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Getting Ocean Acidification on Decision Makers' To-Do Lists

Dissecting the Process Through Case Studies

By Sarah R. Cooley, Elizabeth B. Jewett, Julie Reichert, Lisa Robbins, Gyami Shrestha, Dan Wieczorek, and Stephen B. Weisberg

ABSTRACT. Much of the detailed, incremental knowledge being generated by current scientific research on ocean acidification (OA) does not directly address the needs of decision makers, who are asking broad questions such as: Where will OA harm marine resources next? When will this happen? Who will be affected? And how much will it cost? In this review, we use a series of mainly US-based case studies to explore the needs of local to international-scale groups that are making decisions to address OA concerns. Decisions concerning OA have been made most naturally and easily when information needs were clearly defined and closely aligned with science outputs and initiatives. For decisions requiring more complex information, the process slows dramatically. Decision making about OA is greatly aided (1) when a mixture of specialists participates, including scientists, resource users and managers, and policy and law makers; (2) when goals can be clearly agreed upon at the beginning of the process; (3) when mixed groups of specialists plan and create translational documents explaining the likely outcomes of policy decisions on ecosystems and natural resources; (4) when regional work on OA fits into an existing set of priorities concerning climate or water quality; and (5) when decision making can be reviewed and enhanced.

On November 27, 2012, Washington State Governor Christine Gregoire signs an executive order urging Washington State to accept the findings of the Washington State Blue Ribbon Panel on Ocean Acidification. *Photo credit: Seattle Aquarium*

INTRODUCTION

Known as "a global problem with local effects," ocean acidification (OA) acts at all scales, from multiple nations to individual communities. Oceanic uptake of atmospheric carbon dioxide (CO_2) released by fossil fuel burning causes OA. Average global seawater acidity has already increased by 26%, and business-as-usual forecasts project much more by the end of the century (IPCC, 2013). By changing the acidity, CO_2 content, and ionic balance of coastal seawater (e.g., see detailed explanations in Gattuso and Hansson, 2011), OA changes marine organisms' environments. Nearshore where many economically and culturally valuable species live, other processes enhance OA, such as nutrient pollution, surface water runoff, or groundwater discharge (Doney, 2010; Duarte et al., 2013). OA slows the growth of many marine organisms, particularly shellfish and corals, and alters the behavior and survival of numerous species (Dixson et al., 2010, 2015; Doney et al., 2012; Kroeker et al., 2013). Ocean acidification has therefore been recognized as a potential threat to many marine ecosystems and the benefits they provide to human communities, such as food, income, coastal protection, and tourism opportunities (Cooley et al., 2009). These negative effects warrant factoring OA into natural resource management and development plans.

Addressing OA is complex because other major simultaneous global and local changes also affect seawater and marine ecosystems, including temperature rise, reduction of dissolved oxygen (e.g., Gruber 2011), pollution, and human disturbance (Doney, 2010; Duarte et al., 2013; Strong et al., 2014). At times, these processes interact synergistically (e.g., Gobler et al., 2014); indeed, in most environments, OA cannot be considered alone.

Knowing the degree to which specific human activities stress marine organisms and communities is of prime importance for decision making. However, much of the detailed, incremental knowledge being generated by current scientific research on OA does not directly address bigger-picture questions from decision makers such as: Where will OA harm marine resources next? When will this happen? Who will be affected? What will the economic impact be? What intensifies OA? Which actions will make the greatest difference? These questions are sufficiently urgent for many decision makers to begin to take action to offset risks from OA, even though we do not yet have a detailed understanding of effects on marine resources and attribution to specific processes.

In this review, we explore the needs of groups at different operational levels of governance that are making decisions to address OA concerns. Our analysis is complementary to Yates et al. (2015, in this issue). We use the United States as a primary source of case studies because this paper is the product of a 2013 US Ocean Acidification Principal Investigators' Meeting discussion group, where most attendees were US scientists and program managers. Coauthors from the meeting offered case studies drawn from their own expertise and involvements encompassing local, regional, national, and international scales. We consider why each group is concerned about OA, what resources or constituents each group seeks to protect, and how their goals affect their information needs. We examine how availability of appropriate information eases or complicates the decision-making process, and we explore how the flow of information from providers to users can be improved.

