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Significant challenges to the sustainability of the California coast considering climate change

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Climate change is an existential threat to the environmental and socioeconomic sustainability of the coastal zone and impacts will be complex and widespread. Evidence from California and across the United States shows that climate change is impacting coastal communities and challenging managers with a plethora of stressors already present. Widespread action could be taken that would sustain California's coastal ecosystems and communities. In this perspective, we highlight the main threat to coastal sustainability: the compound effects of episodic events amplified with ongoing climate change, which will present unprecedented challenges to the state. We present two key challenges for California's sustainability in the coastal zone: 1) accelerating sea-level rise combined with storm impacts, and 2) continued warming of the oceans and marine heatwaves. Cascading effects from these types of compounding events will occur within the context of an already stressed system that has experienced extensive alterations due to intensive development, resource extraction and harvesting, spatial containment, and other human use pressures. There are critical components that could be used to address these immediate concerns, including comanagement strategies that include diverse groups and organizations, strategic planning integrated across large areas, rapid implementation of solutions, and a cohesive and policy relevant research agenda for the California coast. Much of this has been started in the state, but the scale could be increased, and timelines accelerated. The ideas and information presented here are intended to help expand discussions to sharpen the focus on how to encourage sustainability of California's iconic coastal region.

sea-level rise | sustainability | management | climate change | coast

Importance of the California Coastal Region

California's coastal and marine zones (hereafter coastal) are of fundamental importance to the environmental and socioeconomic sustainability of the state. The coast is dynamic, continually changing, and comprises complex physical, biological, and societal systems, making climate change planning challenging. The California coastline extends over 2,000 km and includes nine offshore islands. It contains some of the largest estuaries in the United States (US), including Humboldt Bay, San Francisco Bay-Delta, and San Diego Bay. California also includes many small lagoons and estuaries that intermittently open and close from ocean and river influences. The iconic coastline of California also includes sandy beaches, dunes, rocky shorelines (i.e., cliff-backed), seagrass beds, kelp forests, wetlands, forest, and scrub (Fig. 1). Sandy beaches and rocky shorelines dominate the outer coast area with wetlands and seagrass dominating estuaries. This area hosts a variety of ecological systems within the subtidal, intertidal, and upland zones, with associated biodiversity. The Mediterranean climate contributes to making California a global biodiversity hotspot, with governors signing executive orders to protect biodiversity, especially considering climate change [Executive Order B-54-18 (2018); N-82-20 (2020)]. The coastal zone has a variety of public lands, including dozens of State and National parks and over 200 State beaches, as well as an expansive network of Marine Protected Areas (MPAs). The coast of California has the highest native species richness (number of species) within the state (1). The marine biodiversity of the greater California Current Region includes over 10,000 known species and, in the United States, is second only to the Gulf of Mexico Region (2). This region contains many iconic species communities, such as bull kelp (*Nereocystis luetkeana*), giant kelp (*Macrocystis pyrifera*) and southern sea otter (*Enhydra lutris nereis*), beach-dwelling California least tern (*Sternula antillarum browni*), California sea lion (*Zalophus californianus*) and black oystercatcher (*Haematopus bachmani*) on rocky shorelines, and spawning runs by Coastal Chinook salmon (*Oncorhynchus tshawytscha*). Thirty-five percent of California's Audubon Important Bird Areas are located along the coast and are considered important for breeding, wintering, and migrating birds, especially shorebirds and waterfowl using the Pacific Flyway. Thirty-six of these areas were identified for the potential as climate refugia (3).

The 21 California coastal counties are home to approximately 68% of California's 38.9 million people and generate over $888 billion in employment income and about 85% of California's Gross Domestic Product (4, 5). Sixty percent of California's coastline is publicly owned with about 850 public

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Fig. 1. (*A*) Morro Bay, San Luis Obispo County; (*B*) the mouth of San Francisco Bay, the largest estuary in California; (*C*) beach and cliff areas near Pacifica; (*D*) brackish marsh at Rush Ranch Open Space, Suisun Bay; (*E*) Tijuana marsh in San Diego; and (*F*) Seagrass in Monterey Bay. Photo credits *A–E* is USGS, K. Thorne, (*F*) USGS Public Domain.

access sites (6). The California Legislature has deemed tidelands as public trust lands that are owned by the public, cannot be bought or sold, and are held in trust for the people by the state government. Fishing communities are an important part of California's maritime heritage and support subsistence, recreational, and commercial economies. The marine fisheries (including aquaculture) result in $500 million USD annually in sales and employ close to 500,000 people. Important seaports include the Port of Oakland, Port of Los Angeles, and Port of Long Beach, which are some of the largest ports in the United States, managing over a quarter of all containers and cargo traffic (7). Over half a million people are employed via activities related to California's ports, which also generate over $9 billion in tax revenue. California is the leading state for ocean tourism, supporting 41,000 jobs and earning $26 billion in annual income (8). California beaches also receive over 230 million visits a year (9), with 50% of the population visiting some portion of the coast annually (10).

