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Enhancing California's Ocean Acidification and Hypoxia Monitoring Network

Recommendations to the Ocean Protection Council from the California Ocean Acidification and Hypoxia Science Task Force

CALIFORNIA OCEAN SCIENCE TRUST

CALIFORNIA OCEAN PROTECTION COUNCIL

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About the Ocean Acidification and Hypoxia Science Task Force

The California Ocean Acidification and Hypoxia Science Task Force (Task Force) was established through Assembly Bill 2139 (Williams), passed in September 2016, to ensure that the Ocean Protection Council (OPC) decision-making and further action on the issue of OAH continue to be supported by the best available science. The Task Force is convened and managed by the California Ocean Science Trust on behalf of the OPC.

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About the California Ocean Science Trust

California Ocean Science Trust is a non-profit organization dedicated to accelerating progress towards a healthy and productive ocean future for California. Created by state legislation, OST bridges the gap between cutting-edge scientific research and sound ocean management. To learn more, visit www.oceansciencetrust.org

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About the Ocean Protection Council

The Ocean Protection Council (OPC) is a cabinet-level state policy body nested within the California Natural Resources Agency. Created by the California Ocean Protection Act of 2004 (COPA), OPC advances the Governor's priorities for coastal and ocean policy and works broadly to ensure healthy coastal and ocean ecosystems for current and future generations by advancing innovative, science-based policy and management, making strategic investments, and catalyzing action through partnerships and collaboration. To learn more, visit http://www.opc.ca.gov/

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Executive Summary

The California Ocean Protection Council (OPC) has identified ocean acidification as one of its highest management priorities. Recognizing that a firm scientific foundation is necessary for developing and assessing effectiveness of the State's management strategy, the OPC charged its Ocean Acidification and Hypoxia Science Task Force (Task Force) with conducting a gaps analysis to determine how California's OAH monitoring network could be enhanced to improve decision-making. The Task Force developed three primary recommendations:

1. Better connect chemical and biological monitoring
California hosts a wealth of ocean monitoring programs, but poor coordination between chemical and biological monitoring efforts limits managers' understanding of how marine life is affected by changing OAH exposure. The lack of coordination restricts the State's ability to develop OAH water quality criteria, which is a critical element of the OPC's 2020-2025 Strategic Plan and the State of California Ocean Acidification Action Plan (Action Plan). Laboratory studies provide some of the necessary information, but criteria development will require field confirmation, which is dependent on co-located chemical and biological measurements over a wide array of OAH exposure conditions.

2. Continuously improve OAH models as decision-support tools via collection of additional monitoring data
Many key management decisions detailed in the Action Plan, including: identifying areas most vulnerable to future OAH change, determining the best locations to invest in habitat management restoration activities targeting OAH, and assessing the likely effectiveness of reducing local nutrient/carbon inputs, will be based on coupled physical-biogeochemical models that are validated with observations. The OPC has invested heavily in development of these models, which are among the most advanced in the world and provide a firm foundation for such decisions. However, as the questions being posed to the models become more fine-grained, and the habitats to which they will be applied expand, the State would be well-served by continuous improvement of these models given the importance of the decisions being made. Additional OAH observations will be needed for this ongoing expansion of the model as a key decision support tool.

3. Strengthen continuity of OAH monitoring programs across California's coastal environments
Acidification chemistry monitoring efforts are uneven across California, with areas north of Monterey Bay not nearly as well-covered as more southerly areas and there are investment opportunities to ease this spatial disparity. Moreover, monitoring programs that the OPC and the broader scientific community presently rely on for trend assessments have uncertain financial futures, which should be prioritized for continuous support.

This report includes actionable items for each recommendation, with emphasis on leveraged, cost-effective enhancements to the State's existing monitoring activities. The Task Force also identified several gaps in scientific knowledge that, if addressed, would further expand the capacity of OAH monitoring programs to generate relevant managerial information. These recommendations, which largely focus on short-term research needs, are also presented in Appendix A.

Introduction

Access to high-quality, comprehensive monitoring data on ocean acidification and hypoxia (OAH) is a foundational element of West Coast management efforts to protect ecologically and economically important costal resources. Monitoring data enable managers to gain essential insights into how OAH impacts water quality, vulnerable species and habitats, and coastal communities. With access to relevant, actionable information about OAH status and trends, managers are able to make decisions to mitigate OAH's intensifying impacts that are informed by both stakeholder needs and the best scientific understanding.

