited to the southern extremes of California. Future climate scenarios suggest that all of California could become ideal *Vibrio* habitat by the year 2100 (Escobar et al. 2015).

A second group of "winners" in a warmer ocean include a wide range of toxic phytoplankton, collectively known as harmful algae (which produce HABs). Analysis of historical data demonstrates a convincing link between warmer water and larger, more frequent and more toxic outbreaks of HABs (McCabe et al. 2016; McKibben et al. 2017). Some of these HABs produce domoic acid, which can be fatal for people who eat tainted shellfish (Figure 9) (McKibben et al. 2017; Moore et al. 2008). Perhaps the most well-recognized of these organisms is the toxic diatom *Pseudo-nitzschia*, responsible for mass marine organism mortalities and the delay in opening of the Dungeness crab fishery in 2015–2016 described above (McCabe et al. 2016).

Other HABs have also been expanding with climate change. The dinoflagellate *Alexandrium* is of particular relevance because it causes Paralytic Shellfish Poisoning, a potentially lethal toxin that can kill humans with consumption of as little as a single scallop (Sharpe 1981). Climate change has been linked to an expanded "window of opportunity" for these blooms, moving potential toxic events into new regions (geographical expansion) but also pushing blooms into times of year where traditional ecological knowledge (TEK) suggests shellfish consumption is safe

(Hallegraeff 2010; Lewitus et al. 2012). This mismatch between past experience and a reality under the influence of a changing climate can have dramatic, negative consequences for communities relying on TEK and experience to guide decisions about recreational and subsistence harvesting of shellfish, although that knowledge also provides valuable information about historical risks and variability in HAB exposure in response to climate (Okey et al. 2014).

As discussed in the previous section, increased warming, declining dissolved oxygen, and ocean acidification are expected to severely impact California's marine life and the people that rely on wild-caught seafood for protein and employment. Less well known is that deficiencies in micronutrients such as zinc will also increase (Golden et al. 2016). In the coming decades, 10 percent of the world's population may face micronutrient and fatty acid deficiencies simply because wild fish stocks are running out. California is much less susceptible than other regions, but its role in providing wild-caught fish to a global market will undoubtedly be impacted, and already emerging global patterns will eventually impact the health of everyone on the planet.

SEA-LEVEL RISE WILL ALSO IMPACT HUMAN HEALTH.

Sea-level rise will also have potential negative consequences for human health. In addition to direct and indirect impacts from loss of property, rising sea level will threaten built infrastructure such as wastewater treatment plants and hazardous waste sites, potentially exposing communities to toxic substances. A recent analysis (Heberger et al. 2009) estimated that with 1.4 meters of sea-level rise the number of EPA-regulated sites in California that are threatened by flooding would increase from 134 to 332 within areas vulnerable to a 100-year flood event. In addition, 28 wastewater treatment plants, 21 of them in the San Francisco Bay region, are vulnerable in the same scenario. This brings a risk of environmental contamination, especially for communities separated from the coast by strips of industrial facilities, ports, and military installations. For example, the Halaco superfund toxic waste site along the coast of South Oxnard risks spreading contamination to nearby vulnerable communities in the absence of effective planning and adaptation. Moreover, changing precipitation patterns (chiefly from more deluge type rain events) will impact the timing and magnitude of water quality challenges unless runoff flows are better managed.

Flooding itself also damages human-inhabited structures leading to mold growth, bacteria, and spread of toxins at a household to neighborhood scale. Flooding from Hurricane Harvey in Houston (2017) resulted, for example, in at least one documented case of death from flesh-eating bacteria, and extraordinarily high levels of all bacteria; flooding during hurricane Katrina in New Orleans (2005) led to visible mold growth in 44 percent of homes, and the spread of the Zika virus related to more suitable habitat for mosquitos (Du et al. 2017). Predominantly in Southern California, shifts in beach morphology due to increased extreme water level events and sea-level rise may increase estuary mouth closures and provide prime habitat for mosquitos and thus risk of vector-borne diseases (Githeko 2000).

FOOD SECURITY, TOXINS, AND POOR WATER QUALITY AFFECT HUMAN HEALTH.

Climate change will affect the health of all Californians. The large-scale impacts of climate change, such as increasing drought and rising temperatures, will affect the state's entire population, its economy, and natural resources. Direct impacts such as exposure to toxins, bacteria, and poor water quality due to sea-level rise and flooding will disproportionately impact coastal communities, particularly the greater San Francisco Bay area, given that the majority of impacted infrastructure are located in those areas (Heberger et al. 2009). However, while some counties such as San Mateo and Santa Clara currently host the majority of EPA-identified sites at risk, all coastal counties in California have at least one site impacted by 4.6 feet (1.4 meter) sea-level rise (Heberger et al. 2009, p.53).

"Increased warming, declining dissolved oxygen, and ocean acidification are expected to severely impact California's marine life and the people that rely on seafood for protein and employment."

Other direct impacts to human health, such as increases in exposure to HABs and contaminated shellfish, will be widespread, affecting not only Californians consuming seafood or living near the coast, but also resulting in detrimental impacts to California's economy by threatening food security and increasing public health costs. The direct economic impact from the 2015–2016 fisheries closure due to the west-coast wide HAB event was estimated at $30M in California alone (OST 2016), not counting substantial but undocumented impacts to recreational and commercial fisheries and aquaculture, tourism, and wildlife health.

Increasing exposure to algal toxins and poor water quality may also disproportionately impact subsets of the population such as Native American tribal nations, tribal governments, and tribal communities located within the state (hereafter referred to as "tribes") and subsistence harvesters of marine seafood. While studies are limited, one well-documented study from San Francisco Bay found that Asian-American and African-American populations were more likely to consume potentially contaminated seafood (Davis et al. 2014), while California's tribes consume more seafood per capita than other groups, increasing potential exposure (Shilling et al. 2014).

WE KNOW THERE WILL BE IMPACTS BUT DON'T KNOW WHEN AND WHERE.

There is no question that the oceans are changing, and that this will have significant impacts on the health and welfare of all Californians. With regards to human health specifically, the potential impacts are clear. Rising seas will inundate coastal infrastructure, including wastewater treatment plants and EPA-listed sites where toxins and contaminants may be mobilized. There is a clear trend of increasing HABs, and the direct impacts to human health are well-documented. Impaired water quality, increasing disease vectors, reduced air quality, and heat-related illnesses and deaths are also well-studied (Githeko et al. 2000; Sandifer 2014, 2015). In all of these cases, the trends are clear that these impacts will increase under existing climate change scenarios.

The big unknown is when, where, and how these impacts will manifest, and whether new issues will emerge as the environment changes. For example, while HABs have been linked to rising ocean temperatures, no one predicted that the 2015–2016 event would be the largest toxic bloom caused by domoic acid ever recorded, nor was aware of the widespread consequences such as contamination of multiple commercially harvested marine species, and the realization that toxins could directly impact facilities using raw seawater such as desalination plants and aquariums (OST 2016).

WE KNOW ENOUGH TO ACT.