California's coastline is the traditional and unceded territory of many of the state's Indigenous peoples with several coastal reservations, particularly in the northern portion of the state. Recently, the state has allocated authority and funds for the Tribal Marine Stewards Network (https://tribalmsn.org/), which includes the Tolowa Dee-Ni' Nation, the Resighini Rancheria, the Kashia Band of Pomo Indians, the Amah Mutsun Tribe, and the Santa Ynez Band of Chumash Indians, to monitor and comanage portions of the coast and adjacent waters (11).

No coastal areas remain untouched by direct human activities, through human development, loss of native habitats and species (12), degraded water quality (13), diversion of freshwater (14), reduced sediment supply (15, 16), and overfishing (7). Coastal ecosystems provide critical ecosystem services such as protection from storms, flooding, and erosion (17), along with water purification, maintenance of fisheries, habitat for wildlife, and carbon sequestration (18). In recent years, climate change and its impacts on the coastal region have become issues of concern across environmental and socioeconomic sectors. California has been making strides to address climate change impacts through the development of coastal strategic plans, such as the California Coastal Commission Strategic Plan and new funding opportunities for nature-based solutions and climate adaptation (e.g., Proposition 68, Measure AA).

Climate Crisis Is Here

There is conclusive evidence that increased greenhouse gases in the atmosphere since the onset of industrialization are leading to warmer temperatures in the atmosphere, accelerating both surface air and ocean temperatures to record levels (19, 20) which can drive changes in storm frequency and intensity (21). Increasing sea levels are another by-product of higher temperatures (22, 23), with the global rate having more than tripled from 1.2 mm/y from 1901 to 1990 (24) to 4.4 mm/y from 2013 to 2022 (25). In California, sea levels have increased 20 cm over the last century (26), including 4 cm in the last two decades (Fig. 2, 27). Since the 1930s, global warming appears to be causing stronger storms and larger waves off the California coast (28), further compounding the impacts of sea-level rise. Future flood risk across California will double for every 5 to 10 cm of sea-level rise (*SI Appendix*, Fig. S1, 29), which in turn poses increasing permanent inundation and storm-driven flooding threats to both human communities (30) and habitats (30–32),

