Readying California Fisheries for Climate Change

A product of

The Climate Change and Fisheries Working Group and Ocean Science Trust

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About this Document

This document provides scientific guidance to the California Department of Fish and Wildlife (CDFW) regarding the potential impacts of climate change on California fisheries and recommendations for building resilience to buffer climatic forces. At CDFW's request, the California Ocean Protection Council (OPC) provided funding to the Ocean Science Trust (OST) to convene an OPC Science Advisory Team (OPC-SAT) Working Group with relevant ecological, social science, and governance expertise. This guidance was prepared by OST and the OPC-SAT Working Group in partnership with CDFW, in adherence with the requirements in the OPC Staff Recommendation: "California State Fisheries Management: Current Efforts and Future Needs." This project was developed for consideration by the California Department of Fish and Wildlife (CDFW) to help inform the state's process to amend the Marine Life Management Act (MLMA) Master Plan. Products from this project have been submitted to CDFW for review and may be integrated, in full or in part, into a draft Master Plan Amendment. In addition, given the broad potential ecological, social and economic impacts from climate change, we hope the document provides useful guidance for other government agencies and departments, funders, affected individuals and communities, and non-governmental organizations engaging in action on this issue. Additional information about the Master Plan amendment process, including key resources and opportunities for stakeholder engagement, is available at https://www.wildlife.ca.gov/Conservation/Marine/Master-Plan.

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CALIFORNIA OCEAN SCIENCE TRUST

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CCLME	California Current Large Marine Ecosystem
CDFW	California Department of Fish and Wildlife
CPUE	Catch per unit effort
EEZ	Exclusive Economic Zone
ENSO	El Niño Southern Oscillation
FGC	Fish and Game Commission
FMP	Fishery Management Plan
IPCC	Intergovernmental Panel on Climate Change
MLMA	Marine Life Management Act
MLPA	Marine Life Protection Act
MPA	Marine Protected Area
NMFS	National Marine Fisheries Service, aka NOAA fisheries
NOAA	National Oceanic and Atmospheric Administration
NPGO	North Pacific Gyre Oscillation
PFMC	Pacific Fishery Management Council
PDO	Pacific Decadal Oscillation
OPC	California Ocean Protection Council
OPC-SAT	California Ocean Protection Council Science Advisory Team
OST	California Ocean Science Trust
SST	Sea Surface Temperature

READYING CALIFORNIA FISHERIES FOR CLIMATE CHANGE

Executive Summary

Image credit: G. Bergsma

Key Messages

- *Climate change has linked ecological, social, and economic consequences for all fisheries in California.*
- *There are existing management strategies that can make fisheries more resilient.*
- *We are already seeing the effects of climate change and taking action in some fisheries. These approaches can be leveraged and built upon to improve fisheries management in California.*
- *Collaboration with fishing communities, Tribes and Native Communities, and others can support adaptive approaches.*

In California, the ocean supports a diversity of marine organisms and a vibrant fishing economy. However, increased greenhouse gases in the atmosphere are leading to a warmer ocean and more extreme climate variations. This has implications for the location and abundance of fish and invertebrates as well as the people who depend on these species for their livelihoods and wellbeing.

We have seen market squid moving farther north, loss of kelp beds in Northern California, and compromised shellfish populations - which are just some of the climate-related changes in California's oceans in recent years.

To provide guidance to all who are engaged today in building resilient fish stocks and fishing communities, we have identified four possible future scenarios along with the challenges they are likely to pose to ecological systems as well as to the fishermen and communities that depend on them. We then suggest seven adaptable and responsive management strategies to prepare for impacts and opportunities as the climate changes.

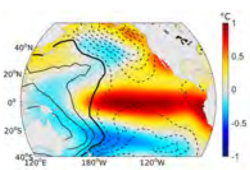
The California Current: A Naturally Variable System

The California Current experiences a great deal of natural variability occurring over inter-annual and -decadal timescales. Simply put, the system fluctuates between cool and warm phases. These phases

Many California fish and invertebrate stocks favor either warm or cool phases

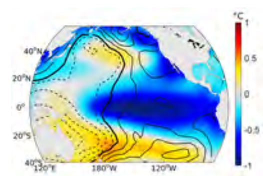
WARM PHASE

- Basses (kelp bass, barred sand bass, spotted sand bass)
- California halibut
- California sheephead
- California spiny lobster
- Kellet's whelk
- Pacific (chub) mackerel
- Pacific bonito
- Pacific sardine
- White seabass



COOL PHASE

- California market squid
- Chinook salmon
- Dungeness crab
- Geoduck clam
- Most groundfish
- Northern anchovy
- Ocean (pink) shrimp
- Pacific halibut
- Red abalone



drive recruitment, species composition and distribution, and overall production. In general, cool phases tend to be more productive and warm phases tend to be less productive, as more nutrients are available for phytoplankton growth in cool waters. Under warmer conditions, including those associated with El Niño events, it is largely warm water or subtropical species that thrive, including Pacific sardine, California spiny lobster, and California halibut. Under cool conditions many northern and transitional species, Dungeness crab, Pacific halibut, and anchovy are productive.

Climate Change: Extremes, Variability, Uncertainty

Historically these warm and cool phases have been fairly consistent. However, long-term temperature records indicate that the California Current is warming. In addition, there has been unusual variability in recent years (2014-2016), as occurred with the large patch of warm water along the West Coast known as "the Blob" followed by an El Niño. Climate change will likely lead to more extreme and variable environmental conditions. Predictions for climate change can be grouped into four scenarios.

Scenario 1 assumes no impact of climate change. Scenarios 2, 3, and 4 assume a long-term directional climate change (i.e., warming) affecting the oceanography and physical conditions of the CCLME:

1. Variability equivalent to that observed in the past ("Historical Variability")
2. Increases in the amplitude and changes to the period (or duration) of natural variations ("Increased Variability")
3. Poleward displacements as tropical waters expand over time ("Range Shifts")
4. Abrupt changes in the ecosystem as thresholds are crossed due to slow and steady or rapid changes in the biophysical and geochemical environment ("Crossing Thresholds")

These scenarios are not mutually exclusive but provide a way to understand the range of possibilities that could occur under climate change.

What is a fishery?

Fisheries are social-ecological systems, involving the physical environment, marine organisms, and the people who harvest, utilize, and make rules about managing these resources. This include not only fishermen (commercial, recreational, and subsistence) but also buyers, processors, wholesalers, retailers and consumers; support industries such as equipment, fuel and ice suppliers; families and community networks; and scientists, managers, administrators, and legislators.

How may California fisheries be impacted by climate change?

Climate change is already impacting California fisheries, affecting fish stocks and fishing communities. The physical changes associated with climate change (warming, ocean acidification, hypoxia, changes in circulation patterns, etc.) will continue to have both direct and indirect impacts on fish stocks. More extreme or variable environmental conditions are predicted to impact species' physiology, habitat availability, prey quality and abundance, species interactions, and/or other factors that influence population dynamics and sustainability of fish stocks. As a result, stock abundance and/or spatial distribution may increase or decrease, expand or contract, or simply become more variable. These changes will in-turn affect fishing communities.

Direct impacts on fishing communities include increased storms or sea level rise and associated damage to fishing infrastructure and businesses. Indirect impacts could include changes in the abundance and/or distribution of fished species and may lead to human responses such as changes in fishing practices, which in turn can affect shoreside support infrastructure, goods, and services.

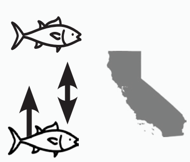
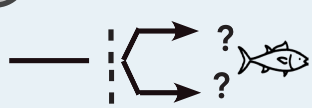
Fishing Communities and Climate Change

Fishery participants have adapted – both more and less successfully – to the range of historic variability and uncertainty in climate and weather in California, such as El Niño events, harmful algal blooms, and declines and increases in fish stocks due to sea surface temperature fluctuations. To do this, they have a variety of strategies, including intensification, substitution, diversification, pluralism, migration, and exit.

Climate change will likely lead to more extreme or altered variability or uncertainty; with certain responses being more prevalent in some scenarios than others. Fishermen's ability to adapt is shaped and constrained by regulatory, economic, social, and ecological factors.

Both NOAA and CDFW have developed a set of social vulnerability indicators for coastal communities to help bolster social resilience.

Table 1. Four Future Ecological Change Scenarios.

	SCENARIO	RESPONSES & IMPACTS	VULNERABILITY
NO IMPACT OF CLIMATE CHANGE	**1 Historical Variability**  Historical climate variability is characterized by fluctuations between warm and cool phases. Cool phases are generally more productive for some fisheries, while warm phases are more productive for others.	***Ecological Impacts*** Productivity of stocks fluctuates with warm (less productive) and cool (more productive) conditions. Species shift their range to 'follow' favorable environmental conditions. ***Potential Human Responses*** No change, increase effort, shift or diversify target species, follow the fish, increase non-fishing activity. ***Potential Social & Economic Implications*** Patterns of activity and associated costs and benefits shift as fishery participants adapt to opportunities or cope with loss; participants modify or expand social networks.	***Fish & Invertebrate Stocks*** Species that favor warm conditions include sardines, highly migratory species, and California spiny lobster. Those that favor cool conditions include Northern anchovy, Dungeness crab, Pacific halibut, and spot prawn. ***Fishing Communities*** Highly specialized and localized fisheries, those without the ability to adapt to new fishing opportunities, and/or those without integrated and diversified socioeconomic systems are more vulnerable.
DIRECTIONAL CLIMATE CHANGE	**2 Increased Variability**  Increased climate and oceanographic variability causes extreme and sometimes unpredictable environmental conditions (e.g., warming, ocean acidification, hypoxia, more extreme/frequent storms, erosion and flooding of coastal areas).	***Ecological Impacts*** Contraction and expansion of species' spatial distributions and variable fish production or possibly reduced fish production. ***Potential Human Responses*** All responses listed in historical variability plus leave fishing. ***Potential Social & Economic Implications*** Variable economic returns; higher costs (fuel, learning, shifting); disruption in fishery support and seafood distribution links; safety concerns due to volatile weather; social, cultural and economic stress; modified or expanded social networks; increased production may lead to economic gains in some sectors; enhanced fishery and community well-being.	***Fish & Invertebrate Stocks*** Highly specialized or localized species and calcifying organisms are more vulnerable. Long-lived species with built-in buffer to high variability are less vulnerable. ***Fishing Communities*** Highly specialized and localized fisheries, small-scale fishing operations, those with specialized gear, and communities dependent on a small number or narrow range of species are more vulnerable.
	3 Range Shifts  Long-term warming trends, more frequent warm phases, and fewer cool phases can lead to changes in acidity, temperature, and ocean circulation.	***Ecological Impacts*** Changes in quality and/or quantity of prey; range contraction and/or reduced production of species that favor cool-more productive conditions; range expansion of species that favor warm-less productive conditions; changes in species life histories due to warming (tropicalization). ***Potential Human Responses*** No change, shift or diversify target species, follow the fish. ***Potential Social & Economic Implications*** Higher costs (fuel, learning, shifting); disruption in fishery support and seafood distribution links; displacement of existing fishery participants; modified or expanded social networks; increases in fishing opportunity result in economic benefits.	***Fish & Invertebrate Stocks*** Populations near the poleward edge of their distribution and species that favor warm conditions are less vulnerable. Short-lived species are more vulnerable. ***Fishing Communities*** Small-scale fishing operations, those without access to permits, and those not in risk-sharing networks are more vulnerable.
	4 Crossing Thresholds  Slow and steady changes in ecosystem properties can result in dramatic, rapid, and step-wise shifts in species composition and food web productivity when a threshold in one or several of these properties is crossed. The properties may be either biotic or abiotic.	***Ecological Impacts*** A step-wise change in the CCLME may result in an extreme case of tropical- or subarctic-dominated systems or to a fundamentally different ecological state. These shifts are difficult to predict in terms of their timing, magnitude, and ecological state. ***Potential Human Responses*** No change, shift or diversify target species, increase non-fishing activity, leave fishing. ***Potential Social & Economic Implications*** Risk of economic disaster for fishing communities; potential for emerging fisheries; participants modify or expand social networks.	***Fish & Invertebrate Stocks*** Highly specialized or localized species are more vulnerable. Generalist species are better able to adapt to changes. ***Fishing Communities*** Communities with less livelihood diversity, smaller-scale fishing operations, or those that rely on a smaller range of fisheries are more vulnerable.

MANAGEMENT APPROACHES

1. **Manage for ecological resilience**
   - Reduce compounding stressors
   - Apply the precautionary principle in stock management
   - Manage for population structure
   - Evaluate the vulnerability of fish stocks
   - Expand climate and fisheries research
   - Protect nursery grounds and/or essential fish habitat
2. **Manage for social resilience**
   - Adopt flexible permitting mechanisms
   - Promote collaborative planning and research among fishermen, managers, and partners
   - Work with fishing communities to plan for unexpected changes
   - Evaluate vulnerability of fishing communities
3. **Increase management adaptability**
   - Incorporate adaptable catch control rules
   - Account for climate change in stock assessments
   - Move single-species conservation area boundaries when needed
   - Change seasonal closures when needed
   - Incorporate changes in indicators/ecological factors into management
4. **Support fisheries transitions**
   - Manage for human well-being
   - Prepare for emerging fisheries
   - Establish a new permitting program/policy to change access to expanded or emerging fisheries
   - Plan for tipping points
5. **Strengthen monitoring and forecasting**
   - Increase collection of effort information
   - Identify critical biophysical, social and ecological indicators to monitor
   - Expand monitoring to inform both MLMA and MLPA objectives
   - Streamline monitoring programs
   - Inventory ecological hotspots
   - Support regional climate change impact projection projects
   - Implement co-monitoring
6. **Expand cross-boundary coordination**
   - Increase interagency coordination
   - Expand transboundary fisheries management
   - Expand meaningful engagement with Tribes and Native Communities
7. **Increase research and management capacity**
   - Identify and address personnel and funding needs
   - Expand training and other capacity-building opportunities for fisheries professionals

Flexible, Responsive, & Adaptive Fisheries Management

To some extent, existing management approaches and tools have allowed communities to adapt to the high degree of variability in the California Current. Yet they may need to be modified to address predicted extremes in weather and climate. Managers must be able to anticipate and respond to current and future changes to help communities adapt to variability. This includes adopting flexible, responsive, and adaptable management approaches that could make the system more resilient to changes that may occur under any scenario.

Based on a review of recent literature from around the nation, the working group generated seven management strategies and associated implementation approaches and actions, which managers can use to prepare and respond to climate change. Some of these approaches require actions that are outside of CDFW's jurisdiction, and therefore will require efforts by other entities to be implemented. In addition, to ensure fishermen and communities are better able to adapt to change, they must be involved in collaborative decision-making regarding changes to fishery management regimes and strategies. These strategies are listed in the Management Apporaches Box to the left. In some cases, such as the market squid fishery, range shifts require management approaches that can help vulnerable human communities adapt. In other cases, such as the California sardine fishery, management measures will protect fish stocks from reaching dangerously low levels under changing ocean conditions.

Expanding and maintaining partnerships with stakeholders, academia, other government agencies, and fishing communities that directly address agency needs is critical to improving data and capacity for management.

Adaptive Fisheries Management Framework

(Governance practices apply throughout)

Legend for Management Approaches Box:

- Plan & Research
- Act
- Governance Practices

Some fisheries are already adopting flexible, adaptable management strategies as they experience the effects of a changing climate

*What they are doing can be leveraged and/or applied to other fisheries to improve management throughout the State.**

» *Harmful algal blooms and whale entanglements*

In 2015 and 2016, California's Dungeness and rock crab fisheries experienced unprecedented impacts when a harmful algal bloom prompted closures to protect public health. The closures delayed the season statewide and caused financial and social impacts on fishing communities. The warmer ocean conditions associated with the 2014-15 climate event also compressed prey species closer to shore, attracting whales to areas where they were more susceptible to entanglement with fishing gear. Climate change may increase the frequency of harmful algal blooms, highlighting the need to better understand these events and prepare for their impacts.

» *New fishing opportunities*

Preparing fisheries governance for climate-related changes means preparing not only for negative impacts, but also for new opportunities that may arise – such as emerging or expanded fisheries. Generalist species, such as lingcod, that are physiologically tolerant to variable or extreme conditions or are able to capitalize on a wide variety of prey, may increase in abundance. These species may become emerging fisheries. We are already seeing examples of expanded fisheries in California, for example in 2014, squid became abundant north of the fishery's typical range and a small number of permittees and associated buyers briefly shifted their efforts into this area, with squid trucked south to processing facilities. The ability to access these opportunities will depend on how large they are as well as the adaptive capacity of fishing communities. Flexible permitting is one management approach that can help fishermen access these new opportunities.

» *Accounting for environmental variability*

The commercial fishery for Pacific sardines is one of two in California for which management accounts for environmental variability by incorporating a climate indicator into its harvest control rule. Because this species responds to warm and cool phases, temperature serves as a valuable indicator of the stock's status and thus helps to support determination of sustainable harvest levels. The expanded use of climate indicators to provide more comprehensive information in the management of other stocks could decrease the likelihood of a collapse (such as that which occurred in the 1950s) when conditions are unfavorable while supporting an active fishery when conditions are favorable. This report outlines a range of strategies to account for environmental variability in fisheries management.

See case studies in the report for more information.

Key References

1. Chavez, F. P.*, Costello, C.*, Aseltine-Neilson, D., Doremus, H., Field, J. C., Gaines, S. D., Hall-Arber, M., Mantua, N. J., McCovey, B., Pomeroy, C., Sievanen, L., Sydeman, W., and Wheeler, S. A. (California Ocean Protection Council Science Advisory Team Working Group). 2017. Readying California Fisheries for Climate Change. California Ocean Science Trust, Oakland, California, USA.

   The report linked to this executive summary. Guidance to California fisheries managers on potential impacts of climate change on fisheries (state-managed fish and invertebrate stocks and associated fishing communities) and management approaches to prepare for these changes.

2. Pinsky, M. L., and N. J. Mantua. 2014. Emerging adaptation approaches for climate-ready fisheries management. Oceanography 27:147-159.

   Presents eight approaches that fisheries managers can use to potentially reduce the impact of climate change on people and ecosystems

3. Sydeman, W. J., and S. A. Thompson. 2013. Potential impacts of climate change on California's fish and fisheries. Farallon Institute.

   Report that synthesizes impacts of climate change on fish stocks and marine ecosystems in California

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Chapter 1. Introduction

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California fisheries are at risk from a variety of forces including a changing climate. Increased greenhouse gases in the atmosphere are leading to unprecedented changes in ocean temperature, acidity, oxygen levels, ocean circulation, sea level, and the frequency and magnitude of extreme events (Sydeman and Thompson 2013, Pinsky and Mantua 2014). The consequences of these changes for marine fish and invertebrates are already being observed in changes in species' metabolic stress (Somero et al. 2016), abundance, and distribution (Parmesan 2006, Sydeman and Thompson 2013), as well as fundamental changes to ecosystem integrity (Williams and Jackson 2007). In turn, fishing communities dependent on these species are being affected (e.g., changes in resource availability and landings, damage to shoreside infrastructure, etc.) (Hamilton and Butler 2001, Pinsky and Fogarty 2012).

Despite these observations, many questions remain about how California fisheries will be affected by climate change and how they can adapt. This report focuses on addressing the following key questions:

1. **What social-ecological changes to fisheries might we expect with a changing climate?**
   We present four future ecological change scenarios, with associated impacts to fishing and ecological communities.
2. **What changes to California's fisheries management would contribute to more resilient, prosperous, and adaptive fisheries, under current climate conditions (i.e., even in the absence of climate change)?**
   There are strategies and approaches that can help fishing communities and fish and invertebrate stocks adapt to existing climate variability.
3. **What additional changes to California fisheries management would help ensure effective adaptation to anticipated future climate change?**
   Proactive changes to fisheries management could help ensure stocks and fishing communities are prepared for and responsive to climate change.

In addressing these questions, we define fisheries as integrated social-ecological systems composed of three dynamic and interacting elements: an ecological subsystem (including fished species and habitat), a social subsystem (people, practices, and relationships), and a governance subsystem (the norms, strategies, and rules that guide fishing behavior). In this view of fisheries, changes in any of these subsystems affect one another and the system itself, with ecological and social outcomes that are of interest to decision-makers (Field and Francis 2006, Ostrom 2009, McCay 2012).