Adaptation actions aimed at reducing threats of sea-level rise and flooding would do a great deal to protect human health. The various state agencies involved in California's fishery and biotoxin management have also been very successful at preventing human illness, even during unprecedented bloom events (OST 2016). Responding to these challenges to human and environmental health will be an ever-increasing burden on California's economy.

Currently, scientists and other experts are engaged in providing scientific recommendations to the state to better track, predict, and project future HAB events and mitigate impacts with early indicators or advanced warning to prepare the industry. Conversations to expand and clarify the current monitoring and sampling procedures and partnerships are beginning. Scientists are also working to understand the impacts of the 2015 event and evaluate the resilience of US west coast communities to HAB events, identify communities that are most vulnerable to future HAB events, understand the factors that contribute to vulnerability and resilience, and empirically test theories related to factors that determine resilience.

Specific recommendations for fisheries and aquaculture have been called out in a recent OST report (2016), and many are relevant to human health. These recommendations include: (1) build out a robust, cost-effective and flexible monitoring program; (2) better understand the dynamics of these events in a changing climate; (3) develop predictive models; (4) improve basic understanding of the biology and ecology of these organisms; (5) improve understanding of how biotoxins move through the food web; and (6) advance research on the link between HABs and human health. Substituting any of the other risks to human health that have been highlighted would generate a very similar list of action items, all of which would improve California's ability to adapt to and mitigate potential negative consequences of climate change.

CASE STUDY 6 | Traditional Ecological Knowledge Can Help Address Impacts from Algal Toxins

There is increasing evidence that climate change is exacerbating the frequency, extent, and timing of HABs along the U.S. West Coast and globally. Human exposure to HABs and associated toxins is complex, involving cultural and socio-economic considerations as well as the occurrence of toxins in seafood. A recent study showed that tribes generally felt more informed about the risk of algal toxins than Community Recreational Harvesters (Roberts et al. 2016) Tribes also consume more potentially toxic food items such as razor clams and mussels containing domoic acid, and this consumption, even when razor clams were well below the regulatory limit for closure, resulted in clinical risk for memory impairment after adjusting for age, sex, and education (Grattan et al. 2016).

Higher than expected exposure to algal toxins is not unique to tribes; others at risk include high consumption rates of recreationally harvested fish and shellfish by minorities, low-income populations, non-native English speakers and recreational fishers (e.g., Ferriss et al. 2017). Existing state and federal management guidelines for human exposure to most algal toxins are based on consumption rates and body weights that do not capture the diverse recreational harvesting community and cultural practices of many populations. HAB events can also have devastating economic impacts on tribes. For example, a fishery closure during 1998–99 caused Washington's Quinault tribe to lose all of their razor clam income and a large portion of their Dungeness crab income, while the Quileute tribe lost 50 percent of their Dungeness crab income (Wekell and Trainer 2000). In 2002–2003, another closure period resulted in a $10.4 million loss in revenue (Wekell et al. 2002).

Klamath, Modoc and Yurok tribes would not eat shellfish when bioluminescence was evident in ocean waters. As documented decades ago (Meyer et al. 1928), "from time immemorial it has been the custom among coastal tribes of Indians, particularly the Pomo, to place sentries on watch for *Kal ko-o* (mussel poison). Luminescence of the waves, which appeared rarely and then only during very hot weather, caused shellfishing to be forbidden for two days; those eating shellfish caught at such times suffered sickness and death." Given the long reliance on coastal seafood by tribes, TEK can be utilized as climate change continues to modify the ocean, but this also introduces risk as historical patterns shift with a changing climate. There is a clear link between rising temperatures and HAB events—knowledge that has been used well before now. Moving forward it will be important to consider how diverse populations are disproportionately impacted – both in terms of human health and economics – by the changing mosaic of HABs in a warmer world (Wells et al. 2015), but also to remember that TEK held by tribes and fishing communities can be a valuable source of information for monitoring and adapting to these changes.

3.4 Economy and Society

Climate has had substantial influence on societies and economies, both past and present, with important implications for the future. In the sections above, we consider ocean-related climate change impacts on California's society and economy. Climate change will directly and indirectly affect Californians in complex, but predominantly, negative ways. The effects will be concentrated in the coastal areas where the majority of California's economy is located but will have impacts both onshore and offshore, and throughout the state and the nation. Communities, businesses, and residents have a wide variety of adaptation options to increase their resilience and/or adapt to the impacts of climate change. These options vary by climate change risk and affected sector, and are highly context-specific. While the size and scale of the impacts on specific sectors of the society and economy are detailed above, we highlight here the cascading effects through the broader structures in the state.

CONTINUOUS AND INCREASING DISRUPTION OF ECONOMIC ACTIVITY.

Climate change will disrupt economic activity and reduce employment and output across both small and large areas for periods which may last from months to years. Cycles of disruption caused by storms and shifts in ocean temperatures and chemical properties will force economic sectors to shift resources to reduce damages, to relocate, or to go out of business. The cumulative cost of these effects will be passed on to customers, reducing the productivity and competitiveness of the California economy (Colgan et al. 2018).

ELIMINATION OF SOME ECONOMIC USES AND ENHANCEMENT OF OTHERS.

Some economic uses will be reduced or eliminated. Some beaches will suffer permanent inundation or be eroded away so that they no longer function for recreation (Limber et al. 2018; Vitousek et al. 2017a). The loss of some beaches may reduce recreational use in those communities but grow it in others as users alter recreational activity patterns. Some fisheries will disappear as a consequence of changes in ocean temperature and acidity. At the same time, some fisheries may emerge or expand from more favorable ocean conditions (Chavez et al. 2017b).

A LOT OF MONEY WILL GO TO CLIMATE CHANGE ADAPTATION, WHICH WILL BE A NET DRAG ON THE ECONOMY.

If all nations adopt the goals of the Paris Climate Agreement and move rapidly away from fossil fuel based economies and towards renewable energy, there would be some optimism for being able to reduce the most expensive adaptation or relocation measures needed for major cities. However, we are still a long way from this scenario and despite a small U.S. reduction in carbon dioxide emissions in 2017, total global emissions increased. The choice, however, is not between spending for adaptation or not spending, but is between spending a great deal for adaptation and an unimaginably large amount. How much will be spent, by whom, and when are all unknowns. For some, such as the construction industry, the increase in spending on modifications to buildings and landscapes to ameliorate flood damages, will be a significant positive. But the increase in economic activity for adaptation purposes should not be confused with creating economic benefits. All of the spending will be paid for by reducing expenditures in other areas that could raise incomes and increase productivity.

GAPS IN ECONOMIC VULNERABILITY ASSESSMENTS.

Currently available information allows for economic vulnerability assessments such as those described here for most of the California coast, although there are some important gaps in information. For example, despite its enormous importance, very little is known about the number of people who use the coast, and particularly beaches, for recreation (King and Colgan pers.comm.). Isolated studies have been done in various parts of the state (e.g, King and McGregor 2012) but a complete picture of the value of coastal recreation is not available.