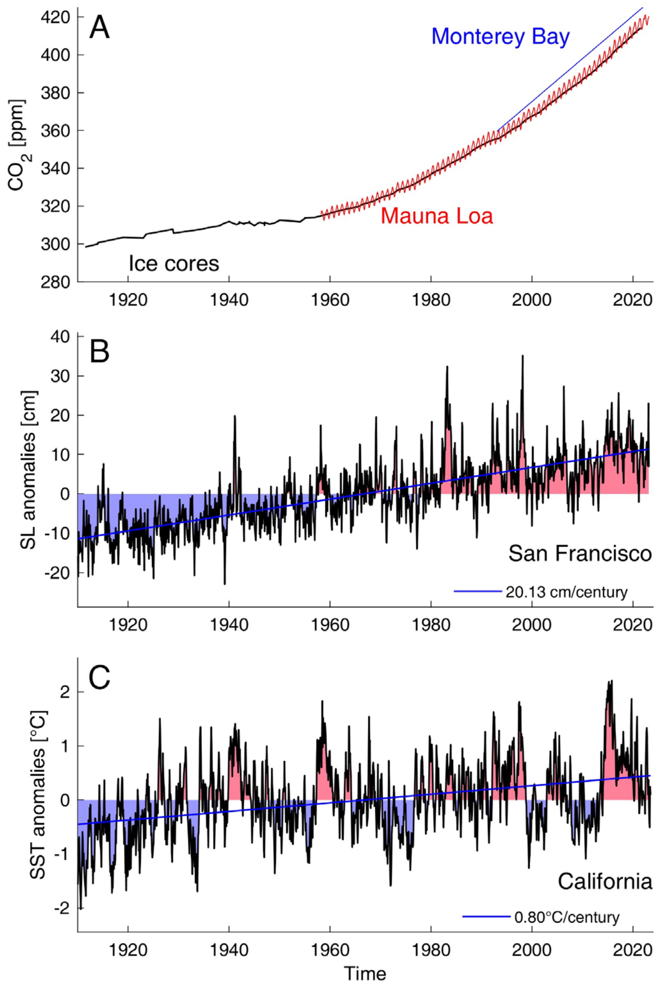

Fig. 2. Time series from 1900 to present of (*A*) atmospheric carbon dioxide (CO_2) measured from ice cores (black) and the Mauna Loa Observatory (red) on the Big Island of Hawaii (48, 49); also shown is the trend in surface ocean pCO_2 in Monterey Bay, California from 1993 (blue; updated from ref. 50); (*B*) Sea level anomalies (seasonal cycle removed) from tide gauge station 9414290 in San Francisco, California (courtesy of the National Oceanic and Atmospheric Administration); (*C*) SST anomalies (seasonal cycle removed) from the California Current along the US west coast (51). Clear increases are evident for all series with atmospheric CO_2 increasing at a faster rate than SST and sea level.

along with increasing wave impacts causing bluff (33) and beach erosion (34), and infrastructure damage (30). Approximately 65,000 coastal residents and $25 billion in property, including 700 km of roads, across California are at risk of flooding under present-day sea level and extreme storm conditions (35). The risk to California coastal communities from flooding could increase up to 80-fold over the 21st century depending on which sea-level rise trajectory is realized (35), with the higher projections from continued and substantial increases in greenhouse gas emissions and/or ice sheet instability (21, 27, 36). However, even curbing emissions immediately will likely result in ~2 m of sea-level rise eventually due to the momentum in the earth's systems (*SI Appendix*, Fig. S1, 37). Although many coastal communities are affluent and might absorb some costs related to sea-level rise and extreme events, disadvantaged or underserved communities with median household incomes of less than $60,000 can be found distributed all along the coast and may have fewer resources available to adapt to increased coastal risks (38).

As noted earlier, ocean temperatures have been increasing and have now reached record-high levels. Ocean temperature seasonal and interannual variability is common in California, but anomalously warm seawater events called Marine Heatwaves (MHWs) (39), which are based on ocean temperatures exceeding a fixed seasonally varying or cumulative threshold (40–42), do occur and have a compounding effect on increasing sea temperatures. MHWs are gaining attention as they can cause devastating impacts to marine biodiversity and ecosystems (e.g., refs. 39, 41, and 43. Laufkötter et al. (2020) state that the occurrence of most documented, large, and impactful MHWs is a result of anthropogenic climate change, which has increased more than 20-fold since preindustrial times (44). MHWs that occurred only once every hundreds to thousands of years in the preindustrial climate are projected to become decadal to centennial events under 1.5 °C warming conditions (i.e., above preindustrial baseline) and annual to decadal events under 3 °C warming conditions. MHWs have been documented off the coast of California over the last decade (Fig. 2), with incomplete understanding of their implications for marine life. MHWs are defined by their length and intensity relative to normal conditions, with the most recent events occurring in 2014 to 2016, 2018, and 2019, with recent research suggesting that they have become more frequent and extreme (Fig. 2). The 2018 MHW had the highest sea surface temperatures (SSTs) recorded in La Jolla, CA over the last 100 y (45). Anthropogenic warming accounted for an increase in the length (19 d) and cumulative intensity (by 56.8 °C) of the 2018 MHW, with reduced upwelling in the area (46). The MHW during 2014/15 likely caused wide-scale food web change and decline resulting in extensive seabird mortality (47).

Challenges of Compound Events and Adaptive Comanagement Approach

Direct impacts caused by individual climate drivers have been discussed; however, as noted, none of these operate in isolation but instead are connected and combine into extreme compounded events. The Fifth National Climate Assessment defines compound events as "events resulting from a combination of climate drivers or hazards.... that have greater impacts than isolated hazards on ecosystems and human systems" (52–54). Teasing apart gradual secular trends that are related to a warming climate from those resulting from natural variability is particularly challenging for the coast given its dynamic nature. Compound events and a changing climate are multifaceted and interconnected (55). Limited studies have been done to assess California coastal sustainability and understand these types of events. For example, the coastal effects of powerful winter storms in California have been well documented and may consist of high air temperatures, high wind speeds, extreme precipitation, elevated coastal water levels (e.g., due to river flooding, storm surge, and large waves), and MHWs (56–59). There is a range of perturbations from small-scale but frequent to large-scale and infrequent events, all of which will increase as the baseline of sea level and ocean warming continues to accelerate (27).