DECISION-MAKING LANDSCAPE

Many organisms, particularly in certain taxa, respond negatively to OA (Kroeker et al., 2013), but little information exists on how these responses will play out at population and ecosystem levels (Andersson et al., 2015, in this issue). Recent reviews (e.g., Pfister et al., 2014; Gaylord et al., 2015) describe likely ecosystem-scale responses to OA based on ecological theory and ecosystem responses to other environmental disturbances. However, these analyses still do not provide specific information that can be directly incorporated into most current coastal resource management efforts even though these efforts are shifting to an ecosystem-based management perspective in which interactions among organisms and populations are also considered. In an ideal world, the rate of acidification in a particular waterway could be forecast (taking into account atmospheric, nutrient, and freshwater inflow contributions), the consequences to specific marine populations and the their ecosystems could be predicted with a high level of certainty, and local fisheries, land use, and other marine resource planners could use this information to adopt practices that would preserve ecosystem resilience and the marine resources important to the local human communities. Without that kind of end-to-end information, decision making about OA must proceed in an environment of uncertainty (Busch et al., 2015, in this issue).

Information that contributes to decisions comes from a variety of sources

(Figure 1). Research conducted by academic, government, or industry scientists provides a large portion of the basic information (Figure 1, column 2) that supports current decision making around research fund allocation, ecosystem consequences of OA, and detecting and monitoring OA. Major users of this basic information include other scientists, coordinating bodies[1], boundary organizations[2], interagency organizations (inter- and intragovernmental), and rule- or lawmakers. The appetite for synthesized information (Figure 1, column 3) is somewhat broader, because in addition to the users mentioned above, nongovernmental organizations (NGOs) and media also seek it. Many of these groups also distill basic research and synthesized information into concise messages (Figure 1, column 4), which are in turn used by rule makers, students, industry, and the public.

Decisions being made about OA range from local to international scales and span a range of topics. Research funding continues to be allocated by public and private organizations that are all seeking to fund the best new scientific ideas. Depending on the aims of the funders, research is chosen that will (1) advance the frontiers of knowledge most quickly, (2) shed light on the economic and/or ecosystem repercussions of OA, (3) develop methods for detecting, offsetting, or overcoming OA, and (4) rank OA relative to other issues. To date, concrete and causally linked policy decisions regarding OA have been scarce. Recently, several US states have begun making decisions about steps to take beyond research. National agencies are beginning to determine how to set policies that could help reduce OA and its effects on important natural resources. International organizations such as the Arctic Council and the Intergovernmental Panel on Climate Change (IPCC) are considering how OA and its impacts relate to greater policy questions about CO_2 emissions, global change, and human development. Examples of each are reviewed in the case studies below.

It is clear that decisions that have already been made have occurred most naturally and easily when information needs were clearly defined and closely aligned with science outputs and initiatives (Table 1). In other words, information being "pushed" from those who generated it (i.e., bottom up) lined up directly with the "pull" for information from those who needed it (i.e., top down). However, it should be noted that these periods when push lines up with pull always followed a period when information was just being pushed by scientists. When information needs are more complex and require synthesized, comprehensive insight into OA's impacts on ecosystems or human communities, or on how acidification and other environmental changes interact, decisions are made more slowly. Generally, information being pushed does not completely

[1] Numerous scientific coordinating bodies exist to help scientists working on similar topics interact, export distilled scientific messages to information users, and provide feedback to decision makers about science findings and new directions. See, for example, http://www.us-ocb.org and http://www.iaea.org/ocean-acidification.

[2] Boundary organizations are groups that convene researchers, decision makers, and stakeholders to facilitate the application of scientific knowledge to policy-relevant problems. They promote communication, identify knowledge gaps, and help scope collaborative activities among participating groups. See also http://www.hks.harvard.edu/gea/pubs/huru1.pdf.

