WORKSHOP

Monitoring for Acidification Threats in West Coast Estuaries: A San Francisco Bay Case Study

October 19th & 20th, 2016

San Francisco Estuary Institute
4911 Central Ave, Richmond, CA

Organized by

San Francisco Estuary Institute
Romberg Tiburon Center for Environmental Studies, San Francisco State University
Coastal and Marine Sciences Institute, University of California Davis
Southern California Coastal Water Research Project Authority
U.S. Environmental Protection Agency
San Francisco Estuary Partnership
California Ocean Science Trust

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U.S. Environmental Protection Agency through the San Francisco Estuary Partnership
Regional Monitoring Program for Water Quality in San Francisco Bay
California Ocean Science Trust
California Sea Grant

Executive Summary

The estuaries of the U.S. Pacific Coast are diverse and productive ecosystems of high ecological, cultural, and economic value. They have many stakeholders, are managed to meet many different, often competing, objectives, and contend with environmental stressors from a variety of sources.

Ocean acidification (OA) is one stressor expected to have widespread impacts on the Pacific coastal ecosystems. Recently, the West Coast Ocean Acidification & Hypoxia Science Panel recommended improved monitoring to assess biological impacts in the coastal ocean and estuaries. However, the current status and impacts of ocean acidification on West Coast estuaries are largely unknown.

A workshop in October 2016 brought together scientists from throughout the West Coast of the United States, leading researchers on San Francisco Bay, the region's largest estuary, and representatives from a variety of management agencies. The main objectives of the Workshop were to assess whether acidification is of concern in the Bay and to identify its potential impacts to beneficial uses, cost-effective monitoring strategies, and potential management actions. Although the Bay was the case study, the aim was to develop general guidance that could be applied to West Coast estuaries.

Ocean acidification is expected to impact estuaries on the West Coast

- Chemical and biological data on the magnitude of acidification threats and impacts are lacking in San Francisco Bay.
- Local and regional experts identified species and habitats in the Bay that could be sensitive to ocean acidification impacts and how they could be monitored.
- Management of ocean acidification in estuaries will require agencies to work across jurisdictions.

Ocean acidification monitoring in San Francisco Bay should follow a stepwise process:

Near Term

- Continue to synthesize existing data from the Bay to develop conceptual models.
- Inventory assets and identify opportunities to add OA monitoring to existing monitoring programs.
- Implement a carbonate-chemistry monitoring program.

Long Term

- Implement a coupled chemical and biological monitoring program.

One intended outcome from of this workshop was an OA monitoring framework that could be applied to estuaries across the West Coast. However, the region's estuaries vary in their morphology, hydrology, biology, and water chemistry, as well as, importantly, management drivers and monitoring assets. Therefore, while some generalizations are possible for similar types of estuaries (e.g., deep bays, river-mouth estuaries, or lagoons), a single framework is not possible for all estuaries. Instead, we recommend that the same process used at this Workshop be applied to develop an OA monitoring frameworks for other West Coast estuaries. Convening a workshop to synthesize the state of knowledge, developing conceptual models, and inventorying monitoring assets in the estuary of interest is a crucial first step. For next steps, coupled chemical and biological monitoring will be an important element to support climate change adaptation and management in all estuaries.

Suggested Citation

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Table of Contents

List of Acronyms

BML - UC Davis Bodega Marine Laboratory

CeNCOOS - Central and Northern California Ocean Observing System

CMSI - Coastal and Marine Sciences Institute, University of California Davis

NERR - San Francisco Bay National Estuarine Research Reserve

OPC - Ocean Protection Council

OST - California Ocean Science Trust

PCC - Pacific Coast Collaborative

RMP - Regional Monitoring Program for Water Quality in San Francisco Bay

RTC - Romberg Tiburon Center for Environmental Studies, San Francisco State University

SCCWRP - Southern California Coastal Water Research Project

SFEI - San Francisco Estuary Institute

SFEP - San Francisco Estuary Partnership

USEPA - U.S. Environmental Protection Agency

USGS - U.S. Geological Survey

DO - Dissolved Oxygen

HAB - Harmful Algal Bloom

OA - Ocean Acidification

OAH - Ocean Acidification & Hypoxia

SAV - Submerged Aquatic Vegetation

Workshop Summary

SECTION 1. INTRODUCTION

Motivation

Ocean acidification (OA) is expected to have widespread impacts on marine ecosystems by reducing calcification in key marine organisms, affecting their physiology, restructuring food webs, and altering the impacts of other water quality contaminants on wildlife. Recently, the West Coast Ocean Acidification & Hypoxia Science Panel recommended improved monitoring to assess biological impacts in the coastal ocean and estuaries. However, the current status and impacts of OA on San Francisco Bay and many other West Coast estuaries are largely unknown. A driver of the workshop was the Comprehensive Conservation and Management Plan for the San Francisco Estuary, a regional blueprint with 32 Actions. Action 29: Engage the scientific community in efforts to improve baseline monitoring of ocean acidification and hypoxia effects in the Estuary.

About the Workshop

The "Monitoring for Acidification Threats in West Coast Estuaries: A San Francisco Bay Case Study" Workshop was held at the San Francisco Estuary Institute (SFEI) on October 19 and 20 of 2016. The workshop was comprised of approximately 50 attendees affiliated with research institutes, government agencies, and universities (see Appendix A for a list of attendees).

The Workshop was held to convene both technical and policy experts to assess whether ocean-derived acidification is a likely concern in the Bay, and to identify its potential impacts to beneficial uses, cost-effective monitoring strategies, and potential management actions. The Workshop commenced with presentations from several experts in ocean acidification who provided context for the Workshop by presenting the current OA body-of-knowledge as well as a brief overview of related work that has been or is being executed. Break-out groups followed, giving attendees the chance to collaborate on conceptual ecosystem models aimed at identifying needs and priorities for OA monitoring in the Bay. The full group spent the remaining time synthesizing the conclusions drawn from the break-out groups and further refining and discussing monitoring needs and options.

Bringing together an interdisciplinary group of experts in the science, local ecology, and management landscape is a necessary first step toward designing a monitoring and research program for any estuary. Before making monitoring investments, it is crucial to:

1. synthesize the current state of knowledge,
2. develop conceptual models,
3. inventory monitoring and modeling assets, and
4. prioritize new actions based on opportunities, resources, and relevance.

This type of collaborative approach leverages existing partnerships, is relevant to management questions, and leads to cost-effective monitoring strategies.

Therefore, while the Workshop focused on San Francisco Bay, its process and outcomes will serve as a case study for how to approach OA monitoring strategies for other West Coast estuaries.

SECTION 2. KEY FINDINGS

Ocean acidification is expected to impact estuaries on the West Coast

There is growing evidence that tidal and gravitational currents can deliver acidified and hypoxic marine waters into bays and estuaries, including San Francisco Bay. Inputs of low pH water from the open ocean may be compounded by local eutrophication-enhanced acidification and hypoxia in nutrient-enriched estuaries. These changes are likely to impact many species important to the functional ecology of the Bay. Outer bay and subtidal, benthic habitats and species may be the most impacted by OA because exposure to cold and dense, low-pH waters is higher in these areas. Impacts on the survival, recruitment, and growth of larval and juvenile shellfish are suspected to be among the earliest consequences of OA. Shellfish beds are also located in areas susceptible to intrusion of low-pH, oceanic water, which may be particularly relevant to current and planned living-shoreline projects.

Chemical and biological data on acidification threats and impacts are lacking in San Francisco Bay

While there is a strong record of biogeochemical and ecological monitoring throughout San Francisco Bay, there are no high-quality, long-term carbonate chemistry time series. Simultaneous monitoring of carbonate chemistry and biological indicators is needed to assess the current exposure to OA, the conditions that may increase the risk of exposure, and the potential for ecological impacts.

Local and regional experts identified species and habitats in the Bay that could be sensitive to ocean acidification (OA) impacts and how they could be monitored

Workshop attendees participated in break-out groups to brainstorm OA monitoring needs through the development of conceptual models. Three breakout groups were each assigned a trophic level (i.e., primary producers, lower-trophic-level consumers, and top predators) and were asked to identify possible first-order effects of OA in San Francisco Bay. Each group also drafted management-relevant science questions and assessment approaches or monitoring indicators for the possible effects (Table 1). The major potential biological impacts of OA in San Francisco Bay that were identified were:

- Changes in the phytoplankton community;
- Loss of filter feeders and cascading effects on primary productivity;
- Increased toxins from harmful algal blooms; and
- Impacts on fisheries and shellfish habitat.

Submerged aquatic vegetation (SAV) was discussed as a possible tool for mitigating OA effects, locally, in key areas or hotspots. More work is currently underway to understand the capacity of SAV as a sink for aqueous carbon, a safe-haven for local organisms, and a buffer for changing pH.

Management of OA in estuaries will require agencies to work across jurisdictions

Because OA is an issue that spans many jurisdictional boundaries and will be just one of many stressors on biological systems, a discussion took place at the Workshop which allowed natural resource managers to voice their questions and comments. The main outcome from the discussion was that, in order to execute successful and sustainable short- and long-term OA monitoring in the Bay, new partnerships across several managerial entities will need to be cultivated. Restoration actions taken by resource agencies will affect water quality management goals and visa versa. Feedbacks between nutrients and low-alkalinity water in the Bay and upwelled water in the coastal ocean will confound traditional jurisdictional boundaries. OA is also likely to affect the management of marine protected areas and fisheries.