Setting the scene

Commercial, recreational, and tribal fishermen harvest more than 350 species of fish and invertebrates and 25 species of kelp and other marine algae from marine ecosystems in California (Leet et al. 2001, Allen et al. 2006). Fisheries exist in almost every marine ecosystem, from intertidal beaches to the upper regions of the continental slope (Bjorkstedt et al. 2015). In 2012, approximately 1,900 commercial fishing vessels landed catch at 34 California ports and several smaller landings, with about 480 dealers buying and distributing the catch (Culver and Pomeroy n.d.). Recreational fisheries, which include charter boat, private boat, and shore-based activity, account for a small fraction of total landings (by weight) overall, but account for the majority of landings of some species, including lingcod (*Ophiodon elongatus*), bocaccio (*S. paucispinus*), and blue rockfish (*S. mystinus*) (Bjorkstedt et al. 2015). In 2011, 1.5 million recreational marine anglers took at least 6.1 million trips and supported approximately 7,700 jobs (NMFS 2012). Tribes and

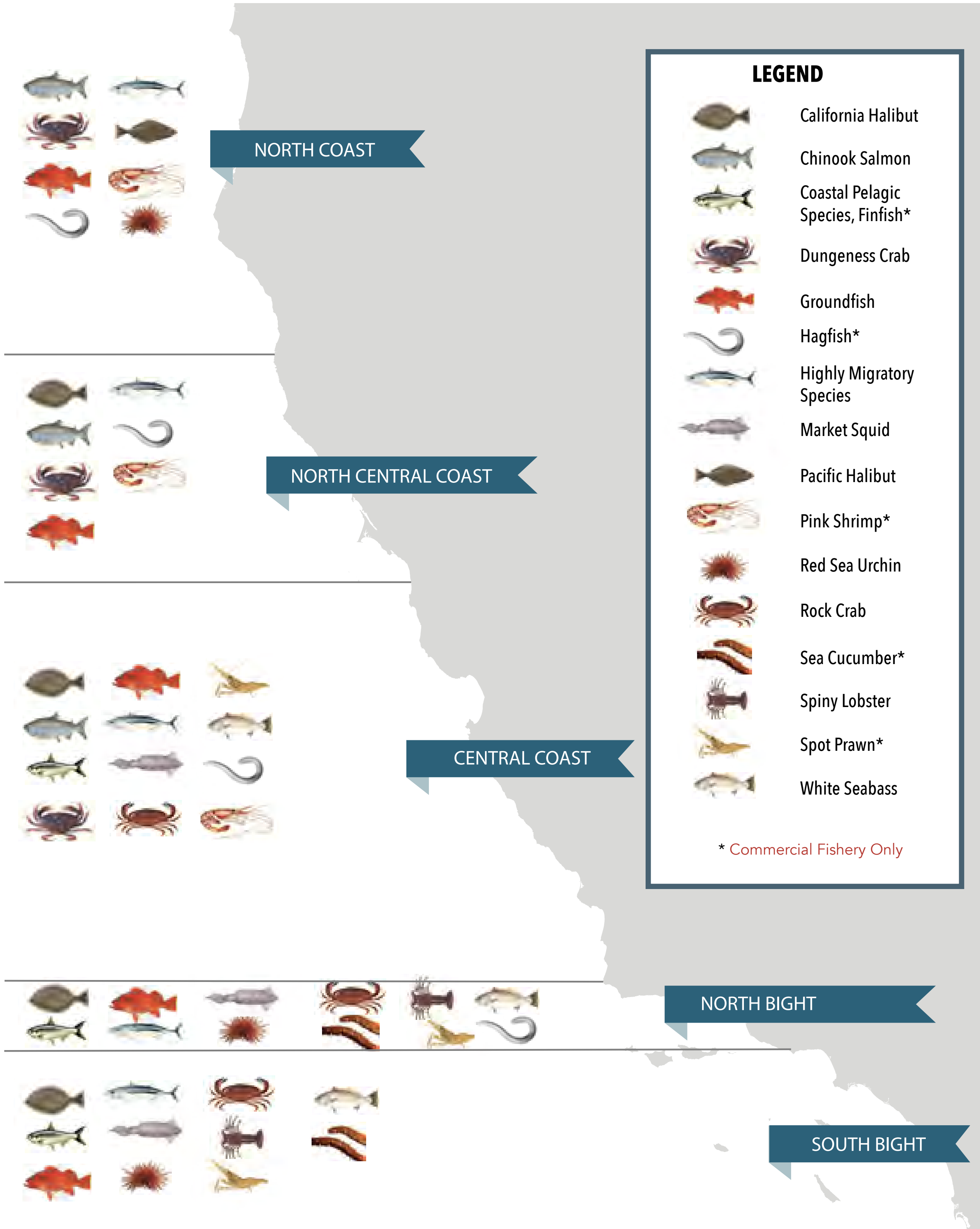


Figure 1. The most common commercially- and recreationally-caught species in each of California's five coastal regions. The North Bight and South Bight comprise the "Southern California Bight." Highly Migratory Species (HMS) include tunas, sharks, billfish/swordfish, and dorado. Coastal Pelagic Species (CPS) include sardine, anchovy, and mackerel. Groundfish is comprised of flatfish, roundfish, and rockfish species. The mix of fisheries in each region of the state has implications for the impacts of and adaptation to climate change. Changes in one fishery can affect other fisheries locally, regionally, and statewide. For example, if one species becomes scarce, fishermen may shift to another, with implications not only for the fished species but also for the human and ecological systems that support and depend upon both fisheries.

Native Communities harvest a variety of fish, invertebrate, kelp and marine algae species along the California coast for long-standing cultural and subsistence, as well as commercial, purposes. The particular mix of species varies among tribes (and regions), but some commonly harvested groups include salmon, algae, rockfish, lingcod, and bivalves.

Fishing communities also differ along the California Coast. For example, high-volume, low price-per-pound commercial fisheries for coastal pelagic species are particularly active in Southern California, though this region also includes low-volume landings like red sea urchin. While less seafood is landed in the North and North Central coast regions, fisheries there include higher price-per-pound species such as Dungeness crab and Chinook salmon (Figure 1). Recreational fisheries are much larger in southern California than in the north (Bjorkstedt et al. 2015). The coastal communities associated with these fisheries vary in their engagement in and dependence on fisheries for social, cultural, and economic well-being, the particular configurations of infrastructure, goods, and services they provide; and the social and economic relationships that bind them to one another and their larger sociocultural and economic context.

Fisheries management in California

The Marine Life Management Act (MLMA), which became effective in 1999, directs CDFW and the California Fish and Game Commission (FGC) to manage state fisheries sustainably "to assure the long-term economic, recreational, ecological, cultural, and social benefits of these fisheries and the marine habitats on which they depend." To help achieve its goals, the MLMA calls for the development of a Master Plan. The Master Plan is intended to help focus management efforts on the highest priority fisheries and to describe specific tools and approaches to be applied in achieving the MLMA's goals. Fishery Management Plans (FMPs) represent the main vehicle for managing fisheries; required FMP components are provided within the MLMA itself, while the specifics on the process for developing and implementing these FMPs are contained within the Master Plan. The existing MLMA Master Plan was adopted in 2001. CDFW is amending the plan to incorporate tools and approaches developed since that time that have the potential to significantly improve fisheries governance and management outcomes. This report is intended to inform that amendment process.

A number of management tools and measures are available to the State for managing its fisheries. These include: harvest control rules; restricted access/limited entry programs; regional management; in-season management with the ability to close fisheries when harvest limits are met; conservation areas (closures to protect one or a few species); MPAs; gear restrictions; and experimental fishing permits. All of these tools are, to some extent, used to manage one or more fisheries at the state or federal level. FGC policies are available for both restricted access and experimental fishing permits, and a network of MPAs is now in place along the entire coast of California. The State has also experimented with a small number of novel data and management tools and measures that leverage fishermen, NGOs, and other stakeholders to help collect data, provide other information, and engage in limited co-management activities.

Considerations of climate variability and change do not figure prominently in the traditional fisheries science that guides management in the United States (Keyl and Wolff 2008, Pinsky and Mantua 2014). Environmental indicators are not incorporated consistently into population models, although most United States fisheries are managed based on either constant mortality rates or threshold harvest control rules (e.g., sloping control rules that are bounded by thresholds). Threshold harvest control rules are a mechanism that can be inherently responsive or adaptive to variability. The only fisheries in California where management has explicitly accounted for environmental variability are the commercial drift gill net fishery for swordfish (NOAA 2007) and the commercial fishery for sardine (Pinsky and Mantua 2014). For most fisheries, climate variability is recognized to be a key factor in variable recruitment and population growth and distribution. However, due to a lack of strong predictive power and mechanistic understanding of the relationship between climate and managed species' productivity, such factors typically can only be explained or quantified retroactively, and can rarely be accounted for or reliably predicted in population or assessment models (DeOliveira and Butterworth 2005, Mohn and Chouinard 2007, Punt et al. 2013).

Additionally, Tribes and Native Communities in California have a long and diverse history of marine resource use and management and have adapted to variability over time. However, little is known about how climate change may impact their cultural, subsistence, and commercial practices. In this document, we primarily address how climate change may affect state-managed fisheries; however, moving forward it will be essential to work closely with Tribes and Native Communities to understand and address these effects.

Climate Change in a Fisheries Context: Adaptation and Vulnerability

We present a framework for considering the impacts of climate change on California fisheries by identifying the vulnerabilities to climate change among fishes, invertebrates, and fishing communities, and how fisheries management may reduce or exacerbate negative impacts and enhance or preclude positive impacts (Figure 2). This framework adopts the approach of focusing on both vulnerability and adaptation to climate change (e.g., Smit and Wandel 2006, Parry et al. 2007). Consistent with the IPCC, we define vulnerability as "the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change" (Parry et al. 2007). It is a function of four elements: exposure, sensitivity, impacts, and human and ecological responses (influenced by their adaptive capacity).

In a fisheries context, exposure is the magnitude and extent of the physical effects of climate change on the human and ecological components of fisheries. Sensitivity is the degree to which human components (fishery participants/communities) and ecological components (fished species) are affected by climate change (e.g., dependence on affected species for the former, magnitude of effects on abundance, distribution, or phenology (Pecl et al. 2014 for the latter)). Exposure and sensitivity influence the type, magnitude, and the potential extent of impacts, as do potential and human or ecological responses. Adaptive capacity is "the ability or potential of a system to respond successfully to climate variability and change, and includes adjustments both in behavior and in resources and technologies" (Parry et al. 2007). It enables potential negative impacts to be offset (e.g., Allison et al. 2009). We focus on human and ecological responses to climate change, but recognize the need for future work.

Climate change may have both direct and indirect effects on marine fish stocks (Parmesan 2006, Sydeman and Thompson 2013). Similarly, some climate change impacts on fishing communities will be direct – such as increased storms or sea level rise (and associated damage to fishing infrastructure and businesses), with implications for how humans interact with the environment. In addition, indirect impacts such as changes in the abundance and/or distribution of fished species may lead to human responses such as changes in fishing opportunities and practices, which in turn can affect economic costs, as well as shoreside support infrastructure, goods and services.

A wide range of stakeholders that comprise "fishing communities" are potentially vulnerable to climate change impacts. In this document, we use the definition of fishing community from the Magnuson-Stevens Act, "a community which is substantially dependent or substantially engaged in the harvest or processing of fishery resources to meet social and economic needs, and includes fishing vessel owners, operators, and crew, and United States fish processors that are based in such a community" (50 C.F.R. ß 600.345(3)). Included in this definition are commercial, recreational, and subsistence fishermen and their families, both tribal and non-tribal; charter boat operators, recreational outfitting, and marinas; receivers (e.g., buyers, processors, wholesalers and retailers), harbors, providers of support goods and services (e.g., fuel, ice, bait, repair and maintenance, groceries); aquaculturists, and consumers, as well as the places where each of these stakeholder groups lives and works.

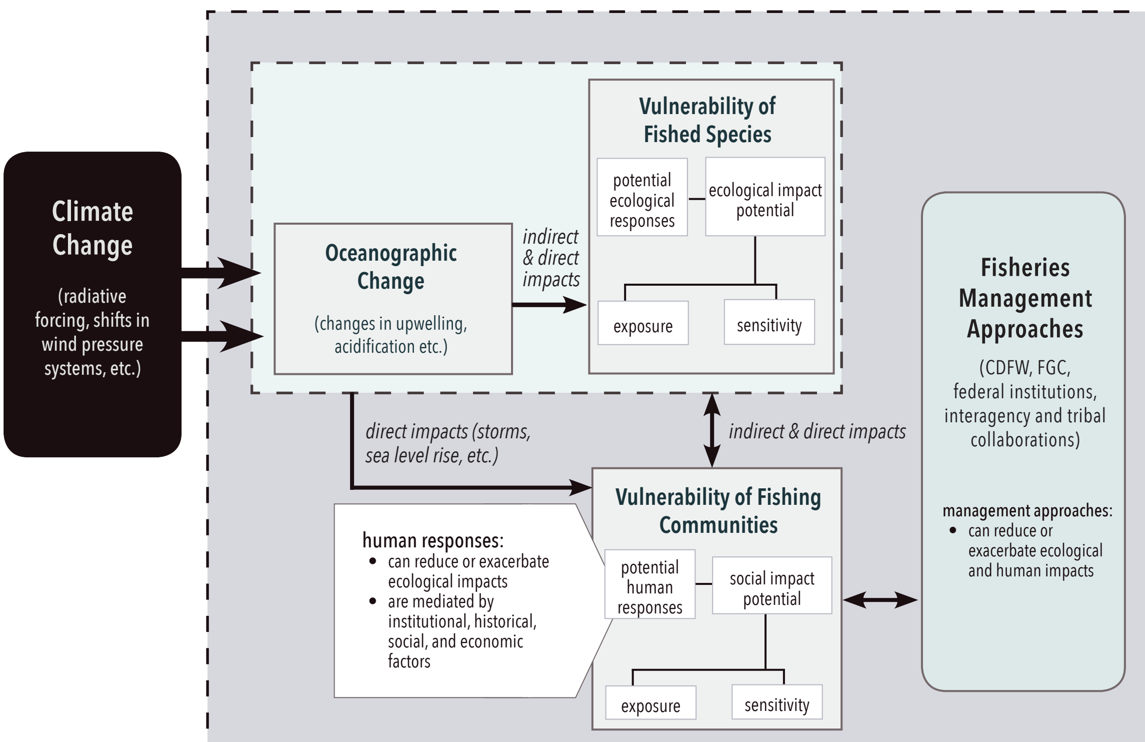


Figure 2. Framework for considering the vulnerability of a fishery as a social-ecological system in the context of climate change.

Chapter 2. Future Ecological Change Scenarios for the CCLME

Image credit: A. T. Nissinen

California's state-managed marine and estuarine waters and living marine resources are part of the much larger California Current Large Marine Ecosystem (CCLME), which is characterized by substantial natural environmental variability (Figures 4 and 5, Appendix B). This natural variability provides a dynamic backdrop to the anticipated changes associated with anthropogenic climate change.

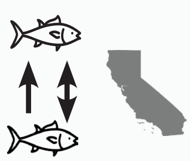
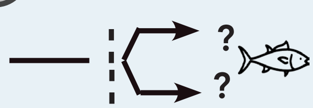
Climate change will affect the dynamics of the CCLME, however, limitations of global and regional climate models make it difficult to provide specific projections of future changes, particularly in coastal environments (Stock et al. 2011). Despite these challenges, we believe sufficient knowledge and information exist to identify climate-related ecological change scenarios for fisheries in the CCLME. We define an "ecological change scenario" as a plausible future situation of the CCLME that has indirect or direct impacts on fish stocks and fisheries (Figure 3; adapted from IPCC 2013).

We describe four potential ecological change scenarios (Table 1). Scenario 1 assumes no impact of climate change. Scenarios 2, 3, and 4 assume a long-term directional climate change (i.e., warming) affecting the oceanography and physical conditions of the CCLME:

1. Variability equivalent to that observed in the past ("Historical Variability")
2. Increases in the amplitude and changes to the period (or duration) of natural variations ("Increased Variability") (Di Lorenzo and Mantua, 2016)
3. Poleward displacements as tropical waters expand over time ("Range Shifts")
4. Abrupt changes in the ecosystem as thresholds are crossed due to slow and steady or rapid changes in the biophysical and geochemical environment ("Crossing Thresholds")

The proposed scenarios are not forecasts; rather, each scenario provides an alternative depiction of future fish stock abundance, behavior and distribution, and the implications for fishery participants and associated fishing communities. The scenarios are not mutually exclusive, although some scenarios may be more relevant to some fisheries and/or communities than others. We also describe potential impacts (both negative and positive) on fishery participants, their potential responses, and implications for fishing communities. Finally, we identify and discuss management approaches that may reduce negative impacts, with a focus on state-managed species.

Table 1. Four Future Ecological Change Scenarios.

	SCENARIO	RESPONSES & IMPACTS	VULNERABILITY
NO IMPACT OF CLIMATE CHANGE	**1 Historical Variability**  Historical climate variability is characterized by fluctuations between warm and cool phases. Cool phases are generally more productive for some fisheries, while warm phases are more productive for others.	***Ecological Impacts*** Productivity of stocks fluctuates with warm (less productive) and cool (more productive) conditions. Species shift their range to 'follow' favorable environmental conditions. ***Potential Human Responses*** No change, increase effort, shift or diversify target species, follow the fish, increase non-fishing activity. ***Potential Social & Economic Implications*** Patterns of activity and associated costs and benefits shift as fishery participants adapt to opportunities or cope with loss; participants modify or expand social networks.	***Fish & Invertebrate Stocks*** Species that favor warm conditions include sardines, highly migratory species, and California spiny lobster. Those that favor cool conditions include Northern anchovy, Dungeness crab, Pacific halibut, and spot prawn. ***Fishing Communities*** Highly specialized and localized fisheries, those without the ability to adapt to new fishing opportunities, and/or those without integrated and diversified socioeconomic systems are more vulnerable.
DIRECTIONAL CLIMATE CHANGE	**2 Increased Variability**  Increased climate and oceanographic variability causes extreme and sometimes unpredictable environmental conditions (e.g., warming, ocean acidification, hypoxia, more extreme/frequent storms, erosion and flooding of coastal areas).	***Ecological Impacts*** Contraction and expansion of species' spatial distributions and variable fish production or possibly reduced fish production ***Potential Human Responses*** All responses listed in historical variability plus leave fishing. ***Potential Social & Economic Implications*** Variable economic returns; higher costs (fuel, learning, shifting); disruption in fishery support and seafood distribution links; safety concerns due to volatile weather; social, cultural and economic stress; modified or expanded social networks; increased production may lead to economic gains in some sectors; enhanced fishery and community well-being.	***Fish & Invertebrate Stocks*** Highly specialized or localized species and calcifying organisms are more vulnerable. Long-lived species with built-in buffer to high variability are less vulnerable. ***Fishing Communities*** Highly specialized and localized fisheries, small-scale fishing operations, those with specialized gear, and communities dependent on a small number or narrow range of species are more vulnerable.
	3 Range Shifts  Long-term warming trends, more frequent warm phases, and fewer cool phases can lead to changes in acidity, temperature, and ocean circulation.	***Ecological Impacts*** Changes in quality and/or quantity of prey; range contraction and/or reduced production of species that favor cool-more productive conditions; range expansion of species that favor warm-less productive conditions; changes in species life histories due to warming (tropicalization). ***Potential Human Responses*** No change, shift or diversify target species, follow the fish. ***Potential Social & Economic Implications*** Higher costs (fuel, learning, shifting); disruption in fishery support and seafood distribution links; displacement of existing fishery participants; modified or expanded social networks; increases in fishing opportunity result in economic benefits.	***Fish & Invertebrate Stocks*** Populations near the poleward edge of their distribution and species that favor warm conditions are less vulnerable. Short-lived species are more vulnerable. ***Fishing Communities*** Small-scale fishing operations, those without access to permits, and those not in risk-sharing networks are more vulnerable.
	4 Crossing Thresholds  Slow and steady changes in ecosystem properties can result in dramatic, rapid, and step-wise shifts in species composition and food web productivity when a threshold in one or several of these properties is crossed. The properties may be either biotic or abiotic.	***Ecological Impacts*** A step-wise change in the CCLME may result in an extreme case of tropical- or subarctic-dominated systems or to a fundamentally different ecological state. These shifts are difficult to predict in terms of their timing, magnitude, and ecological state. ***Potential Human Responses*** No change, shift or diversify target species, increase non-fishing activity, leave fishing. ***Potential Social & Economic Implications*** Risk of economic disaster for fishing communities; potential for emerging fisheries; participants modify or expand social networks.	***Fish & Invertebrate Stocks*** Highly specialized or localized species are more vulnerable. Generalist species are better able to adapt to changes. ***Fishing Communities*** Communities with less livelihood diversity, smaller-scale fishing operations, or those that rely on a smaller range of fisheries are more vulnerable.

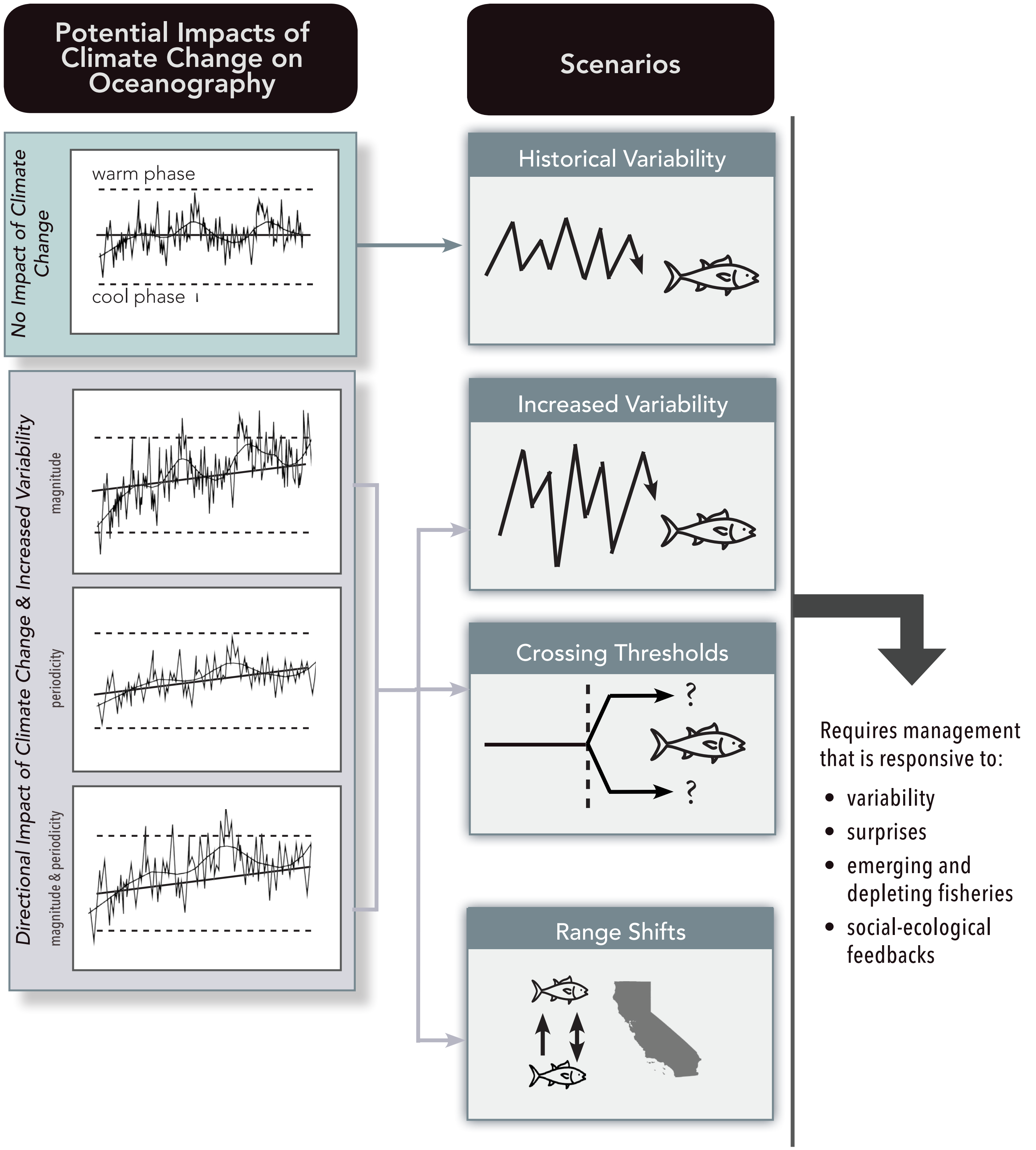


Figure 3. Potential Impacts of climate change on the oceanography of the CCLME and resulting ecological change scenarios. Solid black lines are theoretical representations of oceanographic indicators, such as temperature or the Multivariate Ocean Climate Index, that fluctuate between warm-less productive and cool-more productive states. Dashed lines indicate the range of historic oceanographic variability; for context, these lines are displayed in each of the Potential Impacts of Climate Change on Oceanography. Arrows connecting the Potential Impacts of Climate Change on Oceanography to Ecological Change Scenarios indicate which scenarios may result from a given impact. Scenarios are not mutually exclusive.