With this context, we suggest that extreme event impacts will be exacerbated by rising seas and warming ocean

Fig. 3. Coastal zone impacts from compounded events will result in a variety of geomorphic and biological impacts, observed examples include (*A*) cliff erosion; (*B*) storm waves near Santa Cruz; (*C*) flooded road in San Diego; (*D*) woody beach storm debris; (*E*) fish kill following an algal toxic bloom (photo credits: *A*–*C* and *E* USGS in public domain, *D* from G. MacDonald, UCLA).

conditions, which will increase the risk to California's coastal zone. We suggest that this will be the case even if these extreme events don't increase in frequency or magnitude, due to a nonstationary baseline of rising seas and ocean temperatures (Fig. 2). These compounded events will also operate within other ongoing human stressors in the coastal zone, possibly limiting the sustainability of these ecosystems. Such compounded combinations in coastal systems may result in rates of extirpation and extinction higher than terrestrial taxa (60).

We propose that there are potential solutions, and a great benefit from an adaptive comanagement approach to formulate climate-ready management strategies for the coastal zone of California (*SI Appendix*, Fig. S2). We highlight how compounded interactions can impair and impact a variety of coastal ecosystems and society and we examine how understanding these interactions can help shape decision-making to build holistic coastal sustainability approaches. Here, we define comanagement as a diverse set of stakeholders (across social, political, and ecological entities) working together to address sustainability concerns (*SI Appendix*, Fig. S2). In this perspective, we consider that there are two interlinked key threats to California's sustainability of the coastal zone; 1) sea-level rise and the compounding effects of storms, and 2) warming oceans and compounding effects of MHWs.

Sea-Level Rise and Surging Seas

People. Increasing sea levels and the frequency and intensity of storms, paired with degraded or stressed ecosystems, are exposing coastal areas to higher risks of damage and loss, which presents a complex problem for society (Fig. 3; 21). Sea-level rise brings water levels closer to flood stages and increases the frequency of nuisance flooding (21, 61, 62; Fig. 3) and destructive floods. The average flood losses for socioeconomic systems globally are projected to increase up to $52 billion by 2050, a ninefold increase over 2005 (63). For the annual storm with 1 m of sea-level rise, the intermediate projection by 2100 for California (Fig. 3; 27), over $90 billion in property and 235,000 California residents would be at risk of flooding along the coast, ~7 to 8 times more exposure than under present sea level conditions (30, 35). Landslides on the Big Sur coastline have caused prolonged road closure following storms, these long-term closures impact local tourist economies and cost millions of dollars to repair (61).

Habitats. Many coastal ecosystems are already stressed by modifications to the landscape, contaminants, and overall loss, with 90% of tidal wetlands lost in most estuaries in California (62). Sea-level rise will further exacerbate problems with more flooding, especially during storms, and additionally, ~50% of beaches are projected to be lost under a 1 m sea-level rise scenario, absent coastal management intervention (34). This beach loss is largely driven by coastal squeeze due to a lack of inland migration space, where beaches are drowning between rising seas and the resistant urban landscape. Limited inland migration space for wetlands has also been identified along the Pacific coast (64). Beach and dune wildlife species such as the western snowy plover (*Charadrius alexandrinus nivosus*) and other shorebirds that primarily nest on beaches and in foredunes have increased risk of flooding from sea-level rise and storms (65). In southern California, beach change from sea-level rise (changes in width and volume) and permanent inundation are projected to negatively alter beach access for recreation and expenditures, with an estimated value of $4 billion annually currently spent on beach recreation (66). For example, in a study of the Santa Barbara region, just 0.25 m of sea-level rise is projected to be a tipping point for the sustainability of sandy beach and tidal wetland ecosystems (67, 68). Thorne et al. (2018) project that numerous tidal wetlands across the state will be nearly, if not completely, eliminated by the end of the century under moderate and high sea-level rise scenarios (31). California giant kelp forest (*Macrocystis pyrifera*) and seagrass communities are an iconic feature of the coastline with important endangered species such as Southern sea otters (*Enhydra lutris nereis*) and red abalone (*Haliotis rufescens*). Sea-level rise will change the depth of these subtidal areas and will force kelp and seagrass communities to relocate to more shallow waters.