Table 1. Linking OAH impacts to management-relevant questions and associated approaches or indicators

Impact	Questions	Indicators/Approaches
Currents in the ocean and bay can deliver acidified marine waters into bays and estuaries. This open-ocean effect may be compounded by local eutrophication-enhanced acidification in some estuaries.	What are the sources, pathways, and exposures to altered carbon chemistry and dissolved oxygen? What is the relative importance of low-pH water compared to other stressors? What is the relative importance of local anthropogenic sources of CO2 to low pH water? How do carbonate chemistry and oxygen co-vary?	• Conduct chemical and physical monitoring via cruises/surveys and moored sensors • Develop and test calibrated carbon models, conceptual models, and mass balance calculations • Obtain time series of indices at multiple locations (OA exposure occurs as events)
Changes in phytoplankton community and food quality. Loss of filter feeders and cascading effects on phytoplankton concentration.	To what extent can exposure to lower-pH water change the phytoplankton community or food quality?	• Evaluate changes in phytoplankton taxonomy and fatty acid composition
Increased toxins from harmful algal blooms and effects on higher trophic levels	To what extent can exposure to lower-pH water increase the production of (harmful algal bloom) HAB toxins?	• Assess HABs and toxins in the context of OA conditions
Impact on fisheries and shellfish habitat	To what extent does exposure to lower-pH water decrease shellfish populations and fisheries?	• Assess larval quality, recruitment, and juvenile growth of bivalves, crabs, etc. • Use OA as a lens through which habitat is valued for upper trophic levels • Assess caged salmonid otoliths
Local mitigation of OA impacts by submerged aquatic vegetation	To what extent can existing or restored SAV buffer for lower pH exposure? What's the carbon budget for the different natural and restored vegetative habitats?	• Assess SAV health and buffer capacity, and quantify habitat suitability • Overlay OA "hotspots" over the habitat-suitability maps for SAV to help prioritize restoration or other projects
Other considerations		• Couple biological, chemical, and physical monitoring in association with living shoreline projects • Assess nested indicators in different trophic levels • Assess microbial community and function • Assess the buffering capacity of shells as they dissolve • Evaluate benthic foraminifera characteristics

SECTION 3: RECOMMENDATIONS FOR SAN FRANCISCO BAY

NEAR-TERM

Continue to synthesize existing data from the Bay to develop conceptual models

Although the Workshop outlined the state of the science for OAH in general, more datasets from the Bay should be analyzed to develop better conceptual models for this particular estuary. One specific idea is to use the existing water-quality models for San Francisco Bay and the Gulf of Farallones to identify where and when upwelled water causes exposure to low-pH and low-dissolved oxygen (DO) concentrations.

Inventory assets to identify opportunities to add OA monitoring to existing monitoring programs

There are several long-term monitoring programs in San Francisco Bay. The U.S. Geological Survey (USGS) has been monitoring water quality along the spine of San Francisco Bay since the 1970s. The Regional Monitoring Program for Water Quality in San Francisco Bay (RMP) measures toxic contaminants in water, sediment, and wildlife. Additionally, there is a network of in-situ sensors in San Francisco Bay and coastal waters that is maintained by the USGS, Central and Northern California Ocean Observing System (CeNCOOS), SFEI, San Francisco Bay National Estuarine Research Reserve (NERR), RTC, and the UC Davis Bodega Marine Laboratory (BML). This monitoring infrastructure should be better inventoried in order to facilitate leveraging opportunities for OA monitoring. Finally, the Ocean Protection Council (OPC) and the Pacific Coast Collaborative Interagency Working Group on OA are starting to take action on building a West-Coast Monitoring Program. The monitoring programs in San Francisco Bay should be part of the inventory for this larger West Coast network.

Implement a carbonate-chemistry monitoring program

In order to better understand the current chemical state in the Bay, as well as the relationship between all four carbonate chemistry parameters, an initial carbonate chemistry "snapshot" should be conducted throughout the Bay. This would involve measuring all four parameters (high quality pH, pCO2, total dissolved inorganic carbon, and total alkalinity) over a range of along- and cross-channel distances and depths. The results of such a survey would reveal the two priority parameters to be measured in subsequent surveys and would establish a baseline understanding of the organic-acid contribution to total alkalinity. Further cruises during susceptible periods would be needed to assess spatial patterns in OA exposure.

After the key carbonate parameters have been determined, they should be added to existing ship-based monitoring programs, such as the USGS monthly cruises, to start gathering baseline data for surface and bottom waters, especially near the mouth of the estuary. In addition to ship-based monitoring, high-frequency measurements should be made with in-situ sensors. A MAPCO2 buoy and an associated mooring will be deployed in Central San Francisco Bay by RTC (in collaboration with BML, CeNCOOS and USEPA Region 9) in 2017 to measure concentrations of atmospheric and aquatic carbon dioxide (pCO2), dissolved oxygen, pH, chlorophyll-a; temperature, and salinity at the surface; and pH, DO, salinity, and temperature at depth. Another buoy and mooring array should be deployed in the Gulf of the Farallones to enable scientists to begin characterizing fluxes between San Francisco Bay and coastal waters. SeaFET pH sensors should be added to existing moorings in the South Bay that are maintained by USGS and SFEI. The sensors on these moorings already measure temperature, salinity, turbidity, and, in some cases, dissolved oxygen.

LONG-TERM

Implement a Coupled Chemical and Biological Monitoring Program

Linking OA exposure to biological impacts is critical for establishing management priorities. Coupled physical, chemical, and biological monitoring is needed in order to identify and understand these linkages - supported by modeling of ocean-bay exchanges and water properties. At the Workshop, participants identified the most likely key habitats and species that could be impacted by acidification in San Francisco Bay. Additionally, participants identified potential biological indicators that could be monitored such as abundance of plankton susceptible to low-pH water, harmful algae toxin production, and bivalve larvae morphology (see Table 1).

Special studies should be completed to test the hypothesized linkages between OA and biological indicators before a monitoring program is designed and implemented. For example, analysis of the Smithsonian Institute's benthic grab sample archive could be used to assess changes in benthic foraminifera in order to refine foraminifera monitoring questions and applications. Similarly, the Smithsonian Institute's fouling community dataset could be analyzed for trends.

Participation in West Coast monitoring of SAV was also recommended for the purpose of evaluating the capacity of SAV to locally ameliorate OA. OA monitoring could be co-located with conservation, mitigation, and restoration projects to evaluate both the risks to and benefits from the restoration investment relative to OAH exposure. The following existing monitoring programs were mentioned as possibilities for collaboration: Smithsonian olympia oyster monitoring, the Mussel Watch Program, and the San Francisco Bay Living Shoreline project.

SECTION 4:
RECOMMENDATIONS FOR OTHER WEST COAST ESTUARIES

The workshop process documented in this report is a good model for other West Coast estuaries designing OA monitoring programs

One intended outcome from of this Workshop was an OA monitoring framework that could be applied to estuaries across the West Coast. However, estuaries are varied in terms of morphology, hydrology, biology, water chemistry, as well as, importantly, management drivers and monitoring assets. Therefore, while some generalizations are possible for similar types of estuaries (e.g., deep bays, river-mouth estuaries, or lagoons), a single framework is not possible for all estuaries. Instead, we recommend that the same process used at this Workshop be applied to develop an OA monitoring frameworks for other West Coast estuaries: convening a workshop to synthesize the state of knowledge, developing conceptual models, and inventorying monitoring assets in the estuary of interest is a crucial first step. The next steps may be similar to those identified for San Francisco Bay - or may not - depending on the type of estuary and local management concerns.

Monitoring to Assess OA exposure in West Coast estuaries

Throughout the West Coast of the US, estuaries are susceptible to OA effects imported from open coastal waters. Estuarine water-quality research has historically focused on contaminants, nutrient pollution, freshwater flows, and other anthropogenic drivers connected to watershed-management issues. The intrusion of waters from the ocean watershed, and its influence on salinity and nutrients, is an expected source of natural variation, but has not been considered as a source of concern for water quality. Furthermore, research on estuarine carbonate chemistry and hypoxia/anoxia has focused on detecting the influence of watershed-related factors (e.g., estuarine acidification vs. ocean acidification). Long-term water-quality and ecological monitoring in estuaries was not designed to detect OA impacts and may be inadequate for this purpose. The potential impacts of OA on resident biota, restoration efforts, and nature-based adaptation projects (and vice versa), may go unrecognized as a result.

This workshop focused on San Francisco Bay, the largest estuary on the US West Coast, as a case-study to address the need for increasing our understanding of OA impacts on estuaries and develop a rigorous approach to OA monitoring in San Francisco Bay and other West Coast estuaries. The process outlined here can be used to develop specific monitoring plans for other estuaries though scientific workshops that consider their unique and shared estuarine characteristics. This process is comprised of four steps:

1. Compile existing data and current knowledge and assemble experts to synthesize this information.
2. Develop conceptual models that identify key pathways to impairment.
3. Inventory assets and efforts with a view to building an OA monitoring and research program.
4. Prioritize new actions based on opportunities, resources, and relevance.

In reviewing the diversity of estuaries in a state such as California, one can identify three types of estuaries in terms of susceptibility to acidification and hypoxia. The first type are the larger/deeper ocean-forced bays like San Francisco Bay – and comparable estuaries like Humboldt Bay, Tomales Bay, and San Diego Bay. Low-pH and low-DO waters associated with upwelling along the open coast may intrude into these bay estuaries, accounting for minima in oxygen and pH – with greatest exposure at depth and near the mouth. The second type are the narrow river-mouth estuaries that are characterized by strong outflow during winter, such as the Russian River, Eel River and Klamath River. Less susceptible to ocean-derived acidification and hypoxia, these estuaries may differ in the alkalinity of freshwater inflows. The third types are lagoon estuaries in which waters may be retained for long enough that internal biogeochemical processes dominate and pH/oxygen conditions are susceptible to organic loading of inflows from land. In these systems, low-pH and low-DO are typically associated with eutrophication, often during closed-mouth periods (e.g., Pescadero Lagoon, Los Peñasquitos Lagoon). With seasonal variability, however, it is possible to see characteristic of all three types of estuaries in one basin through a seasonal cycle (e.g., in Russian River, low-oxygen intrusions have been observed in upwelling season, locally produced low-oxygen conditions have been observed when a lagoon forms in late summer, and low-pH is associated with strong freshwater flows in winter).