West Coast states have boosted OAH monitoring capacity, both geographically and via the addition of new OAH monitoring parameters, in recent years. They also have invested in coordinating and aligning these monitoring efforts. However, the scale of West Coast monitoring programs and the myriad different programs responsible for monitoring lead to inevitable disparities and unevenness among monitoring programs that impede the ability to share, compare and leverage OAH monitoring data within and among states.

In 2016, an expert advisory panel of West Coast OAH scientists issued a series of recommendations that, among other things, urged West Coast states to establish a unified, comprehensive OAH monitoring network. To lay the groundwork for a sustainable and adaptive monitoring network, the West Coast OAH Science Panel recommended that West Coast states work together to complete two foundational tasks: (1) inventory existing monitoring resources and capacity, and (2) analyze gaps between existing monitoring efforts and management needs, known as a gaps analysis. These recommendations have been codified by the California Ocean Protection Council (OPC) into the State of California Ocean Acidification Action Plan (Action Plan), which explicitly calls for targeted investments in a monitoring and observation system that is optimized to deliver decision-relevant information to managers and other end users. In response to the Panel's recommendations, the OPC partnered with the other west coast States and the federal Interagency Working Group on Ocean Acidification (IWG-OA) to build a comprehensive inventory of relevant OAH field monitoring efforts along the West Coast. The inventory, completed in 2018 and available online at https://oceanmonitoring.cnra.ca.gov/, has been incorporated into a geospatial map that includes records from over 125 participants describing over 200 OAH monitoring projects, from Alaska to Baja California.

Following completion of the West Coast OAH monitoring inventory, the OPC charged the California Ocean Acidification and Hypoxia Science Task Force (Task Force) with conducting a comprehensive OAH gaps analysis for California. The Task Force, consisting of eight prominent scientists in the field, was established through Assembly Bill 2139 (Williams), passed in 2016, to ensure that the OPC's decision-making and action on OAH continue to be supported by the best available science.

The goal of the gaps analysis is to help managers decide how to optimally direct limited monitoring resources. The Task Force focused primarily on monitoring needs for managing ocean acidification (OA) in accordance with the Action Plan, though also considered monitoring needs for hypoxia as a co-occurring stressor. The Task Force recognized early in its investigation that the most consequential monitoring gaps do not necessarily revolve around spatial and temporal coverage of OAH monitoring, but can also lie in OAH parameters that aren't measured, or in the availability and quality of the data being generated. Therefore, the Task Force considered six main types of potential monitoring gaps during its analysis (Table 1).

The Task Force recognized that OAH monitoring programs have more gaps than managers are likely to have the resources to remedy over the short term. Thus, the Task Force members ranked the gaps it identified, and then worked to develop consensus recommendations on how to optimally address priority gaps. Ultimately, the Task Force reached consensus on three priority recommendations that, if implemented, will best position California to build a comprehensive, sustainable, adaptive OAH monitoring network.

During its deliberations, the Task Force also identified additional key gaps in scientific knowledge and understanding that, if addressed, would further expand the capacity of OAH monitoring programs to generate managerially relevant, actionable, insightful data. These recommendations, which largely focus on short-term research needs, are presented in Appendix A.

Table 1. The different types of monitoring gaps considered by the Task Force in this analysis

- **Spatial gaps** – *Are we measuring in the right places?*
  - Along the coast
  - Cross-shelf
  - Vertically within the water column
- **Temporal gaps** – *Are we measuring frequently enough?*
- **Parameter gaps** – *Are we measuring the right things?*
- **Integration gaps** – *Is collection of the various types of measurement parameters well-coordinated and synergistic?*
- **Data quality gaps** – *Are we making the measurements with sufficient accuracy and precision to support management use?*
- **Data availability gaps** – *Are the data accessible?*

Approach

The Task Force began by identifying a wide array of OAH monitoring gaps. Then, the Task Force took the following steps to guide its initial deliberations:

1. **Identify management decisions most dependent on monitoring data in the Action Plan**
2. **Assess how well existing data collection systems address specific management questions**
3. **Determine future investments that will most improve the State's ability to manage OAH and its impacts**

The Task Force determined that the management decisions most dependent on monitoring data were those identified in the Action Plan. Specifically, the Action Plan's Appendix A identifies the science needed to support potential management actions. Drawing on this, the Task Force defined two broad categories of management needs and five monitoring information priorities on which to base the gaps analysis:

1. Characterize the magnitude, spatial pattern and trend of OAH in the following respects:

- In ocean carbon chemistry and dissolved oxygen
- In biological vulnerability of species and ecosystems
- In socioeconomic impacts of OAH