Another major gap is that the vulnerability studies that have been done have generally compared the risks of future sea-level rise against the current distribution of economic activity, effectively ignoring population and economic growth that will continue into the future. From 1970 to 2016, the population of coastal counties increased by 70 percent but employment increased by 139 percent (BEA.GOV, Bureau of Economic Analysis). One recent study examined the impacts of 1.8 m of sea-level rise (estimated by 2100) with today's current population compared to projections of coastal populations assuming continued growth and determined a five-fold increase in the number of people at risk from sea-level rise (216,174 vs. 1,046,057) (Hauer et al. 2016).

Current growth rates along the coast are unlikely to be sustained into the future, but even at half these rates, the economic vulnerabilities 50 years hence, when sea-level rise under even relatively optimistic scenarios will begin to approach three feet (one meter), will be substantially larger. Incorporating growth rate forecasts into vulnerability assessments and into adaptation planning is essential for making more realistic assessments of the economic risks of climate change. At a minimum, forecasts done for transportation planning, should be incorporated into adaptation planning.

PLANNING AND FUNDING CAN ADDRESS ECONOMIC ISSUES RAISED BY CLIMATE CHANGE.

There are two actions that the state could take to better address the economic issues raised by climate change, the first related to planning, the second related to funding.

The first is to make sure that the economic aspects of adaptation planning are thoroughly examined by state and local agencies. This includes expanding the types of vulnerability analyses discussed above by including as much detail at the local level as possible, including incorporating economic and population forecasts that will permit analysis to match estimates of vulnerable assets with projections of sea-level rise.

Addressing the economics of climate change also requires merging the types of economic assessments of options that are currently being used to the emerging perspective that climate change in general and sea-level rise in particular be viewed as occurring within a range of probabilities rather than simple high or low scenarios. This new view of sea-level rise is reported in the summary of the most recent science prepared for the OPC. This report will encourage plans that recognize some increases in sea level are more probable than others and that extreme cases exist that are of lower probability, but could have crippling impacts to communities and the broader economy. The probabilities selected for sea-level rise planning should be incorporated into the assessment of the costs and benefits of the adaptation options under consideration to provide a clearer picture of the relationship among different possible futures.

The other major action should be to make sure that state agencies and local governments are fully informed about the rapidly-changing options to finance adaptation and to make any changes in state institutions that would facilitate innovative financing (Box 3).

THE COST OF ADAPTATION WILL BE LOWER IF EFFECTIVE MITIGATION MEASURES ARE PUT IN PLACE NOW.

The economy is already beginning to feel the impacts of climate change. These impacts vary by sector and group; however, if the current rate of greenhouse gas emissions continues, Californians will face serious economic and societal impacts including loss of coastal property and infrastructure, impacts to fisheries and associated human health, and loss of cultural and spiritual values. However, if aggressive actions are taken to both adapt to the changing climate and to mitigate future impacts by reducing emissions, the exposure to the worst economic risks from climate change can be significantly reduced (Risky Business 2014). This path would significantly reduce the odds of costly climate outcomes, but only if business and public policy practices start changing today (Risky Business 2014).

BOX 4: FUNDING FOR ADAPTATION IS A MAJOR ISSUE BUT CAN BE ADDRESSED

Just contemplating the resources necessary to confront climate change impacts on California's coast and ocean dissuades many from taking necessary actions to begin adaptation. Information gathered from local governments throughout California has shown that finding the funding and/or financing to support effective adaptation strategies, particularly to address flooding associated with sea-level rise, is perhaps the most serious barrier to even beginning the process of adaptation (Moser et al. 2018a). The challenge is daunting and will strain public and private resources throughout the decades ahead. But the resources that may be available for climate change mitigation and adaptation are larger than many realize; economic opportunities created by the requirements of climate change have begun to attract private capital and encourage new arrangements for public financing that significantly increase the available funding resources. California also has financing institutions that could be particularly helpful in funding adaptation actions such as the Mello-Roos Community Financing Districts (http://www.co.imperial.ca.us/TaxCollectorTreasurer/Treasurer/PdfDoc/Mello-Roos.pdf) and the California Infrastructure and Economic Development Bank (www.ibank.ca.gov).

Funding adaptation measures will require significant efforts to combine existing and novel combinations of public and private resources. Each jurisdiction must find a combination suitable to its adaptation plan and to the distribution of benefits and costs of adaptation within the community. Strategies need to reduce risks from flood disasters, but must also use recovery from flood disasters (and the resources made available through insurance and other sources) as an opportunity to make further reductions in risk. Significant recent innovations on private finance through mechanisms such as catastrophe bonds (a form of customized insurance which can be very flexibly designed) can augment insurance against flooding and other hazards, particularly for public property. "Blue" or "climate bonds" can draw on large international pools of capital to fund resilience and adaptation actions.

These complex financing packages present particular problems for smaller governments that may lack sufficient population size or local expert capacity, or with a high proportion of disadvantaged groups. Financing packages will likely need to be compiled by consortia of governments that work together to assemble funding streams. California does have a history of creating cooperative cross-jurisdiction institutions. These include energy consortia such as Monterey Bay Community Power (2018) as well as special revenue mechanisms such as the Mello-Roos Community Financing Districts mentioned above. Creating the capacity to assemble complex financing for adaptation is a task for state government. The California Infrastructure and Economic Development Bank, could be instrumental in helping communities and agencies assemble multiple-source financing approaches for adaptation.

3.5 Natural Heritage

Some of California's iconic natural areas and species may be lost, reorganized, or relocated and some new or unfamiliar ones may become common. The scale and pace of change will surpass that seen in recent human history.

CLIMATE CHANGE WILL IMPACT SOCIALLY, CULTURALLY, AND SPIRITUALLY VALUED PLACES AND WILDLIFE.

The natural places people enjoy visiting, the wildlife that inspires awe, the habitats that support fishing, and the economic scope and reach of California's coastal and ocean economy all rely on healthy coastal and marine ecosystems. The disruption of these ecosystems due to climate change will threaten many iconic aspects of California's identity. The social, spiritual, and economic value associated with the natural places people are familiar with and acculturated to along the coast or in the ocean are already being altered and may be lost entirely in the future. Natural heritage (UNESCO 1972) and cultural ecosystems services (Butler et al. 2003) are terms used to encompass the universal, non-material value of nature to people. Nature's influence on cultural practices, sense of place and human well-being, derived from spiritual enrichment, cognitive development, reflection, recreation and aesthetic experiences, provides unique and often non-monetized opportunities for tourism and recreational activities, education and science, and inspiration for culture, art, and design (De Groot 2010; MA 2005; UNESCO 1972).

Climate change is already starting to alter natural areas and wildlife along the coast and in the ocean directly through sea-level rise and increased ocean temperature, acidification, and declining dissolved oxygen (Kroeker et al. 2010; Levin 2017). Some recent examples include the HAB-induced delay of the Dungeness crab season and a storm-induced closure of Stinson Beach (Figure 10). These impacts, and similar ones, will likely increase in the future. Altered precipitation patterns and the frequency and extent of wildfires on land will also influence salinity of and atmospheric deposition to coastal waters, indirectly impacting these ecosystems (Abram et al. 2003; Chang et al. 2017; Prospero et al. 1996). Places where these impacts co-occur will be especially vulnerable to the loss of extant natural heritage and cultural ecosystem services.