In all estuaries, new monitoring will be built on existing programs – leveraging existing monitoring assets and sampling programs to build an OA monitoring program. Further, considering the concordance of OA monitoring with local conservation, mitigation, and/or restoration projects may resolve or support management decisions related to project evaluation and long-term climate adaptation planning. Also, synergy between individual estuary programs may be advanced by participating in the monitoring inventory being developed by the OPC, the Pacific Coast Collaborative (PCC), and the Interagency Working Group on OA. However, specific actions will be most similar within similar types of estuaries. For example, in the deeper, stratified bay estuaries, near-bottom chemical monitoring is essential – while in lagoon systems, monitoring during closed or constrained-mouth periods is critical for properly characterizing exposure to minimum pH and oxygen conditions, which are not due to OAH intrusions. These considerations will influence the number, duration, and location of moorings and carbonate chemistry water surveys needed to adequately characterize exposure to OAH or other low-pH and low-oxygen conditions. Estuarine habitats will also vary within and between basins due to additional characteristics, such as the location, extent and depth of SAV, phytoplankton and other photosynthesizers. Through site-specific or type-specific workshops, these multiple factors can be assessed within a conceptual model that can prioritize deployment of monitoring assets within the context of existing programs and ecological assets of primary concern.

The Pacific West Coast's estuaries are diverse and productive ecosystems of high ecological, cultural, and economic value. They have many stakeholders, are managed to meet many different, often competing, objectives, and contend with environmental stressors from a variety of sources (i.e., watershed, coastal development, ocean watershed). This Workshop brought together OA scientists from throughout the West Coast of the United States, scientists and scientific organizations leading research on San Francisco Bay, and representatives from a variety of agencies involved in managing the Bay. The charge to this group was to develop a monitoring approach for this large, complex, and urbanized estuary. Although San Francisco Bay was the case study, the aim was to develop more general guidance for all West Coast estuaries. The approach outlined above, based on the expertise of leading subject area specialists and currently available science, provides guidance for scientists, policymakers, and other stakeholders about how and what to monitor to assess exposure to OA in West Coast estuaries. It also highlights the importance of monitoring estuaries for emerging water-quality concerns, such as OA, to ensure there is sufficient context for understanding their ecology to support effective management and restoration efforts

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Appendix A. Workshop Participants

Name	Affiliation	Expertise	Break Out Group
Jonathan Bishop	State Water Resources Control Board	manageement	top predators
Kathy Boyer	SFSU/RTC	biological effects, marshes/ seagrasses	primary producers
Phil Bresnahan	SFEI	chemistry/sensors	top predators
Hayley Carter	OST	science integration in marine/ coastal decision-making	lower trophic level consumers
Francis Chan	OSU	chemistry, biogeochemistry	top predators
Andy Chang	SERC	biological effects, bivalves	lower trophic level consumers
Jim Cloern	USGS	monitoring networks, phytoplankton, HABs	primary producers
Richard Feely	UW/NOAA	chemistry, biogeochemsity	lower trophic level consumers
Matt Ferner	RTC	monitoring networks	lower trophic level consumers
Tessa Hill	UC Davis, Bodega Marine Lab	biological effects, marshes/ seagrasses	primary producers
James Hobbs	UC Davis	fisheries in the Bay	top predators
Gretchan Hofman	UCSB	biological effects, invertebrates/ bivalves	primary producers
Wim Kimmerer	SFSU	zooplankton in the Bay	lower trophic level consumers
Emily Knight	OST	science integration in marine/ coastal decision-making	lower trophic level consumers
Kristy Kroeker	UC Santa Cruz	biological effects of OAH	top predators
John Largier	UC Davis, Bodega Marine Lab	coastal/estuarine oceanography (OAH patterns)	primary producers
Marilyn Latta	SCC	management (biological responses)	lower trophic level consumers
Dina Liebowitz	OST	science integration in marine/ coastal decision-making	primary producers
Tom Maloney	OST	management (coastal)	lower trophic level consumers
Skyli McAfee	Nature Conservancy	management	top predators
Tom Mumley	SF Bay RWQCB	management (WQ)	primary producers

Appendix A. Workshop Participants (continued)

Name	Affiliation	Expertise	Break Out Group
Jan Newton	UW & NANOOS	chemistry, biogeochemistry	top predators
Karina Nielsen	RTC/SFSU	biological effects of OAH	top predators
Heidi Nutters	SFEP	management (coastal)	top predators
Jenn Phillips	OPC	policy, management (coastal)	primary producers
Brian Rappoli	US EPA Region 9	management (water quality)	primary producers
Jennifer Ruesink	UW	biological effects of OAH	top predators
Martha Sutula	SCCWRP	management (water quality)	primary producers
Phil Trowbridge	SFEI		primary producers
Luisa Valiela	US EPA Region 9	management (water quality)	lower trophic level consumers
George Waldbusser	OSU	biological effects of OAH	lower trophic level consumers
Sarah Wheeler	OST	science integration in marine/ coastal decision-making	top predators
Dave Williams	BACWA	management (wastewater)	lower trophic level consumers

Appendix B. Workshop Agenda

WORKSHOP

Monitoring for Acidification Threats in West Coast Estuaries: A San Francisco Bay Case Study

Location:
San Francisco Estuary Institute
4911 Central Avenue
Richmond, CA 94804

Remote access will be available on 10/19/16 from 9 am to 12:30 pm only.

Phone number: (415) 655-0381
Access Code: 943-326-397#
Screen Sharing Website: https://join.me/sfei-conf-cw1

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SUMMARY

Ocean acidification has the potential to have widespread impacts on marine ecosystems by reducing calcification in key marine organisms, restructuring food webs, and altering the impacts of other water quality contaminants on wildlife. Recently the West Coast Ocean Acidification & Hypoxia (OAH) Science Panel recommended improved monitoring to assess biological impacts in the coastal ocean and estuaries. However, the current status and impacts of acidification on the San Francisco Bay and many other west coast estuaries are largely unknown. This workshop will convene scientists, managers, and monitoring entities to assess whether ocean-derived acidification and hypoxia is a likely concern in the Bay, and to identify its potential impacts to beneficial uses, cost-effective monitoring strategies, and potential management actions. San Francisco Bay, as the largest estuary on the west coast, will serve as a case study for how to approach the development of OAH monitoring strategies for west coast estuaries.

Day 1 - October 19, 2016

TIME	TOPIC	LEAD BY
8:30	Light Breakfast (provided)	
9:00	Welcome, Introductions, and Goal for Workshop	**Warner Chabot**
9:15	Opening Remarks: Why is OA a concern for California?	**Jon Bishop** **Jenn Phillips**
	Why should we care about acidification in the Bay?	
9:30	What do we know about OA along the West Coast?	**Dick Feely**
10:00	Where might acidified waters get into the Bay and how does water from the Bay affect the Gulf of Farallones?	**John Largier**
10:30	How might OA affect the Bay ecosystem?	**Karina Nielsen**
11:00	Short break	
11:15	How can the findings of the West Coast Ocean Acidification and Hypoxia Science Panel for monitoring and management be applied to San Francisco Bay?	**Francis Chan**
12:00	Discussion Desired outcomes: • Understanding management needs for OA monitoring • High level objectives for OA monitoring in the Bay	**Philip Trowbridge**
12:30	Lunch (provided)	

TIME	TOPIC	LEAD BY
	What are the potential pathways of biological impact and what are the critical chemical and biological indicators to measure those impacts in the Bay?	
1:15	Conceptual ecosystem model for OA effects in the Bay and charge to break-out groups Desired outcome: • Agreement on a "big picture" framework • Agreement on organization of break-out groups	**Phil Bresnahan**
1:45	Break-out group discussions to refine conceptual ecosystem models for biological impact from OA in the Bay at different trophic levels. Each group will be facilitated by a subject matter expert and staffed with a note-taker. The group is expected to: • Prepare a refined conceptual model for the trophic level with pathways feedback loops, and cascades of biological impact from OA in the Bay. • Identify the key assessment questions and the chemical and biological indicators needed to answer these questions. • Provide a concise explanation why managers should care about the impacts.	**Break-out group leads**
2:30	Reports from break-out groups Each group will have 15-20 minutes to report on their findings	**Break-out group leads**
3:30	Short Break	
4:00	Discussion Desired outcome: • Integration of conceptual ecosystem models across all trophic levels • Priority assessment questions and associated chemical and biological indicators (straw poll)	**Philip Trowbridge**
5:00	Wrap up and focus of Day 2	**Philip Trowbridge**

3

Day 2 - October 20, 2016

TIME	TOPIC	LEAD BY
8:30	Light Breakfast (provided)	
9:00	Recap of Day 1 and goals of Day 2	
	What monitoring designs should be used in the Bay to accurately track acidification levels and biological responses, and to what extent are these designs generalizable to other west coast estuaries?	
9:15	Challenges and opportunities for monitoring chemical indicators of acidification in estuaries and coasts	**Jan Newton**
9:45	Monitoring acidification in estuaries using bivalves	**George Waldbusser**
10:15	Short break	
10:30	Break-out group discussions to develop monitoring designs for priority assessment questions for OA impacts in San Francisco Bay and other west coast estuaries. Each group will be facilitated by a subject matter expert and staffed with a note-taker. The group is expected to: • Develop monitoring elements that answer priority assessment questions from Day 1 with as many details as possible. • Identify factors that would need to be considered when applying the case study of SF Bay to other west coast estuaries.	**Break-out group leads**
11:15	Reports from break-out groups Each group will have 10 minutes to report on their findings	**Break-out group leads**
11:45	Discussion Desired outcomes: • "Proto-monitoring design" for OA impacts in SF Bay • Guidance for generalizing these designs to other west coast estuaries	**Philip Trowbridge**
12:15	Summary of Workshop Outcomes and Next Steps	**Philip Trowbridge**
12:30	Adjourn then lunch (provided)	

4

Appendix. C Full Workshop Proceedings

Full Workshop Proceedings Prepared by:

CALIFORNIA OCEAN SCIENCE TRUST

Day 1 - October 19th, 2016

Welcome, Introductions, and Goal for Workshop

Warner Chabot, Executive Director, San Francisco Estuary Institute

Welcome, scientists, managers and SFEI staff to today's workshop. This gathering is exactly why this institute exists. SFEI's mission is to ask fundamental management questions to help improve water quality in San Francisco Bay and to provide rigorous science and tools to decision makers. Our goal is to identify solutions based on the best available science. Today's workshop is the ultimate extension of that effort and we thank you all for your participation. The State and the OPC have demonstrated leadership in advancing on OAH through the West Coast OAH Science Panel. Now we will build upon this effort in the Bay–Delta Estuary.