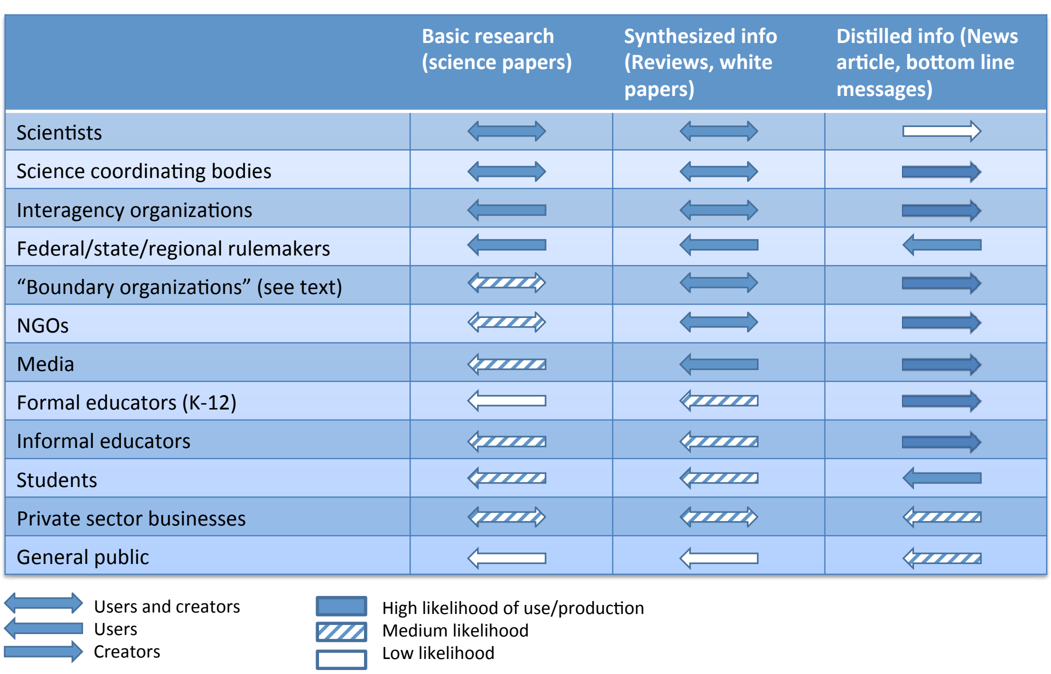

FIGURE 1. Creators and users of information about ocean acidification (OA; column 1) and the types of information they generate or consume. Scientists and technical groups are very likely to use (left-facing arrows) and produce (right-facing arrows) basic research (column 2). A wider range of groups uses and produces synthesized information (column 2) often, while nearly every group uses distilled information (column 3) to varying degrees. High likelihood of doing/using this information = filled arrows. Medium likelihood = hatched arrows. Low likelihood = open arrows.

TABLE 1. Major questions being asked by decision makers (left column) with examples of information needed at different scales (top row). Italicized entries indicate areas where scientific studies are generating reliable answers. When information with a high degree of confidence is available to answer all four questions, decision making seems to proceed more rapidly (e.g., Washington State process, West Coast Ocean Acidification and Hypoxia panel). The bottom row suggests confounding factors that might prevent the implementation of particular actions.

	Local	Regional	National	International
Who?	*Individuals*			
	Towns			
		Counties		
		Watersheds		
		States	States	
			Regions	
				Countries
				International organizations
When?	*Today, tomorrow*	*Today, Tomorrow*	*Today, tomorrow*	
		Years	*Years*	
		Decades	*Decades*	*Decades*
What resource?	*My hatchery's stock*			
	My fishery	Estuaries		
		Iconic species		
		Major taxonomic categories	*Major taxonomic categories* (e.g., coral reefs, commercial fisheries, shellfish aquaculture)	
			National food security	Global food security
		Ecosystems	Large marine ecosystems	Large marine ecosystems
	Ecosystem services (e.g., food, shoreline protection, economic livelihood)	Ecosystem services	Ecosystem services	Ecosystem services
Fixes available?	*Local monitoring*			
	Timing activities (such as when to plant out oyster seed)			
	Choose target species	*Choose target species*		
	Adding buffer, such as oyster shell, to local watersheds			
	Fishery Harvest Management	Fishery Harvest Management	Fishery Harvest Management	
		Address co-stressors (e.g., pollution, disturbance, harvests)	Address co-stressors (e.g., pollution, disturbance, harvests, temperature, deoxygenation)	Address co-stressors (e.g., pollution, disturbance, harvests, temperature, deoxygenation)
			Cut CO_2 emissions	Cut CO_2 emissions
Possible confounding factors	Expertise, money, more urgent priorities	Scientific uncertainty, other environmental stressors, lack of functional regional decision making bodies, money	Scientific uncertainty, other environmental stressors, lack of political leadership, money	More urgent priorities (e.g., political/economic/health crises, geopolitics, climate negotiations' latency periods)

line up with pulls requesting these complex products. Although this is not wholly unexpected, it is useful to consider the current state of decision making on OA to locate the information gaps that can be closed soonest and to identify the types of information that are most useful for each type of decision maker.

CASE STUDIES

Decision-relevant information on OA has been sought in several instances to date. Here, we present case studies that illustrate who sought information about OA, what sort of data was needed, and for what purpose, as well as how the information gathering and any subsequent decision-making process occurred. Most case studies do not fall entirely into a purely bottom-up or top-down situation and are a combination of both. Many of the case studies reviewed here demonstrate instances where bottom-up provision of data, or "pushed" information, has contributed to decision-making progress and where top-down requests for data, or "pulled" information, have generally followed. The case studies presented range from local to international scales.