FIGURE 10: STINSON BEACH PARKING LOT CLOSURE

Stinson Beach parking lot closed in 2018 after a storm caused part of it to fall into the ocean (Figure source: David Briggs, The Point Reyes Light).

DRAMATIC CHANGES TO THE COASTAL LANDSCAPE ARE PROJECTED.

Sea-level rise threatens access by the public to natural areas of the coast by reducing the area of beaches and other shoreline habitats used for recreation as they are progressively squeezed against coastal armoring and development. "Coastal squeeze" can occur when barriers (which can be natural or manmade) prevent the migration of beaches inland or when the beach migrates up to and underneath elevated structures (CCC 2018). It also threatens the infrastructure that supports their visitation, recreation, and enjoyment of the coastal and ocean environment such as roads, trails, harbors, public facilities, and shore-based businesses. For example, along 500 km of the Southern California coast, a new model predicts that up to 67 percent of beaches may completely erode by 2100 without large-scale human interventions (Vitousek et al. 2017a). Ironically, many of the hard interventions such as seawalls, riprap, and revetments constructed to protect coastal infrastructure and development from flooding, inundation, and erosion actually reduce the extent of natural areas wildlife need to survive and thrive, and that attract people to the coast (Arkema et al. 2013; Dugan et al. 2008). Failure to address impacts related to coastal squeeze presents challenges for carrying out the public trust doctrine (CCC 2018) (Box 6).

BOX 6: THE PUBLIC TRUST DOCTRINE AND SEA-LEVEL RISE

In 1970, a legal review article extended the public trust doctrine beyond its traditional application to commerce, navigation, and fishing, to encompass environmental values and protection (Sax 1970; Frank 2011). It is a foundational tenet of modern environmental law. The public trust doctrine is derived from English common law system, but has a much deeper historical origin. In California, it provides that tide and submerged lands and the beds of lakes, streams, and other navigable waterways are held in trust by the state for the benefit of the people of California. Legal decisions since 1970 have extended the public trust doctrine to include the right to swim, boat, and engage in other forms of water recreation, and to preserve lands in their natural state in order to protect scenic and wildlife habitat values (www.slc.ca.gov/PublicTrust/PublicAccess.html). The California Civil Code defines the boundary of tidelands as the ordinary high water mark (Civil Code §§ 670, 830). Thus most of the tide and submerged lands under the State Lands Commission's jurisdiction are defined by an ambulatory boundary that depends on where the water lies. As sea levels rise, the ambulatory boundary between public and private lands will change and some private property may pass into the domain of public trust lands.

Put simply, local coastal planners should be mindful of the implications of contemporary land use decisions for current private property as rising sea levels may—in time—make these areas part of the public trust.

Coastal aquifers and wetlands will be increasingly threatened as ocean water intrudes farther inland in areas of low relief (Caldwell et al. 2013). Over 90% of California's historic tidal wetlands, along with their carbon storage capacity, have already been lost. Through a combination of excessive pumping from coastal aquifers and a slow but continuing rise in sea level, saltwater intrusion has also become a serious problem along many of California's coastal areas. In the Monterey Bay area, saltwater intrusion has now progressed as far as eight miles inland into the Salinas Valley, America's salad bowl (Griggs 2017). The resulting loss of land and forced changes in land use and habitat will fundamentally change the coastal landscape. Further north, California's iconic coastal redwoods are threatened by the reductions in summer fog that are predicted with changing ocean upwelling timing and intensity.

THE PACE AND SCALE OF ECOSYSTEM CHANGES WILL SURPASS ANY SEEN IN RECENT HUMAN HISTORY.

The physical and chemical properties of ocean and coastal waters define where coastal and marine habitats and wildlife occur. Climate change will alter these in unprecedented ways. Some of California's iconic natural areas and species may be damaged, lost, or relocated and some new or unfamiliar ones may become common. Marine animals and plants are expected to shift their geographical distribution and change the timing of growth, migration, and reproduction as they adjust to new conditions (Molinos et al. 2015). Marine and coastal animals, plants, and habitats that cannot migrate landward to avoid sea-level rise or move to cooler, less acidic or more oxygenated waters may be lost. Habitats essential to shorebirds along migratory flyways may shrink or become more fragmented due to sea-level rise, reducing the areas available for feeding, resting, and breeding (Galbraith et al. 2002). Increases in density also alter the nature of species interactions. Marine mammals may track prey into new habitats and face novel threats or suffer a loss of haul-out sites (Learmonth et al. 2006). Both of these factors can result in reduced population sizes and viability. The reorganization of species as they move into new locations and communities may result in unexpected ecological interactions that fundamentally change marine food webs.

The iconic ecosystems and species of California today have themselves been shaped by human intervention. Importantly, however, projected climate-driven changes are anticipated to dramatically exceed these historical shifts. The nearshore waters of California's central and south coasts are today unrecognizable from the early 1900's when schools of sardine dotted the coastline and the associated fishery supplied the canning industry in locations such as Monterey's Cannery Row. Today these are iconic reminders of California's past ocean ecosystems and wildlife and a glimpse into the scale of future projected changes.

In the last two to three years, some of the first visible signs of climate-induced losses to California's natural heritage have become visible. For example, over the past four years Will kelp (*Nereocystis luetkeana*), usually common on the northern California coast, has declined by 93% (Teck et al. 2018). A number of closely clustered environmental events preceded and contributed to the kelp decline including a HAB in 2011, emergence of seastar wasting disease in 2013, the marine heat wave (aka the "warm blob") from 2014–2016, and an El Niño in 2015. This occurred in the context of the historic loss of sea otters from this ecosystem, top predators that promote kelp forest persistence through a cascade of ecological interactions known from introductory biology textbooks. The reduction in kelp has created starvation conditions for the herbivores that depend on it for food and habitat, including abalone and sea urchins, and resulted in the creation of "urchin barrens" devoid of kelp (Teck et al. 2018).

Diving for abalone has traditionally been an important part of the cultural identity of people on the northern California coast. It is a celebrated activity, rooted in tradition and camaraderie, drawing thousands of people to the campgrounds, motor lodges, and bed-and-breakfasts of the northern California coast (Branch 2014). In addition to the dramatic loss of this iconic ecosystem, the only remaining fishery for abalone in California, an exclusively recreational one, was officially closed in December 2017 (CDFW 2017). The emerging expressions of disruptive change, or ecosystem shifts, represent what scientists anticipate will become more common and frequent as the climate continues to change. It also provides a clear example of the potential costs to California's coast and ocean economy and culture.

People rely on nature for physical, economic, and cultural benefits (Daily 1997). Tools exist for documenting the many ways people are connected to the environment but data gaps exist for coastal and ocean ecosystems (Rodrigues et al. 2017). In the case of the red abalone fishery, the recent fishery closure will negatively affect the contemporary economy and culture of the northern California coast, in an attempt to ensure its existence in the future. The decision to close the recreational abalone fishery was not made lightly and is evidence of the importance people place on both protecting the abalone populations and northern California cultural traditions.