Opening Remarks: Why is OA a concern for California?

Jon Bishop, Chief Deputy Director, State Water Resources Control Board

OA is real and we are already seeing impacts along the California coast. Current monitoring schemes are not able to sufficiently judge the magnitude of acidification and there are outstanding questions that need to be addressed, such as,

- Do local nutrient inputs contribute to or exacerbate acidification from atmospheric CO2 or upwelling of low-pH waters?
- Do water quality standards need to be changed to address OA?

Looking at our largest estuary is an important step in identifying impacts on ecosystems in California. I am delighted to participate in this Workshop and figure out next steps to address this issue.

Opening Remarks: Why is OA a concern for California?

Jenn Phillips, Program Manager, Ocean Protection Council

The OPC is working in the State and the region to take action on OAH. OPC just funded over $3 million for six different OA related projects. Additionally, the state just passed two bills, SB 1363 and AB 2139, which support taking action on this important issue. SB 1363 charges OPC to implement an OAH Reduction Program. AB 2139 authorizes the Council to develop an OAH science task force to ensure that council decision-making is supported by the best available science.

OPC is also working with the Pacific Coast Collaborative (PCC) which brings together leaders of West Coast states and provinces, to raise awareness of OA and to build collective progress regionally and internationally. At the recent Our Ocean conference, the PCC launched an international alliance to combat OA, receiving strong support from countries and organizations around the world. The PCC, together with the federal Interagency Working Group on Ocean Acidification, is also focusing on characterizing and advancing OAH monitoring and research. This state/federal working group is building partnerships to coordinate and align research and monitoring and, as part of this effort, it is creating a comprehensive inventory of monitoring assets throughout the West Coast. Specifically, the inventory will help California identify future investments that are needed to best characterize OAH in the region and in San Francisco Bay.

Topic: Why should we care about acidification in the Bay?

What do we know about OA along the West Coast?

Richard Feely, Senior Scientist, NOAA Pacific Marine Environmental Laboratory

Changes in pH from OA are already measurable. We are finding that pH is decreasing by an average of about 0.002 per year, with the highest rates of change in northern latitudes. Along our coast, we have particularly corrosive waters that are shoaling and coming all the way to shore onto our beaches. This is the reason our estuaries are so affected; we have this natural process of upwelling and biogeochemical cycles that, in addition to anthropogenic CO2, make waters especially low in pH. It is our job to track these changes.

Changing ocean chemistry has physiological impacts on organisms, making it difficult for species to meet their energetic demands or form shells during calcification. There are other factors that exacerbate the effect of acidification, including changing temperature and oxygen concentration. At the same time there are compounding stressors that impact organisms living along our coast (e.g. overfishing, pollution, oil spills.) There is a need to tease out the biological response to OA among these other stressors.

Aragonite saturation state (Ω_{Ar}) is an indicator we can use to characterize whether water chemistry is suitable for shell growth. My job is to determine where $\Omega_{Ar} < 1$, a value that indicates undersaturation of aragonite, a critical mineral used in the formation of shells.

The Global Ocean Acidification Observing Network (GOA-ON) is an international partnership of 33 nations and 100 scientists documenting the status of OA in the open ocean, coastal, estuarine and coral reef habitats, and understanding the impacts of changing ocean chemistry. The West Coast observing system involves federal, state, and tribal partnerships in monitoring OA through the Integrated Ocean Observing System (IOOS). Our first observation of OA on the West Coast was published in 2008, when we found corrosive waters reached the surface during summer upwelling and traveled close to shore into estuaries (Feely et al. 2008). This process is why the San Francisco Bay region is so sensitive to OA. Point Reyes has some of the lowest pH waters, which makes this region an "OA hotspot". Since 2008, we have continually found the Point Reyes region to have low pH water during upwelling.

A long-term mooring has also shown that the capacity of our West Coast region to buffer changes in pH is diminished compared to other regions (i.e. the Gulf of Mexico.) Changes in chemistry are occurring faster here than other regions, which highlights the need for science and monitoring to answer the question, "why are we more sensitive?"

Newly published science indicates that these changes are just getting underway. Gruber et al. (2012) estimate that by 2050, the region may have corrosive waters up to 50% of the time. Additionally, numerous field and laboratory studies have demonstrated negative effects on bivalves, pteropods, coralline algae, crabs and other organisms.

OA is a global condition with local effects here and now. Rates of OA will increase over the coming years and decades. There is a need to determine the anthropogenic changes and biological impacts against the backdrop of natural variability and we have the tools to account for that now. Co-located chemical and biological observations are critical to achieve this aim.

Where might OAH waters get into the Bay and how does water from the Bay affect the Gulf of Farallones?

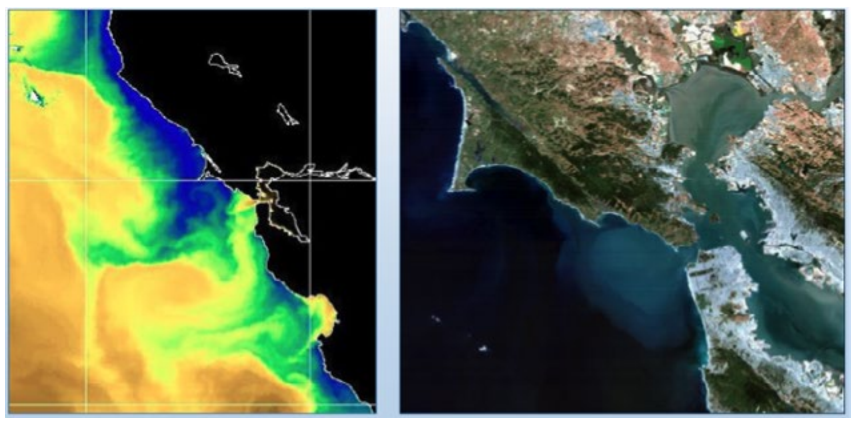
John Largier, Professor, Bodega Marine Laboratory, University of California, Davis

Currently, we have very limited information to assess the exposure of San Francisco Bay to OA because there has yet to be any comprehensive monitoring of carbonate chemistry. However, we do have a conceptual understanding of acidification exposure from preliminary studies combined with our knowledge of coastal oceanography, tidal exchange, and from OA monitoring and research in nearby locations.

Are bay habitats exposed to water with low pH, low aragonite saturation state, low oxygen and high nitrate waters?

A key process that influences coastal and estuarine chemistry is upwelling, which brings to the surface and shoreward water that is cold, salty, low in oxygen and pH, and high in pCO_2 and NO3. For this reason, cold, saline water serves as an indicator of the presence of upwelled low-pH, low-saturation-state water. Since there are no carbonate chemistry time-series in San Francisco Bay, scientists are using temperature, salinity and oxygen data as proxies to gain insight into how deep/cold, newly upwelled waters move into the estuary, waters that are also acidic.

There is already evidence that low-oxygen upwelled waters can travel into San Francisco Bay. In a 2011 USGS survey, a sub-surface hypoxic intrusion was observed extending from Central San Francisco Bay into South San Francisco Bay, which suggests that low-pH water can do the same. Coastal upwelling varies seasonally and spatially, and it is unclear how common low-pH incursion events are, or where exposure is most extreme. No intrusion events were observed during 2014 and 2015, when moored sensors were deployed at depth in San Francisco Bay. However, a mooring in the Gulf of the Farallones in 2015 has tracked low temperature, pH and oxygen events, which is consistent with the intrusion of deep upwelled waters into the Gulf, perhaps enhanced by the effect of Point Reyes.



Left panel: Sea surface temperature from NOAA AVIRIS satellite data in 1993, showing interaction of cold upwelled waters (blue, <10C) nearshore and warmer San Francisco Bay outflow and offshore surface waters (brown, >15C). Right panel: Photo from space of turbid outflow from San Francisco Bay.

The type and shape of bays and estuaries in California, the strength of river inflow, and the nature of the ocean-bay mouth channel will influence how easily OAH waters may enter estuarine systems.

<u>Water gets into the bay or is exchanged through two primary mechanisms:</u>

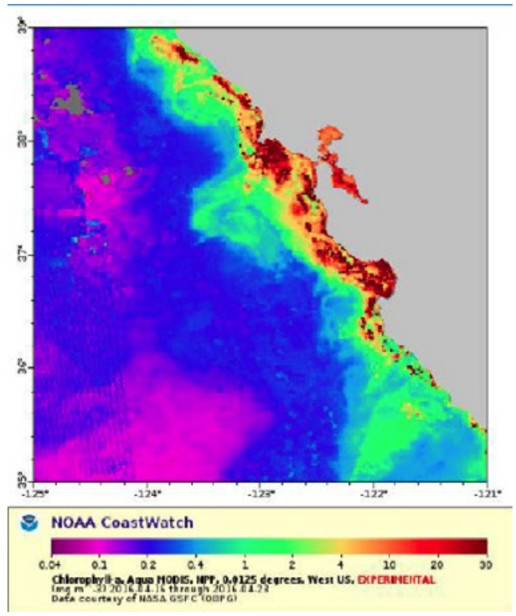
1. **Well mixed tidal flows or "tidal pumping"**

   Tidal exchange between San Francisco Bay and the coastal ocean does not exhibit vertical structure and much of the water that flows into the Bay on the flood tide is exported again on the subsequent ebb tide.

2. **Stratified flows or "salt-wedge" intrusion**

   In this case, recently upwelled water enters the bay as a dense lower layer. For the coldest/densest/most acidic waters to enter San Francisco Bay, the thermocline along the open coast has to upwell above 10m, which is the height of the tidal bar that can obstruct the inflow of the densest waters. On the subsequent ebb tide, this dense deep water may remain in the Bay as the outflow is strongest in the surface layer.

While well-mixed tidal flows may expose both shallow and deep habitats in Central Bay to OAH, the exposure is likely to be brief in time (just a few hours before the tide turns) and limited in landward extent (less than the tidal excursion, not much beyond Central Bay). In contrast, stratified inflows may penetrate further into San Francisco Bay without mixing or photosynthesis sufficient to condition the pH and oxygen extremes and be more persistent, but exposure will be mostly confined to subsurface habitats (below stratification and the euphotic depth).