Scenario 1: Historical Variability

Historical variability in atmospheric and oceanographic forcing in the CCLME, occurring over seasonal, interannual, and multidecadal timescales (Baumgartner et al. 1992, Mantua et al. 1997, Checkley and Barth 2009) has driven substantial variability in recruitment, fish production, and fish distributions over comparable timescales (MacCall 1996, Chavez et al. 2003, King et al. 2011, García-Reyes et al. 2015, MacCall et al. 2016). This inherent variability fluctuates along a continuum between ecological endpoints (or regimes) that differ in their environmental conditions, species composition and distribution, and overall food web productivity (Hare and Mantua 2000, Chavez et al. 2003). For simplicity, these endpoints can be considered as "warm-less productive" or "cool-more productive" regimes (Figure 4). While most species favor either warm or cool phases (Table 2), there are exceptions to this rule. As such, there are (and will be) different sets of "winners and losers" among California fisheries under warm versus cold conditions.

Many fishery species exhibit a broad range of life history strategies and respond to variable environmental conditions in diverse ways (e.g., recruitment). Although the magnitude of such variability and the nature of the precise response vary tremendously by taxa, and each taxa responds to a unique set of environmental conditions (as well as within-population density dependent processes), some broad generalities have been identified. For example, under cool conditions (associated with a mix of greater advection of subarctic water, cooler ocean temperatures, and/or stronger upwelling), many northern and transitional species – including market squid, Dungeness crab, Pacific ocean (pink) shrimp, northern anchovy, Chinook salmon, and most groundfish – are particularly productive (Hannah 2010, Koslow and Allen 2011, Shanks 2013, Stachura et al. 2014, Ralston et al. 2015) (Table 2). Under warmer conditions, including those associated with El Niño events, it is largely warm water or subtropical species that thrive, including Pacific sardine, spiny lobster, and California halibut (Jacobson and MacCall 1995, Lindegren et al. 2013, Koslow et al. 2012) (Table 2).

For relatively short-lived species (with maximum lifespans of 1-2 years), such as market squid and Pacific ocean (pink) shrimp, variable temperatures often translate directly into high volatility in abundance and, in turn, highly variable availability to both predators and fisheries. On the other extreme, despite the fact that many groundfish and rockfish exhibit year-to-year recruitment variability of several orders of magnitude, their longevity typically leads to relatively modest year-to-year shifts in total population abundance and availability to fisheries.

Favored phase	Selected CA fish and invertebrate stocks
warm	• basses (kelp bass, barred sand bass, spotted sand bass) (Jarvis et al. 2014) • California halibut (Allen 1990) • California sheephead (Lenarz et al. 1995) • California spiny lobster (Koslow et al. 2015) • kellet's whelk (Zacherl et al. 2003) • Pacific (chub) mackerel (Parrish 1978) • Pacific bonito (Radovich 1961) • Pacific sardine (Jacobson and MacCall 1995) Lindegren and Checkley 2013) • white seabass (Williams et al. 2007)
cool	• California market squid (Koslow and Allen 2011) • Chinook salmon (Mantua et al. 1997, Lindley et al. 2009, Wells et al. 2016) • dungeness crab (Shanks 2013) • geoduck clam (Zhang and Hand 2006) • most groundfish (flatfish, rockfish, roundfish) (Ralston et al. 2013, Stachura et al. 2014) • Northern anchovy (Lindegren et al. 2013) • Pacific ocean (pink) shrimp (Hannah 2010) • Pacific halibut (Clark et al. 1999) • red abalone (Vilchis et al. 2005)
unknown, limited data, or large group where not all members favor the same regime	barred surfperch, bay shrimp, California corbina, some groundfish (flatfish, rockfish, roundfish), hagfish, Pacific herring (roe), highly migratory species (tuna, shark, swordfish), jacksmelt, night smelt, ocean whitefish, pismo clam, red sea urchin, redtail surfperch, ridgeback and spot prawn, rock and spider crab, sea cucumber (giant red, warty), shark (brown smoothhound, Pacific angel), shiner seaperch, spot prawn, white sturgeon

Table 2. Selected fish and invertebrate stocks in California grouped by favored climate phase (warm-less productive vs. cool-more productive) for production in California waters, based on best available data.

A wide variety of additional species, including some that range or recruit well outside of CCLME coastal waters, experience notable shifts in distribution in response to warm or cool conditions. These include yellowtail, bluefin and yellowfin tuna, barracuda, and other coastal or highly migratory species that may become more locally abundant during warm conditions (particularly in the Southern California Bight), and northern albacore, which may become less abundant locally during warm conditions (MacCall 1996, Phillips et al. 2014).

The seasonal timing, duration, and intensity of winds conducive to upwelling (spring transition) are also highly variable and can affect marine life. Delayed upwelling and the associated spring bloom in productivity can have substantial negative consequences on food web productivity and fisheries production (Barth et al. 2007). For example, in 2005, delayed upwelling caused recruitment failures for many species including rockfishes and Dungeness crab.

Historically, the characteristics of warm-less productive and cool-more productive phases have been relatively consistent; however, our understanding of these ecological states is restricted by limited time series data, which only encompasses one warm (~1977-1998) and two cool phases (~1945-76 and 1999-2012) of the Pacific Decadal Oscillation (PDO) (McGowan et al. 2003, Pinsky and Mantua 2014). The ecological impact of El Niño Southern Oscillation (ENSO) differed in the previous warm and cool phases of the PDO, with El Niño events during warm phases having stronger impacts than those during cool phases. Scientists often have used previous ENSO and PDO cycles to gain insight into potential future climate change impacts (such as warming) on biological productivity. However, an analysis of recent ENSO events identifies substantial diversity among those events' characteristics (Capotondi et al. 2015), making it difficult to use any one event as an analog for the future. Further, the CCLME has displayed a pattern of unusual variability, as occurred in 2014-2016 with "the Blob" followed by an El Niño, leading some to suggest that climate change may be pushing the CCLME into a state of increased variability (Di Lorenzo and Mantua 2016). Nevertheless, the general characteristics of warm and cool phases provide a useful set of conditions that can be summarized into this potential future ecological change scenario. Environmental indicators such as sea surface temperature (SST) and the Multivariate Ocean Climate Index (MOCI) (Figure 5) can be used to characterize the degree to which the CCLME is operating in a warm-less productive or cool-more productive ecological state. These indicators could be used to better assess the status of fish stocks and design and evaluate management responses.

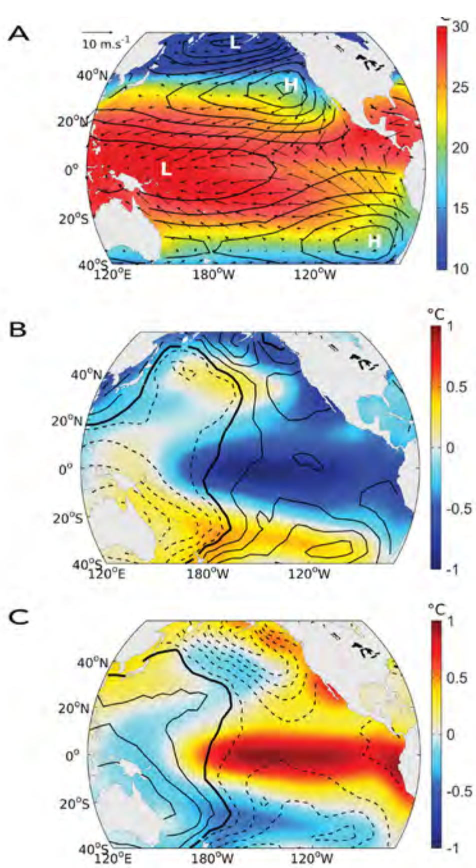


Figure 4. Average SST, sea level pressure, and sea surface winds (A), and cool (B) and warm phase (C) anomalies of the Pacific. The cool Northwest Pacific waters of the CCLME result from the atmospheric circulation around the North Pacific High that generate coastal upwelling and favorable winds that drive the California Current. The North and South Pacific Highs drive trade winds toward the Indonesian Low in the western equatorial Pacific. The mean state is disrupted on interannual to multidecadal time scales. These disruptions are depicted in panels B and C. During El Niño (C) a western migration of the Indonesian Low reverses and weaken the trade winds. The low pressure Aleutian Low, an important player in North Pacific dynamics, intensifies and shifts west and south during El Niño. The North Pacific High weakens as do the upwelling favorable winds. The oceanic propagation occurs via subsurface waves that deepen the thermocline and cause ocean warming. The timing and spatial extent of the atmospheric and oceanic effects differs latitudinally and from event to event. The opposite occurs during cool phases (B). These same players (low and high pressure systems, ocean temperatures) but with differing timing and intensity are involved in decadal and multi-decadal variations such as the North Pacific Gyre Oscillation (NPGO) and the Pacific Decadal Oscillation (PDO). El Niño, the NPGO and the PDO are connected but in ways that have not been fully elucidated. Predictions for climate and global change are for a poleward shift in the North Pacific High as tropical warm waters expand. This may result in enhanced variability in the CCLME. (Figure courtesy of Monique Messié, MBARI)

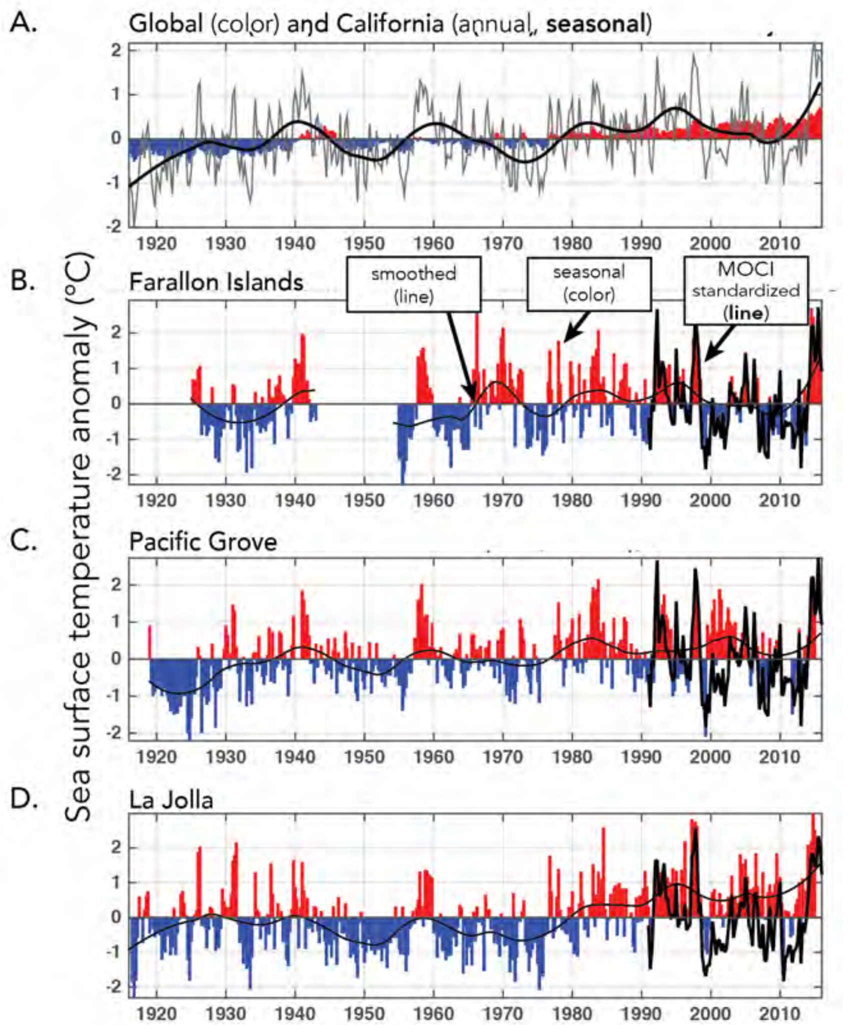


Figure 5. Global mean SST and CCLME mean SST (grey and black lines) (A) and seasonal and smoothed SST anomalies from the University of California's shore station program (B: Farallon Island station, C: Hopkins Marine Lab/Pacific Grove station, D: Scripps Pier/La Jolla station). Multiyear and longer variability is illustrated with a LOWESS filter on top (black line) (Figure courtesy of Monique Messié, MBARI, A, and Marisol García-Reyes, Farallon Institute, B-D).

Vulnerability of key fish stocks

For most fishery management plans (FMPs), there is an underlying assumption that population replenishment is stable when averaged over long periods of time, spanning multiple favorable and unfavorable environmental states. However, climate change (or any other non-stationarity in the system) may alter the fundamental population dynamics of a given stock, thereby challenging the assumption of a "stable" stock-recruitment relationship. This understanding has led to intense interest in developing stock assessment approaches that account for ecosystem changes in ways that better contribute to adaptive management. Sardines, like many other fishes, exhibit temporal dynamics in recruitment that reflect the natural fluctuations between warm (higher recruitment) and cool phases (lower recruitment). Today, the sardine fishery is the only California fishery with an FMP that accounts for natural variability in its harvest control rule to support stock health (see sardine case study).

Most contemporary population models do not account for variable production regimes, whether with respect to the recruitment, distribution, or growth of individuals in a population, as the estimation of explicitly climate-driven productivity functions is extremely challenging in the absence of comprehensive population data (Hollowed et al. 2013, Punt et al. 2013, Szuwalski and Hollowed 2016). For example, in an evaluation of the potential to improve management of the South African anchovy fishery, De Oliveira and Butterworth (2005) demonstrated that an environmental index would have to explain over half of the total recruitment variability before benefits of the management procedure outweigh the risks of poor recruitment forecasts. By contrast, Mohn and Chouinard (2007) developed a case study of changing productivity regimes for Northwest Atlantic (Canada) cod and haddock, in which a harvest control rule regime could account for three to eightfold differences in productivity in response to climate shifts. Although it is not clear that their framework has been adopted by managers, their work also highlighted the need for monitoring programs and time series data, neither of which is readily available for many species targeted in California fisheries. Thus, despite broad recognition of climate factors as drivers of such shifts (e.g., MacCall et al. 1996, Barange et al. 2008, Schirripa et al. 2009, Hollowed et al. 2013) and the potential benefits of developing population models that account for climate-driven shifts in productivity, the inability to accurately predict or assess changes in stock-specific productivity typically constrains most population models to the assumption of stationarity. In California fisheries, only a handful of state-managed species are managed based on assessment models that are updated and applied to management on a routine basis.

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Box 1. Potential human responses to environmental variability and change

Fishery participants have adapted – both more and less successfully – to the range of historic variability and uncertainty in climate and oceanographic events in California, such as El Niño, harmful algal blooms, and declines and increases in fish stocks due to SST fluctuations. To do this, they have responded in a variety of ways:

- Intensification
- Substitution
- Diversification
- Pluralism
- Migration
- Exit
- No change

Climate change likely will lead to more extreme or prolonged variability and/or uncertainty. Relatively minor and less costly responses to environmental change are predicted to occur first, with more substantial and costly (and perhaps less reversible) responses occurring if the initial response is not sufficient or conditions do not improve (McCay 1978, Smit and Wandel 2006). Human responses can reduce or accentuate pressure on fish stocks and ecosystems (McCay et al. 2011). While fishermen may respond in any of these ways under a given scenario, we highlight the responses that are expected to be more common under each scenario.

Intensification

Intensification refers to increased effort on available species already targeted.

Substitution

Fishermen may choose to target alternative (previously targeted) or new (previously untargeted) species in place of the preferred/targeted species.

Diversification

Diversification refers to targeting a (larger or broader) mix of species. It has the effect of "spreading of the risk" by expanding alternatives for coping with change (McCay 1978).

Pluralism

Fishermen may choose to engage in income-generating (e.g., occupational pluralism, McCay 1978) or recreational activities other than fishing, whether ocean or land-based, while continuing to participate in fisheries.

Migration

As stock distributions fluctuate with changing oceanographic conditions, fishermen may follow the fish or relocate to a different coastal area to more easily access desired species. Such movement may occur within or across fishing seasons.

Exit

Fishermen may respond to a downturn in resource availability by leaving fishing altogether and seeking alternative employment to compensate for their inability to pursue traditionally-caught stocks (e.g., Colburn et al. 2016). However, studies have found that fishermen are often unwilling to leave the industry, even in the face of adverse economic conditions (Sievanen et al. 2005, Pollnac et al. 2001, Pollnac and Poggie 2008, Coulthard 2009, Colburn et al. 2016). Nonetheless some may choose this option, particularly those close to retirement.

No change

Some fishermen may not respond in any of the foregoing ways, continuing instead to fish and land what they can and will, through a range of environmental conditions and upswings and downturns in resource availability.

Fishermen's ability to adapt is shaped and constrained by regulatory, economic, social, and ecological factors (McIlgorm et al. 2010, 2012, Pinsky and Fogarty, 2012). Specifically, their ability to adapt is influenced by the nature of their fishing operation; regulations; social and economic considerations; market forces; their experience, knowledge, and skills; and the availability and flexibility of seafood buyers. The size and nature of operations affects their ability to move among regions. For instance, in the California market squid fishery, purse seiners can move more easily between Central and Southern California, whereas smaller brail boats typically are more limited to operating in a single region. The type of fishing gear used and how specialized it is also can influence fishermen's capacity to adapt to changing fishing conditions. Shifting among (or to other) species may be easier for those with less specialized gear (Pinsky and Fogarty 2012), however access may be limited by the availability and (market) cost of permits where restricted access is in place, as is the case for some California commercial fisheries.


Image credit: C. Pomeroy

Regulations can affect a fisherman's flexibility to respond to varying ocean conditions. For example, in the northeastern United States, when red hake fish stocks shifted northward, participants in the commercial fishery were not able to move northward because of regulations that prevented fishing there due to bycatch concerns (Pinsky and Fogarty 2012). Similarly, California commercial nearshore fishery permits restrict access to one of four regional management areas, and fishing access may be lost if stocks shift their range outside of the permitted area. Recreational fishermen adapt to variable resource availability and fishing conditions by targeting available (or alternative) species or, less commonly, by moving to an area where they are more likely to catch the species they prefer.

Finally, the processing and supply chain can greatly affect what options are available to fishermen. For example, in 2012 processing facilities and markets were unable to adapt when American lobster landings increased sharply due to a heat wave in the Gulf of Maine (Mills et al. 2013). This was largely due to the timing of the catch, coming much earlier in the year when the processors were not operating (Mills et al. 2013). Lobster prices unexpectedly dropped and as a consequence fishermen increased their effort.

For tribal fishermen, who may participate in subsistence as well as recreational and/or commercial fisheries, adaptation to variable and uncertain resource availability is constrained by particular social and cultural ties to (and values associated with) species and places. For them, adaptation entails adjusting use and other activities in place, relative to a range of local species.


Image credit: C. Pomeroy

continued from page 10

It will be important to develop assessment models for remaining species and incorporate climate-linked productivity functions. Species already managed with assessment models with routine updates could benefit by incorporating climate-related shifts in productivity.

Potential human responses

Fishermen historically have responded to variations and changes (both increases and decreases) in the abundance and distribution of stocks using one or more of the basic responses described in the box on pages 11-12.

Intensification has been used in the commercial fishery for market squid, for example, at the beginning of El Niño events, as waters warm and squid become less abundant and available to the fishery (Pomeroy et al. 2002). Fishermen also may intensify their effort (whether in terms of time fishing, gear used, or other inputs) in response to variable markets, as has occurred in some California fisheries in response to increased or new demand (e.g., in China for crab and lobster). Similarly regulatory changes, from plans to restrict access to a fishery to reduced opportunities in other fisheries can prompt intensification (singly or in concert with other factors such as environmental or market variability), as occurred in the market squid and Dungeness crab fisheries (Mangel et al. 2002, Pomeroy et al. 2002, 2010).

Substitution has been used by purse seine fishermen who may shift among squid, sardine, anchovy, and mackerel depending on species availability and market demand (Pomeroy et al. 2010, Aguilera et al. 2015). Substitution also has occurred when less common species become more available, as with various tuna species during warm water phases or the increase in abundance of jumbo squid between 2002-2006.

Diversification has been used by commercial fishermen in California. Historically they have relied on a mix of fisheries and species as part of an "annual round" and as a hedge against risk due to commonly experienced environmental variability in any one fishery. Fishermen may invest in equipment, gear, and knowledge to target a variety of species, thereby diversifying their options and reducing the risk of failure due to reduced revenue from any one fishery alone (Pinsky and Fogarty 2012, Kasperski and Holland 2013). This "annual round" or "portfolio" strategy can mitigate the risk of any one fishery being less productive - whether for a single season, a year, or longer. This strategy has some downsides, including costs associated with the unique facets of each fishery and (e.g., gear, and for commercial fishermen, permits, and buyers) and with transitioning from one fishery to another.

Pluralism is evident in California fisheries such as the salmon fishery, with many fishermen historically working in other professions (e.g., teaching) during the fall, winter, and early spring, and fishing during the summer salmon season. Other salmon fishery participants diversify within fishing, working in other fisheries such as Dungeness crab or albacore tuna, at other times of the year. Similarly, some participants in the nearshore fishery (as managed by the state) complement their commercial fishing activities with other, non-fishing sources of livelihood.

Migration has been used historically, for example, by salmon and albacore fishermen, many of whom migrate up the coast to "follow the fish" over the course of the season in response to environmental conditions. In the salmon fishery, such migration is mediated by spatial management of the fishery, whereby salmon fishery management zones along the West Coast are open to fishing at specified times of the season to ensure adequate escapement of the fish for spawning. Some California squid fishery participants also migrate in response to environmental variability and related fishing opportunities. Beginning in the late 1980s and increasingly through the 1990s, purse seine fishermen based in Central California migrated to Southern California to participate in the winter fishery there, returning to Central California for the spring and summer fishery (along with local sardine or anchovy and for some, Bristol Bay salmon). As the market for squid grew through the 1990s, opportunities in the squid fishery in Southern California attracted fishermen from Washington and Alaska, some of whom had strong family ties to the Los Angeles area; they, along with Central Coast fishermen and some buyers have since migrated seasonally to participate in the Southern California fishery each year (Pomeroy et al. 2002). More recently, a short-term migration occurred when fishermen from Southern California temporarily migrated to the Eureka area when squid became abundant (and markets were strong) enough to fish there (see market squid case study).