2. Determine the likely effectiveness of two classes of management decisions:

- Pollution control measures to lessen local anthropogenic nutrient and carbon input
- Conservation and enhancement of living systems to remove carbon or ameliorate impact from stressors

For each of these, the Task Force assessed how well existing assets addressed specific management questions and how that could be improved with additional data collection. This effort revealed that current monitoring efforts are inadequate to guide some of California's OA management needs. This led the Task Force to develop specific recommendations to enhance existing OA monitoring assets, as well as research recommendations for other science investments beyond monitoring to support the implementation of the Action Plan. The Task Force then prioritized actions from among all the proposed recommendations based on factors such as the extent of likely improvement in the management decision, the cost-effectiveness of the investment, and the applicability of the investment for supporting multiple management actions.

The Task Force was asked to provide recommendations about the most cost-effective ways to fill those gaps. In so doing, the Task Force looked for opportunities to fill gaps by leveraging existing programs, rather than starting new monitoring programs from scratch as that can be prohibitively expensive. The Task Force was also asked to prioritize gaps that could be filled with short-term capacity-building investments, as the presently-available OPC funding resources are incompatible with recurring long-term expenses.

Recommendations for Enhancing California's OAH Monitoring

The Task Force has developed three primary recommendations for improving the State's existing OAH monitoring investments. If implemented, these consensus recommendations will give California maximum value in enhancing understanding of OAH trends and improving assessments of the effects of regulatory and/or management actions.

Recommendation #1
Better connect chemical and biological monitoring

Background: California has invested in building capacity to monitor OAH via chemical measurement approaches, as chemical monitoring is essential for tracking changes to seawater chemistry itself. However, the chemical changes ultimately manifest as impacts to biology – and considerably less effort has been invested into understanding OAH's impacts on the status and trends of marine life populations and habitats that agencies are charged with managing. Most present biological measurements are part of short-term research programs focused on assessing conditions on a local scale, often near the research institute conducting them. The few ongoing regional monitoring programs that are assessing biological condition with respect to OAH are not well coordinated, with inconsistencies in the parameters measured and lacking standard measurement methods where they do overlap. As such, California managers are not presently well-positioned to describe the spatial extent of biological effects from acidification, where OAH has the most consequential effects, where the most rapid changes are observed, or how fast those effects are changing.

Biological monitoring information is essential because most management actions being considered in California to manage OAH are directed towards protecting biota. In the OPC's 2020-2025 Strategic Plan, the need for biological monitoring is called out in areas such as (1) the development of a Report Card on the state of California's Coast and Ocean (Target 3.6.1), (2) the need for an integrated understanding of coupled changes in ocean chemistry and ecology that are fundamental for priorities such as the development of adaptive management approaches to assess and respond to climate-driven shifts in fish populations and fisheries (Target 3.3.4), (3) the need for rapid response capabilities to biodiversity/fishery emergencies (Target 3.3.4), and (4) the need for MPA resilience to climate change (Target 1.4.1). Key parts of the Action Plan and the OPC Strategic Plan further focus on developing new water quality criteria for OAH. Development of such criteria rely heavily on laboratory studies (see Research Recommendation #1 in Appendix A), but laboratory studies provide only some of the necessary information. Criteria development will require confirmation that the patterns observed under laboratory conditions are evident in much more complex real-world systems. Such confirmation depends on having co-located chemical and biological measurements over a wide spatial array of OAH exposure conditions.

Recommendation: The Task Force recommends that California expands capacity for biological monitoring that is integrated with biogeochemical monitoring programs, as well as coordination activities necessary to make integration and access to data products possible. Two approaches are available to enhance biological monitoring to be optimally responsive to management needs: (1) Enhance and standardize OA-sensitive biological measurements into the best ongoing programs measuring OAH chemistry, with emphasis on regional programs that allow description of the spatial extent of effects, and (2) add OAH chemistry monitoring into several of the best biological monitoring programs active in the State.