Chlorophyll levels (mg/m^3, log-scale color) averaged over a week in April 2016. Image shows high levels in coastal waters from Monterey Bay to Bodega Bay and in San Francisco Bay. Image credit: NOAA Coast Watch

Some of the key questions challenging scientists are:

- How does upwelled, low pH water 'crest the bar' and how frequently?
- To what extent is low-pH water conditioned by mixing, photosynthesis/respiration, and other processes as it flows into San Francisco Bay?
- How far does unconditioned low-pH water go into the bay?
- How does outflow from San Francisco Bay impact the outer coast? and how does biological response to bay outflow (via photosynthesis, respiration and mixing) feedback to impact the estuary

Monitoring is essential for assessing exposure to OAH and the potential impacts in coastal bays and estuaries. At a minimum, we need to track water quality and chemistry, so that we can identify the degree and extent of OAH exposure. The planned deployment of a moored, instrumented buoy in San Francisco Bay is a great start, but it is unfunded. There is a need and value to deploy another mooring in the Gulf of the Farallones because the 2-buoy array would enable scientists to characterize feedbacks and drivers between estuarine and coastal environments. The fine-scale temporal monitoring of these buoys will enable the development of transport indices to characterize low pH events and the risk of exposure.

How might OA affect the Bay ecosystem?

Karina Nielsen, Director, Romberg Tiburon Center for Environmental Studies; Professor, San Francisco State University

San Francisco Bay is profoundly modified and highly valued. The 2016 Comprehensive Conservation and Management Plan, led by the San Francisco Estuary Partnership, outlines actions to:

- sustain and improve estuaries, habitats and living resources;
- bolster resilience;
- improve water quality; and
- champion the estuary.

And here we are today, in the spirit of Action 29, engaging the scientific community in efforts to improve baseline monitoring.

There is already evidence that "ocean climate" impacts community structure in San Francisco Bay (Cloern et al. 2010). Under the appropriate conditions, dense, upwelled waters will enter the bay along its deepest channels (Largier 1996; Barnard et al. 2013). Upwelled water along the coast is the source of low pH and DO oceanic waters for San Francisco Bay. The way the Bay is structured into distinct sub-regions, each with different circulation patterns and proximity to the Golden Gate, suggests that there will be different spatial patterns of OAH exposure and impacts in each sub-region. Deeper water habitats and benthic communities will be most vulnerable to OAH exposure upon the incursion of upwelled waters (i.e., via the estuarine intrusion or salt-wedge mechanism described in the prior presentation; see also Feely et al. 2010 for a Puget Sound example). Depending on the depth and extent of the intruding waters, and their interaction with local conditions in the estuary, other Bay habitats and organisms may also be vulnerable.

Subtidal benthic habitats include mud, shell, rock, artificial structures, shellfish beds, eelgrass beds, macroalgal beds, and the water column. The vision for managing these habitats is outlined in the report, Subtidal Habitat Goals for San Francisco Bay. This report calls for science-based protection and to preserve and restore the species and services supported by subtidal habitats.

There are multiple potential ecological pathways of OAH impacts, including:

- physiological response to direct OAH exposure;
- changes in ecosystem state due to altered species interactions (e.g, trophic cascades, distributional shifts, changes in species vulnerability to predation, etc.); and
- changes in the sensitivity of species and communities to other stressors, as a synergistic or antagonistic interaction with other stressors or drivers alters the sensitivity of species and communities to changing environmental conditions in unexpected ways (i.e., may result in the crossing of an ecological threshold or tipping point) (Kroeker et al 2014, Gaylord et al. 2015, Somero et al. 2016.)

Impacts to shellfish beds

Larval and juvenile shellfish are particularly sensitive to OAH (Waldbusser et al. 2014, Waldbusser et al. 2016). Exposure during early life stages may also have consequences on growth and survival beyond the larval stage (Hettinger et al. 2012). Shellfish beds are also located in areas susceptible to intrusion of low pH water. These impacts may be particularly relevant to living shoreline projects that are currently underway and planned for future implementation. For example, there is a value of understanding whether or not restoration sites overlap with areas most vulnerable to OAH exposure. Additionally, there may be a value of co-locating shellfish beds with submerged aquatic vegetation (SAV), because SAV may ameliorate acidification (Palacios and Zimmerman 2007), making the habitat more suitable for shellfish and other organisms. Monitoring, however, is needed to identify sites and determine whether co-location has benefits to shellfish and the ecosystem.

Impacts to submerged aquatic vegetation (SAV)

We currently do not fully understand how water enriched in CO_2 will impact SAV because there are many interacting factors that influence growth, including CO_2 enrichment, water quality (nutrients, etc.), sediment quality, light availability, temperature, and sea level rise. High pCO_2 may also impact the production of defensive compounds (i.e., phenolic compounds) by some seagrasses, which highlights the potential for changes in the strength of herbivory (Arnold et al. 2012).

Impacts to fishes

Most OA research on fish has been conducted in coral reef systems. These studies have identified that OA can have behavioral impacts such as altered navigation, predatory detection and sensory capabilities (see review by Clements and Hunt 2015). While there is much to learn about OAH impacts on fishes in the California Current, these studies highlight the need to support coupled chemical and biological monitoring to identify exposure, impacts and potential responses.

Should we be monitoring in the Bay?

Yes. There are no long-term carbonate chemistry time-series in San Francisco Bay. These are needed to understand the extent, duration, and frequency of acidified waters entering the Bay. OA impacts are known for many species (or related taxa) important to the functional ecology of the Bay ecosystem, and associated with conservation and restoration goals. In addition, there are major habitat restoration projects in the pipeline, including living shorelines, horizontal levees, and recent legislation (SB 1363) that encourages restoration of eelgrass, that may be impacted by or have the potential to ameliorate OA. Establishing a carbonate chemistry monitoring program for San Francisco Bay is essential to evaluating exposure to OA in this ecosystem. It is also needed to understand whether or not management and restoration efforts are meeting their goals, and to support adaptive management in the face of changing ocean conditions.

How can the findings of the West Coast Ocean Acidification and Hypoxia Science Panel for monitoring and management be applied to San Francisco Bay?

Francis Chan, Associate Professor, Oregon State University

Why should acidification be a focus for managers? The West Coast is vulnerable and being behind the curve on this issue doesn't seem like the best option. Our planet is committed to more extreme conditions in CO2 chemistry against a background of increasing hypoxia stress (we are 'locked in' due to CO2 already emitted) and the chemical changes are not linear. More changes will impact a wider suite of organisms not yet affected, with compounding effects of OAH. Physiological impacts can also accelerate quickly when thresholds are crossed.

We can view the challenges as "a global problem that we wait to happen to us," or "a problem that we can and should get out in front of." Here is what we know now:

- We need to proceed with sound science.
- Certain actions will bring disproportionate results.
- We need to consider how "the rubber hits the road" and translate the general recommendations of the Panel into place-based actions.

[At this point during the presentation, Francis Chan provided an overview of the Findings, Recommendations and Actions of the West Coast Ocean Acidification and Hypoxia Science Panel (Chan et al. 2016). For a full description of the Panel (as summarized by Chan) and to access its products, please visit www.westcoastoah.org.]

The Panel outlined a "roadmap" of actions we can take at the regional and local level to address the global problem (Fig 1).

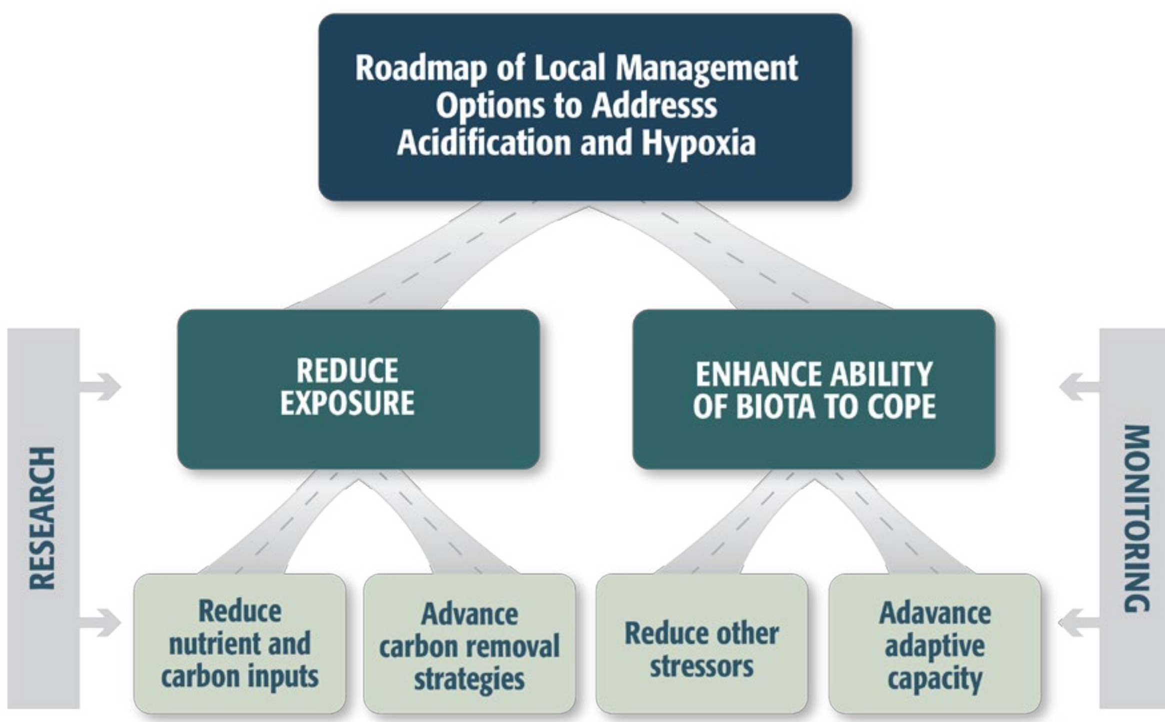


Fig. 1 Roadmap of local management options to address ocean acidification at the local scale (Figure Credit: Ocean Science Trust).

Some of the Panel's recommendations are already underway.