Although fishermen have adapted more or less successfully to natural variability, extremes and/or prolonged change have led to temporary "tipping points," as occurred in the West Coast sardine fishery in the mid-20th century due to combined and interacting changes in the fishery's ecological and social systems (Radovich 1982). Such shifts also can include expanded and/or new opportunities, if valued species become more available and accessible to fishery participants. These conditions have implications for infrastructure,

continued on page 15

Case Study 1: Adaptation to variability in the market squid fishery

Image credit: G. Bergsma

California market squid are very sensitive to environmental variability, which affects their abundance and distribution, in turn posing challenges and opportunities to fishery participants and communities. For example, catches plummeted during the 1982-83 and 1997-1998 El Niño events, then rebounded dramatically in the years immediately following.

Population models and survey data indicate that the volatility in the landings of this very short-lived species (most individuals are thought to live less than one year) is the consequence of variable recruitment, growth, and survival of squid populations in response to variable ocean conditions (Zeidberg et al. 2006, Dorval et al. 2013, Ralston et al. 2015), with higher recruitment during cool-more productive phases of the CCLME.

During the 1982-83 El Niño event, squid became scarce from traditional fishing grounds. Despite intensified and expanded searching, landings dropped precipitously to some of the lowest on record (CDFG Marine Resources Division 1984, 1985, 1986). As conditions began to improve in the southern fishery in 1985, some Monterey area fishermen (who operated smaller vessels equipped with lampara nets, as the use of purse seine nets had been prohibited since 1953) and buyers temporarily shifted operations to that region, often fishing in pairs with one boat lighting and the other catching the squid (CDFG Marine Resources Division 1986).

When the 1997-98 El Niño event occurred, fishery participants adapted largely as they had in 1982-83, albeit in the context of a substantially expanded, higher value fishery and a changing regulatory context. Growth in the fishery had prompted efforts to restrict access, resulting in a 1998 moratorium on entry into the fishery. Despite vivid and widely discussed memories of the absence of squid on traditional grounds during the 1982-83 event, fishermen – including several from out-of-state who had entered the fishery just prior to the moratorium – spent considerable effort and expense searching for squid, in part to ensure they would qualify for long-term restricted access (under an FMP to be developed by the state). Nonetheless, squid landings again dropped precipitously through 1998, then rebounded strongly in the southern fishery in early 1999, while recovery was slower in the northern fishery.

Recently, the fishery has experienced renewed temporal and spatial variability, due to a mix of environmental, regulatory and socioeconomic factors. In 4 of the past 6 seasons (through 2015-16), the fishery was closed in the fall as the season quota was reached 4-5 months early. Moreover, beginning in 2010, landings began to strengthen in Central California relative to Southern California. During the 2014-15 season, for the first time in recent history, squid was sufficiently abundant north of the fishery's typical range that a small number of permittees and associated buyers briefly shifted their efforts to the Eureka area landing 2,175 t of squid (CDFW 2015), then trucking it to their processing facilities in central and southern California. Temporarily moving operations to a new location posed economic and logistical challenges (finding fishable aggregations of squid on the grounds, lack of local cold storage, high cost of trucking to established processing facilities). Although the short-term activity north of the fishery's historic focus afforded some benefits to the local economy, local fishermen were unable to participate in the fishery due to the high cost of entry (requiring purchase or lease of a squid limited entry permit and associated purse seine or brail vessel) and lack of management flexibility allowing alternative, cost-effective ways to participate in the local fishery.

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product quality, and markets, as well as buyers, fishery-supported businesses, ports, and coastal communities that provide essential goods and services and, in turn, depend on fisheries.

Potential social and economic implications

Fluctuations in fishery activity due to fishermen's responses to increased variability in ocean conditions and fish stocks have social and economic implications for fishermen and throughout the associated human (social) system. For instance, when commercial fishing activity and landings decrease, revenue to fishing operations, vessel owners, captains, and crew decline in turn, causing economic and social stress to individuals and their families. In addition, some captains then may operate with fewer (or no) crew and/or defer maintenance, increasing the potential for safety issues. Reduced (or highly variable) commercial landings to seafood buyers can result in shifts in supply and demand as has occurred at times, for example, in the state's salmon and squid fisheries. Variable quantity and timing of fishery landings to buyers can contribute to increased price variability and supply chain instability (Ogier et al. 2016). Variability in production also often results in inconsistent demand for and use of fishery-support infrastructure, goods and services (e.g., fuel, ice, trucking), with concomitant impacts on ports and other such providers. Where ports depend on commercial fishery landings to help qualify for federal dredging support, declines in fishery landings, whether due to climate or other factors (e.g., regulations, market demand) can undermine efforts to secure that support and ensure navigation channels are maintained for all port users. On the other hand, increases in activity and landings can help mitigate and buffer against losses and associated stresses. However, increased activity can increase stress on fishery participants seeking to make the most of the potentially short-lived opportunity, resulting in on-the-water conflict and related safety issues. Such pulses of activity also can result in more production than buyers can handle at one time, flooding markets and limiting or reducing prices, as has occurred in the state's squid and Dungeness crab fisheries at times. Moreover, if demand for goods and services is irregular but at times intense, rates can increase (Clay and Olson 2008). For example, in Maine, a shift in herring landing days resulted in dealers having to arrange for multiple trucks on the landing days, rather than being able to spread the use of company-owned trucks over multiple days (Maine Bait Dealer 2008, personal communication). Although recreational fishermen's responses to historic climate-related variability in fisheries do not have direct implications for the seafood supply chain, many of the above-noted implications for fishery participants, the individuals and businesses that comprise the fishery-support system, and their communities pertain.

Vulnerability of fishing communities

Fishing communities' vulnerability to historic climate variability and uncertainty varies with their engagement and dependence on fisheries. All else equal, communities that are more engaged and dependent on particular fisheries, such as North Coast fishing communities in California, are more sensitive to its effects on the availability of stocks and/or access to fishing grounds (Pomeroy et al. 2010). NMFS is currently engaged in an effort to characterize the relative vulnerability of fishing communities to climate variability.

Scenario 2: Increased Variability

Climate change may alter the natural cycles of the CCLME by increasing the magnitude (or widening the envelope) of variability in the system, leading to more extreme conditions. Similarly, changes in atmospheric and oceanographic forcing may change the period of natural fluctuations among ecological phases, increasing or decreasing the length of warm-less productive or cool-more productive states. Additionally, climate change could simultaneously increase the magnitude of environmental variability and alter its periodicity (Di Lorenzo and Mantua 2016). Synergies among these impacts could take the CCLME into "uncharted territory."

Extreme environmental conditions

With increased climate and oceanographic variability added into the system, the physical and biological characteristics of the CCLME may exhibit more extreme conditions. The environmental conditions typically associated with seasonal cycles, ENSO, PDO, or NPGO may be more extreme, prolonged, or shortened. Changes in the dynamics of these cycles may lead to extreme warming events, hypoxia, stratification, storm activity, precipitation, or changes to seasonality. We consider extreme environmental conditions within this 'Increased Variability' scenario but also acknowledge the close links to the 'crossing thresholds' scenario described below.

Extreme environmental conditions may increase the frequency or intensity of harmful algal blooms (Anderson et al. 2015) or disease or parasite outbreaks (e.g., withering syndrome, sea star wasting disease) (Pörtner et al. 2014, McCabe et al. 2016). Extended warming events and higher storm activity may lead to possible declines in kelp abundance and distribution, such as that observed in 2015-2016 (Figure 5), which will have direct and indirect effects on species that depend on kelp for food, habitat or through species interactions. In addition, the abundance and distribution of seagrasses, including estuarine eelgrasses, may decline due to stress from warming events or physical disturbance from storms, which is compounded by the potential loss of suitable habitat and submergence due to sea level rise (Short and Neckles 1999, Orth et al. 2006, Kairis and Rybczyk 2010). Critical nursery habitat, such as salt marsh, tidal flats, and drift algae, also may be impacted in a similar manner (Gleason et al. 2011, Hughes et al. 2014). Other compounding stressors, such as nutrient pollution or water quality, may reduce the capacity of these habitats to withstand additional stress due to increased variability or sea level rise.

Contraction and expansion of species' spatial distribution

Associated with increased variability in environmental conditions, the spatial distribution of many species could fluctuate poleward and equatorward within the envelope of their range, resulting in short-term range shifts in response to favorable environmental conditions. We distinguish these short-term shifts from the long-term 'Range Shifts' scenario described below. Changes in species distribution due to increased variability may result in density-dependent habitat utilization and the contraction and expansion of species ranges (MacCall 1990, Cochrane et al. 2009). Distributional shifts in species ranges may result in new and/or lost fishing opportunities, as well as shifts in the distribution of species that may have negative impacts on valued stocks (Figure 6). Similarly, if extended warming events become more extreme in the future, the range of coastal pelagic species and/or market squid may temporarily extend further north than previously observed, thus creating the potential for an expanded fishery for more northerly fishing communities (see market squid case study). Such a phenomenon is observed on an interannual basis with Pacific hake, which is the largest (by volume) fishery on the West Coast of both Canada and the U.S. (Although Pacific hake spawn in California waters in the winter, the Pacific Northwest and Canadian fisheries occur primarily during summer months). Pacific hake exhibit wide shifts in their distribution as a function of ocean conditions and prey availability, such that in warm years the majority of the biomass is off of the Canadian West Coast, and thus less available to U.S. fishermen, while in colder years the majority of the biomass is in U.S. waters and thus Canadian catches decline to very low levels (Dorn 1995, Agostini et al. 2006, Hamel et al. 2015).

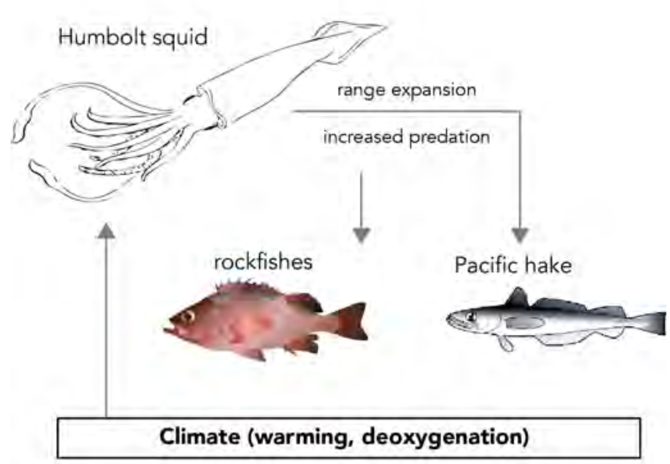

Figure 6. Humboldt squid (*Dosidicus gigas*) undergo periodic range expansions into the CCLME from either southern or offshore waters related to shifts in ocean conditions (particularly the depth of the Oxygen Minimum Layer), which consequently has likely (but difficult to quantify) impacts on valued species such as coastal pelagic species, rockfish, and Pacific hake (Zeidberg and Robison 2007, Field et al. 2013, Stewart et al. 2014, Sydeman et al. 2015).

Vulnerability of key fish stocks

The life history strategies of long-lived species buffer them from high variability in environmental conditions and recruitment, and thus are less vulnerable to variability, but some (e.g., rockfishes) may be vulnerable in the longer term to monotonic change. However, no species exists in isolation, and individual species declines may alter food web dynamics and impact fish or invertebrate stocks via species interactions. Highly specialized species (e.g., specialized diet, habitat requirements, or complicated reproductive strategy) are more vulnerable to increased variability. Examples of highly specialized species include splitnose rockfish, anchovy and bat rays (i.e., their jaws adapted to crush clams). Mobile species that are able to avoid unfavorable conditions by shifting their range, like market squid, may also be less vulnerable to increased variability.

Potential human responses

As noted above, variability is an accepted and expected condition of fishing to which the whole industry adapts. While fishermen likely may exercise similar responses to those discussed in the human responses box, increased variability may lead to amplified responses by commercial, recreational, and subsistence fishermen.

Commercial fishermen may adapt through diversification or migration (Cheung et al. 2013). Alternatively, fishermen may need to develop and acquire new technologies to better forecast conditions and identify areas where stocks have shifted. In addition to the ability of fisherman to modify their fishing practices, flexible fishing regulations that take stock sustainability into account are necessary to enable adaptation to changing fish distributions (Pinsky and Fogarty 2012).

Potential social and economic implications

The ability of commercial, recreational, and subsistence fishermen to maintain their livelihoods will be affected by the degree of adaptation needed. Amplified responses by fishermen will likely result in larger changes in the types of social and economic implications noted in the previous scenario as well as increased cumulative impacts on the whole production chain.

Increased variability may also have social implications such as increased safety issues related to more volatile weather and ocean conditions - or to reduced crew sizes due to economic constraints - leading, in turn, to individual, family, and community stress. Economic changes following from increased variability also may increase social as well as economic stress in fishing communities overall (Colburn et al. 2016).

If increased variability results in increased abundance of certain species, this scenario could also have both positive and negative economic implications. Increased production may lead to economic gains in some sectors. In addition to economic benefits, there may also be enhanced fishery and community well-being (e.g., through fisheries employment, participation in fish sharing networks, etc). However, increased production could also lead to crowding and conflict within and across fisheries (McCay et al. 2011) as well as place pressure on limited shore infrastructure. Furthermore, it could result in increased bycatch (Griffis et al. 2013), thus jeopardizing fishery resources, and/or flood markets, resulting in price declines. Sea level rise, combined with physical disturbance from storms, could also result in damage to fishing infrastructure and businesses, leading to economic costs.

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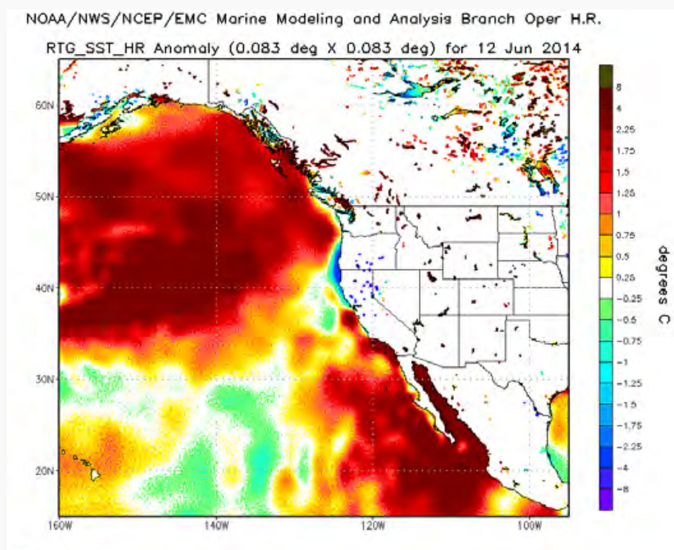
Case Study 2: Harmful algal blooms, whale entanglements, and the Dungeness crab fishery

Image credit: C. Pomeroy

The California Dungeness crab fishery has long been one of the most important fisheries in the State and throughout much of the West Coast of North America. The commercial and recreational fisheries are managed using the "three S's:" size, sex, and season, with a minimum size requirement for the targeted male crabs, a ban on the harvest of female crabs, and a season (typically November or December through June) to protect molting animals. Since 1995, participation in the commercial fishery has been limited by restricted access (with ~560 permittees), with a tiered trap limit program implemented for the 2013-14 season. Despite strong variability in landings over time that are thought to be climate-driven (Wild et al. 1983, Higgins et al. 1997), the relative health of the resource is well recognized. As a consequence, the commercial fishery has been one of the largest and most lucrative in recent decades, with an active recreational fishery as well. For the cumulative 2001-2010 period, the commercial fishery ranked first in the State based on value, and fourth in volume, after market squid, Pacific sardine and northern anchovy. However, in fall 2015, the State's Dungeness crab fishery (along with the fishery for rock crab) experienced unprecedented impacts when a toxic algal bloom led to closures, causing tremendous financial and social impacts on fishermen and fishing communities, and raising widespread concerns regarding the potential consequences of future climate change impacts on the resource and the larger social-ecological system.

The 2014-2015 harmful algal bloom event

The 2014-2015 North Pacific marine heatwave, commonly referred to as the "warm blob," was associated with record-breaking warm temperatures throughout the Gulf of Alaska and California Current (Di Lorenzo and Mantua 2016). This event, in turn, has been linked to a bloom of the highly toxic diatom (marine algae) *Pseudo-nitzschia*, known for producing domoic acid. Domoic acid accumulates in the food web, particularly in invertebrate species. When consumed, domoic acid is highly toxic to humans, potentially leading to memory loss (thus earning it the name, Amnesic Shellfish Poisoning), dizziness, nausea, vomiting, coma, and in rare cases, death. To protect public health, the bloom resulted in widespread closures of the Dungeness crab and rock crab fisheries along most of the U.S. West Coast (a chronology of the sequence of events is detailed in OST 2016). This event, which included some of the highest concentrations of domoic acid ever observed in the California Current ecosystem, is consistent with what would be expected under changing ocean conditions related to climate change.



The 2014-2015 harmful algal bloom event was a consequence of a series of abnormal ocean changes in the Pacific Ocean, including a large mass of warm and nutrient-poor water, named "the blob," combined with warm water driven by El Niño (PC: NOAA/NWS/NCEP/EMC Marine Modeling and Analysis Branch).

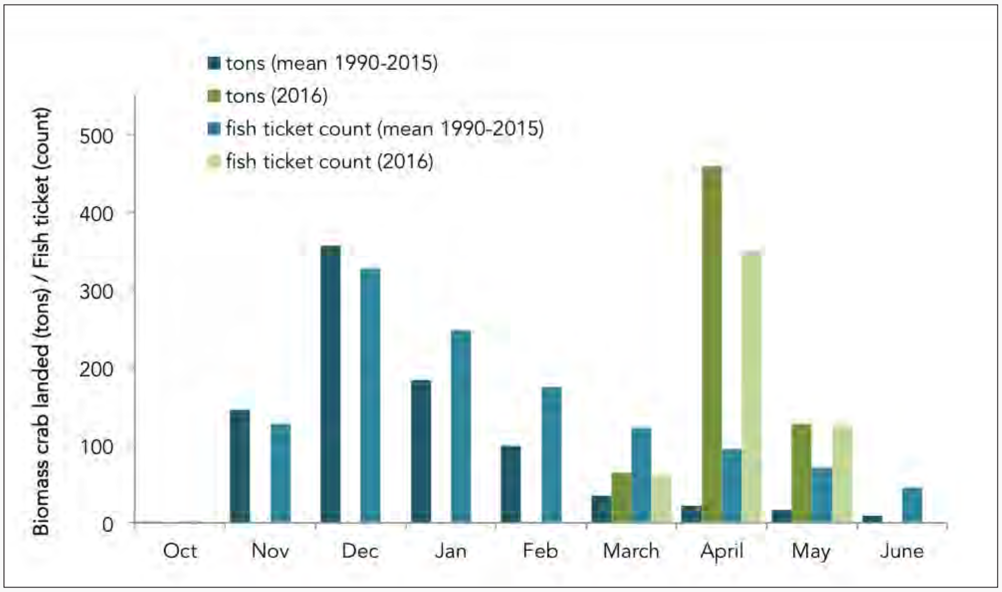


Figure 7. In 2016, the timing of the California commercial Dungeness crab fishery was delayed due to elevated levels of domoic acid in crab viscera and meat (based on mean tons landed in California and number of fish tickets for 2016 relative to 1990-2015).

Social and economic impacts of the harmful algal bloom event

For many central and northern California fishing communities, dependence on and engagement in the commercial fishery has markedly increased, especially following substantial reductions in groundfish and salmon fishing opportunities, effort and catches (Pomeroy et al. 2010). In recent years, between 412 and 461 of the 561 permitted vessels have participated in the fishery. Although some fishermen caught up on their landings and ex-vessel revenues when the fishery eventually opened, the lapse in income, especially after fishermen had invested considerable time and money gearing up for the season, caused substantial economic hardship. Buyers, fishery support businesses, and associated fishing communities likewise were affected. In response, Governor Brown requested that the U.S. Secretary of Commerce declare a fishery resource disaster for the Dungeness crab and rock crab fisheries under the Interjurisdictional Fisheries Act and the Magnuson- Stevens Fishery Conservation and Management Act. (A fishery resource disaster is defined as a sudden and unexpected loss of commercial fishery production due to natural or man-made factors, which leads to serious economic impacts on fishermen and their communities.) The State's crab fisheries were declared a disaster on January 18, 2017, providing Congress with a basis for appropriating disaster relief funding to affected fishing communities.

The challenge of whale entanglement

Although the California fishery opened partially in March 2016, roughly four months later than the typical opening date, new challenges quickly arose. As a result of the late opening, the density of crab pots in coastal fishing grounds in May and June was far greater than usual at that time of year (Figure 7), and migrating humpback, blue, fin, and other whales foraging in coastal waters encountered densities of gear that appear to have contributed to record numbers of whale entanglements in the buoy lines that fishermen use to tether and locate their traps. Research indicates that humpback whales may alter their foraging behavior among krill and anchovies and other schooling fishes, depending on which prey is abundant, and that they may be more broadly dispersed when anchovies or other schooling fishes are their primary prey (Fleming et al. 2016). Krill were at relatively low abundance levels in the late spring of 2016. Similarly, the abundance of anchovy, sardine and other schooling fishes was low, resulting in more shallow and coastal distributions of these species (MacCall et al. 2016). Whales may have been more vulnerable to entanglement in crab pot gear in part due to the anomalous distribution of forage that also was attributed to the unusually warm ocean conditions.

Whale entanglements with fishing gear had been at record levels before the closure; in 2015 a total of 61 entanglements were recorded off the U.S. West Coast, with 59 of these in California waters. This level was the highest observed since record keeping began in 1982 and considerably greater than the average of approximately 10 entanglements per year in the 2001-2010 period (NMFS 2016, Saez et al. 2013). In 2016, a total of 71 whale entanglements were reported along the West Coast, with 48 of those confirmed and 29 identified as associated with specific fisheries or gear type (NMFS 2017). Total effort in the California Dungeness crab fishery is limited to a fleetwide total of 175,000 pots based on the current trap limit program, although not all of these are fished due to some permittees not fishing some or all of their permitted traps. Estimates of lost gear suggest that approximately 10% of the gear used may be lost in any given year (PFMC 2013). In a typical crab season, more of this gear would have been set in winter months (Figure 7), when fewer whales typically are present. As such, the delayed season, combined with climate-driven shifts in the abundance and distribution of forage species, likely contributed to recent record numbers of entanglements. Thus, the impacts of the climate/blob-induced toxic algal bloom extended beyond the already severe ecological and social impacts to include increased interactions with and mortality of marine mammals, which themselves may have also been directly impacted by the toxic algal bloom.