Many coastal ecosystems rely on sediment and sand supply to respond to rising sea levels, but supply is decreasing in many areas of California, putting ecosystem sustainability into question (69). Dams and debris basins have impounded sediment across the state, reducing sand supply rates to the coast by 23% compared to the natural state (15). In San Francisco Bay, where >90% of tidal wetlands were leveed or filled from the mid-19th century to the late 20th century (70), the existing tidal marshes would require an order of magnitude more sediment than is currently available to keep up with sea-level rise beyond 2100 (71, 72). In contrast, some coastal areas in California struggle with extensive sediment runoff during storms that result in decreased water quality and infilling of habitats (73). For example, in the Eel River, which is a key sediment source for northern California coastal areas, there is a possible increase of suspended sediment discharge of up to 99% by the end of the century due to increased precipitation and stream flows (74). Also, storm-related debris flows or landslides can affect rocky intertidal habitats; for example, in 2017, heavy rains caused a landslide along the Big Sur coastline that buried 1,500 m of designated critical habitat for the endangered black abalone (*Haliotis cracherodii*) (75), a species of intrinsic value to indigenous communities.

Mass Mortality Events and Tipping Points. Coastal ecosystems are highly productive but physically stressful environments, where small changes in flooding, inundation, salinity, temperature, and other abiotic factors can trigger abrupt change in structure and function (76). Changing abiotic processes such as flooding and inundation can lead to ecosystem transformations, such as conversion of tidal wetlands to open water (77), vegetation loss following tropical and extratropical extreme storm events (32), and cliff erosion and beach loss (78). For example, storm events can have substantial impacts on kelp, seagrass, and macroalgal communities, from changes in the relative abundance of species within a community to total habitat loss. Storms can cause widespread mortality in aquatic communities from physical damage and dislodgement and increases in turbidity (79). The presence of breaking waves and longshore variability in wave intensity has been found to affect kelp and seagrass perturbations (80). Kelp and seagrass need high recruitment of juveniles to recover following a severe storm; however, recovery may not be possible if the population is under continued stress from sea-level rise or warming ocean conditions. The combined stress of increasing sea levels and storm disturbance suggests that large-scale, low-frequency phenomena can threaten the sustainability of aquatic and terrestrial plant species and benthic and fish communities.

As dry lands become intertidal or subjected to storm flooding, new regulations and protection may come into place. An adaptive comanagement approach could improve decision-making to prepare for and respond to changes in flooding and inundation regimes (*SI Appendix*, Fig. S2). For example, tidal wetland restoration as a nature-based solution throughout California has been conducted and achieved multibenefits through comanagement. For example, through comanagement efforts (Fig. 2), former salt ponds have been restored in San Diego and San Francisco Bays to restore tidal wetland habitat (81, 82). Concerted efforts to protect and build coastal sustainability have shown promise and will be important for California. Specifically, an effort in north San Francisco Bay restored tidal waters to former diked farmland (Cullinan Ranch Restoration Project, https://www.fws.gov/refuge/san-pablo-bay). This was done in a comanagement framework with federal agencies (e.g., US Fish & Wildlife Service, US Army Corps of Engineers), state agencies (e.g., California Department of Fish and Game, California Department of Transportation), local government (e.g., City of Vallejo), and nongovernment organizations (e.g., Ducks Unlimited, https://www.ducks.org/). The project used locally sourced dredged material to build subsided elevations of the site as a nature-based solution to bolster sea-level rise resilience. It also restored tidal marsh habitats for protected wildlife species and provided flood protection for California Highway 37. In addition, it provided public access for hiking, kayaking, hunting, and fishing to local disadvantaged communities.

Based on our review above, we identified several potential solutions and management strategies to enhance sustainability considering sea-level rise and storm events include the following:

- Planning and implementing inland migration for ecosystems
- Actively implementing actions to resist ecosystem loss in place using nature-based solutions
- Developing novel approaches to sustain wildlife species
- Leverage efforts for coastal communities' preparedness and relocation to improve socially equitable outcomes

Ocean Warming and Marine Heat Waves

People. There is a growing recognition of the importance of ocean and marine ecosystems for California's communities and economy, but there are many "hidden" ecosystem service connections to people that may not be well recognized. Marine management involves recognizing and addressing interactions among different spatial and temporal scales across California within and among ecological and social systems, and communities interested in the health and stewardship of marine areas. For example, in 2015 it was reported that anglers spent approximately $156 million on saltwater recreational fishing in California's four national marine sanctuaries (83). There is a growing need to understand the individual and cumulative impacts of warming ocean conditions as well as MHW, defined as periods of anomalously warm water (warmer than the seasonal 90th percentile for five or more consecutive days) (41). Severe MHWs have socioeconomic impacts from loss of fisheries income, mass mortality of species, and tourism decline with an estimated economic loss of $800 million USD for a single MHW and over $3.1 billion USD in indirect losses (84).