Recommendation 1: Reduce Local pollutants that exacerbate OAH

Stakeholders involved in the Nutrient Management Strategy are already supporting the development of a coupled physical-biogeochemical model of San Francisco Bay. This effort could be built upon to address carbon chemistry changes, but would require monitoring data to inform and validate the model. As models of the California Current are developed to include carbonate chemistry they will be able to provide information about the fluxes of pH, oxygen, chlorophyll-a, and nutrients to the ocean boundary models of San Francisco Bay. However, to reliably use these models to predict future trends of OAH incursions into San Francisco Bay and investigate whether Bay outflow impacts coastal OAH dynamics, they will need to be properly coupled and the model output validated.

Recommendation 2: Advance approaches that remove CO2 from seawater

Scientists from California and Oregon are beginning to study the role of seagrasses to ameliorate OA in coastal systems.

We don't have enough observations in San Francisco Bay and many other West Coast estuaries, and what we do have may not meet management goals. The PCC Interagency Working Group on OA is starting to take action on building out a West Coast Monitoring Program. Long-term monitoring is not a trivial commitment, but is essential for characterizing changes in vulnerability. Long-term monitoring is also fundamental for assessing the effectiveness of adaptation and mitigation investments, and calibrating or improving OAH modeling and forecasting tools. Partnering with stakeholders will help identify hotspots and refuges and is cost-effective.

How can we change course today?

- Today we are on a "low info diet." We need a "high info diet" to open up opportunity and accelerate place-based solutions.
- Prioritize innovative, relevant research.
- Implement "smart monitoring" to know where we are heading.
- Facilitate and support partnerships between scientists and decision-makers to translate new knowledge into actual solutions.

San Francisco Bay is well-poised to be a model for getting ahead of the curve on OAH because of its strong potential for growing partnerships; Its already established long term Regional Monitoring Program RMP) for water quality can be leveraged with additional partners and funding sources to build our understanding and to accelerate solutions.

Topic: Management Needs and Objectives for OA Monitoring

Discussion: Understanding management needs and brainstorming high-level objectives for OA monitoring in the Bay

Led by Philip Trowbridge, San Francisco Estuary Institute

Following the first set of presentations, natural resource managers in the audience were asked to discuss the management implications of what had been presented. The following key points and questions were raised in the discussion

Key points and questions raised in the discussion:

Monitoring:

- Water quality benchmarks for OAH are needed.

- Paired biological and chemical monitoring is inherent to understanding the link between OAH exposure and impacts to species and ecosystems. Chemical monitoring is a critical first step.
- Biological monitoring should focus on non-motile species, given the challenges associated with monitoring and teasing out factors that impact mobile species.
- There is a need to understand how outflow from San Francisco Bay impacts coastal OAH and whether this process further exacerbates OAH exposure in the Bay.
- Harmful algal blooms are an emerging problem that may be influenced by elevated pCO_2 levels. There is a need to understand these as potentially co-occurring stressors.

Management:

- What management levers exist to address this issue? And how receptive is the management community to work together on an issue that spans multiple jurisdictional boundaries?
- How does OAH factor into management of protected areas? There is a need to look at restoration and protected areas now and into the future.
- How might managers consider OAH when evaluating development permits in San Francisco Bay? What are the opportunities for mitigation to answer some of the outstanding questions about OAH?
- Fisheries managers need to think about how to include OAH as one of the many stressors considered in fisheries management.
- Restoration managers should consider siting projects where they might make the biggest impact (e.g., locating seagrass restoration projects near oyster reefs).

Break-out group discussions followed up by reports from break-out groups.

Break-out groups were divided by trophic level:

- primary producers
- lower trophic level consumers
- top predators and community impacts

The groups were asked to develop detailed conceptual models for the trophic level assigned.

The outputs of the groups have been organized below in the following categories:

- key taxa that are representative of each trophic level and identified;
- potential impacts and interactions specific to their specified trophic level and science questions that may be used to assess the biological impact of acidification; and
- monitoring goals.

This break-out session was intended to be one of open brainstorming, not final recommendations, and the suggestions written here should be considered accordingly. The recommendations resulting from the Workshop can be found in the Executive Summary and at the end of the *Proceedings*.

Impacts on Primary Producers

Key taxa:

phytoplankton, microcystis, marsh plants, seagrasses, macroalgae

Assessment Questions/Objectives:

- How does acidification influence the productivity of phytoplankton, harmful algal blooms and the San

Francisco Bay ecosystem?

- What effect do pH and elevated CO_2 have on primary production?
- What effect does pH have on the lipid content of phytoplankton? And how does this impact consumers?
- To what extent does SAV ameliorate or buffer seawater chemistry (pH, pCO_2, alkalinity, aragonite saturation state) - or even have a negative effect - in local waters? What is the potential for SAV to serve as an OAH refuge for other organisms?

Goals:

- Ability to rank impacts on primary production in Bay systems

  Impacts: light, turbidity, nutrients, temperature, mixing, tides, grazing, as well as anthropogenic impacts such as physical habitat disturbance, heavy metals, pesticides, and water inputs
- Understanding how OAH may change the role of primary production in bay ecosystems

Impacts on Lower Trophic Level Consumers

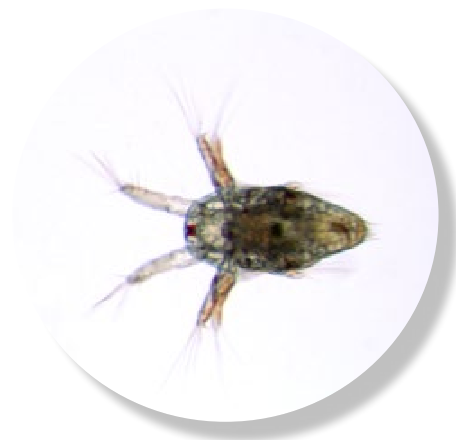
Key taxa:

bivalves, crustaceans, microbial assemblages (bacteria, archea), zooplankton (pteropods, copepods, calcifying larvae, jellyfish)

Pteropod. Photo credit: Nina bednarsek

Assessment Questions/Objectives:

- How does OAH impact lower trophic level consumers?
  - Consider changes in food quality, reproductive success, species composition, and grazing rates.
  - Link chemical changes to performance of organisms, gene expression, changes in species abundance and distribution.
- To what extent can benthic foraminifera serve as biological indicator of pH exposure?



Copepod (*Tortanus* spp.).
PC: Carrie Craig

Goals:

- Develop and use models to identify likely OAH hotspots in the Bay to narrow the range of priority locations to monitor.
- Enhanced monitoring:
  - Monitor physical parameters (salinity, temperature, O2, pCO2, pH, DIC, alkalinity, Chl, turbidity, total nitrogen).
  - Monitor biological indicators, such as juvenile settlement, zooplankton species assemblage, benthic forams.
  - Develop species distribution and abundance maps.
- Conduct risk analyses.

Top Predator and Community Impacts

Key taxa:

Sensitive fishes: green sturgeon, winter and spring chinook salmon, longfin smelt

Other fishes: halibut, Dungeness crab, striped bass, shellfish, pacific herring, leopard sharks, bat rays, etc.

Birds: shorebirds, snowy plover, clapper rail, surf scooters, diving ducks, cormorants, etc.

Mammals: river otters, porpoises, harbor seals, sea lions

Non-native species

Dungeness crab
PC: Rick Starr

Potential Impacts and Assessment Questions/Objectives:

- Compare the composition of organisms that are more/less vulnerable among different sites in the bay in order to identify regional differences in vulnerability and changes over time.
- Monitor the relative susceptibility of organisms in different regions of San Francisco Bay and over time.
- How does OAH impact salmon in San Francisco Bay? Leverage the salmon rearing that is being conducted in the Bay to relate changes in OAH to impacts on fish.

Goals:

- Use OA as a lens through which habitat is valued for upper trophic levels.
- Examine feedback loops affected by OA with impacts on upper trophic levels, including effects of HABs and changing food quality.

Facilitated Discussion of Priority Issues and Assessment Questions

Led by: Philip Trowbridge

The conceptual ecosystem models and assessment questions developed break-out were synthesized through a facilitated discussion. Each of the break-out groups reported the outcomes from its discussion. The full group developed a master list of potential impacts and monitoring goals across all trophic levels and then prioritized the items.

Highest Priority Issues:

- Changes in phytoplankton community and food quality
- Increased toxins from harmful algal blooms and effects on higher trophic levels
- Local mitigation of OAH impacts by submerged aquatic vegetation

Other Priority Issues:

- Loss of filter feeders and cascading effects on phytoplankton concentration
- Impact on fisheries
- Shellfish habitat

Highest Priority Monitoring Indicators:

- Add carbon parameters to water quality monitoring (high quality pH, pCO2, total dissolved inorganic carbon, and total alkalinity, in addition to high quality physical measurements)
- Obtain time-series data at depth in several locations (some sites with carbonate parameters and others with more affordable indicator parameters, e.g., temperature, salinity, oxygen)
- Larval bivalves, larval Dungeness crab, foraminifera

- Phytoplankton, taxonomy, toxins, fatty acids
- SAV habitat suitability, plant health, and buffer capacity
- Map OAH "hotspots" over the suitability of SAV to help prioritize restoration or other projects

Other Priority Monitoring Indicators:

- Assess salmonid otoliths that are caged in San Francisco Bay
- Nested indicators in different trophic levels
- Use OA as a lens through which habitat is valued for upper trophic levels
- Microbial community and function
- Buffering capacity of shells as they dissolve

Day 2 - October 20, 2016

Recap of Day 1 and goals of Day 2

Philip Trowbridge started the discussion by reviewing the focus for the second day of the Workshop: What monitoring designs should be used in the Bay to accurately track acidification levels and biological responses, and to what extent are these designs generalizable to other California estuaries?

To refresh everyone's memory on where we left off on Day 1, Trowbridge provided a summary of the shared understanding developed around the problem, the solution, and the assets in place.

Problem:

We do not know if OA is a problem in the Bay. We do not know the range and scope of what changes in carbonate chemistry might be. We do not know which species are most at risk.

Solution:

We need a strategic plan for how we will answer these questions.