Californians have adapted to these types of linked socio-ecological shifts in the past. The connections between ecosystem status and natural heritage along the California coast extend back for millennia. Tribal economies, cultures, and traditions routinely included a variety of marine species, like smelt and Chinook salmon (Figure 11) (Anderson 2005; Gifford 1965; Greengo 2004). For example, evidence suggests the emergence of the abalone and red urchin fisheries (by tribes and others) resulted from population reductions or elimination of sea otters (Erlandson et al. 2008). Conversely, red urchins are not abundant enough to support a commercial fishery in central CA where sea otter populations have been restored (CDFG 2004). In a future where climate change is expected to drive more environmental variability and more frequent extremes like those described above, and where there is a knowledge gap of the value of non-material cultural services, the challenge for California is how to better anticipate how ecosystem changes will drive the need for cultural and economic adaptation.

FIGURE 11: NATURAL HERITAGE

A coastal tribe drying fish on the North Coast of California. (Figure Source: Tolowa Dee-ni' Nation archive).

DEEPENED UNDERSTANDING OF CULTURAL ECOSYSTEM SERVICES IS NEEDED TO ADAPT.

The actions of the Coastal Commission are underpinned by the Coastal Act (Box 1). They express the cultural and societal value of beach access, coastal development, and other aspects of natural heritage. In the marine environment, very few mandates or management frameworks explicitly recognize non-utilitarian values of marine biodiversity. A notable exception is the Marine Life Protection Act that led to the creation of a statewide network of MPAs designed to, among other goals, "protect the natural abundance and diversity of marine life, and the structure, function and integrity of marine ecosystems" (MLPA 1999, Case Study 7).

Confronting the projected changes to California natural landscape, habitats, and wildlife will require challenging dialogues about what specifically confers value in the marine and coastal environment. What might be lost? How can tradeoffs be evaluated (for example, between preserving a landscape vista of the ocean and preserving function of marine ecosystems)? How can communities better prepare for surprises and unexpected changes to marine habitats? While a consensus opinion on answers to these questions is unlikely, a broad and inclusive dialogue is essential to align scientifically-derived adaptation strategies with the value set of California's residents. New scientific research can support this conversation and inform the choices made by the Coastal Commission and other state agencies as well as the choices about how to manage the statewide network of MPAs into the future. We can build upon new tools and approaches developed to identify and quantify cultural and other non-utilitarian values of nature and wildlife (e.g., Rodrigues et al. 2017).

In the meantime, additional ecosystem-based approaches to management and conservation offer the opportunity to foster resilience to the changes ahead and support the adaptive capacity of nature (Klinger et al. 2017). New protection and restoration approaches based upon growing scientific understanding of natural infrastructure options (e.g., Newkirk et al. 2018, Case Study 8) have the potential to provide co-benefits, protecting both the utilitarian and non-utilitarian values of California's coast and ocean. At minimum these strategies can buy time, reducing the impact of multiple stressors while research, testing, and evaluation of adaptation strategies builds a deeper body of knowledge and experience to frame future choices. Alongside academic efforts, projects that continue to provide access to the coastal environment, that continue to educate, and that meaningfully engage a diverse constituency in scientific data collection and interpretation, will create the venues for discussions about the value we place on our coast and ocean.

CASE STUDY 7 | California's Statewide MPA Network: A Climate Adaptation Strategy for Biodiversity?

California took a bold policy step in enacting the Marine Life Protection Act (MLPA 1999). The MLPA included six goals: (1) to protect the natural diversity and abundance of marine life, and the structure, function, and integrity of marine ecosystems; (2) to help sustain, conserve, and protect marine life populations, including those of economic value, and rebuild those that are depleted; (3) to improve recreational, educational, and study opportunities provided by marine ecosystems that are subject to minimal human disturbance, and to manage these uses in a manner consistent with protecting biodiversity; (4) to protect marine natural heritage, including representative and unique marine life habitats in California waters for their intrinsic value; (5) to ensure that California's MPAs have clearly defined objectives, effective management measures, and adequate enforcement, and are based on sound scientific guidelines; and (6) to ensure that the state's MPAs are designed and managed, to the extent possible, as a network.

The adaptive value of California's network of MPAs to conserve marine natural heritage and biodiversity in the face of climate change may be more important than previously appreciated. Few scientists, managers, and members of the public appreciate and recognize the potential for beneficial network effects that differ substantially from just conservation within the boundaries of the protected area and the corresponding reduction in areas open to fishing. However, the potential for win-win network benefits was a major scientific and policy basis for establishing the MLPA and designing MPAs so that they would function as a network.

Recent studies have consistently demonstrated the ability of scientifically designed MPA networks to reduce or eliminate tradeoffs between conservation and fishery benefit (Gaines et al. 2010). Additional benefits can accrue when a subset of protected areas with robust source populations are connected to the broader network through larval dispersal. These include supporting population persistence in the face of environmental uncertainties and catastrophes (e.g., increased variability, extreme events as predicted with climate change) and enhancing economic value (Allison et al. 2003; Armsworth and Roughgarden 2003; Grafton et al. 2005).

Questions about whether California's MPA network is optimally configured to provide genetic adaptation benefits have emerged recently in response to new research showing the risk of exposure to increasing ocean acidity varies from location to location due to a persistent spatial mosaic of ocean conditions (Chan et al. 2017). For example, do current MPAs include locations with environmental conditions conducive to selection for genotypes that may be adapted to warmer or more acidic waters? Are they located in areas buffered against increasing background acidity? Or are they distributed to accommodate larval connectivity and migration in the face of changing ocean currents? Marine species relocating or evolving due to climate change may benefit by having suitable protected habitats to support population adaptation, relocation and community reorganization in a coastal network that spans biogeographic and oceanographic conditions and regions. Investments in ongoing monitoring and research will illuminate the potential value of the MPA network as a climate adaptation strategy.

CASE STUDY 8 | Piloting Natural Infrastructure Solutions for Coastal Adaptation to Sea-Level Rise

In an effort to highlight alternatives to seawalls to address impacts from sea-level rise and erosion, a funded Fourth Assessment project highlights natural infrastructure projects for a range of settings in coastal California (Newkirk et al. 2018). Using five case studies, they demonstrate natural shoreline infrastructure projects that range from fully natural approaches that preserve or restore natural systems, hybrid solutions that integrate engineered aspects into restored or created natural features, and fully engineered structures like seawalls and revetments. For example, nature-based adaptation studies with oysters and eelgrass in San Francisco Bay show promise for slowing flow, reducing erosion, and helping enhance sedimentation (Boyer et al. 2017).

These case studies were designed to be useful examples for coastal planners, local governments, and others working on solutions and making decisions regarding climate-related coastal hazards. The cases take into consideration the diversity of the California coast and need for tailoring one's project to particular conditions and provide some overarching lessons such as the importance of establishing a multi-agency stakeholder process, coordinating with permitting agencies early in the design phase, engaging with community groups, and supporting demonstration projects that collect detailed monitoring information.