Local Scale: The Local Network Model

Starting in 2005, hatcheries in Oregon and Washington began experiencing a four-year period of massive mortality of Pacific oyster larvae that could not be explained by disease, contamination, or other problems previously experienced by the hatcheries (Barton, et al. 2012, and 2015, in this issue). Around the same time, several high-impact scientific papers were published showing that oceanic uptake of atmospheric CO_2 was changing the ocean's acid-base balance and had the potential to harm marine zooplankton (Feely et al., 2004; Sabine et al., 2004; Orr et al., 2005). Hatchery scientists teamed up with local oceanographers to uncover the cause of the mass mortality. They discovered that wind-driven coastal upwelling was bringing water made corrosive (and likely dissolving shells) by anthropogenic CO_2 into hatchery intakes (Feely et al., 2008; Barton et al., 2012, and 2015, in this issue). A regional workshop, organized by the Southern California Coastal Water Research Project Authority (SCCWRP), in partnership with the four West Coast National Oceanic and Atmospheric Administration (NOAA) Sea Grant programs, brought together representatives from the shellfish industry, decision makers, and researchers to increase collective understanding of OA effects on the nearshore environment (SCCWRP, 2010). The resultant group, the California Current Acidification Network (C-CAN), has since expanded to include other ocean-dependent industries, environmental advocacy groups, regulatory agencies, and tribal groups (McLaughlin et al., 2015, in this issue). (*Note*: Websites for many of the agencies, organizations, and other entities mentioned in this article are listed in Box 1.)

C-CAN has been transformative at two levels. First, it changed the OA information transfer dynamic. The initial C-CAN workshop was held in response to a special request, or information pull, from a nontraditional audience—the shellfish industry. Members of the industry had suspected their recruitment failures stemmed from acidification issues, but they needed scientific input as to whether their hypothesis was valid. This was initially addressed through interactions with individual scientists collaborating with a few individual hatchery facilities, but the effort blossomed into a larger conversation and consensus-building exercise through C-CAN. The scientific consensus formed through the C-CAN network—that oceanographic processes were endangering the industry's revenue—also changed the nature of the conversation. Business people were able to effectively communicate that a problem existed, that the science was agreed upon, and that action was required.

C-CAN was also transformative in changing the spatial scale of interest. Until the network came together, most OA research on the US West Coast was focused on the ocean and examining the effects of global atmospheric inputs. Interaction with industry led to wider recognition of science issues taking place much closer to shore, and even within estuaries, that have fundamentally different drivers (e.g., tides, freshwater inputs), which were not being addressed by offshore floats and moorings. Simultaneously, decisions were needed at the local spatial scale, such as how to manage water intake at a hatchery or how to regulate nearshore nutrient discharges (Strong et al., 2014). These decision makers were fundamentally different entities, with fundamentally different science questions, than the groups interacting previously with West Coast OA scientists on atmospheric CO_2 cycling questions. The Washington State Blue Ribbon Panel on Ocean Acidification (hereafter, the Blue Ribbon Panel), described below, effectively built on this transition to frame the local management questions and help redefine the science needs that are presently driving West Coast OA scientists. Other regions, like the Northeast United States, are also following this successful local network model (Gledhill et al., 2015, in this issue).

State Level

Washington State

While knowledge and energy increased in the C-CAN network, energy was also building in Washington State. Vocal industry leaders explained OA impacts on local oysters from an economic perspective (Kelly et al., 2014), highlighting Washington State's large oyster industry, which supports more than 3,200 jobs and has an annual economic impact of \$270 million (Washington State Blue Ribbon Panel on Ocean Acidification, 2012). In addition, congressional hearings on OA in 2004 and a progressive governor (Christine Gregoire) led to the February 2012 creation of the Washington State Blue Ribbon Panel on Ocean Acidification. This panel was part of the Washington State Shellfish Initiative, itself a regional component of the NOAA National Shellfish Initiative, which promotes and facilitates development of shellfish aquaculture opportunities in the United States.

The Blue Ribbon Panel was the first state-based entity addressing OA. It included biologists and chemical oceanographers from federal, state, and academic institutions; federal and state policy makers; and NGO representatives. The governor charged the panel to review and summarize the current state of scientific knowledge about OA, identify the research and monitoring needed, develop recommendations to respond to OA and reduce its causes and effects, and identify opportunities to improve coordination and partnerships to enhance public education about OA.