Assets:

There is excellent although incomplete monitoring infrastructure in place and OA expertise in local institutions. Additionally, there is a strong potential for local and regional partnerships. This Workshop will also provide provide valuable science advice that may be used to develop an OA monitoring framework in San Francisco Bay and other California estuaries.

Overview of monitoring conducted in San Francisco Bay

David Shen, Senior Scientist, San Francisco Estuary Institute

There are multiple existing monitoring programs that are ongoing in San Francisco Bay that may be leveraged to understand OAH exposure and impacts. [Senn provided overview of each program. For reference, a list of major programs are provided below. This list may be incomplete.

- Regional Monitoring Program for Water Quality in San Francisco Bay (www.sfei.org/rmp)
- San Francisco Bay Nutrient Management Strategy (SFEI and collaborators) (http://sfbaynutrients.sfei.org)
- Central and Northern California Ocean Observing System (CeNCOOS)(http://www.cencoos.org)
- Department of Water Resources and the Interagency Ecological Program (http://www.water.ca.gov/iep)
- National Marine Sanctuary Observation and Forecasting Program (http://sanctuaries.noaa.gov/science/monitoring/mi_gfnms.html)

- USGS California Water Science Center (http://ca.water.usgs.gov)
- USGS Water Quality of San Francisco Bay (https://sfbay.wr.usgs.gov/access/wqdata/index.html)
- San Francisco Bay National Estuarine Research Reserve (NOAA) (http://www.sfbaynerr.org)

Challenges and opportunities for monitoring chemical indicators of acidification in estuaries and coasts

Jan Newton, Senior Principal Oceanographer, Affiliate Assistant Professor, University of Washington; Executive Director, Northwest Association of Networked Ocean Observing Systems (NANOOS)

We need local through global scale observations in order to develop an accurate understanding of both local or global patterns.

There are multiple challenges to monitoring OAH, especially in coastal waters. But there are also opportunities from these challenges. First, natural variability is considerable in coastal waters and there are many sources of variation. But, if we observe on appropriate temporal and spatial scales, the data will reveal the underlying mechanisms driving patterns of variation. Quantifying the contributions of each source to the overall signal in is difficult, but it is possible! This means we need to understand the system and using more than one approach is powerful. Lastly, OA has potential for widespread biological effects that we don't fully understand. This challenge requires an interdisciplinary, integrated approach.

The West Coast waters are particularly vulnerable to OA, with impacts appearing sooner than anticipated. Regional factors—coastal upwelling, runoff/discharge of nutrients, and the decay of organic matter in subsurface waters—can exacerbate acidification caused by global CO_2 emissions (Feely et al. 2008, Kelly et al. 2011). The most important thing is to understand the factors affecting your system. For instance, West Coast coastal shelf waters show different mechanisms than those observed on the East Coast (e.g., Jiang, et al., 2010.)

How much coastal acidification is due to upwelling, respiration, and rising CO_2 emissions?

Data from offshore monitoring have enabled scientists to quantify the different drivers of acidification. While there are regional differences, global emissions can explain up to 28% of acidification in some regions (Southern California) (Feely, Alin, et al. in prep). In the Hood Canal, OA contributes 25-50% of the signal compared to respiration. Even though the contribution of anthropogenic CO_2 has a smaller effect on short timescales than natural variability, the cumulative effect is substantial and has already reduced aragonite saturation state (Ω_{Ar}) by 0.5. With this reduction, some areas are now crossing the aragonite undersaturation (Ω_{Ar} = 1) threshold 33% of the time (three times more frequently than in preindustrial time) (Harris et al. 2013). This is making a bad day worse and may have important consequences for species.

What can San Francisco Bay learn from efforts in Washington?

[Newton provided overview of the findings of the WA Blue Ribbon Panel report, "Ocean Acidification: From Knowledge to Action," and the Washington OA Center.]

The Washington OA Center is taking efforts to understand drivers, impacts and adaptation responses to OAH. At the Center, there are three major efforts underway:

1. to monitor water conditions and plankton in Washington's diverse coastal waters (outer coast, Puget Sound, Columbia River estuary);
2. to conduct experimental work on how local species are responding to OA; and
3. using the monitoring data to develop forecast models that may be used to facilitate adaptation.

The value of the WA OA Center is to accelerate and coordinate research and monitoring, leverage resources and networks, and provide input to regional assessments, management and policy needs. Through this approach, the output from the Center's state-funded efforts on integrated monitoring, biological experiments on local species, and forecast modeling to facilitate adaptation.

These actions are complemented by other regional efforts.

- Global process observation, primarily done by NOAA and in partnership with them in WA
- Source attribution modeling, currently being done through USEPA and state agency efforts
- Adaptation strategy evaluation, currently being funded by private foundation funding

Together, these efforts build knowledge of OAH exposure as well as mitigation and adaptation responses. The center is working to assess OAH impacts through both chemical and biological monitoring. The monitoring program is designed to capture both temporal variation (via moored sensors) and spatial variation (via surveys). Pteropods, and the extent these organisms show signs of dissolution, are proving to be a useful biological indicator species to understand impacts and drivers (Bednarsek et al., 2017). Additionally, benthic foraminifera may also serve as valuable indicators of OAH exposure (Nesbitt et al. 2015).

Why monitor OA?

BOX 1. Types of questions an OAH monitoring network can answer

Long-term monitoring data can provide input to answer a number of questions that resource managers want to know the answers to, such as:

1. What are the trends in OAH with time? How rapidly is change occurring?
2. What is the variation in OAH in the region? How does this compare to other sites? How does this change seasonally? How is this different in estuaries and the nearshore versus offshore?
3. What are the effects of OAH on biota? Is OAH impacting biota now? What are the most sensitive species, populations, or ecological properties to OAH?
4. Are human activities aside from the atmospheric input of CO_2 contributing to OAH? What are these and where?
5. When management actions have been taken to offset changes in OAH or to enhance ecological resilience, are these resulting in their anticipated effect?
6. Can corrosive conditions in the nearshore or at hatcheries be anticipated by conditions offshore?

Box 1 Credit: Newton, J., Hill, T.M., Feely, R.A., Barth, J.A., Boehm, A.B., Chan, F., Chornesky, E.A., Dickson, A.G., Hales, B., Hofmann, G., Ianson, D., Klinger, T., Largier, J., Pedersen, T.F., Somero, G.N., Sutula, M., Wakefi eld, W.W., Waldbusser, G.G., Weisberg, S.B., and Whiteman, E.A. Ocean Acidification and Hypoxia Monitoring Network: Tracking the Impacts of Changing Ocean Chemistry to Inform Decisions. Ocean Science Trust, Oakland, CA, 2016)

Success tips:

- Convene scientists, federal/state/tribal managers, policy makers, industries and NGOs together, to prevent working in silos. Communication between these groups is critical to success.
- Assure monitoring methods and adaptation measures are appropriately place-based. Use knowledge of the system to guide implementation.
- Coordinate with external groups and integrate and leverage efforts and assets, in order to develop a lean and focused effort, strategically fill needs.
- Design projects at the local level so that they may scale to global integration (make them relevant!). The GOA-ON portal (www.goa-on.org) is a way to make these connections, and working through US IOOS (e.g., on West Coast, CeNCOOS, NANOOS, SCCOOS).
- Sustaining all these efforts is critical.

Monitoring acidification in estuaries using bivalves

George Waldbusser, Associate Professor, Oregon State University

Biological monitoring of bivalves has been used in other systems to understand anthropogenic impacts. We can learn from these case studies to understand how bivalves may be used to monitor acidification in estuaries.

Why use bivalves as biological indicators of OAH?

Bivalves are osmoconformers and have been shown to be sensitive to OA. Their shells can also record water conditions, though there are challenges with analyzing shells to reconstruct chemical records. Bivalves have a large cultural value making them a good "poster child" to showcase biological impacts. Though some have argued they are functionally extinct today, bivalves are and used to be iconic organisms.

Potential use of bivalve monitoring in San Francisco Bay

Bivalves have been used as biological indicators for other purposes in estuaries such as Chesapeake Bay, Willapa Bay, and Netarts Bay. Biological monitoring of bivalves is possible in San Francisco. Oyster condition index, lipid content and calcification can be measured using two fluorescent stains. This type of monitoring is currently being tested in collaboration with 3-4 shellfish growers in the Pacific Northwest, and interest from a many others following a workshop at the Pacific Coast Shellfish Growers Association meeting. Monitoring in San Francisco Bay may be achieved by deploying oyster spat at select locations with subsequent monitoring of oyster condition, growth and survival. After 2 years of oysters being deployed, their tissue weight can be used to evaluate longer-term impacts and chemical analysis of shells may serve as indicators of the chemical conditions experience during that time period. This type of monitoring takes time, dedicated staff, and it may take many years to have useful data. If biological monitoring is coupled with chemical monitoring, strong inferences are possible. Ultimately, use of bioindicator species such as bivalves, requires a clear vision on what environmental conditions are ultimately to be monitored, and how this connects to the organismal physiology.

Topic: Monitoring for Acidification Threats in West Coast Estuaries

Break-out group and facilitated discussions to develop monitoring designs for priority assessment questions for OA impacts in San Francisco Bay and other California estuaries.

Led by: Philip Trowbridge, San Francisco Estuary Institute

The synthesis and conceptual diagrams generated in the break-out group sessions from Day 1 were discussed and assimilated into management-relevant science questions that might be used to evaluate acidification threats in California estuaries (Table 1). In addition, assessment approaches and/or indicators were developed for each science question. The list of science questions represents the discussions at the Workshop, but does not necessarily represent all management-relevant science questions discussed or available.

Facilitated Discussion: Developing a Monitoring Framework for San Francisco Bay

Led by: Philip Trowbridge, San Francisco Estuary Institute

Finally, the group discussed a plan to phase in monitoring for OAH in San Francisco Bay. A step-wise approach was suggested.

Near term

Continue to synthesize existing data from San Francisco Bay to develop conceptual models

- Because there will be linked models of water quality in the Bay and the coastal zone, these models should be used to predict the fate of upwelled water in the nearshore and estuarine environment. The model results can be used to understand which parts of the Bay are likely to be exposed to low-pH water. Field data will be needed to validate the ability of the model to reproduce OA events in correct locations.
- Other datasets from the Bay should be analyzed to develop better conceptual models for this particular estuary.