For the first approach, the Task Force identified five regional programs with important ongoing chemical OAH monitoring programs and OAH-relevant biological programs that should be leveraged:

- CalCOFI (California Cooperative Fisheries Investigations)
- CCE LTER (California Current Ecosystem Long-term Ecological Research)
- SCCWRP (Southern California Coastal Water Research Project Authority) – Southern California Bight Regional Monitoring Program
- NOAA West Coast Ocean Acidification Regional Survey Cruises
- ACCESS (Applied California Current Ecosystem Studies)

This list was generated by the members of the Task Force and was vetted at a workshop held at a public forum at the Ocean Science Meeting in San Diego. The first three programs provide extensive cross-shelf coverage in Southern California, from nearshore to more than 100km offshore. The fourth program spans federal and state waters across the National Marine Sanctuaries on the central coast. The fifth program is a large-scale survey covering the entire U.S. West Coast, which is particularly important because there are no spatially-extensive long-term OAH chemistry programs in the northern part of the state and this NOAA program provides that remaining coverage; it also allows placement of California conditions into perspective of other West oast states. Together, these programs provide a wide spatial range of OAH exposure conditions, which is necessary to achieve the desired correlation between biological condition and OAH exposure. All of these programs have been ongoing for more than a decade and are anticipated to continue for the foreseeable future. All are conducting some form of biological measurements such as food web conditions, status of OA indicator taxa, and/or abundance of larval fish and invertebrates that replenish coastal fisheries, but they are not all measuring the same parameters, using the same measurement methods or even using the same sample collection gear. These programs have all expressed willingness to coordinate their efforts. This is the Task Force's highest recommendation because it fills the greatest management gap, can be accomplished through an unparalleled leveraging opportunity from these ongoing programs, and can achieve coordinated, ongoing monitoring enhancements within only a few years. The OPC should engage an OAH biological assessment team from among these programs to determine which of their nascent measurement are most compatible for standardization across these programs and then invest in that program coordination.

Beyond coordinating established biological measurement types, the Task Force recognizes that biological observation technologies such as eDNA and plankton imaging enumeration techniques are advancing rapidly. The State's information needs will be well-served by early adoption of such tools as part of a cost-effective monitoring portfolio. Established monitoring programs such as those highlighted here also represent opportunities to speed the development, testing, and operational implementation of new biological monitoring capabilities. The readiness of these technologies varies, and the Task Force recommends investments to move the tools forward as part of our Research Recommendations (Appendix A).

For the second approach, the Task Force suggests issuance of a competitive call for proposals that would add OAH chemistry to ongoing biological monitoring programs. The Task Force identified a number of biological monitoring programs (such as the NOAA groundfish survey, the NOAA hake survey, SCCWRP's Bight Trawl Monitoring Program, and the State's MPA monitoring program) for which carbonate chemistry measurements could be added to enhance their value. These programs tend to support fisheries management or conservation priorities, have long track records and provide great leveraging opportunity. Furthermore, the Task Force recognizes that some of these programs already measure oxygen, temperature and salinity, which could be used collectively as surrogates for OAH to examine the historical relationship between chemistry and biological response.

The OPC can take advantage of these opportunities for retrospective analyses to inform approaches that optimize which programs would gain most by addition of more expansive chemistry monitoring.

Goals and Outcomes: The recommended leveraged investments will provide OPC with two critical products: (1) a first-of-its-kind, coordinated statewide monitoring effort that leverages existing monitoring infrastructure to provide an ongoing assessment of the magnitude and trend in OAH-associated effects on biota, and (2) the real-world data necessary to enhance our understanding of the biological impacts of OAH and support the development of OAH water quality criteria. By leveraging multiple ongoing regional programs, the State can quickly build a baseline understanding of how key fish and shellfish populations and food web elements respond across the wide range of OAH conditions encountered across the state.

Recommendation #2
Facilitate maintenance of OAH models as management decision support tools via ongoing monitoring data collection and model validation

Background: Many of California's OAH policy decisions will be based on the outputs of coupled physical-biogeochemical ocean models that evaluate alternative management scenarios for reducing OAH's intensifying impacts on coastal waters. The models describe conditions over a range of spatial and temporal scales that are impossible to achieve with high-quality OAH field measurements alone. The models also provide predictive capacity for understanding the likely outcomes of potential alternative management strategies. Two management applications are called out in the Action Plan and the OPC Strategic Plan that will necessitate the use of the OAH models: (1) Assessments of whether anthropogenic nutrient input reductions, particularly from wastewater treatment plant upgrades, will lessen OAH impacts, and if so, how benefits can be maximized by optimal allocation of those nutrient reductions across a range of inputs from specific facilities, and (2) use of model output for vulnerability assessments that identify the places most at risk of water quality deterioration, and the timing and scope of that impairment. Other priorities identified in the OPC Strategic Plan include the development of approaches to assess and respond to climate-caused shifts in marine life populations and fisheries (Target 3.3.4), an aquaculture action plan (Target 4.2.1), and approach for predicting climate-change impacts on rocky intertidal and beach ecosystems (Target 3.1.3). Collectively, these management applications underscore the essentiality of model-driven understanding of current and future exposure to OAH stressors.