The panel ultimately provided 42 recommended actions (Washington State Blue Ribbon Panel on Ocean Acidification, 2012). The actions focused on understanding OA effects in Washington waters and co-occurrence of OA with other environmental issues, largely through establishment of the Washington OA Center (WOAC). Funding WOAC extended the intensity of the OA research endeavor in the state and enhanced the state's ability to aid industry. Another recommendation was to establish a Marine Resource Advisory Committee (MRAC), with similar members as the original Blue Ribbon Panel, to sustain attention on OA in the state legislature and act as a conduit for newly emerging scientific information. The MRAC was enacted in 2013 by Washington's legislature and has been evaluating options for mitigating the impacts of OA within Washington State waters. Unfortunately, options are limited and expensive, so funding has been directed so far toward core research and monitoring activities.

The Blue Ribbon Panel and its outputs are widely regarded as a success and a model for other state actions on OA. Because of the mixed expertise of the panelists, clear communication was a cornerstone of the process. Science experts on the panel had to present detailed research findings clearly, and policymakers had to efficiently connect existing information with policy needs. Along with the panel's commitment to conducting a fully transparent process, this greatly streamlined efforts to educate nonspecialists and the public on the issue. Moreover, the high level of existing knowledge about local OA drivers, the region's baseline acidity, and OA's demonstrated measurable impacts on a valuable natural resource gave the Blue Ribbon Panel a clear starting point. Established committees and trusted organizations like the WOAC and MRAC that resulted from this process are integrating OA into long-term state resource management plans.

Box 1. List of websites for many of the agencies, organizations, and other entities mentioned in this article.

Biological Impacts of Ocean Acidification (BIOACID; Germany)
http://www.bioacid.de

California Current Acidification Network (C-CAN)
http://c-can.msi.ucsb.edu

California Ocean Science Trust
http://calost.org/science-advising/?page=ocean-acidification-and-hypoxia-panel

European Project on OCean Acidification (EPOCA)
http://www.epoca-project.eu

Kiruna Declaration
http://www.arctic-council.org/index.php/en/document-archive/category/425-main-documents-from-kiruna-ministerial-meeting?download=1757:kiruna-declaration-final-signed-version

Marine Resource Advisory Committee (MRAC)
http://www.ecy.wa.gov/water/marine/oceanacidification.html

Mediterranean Sea Acidification in a Changing Climate Project (MedSeA)
http://medsea-project.eu

NOAA National Shellfish Initiative
http://www.nmfs.noaa.gov/aquaculture/policy/shellfish_initiative_homepage.html

Northeast Coastal Acidification Network (NECAN)
http://www.neracoos.org/necan

Ocean Acidification International Coordination Centre (OA-ICC)
http://www.iaea.org/ocean-acidification

Ocean Acidification International Reference User Group (OAiRUG)
http://www.iaea.org/ocean-acidification/page.php?page=2221

Ocean Acidification Research Programme (UKOA; United Kingdom)
http://www.oceanacidification.org.uk

Southern California Coastal Water Research Project Authority (SCCWRP)
http://www.sccwrp.org/Homepage.aspx

Surface Ocean Lower Atmosphere Study-Integrated Marine Biogeochemistry and Ecosystem Research Ocean Acidification Working Group
http://www.imber.info/index.php/Science/Working-Groups/SOLAS-IMBER-Carbon/Subgroup-3

Washington OA Center (WOAC)
http://coenv.washington.edu/research/major-initiatives/ocean-acidification

Washington State Blue Ribbon Panel on Ocean Acidification
http://www.ecy.wa.gov/water/marine/oa/2012panel.html

West Coast Ocean Acidification and Hypoxia Panel
http://westcoastoah.org

Maine

Recent conditions consistent with OA recorded by scientists and shellfish growers in Maine also led to state action. Oceanographic surveys made in 2007 showed acidified water in the Gulf of Maine compared to waters further south (Salisbury et al., 2008; Wang et al., 2013), shellfish growers found that acidified "dead muds" were killing young clams (Green et al., 2009), and one Maine shellfish hatchery owner noted much higher mortality of larvae over the past five to six years in tandem with lower pH (Bill Mook, Mook Sea Farms, *pers. comm.,* April 10, 2014). The Northeast Coastal Acidification Network (NECAN; Gledhill et al., 2015, in this issue), formed and led by regional scientists and federal and state managers, began to synthesize regional scientific OA information in January 2013. Partly due to NECAN's and various other NGOs' scientific and community building activities, and partly to Maine communities' heavy reliance on marine resources, Maine's legislature established a commission to study the effects of OA on commercial shellfisheries in the Gulf of Maine, identify information gaps, and figure out what steps must be taken to protect state fisheries. The commission's approaches of incorporating diverse expertise and reviewing the state of the science, in partnership with NECAN, are two examples of how this process has adopted the most successful aspects of the Washington State process. The final report offers recommendations aligned with Maine's long-term interests in sustaining marine harvests and healthy marine ecosystems (Johnson et al., 2014). Four state bills have since been proposed to cut nutrient pollution from farms and septic systems and to support OA research and coordination in Maine (Moretto and *Bangor Daily News* Staff, 2015).