To address the increase of whale entanglements in crab fishing gear, a California Dungeness Crab Fishing Gear Working Group was convened by the CDFW, in partnership with the OPC and NMFS, in the fall of 2015. The working group is collaborating to provide recommendations on how to minimize entanglements through identifying measures that can be developed or implemented by the fishing community, as well as addressing key information gaps to reduce the risk of further entanglements. As it is believed that lost fishing gear may increase entanglement risk, Senate Bill 1287 (McGuire, 2016) was passed by the Legislature which tasks the California Department of Fish and Wildlife to establish a program, in coordination with partners, to recover lost or abandoned crab trap gear.

Climate change likely increases the risk of harmful algal blooms

Harmful algal blooms are already thought to be on the rise in California waters and throughout the world as a consequence of anthropogenic activities (Anderson et al. 2015), and further increases in such events are a likely effect of global climate change (Wells et al. 2015). Warmer sea surface temperatures extend the seasonal period of phytoplankton growth and the geographic range of blooms, which enhances the risk of algal blooms becoming toxic events (OST 2016). Both paleoecological and sediment trap monitoring studies had suggested a trend of increasing abundance and severity of blooms of *Pseudo-nitzschia* in the Southern California Bight (Barron et al. 2010, Sekula-Wood et al 2011).

Thus, considerable uncertainty remains with respect to whether this chain of interactions indeed links the *Pseudo-nitzschia* bloom to increased whale entanglements. The evidence suggests that the bloom itself, and the resulting impacts to fisheries, were climate driven, and may indeed be harbingers of the climate impacts that will unfold in the future. These changes and impacts will challenge both fishery participants and managers seeking to maintain the sustainability of fisheries and protect human health while also ensuring the protection of vulnerable, threatened, and endangered marine populations.

Management implications

From a human health perspective, the state agencies involved succeeded in preventing major human illnesses directly linked to the elevated levels of domoic acid in the marine food web in 2015-16. The California Department of Public Health's (CDPH) Marine Biotoxin Monitoring Program and Phytoplankton Monitoring Program scientists and others were able to detect and track bloom progression and toxin transport, and communicate across the appropriate agencies to protect the health and safety of seafood consumers. However, from a socioeconomic perspective, the impacts on California's commercial crab fishing communities were substantial. There is a need for the State to better understand and help mitigate the socioeconomic impacts associated with future harmful algal bloom events.

Currently the SAT is engaged in providing scientific recommendations to the State to better track, predict, and project future harmful algal bloom events and mitigate impacts. There is great value in involving fishermen and citizen scientists in these monitoring efforts as with past events. In addition, there is a need to work with fishery participants to plan for economic hardships resulting from future fisheries closures to allow them to better cope with and adapt to such challenges.

Image credit: C . Pomeroy

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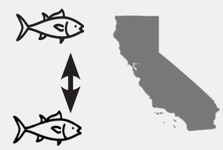
Vulnerability of fishing communities

Commercial and recreational fishing infrastructure and businesses are especially vulnerable to impacts from sea level rise and associated storm surge (Colburn et al. 2016). Different types of fishing communities are likely to be more and/or less vulnerable to increased variability.

Highly specialized and localized fisheries are likely to be more vulnerable due to their limited ability to respond to changes like shifts in species distribution or changes in stock levels (Lipschutz and Pomeroy 2003). Conversely, fishing communities with broader portfolios that target multiple species could give fishermen the opportunity to be flexible, fishing species that remain plentiful and foregoing those that may be adversely impacted by climate change (Morrison and Termini 2016). Even with fishing communities that target broad portfolios, one potential problem is cost: broad portfolios require significant financial resources, if controlled by quota, since quota prices follow demand. In addition, fishermen may face additional costs from increased travel time, fuel, and ice needed to access new fishing grounds, and from purchases of specialized fishing and processing gear to target different species (Sumaila et al. 2011, Pinsky and Fogarty 2012). Fisheries management approaches also can exacerbate or ameliorate the effects of variability on fishing communities. More flexible management strategies can alleviate some of the negative effects of variability on fishing communities.

Scenario 3: Range Shifts



We define the scenario "Range Shifts" as a long-term shift in a fish stock's range due to direct or indirect effects of climate change and/or natural variability.

Changing ocean conditions and changes to prey quality

Global trends in sea surface temperature and projections with future climate change indicate that mean SST will continue to increase as a result of climate change (Belkin 2009, Burrows et al. 2011, IPCC 2013). Long-term records of SST off California highlight that natural variability occurring over seasonal and interannual timescales far exceeds changes in mean temperature detected over longer time scales (Figure 5). Long-term datasets show evidence of a century-scale warming trend, consistent with long-term trends in coastal surface air temperature trends along the West Coast (Figure 5) (Sydeman and Thompson 2010, Johnstone and Mantua 2014). Increased stratification has also been observed in the CCLME over the last several decades, due to changes in basin-scale circulation and long-term trends in ocean heat content (Palacios et al. 2004). Reduced nutrient exchange between deep and surface waters during this time period has been attributed to the consequent decline decline in biological production (Palacios et al. 2004, Lavaniegos and Ohman 2007).

A directional trend in SST is expected to drive changes in species distributions, and thus, species abundance and community composition in any given location. There is evidence to suggest that regional changes in upwelling and sea surface temperatures (i.e., warming) may alter the abundance of high quality zooplankton prey that are important for upper trophic level productivity. For example, the abundance of highly nutritional copepods (e.g., lipid-rich copepods) fluctuates with climate forcing and the timing of upwelling, such that prey availability is higher and/or more nutritious during cool phases (McGowan et al. 1998, Peterson et al. 2014, Fontana et al. 2016). Also, the abundance of ichthyoplankton declined 72% over a ~40-year period (1972 - 2012) in Southern California, particularly for species that favor cool-more productive conditions (Koslow et al. 2015), which was consistent with the 78% decline in the total abundance of nearshore fishes entrapped by Southern California power plant intakes over the same period. This study highlights the potential impact of long-term warming - increasing temperatures may shift the ecosystem into a more warm-less productive state that is unfavorable for species that favor cool-more productive phases.

Changes to species migrations, composition and abundance

A directional trend in SST is expected to drive changes in species distributions, and thus species abundance and community composition, (Parmesan 2006, Molinos et al. 2016), similar to the northwest Atlantic (Nye et al. 2009). Globally, species distributions have shifted poleward on average 30.6 +/- 5.2 km per decade due to increasing temperatures (Poloczanska et al. 2013). A continued increase in mean temperature is expected to lead to poleward shifts or range contractions for species that favor cool-more productive conditions and range expansions for species that favor warm phases (Weber and McClatchie 2010). Species composition will likely reflect these shifts, resulting in a greater mix of subtropical, local and oceanic species (i.e., sardines, hake, tuna), particularly in the nearshore environment and in Southern California (MacCall 1996, Perry et al. 2005, Dulvy et al. 2008, Mueter and Litzow 2008, Cheung et al. 2010, Poloczanska et al. 2013). Changes in species distribution may have indirect consequences for inter-species interactions and/or increased negative interactions among protected species and fisheries (see Dungeness Crab Case Study).

Some species that favor cool-more productive waters may decline in abundance, particularly those with characteristics that limit range expansion (e.g., limited dispersal potential, specific habitat or prey requirements, etc.). Also, some species that favor warmer waters (i.e., those of tropical stock in Southern California) may have difficulty expanding north of Point Conception. Presently, the southerly flowing currents and strong upwelling that occur off northern and central California carry pelagic eggs and larvae southward or into unfavorable environments (Cowan 1985, Hobson 2006), with the Point Conception area at the southern end of this oceanographic region essentially acting as a dispersal barrier. Many of the southern species have pelagic eggs and larvae, a reproductive strategy that is suitable for the surface currents in the Southern California Bight, but not for the oceanographic conditions north of Point Conception (Hobson 2006). If these oceanographic conditions continue or strengthen (García-Reyes et al. 2015), then even with warmer coastal waters, these southern species may not be able to establish reproductively successful populations in areas north of the Southern California Bight.

Changes to species life histories

Associated with these changes in temperature and species distributions is the predicted change in the phenology and phenotypic expression of fishes. For some species, the phenotypic expression of life history traits is predicted to reflect trends consistent with tropicalization, such as shorter pelagic larval durations, faster growth, and younger age at maturity (Poloczanska et al. 2013). A recent study analyzing 43 species over 58 years of data found that 39% of phenological events occurred earlier in recent decades (Asch 2015). Changes in phenotypic expression of life history traits, particularly changes in phenology, could lead to recruitment failures if phenological shifts result in temporal mismatches with the seasonal abundance of prey resources (e.g. spring bloom in productivity). For example, earlier spawning, and shorter larval durations could result in a temporal mismatch between peak larval production and the production of zooplankton prey. Snyder et al. (2003) found evidence that climate change may lead to delays in the onset of the upwelling season, which further increases the likelihood of a temporal mismatch between larval production and spring blooms in productivity. Species that time reproduction and larval release to the spring bloom in productivity are particularly vulnerable to temporal mismatch dynamics and, ultimately, reduced recruitment (e.g. rockfishes, Dungeness crab).

Vulnerability of key fish stocks

Shifts in species ranges due to climate change are likely to result in both emerging fisheries and also fisheries closures (Sumaila et al. 2011). Species that favor cool-more productive phases are particularly vulnerable to a directional impact of climate change on ocean temperature. Vulnerable species include Dungeness crab, rockfishes, anchovies and salmon (Shanks 2013, Koslow et al. 2015) (Table 2). Subtropical species such as tunas, white seabass, and sardines are likely to exhibit poleward range expansions, leading to expanded fisheries. In general, range expansions and contractions will lead to corresponding changes in the distribution and composition of catch (Perry et al. 2005, Dulvy et al. 2008, Cheung et al. 2010, Wernberg et al. 2013).

Potential human responses

If climatic conditions shift and result in long-term warming trends, higher frequency of warm-less productive conditions, and decreased frequency of cool-more productive conditions, thus resulting in shifting range of fish stocks, fishing communities are likely to respond in a variety of ways. Some fishermen may choose to migrate to follow fish stocks, others may exit the fishery completely, while others may diversify (if possible given regulations and other constraints), others may intensify effort on the species that remain in the original region (Pinsky and Fogarty 2012), or focus less effort if they see low returns.

Potential social and economic implications

Range shifts may result in substantial increases in fishing opportunity for fishermen with the ability to access emerging or expanded fisheries. This could result in economic benefits for ports as well. The degree of economic benefit will depend on the extent that fishing opportunity increases, the degree of access, and the ability of participants to travel, if needed.

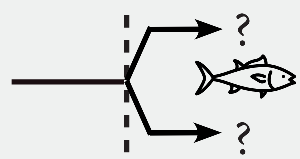
If fishermen choose to shift their fishing grounds to target moving stocks, this is likely to lead to social disruption of fishing communities at various points in the supply chain. For instance, fishermen may experience higher fuel expenditures (Clay and Olson 2008). Shoreside services could experience loss of relationships with fishermen, lower revenue, and income flow into the larger community as fishermen move away from their traditional grounds (i.e., fleet migration) if they choose to land and process their landings in new locations (Colburn et al. 2016). Conversely, as a result of fleet migration and changes to landing sites, shoreside services and infrastructure could also become overtaxed and community relationships disrupted in ports with influxes of new fishermen. Finally, if fishermen follow stocks to new areas, this could also lead to displacement of existing fishery participants as newer, and potentially larger, fishing operations enter the area. This phenomenon has already happened, for example, the squid fleet moves between central and southern California and, similarly, recreational albacore fishermen drive long distances to launch their boats closer to schools.

Fishermen who modify their fishing grounds may find it economically costly to do so, and it may also prove difficult to learn about and fish in a geographically new area. Fishermen also may have difficulty obtaining permits in new areas to fish species they were formerly targeting (particularly if fish cross state or regional boundaries) and to access new, emerging fishery species that are migrating into their traditional fishing grounds (Pinsky and Mantua 2014). Acquiring permits can be cost-prohibitive and otherwise challenging. Although most California fishery permits are not tied to a specific place or region (except nearshore fishery permits), they typically are tied to a vessel (and gear). If fishermen choose not to "follow the fish", they may shift their fishing effort to target a new species mix (Sumaila et al. 2011). Range shifts also could result in social disruption for fishing families, if fishermen travel further to follow fish stocks. Communities also could experience a loss of subsistence value if fishermen who formerly shared locally-caught fish with friends and neighbors are no longer able to do so (Griffis et al. 2013).

Vulnerability of fishing communities

Fishermen likely to be the most vulnerable to range shifts of fish stocks are those who do not currently travel far to fish due to regulatory, social, or economic constraints; those communities may find it difficult to adjust their operations to follow fish stocks (Pinsky and Mantua 2014). This is more apt to be smaller-scale fishermen, whereas larger-scale fishing operations that may already travel extensively to fish are likely to be capable of following fish stocks to new fishing grounds (Griffis et al. 2013, Pinsky and Mantua 2014). On the other hand, if new species appear in their traditional grounds, smaller-scale fishing operations can be nimbler, needing less gear and smaller catch quantities to cover costs and make a profit. Regardless, fishermen who are able to access permits – such as permits in other states – will be less vulnerable than those who are unable to access new permits (Morrison and Termini 2016).

Scenario 4: Crossing Thresholds



We use the term "crossing thresholds" to describe a scenario in which climate change causes the state of the CCLME (locally, regionally, or throughout) to undergo a dramatic shift in ecosystem community structure and function, and food web dynamics. Thresholds are crossed when one or more fished stocks rapidly decline or increase in abundance and then persist at a new baseline level as a result of these widespread changes to the physical and biological components of the CCLME.

Changing ocean conditions and rapid changes in the state of an ecosystem

Changing ocean conditions - the suite of direct and indirect physical changes associated with ocean acidification, hypoxia and increasing temperatures (Hales et al. 2015, Chan et al. 2016) -may cause ecosystems to shift into novel ecological states. Although conditions are projected to occur gradually over the coming decades, the ecological impacts of these changes may manifest in sudden surprises or biological tipping points that shift ecosystems into dramatically altered states or "uncharted territory" (i.e., crossing thresholds) (Selkoe et al. 2015). Although theoretically plausible, such tipping points have not yet been causally linked to anthropogenic climate change.

Nevertheless, California is already experiencing physical changes to the properties of seawater that are consistent with climate change projections and have the potential to elicit dramatic ecological shifts. An overall decline in aragonite saturation state and pH has been recorded in California and globally (see Somero et al. 2016). Additionally, there has been an increase in frequency of conditions below the aragonite saturation state ($\Omega = 1$), a threshold that represents conditions that destabilize, dissolve or prevent the assimilation of calcified structures (e.g., shells, urchin tests etc.) (Feely et al. 2008, Harris et al. 2013). In an analysis by Gruber et al. (2012), seawater suitable for shell growth (above 1.5 Ω) will largely disappear in the nearshore CCLME by 2050, and more than half of the waters will be undersaturated (below 1 Ω) year-round. These projected changes highlight the potential for dramatic shifts in the physical, biological and social-ecological system.

In addition to declines in pH and aragonite saturation, the CCLME is projected to experience declines in oxygen concentrations. Long-term declines in oxygen content have been observed in Southern California in recent decades, with the hypoxic boundary shoaling by as much as 60 m (Bograd et al. 2008, McClatchie et al. 2010, Booth et al. 2014). In addition to the shoaling of deoxygenated zones, regions in Northern California experience short-term hypoxic events during periods of strong upwelling, which brings water that is both low in oxygen content and pH to nearshore surface waters (Feely et al. 2008, Booth et al. 2012, Gilly et al. 2013). Because deeper water reflects anthropogenic CO_2 concentrations from ~20-30 years in the past (Feely et al. 2008), the CCLME can expect upwelled water in the coming decades to be increasingly depleted in oxygen and more acidic. Due to regional differences in oceanography, the impacts of climate change will differ in Northern and Southern regions of California. For example, if upwelling intensifies in northern regions but not in southern regions, it will likely lead to more extreme acidification and hypoxia in the north relative to the Southern California Bight (Bakun et al. 2015, García-Reyes et al. 2015). Both more variable and monotonic shoaling of oxygen minimum layers can have tremendous impacts on fisheries resources, including habitat compression that may make some species more vulnerable to either predators or fisheries, potentially resulting in bias with respect to the interpretation of catch rates in vertically compressed pelagic zones (Pörtner and Knust 2007, Stramma et al. 2012, Gilly et al. 2013). Upwelling intensification in northern California may also have a positive effect on productivity, as increased upwelling may bring a higher concentration of nutrients to the surface, stimulating primary and secondary production.

Changes in species abundance and composition and food web productivity

Upwelling intensification in northern California may increase primary production (García-Reyes et al. 2015), which may benefit larval feeding and translate into higher recruitment and abundance of fish stocks. Whether or not increased upwelling translates into higher fish production depends on the timing and strength of upwelling (as it related to larval production) and the extent other factors associated with upwelling (e.g., acidification and hypoxia) impact primary production or the stocks directly.

Changing ocean chemistry will likely have direct impacts on the physiological stress of organisms sensitive to chemical changes. Species may experience direct impacts of changing ocean chemistry from metabolic stress or by crossing physiological thresholds in their tolerance of temperature, oxygen, pH and other associated factors with changing ocean chemistry (Miller 2012). Calcifying organisms may lose their ability to grow hard-structures with indirect impacts on survival (urchins, molluscs, crabs, squid paralarvae, and calcifying phytoplankton and zooplankton) (Washington State Blue Ribbon Panel on Ocean Acidification 2012, Hettinger et al. 2012, 2013, Kaplan et al. 2013, Somero et al. 2016). The calcium carbonate structures of shellfish, urchins and other calcifying organisms weaken under acidified conditions (Hettinger et al. 2012, 2013, Somero et al. 2016). Calcifying zooplankton are already experiencing physiological stress from ocean acidification, with evidence of weak or thin calcified structures. For example, in California and the CCLME, planktonic sea snails (e.g., Pteropods) that are prey for salmon and herring, among other species, are exhibiting signs of damage from low pH seawater enhanced during upwelling (Bednarsek et al. 2014). The shellfish aquaculture industry has also experienced severe larvae die-offs in the Pacific Northwest and in Northern California, primarily related to corrosive waters that surfaced during upwelling (Washington State Blue Ribbon Panel on Ocean Acidification 2012, Chan et al. 2016). Non-calcifying organisms also experience metabolic stress from ocean acidification due to increased energy required for internal pH balance, particularly under hypoxic conditions (Somero et al. 2016), with growth and survival consequences.

In addition to calcifying organisms, larval fishes are particularly susceptible to stress by changing ocean conditions (Levitan 2004, Levitan et al. 2007, O'Donnell et al. 2009, Reuter et al. 2011). Larvae are generally more sensitive to changes in water chemistry, temperature, and food deprivation. In areas where upwelling is predicted to increase in strength, increasing water column turbulence may also impact larvae by physically limiting their capacity to capture planktonic prey (China and Holzman 2014). Thus, if turbulence exceeds the maximum level possible for larval feeding for extended periods of time, larval survival and ultimately recruitment may dramatically decrease for planktotrophic species. Since many species undergo their larval stage during the upwelling season (rockfishes, crabs), upwelling intensification and turbulence may impact multiple species simultaneously. Crossing this type of biological tipping point may reverberate through the food web and cause shifts in the state of the ecosystem. High rates of larval mortality may lead to recruitment failures for species unable to meet energy demands with added stress from turbulence, ocean acidification, or hypoxia.

Organisms less sensitive to changes in the physical properties of seawater may be impacted indirectly, if acidification negatively impacts prey of higher trophic level species (Hales et al. 2015, Marshall et al. 2016, Somero et al. 2016). Warming will lead to increased metabolism for ectothermic organisms and, depending on whether sufficient food is available to meet increased metabolic demands, their condition and reproductive success may be either increased (sufficient food) or decreased (insufficient food).

Most adult fishes are not predicted to cross physiological thresholds in their tolerance to pH and temperature, though benthic organisms residing along continental margins could be directly impacted by depleted oxygen. Mobile or pelagic animals may be capable of avoiding hypoxic zones, while others, such as Humboldt squid, may actually associate with them and expand their range concurrently with the shoaling of hypoxic areas (Gilly et al. 2013, Stewart et al. 2014). This could possibly lead to new fishing opportunities, but could also result in negative impacts to existing commercial species or fisheries. For example, the expansion and shoaling of hypoxic zones may significantly compress the availability of suitable habitat for some species (Bograd et al. 2008, McClatchie et al. 2010). Reduced abundance of mesopelagic fishes during periods of lower oxygen and the shoaling of the hypoxic boundary layer suggests that these species are vulnerable to hypoxia, which may be because they avoid hypoxic zones, making them more susceptible to visually orienting predators (Koslow et al. 2011, Stewart et al. 2014).

Additionally, extreme environmental conditions may increase the frequency or intensity of disease, parasite, or biotoxin outbreaks (e.g., withering syndrome, sea star wasting disease, harmful algal blooms) (Pörtner et al. 2014, Anderson et al. 2015), which can have direct or indirect impacts on fisheries (De Wit et al. 2014). For example, extremely warm temperatures contributed to the unprecedented size and persistence of the 2015-2016 harmful algal bloom event, which led to temporary closures of the razor clam, Dungeness crab, and rock crab fisheries (see Dungeness crab case study) (McCabe et al. 2016). Extreme warming during 2015-2016 also contributed to the dramatic reduction in kelp distribution (M. Fredle unpublished data), particularly in Northern California. El Niño events can have substantial impacts on the distribution and function of kelp forest ecosystems (Dayton and Tegner 1984, Dean and Jacobsen 1986, Tegner and Dayton 1987), though kelp species historically have returned rapidly to "normal" conditions after environmental conditions returned to less extreme warming conditions. Persistent warming over several consecutive years, however, may reduce the capacity of annual kelp species (e.g., *Nereocystis*) to successfully reproduce. Extended warming events in combination with higher storm activity and/or other anthropogenic impacts may reduce kelp abundance dramatically (though likely temporarily), which could have significant

Parts of California's coast have transitioned from kelp forests into urchin barrens.

impacts on species that depend on kelp habitat. These shifts could make the ecosystem vulnerable to crossing thresholds into a new ecosystem state (e.g., urchin barren, desert, or novel community) (Filbee-Dexter and Scheibling 2014). The decline of kelp forests in California would result in severe consequences for species that depend on kelp forest ecosystems for food, habitat, or indirectly via species interactions (e.g., urchins, red abalone, nearshore rockfishes). Similarly, sea level rise, in combination with rising temperatures and other compounding stressors (e.g. impaired water quality), may reduce or eliminate suitable habitat for seagrasses and saltmarsh plants. As a result, the ability of aquatic vegetation to persist as functional nursery habitat may be limited in this scenario, which may impact species that rely on these habitats.