The OPC already has invested in the development and validation of coupled physical-biogeochemical ocean models, which are among the most advanced of their type in the world. The ongoing modeling efforts – led by UCLA, University of Washington, SCCWRP and NOAA researchers and hereafter termed the West Coast OAH model – have been well-received by the scientific community and provide a firm foundation for the State's management decisions. However, model development and validation has been focused initially on addressing regional scale questions about effects of nutrient inputs on chemistry and lower trophic level responses in the Southern California Bight. As OAH management advances, the models will likely be applied to answer questions at smaller spatial scales and perhaps in more nearshore, shallower habitats and/or more directly for upper trophic taxa than what the models were initially developed for. It will also be expanded to other geographies in the State.
The State would be well-served by continuous advancement of these models, particularly as the models may be applied to different spatial scales, locations and ecosystems. Additional OAH observations will be needed for this ongoing advancement and validation of the model will need to continue as the model's applications expand. Central to assessing the performance of the model is its ability to reproduce biologically relevant OAH exposure regimes across oceanographic domains in Southern, Central and Northern California, particularly in dynamic nearshore environments.

Recommendation: The Task Force recommends that OPC plan to address potential gaps in monitoring data needed for evolving model advancement. In conversations with the modelers and the users of the models, there were suggestions that this investment could come in three forms: more chemical measurements in shallow nearshore habitats, more coupled measurements of chemistry and biology, as well as more biogeochemical rate process measurements. However, the Task Force recognizes that the model validation process is a complex one, both technically and interactively, with a broad constituent base that will have vested interest in the outcomes from the model output. Because of the specialized knowledge needed, and because the future modeling applications cannot be fully defined at this time, the Task Force recommends that the OPC engage a group of modeling experts to recommend specific additional measurements and/or modeling activities that are most important for assessing the ability of models to support growing applications. The Task Force notes that while this recommendation is focused on a specific management-driven modeling effort, the targeted collection of nearshore time-series data, synthesis of data products for model-data comparisons, and engagement of the broader scientific and end-user communities in defining performance milestones are likely to be useful for developing and assessing the applications of models in a wider array of decision support, including the use of models to help optimize location for future deployments of coupled chemical and biological monitoring assets.

Goals and Outcomes: OPC investments in the evolution of the OAH models will enhance the foundation for this tool that is central to many key management decisions. Data collection that supports further model development and quantification of model performance, will allow the modeling applications to expand beyond its present focus on addressing water quality management and toward its use in examining upper trophic level ecosystem, fishery and management OAH resilience strategies.

Recommendation #3
Ensure the long-term continuity of OAH monitoring programs across California's coastal environments

Background: Coastal ecosystems are dynamic environments where local processes can accentuate or dampen global trends in not just OA, but also in stressors such as hypoxia and warming that can compound the impacts of acidification. Understanding if OA and other stressors are intensifying more rapidly than anticipated, and which areas, habitats, or fisheries are experiencing the earliest and most severe changes is vital for planning and prioritizing management responses. The need for this monitoring information aligns directly with OPC's Strategic Plan priority calling for the creation of an annual California State of the Coast and Ocean Report and a scientific, indicator-based Report Card (Target 3.6.1). Indeed, the ability to produce these comprehensive documents is dependent on preventing temporal gaps and closing existing spatial gaps.

While long-term time-series are fundamental for detecting and interpreting trends in mean and episodic exposure to OAH stress, California faces the possibility of gaps or even wholesale loss of essential time-series. Many observation programs do not presently have sustained support for collecting long-term OAH monitoring data, as many existing efforts are add-ons to other programs that have missions which are not focused on OAH.

Basic capacity to detect and track long-term changes in OAH exposure is also unevenly distributed across the state. Southern California is home to a considerable array of long-term observing programs that provide some of the most important records in the nation for understanding carbonate chemistry and oxygen dynamics. The Central Coast is well-served by MBARI's long-term cruises and moorings.

But north of Monterey Bay, long-term observations are scarce, leaving large portions of State waters under-observed for status and trends. Because of pronounced regional oceanographic differences, status and trends observed from one region cannot be readily assumed for another. Across regions, spatial gaps in long-term observations are also pronounced for nearshore coastal waters and for measurements at depth, where exposure to OAH stress is the greatest.