Cross-Border Level West Coast States and Provinces

California convened an OA and Hypoxia Science Panel (the OAH Panel) in 2013, but given that OA extends beyond state and national boundaries, it was expanded into the West Coast OAH Panel, including the governments of Oregon, Washington, and British Columbia. The OAH Panel is charged with synthesizing and translating knowledge for decision makers. It focused its initial attention on three topic areas (synthesized information as in Figure 1, column 2): (1) a description of the current decisions made by West Coast managers and the science products needed to support those decisions (Boehm et al., 2015, in this issue), (2) a summary of existing scientific information on the interacting impacts of hypoxia, ocean acidification, and changes in temperature on the physiology of West Coast species, and (3) a state-of-the-science summary about how physiological effects will likely drive population and community effects.

The panel subsequently turned to synthesizing those documents, primarily written for a scientific audience, into translational products that target a management and policy audience in order to support decisions made at both local and regional levels (synthesized/distilled information as in Figure 1, columns 2 and 3). These products will include (1) a vision document describing outcomes of a fully successful management environment, (2) a review of the technical efficacy of conducting a Clean Water Act (CWA) section 303(d) OA listing for local water bodies, (3) a research priorities plan that will most effectively advance knowledge to support decision making, and (4) a concept sketch for region-wide monitoring. The panel affirmed the value of regional-scale management, recognizing that the physical conditions driving West Coast vulnerability were common along the entire California Current System and that species do not respect state boundaries. The panel recommended developing an integrated regional monitoring program and modeling efforts that span the region. With these recommendations, the governors of the three West Coast states and the Premier of British Columbia acknowledge that OA is a regional issue that they must address in a coordinated fashion.

The OAH Panel incorporates several key features of the successful Washington State Blue Ribbon Panel that preceded it. Like the Blue Ribbon Panel, the OAH Panel has included a wide range of specialists from the beginning. Because information users and producers were engaged at the outset, the OAH Panel has been able to develop a range of information products that respond to the needs of decision makers, as set out during previous rounds of decision making, and that span the full range from peer-reviewed science all the way to distilled messages (Figure 1). Unique to the OAH Panel is a boundary organization working alongside it, the California Ocean Science Trust, which arranges strategic opportunities for communicating OAH Panel products. While the West Coast governors and the British Columbia premier initiated the process as an informational pull, the effectiveness will be largely driven by Ocean Science Trust's ability to push the information when the panel's tenure is complete. The process has also evolved over a long enough time frame (almost two years) that the scientific community has had time to develop answers to some decision-maker questions.

Regional to National Levels

Fisheries Management

The majority of the activity around OA in fisheries consists of information pushed by individual scientists who work with specific species or habitats and who are seeking to help stock assessment groups successfully incorporate this species-specific information into models. Decision making at NOAA's National Marine Fisheries Service (NMFS) does not currently address OA, as environmental data are not used to set catch limits for marine harvests. Rather, the harvest limits for individual species are set using models based on stock assessments or on regular surveys that assess and monitor stock size, location, and condition. Survey data are incorporated into numerical models to produce fisheries guidance associated with specific management activities. Fisheries management decisions are made following a stock assessment meeting to review this information. Environmental forecasts are generally not included in this process because they have much greater uncertainties than stock assessment-based population models.

Many obstacles inhibit including environmental data on OA into fisheries-relevant models at this time. Few commercially harvested species have been tested for their responses to OA (Kroeker et al., 2013). In addition, completed experiments generally focus on a specific life stage (Hurst et al., 2013; Long et al., 2013a,b), making it challenging to anticipate population-scale responses without additional experiments to inform mechanistic population models (Punt et al., 2014). Moreover, OA acts in combination with other chemistry-altering processes in most habitats (Duarte et al., 2013), but their relative contributions to acidification have been discerned in only a few cases (e.g., Alin et al., 2012). There is considerable uncertainty concerning the relative influence of environmental data on year-to-year stock changes, let alone changes forecast for the future. The specific types of OA information needed and their impacts for decision-making models are still being explored. However, as fishing pressure on stocks decreases and environmental pressure increases, including environmental data in decision-making processes becomes more important (e.g., Hare et al., 2010). This is already under discussion as part of West Coast OAH panel work (Boehm et al., 2015, in this issue). The NMFS is also currently developing a robust climate science strategy to incorporate large-scale, long-term environmental change into the fisheries management process (NMFS, 2015). This plan will help align information pushes from the scientific community and will pull relevant information into stock assessments and, eventually, into ecosystem management.