Ocean Environment. Along the California coast SSTs are warming at a rate of close to 1 °C per century and will continue to warm over the coming decades (Fig. 2), consistent with the global ocean, with subtle spatial variations (21). Approximately 90% of the heat generated by greenhouse gas emissions and warming air temperatures is absorbed by the ocean and is stored at depth and hence mitigates warming of the atmosphere (21, 85). Large-scale ventilation processes routinely replenish this deep water with oxygen, but recent evidence from the California Current suggests that this ventilation is slowing (86). The consequences of this slowing process are 1) areas of very low oxygen are increasing, limiting the area occupied by aerobic organisms; and 2) additional CO_2 accumulates and increases ocean acidification.

In conjunction with the increasing mean water temperatures, the frequency and intensity of extreme temperature events have also been increasing because of climate change, and this trend is expected to persist (Fig. 2 and *SI Appendix*, Fig. S1, (87). A MHW in 2014 through 2016 (the "Blob") was the most extreme North Pacific MHW on record that occurred off the Pacific Coast, including California. The three major MHWs since 1990 cooccurred with the El Niño-Southern Oscillation ears of 1993, 1997, and 2015 (88). Increases in SST of several degrees Celsius are associated with significant changes in local climate, higher sea levels, increased storm activity, and decreases in marine productivity (89).

Species. The California coast is an upwelling environment driven by wind-generated currents that bring deep nutrient-rich water to the surface and changes related to SST increases are uncertain (90). Under normal conditions, cool ocean conditions and associated upwelling create favorable conditions for nutrient supply and complex food webs, supporting the productivity and growth rates of many species, including foraging species like marine mammals and salmon (91, 92). SST increases have been linked to rapid decline in zooplankton and krill abundance in California (93). Fur seal (*Arctocephalus townsendi*) pup production has also been tied to SST anomalies in the southern California Current (94).

A modeling study done by Oliver et al. (95) suggests that MHW's intensity and length are projected to significantly increase from climate change, which will have extensive impacts to ecosystems and species. About 30 species of fish, invertebrates, marine mammals, birds, and reptiles found in the California Current ecosystem are threatened or endangered (96). The potential disruptive impacts of major changes to California's Current and upwelling are largely unknown with respect to future climate variability; however, impacts could be widespread (90).

MHWs are prolonged periods of anomalously high SST; their location, movement, and duration directly affect ecological systems especially in the distribution of zooplankton and forage fish (41, 97). In central and southern California, 29 species were recorded to respond to MHWs over 5 y, which included range expansions, reappearances, and abundance increases (98). For example, seven species established new range records north of their previous known range—three crab species (*Achelous xantusii, Malacoplax californiensis*, and *Uca princeps*), two mollusks (*Aplysia vaccaria* and *Lobatus galeatus*), one urchin (*Arbacia stellata*), and one fish (*Alphestes immaculatus*) (98). In contrast, many seabirds and sea lions are tied to their breeding or nesting areas and are limited in their capacity to respond in changes of prey food (97). MHWs have exacerbated fishing and whale conflicts, emphasizing the potential benefits of adaptive management and policy interventions for sustainability of the fishery and whale species (99, 100). Harmful algal blooms in Monterey Bay have also been linked to MHWs (101). Additionally, a drastic decline in the subtidal predator the sunflower star (*Pycnopodia helianthoides*) and bull kelp forests coincided with MHWs (102).

Over 25 y ago, California passed the Marine Life Protection Act (103), which aims to protect marine natural heritage through a network of MPAs. California was the first state to establish a network of MPAs, designed to protect the diversity and abundance of marine life and habitats, and has 120 MPAs covering approximately 852 sq. miles (16% of all coastal waters) of the state's marine water. In addition, California is home to 4 of the 15 National Marine sanctuaries in the United States, with a proposal pending, the Chumash Heritage National Marine Sanctuary (https://chumashsanctuary.org/), which would be the area proposed by Indigenous people of California. It would encompass 15 miles of coastline and over 7,000 sq. miles of the ocean. It is uncertain whether MPAs could mitigate impacts from warming oceans and MHWs (104, 105). Although climate change was not considered when they were established, the use of MPAs as refugia could bolster the resilience and sustainability of species if climate change responses, such as warming oceans and MHWs, are considered in their design and placement in the future (106, 107). For example, MPAs may contribute to the long-term resilience of nearshore fish communities (108). Future MPAs could take advantage of temperature variation along coastlines that provide refugia for kelp forests (109).

Mass Mortality Events and Tipping Points. Water temperature is a central driver of metabolic processes, and therefore, a key driver of species and ecological responses. Warming SST can have notable ecosystem impacts, including, for example, a breakout of harmful algae whose toxins accumulate in higher trophic level species and can cause severe illness when consumed by humans (110–112). These toxins have led to substantial die-offs of marine mammals and coastal bird species in southern California (111, 113).