Inventory assets to identify opportunities to add OAH monitoring to existing monitoring programs

- There are several long-term monitoring programs in San Francisco Bay. This monitoring infrastructure should be better inventoried to facilitate leveraging opportunities for OAH monitoring.
- The OPC and the PCC Interagency Working Group on OA are starting to take action on building a West-Coast Monitoring Program. The monitoring programs in the Bay should be part of the inventory for this larger West Coast network.

Implement a Carbonate Chemistry Monitoring Program

- Conduct an initial carbonate chemistry "snapshot" throughout the Bay, measuring all four carbonate chemistry parameters (high quality pH, pCO_2, total dissolved inorganic carbon, and total alkalinity) over a range of along- and cross-channel distances and depth. Use survey results to select the two priority parameters to be measured in subsequent surveys and to establish a baseline understanding of the organic acid contribution to total alkalinity. Conduct cruises during susceptible periods to assess spatial patterns in OAH exposure.
- Add chosen carbonate chemistry parameters to monthly water quality monitoring cruises by the USGS.
- Use moored sensors to assess temporal trends. Complete the planned deployment of buoy in Central Bay, with carbonate chemistry sensors at the surface and near bottom. Deploy multiple low-cost bottom sensors for indicator variables (temperature, salinity, oxygen) to assess temporal trends in different locations. Begin planning for subsequent deployment of moored sensors in the Gulf of the Farallones and other regions to enable scientists to begin characterizing fluxes between the Bay and the coastal waters.
- Add a SeaFET sensor to existing moorings in the South Bay (following Rivest et al. 2016, Bresnahan et al. 2014).

Table 1. Linking OAH impacts to management-relevant questions and associated approaches or indicators

Impact	Questions	Indicators/Approaches
Ocean currents can deliver acidified marine waters into bays and estuaries. This open ocean effect is compounded by local eutrophication-enhanced acidification in many nutrient-enriched estuaries.	What are the sources, pathways and exposures to altered carbon chemistry and dissolved oxygen? What is the relative importance of low pH water compared to other stressors? What is the relative importance of local anthropogenic sources of CO2 to low pH water? How do carbonate chemistry and oxygen co-vary?	• chemical monitoring via cruises/surveys and moored sensors (buoys) • develop and test calibrated carbon models, conceptual models, and mass balance calculations
Changes in phytoplankton community and food quality Loss of filter feeders and cascading effects on phytoplankton productivity	To what extent can exposure to lower pH water change the phytoplankton community or food quality?	• evaluate changes in phytoplankton taxonomy and fatty acid composition
Increased toxins from harmful algal blooms and effects on higher trophic levels	To what extent can exposure to lower pH water increase the production of HAB toxins?	• assess HABs, toxins, in context of OA conditions
Impact on fisheries and shellfish habitat	To what extent does exposure to lower pH water decrease shellfish populations and fisheries?	• assess larval quality, recruitment, and juvenile growth of bivalves, Dungeness crab, etc. • use OA as a lens through which habitat is valued for upper trophic levels • assess caged salmonid otoliths
Local mitigation of OAH impacts by submerged aquatic vegetation	To what extent can existing or restored submerged aquatic vegetation buffer for lower pH exposure? What's the carbon budget for the different natural and restored vegetative habitats?	• assess submerged aquatic vegetation health, buffer capacity and quantify habitat suitability • overlay OAH "hotspots" over the habitat suitability maps for SAV to help prioritize restoration or other projects
Other considerations		• coupled biological and chemical monitoring in association with living shoreline projects • nested indicators in different trophic levels • microbial community and function • buffering capacity of shells as they dissolve • evaluate benthic foraminifera characteristics

Long Term

Implement a Coupled Chemical and Biological Monitoring Program

- Couple chemical monitoring with biological monitoring programs
  - There are existing monitoring programs that may be built upon to understand OAH impacts (e.g., the Smithsonian olympia oyster monitoring, The Mussel Watch Program, the San Francisco Bay Living Shorelines project, and the Invasive Spartina Project).
  - Monitor plankton community at a limited number of stations (e.g., measure percent composition of species susceptible to OAH or fatty acid composition).
  - Participate in West Coast monitoring of SAV to evaluate the capacity and extent SAV ameliorate OA.
- Map vulnerability "hotspots" in San Francisco Bay

Conduct scientific research to satisfy research needs related to monitoring

- Co-locate carbonate monitoring with conservation, mitigation, and/or restoration projects to evaluate both the risks to and benefits from the restoration investment relative to OAH exposure.
- From moored sensor data, determine mechanisms controlling OA intrusion events and extent/ persistence of exposure in the Bay. Project future conditions under climate change.
- Evaluate phytoplankton toxin production as a function of OAH and salinity.
- Explore fouling communities to lower pH to test resilience.
- Analyze the Smithsonian Institute fouling community dataset for trends.
- Analyze the Smithsonian Institute benthic "grab sample" archives for changes in benthic foraminifera to refine foraminifera monitoring questions and applications

Monitoring to Assess OAH exposure in West Coast Estuaries

Throughout the West Coast of the US, estuaries are susceptible to OAH effects intruding from open coastal waters. Estuarine water quality research has historically focused on contaminants, nutrient pollution, freshwater flows and other anthropogenic drivers connected to watershed management issues. The intrusion of the ocean watershed, and its influence on salinity and nutrients, is an expected source of natural variation, but has not been considered as a source of concern for water quality. Furthermore, research on estuarine carbonate chemistry and hypoxia/anoxia has focused on detecting the influence of watershed-related factors (e.g., estuarine acidification vs. ocean acidification). Long-term water quality and ecological monitoring in estuaries were not designed to detect OAH impacts, and may be inadequate to the task. The potential impacts of OAH on resident biota, restoration efforts, and nature-based adaptation projects (and vice versa) may go unrecognized as a result, creating inefficient use of human and economic resources.

This Workshop focused on San Francisco Bay, part of the largest estuary on the West Coast of the US, as a case-study to address the need for increasing our understanding of OAH impacts to estuaries and develop a rigorous approach to OAH monitoring in San Francisco Bay and other California estuaries. The process outlined here can be used to develop estuary-specific monitoring plans for other estuaries though scientific workshops that consider their unique and shared estuarine characteristics. This process is comprised of four steps:

1. Compile existing data and current knowledge and assemble experts to synthesize this information.
2. Develop conceptual models identifying key pathways to impairment.
3. Inventory assets and efforts, with a view to building an OAH monitoring and research program.
4. Prioritize new actions based on opportunities, resources, and relevance.

In reviewing the diversity of estuaries in California (see Largier presentation), one can identify three types of estuary in terms of susceptibility to acidification and hypoxia. The first type are the larger/deeper ocean-forced bays like San Francisco Bay – and comparable estuaries like Humboldt Bay, Tomales Bay, and San

Diego Bay. Low-pH and low-DO waters associated with upwelling along the open coast may intrude into these bay estuaries, accounting for minima in oxygen and pH – with greatest exposure at depth and near the mouth. The second type are the narrow river-mouth estuaries that are characterized by strong outflow during winter, such as the Russian River, Eel River and Klamath River. Less susceptible to ocean-derived acidification and hypoxia, these estuaries may differ in the alkalinity of freshwater inflows. The third types are lagoon estuaries in which waters may be retained for long enough that internal biogeochemical processes dominate and pH/oxygen conditions are susceptible to organic loading of inflows from land. In these systems, low-pH and low-DO are typically associated with eutrophication, often during closed-mouth periods (e.g., Pescadero Lagoon, Los Peñasquitos Lagoon). With seasonal variability, however, it is possible to see all three types in one basin through a seasonal cycle (e.g., in Russian River, low-oxygen intrusions have been observed in upwelling season, locally produced low-oxygen conditions have been observed when a lagoon forms in late summer, and low-pH is associated with strong freshwater flows in winter).

In all estuaries, new monitoring will be built on existing programs – leveraging existing monitoring assets and sampling programs to build an OAH monitoring program. Further, considering the concordance of OAH monitoring with local conservation, mitigation, and/or restoration projects may resolve or support management decisions related to project evaluation and long-term climate adaptation planning. And synergy between individual estuary programs may be advanced by participating in the monitoring inventory being developed by the OPC, the Pacific Coast Collaborative PCC, and the Interagency Working Group on OA. However, specific actions will be most similar within similar types of estuaries. For example, in the deeper, stratified bay estuaries, near-bottom chemical monitoring is essential – while in lagoon systems, monitoring during closed or constrained-mouth periods is critical for properly characterizing exposure to minimum pH and oxygen conditions, which are not due to OAH intrusions. These considerations will influence the number, duration and location of buoys and carbonate chemistry water surveys needed to adequately characterize exposure to OAH or other low-pH and low-oxygen conditions. Estuarine habitats will also vary within and between basins due to additional characteristics, such as the location, extent and tidal-depth of SAV. Through site-specific or type-specific workshops, these multiple factors can be assessed within a conceptual model that can prioritize deployment of monitoring assets within the context of existing programs and ecological assets of primary concern.

California's estuaries are diverse and productive ecosystems of high ecological, cultural and economic value. They have many stakeholders, are managed to meet many different, often competing, objectives, and contend with environmental stressors from a variety of sources (i.e., watershed, coastal development, ocean watershed). This Workshop brought together OAH scientists from throughout the West Coast of the United States, scientists and scientific organizations leading research on San Francisco Bay, and representatives from a variety of agencies involved in managing the Bay. The charge to this group was to develop a monitoring approach for this large, complex, urbanized estuary. Although San Francisco Bay was the case study, the aim was to develop more general guidance for California and other West Coast estuaries. The approach outlined above, based on the expertise of leading subject area specialists and currently available science, provides guidance for scientists, policymakers and other stakeholders about how and what to monitor to assess exposure to OAH in West Coast estuaries. It also highlighted the importance of monitoring estuaries for emerging water quality concerns such as OAH to ensure there is sufficient context for understanding their ecology to support effective management and restoration efforts.

- Adjourn -

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