Vulnerability of key fish stocks

Generalist species that are physiologically adapted to variable or extreme environmental conditions will be less vulnerable in this scenario. Additionally, species with a generalist diet will be less susceptible to individual species declines of potential prey or may be able to capitalize on new prey species that become available. Examples include skates and lingcod. Highly specialized species are more vulnerable to increased variability (e.g., specialized diets, habitat requirements, or complicated reproductive strategies) and may be more vulnerable to "crossing thresholds" in ecological states or ecosystem function. Calcifying organisms are particularly sensitive to physiological stress from ocean acidification.

Potential human responses

Fishermen are likely to be negatively affected by abrupt declines in fisheries if fish species or ecosystems cross sudden tipping points (Coulthard 2009, McCay et al. 2011, Pinsky and Fogarty 2012). Fishermen could exit the fishery and look for alternative forms of employment to compensate for their inability to pursue traditionally-caught stocks.

Potential social and economic implications

If commercial or recreational fishing communities are unable to target stocks they are accustomed to fishing for and are forced to stop fishing and search for alternative employment, there is a risk of economic disaster for fishing communities due to the abrupt loss of opportunity (Sumaila et al. 2011). There is the potential for emerging fisheries; however, the ability to access these opportunities will depend on how large these opportunities are as well as the adaptive capacity of fishing communities. This can be exacerbated in communities where members of fishing families are employed in shoreside support industries that are vulnerable to loss of product or business (Link et al. 2015, Colburn et al. 2016). Transitioning to other forms of livelihood could also place great social stress on fishermen and their families (Clay and Olson 2008). For recreational fishermen, a sudden decline in species abundance could limit the ability of recreational fishermen to engage in fishing and lead to both social disruptions due to the loss of the activity, as well as negative economic impacts for recreational fishing operators and their associated communities (Griffis et al. 2013).

Vulnerability of fishing communities

Larger scale fishing operations may be less vulnerable to abrupt shifts in species levels and distribution, since they are likely to be able to move farther, following stocks more easily and at a lower cost than small-scale fishermen (Fulton 2011, Pinsky and Fogarty 2012). However, this adaptation could be limited by fuel cost increases and absence of storage and processing facilities (Holbrook and Johnson 2014). Conversely, small-scale or family fishing operations may be able to adapt more quickly to target alternative species. Overall, both large- and small-scale fishing operations are important to the resilience of the larger California fishing community, and the development of strategies to allow for the continued vitality of both sectors of the community is essential.

Chapter 3. Potential Management Approaches

Image credit: USC Dyer

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 MLMA provides a framework for Ecosystem-Based Fisheries Management (EBFM). EBFM is "a systematic approach to fisheries management in a geographically specified area that contributes to the resilience and sustainability of the ecosystem; recognizes the physical, biological, economic, and social interactions among the affected fishery-related components of the ecosystem, including humans; and seeks to optimize benefits among a diverse set of societal goals" (NMFS 2016). Many of the management actions described in this report can be grouped under EBFM (e.g., scenario planning, protecting age structure, protecting key habitats and species, designing appropriate marine reserves, and applying ecosystem models).

The 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). However, implementation of the MLMA has been hindered by data gaps, fragmented authority, and a lack of resources (e.g. tools, personnel, funding, and expertise) (Harty et al. 2010).

Building on existing approaches

One promising guiding principle for effective adaptation to climate change is to use and build upon existing management approaches that have been designed to respond to historical variability. At present, the ability to anticipate future changes in California's fisheries and marine ecosystems is limited; however, more research, monitoring, and stock and fisheries assessments could address this limitation. Existing management approaches need to be evaluated and updated, as appropriate, to ensure that they are flexible, responsive and adaptable to both natural and anthropogenic change (McIlgorum et al. 2010, Punt et al. 2013).

Moreover, preparing fisheries governance for climate-related changes means preparing not only for negative impacts, but also for new opportunities that may arise – such as emerging fisheries and increased species abundance (Pinsky and Mantua 2014). For example, policies that accommodate rapid shifts in species abundance and distribution could prevent missed opportunities (e.g., emerging and/ or expanded fisheries) when conditions are favorable and build resilience within fishing communities.

Management strategies to adapt to climate change impacts

Based on a review of recent literature we identify seven broad management strategies that managers and decision-makers should consider in preparing fisheries for the ecological scenarios outlined above. These are described in Table 3. Table 3 and the narrative below include a description of potential management approaches, describe the alignment of each approach with the MLMA, and list actions that leverage existing efforts. For each approach, we also list the most relevant ecological change scenarios. These strategies are intended to provide decision-support to a broad spectrum of managers, funders, fishery participants, and many partners in sustainable fisheries. We focus on strategies and potential actions that can be taken by CDFW but acknowledge that some of the recommendations extend beyond the authority or jurisdiction of state fisheries managers.

We also recognize that some of the suggested approaches and actions are already being implemented in California under the MLMA. For example, two FMPs under development address climate change considerations. In the Pacific herring FMP, climate change scenarios are being incorporated into the Management Strategy Evaluation. Specifically, information in this report is being used to simulate plausible scenarios and their possible effects on herring, and candidate harvest control rules are being tested against those scenarios to determine how those rules are likely to perform if a given scenario were to occur. For the red abalone FMP, CDFW is incorporating environmental indicators into a fisheries management framework to enable adjustments to catch in future fishing seasons. The development of these indicators is based on recent experiences with harmful algal blooms and environmental conditions currently affecting the North Coast.

Effectively addressing both existing variability and the effects of future climate change will require a thoughtful portfolio of approaches and actions. To assist in the uptake and adoption of the recommended approaches and actions, we place them into an adaptive fisheries management framework (Figure 8).

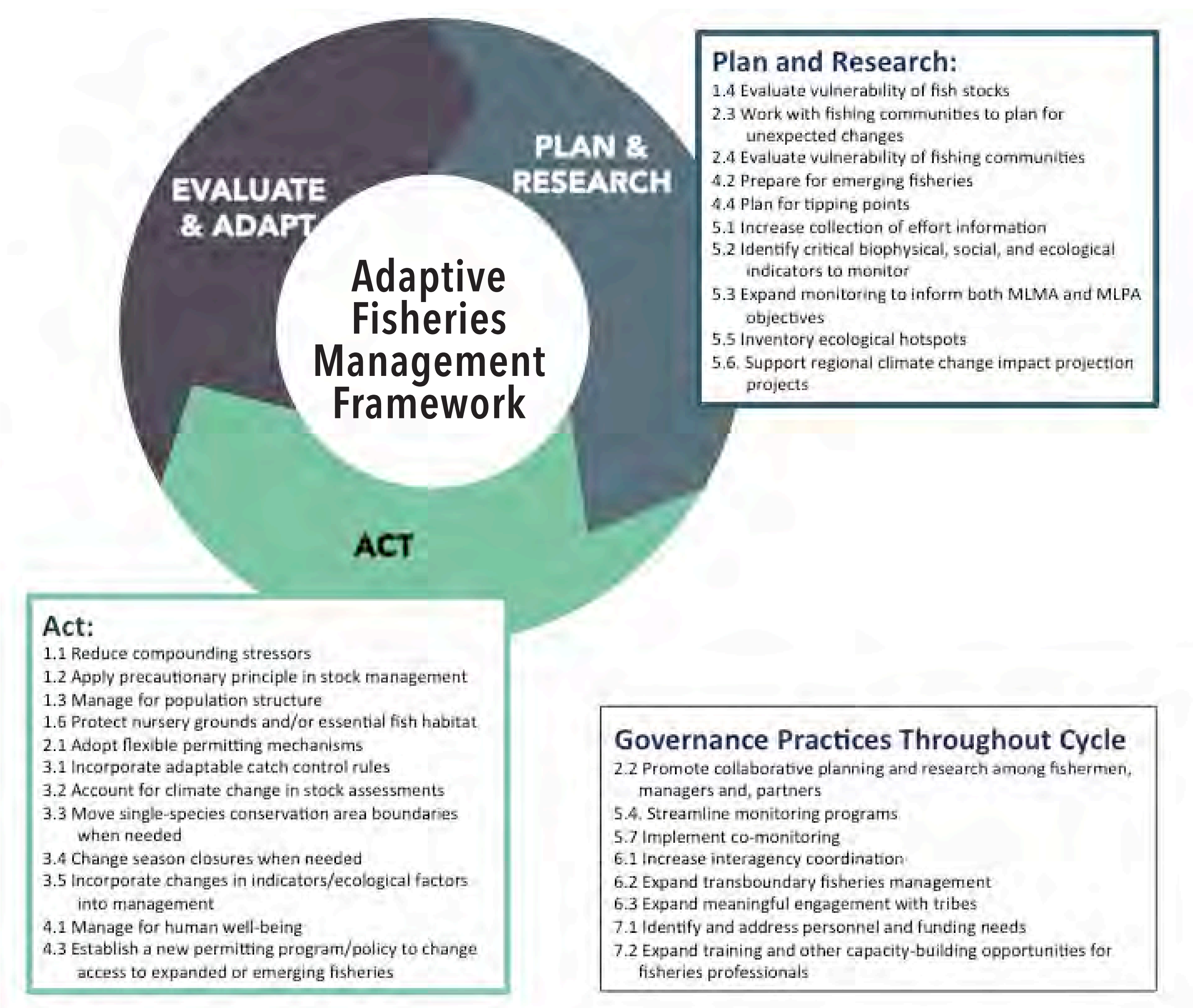


Figure 8. Potential Management Approaches displayed in a policy cycle.


Image credit: C. King

1 MANAGE FOR ECOLOGICAL RESILIENCE

Resilient fisheries are those that are able to withstand, adjust to, and recover from any climatic changes that occur. Resilience can be defined as "the ability of a system to absorb perturbations, or the magnitude of disturbance that can be absorbed before a system changes its structure by changing the variables and processes that control its behavior" (Holling et al. 1995). Managing for ecological resilience includes bolstering fish stock health and protecting the characteristics of ecosystems and species (e.g., genetic and species diversity, age structure, persistence of keystone species, ecosystem connectivity) that make them better able to withstand or recover from acute stress (e.g., heat waves, storms) and long-term change (e.g., temperature rise, ocean acidification, hypoxia) without losing ecological function. This strategy has been highlighted as a no-regrets approach to manage for the impacts of ocean acidification and hypoxia (Klinger et al. 2017). The challenges and uncertainties in determining the status of many fish stocks, however, highlights the need and value of data-limited fisheries management, in addition to the approaches below to manage for ecological resilience.

1.1 Reduce compounding stressors

Relevant scenarios: Historical Variability, Increased Variability, Crossing Thresholds

Reducing compounding non-climatic stressors (e.g., water quality, harvest impacts) that interact with climate change impacts and have negative effects on fish could help make fished species more resilient, and thus less likely to undergo sudden and dramatic changes (Hansen et al. 2010, Glick et al. 2011). For example, managing high levels of eutrophication from runoff can decrease the severity of the impacts of localized ocean acidification and hypoxia on fish stocks (Ekstrom et al. 2015). Increased interagency coordination among fishery management agencies and other state agencies (e.g., coordination with the California Department of Water Resources and the State Water Resources Control Board to address water quality issues) could help create management strategies to reduce compounding stressors on fish stocks, thus strengthening fishery resilience and the ability to adapt to rapid change (e.g., Fluharty 2011, Griffis et al. 2013, Sydeman et al. 2015).


Image credit: U.S. Department of Agriculture

1.2 Apply the precautionary principle in stock management

Relevant scenarios: Historical Variability, Increased Variability, Crossing Thresholds

Challenges in determining the status of fish stocks have led to uncertainty about stock abundance and/or biomass. Additionally, with increased climate variability (magnitude and/or periodicity) the biomass of fish stocks may respond in unpredictable ways that may be more difficult to estimate or project. Some species may be more vulnerable to variability than others. For these reasons, applying the precautionary principle for stocks that are expected to be negatively impacted by climate change can help ensure that sufficient biomass remains in the environment so that the stocks are better able to respond to environmental variability or other stressors (Garcia 1994, Hilborn 2001, Sydeman and Thompson 2013). Management actions that may be implemented include increasing the buffer in catch limits or managing for population structure (see below). Harvest control rules that reflect threshold-based approaches within which fishing mortality rates decline to levels approaching zero as stocks decline, (e.g. 40:10, 60:20 rules) could reduce the likelihood of overexploitation, and such rules can be tuned or simulated to develop the appropriate levels of risk avoidance and precaution as determined by managers (Restrepo and Powers 1999, Deroba and Bence 2008, Punt et al. 2008). For example, the Pacific Fishery Management Council (PFMC) applied a biomass ratio to manage groundfish and it is included in the control rules within the State's Nearshore Fishery Management Plan. Applying the precautionary principle does affect the amount of fish available for fishing, so managers and decision makers should collaboratively work with fishermen to help ensure that the catch limits protect vulnerable species as well as fishing communities.

1.3 Manage for population structure

Relevant scenarios: Increased Variability

Fecundity (e.g., egg and/or larval quantity or quality) and reproductive behavior (e.g., timing of spawning) typically increase and/or change, respectively, as fish age. Populations that have a diverse age-structure are better able to respond to environmental variability and prevent age- or size-truncation. The benefits of a diverse age-structure are especially true for long-lived stocks (Longhurst 2002, Berkeley et al. 2004, Hixon et al. 2014). Implementing slot limits, in addition to the minimum size regulations currently implemented, can protect older age classes and increase the range of age-classes of a stock, although such approaches are difficult to implement for species that have significant mortality associated with catch and release. Additionally, MPAs may be able to provide protection for the full range of ages for some key species. Some MPAs have shown evidence of increasing mean fish size and abundance within MPAs following implementation, and in some cases, even beyond MPA boundaries (Caselle et al. 2015, Starr et al. 2015).

1.4 Evaluate vulnerability of fish stocks

Relevant scenarios: Historical Variability, Increased Variability, Crossing thresholds, Range Shifts

A ranked vulnerability index of fish stocks would assist in the prioritization of investment and management action, including FMP development. Efforts are underway in California and elsewhere to evaluate the potential of using ecological risk assessments that incorporate risk due to climate change to evaluate fisheries. It will be important to evaluate and build from tools already developed (e.g., Samhouri et al. 2012, Hare et al. 2016) to be efficient among the state and federal entities that manage fisheries.

1.5 Expand climate and fisheries research

Relevant scenarios: Historical Variability, Increased Variability, Crossing thresholds, Range Shifts

Increased understanding of how fisheries (the governance, social, economic, and ecological system components) respond to climate change allows managers to make better decisions. Identifying gaps in knowledge and encouraging research in these areas is a critical first step. Funding and institutional support for research and collaboration with independent scientists is needed. In particular, research that evaluates the outcomes of management actions under different ecosystem, economic, and policy scenarios will help identify approaches that are most successful in achieving ecosystem-based management goals in a changing ocean.

1.6 Protect nursery grounds and/or essential fish habitat

Relevant scenarios: Increased Variability

As nursery habitat for fish such as salt marsh, tidal flats, and drift algae may be impacted by sea level rise, storms, or other sources of degradation, these habitats should be protected. Doing so will benefit species during early life stages, which are particularly sensitive to stressors (Griffis et al. 2013, Hughes et al. 2014). In addition, important breeding and foraging grounds may warrant protection or restoration to support healthy fish stocks and facilitate range shifts. Collaborations among federal, state, and local agencies and non-governmental organizations are essential for identifying these critical habitats and developing and implementing strategies to buffer, protect, and increase these habitats' resilience. Examples include the Pacific Marine and Estuarine Fish Habitat Partnership's Nursery Habitat Assessment and projects through the North Pacific Landscape Conservation Cooperatives.

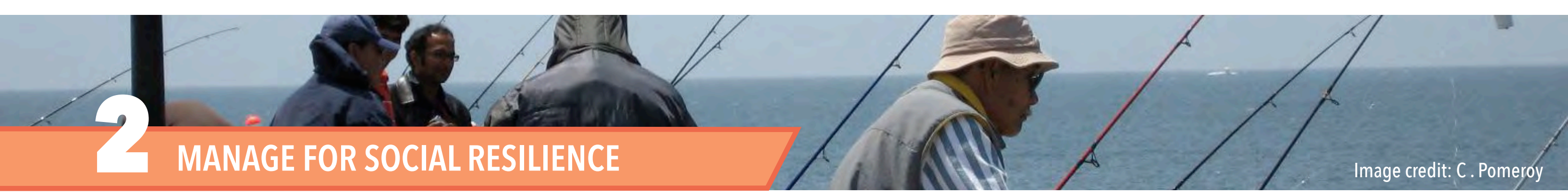


Image credit: C . Pomeroy

2 MANAGE FOR SOCIAL RESILIENCE

There are many approaches that managers could take to make the social system better able to respond and recover from impacts related to climate and ocean changes. We define social resilience as "the ability of groups or communities to cope with external stresses and disturbances as a result of social, political and environmental change" (Adger 2000). Managing for social resilience includes approaches that allow fisheries participants to change the mix of fisheries targeted, take advantage of new fisheries, and withstand or recover from fisheries collapses and long-term change.

2.1 Adopt flexible permitting mechanisms

Relevant scenarios: Increased Variability, Range Shifts

Flexible permitting mechanisms could provide a means to allow fishery participants to hedge their risk, adapt to variable production or unexpected closures, and respond to shifts in species spatial distribution or range shifts (Miller and Munro 2004, MacNeil et al. 2010). Flexible permitting could include measures such as annual leasing of permits, transferrable permits, and integrating gear flexibility into permits or other regulations. In addition, flexible permitting could include allowing fishermen to transfer their permits to other fishermen or gain new permits to facilitate matching their effort to fishery shifts (Morrison and Termini 2016). This strategy already exists in some fisheries (e.g. hagfish fishermen have a choice of three different gear types). Additionally, mechanisms for supporting transition among fishery participants to different fisheries could help account for changes in species composition and abundance and allow fishermen to target locally abundant fish stocks (e.g., one stock becoming more plentiful, while another decreases) (MacNeil et al. 2010, Mills et al. 2013). Similarly, transferable and leasable permits could allow fishermen to change what they fish for and adapt to changes in species composition and abundance (Mills et al. 2013). One of the challenges of flexible permitting mechanisms, however, is how to keep effort, as well as costs to fishermen, under control. Another challenge is the time and resources required to change law and regulations.

2.2 Promote collaborative planning and research among fishermen, managers, and partners

Relevant scenarios: Historical Variability, Increased Variability, Crossing Thresholds, Range Shifts

Fishermen have a wealth of local knowledge regarding fish stocks and fish migration patterns, and local knowledge is an important source of information in understanding fisheries. The cumulative local knowledge that fishermen have regarding fishery conditions (e.g., ocean conditions, fishing grounds, stock distribution, and behavior) is crucial in helping monitor and understand fish stocks (Lipschutz and Pomeroy 2003). Fishermen may be able to recognize patterns of change in local fish stocks earlier than scientists due to their frequent fishing trips. Additionally, fishermen may be able to provide explanations for the patterns and shifts they are seeing. Based on culture, perception, and capabilities, fishermen may have ideas regarding adaptation options that could help shift management to better adapt to variable oceanographic conditions and associated fishery changes (Clay and Olson 2008). For example, a Sentinel Fleet is collecting data on stock abundance indices in Canada and in Maine for spatially explicit groundfish data. Collaboratively mapping community spaces has also been useful for gathering fishermen's knowledge and information about fishing practices in the Northeast (St. Martin and Hall-Arber 2008). Some studies posit that those who have a role in decision-making are more likely to consider resulting regulations legitimate, leading to increased compliance (e.g., Wilson et al. 2003). Despite these benefits of collaborative research, it can be more time-consuming than top-down approaches and some fishermen may be reluctant to participate as a result of mistrust, fear of more restrictive regulations, and negative past experiences.

2.3 Work with fishing communities to plan for unexpected changes

Relevant scenarios: Increased Variability, Crossing Thresholds

In light of potential fisheries closures related to natural variability or climate change (e.g., the 2016 delayed opening of the Dungeness crab fishery), there is a need for managers to work with fishery participants (among others) to identify and implement strategies for coping with and adapting to such challenges. Existing strategies for coping, adapting, and minimizing negative consequences are often insufficient (see Dungeness crab case study). Mechanisms to consider include: a fisheries insurance program (see Greenberg et al. 2002, Herrmann et al. 2004, Sethi 2010 for pros and cons), development of an emergency fund for fishing communities, increasing livelihood diversification, and training programs for skills that could be used in or out of the fishing industry.

2.4 Evaluate vulnerability of fishing communities

Relevant scenarios: Increased Variability, Range Shifts

Some communities, as well as individuals within communities, will be more severely affected by climate change than others. Methods to rapidly assess vulnerabilities of fishing communities to climate change impacts (including infrastructure damage from sea level rise and changes in the abundance and distribution of fished species) can provide the information needed by managers to minimize impacts when developing management plans and regulations. Vulnerability assessments should be scaled appropriately, consider the interconnectedness of fishing communities at a regional scale, and account for the complex social dynamics of fishing communities.

The National Marine Fisheries Service (NMFS) is measuring vulnerability of federal fish stocks and fishing communities to climate change (Hare et al. 2016, Colburn et al. 2016) on the west coast, and is willing to work with the state of California to develop a state vulnerability assessment (M. Nelson, pers. comm., 2016). In building this assessment, we caution against relying too heavily on economic data to evaluate trade-offs or identify vulnerabilities, as such data do not adequately capture the diversity of social and cultural values and drivers of human behavior and well-being, and can lead to unintended negative consequences (e.g., Lyons et al. 2016).


Image credit: C. Pomeroy

3 INCREASE MANAGEMENT ADAPTABILITY

Given the substantial variability and uncertainty that is expected to be associated with climate change, it will be important to ensure that fisheries governance is prepared to anticipate and respond effectively and appropriately to climate change. Implementing strategies to increase management adaptability should not be done at the expense of stock sustainability, as per the mandate of the MLMA.