MHWs can expose marine life to conditions beyond their usual exposure. MHWs can reduce breeding success (114), cause trailing edge extirpations and habitat shifts or contractions (115), exacerbate infectious diseases (102), and benefit invasive species (116). One of the most dramatic impacts of MHWs was the change in marine organisms in California kelp forests following the Blob MHW event, which has persisted since this event (117). The Blob also had substantial effects on fish and fisheries (97), including an unexpected switch in the dominant California forage fish, from sardines to anchovies. Additionally, multiyear and multicolony reproductive failures for common murres (*Uria aalge*) were also observed

(118). During this event, the maximum SST reached 6.2 °C in California. The US government declared the Blob a Federal fisheries disaster and allocated $141 million in relief due to impacts on commercial and Indigenous fishery species such as crab, sardine, and salmon (119). Although range shifts are a commonly studied ecological responses to climate change, information is lacking for the coastal zone. Species may seek refuge at depth and latitudinally, but this remains greatly uncertain in California.

An adaptive comanagement approach could enhance California's capacity to implement climate-ready fisheries (120) to improve decision-making needed to prepare for and respond to impacts to ensure sustainability. Climate-ready fisheries strategies are those that seek to proactively mitigate, adapt, or respond to the impacts of climate change to reduce impacts and inform adaptive management frameworks (120–122). This can be done by optimizing the skills, technology, and resources available under the current governance system. We focus on the potential to improve information flow as a means to achieve climate-ready fisheries via adaptive comanagement but suggest that a greater level of partnership in the management process may be possible in the future after a period of formal experimentation and learning (123).

Based on our review above, we identified several potential solutions and management strategies to enhance sustainability considering warming oceans and heatwaves:

- Defining a common vision for ocean sustainability
- Establishing a monitoring network to detect and anticipate change
- Bolstering resilience with MPA expansion and modifications
- Developing climate-ready fisheries approaches

Challenges and Opportunities.

A survey documented that 69% of Californians think climate change has already begun and is impacting the state, and eight in ten say that climate change is one of their top concerns (124, 125). State and local leaders have acknowledged that climate justice and frontline community impacts are an important consideration in understanding climate vulnerability (126). Future risks to coastal ecosystems from climate change are projected to mirror the impacts already observed, especially from extreme compounded events, and the severity of these may escalate with cumulative greenhouse gas emissions (21). Climate change is likely to accelerate into the future, prompting further compounding effects with existing stressors, exacerbating challenges to sustainability (127). We have suggested that an adaptive comanagement approach could improve the development of management strategies for the coastal zone of California. Here, we focused on a select set of challenges that are critical to sustainability, and we offer some views on potential strategies to reduce climate risks to people and nature. However, we acknowledge that there is a wide range of climate impacts documented and that there are unknown changes we currently don't anticipate or understand.

The Coastal and Marine Zone is Connected, Complex, and Dynamic. The coastal and marine zones are influenced by natural variability in currents, waves, winds, and tides, which are constantly changing across a wide range of temporal cycles (e.g., daily, lunar, seasonal, interannual, decadal, etc.). These processes move sediment, nutrients, and marine organisms along and within the coastline and continental shelf (128). Also, land–sea interactions are present, including freshwater riverine inputs which alter temperature and salinity (129) and which also bring nutrients and sediments to the coast. These are subject to change over the coming decades from climate (76). Detection of perturbations from these natural variable patterns can be difficult to detect without an array of observations in the ocean and coastal zone. Observations can be collected by deployed sensors (27, 59), long-term monitoring of ecological communities and species (130) and citizen or community science observations (131). Also, ocean landscapes are linked, and therefore, changes to structure and function from climate change in one area will affect what happens elsewhere, such that acute erosion and sediment loss from one has major repercussions for sediment transport to nearby supratidal habitat (e.g., sand dunes). These interconnections and linkages are particularly important in the coastal zone because boundaries are permeable and flowing. The establishment of an extensive long-term monitoring program would inform nature-based solutions and bolster comanagement.

It's Difficult to Detect and Understand Change under the Water. The impacts of sea-level rise, storms, and more variable and extreme SSTs and MHWs will put marine life at risk, but the exact nature of the risk is uncertain for California. The primary reason for this uncertainty comes from the paucity of data—the ocean is a very difficult medium to observe and monitor. Great strides have been made in observing the physical environment, and improvements are being made in observing chemical properties (132–134). Observations of life in the sea, however, are currently hampered by the lack of autonomous systems capable of surveying the full tree of life, making understanding sustainability difficult (135). Remote sensing observations of surface chlorophyll (136), the only biological property observed routinely, are much shorter in duration and have more error, than those of SST. Similarly, trends in marine species are difficult to detect from the data available; the data are usually from fisheries landings and surveys, surveys of MPAs (137), and a myriad of other observing efforts (138) that are hampered by short records and poor temporal and spatial coverages (139). Technologies, such as environmental eDNA sampling (140), may increase our ability to detect climate-related species changes.