Recommendation: The Task Force recommends a two-pronged approach to ensure the long-term continuity and spatial representation of OAH monitoring programs in California: (1) Support efforts to ensure the longevity of key, existing OAH time-series monitoring data collection, and (2) enhance the ability of existing observational programs to fill spatial gaps in OAH measurements.

Regarding support for long-term monitoring sets, the Task Force places high priority on ensuring the continuity of the CalCOFI survey carbonate chemistry measurements, which provide a unique historical resource dating back many decades. The analyses of these data are currently supported primarily in an ad hoc basis by individual researchers. The Task Force sees the CalCOFI data as particularly important because of the highly leveraged opportunity afforded by fishery recruitment potential and food-web time-series. The Task Force recognizes that long-term program funding is incompatible with the OPC's present funding resources, but also recognizes that this goal of program continuity might be assisted by the high level leadership embodied by the OPC reinforcing the value of these measurements to the existing program funders.

Regarding support for closing spatial monitoring gaps, the Task Force recommends enhancing OA observing capacity in under-observed areas in the North Coast and at depth in the Central Coast. The former can be achieved by supporting glider observations that are collocated with ichthyoplankton and zooplankton monitoring efforts on the Trinidad Head Line, particularly through investments in oxygen calibration and verification of algorithms to estimate seawater carbonate parameters. The latter would involve support for adding climate-grade carbonate chemistry sensors at depth to the M1 mooring in Monterey Bay.

The Task Force also noted that the myriad of ongoing chemistry programs share neither a common data quality assurance program or database management system. The Task Force felt that the data quality among programs was high, but that limited data management capacity and database incompatibilities among the range of individual researcher efforts presently hamper ready access by the research and management communities. Development and implementation of mechanisms to ensure effective end-user access to OAH datasets across these programs should be a priority for the OPC, and participation in such a system should be standard practice for OPC-supported monitoring projects.

Goals and Outcomes: The leveraged priority monitoring investments outlined above represent a step towards sustained, comprehensive statewide acidification chemistry monitoring. The overarching goal is to ensure that decision-makers and the public have access to a data-based report card on the status and trends of OAH-related ecosystem and fishery stressors. By leveraging long-term biological and chemical observation programs across different oceanographic regions, the State will be positioned to increase its capacity to connect changes in OAH to changes in fish population replenishment and food web dynamics. In addition, because gliders are distributed widely across California, investments in calibration and carbonate chemistry proxy verification will be able to be scaled up to maximize high-quality OAH monitoring across the state.

Appendix A: Supplementary OAH Research Recommendations

Although the emphasis of this report is on enhancements to the State's OAH monitoring capacity, the Task Force also identified additional key gaps in scientific knowledge and understanding that, if addressed, would further expand the capacity for interpreting OAH monitoring program data in a managerially relevant, actionable, and insightful manner. These recommendations largely focus on short-term research needs that were identified during the Task Force's deliberations as being important for Action Plan implementation.

Research Recommendation #1
Account for socioeconomics impacts

Background: Socioeconomic impacts from OAH have already been documented, particularly for the shellfish industry in the Pacific Northwest. Accounting for current and anticipating future socioeconomic impacts are a necessary part of scaling the management response from the State, as clearly delineated in the Action Plan and the OPC Strategic Plan (Target 3.3.2). Socioeconomically relevant questions being asked in CA and elsewhere include: Which marine resources will be affected by OAH? What is their value to industries, local communities, and the State? What is the capacity for stakeholders and management agencies to adapt to anticipated impacts of OAH? At this time, just a few studies are beginning to identify which California marine resources and users are most likely to be impacted, but much more information is needed to understand the direct and indirect impacts of OAH on California's social-ecological system, and what management activities can minimize these impacts.

There is a need to account for socioeconomic impacts as part of a larger, systematic effort to identify and assess a) the impacts and implications of climate change (and other factors) on California's fisheries/aquaculture-human systems, and b) the value, feasibility and efficacy of mitigation and adaptation measures. However, there is little ongoing work that could provide the foundation for a broader socioeconomic monitoring program at this time. The socioeconomic costs of OAH encompass a broad suite of impacts that differ in who is affected, the time horizons for effects, and the kinds of monetary and non-monetary losses incurred. This breadth challenges our ability to identify socioeconomic indicators that are the most meaningful for monitoring at this time. Equally challenging is a clear understanding of the compensatory tactics that marine resource users and managers can apply when challenged by disruptions in marine resources and associated ecosystem services.