3.1 Incorporate adaptable catch control rules

Relevant scenarios: Historical variability, Increased Variability, Crossing Thresholds, Range Shifts

Adaptable harvest control rules may be applied to adjust fishing effort in accordance to historical and increased variability due to climate change (e.g., changes in stock levels and shifts in spatial distribution) (Mohn and Chouinard 2007, Ogier et al. 2016). Current management decisions for assessed species are often based on estimates of sustainable fishing mortality rates (often in addition to biomass thresholds or other measures), which represent the instantaneous mortality rates of fishes in a population as a result of fishing, while also accounting for natural mortality due to predation or disease. Sustainable mortality rates are based on estimates or proxies (derived from meta-analyses or simulation studies), and applied to estimates of stock abundance to determine total allowable catches. Although these are typically static values representing equilibrium-based estimates, in some instances fishing mortality rates have been based on climate proxies (reference sardine breakout box). Similarly, threshold-based harvest control rules could allow for adjusting maximum catch levels based on shifts in stock biomass in response to variable, increasing, or declining fish and invertebrate stock production (Restrepo and Powers 1999, Deroba and Bence 2008, Hoggarth et al. 2006). Effort-based control rules instead of catch-based control rules could help account for variability in fisheries production in species with fast responses to climate variability that will be difficult to monitor (e.g., market squid). Implementing control rules based on catch-per-unit-effort (CPUE) could also be useful when other fishery data are limited (Little et al. 2011), potentially even using MPAs as reference areas to design harvest control rules (McGilliard et al. 2010, Babcock and MacCall 2011). However, CPUE can be influenced by many factors, including trends in knowledge, fishing power or efficiency over time that may bias the perceived status of resources if not standardized appropriately, reducing the ability to rely on this metric for management decisions (Maunder and Punt 2004). Incorporating any of these adaptable catch control rules requires quality data and monitoring, staff to interpret and analyze data, and it is far more reliable when based on fisheries independent data. These needs pose a challenge for implementation, which highlights the need for social and ecological indicators and collaborative, streamlined monitoring articulated further below.

3.2 Account for climate change in stock assessments

Relevant scenarios: Historical Variability, Increased Variability, Range Shifts

Predictions of stock biomass may be improved by incorporating environmental variability and uncertainty into stock assessments. Stock assessments should be modified, where it is deemed useful, to capture effects of environmental variability on stock productivity, which may be relevant for species with density-independent recruitment patterns associated with environmental variability (e.g., PDO, ENSO). Developing and adding climate or ecological indicators, such as temperature or Multivariate Ocean Climate Index, into stock assessments (e.g., MacKensie et al. 2008) has the potential to make them inherently responsive to variability, whether it be natural or anthropogenic climate change. In addition, stock assessments that are spatially-explicit will be better at capturing regional differences in stock productivity. A clear challenge in this endeavor is the need for much improved monitoring, data, and understanding of the population dynamics of most of California's managed stocks.

3.3 Move single-species conservation area boundaries when needed

Relevant scenarios: Range Shifts

Long-term shifts in species spatial distribution raises the concern for the potential spatial mismatch between conservation area boundaries and the target fished species they were designed to protect. As species distributions shift, managers will need to evaluate conservation area boundaries and consider adjusting these zones if they are no longer effective in protecting the target fished species (e.g., rockfish/cowcod conservation areas). Boundaries may be defined by latitude or longitude coordinates or by depth, which may be particularly relevant for species that shift their vertical distribution to avoid hypoxic zones. Challenges with conservation area boundaries relocation include determining the appropriate placement of refugia to protect stocks and implementing changes in time to help protect species. Conservation areas are implemented for a different management purpose than broad-purpose MPAs (e.g., California's statewide MPA network, the purpose of which is provided in the MLPA goals and objectives). This management approach targets conservation areas and is not intended to be applied for broad-purpose protected areas.

3.4 Change seasonal closures when needed

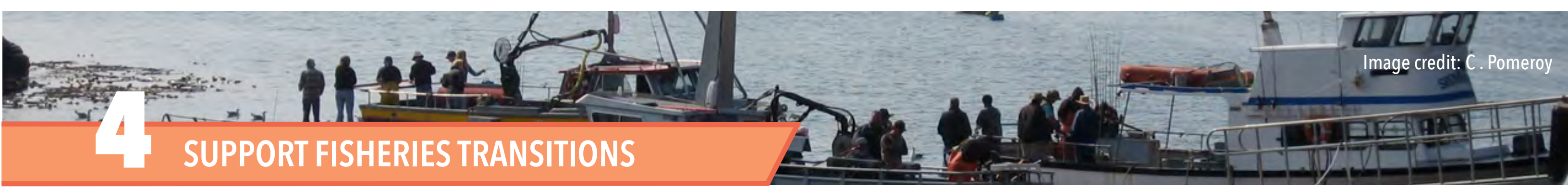
Relevant scenarios: Range Shifts

Seasonal closures are an important management tool to protect species reproduction. Change in species phenology due to changing ocean conditions (e.g., temperature rise, earlier onset of the spring transition) may result in temporal mismatches between seasonal closures and the phenology of species. There is a need to evaluate and adjust (shortening, lengthening, or shifting) seasonal closures to reflect current stock phenology. Relevant ecological indicators and monitoring are needed to determine when and which species may be appropriate to adjust seasonal closures. Once identified, ecological indicators could be incorporated into protected area monitoring and planning efforts to help identify changes.

3.5 Incorporate changes in indicators/ecological factors into management

Relevant scenarios: Historical Variability, Increased Variability, Crossing Thresholds, Range Shifts

Equally important as monitoring and forecasting for effectively integrating and responding to existing variability, is linking monitoring information to management approaches. There is a need to evaluate monitoring programs and develop social and ecological indicators from these data collection efforts that appropriately and accurately reflect the status, vulnerability, and/or feedbacks within the social-ecological system. For management to appropriately and effectively prepare for and respond to natural variability and climate change impacts, there needs to be a mechanism by which monitoring and forecasting information is linked or incorporated into management tools (e.g., setting harvest control rules, adaptable catch control rules, timing of seasonal closures, etc.), such that a decision or regulation is influenced by a change in an indicator. Modeling or scenario testing can identify appropriate thresholds. Pre-arranged thresholds can be helpful for triggering action. In addition, dynamic ocean management provides an opportunity to link real-time data on environmental changes to management approaches or options that move with environmental features (Hobday et al. 2014, Lewison et al. 2015, Maxwell et al. 2015, Dunn et al. 2016). CDFW is also developing an electronic fishery landings reporting system, which will increase the speed and flow of information to enable more timely management actions.



4 SUPPORT FISHERIES TRANSITIONS

If the productivity of fish and invertebrate stocks is reduced with changing ocean conditions, this could negatively impact fisheries participants and necessitate diversification or even transition out of capture fisheries. On the other hand, there could be opportunities to support fishermen in targeting emerging fisheries for stocks that have not been targeted historically (Pinsky and Mantua 2014).

4.1 Manage for human well-being

Relevant scenarios: Historical Variability, Increased Variability

Tracking only economic growth has been detrimental to social and environmental systems, and has prompted the need for measuring human well-being. Human well-being is multi-dimensional; "a state of being with others and the environment" arising "when human needs are met, when individuals and communities can act meaningfully to pursue their goals, and when individuals and communities enjoy a satisfactory quality of life" (Hicks et al. 2016, p. 38). Recent work (Breslow et al. 2016, Hicks et al. 2016) established a framework of human well-being with a wide range of indicators developed as part of work on an integrated ecosystem assessment of the CCLME. The framework offers a way to make social science usable by environmental scientists, managers, and others, in addition to drawing attention to needed research. Ultimately, the goal is to improve human well-being as an integral part of environmental sustainability. Critical gaps still remain with respect to indicator development as well as qualitative assessments for development, implementation, and interpretation of robust measurement systems (Hicks et al. 2016). Managers may consider coordinating with fishing communities and organizations, such as Sea Grant, on indicator development, qualitative assessment, and marketing programs. Additionally, shoreside service providers such as wharves, processing plants, and institutional buyers of seafood must be included in management discussions.

4.2 Prepare for emerging fisheries

Relevant scenarios: Increased Variability, Range shifts

To prepare for new and growing fisheries that are not currently subject to specific regulation (emerging fisheries), managers and decision-makers should create a defined management strategy that provides opportunities for fishermen to target new species while ensuring that any new fishery is sustainable. This strategy should include increased monitoring efforts including fishing effort (Madin et al. 2012), and a moratorium on targeting new fish stocks that are available because of range shifts until stock levels can be addressed (Pinsky and Mantua 2014). The Pacific Fisheries Management Council recently implemented such a moratorium on new fisheries for a broad suite of forage species, including those that may expand northward in range into U.S. West Coast waters, such as round herrings and thread herrings (PFMC 2016). A management strategy that outlines how to target potential emerging fisheries could also help account for potential future shifts in fisheries production. Challenges include the ability to adapt quickly enough to newly emerging fisheries in California due to migration shifts to capitalize on new and abundant species (see market squid case study). Research indicates that it is better to limit harvest of species shifting into the area until the populations establish themselves (Pinsky and Fogarty 2012).

4.3 Establish a new permitting program/policy to change access to expanded fisheries

Relevant scenarios: Increased Variability, Range Shifts

In the event that fish stocks undergo range shifts, opportunities may arise to target expanded fisheries. A new program, legislation or policy may be developed utilizing indicators of stock range shifts and status to allow temporary changes to access expanded fisheries. Such a program could create a special permit lottery with a multi-criteria qualifying scheme based, for example, on factors such as number of years as a fishery participant, geographic criteria, dependence of fishing for livelihood, etc. Expanding existing permitting processes into a program for expanded fisheries may improve resilience to variable conditions.

4.4 Plan for tipping points

Relevant scenarios: Crossing Thresholds

To prepare for potential tipping points, managers and decision makers could develop a plan as a precautionary measure to prevent avoidable costs. As part of this planning process, managers may define what constitutes a tipping point for a fishery (e.g., a level of an indicator) and outline appropriate approaches to alleviate social, ecological, and economic costs associated with that tipping point being crossed. These approaches may include processes for rebuilding the fishery and addressing larger tipping point events. Annual efforts to characterize the status of the CCLME (e.g., CalCOFI reports of the State of the California Current) may help identify changes in ecosystem integrity and support efforts to define ecological tipping points.

Case Study 3: Climate indicators in the California Sardine fishery

Image credit: NOAA National Marine Sanctuary

The operational use of environmental indicators in fisheries management is currently limited to a small number of applications. The limited use of environmental indicators in stock assessments stems in part from a history of frequent failures of environment-recruitment relationships when applied in true forecast settings (Myers 1998). These failures are thought to be a consequence of the extreme difficulty in observing early life history dynamics. In addition, the complex nature of natural variation (e.g., ENSO, PDO) makes it difficult to isolate a single factor that drives or predicts recruitment. The dominant processes driving variation are also thought to change through time. It is clear that variable survival of early life stages in many cases substantially contributes to recruitment variations for many marine fish and invertebrate populations.

The California sardine fishery is one of two having a climate indicator explicitly written into its harvest control rule. Studies have repeatedly shown that upper ocean temperatures are related to both spawning biomass and recruitment (Jacobson and MacCall 1995, Jacobson and McClatchie 2013). The harvest rule includes a cutoff, the lowest level of biomass at which a direct harvest is allowed, and a harvest rate on the biomass above the cutoff. The harvest rate depends on temperature, with higher harvest under warmer temperatures and lower under cooler temperatures, though always between 5 and 20% of the allowable harvest (PFMC 2014, Hill et al. 2015). Simulations suggest that the probability and duration of the drastic sardine collapse in the early 1950s could have been substantially reduced if harvest rates had been lower during that cold phase (Lindegren et al. 2013).

Generally, the ability to develop robust management rules related to environmental indicators depends on either clearly understood physical-biological links or robust statistical relationships that have been identified with long time series of historical data. The tight link between temperature, recruitment, and biomass observed in Pacific sardine may favor use of a harvest control rule that incorporates ecosystem and population factors, but the approach may not be useful in other stocks where these links are weaker or less consistent over time (Kvamsdal et al. 2016).

Image credit: Viinzography

5 STRENGTHEN MONITORING AND FORECASTING

Image credit: J. Pederson / NOAA MBNMS

Improving targeted monitoring and forecasting will help managers better understand fluctuations in oceanographic conditions and ecosystem responses (Pecl et al. 2014).

5.1 Increase collection of effort information

Relevant scenarios: Historical Variability, Increased Variability, Crossing Thresholds, Range Shifts

Improved data collection on fishing effort in addition to fisheries landings (i.e., catch) is needed to adequately calculate CPUE and effectively detect trends in fish stocks on relevant timescales. Without CPUE data, it will be very difficult for managers to detect declines in fish and invertebrate stocks and, as a result, implement management actions in time to slow or reverse declines in catch. One implementation strategy is to expand effort information in logbook reporting for key fisheries, which is currently implemented for some fisheries (e.g., Spot prawn).

Effort and outcomes can be influenced by many factors, including changes in costs, buyers and prices (for commercial fisheries), information and knowledge, conditions in other, related fisheries, technology (equipment, gear), as well as individual values and preferences. Understanding how these forces affect effort and outcomes (including CPUE) is essential to ensuring that it is interpreted appropriately and accurately (Maunder and Punt 2004).

5.2 Identify critical biophysical, social, and ecological indicators to monitor

Relevant scenarios: Historical Variability, Increased Variability, Crossing Thresholds, Range Shifts

In anticipation of the potential for biological and/or ecological tipping points, development of biophysical and ecological indicators can allow better detection and prediction of when species have begun to experience range shifts, decline in abundance or cross thresholds (e.g., abrupt shifts in SST and concomitant declines in stock abundance described in Bernhardt and Leslie 2013). There are some existing data streams that may be evaluated for their potential utility as indicators in this context.

For example, MOCI synthesizes a number of local and regional ocean and atmospheric variables that capture and represent, in a holistic manner, the state of the coastal ocean, and as such provides management with up-to-date information on seasonal and regional ocean conditions. Data included in MOCI was selected as indicator of a physical process that is known to influence the marine ecosystem. The index illustrates major ENSO events, as well as the phasing and magnitude of the most recent North Pacific marine heat wave, 'The Blob'. The index may also enable forecasting marine ecosystem dynamics, from zooplankton to top predators, and therefore may be useful in establishing bio-physical relationships important to ecosystem-based fisheries and wildlife management in California. While the ecological relevance and climate connection of MOCI has been clearly demonstrated (Sydeman et al. 2014, Garcia-Reyes and Sydeman 2016), the application of MOCI to management, and particularly management of fisheries relative to climate change, requires additional synthesis of long-term fisheries and environmental data and further research.

Currently, CDFW collects landing receipts that record the port of landing making this a potential way to detect if range shifts of target species have occurred. Coordinating with partners (researchers, fishermen) should be part of the development process, to ensure indicators are appropriate, relevant, and effective at detecting changes in the status of stocks or fisheries on a time-scale that is sufficient to implement management interventions prior to any significant collapse or threshold being crossed. Strengthened monitoring would also help determine potential increases in fishery productivity. This could help predict subsequent needs for fishing communities to alter their fishing grounds or fished species to adapt to changing conditions (Griffis et al. 2013). The key social indicators noted in #2 under "Support fisheries transitions" should also be monitored since the well-being of fishermen and their communities can affect responses to climate change, leading to social "tipping points." In addition, indicators of ecosystem integrity within the NMFS Integrated Ecosystem Assessment may help identify useful indicators for state-managed fisheries as well as provide an ecosystem perspective to support ecosystem based fisheries management.

5.3 Expand monitoring to inform both MLMA and MLPA objectives

Relevant scenarios: Historical Variability, Increased Variability, Crossing Thresholds, Range Shifts

There is a need for continued and improved ecological and socioeconomic monitoring, particularly under a variable and changing climate. It will be important to collaborate with partners (researchers, fishermen, shoreside businesses, and organizations) to expand monitoring programs. MPAs should be used to identify separate and combined ecological consequences of fishing and climate change. There are currently efforts in California to develop MPA monitoring metrics that will also benefit fisheries management. A wide range of indicators already exists for measuring well-being, values, agency, and inequality (Hicks et al. 2016) and could be adapted to the California context.

5.4 Streamline monitoring programs

Relevant scenarios: Historical Variability, Increased Variability, Crossing Thresholds, Range Shifts

Considering the costs associated with monitoring, and the limited funding and capacity available, monitoring programs need to coordinate their efforts so that costs may be minimized or leveraged by streamlining monitoring and reducing duplicative or unneeded monitoring effort. For example, monitoring of key social and ecological indicators may serve to inform when it is important to increase monitoring efforts (i.e., additional monitoring or higher frequency), such as during a harmful algal bloom. This type of use of indicators will help prevent unnecessary costs of continuous, high-frequency monitoring, while also ensuring that additional monitoring assets are deployed when needed. As part of this process, collaboration with partners is needed to identify overlaps and complementarities among existing monitoring programs. However, programs should ensure that the frequency and spatial resolution of monitoring as well as key data requirements are addressed in these collaborations so that programs continue to meet management/study goals.

5.5 Inventory ecological hotspots

Relevant scenarios: Increased Variability, Crossing Thresholds

The ability to focus resources on areas that may be more seriously affected than other areas will help to prioritize future funding, research, and management investments. Identifying and mapping locations vulnerable to ocean acidification, hypoxia, and other climate change impacts will help clarify next steps. Collaborating with researchers will help determine which locations, including MPA sites, may be more vulnerable to climate change. The hotspots inventory should be used to focus management efforts on specific coastal regions and the associated marine resources and fishing communities. Initial efforts are underway, including California Ocean Protection Council investment in inventorying areas vulnerable to ocean acidification.

5.6 Support regional climate change impact projection projects

Relevant scenarios: Increased Variability, Crossing Thresholds, Range Shifts

There is a need to downscale climate models to provide long-term forecasts with greater temporal and spatial resolution to inform management decisions. High spatial resolution downscaling and seasonal forecasts are particularly important to capture processes like upwelling. Improved climate projections would allow managers to more quickly align management approaches to changing conditions. In addition, fishery participants may benefit from projection models because they allow them to plan for potential fishery closures (e.g., domoic acid projection models may provide valuable information to the Dungeness crab fishery participants) or other outcomes. To initiate this process, we recommend collaborating with researchers with expertise in climate modeling to develop these models and subsequently produce long-term projections for priority locations.

5.7 Implement co-monitoring

Relevant scenarios: Historical Variability, Increased Variability, Crossing Thresholds, Range Shifts

Incorporating ongoing data collection by fishermen and citizen science groups into monitoring programs could improve cost-effectiveness of monitoring to meet high data requirements. These efforts are already underway in state and federal fisheries management. For example, scientists and fishermen collaborated to research lobster populations in Southern California as part of MPA baseline monitoring to support MLPA implementation. There is a need to build on and learn from this and similar efforts as well as identify mechanisms to increase salience, credibility and legitimacy. By working collaboratively and including fishermen's knowledge to identify species shifts and fisheries responses, managers and fishing communities may be able to act rapidly, such as implementing changes in control rules or adjustments of quotas and permits.

Image credit: S. Johnson

6 EXPAND CROSS-BOUNDARY COORDINATION

As fish shift northward and into new areas, there will be a need for more regional, national, and international coordination (Pinsky and Mantua 2014). Management solutions must also address both coordination and equity issues as fish stocks relied on by one community move into neighboring fishing areas (Fenichel et al. 2016).

6.1 Increase interagency coordination

Relevant scenarios: Historical Variability, Range Shifts

Solutions to address the effects of climate change on marine resources require collaboration and coordination among agencies (e.g. across the land-sea interface and between jurisdictions). For example, sea level rise could affect nursery grounds of valued species and necessitate coordination between CDFW and the State Water Resources Control Board or other agencies.

One of the challenges of EBFM is to fashion ways to ensure that the actions of the coastal and fisheries institutions at each level of government are harmonized with one another and are consistent with agreed EBFM goals and policies. Though challenging, management decisions that are matched to the spatial scale of the ecosystem, to the programs for monitoring all desired ecosystem attributes, and to the relevant management authorities are likely to be more successful in achieving ecosystem objectives.

6.2 Expand transboundary fisheries management

Relevant scenarios: Historical Variability, Increased Variability, Range Shifts

Both short- and long-term shifts of species across political boundaries require coordination to protect stocks from overfishing and address questions of equity. Species previously common to California that shift their range into Oregon, for example, could require inter-state cooperation on issues such as permitting, catch limits, and stock monitoring (Miller and Munro 2004). For example, increasing temperature could result in a northward shift in the range of some nearshore rockfishes, such that the core of their range moves into Oregon. One example of transboundary fisheries management occurred in 1996, when the Tri-State Dungeness Crab Committee was established to enable the three West Coast states to coordinate management of their respective fisheries. The committee is composed of state agency, processor, and fishermen representatives from Washington, Oregon, and California. Similarly, international cooperation could be necessary between California and Mexico for subtropical species that shift northward from Mexico into California.

Currently, federally-managed fisheries are coordinated among states and the federal government through the PFMC. NMFS coordinates with other countries to manage some Eastern Pacific stocks. One could build upon these efforts and facilitate coordination across political boundaries, particularly for stocks with a high potential for either short- or long-term range shifts. There is a need to track trends in fishing of key stocks by adjacent states or countries and begin a dialogue to facilitate management coordination if changes in catch or effort reaches levels, which if sustained, may cause the stock to be overfished. Differences in size and complexity among California, Oregon, and Mexico create inherent challenges to alignment of management for new transboundary fish or invertebrate stocks. Early cooperation, before changes are significant, is essential.

6.3 Expand meaningful engagement with Tribes and Native Communities

Relevant scenarios: Historical Variability, Range Shifts

As marine populations shift, collaboration and coordination will be needed to address tribal and Native Communities' fishing needs if stocks traditionally harvested move out of the area and other stocks become available. Collaborating closely with Tribes and Native Communities could help to determine potential effects, including distribution shifts, from climate change on traditionally harvested stocks as well as cultural, subsistence, and commercial practices. Tribes and Native Communities will also need assistance in developing capacity to address climate change impacts. Tribes and Native Communities are currently consulted on a government to government basis through the FGC and the Department's Tribal Policies. Similar to the transboundary consideration, early communication and steps toward cooperation are essential.

Image credit: C . Pomeroy

7 INCREASE RESEARCH & MANAGEMENT CAPACITY

7.1 Identify and address personnel and funding needs

Relevant scenarios: Historical Variability, Increased Variability, Crossing Thresholds, Range Shifts

One of the hindrances to fully implementing the MLMA has been limited resources for fisheries management (Harty et al. 2010). Climate change will exacerbate this issue. Identifying personnel and funding needs, ways to use existing resources more efficiently, and partnering with independent scientists are all strategies currently being employed by CDFW to address this challenge. New dialogues with partners (including potential funders, researchers, and fishermen) may reveal new creative approaches to meet resource needs.