4. Science and Practice of Coastal and Ocean Adaptation

Denial of climate change, lack of financing, and uncertainty are all major barriers in moving from adaptation planning to implementation. The adaptation pathways approach is one way of removing such barriers that could be applied across sectors.

WHAT ARE WE LEARNING FROM ADAPTATION?

Adaptation is not a completely new phenomenon in California, even if adaptation actions have not always gone by that name. For example, the Coastal Commission requires new structures to be set back from bluff edges to account for future erosion. These and similar strategies can be used to address sea-level rise vulnerabilities when structures are sited or designed to account for the increased risks of hazards associated with rising seas over their anticipated lifetimes. We also can and should learn from examples outside of California. There are lessons we can learn from rebuilding efforts after Hurricane Sandy; communities in southern Florida have been adapting to king tides; Houston has been learning about toxic waste sites and flooding potential after Hurricane Harvey; the military base in Norfolk, Virginia, is adapting to sea-level rise; and we have been learning about the ability of regional fisheries management organizations to respond to resource fluctuations from climate change (Pentz 2018). There are important lessons California can learn. For instance, where did things go wrong and where did things go right, and how can these lessons be applied to coastal communities in California?

THE NEED FOR CROSS-SECTORAL APPROACHES.

Increasing research evidence and experience highlight that climate impacts are cross-sectoral, with often linked natural and social impacts, and require responses from across government jurisdictions. Because societal systems are so highly interconnected and interdependent, a climate impact on one sector could lead to cascading impacts on other sectors that are not immediately impacted. The 2017–2018 natural disasters (for example, hurricanes, fires, and mudslides) provide grim glimpses into how quickly disruptions to individual lifelines can cascade through a local community and economy - and then globally. A complementary Fourth Assessment study mapped how climate change impacts to the electrical grid in Los Angeles impacts downstream lifelines, such as water, transportation, communication, emergency services, and public health (Moser and Finzi Hart 2018). The importance of a functioning electrical grid to human well-being was substantiated by the study; but the centrality of the communications systems also emerged. Moreover, as climate impacts one lifeline, it impacts the others at the same time, limiting their ability to be fully responsive to the emergency at hand. Very few communities are considering these interconnections and thus are exposing themselves to increased vulnerability.

Moreover, societal teleconnections - impacts that originate from afar but have local consequences - are not often considered in adaptation planning and further increase a particular community's vulnerability. Hurricane impacts in Puerto Rico and the resulting loss of power, for instance, resulted in disruptions to production of approximately 14 critical medicines that are only produced in Puerto Rico, impacting health service provision throughout the nation, including California (United States Subcommittee on Oversight and Investigations Committee on Energy and Commerce, 2017). While it may seem overwhelming for a community to try to address all climate impacts everywhere, developing systematic methodologies for helping communities begin to identify their global vulnerabilities will help them be better prepared for the future (Moser and Finzi Hart 2015, 2018).

Though many communities and sectors are actively engaging in climate adaptation planning, without coordinated and scalable efforts there could be unexpected regional impacts. For example, deciding to pursue coastal armoring could make sense for property protection but could have adverse impacts on recreation (Ruckelshaus et al. 2013). Equally, however, cross-sectoral and regional-scale adaptation planning has multiple benefits that can translate to broader resilience, and can also serve to bring along vulnerable communities that may not have the resources to fund their own studies, or analyze their own adaptation strategies.

A NEED FOR NEW DECISION-MAKING PROCESSES?

The challenge of adaptation planning is to recognize that choices about strategies must be made in the context of continually shifting conditions and circumstances. The direction of climate change and its effects can be projected with confidence, but the exact pace and ultimate extent are still uncertain. Adaptation actions change risks, but rarely permanently. Adaptation is not a single set of decisions to be made in the near future, but a decades-long process that continually reassesses risks and selects the best strategy for that time, and which does not foreclose future options. Despite persistent uncertainties, the pace and scale of impacts already observable highlight the urgency of action. Scientific understanding of impacts and adaptation options will continue to evolve, but a foundation of information is available to support choices about strategies for adaptation. These strategies can include alterations to currently planned investments as well as new actions.

It is as yet unclear if current legal, policy, and decision-making processes are appropriately structured to address climate impacts that will continue to increase in intensity and/or frequency. As the rate of climate change increases, decision-making frameworks and processes that we develop will need to better prepare us for projected future impacts. There is little current experience or mechanisms that are appropriate for addressing and responding to the projected human and social-system wide impacts of climate change. Understanding vulnerabilities and potential impacts as described above is useful in order to make the case for mitigation and adaptation. However, knowledge is not the main constraint on moving forward with adaptation. Funding, staff capacity, climate denialism, challenges involved in changing human behavior, and uncertainty are all major barriers to adaptation (e.g., Moser et al. 2018b). We can draw on recent advances in adaptation science and research that provide for making decisions now, even given persistent uncertainties.

A PATHWAYS APPROACH TO ADAPTATION.

With ever-evolving science and associated uncertainty, we should be prepared to act. Decisions will need to be made with incomplete information. A new model of taking action in the face of uncertainty is needed based on flexibility, caution, and the capacity to proceed with partial knowledge. Inaction now will reduce options and impose higher costs later. The concept of adaptation pathways offers one approach for transitioning from current decision-making frameworks that rely on stability to those that allow for uncertainty and a changing environment. Strides have been made in California, and elsewhere, to advance the use of an adaptation pathways approach to address sea-level rise (Griggs et al. 2017; Haasnoot et al. 2013; Reeder and Ranger 2011). The adaptation pathways concept focuses more on the process of decision-making than on a climate-induced harm projected to occur in any pre-determined scenario.

It involves creating a strategic vision for the future, committing to short-term actions, and establishing a framework to guide future actions (Haasnoot et al. 2013). This concept allows for a framework that provides a way to manage under uncertainty and adapt over time to meet changing circumstances. Communities can pre-determine observable threshold events that exceed their risk tolerance such that they will 'trigger' a management response (Center for

Ocean Solutions 2018). OPC's State of California Sea-Level Rise Guidance (2018) recommends pursuing adaptation pathways for critical infrastructure and assets in the coastal zone. Some fisheries, like the sardine fishery, also use this strategy through harvest control rules (allowing a higher harvest under warmer temperatures and lower harvest under cooler temperatures to reduce fishing pressure when the population is particularly vulnerable). A trigger might also be observed when annual sea level rises above a threshold height or financial harm is incurred above a threshold value. These triggers should be informed by local community involvement, and will reflect a community's risk tolerance, abilities, and preferences.