Recommendation: The Task Force recommends a two-step approach as the initial steps in developing a socioeconomic monitoring program. First, an assessment of socioeconomic information should be conducted, including: (1) the value of the range of resources and services (beyond dockside harvest values) that are at risk from the progression of OAH, and (2) the preparedness of California's current marine resource management to accommodate OAH within the context of challenges such as whale entanglement in fishing gear, warming, harmful algal blooms, and the interaction of these effects. This will provide initial context for decision-makers weighing investments and actions, and broaden engagement by stakeholders and managers who may be affected by OAH. Second, the Task Force recommends development of a strategic road map to track the socioeconomic impacts of, and capacity for adaptive response, to OAH. The goals of this investment would be to forge agreement around a suite of socioeconomic indicators that best track (1) OAH impacts that are of direct value to management and policy planning, and (2) changes in capacity of stakeholders and managers to respond adaptively to the progression of OAH.

Goals and Outcomes: Research on impact pathways will clarify the risks that OAH poses for different industries, communities, and agencies, and will provide sector-specific scenarios where harm may be avoided through precautionary resource management or adaptive capacity enhancement within marine-dependent communities. This can also provide economic and employment data for cost-benefit analyses, which may inform short- to medium-term decisions about decadal-scale investments and capacity building. The goal of the Task Force's recommendation is to translate the many socio-economic considerations into an actionable plan that can be implemented to detect and track societal impacts of OAH and the value of mitigation and adaptation measures to affected stakeholders, coastal communities and the State as a whole.

Research Recommendation #2
Quantify key species sensitivity and capacity for adaptation

Background: There is a notable disconnect between the suite of species for which sensitivity to OAH has been studied, and the suite of species that are of highest priority for natural resource managers. For example, of the 100 most economically valuable species of fish and invertebrates that support California's commercial fisheries, perhaps 1 in 5 have been assessed for their direct sensitivity to OA, with much fewer studied for OAH impacts or impacts in more than one life stage. As a consequence, there is scant understanding to evaluate what species are at risk, if current management actions increase or decrease the impacts of OAH across species, or how management actions could or should be adjusted to bolster the resilience of at-risk populations to continued water chemistry changes as called for in the Action Plan and the OPC Strategic Plan (e.g., Objective 1.4, Target 3.3.4).

Equally important to the Action Plan is the development of new water quality criteria for acidification. These criteria not only provide a management target, they also have regulatory significance, opening additional management options for water quality improvement. However, existing data for criteria development are deficient. OA is a relatively newly recognized threat, so laboratory studies of acidification have only been conducted for a limited number of biological endpoints on a limited number of species. Most of those endpoints have been exposure measures, such as shell condition, which document that an organism is affected by carbonate chemistry conditions. However, water quality criteria development also requires assessment of organism health, such as their ability to grow, reproduce or survive, which requires more types of testing than has been done for most organisms to date.

Most existing studies have also been conducted as static exposure experiments, where organisms are tested at constant pH levels. In the near coastal ocean, though, some organisms are exposed to pH levels that can fluctuate a full pH unit or more over the course of tidal cycle or over a diurnal period. Furthermore, most of the existing studies have been conducted examining acidification alone, but CO_2 levels in the ocean covary substantially with oxygen and temperature conditions that can act to amplify or dampen OA impacts. Dynamic and multi-driver exposure experiments (in which conditions more closely mimics the duration and environmental context of exposure that organisms typically see in the real world) are necessary to determine actual species sensitivity, the relative importance of exposure duration vs. exposure magnitude, and interactions with other stressors when setting water quality criteria.

As noted in the Action Plan, management levers such as harvest size restrictions, MPAs, and effluent discharge controls have the potential to exert important controls on attributes of populations, species, communities, ecosystems and fisheries that play key roles in resisting or recovering from the impacts of OAH stressors. For example, a population with more diverse age or genetic structure may better buffer against the effects of environmental variability than one dominated by a single age or low diversity cohort. However, whether and how strongly different biological attributes map onto adaptive capacity to modulate the impacts of OAH is only beginning to be examined. Because adaptation and mitigation represent the two pathways available for the state to locally manage coastal ecosystems in the face of progressive OA and climate change, growing our understanding of opportunities for biological and ecological resilience management is an essential path forward.