7.2 Expand training and other capacity-building opportunities for fisheries professionals

Relevant scenarios: Historical Variability, Increased Variability, Crossing Thresholds, Range Shifts

There is a need to invest in training for fisheries professionals. The increasing complexity of managing fisheries, particularly with climate change, requires that fishery researchers and managers have the necessary knowledge and required skills to address the problems they may face. Training would be beneficial to those currently in positions or those who are studying to take on this work. The Marine Resource Education Program (MREP) in the Northeast could be a useful model. Working with university partners, other educational organizations, Sea Grant, and the American Fisheries Society could help ensure that required training classes and materials are available to meet the needs of current and future fishery researchers and managers.

Image credit: R. Starr

Table 3. Management approaches for climate-ready fisheries in California.

1. Manage for Ecological Resilience

Approach	Management Context	Potential Actions
1.1 Reduce compounding stressors Reduce compounding non-climatic stressors (e.g., pollution) that interact with climate change impacts and have negative effects on fish	• supported by MLMA and MLPA • addressed in NMFS Ecosystem plan, essential fish habitat designations, and associated initiatives • addressed in CA 2015 State Wildlife Action Plan	• increased interagency coordination to reduce stressors on fish stocks • reduce habitat loss and degradation • use MPAs or other protected areas to create refugia from harvest and to support resilience from other stressors
1.2 Apply the precautionary principle in stock management Apply the precautionary principle in stock management for those stocks that are expected to be negatively impacted by climate change	• supported by MLMA with gradual implementation	• increase buffer in catch limits • adjust catch limits using the status of current biomass to unfished biomass and life history traits
1.3 Manage for population structure Protect age-structure diversity in fish stocks	• supported by MLMA and MLPA • MPAs implemented	• implement slot limits • ensure that MPAs protect full range of ages for key species
1.4 Evaluate vulnerability of fish stocks A ranked vulnerability index of fish stocks would assist in the prioritization of investment and management action	• supported by MLMA • NMFS implementing for federally managed stocks	• build on tools and existing projects to evaluate vulnerability of stocks • coordinate with state and federal entities that manage fisheries
1.5 Expand climate and fisheries research Increase understanding of how fisheries respond to climate change	• supported by MLMA	• identify key gaps in knowledge and encourage research on social-ecological systems
1.6 Protect nursery grounds and/or essential fish habitat Work with agencies and partners to protect fish habitat	• supported by MLMA • supported by MLPA	• collaborate with federal, state, and local partners to identify critical habitats

2. Manage for Social Resilience

Approach	Management Context	Potential Actions
2.1 Adopt flexible permitting mechanisms Processes that provide flexible permitting, both at the individual fisherman level as well as for groups (co-ops; fishing communities)	• supported by MLMA with gradual implementation	• facilitate lease/transfer their permit(s) to other fishermen • integrate gear flexibility into fishing permits or other regulations
2.2 Promote collaborative planning and research among fishermen, managers and partners Fishing communities brainstorm with managers about adaptation approaches; collaborative research projects can improve fisheries and MPA management	• supported by MLMA and MLPA • MPAs implemented • addressed in CA 2015 State Wildlife Action Plan	• create space for fishing communities to identify ways to bolster resilience • brainstorm adaptation approaches
2.3 Work with fishing communities to plan for unexpected changes Collaborate to identify and implement strategies for coping with and adapting to challenges associated with climate change	• federal disaster relief programs • FGC fishing community discussions	• coordinate with fishing communities to brainstorm adaptation strategies
2.4 Evaluate vulnerability of fishing communities Develop methods to rapidly assess vulnerability of fishing communities	• supported by MLMA • NMFS implementing for federally managed stocks	• build on tools and existing projects to evaluate vulnerability of fishing communities • coordinate with state and federal entities that manage fisheries

Table 3 cont. Management approaches for climate-ready fisheries in California

3. Increase Management Adaptability		
Approach	**Management Context**	**Potential Actions**
3.1 Incorporate adaptable catch control rules Adopt rules to adjust fishing effort in accordance to historical and increased variability due to climate change	• supported by MLMA • limited implementation • requires additional information	• control rules based upon CPUE when other fishery data are limited • catch control rules that integrate measurements of "fishing mortality rates" as a parameter that is responsive to a stock productivity indicator • "sliding" control rules (e.g., threshold-based harvest control rules)
3.2 Account for climate change in stock assessments Incorporate environmental variability and uncertainty into stock assessments	• supported by MLMA • limited implementation by NMFS • requires additional information	• develop and add climate indicators to stock assessments • implement spatially-explicit stock assessments
3.3 Move single-species conservation area boundaries when needed Adjust conservation area boundaries if no longer effective in protecting the target fished species (e.g., rockfish conservation areas)	• supported by MLMA and MLPA • limited implementation	• evaluate conservation area boundaries (depth, latitude/longitude) and adjust if no longer effective in protecting the targeted species, species groups, or communities
3.4 Change seasonal closures when needed Adjust seasonal closures to reflect current stock phenology, if needed	• supported by MLMA • limited implementation	• develop and test ecological indicators to determine when and which species may require adjustments to seasonal closures
3.5 Incorporate changes in indicators/ ecological factors into management Link monitoring information to management approaches	• supported by MLMA and MLPA • limited implementation	• develop indicators as they relate to management decisions

4. Support Fisheries Transitions		
Approach	**Management Context**	**Potential Actions**
4.1 Manage for human well-being Improve human well-being as an integral part of environmental sustainability	• supported by MLMA • limited implementation	• coordinate with organizations on marketing programs • include shoreside service providers in management discussions
4.2 Prepare for emerging fisheries Create a management strategy that provides opportunities for fishermen to target new species while ensuring that any new fishery is sustainable	• supported by MLMA • no plan in place for emerging fisheries	• develop default management plan for emerging fisheries
4.3 Establish a new permitting program/ policy to change access to expanded or emerging fisheries Develop new program, legislation or policy utilizing indicators of stock range shifts and status to allow temporary changes to access expanded fisheries	• supported by MLMA • an experimental fisheries permit process for federally-managed species exists through the PFMC and NMFS	• expand existing permitting processes
4.4 Plan for tipping points Prepare management for crossing thresholds	• supported by MLMA • Abalone Recovery and Management Plan includes a measure for closing the fishery if densities decrease to designated levels	• define what constitutes a tipping point for a fishery (e.g., a level of an indicator) and outline approaches to alleviate costs associated with that tipping point being crossed

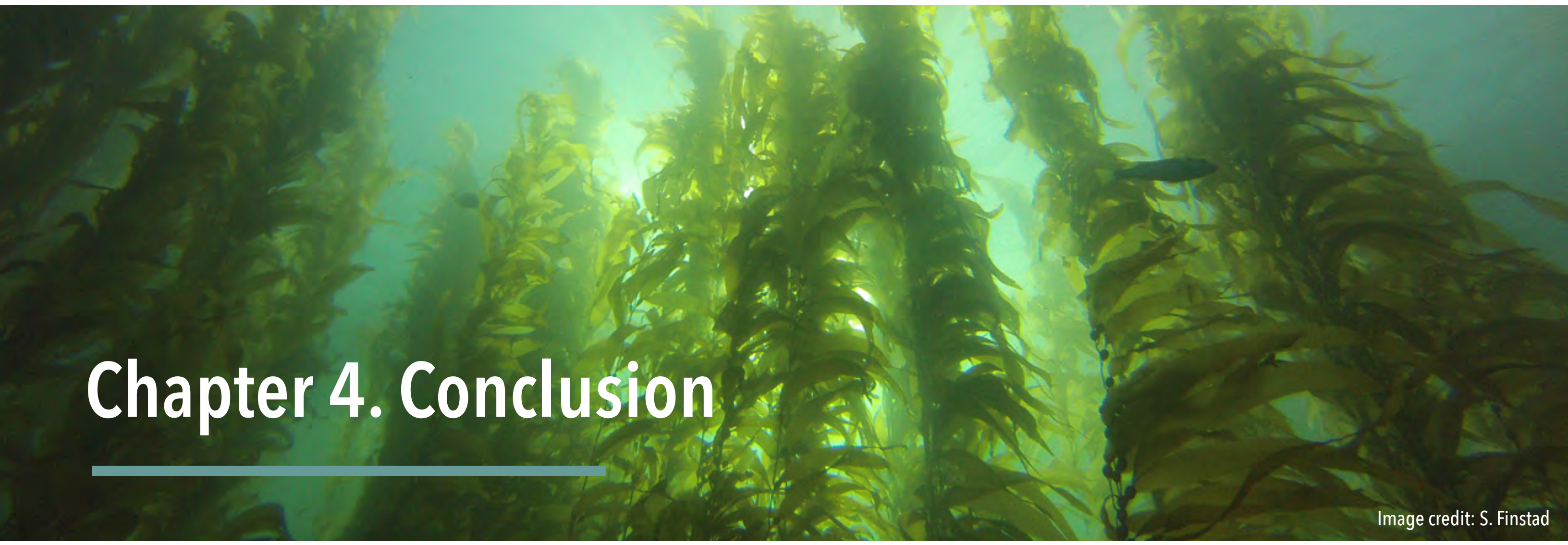
Table 3 cont. Management approaches for climate-ready fisheries in California

5. Strengthen Monitoring and Forecasting		
Approach	**Management Context**	**Potential Actions**
5.1 Increase collection of effort information Improve data collection on fishing effort in addition to fisheries landings	• supported by MLMA • limited implementation for some species	• expand effort information in logbook reporting for key fisheries
5.2 Identify critical biophysical, social and ecological indicators to monitor Develop indicators for better detection and prediction of when species have begun to experience range shifts, decline in abundance, or cross thresholds	• supported by MLMA and MLPA • limited implementation	• strengthen monitoring
5.3 Expand monitoring to inform both MLMA and MLPA objectives Develop MPA monitoring metrics that will also benefit fisheries management	• supported by MLMA • baseline monitoring implemented under MLPA • Facilitation of MLMA-MLPA integration in progress	• collaborate with partners to expand monitoring programs • adapt and incorporate indicators for measuring well-being, values, agency, and inequality
5.4 Streamline monitoring programs Coordinate efforts so that costs may be minimized or leveraged by streamlining monitoring and reducing duplicative or unneeded monitoring effort	• supported by MLMA and MLPA	• collaborate with partners to identify overlaps and complementaries between existing monitoring programs • monitor key social and ecological indicators to determine when to increase monitoring efforts
5.5 Inventory ecological hotspots Identify and map locations vulnerable to ocean acidification, hypoxia, and other climate change impacts	• supported by MLMA and MLPA • West Coast Ocean Acidification and Hypoxia Science Panel Recommendations and Actions	• collaborate with researchers to determine locations most vulnerable to climate change • use information to focus efforts on specific coastal regions (marine resources and associated fishing communities)
5.6 Support regional climate change impact projection projects Downscale climate models to provide projections for specific locations and build long-term forecasting	• supported by MLMA and MLPA	• collaborate with researchers to downscale global climate models and provide long-term projections for specific locations
5.7 Implement co-monitoring Incorporate data collection by fishermen and citizen science groups into monitoring programs	• supported by MLMA and MLPA • Sea Grant has completed pilot projects with the lobster and crab fisheries	• continue to coordinate with partners for small-scale demonstration projects • identify and develop funding mechanisms

6. Expand Cross-Boundary Coordination		
Approach	**Management Context**	**Potential Actions**
6.1 Increase interagency coordination Facilitate coordination across agencies	• supported by MLMA, MLPA, and the 2015 State Wildlife Action Plan	• identify priority fisheries management problems which require broad interagency solutions and develop collaborations among appropriate agencies to address these problems
6.2 Expand transboundary fisheries management Facilitate coordination across political boundaries	• supported by MLMA • coordination of federally-managed fisheries between states and the federal government through PFMC • NMFS coordinates with other countries for some Eastern Pacific stocks	• track trends in fishing of key stocks by adjacent states or countries and begin dialogue to facilitate management coordination if changes in catch/effort reach levels which, if sustained, may cause the stock to be overfished
6.3 Expand meaningful engagement with Tribes and Native Communities Collaborate with California Tribes and Native Communities to determine potential climate change impacts on traditionally harvested stocks	• consulted on a government-to-government basis through FGC and CDFW tribal policies	• early communication and close collaboration with Tribes and Native Communities • assist in developing capacity to address climate change impacts

Table 3 cont. Management approaches for climate-ready fisheries in California

7. Increase research and monitoring capacity		
Approach	**Management Context**	**Potential Actions**
7.1 Identify and address personnel and funding needs Additional personnel and funding will be needed to address new research and management efforts	• supported by MLMA and MLPA • limited resources for fisheries management	• work with partners (including potential funders, researchers, and fishermen) to identify ways to address the need for additional resources
7.2 Expand training and other capacity-building opportunities for fisheries professionals Invest in training for fisheries professionals	• supported by MLMA and MLPA • limited implementation	• work with partners to ensure training and materials are available to meet needs of current and future fishery researchers and managers



Chapter 4. Conclusion

Image credit: S. Finstad

The CCLME is an inherently dynamic system that will continue to experience variability as the impacts of climate change manifest over the coming years and decades. As requested by CDFW, the guidance provided above is intended to allow fisheries managers to continue to foster resilience in California's ecological and fishing communities in light of these changes as the MLMA Master Plan is revised.

The dynamic nature of California's oceanographic and ecological system requires management that is flexible and responsive. Many of the existing management approaches are built upon traditional fisheries management concepts as well as historical trends in fisheries and so are limited in their ability to respond to greater change over relevant temporal or spatial scales. The ability to adaptively manage will be vital to capitalize on new opportunities when conditions are favorable and to prevent unnecessary costs from inadequate planning, research, or precaution. The recommendations described in this guidance document can help build an inherent flexibility and responsiveness of management so that it will be robust to both natural variability and climate change. Collaboration with fishing communities, federal and state agencies, and Tribes and Native Communities is critical to identifying fisheries management challenges and opportunities and to developing approaches that are both effective and equitable.

Appendix A: Glossary

Image credit: T. Fassbender

Adaptation. Adjustments in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities

Adaptive capacity. The ability or potential of a system to respond successfully to climate variability and change, and includes adjustments both in behavior and in resources and technologies

Climate change. A change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer

Ecological change scenario. A plausible future situation that has indirect or direct impacts on fish stocks and fisheries

Emerging fishery. A new and growing fishery that is not currently subject to specific regulation

Expanded fishery. An established fishery that occurs in an area of California that is outside of its historical fishing grounds

Fishery. An integrated social-ecological system composed of three dynamic and interacting elements: an ecological subsystem (including target species and habitat, broadly defined), a social subsystem (people, practices and relationships), and a governance subsystem (the norms, strategies and rules that guide behavior)

Fishing community. A community which is substantially dependent or substantially engaged in the harvest or processing of fishery resources to meet social and economic needs, and includes fishing vessel owners, operators, crew, and fish processors that are based in such a community

Resilience. The ability of a system to absorb perturbations, or the magnitude of disturbance that can be absorbed before a system changes its structure by changing the variables and processes that control its behavior

Tipping Point. The point at which a system undergoes a transition from one regime to another

Vulnerability. The degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change

Appendix B. Overview of California Oceanography and Climate Variability

Image credit: M. Brett

California's state-managed marine waters and living marine resources are part of a much larger feature known as the California Current Large Marine Ecosystem (CCLME). The CCLME is characterized by substantial natural environmental variability (Figures 4 and 5).

The CCLME occupies the region between the east-flowing North Pacific Current (~50°N) and the subtropical waters off Baja California, Mexico (~15-25°N) (Hickey 1979). Within the CCLME is the California Current - a broad, relatively shallow, wind-driven, equatorward-flowing surface current that represents the eastern limb of the North Pacific Gyre - a more swiftly flowing coastal jet, and at depth the California Undercurrent. Seasonal changes in the CCLME follow the seasonal patterns of atmospheric sea level pressure and related surface winds over the Northeast Pacific. Beginning about mid-October, a semi-permanent atmospheric low-pressure cell, the Aleutian Low, intensifies and migrates southeastward to a location centered over the Aleutian Islands and the Gulf of Alaska. Winter surface winds blow in a counterclockwise circulation around the Aleutian Low. To the southeast, winds blow in a clockwise circulation around the North Pacific High, a semi-permanent center of high pressure centered offshore of southern California (Figure 4A).

Together, these high and low atmospheric pressure cells typically bring moist, mild, onshore southwesterly and westerly flow into the northern half of the CCLME through early spring. During late spring, the Aleutian Low retreats to the northwest and becomes less intense, the North Pacific High expands northward and intensifies, and a broad thermally-driven low pressure area develops over the continent. The intense onshore pressure gradient in spring and summer causes a dramatic intensification of equatorward winds along the coast from Southern Oregon to Central California (Hickey 1979, 1998). These winds influence the intensity of equatorward transport and upwelling, two critical processes in the CCLME. Because of the Earth's rotation, equatorward winds drive surface ocean currents offshore, and the transported surface waters are replaced by cool, nutrient-rich waters from greater depths in a phenomenon known as coastal upwelling. Upwelling in the CCLME supplies essential phytoplankton nutrients to the upper ocean where sunlight is abundant. In contrast, poleward winds move nutrient-poor surface waters onshore where they increase the vertical stratification (or layering) of the water column. The resulting stratification and coastal downwelling suppresses the supply of deep nutrient rich waters to the upper ocean. High stratification and downwelling limit the nutrient supply and phytoplankton production leading to "bottom-up" limitations on the productivity of other parts of the marine food-web (Bakun 1996).

A simple model for this strong seasonal variability in the CCLME has a winter characterized by weak upwelling in the south off Baja and Southern California, and strong downwelling in the north off the Oregon coast. The spring transition, a rather abrupt change to strong upwelling, occurs earlier off Central California (March) relative to Oregon (May). During spring and summer, upwelling is interrupted regularly by the passage of weak low pressure systems. Variability between cool-more productive and warm-less productive states is dominated by wind-driven variations at timescales ranging from seasons (Hickey 1979) to years and decades (Hickey 1998, Checkley and Barth 2009), and out to century-long time scales (Johnstone and Mantua 2014). Three basin-scale modes of yearly-to-multidecadal climate variability have had important impacts on the CCLME over the past century: the El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the North Pacific Gyre Oscillation (NPGO). Sedimentary records indicate that centennial and longer variations associated with little and large ice ages have impacted the CCLME. These large-scale climate variations both influence the local atmospheric forcing and remotely generated changes in subsurface ocean properties (nutrient and dissolved oxygen concentrations in source waters for upwelling, subsurface temperature, salinity, depth of the thermocline, etc.).

El Niño events occur once every 3 to 8 years with varying intensity and last between 12-18 months. Their influence on the CCLME is especially strong from October through March (Jacox et al. 2015). El Niño events favor an intense winter/spring Aleutian Low and weakened North Pacific High (Figure 4C), resulting in relatively strong onshore and poleward winds that intensify seasonal downwelling over the northern half of the CCLME, and sometimes weakened equatorward alongshore winds in the southern half of the CCLME leading to weaker than normal upwelling (Jacox et al. 2015).

In addition to the remotely forced changes via the atmosphere in North Pacific winds, ENSO events also produce remotely forced ocean disturbances that influence California's coastal ocean conditions. During El Niño, the easterly trade winds first reverse in the western Pacific and then slacken across much of the tropical Pacific. These westerly wind anomalies send upper ocean "internal waves" from the western Pacific along the equatorial belt to the South American coast and then poleward along the coasts of North and South America (Enfield and Allen 1980, Chelton and Davis 1982, Parres-Sierra and O'Brien 1989). In some years, the El Niño-year coastally-trapped waves propagate all the way to the Gulf of Alaska, deepening the thermocline and eventually warming and stratifying the surface waters along the North American coast, initiating or reinforcing the impacts from the intense Aleutian Low and weak North Pacific High. Likewise, La Niña produces tropical-origin coastally trapped internal waves that shallow the thermocline, cool and weaken the stratification in the surface waters of the California coastal ocean, initiating or reinforcing the wind-driven cooling associated with a weak Aleutian Low circulation (Figure 4B).

The remote atmospheric and oceanic impacts of El Niño events cause warmer conditions in the CCLME that can favor subtropical, more diverse and less productive food-webs. The PDO has been described as a long-lived (25-40 years) weak El Niño-like pattern of Pacific climate variability. The PDO influences the CCLME in ENSO-like ways, with the primary difference being that ENSO events and impacts are stronger but of shorter duration, while those associated with PDO are weaker and persist for a few decades but with strong impacts on the ecosystem (Mantua et al. 1997, Chavez et al. 2003). Recently, a new mode of variability has been recognized and named the NPGO (Di Lorenzo et al. 2008). The periodicity of the NPGO is between that of El Niño and the PDO. The amplitude of its fluctuation appears to be intensifying (Chavez et al. 2011, Messié and Chavez 2011) and may explain its recent discovery. The NPGO is associated with the strength, location and intensity of the North Pacific Gyre and as such is well correlated in variations in salinity in the CCLME. While El Niño, NPGO and PDO can be recognized as independent modes of variability (Messié and Chavez 2011) they are related by the shared nature of forcing (variations in atmospheric pressure systems and ocean thermal dynamics) and have been well correlated to each other over the past decades.

In addition to climate impacts on the general productivity and fisheries of the CCLME there are also climate-related impacts on the oxygen content of subsurface waters, carbon dioxide concentration and the community composition of the primary producers with subsequent effect on fisheries. Oxygen can be an important regulator of benthic and deeper water living marine resources. Coastal upwelling regions are regions where the average subsurface oxygen is naturally lower than the rest of the ocean due to weaker ventilation from the atmosphere and higher primary productivity. Oxygen at depth tends to be lower during cool periods and higher during warmer multi-decadal climate regimes (Keeling and Garcia 2002, Keeling et al. 2010). Paradoxically on longer time scales the warm/cool variation flips meaning higher oxygen during ice ages and lower oxygen during inter-glacial periods (Kennett and Ingram 2002). A warmer world is predicted to result in lower subsurface oxygen by reducing "ventilation" from the atmosphere. A by-product of lower oxygen (from respiration) is increased concentration of carbon dioxide (CO_2). The upwelling of higher CO_2 waters may further exacerbate ocean acidification (Chan et al. 2016, Somero et al. 2016). Ocean acidification is occurring as the burning of fossil fuels increases concentrations of CO_2 in the atmosphere; part of the CO_2 is absorbed by the oceans, lowering pH. The impacts of changes in oxygen and pH on fisheries are yet to be fully understood but need to be considered along with climate (Chan et al. 2016).

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