Clean Water Act Authorities

As the need for policy responses to OA grows, the CWA has been suggested as a way to help address OA-related impairments in US coastal waters (US EPA, 2010; Kelly et al., 2011; Kelly and Caldwell, 2013; Lombardi, 2013). Particularly, section 303(d) of the CWA could support national identification of US waters affected by OA and differentiation of anthropogenic sources (e.g., atmospheric versus land-based) contributing to observed acidification, and it could address acidification-causing pollutants that are within the legal purview of the CWA. The CWA also offers a collaborative framework across different operational scales because many of its programs require coordination between the states, the federal government, and the public. For example, under CWA Section 303(d), every two years US states and territories (hereafter, "states") must submit to the US EPA lists identifying bodies of water that are impaired or threatened by pollutants based on that state's US EPA-approved water quality standards, which are determined by evaluating all existing and readily available data. States are then required to develop pollutant cleanup plans, commonly known as total maximum daily loads (TMDLs), for those waters.

While the CWA has the potential to help identify OA-related impairments in US waters, there are regulatory challenges to addressing these impairments. For instance, the CWA lacks regulatory authority for states to address atmospheric pollutants (e.g., CO_2 emissions) and land-based nonpoint source pollutants (e.g., nutrient runoff from rain or groundwater), yet both are known to contribute to acidification (Cai et al., 2011; Strong et al., 2014). Although there are CWA programs that address land-based nonpoint source pollution (e.g., Section 319), these programs are voluntary. Only land-based point source pollutants (e.g., from a drainpipe into a river) are regulated through the CWA. These regulatory gaps create challenges for implementing TMDL pollutant cleanup plans for OA-related impairments, because these impairments will likely be caused by a combination of atmospheric and land-based nonpoint sources. Although TMDLs could be developed to help parse these sources, successful implementation would depend on actions through the Clean Air Act and/or voluntary programs through the CWA.

To date, no state has added waters to its 303(d) list because of impacts directly attributed to OA. Puerto Rico and the US Virgin Islands have included pH-impaired coastal water segments on their past and current 303(d) lists, but the causes of impairment remain unknown. There appear to be three major obstacles to applying the CWA 303(d) program to address OA-driven water quality impairments. First, as discussed above, the CWA was not designed to specifically regulate pollutants from atmospheric and nonpoint sources and therefore may lack the capacity to address long-term, atmospherically sourced change that is also influenced by local land-based nonpoint sources. Second, existing water quality standards on which 303(d) water quality assessment decisions are made were developed without knowledge of OA impacts to water chemistry and aquatic life, and therefore may not adequately capture impairments associated with OA. Furthermore, many existing water quality standards have "natural condition provisions," which require knowing what proportion of chemical change is caused by natural phenomena versus anthropogenic influences. The state of knowledge to answer that question is in its infancy. Third, the amount and quality of historical and present-day OA-related data and information on which to base 303(d) water quality assessment decisions is limited. A recent court decision in a case brought by the Center for Biological Diversity upheld the US EPA's decision not to designate marine waters as impaired on Washington's and Oregon's 2010 303(d) lists for failure to meet water quality standards (i.e., marine pH criteria, aquatic life designated uses) due to pollutants associated with or conditions attributable to OA (*Center for Biological Diversity v. EPA*, 2015, US Dist. LEXIS 25945 [Western District of Washington, March 2, 2015]). The US EPA's decision to not list these waters was based on conclusions that the scientific literature submitted by the Center for Biological Diversity did not demonstrate impairment of existing water quality standards or was not sufficient to make that determination. (The Washington and Oregon 2010 303(d) lists are located at http://yosemite.epa.gov/r10/water.nsf/tmdls/WA-303d-2010-approval and http://yosemite.epa.gov/r10/water.nsf/TMDLs/R10addsto2010ORList.)