Coastal Management and Regulation Are Complicated. The California coast is a linked social–ecological system; therefore, to strive for sustainability within a changing climate, both aspects need to be considered in the decision-making framework (141). Policy and programmatic decisions are beginning to address the climate crisis, but there are challenges to working across jurisdictions and at the scale needed to bolster resilience quickly. A vast majority of Californians live along the coastline, with 58% of Californians saying the ocean and coast conditions are very important for the economy and their quality of life (125). We suggest here that many future scenarios predicted in the scientific literature are already upon us or are emerging quickly, and so the time for decision-making is imminent and could benefit from a widespread comanagement framework (*SI Appendix*, Fig. S2).

Approximately 16% of the state shoreline is armored (142), including 38% of the southern California shoreline (143). As storms change and sea level continues to rise, there will be growing pressure to armor the coast (144), given documented beach and bluff erosion (*SI Appendix*, Fig. S2, 155, 158) and more frequent flooding events (145). Sea walls and other gray infrastructure will "freeze" the coastline in place, having significant impacts to the sustainability of ecosystems due to restriction on habitat migration (i.e., coastal squeeze) while protecting human communities. Armoring can also amplify sea-level rise impacts in other areas, possibly having unintended consequences to adjacent communities (146–148). If shoreline protection is needed, nature-based solution elements (e.g., marshes, beaches, oyster reefs, eelgrass), including living shoreline projects, could enhance cobenefits to human communities and ecological sustainability, providing an alternative approach to hard structures.

There is a range of policy and legislative barriers in California to comanagement which can be often unclear to identify and can hinder progress. In Australia a review of legislative frameworks for coastal restoration found that there is a critical need for increased transparency and better integration in coastal policy to achieve their goals (149). California has similar challenges as policy, plans, and decisions are usually constrained by existing laws and policies. For example the McAteer-Petris Act of 1969 (150) is a key piece of legislation that prevented the indiscriminate filling of San Francisco Bay, but has become a barrier in recent years for testing sediment addition projects to existing tidal wetlands to build elevations relative to raising sea levels.

Conclusion

Climate change is rapidly altering the conditions within the coastal zone of California. Because of the ocean's vastness, the difficulty of observing changing conditions beneath its waters, and the inherent variability of the shoreline due to daily tides, storms, and natural variability over seasonal, annual, and decadal time scales, the changes that climate change is producing may not always be clear. While terrestrial phenomena such as heatwaves, drought, or wildfires often make the news and are well advertised, equivalent impactful ocean phenomena receive relatively little attention. Nonetheless, our coastal waters and shoreline environments are experiencing the effects of climate change and these impacts are accelerating (21). The warming of the oceans and rising sea level are exacerbating the impacts of episodic events such as MHWs and storms. Although we still have only partial knowledge of the interrelationships and potential cascading effects of these changes on coastal ecosystems and economies, the challenges posed to coastal system sustainability in California are clear. Sea-level rise and continued ocean warming are now baked-in to the 21st century by existing greenhouse gas concentrations (21), and future conditions will further deteriorate if emissions continue to increase or go unchecked. There are actions people can take to help mitigate and adapt to these challenges over the coming years. However, we suggest such actions will be most effective if they utilize a comanagement approach (see *SI Appendix* for more details) due to the complex and interlinked nature of coastal environments. The time to act to increase the understanding of, and begin instituting, adaptation measures to build coastal sustainability is limited. This perspective aims to benefit the California coastal zone by stimulating research and policy development that will underpin information on the prevention, mitigation, management, and conservation approaches for coastal sustainability. The ideas and information presented here are intended to help expand discussions to sharpen the focus on how to encourage sustainability of California's iconic coastal zone. We acknowledge that climate change impacts often seem to be an intractable problem, but if concerns are tackled across public, political, and scientific communities, there will be a greater likelihood of success. Climate change impacts on the coast present an imminent challenge to California, and an unprecedented whole-of-society response can meet this challenge, including the integration of research institutions, land use and urban planners, policy makers, and community-based groups to reach sustainability goals.

Data, Materials, and Software Availability. There are no data underlying this work.

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