(Photo Source: Carrie Pomeroy)

CASE STUDY 9 | Approaches to Shoreline Erosion and Sea-Level Rise

There are essentially three responses to shoreline erosion in California, which will become an even more challenging problem in the future with continuing and accelerated sea-level rise: 1) armor, or harden the shoreline; 2) nourish, or add more sand to widen beaches; and 3) retreat, or manage relocation of coastal assets. Each of these approaches have their benefits as well as their costs and impacts. Individual communities as well as state agencies armed with the new Sea-Level Rise Guidance document are in the process of developing responses to the threat of additional sea-level rise and shoreline retreat. Individual cities, counties, or state agencies may develop somewhat different approaches depending upon their regional concerns that will no doubt change or evolve over time.

The impacts of shoreline armoring in California have been well studied (Griggs and Tait, 1988; Griggs, 1999; Griggs, 2005) and have been known for decades, including: visual impacts, impoundment or placement losses, reduction of beach access, loss of sand supply from eroding cliffs or bluffs, and passive erosion. Because of these impacts, the California Coastal Commission, the agency responsible for approving any permit for a new seawall or revetment, has taken a strong position of only granting permits when a primary structure is in imminent danger. As a result, it is unlikely that there will be any significant amount of new armoring along California's shoreline. It is ultimately not a long-term solution.

Beach nourishment in California has historically been primarily opportunistic or the by-product of coastal construction or dredging projects (harbors, marinas, or river channels). Two recent projects in San Diego County (Regional Beach Sand Projects I and II in 2001 and 2012 respectively) were the first large-scale efforts where large volumes of sand were added to the shoreline from offshore sources for the sole purpose of widening the beach with the objectives of both protecting back beach development and increasing recreational opportunities. Combined, these two nourishment projects added 3,500,000 yds^3 of offshore sand to beaches in San Diego County at a total cost of $46 million. Detailed beach survey data showed that both nourishment projects had very short life spans with most of the added sand removed from the beach within several years. A new plan to spend $150 million over the next 50 years to continue this nourishment effort has now been put forward. Beach nourishment in most places along California's high littoral drift rate shoreline is very expensive, will likely be very short-lived, and will not be an effective long-term strategy for dealing with shoreline retreat and sea-level rise (Griggs and Kinsman 2016; Patsch and Griggs 2006). There may be locations, however, where beach usage is very high and the direct economic benefits of beach nourishment may make this a viable option in the near term. Any future nourishment projects should be seen as pilot projects where the benefits, impacts, costs, and lifespan of these efforts can be carefully evaluated in order to be able to inform future decision-making.

As sea levels continue to rise, neither beach nourishment nor armoring will be able to permanently stop flooding of coastal development, critical infrastructure, and natural resources. The need for planning and implementation of managed shoreline retreat thus seems inevitable. To date, there have been only a few examples of managed shoreline retreat and infrastructure relocation in California (e.g., Case Study 1), and future efforts will no doubt prove to be even more difficult and politically-charged than current beach nourishment and armoring projects. Despite the political challenges, coastal communities should begin to consider managed retreat as early as possible. Having socially inclusive discussions with private property owners, regulatory agencies, and community-based organizations today can help begin the future complicated process of managed shoreline retreat along California's treasured coast (Siders 2013).

5. Looking Ahead

The more we mitigate the less we will be impacted by climate change. California has been a national and global leader in both developing solutions to climate change and advancing bold ocean management strategies. In particular, ambitious climate change mitigation efforts are already transforming industries such as electric power generation and automobile manufacturing. And now, looking ahead, there is an opportunity to choose actions that serve both mitigation and adaptation purposes and those that address impacts across sectors and provide multiple benefits.

Scientific research is already illuminating an expanding portfolio of "no-regrets" strategies that couple adaptation objectives with low-impact carbon choices. For example, preserving or restoring wetlands could provide a combination of benefits from habitat provision and flood damage reduction to carbon storage and sequestration. Sustained science investments will further the understanding of blue carbon contributions to achieving greenhouse gas reductions goals, for instance, and provide the knowledge needed to achieve legislative aspirations (e.g., Assembly Bill 398, 2017, which outlines climate adaptation and resiliency as a priority in the expenditure plan of Greenhouse Gas Reduction Fund). At the same time additional adaptation actions are a necessary response to the climate change impacts that can no longer be avoided. The 2018 update to California's Climate Adaptation Strategy, *Safeguarding California,* provides a starting point, outlining ongoing activities and prioritizing key recommendations for and next steps of state agencies that can be bolstered and scaled into the future. The recent adaptation efforts underway to prepare for sea-level rise and climate-related fisheries and ecosystem impacts suggest that planners and managers recognize that while there are still some uncertainties, they have enough information to take steps that still maintain some degree of adaptive capacity. The realities are such that they cannot wait for perfect information. New decision-frameworks, such as the concept of adaptation pathways, provide the basis for evaluating and selecting actions now. Strategic investments in monitoring and evaluation could enable future science-informed updates to management choices. Moreover, there are opportunities to advance development of these decision-making frameworks themselves to better support coordinated cross-jurisdictional decision-making and broad constituency engagement in the decisions shaping the future of California's coast and ocean.

As California's climate, coastal population, and societal needs continue to change, the state needs to remain creative in developing and applying science and in approaches to policy. Evolving science can continue to provide important context and perspective on many policy issues and opportunities such as offshore renewable energy utilization, expanded aquaculture, and desalination.

KEY RESEARCH NEEDS: PROBLEMS, OPPORTUNITIES, AND BENEFITS.

We conclude this report with a summary of identified research needs and the potential adaptation benefits of thoughtful, leveraged science investments (Box 5). Some of this work is beginning, and the development of relevant science questions and research needs is also underway in other venues. For example, scientists and other experts are engaged in providing scientific recommendations to the state through the OPC-SAT to better track, predict, and project future HAB events and mitigate impacts with early indicators or advanced warning to prepare the affected industries. Similarly, a newly formed and legislatively mandated ocean acidification Science Task Force now serves as a responsive advisory board to inform future actions on OA in California and along the West Coast. Collectively these and other efforts, and the research needs described here, provide a roadmap for scientific research that can underpin effective adaptation to the climate and ocean changes ahead.

BOX 6: KEY RESEARCH AND ADAPTATION NEEDS: PROBLEMS, OPPORTUNITIES, AND BENEFITS

Research Needs:

1. Assessment of the socio-economic consequences of climate change currently relies on syntheses of forecasts of future sea levels and other oceanic changes with data on current socio-economic conditions. Integrating projected future socio-economic conditions (such as changes in the location of population and employment that are incorporated in infrastructure planning) with forecasts of climate change effects can provide predictions and scenarios that can be used to prioritize and select among adaptation options.

2. Changing ocean conditions are already impacting California's marine life and fisheries. Economically and ecologically important marine organisms can be negatively affected by the simultaneous occurrence of different stressors such as increasing temperatures, ocean acidification, and lowered oxygen levels. Improving the current understanding of the combined effects of these ocean changes and whether thresholds exist for potential collapse of ecosystems or fisheries, or significant loss of individual species, can provide guidance for management decisions that can help reduce future losses and impacts.