Recommendation: While the number of OA impact studies has grown substantially, the Task Force notes that progress in three areas is urgently needed if research is to deliver on the next generation of management-relevant knowledge. Thus, the Task Force recommends support for studies that build understanding of OA impacts (1) under realistic dynamic exposure regimes, (2) within the context of key multi-stressors of hypoxia and warming, and (3) that links responses from lab studies to population parameters and patterns in the field. The Task Force further specifically recommends that these approaches be applied to quantify critical values where biological impairment begins, identify managed species that are at risk from OA and how management actions affect that risk. Complementary to these studies of sensitivity are efforts to identify biological and ecological attributes that offer opportunities for management intervention to preserve or bolster species resilience to OAH. The Task Force recommends investments in research that assesses the effects of management actions in altering resilience.

Goals and Outcomes: This work will enable the State to set water quality targets for OAH. These targets are central for management actions ranging from effluent discharge controls, water quality protection in MPAs (Target 3.4.1), siting and design of mariculture operations (Target 4.2.1), as well as defining indicators of healthy oceans (Target 2.4.2) for a state Coast and Ocean Report Card (Target 3.6.1). Expanding the understanding of the suite of species at risk from OAH progression will also be important in broadening engagement by stakeholders and managers whose activities will be impacted but currently lack evidence that they can use in prioritizing attention. An additional crucial outcome of the recommended investments is to move OAH actions from detection and monitoring to active adaptation management.

Research Recommendation #3
Assess ecological system sensitivity and resilience

Background: Ocean acidification is an ecosystem problem. Most OAH research is focused on impacts to individual organisms, but impacts on food webs that support diverse ecological communities and productive fisheries represent an even greater threat. By altering the growth, survival, and interactions within and among species, OAH can reshape California's coastal ecosystems and the services they provide. The challenge is that despite an exponential growth in studies of single-species responses to OA over the past decade, our ability to forecast how whole ecosystems will be reshaped remains poor. As a result, managers have little guidance as to which systems are most at risk, when changes will become evident, or what actions can and should be taken to manage those risks. This puts OA actions in a reactive posture though the costs of inaction may be substantial as impacts intensify and become more difficult to reverse.

Predicting how complex ecological systems will respond to the progression of OAH and warming is a substantial research challenge. Results from single-species sensitivity studies alone cannot be used to project impacts of OAH and warming on ecological communities. Laboratory experiments with multiple species tend not to replicate ecological communities or interactions well. In situ experiments are logistically challenging and feasible in only a limited set of environments. Coupled biological and chemical OA time-series are rarely of sufficient length to resolve OA-specific impacts. Ecosystem models that predict species distribution patterns and processes are challenged both by uncertainties in the value or identity of key parameters that describe complex ecological interactions and by limited availability of coupled biological and chemical datasets that can be used to evaluate and improve model performance.

Recommendation: Research into OA ecological sensitivities can span many approaches and directions, each of which will differ in overcoming research bottlenecks or delivering management-relevant information. The Task Force recommends an investment strategy that focuses on addressing specific key research approaches: (1) Utilize observations across OA and other relevant environmental exposure gradients to identify and test predictions of ecological impacts, and (2) employ an ecosystem modeling framework that explicitly tests predictions against empirical observations and identifies model sensitivities to model formulation and parameterization. Information from sensitivity analyses can in turn serve to guide where future research in mechanistic or correlative studies will be most valuable for refining models. Enhancing biological/ecological observations across broad environmental gradients is needed, and the Task Force recommends investments into techniques such as eDNA that may be able to speed the delivery of needed datasets in a more cost-effective manner. The Task Force further recommends that ecological sensitivity research be scoped to address questions that are of most direct management-relevance. For example, what are the OAH-mediated ecosystem changes that are most important for specific fisheries? What are the best indicators of such ecosystem changes that can be used to inform a State of the Coast and Ocean Report Card (Targets 2.5.1 and 3.6.1)? How will OAH-mediated ecosystem changes affect the performance of the State's MPA networks? Can the MPA network or other management activities be employed to inform and/or manage for the ecological impacts of OAH (Targets 3.1.1 and 1.4.1)? Just as biological attributes such as population structure and genetic diversity can mediate resilience to environmental change, ecological attributes such as species diversity, trophic structure, community connectedness or modularity have the potential to mitigate vulnerability to OAH.

Goals and Outcomes: A direct goal is to quicken the pace and sharpen the focus of new inquiries to produce decision-relevant knowledge on the risks to biodiversity, ecosystems, and fisheries posed by OAH. Moving from speculative understandings, however well-reasoned, to a body of evidence-based knowledge increases the likelihood that broader sets of stakeholders and managers will be actively engaged in OAH monitoring and solutions building.

To learn more about the California Ocean Acidification and Hypoxia Science Task Force, visit
http://westcoastoah.org/taskforce/about/