3. Specific toxins associated with harmful algal blooms (HABs, such as domoic acid and *Pseudo-nitzschia*) can have major effects on both human health and commercial fisheries (such as the delay in the opening of the Dungeness crab fishery in 2015-16). Improving scientific understanding of the environmental conditions or triggers for these harmful algal blooms, including their interactions with changing ocean temperature and ocean chemistry, and developing early warning systems can help to ensure the protection of human health. It can also provide guidance for control of terrestrial runoff and wastewater discharge to help reduce the future frequency, duration, and intensity of harmful algal blooms.

4. Sequestration and drawdown of carbon by marine vegetation has the potential to reduce the impact of rising carbon dioxide concentrations and associated ocean chemistry changes. A key need is to understand and quantify the importance of different habitat types and the role that restoration or conservation of these habitats may play in reducing the impact of rising carbon dioxide levels on coastal marine environments.

5. Ocean acidification is already impacting key coastal species throughout the food chain. Maintaining and expanding monitoring of ocean acidification and dissolved oxygen to improve understanding of long-term trends can aid both in developing adaptive responses and in assessing impacts of policy changes. In particular, a clear understanding of the spatial and temporal variability in ocean acidification and declining dissolved oxygen is needed and can be obtained through commitment to statewide monitoring efforts.

6. Reduced dissolved oxygen levels (ultimately leading to hypoxia) in nearshore waters are detrimental to almost all marine animals. A clear understanding of the frequency and extent of low oxygen zones, and the mechanisms causing them, could help inform efforts to reduce these events and their biological impacts.

7. Coastal and ocean monitoring and observation systems have enabled scientists and others to document and quantify individual climate-related changes to the coast and ocean. Continuing to monitor environmental indicators of climate change can expand California's ability to track the extent of climate change effects and respond with appropriate and timely mitigation and adaptation measures.

8. The combination of sea-level rise and extreme water level events (El Niño and king tides, for example) will continue to affect the coast and lead to significant changes to its beaches, dunes, cliffs and bluffs. These will have important implications and impacts to existing coastal development and infrastructure, as well as coastal habitats and ecosystems. There is a need to continue to improve our understanding of how cliffs, bluffs, dunes and beaches will erode and change with increased wave impact and extreme water levels. Continuing to monitor both short- and long-term coastal change over time through our existing and developing tools and technologies will allow for more accurate predictions of future change and how the coast will respond to a shifting climate.

Adaptation and Education Needs:

9. Although a variety of strategies have been used historically to address coastal hazards, policies are now being developed and experience is growing in implementing sea-level rise adaptation strategies at state and community-wide scales that attempt to balance environmental and social needs. The longer we wait to adapt, however, the greater the future costs and losses will be. Developing successful approaches to adaptation and publicizing the financial mechanisms for applying them statewide will save money and reduce future risks.
10. Uncertainty remains in the minds of many California residents regarding what they might expect or experience in the future from a changing climate, and how they might better prepare. State efforts to continue to evaluate, assess, and educate all Californians about how climate change is affecting the coastal zone and ocean waters can result in a more informed public and improved decision-making.
11. As communities begin to plan for the impacts of climate change, they should be encouraged to have broad engagement from throughout the community. Social inclusion, in combination with evolving scientific research and understanding, will be critical to advancing coastal adaptation strategies that incorporate all sources of relevant information, are fair and just to all community members, and ultimately have a better chance of adoption and implementation.
12. The roles and responsibilities of multiple public agencies will be impacted by climate change and there are many opportunities for coordination and cooperation between agencies and sectors. Through the engagement of affected stakeholders and the assessment of social and economic costs and benefits, California can develop more transparent and information-based adaptation approaches. Better coordination can promote learning about opportunities for and barriers to working together. New governance structures may be needed to fully address the impacts of climate change.
13. A unique opportunity exists to test and evaluate adaptation strategies in different physical and biological environments as they are implemented, to assess how well they meet different environmental and social needs, and to then export and scale successful adaptation strategies along the coast.

Glossary

Adaptation: An adjustment in natural or human systems to a new or changing environment. Adaptation to climate change refers to adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities (EPA, 2013).

California Current System (CCS): The Eastern Boundary current extending approximately 1000 km off the U.S. west coast, extending from Washington State to Baja California.

Climate Change: A change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer.

Cultural ecosystem services: Non-material benefits people obtain from ecosystems including: spiritual and religious, recreational and ecotourism, aesthetic, inspirational, educational, sense of place, and cultural heritage (UNESCO 1972).

Dissolved Oxygen (DO): Microscopic bubbles of gaseous oxygen that are mixed in water and available to aquatic organisms for respiration.

Domoic Acid: A naturally occurring toxin that is related to a bloom of a particular single-celled diatom called *Pseudo-nitzschia*.

El Niño Southern Oscillation (ENSO): Large-scale ocean-atmosphere climate interaction linked to a periodic warming in sea surface temperatures across the central and east-central Equatorial Pacific.

Greenhouse Gas: Gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the Earth's surface, the atmosphere itself, and by clouds. Water vapor (H2O), carbon dioxide (CO2), nitrous oxide (N2O), methane (CH4), and ozone (O3) are the primary greenhouse gases in the Earth's atmosphere.

Harmful Algal Bloom (HAB): Any large increase in the density of algae that is capable of producing toxins.

Hypoxia: Oxygen depletion; a phenomenon where the concentration of dissolved oxygen in the water column decreases to a level that can no longer support living aquatic organisms.

King Tide: The highest predicted high tide of the year at a coastal location; above the highest water level reached at high tide on an average day.

Marine Heat Wave: A coherent area of extreme warm sea surface temperature that persists for days to months.

Mitigation: A human intervention to reduce the human impact on the climate system; it includes strategies to reduce greenhouse gas sources and emissions and enhancing greenhouse gas sinks.

Natural Heritage: Natural features, geological and physiographical formations and delineated areas that constitute the habitat of threatened species of animals and plants and natural sites of value from the point of view of science, conservation, or natural beauty. It includes nature parks and reserves, zoos, aquaria and botanical gardens (Butler et al. 2003).

Natural Infrastructure: Utilizing the natural function of ecological systems or processes to reduce vulnerability to specific environmental hazards and increase resilience of the shoreline in order to perpetuate or restore its ecosystem services.

Ocean Acidification (OA): The term given to the chemical changes in the ocean as a result of the absorption of carbon dioxide emissions to the atmosphere.

Representative Concentration Pathways (RCPs): Four greenhouse gas concentration trajectories adopted by the IPCC for its Fifth Assessment Report in 2014. RCPs describe four different 21st century pathways of greenhouse gas emissions and atmospheric concentrations, air pollutant emissions, and land use. The RCPs include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0) and one scenario with very high greenhouse gas emissions (RCP8.5).

Sea-level Rise: The average rise in mean sea level, which may be due to a number of different causes, such as the thermal expansion of sea water and the addition of water to the oceans from the melting of glaciers, ice caps, and ice sheets.

Teleconnections: Impacts that originate from afar but have local consequences.

Vulnerable communities: Communities that have experienced decades-long pervasive socio-economic conditions that are perpetuated by systems of inequitable power and resource distribution and hence have fewer social and economic resources to prepare for, adapt to, and recover from the effects of climate change.

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