While the above obstacles present various decision-making challenges, there is movement by the state of Washington and the US EPA to identify information needed to refine the use of the CWA to address OA-driven water quality impairments. Specifically, as an action item identified during Washington's Blue Ribbon Panel on OA, the state of Washington asked for US EPA's assistance in assessing the need for water quality criteria relevant to OA (Washington State Blue Ribbon Panel on Ocean Acidification, 2012). The US EPA responded with a letter to Washington's Department of Ecology stating that it will begin to identify and evaluate data and research on water quality parameters that will better contribute to the understanding of OA impacts to aquatic life, the relative contributions of drivers and sources, and meaningful metrics for assessment of trends (Stoner, 2013). Overall, this information-gathering effort could aid the CWA Section 303(d) program in answering decision-relevant questions, including: Are existing water quality standards pertaining to marine pH and aquatic life adequate to assess OA impacts? Do water quality standards need to be developed (e.g., aragonite saturation) or refined (e.g., pH) to better reflect the point at which impacts to aquatic life are detected? and What are the most reasonable monitoring strategies and pollutant source identification methods for OA-driven water quality impairments?

National Efforts Beyond the United States

Initiated through a grass-roots effort, Brazil's OA activities started with an information push from the scientific community. A technically oriented, capacity-building OA workshop in 2012 instructed Brazilian marine scientists on OA research best practices and created a long-lasting network of Brazilian scientists with different specialties studying OA. In 2013, following from the energy in the scientific community, the Brazil OA research network (BROA) was officially registered with the Brazilian National Directory of Research Groups. This group of 35 researchers created a five-year plan and writes regular reports regarding OA research (http://broa.furg.br/index.php/documentos.html). This activity, along with a follow-on 2014 capacity-building workshop and seminars in Chile for Latin American scientists, is helping to galvanize the Latin American scientific network, providing a push of information to decision makers.

Other nations' OA activities are beginning with pulls for information from local industry or decision makers. Shellfish industry losses from OA on the US West Coast and subsequent adaptations have been of particular interest in New Zealand because shellfish aquaculture, especially of mussels, provided over $400 million New Zealand (US$300 million) revenue in 2011 for the nation (http://aquaculture.org.nz/industry/overview). A 2013 workshop coordinated by NGOs, the US State Department, and the New Zealand government convened New Zealand and Pacific Northwest shellfish industry representatives, scientists, and government representatives to educate the shellfish industry proactively on OA and to identify suitable actions to take locally to offset the problem. Since the workshop, an initiative to monitor OA in New Zealand's coastal waters has progressed along with individual research projects on aquaculture. Planned next steps seek to close knowledge gaps most critical for industry, including acquisition of baseline chemical data from coastal waters and determining its variability. In a different sort of pull, Cuban decision makers have recognized that climate change issues could threaten to destabilize their island nation, and as a result have mandated that Cuban scientists study climate change issues, including OA. Data from these studies are being used to help determine where governmental monies will be applied, including infrastructure growth and modification projects.

International-Scale Activity

Some of the aforementioned national efforts were coordinated with or were aided by the OA International Coordination Centre (OA-ICC) in Monaco, which evolved from the SOLAS-IMBER (Surface Ocean Lower Atmosphere Study-Integrated Marine Biogeochemistry and Ecosystem Research) OA working group and international coordination of OA research and communication that began during the European Project on OA (European Project on OCean Acidification [EPOCA]; see below). Advised by a board of scientists, international organizations, governmental agencies, and philanthropic foundations, the OA-ICC focuses on science coordination, capacity building, and communication about OA. In addition, OA-ICC scientists generate synthesized information and distilled messages. The affiliated OA international Reference User Group (OAiRUG), composed of scientists and industry, government, and NGO representatives, also pushes out distilled messages for decision makers (Figure 1, columns 1, 2). These messages inform and respond to international requests for information, such as those from the Arctic Council, IPCC, and the United Nations Framework Convention on Climate Change

(UNFCCC), discussed below.

International efforts have gathered momentum once initial scientific studies have captured the attention of policymakers or industry. For example, EPOCA, a large (32 institutions in 10 countries) European Union-funded research project that took place from 2008–2012, advanced understanding of biological, ecological, biogeochemical, and societal implications of OA in a coordinated way. EPOCA jump-started the international bottom-up push of OA information from scientists and created a theoretical framework for considering the end-to-end (i.e., chemistry to human impacts) aspects of OA. The program involved basic research, synthesized information, distilled messages (Figure 1), and coordinated international OA science. Individual countries also established national programs to complement EPOCA and continue critical research (e.g., Germany's Biological Impacts of OA program [BIOACID] and United Kingdom's Ocean Acidification Research Programme [UKOA]). The European Union subsequently supported the Mediterranean Sea Acidification in a Changing Climate project (MedSeA), a large regional initiative composed of 18 institutions from 12 countries. Like EPOCA, each of these projects seeks to provide both basic scientific research and decision-relevant information on OA. In each of these cases, there has not only been a push driven by scientific investigations and research projects but also a significant pull by policymakers.

Arctic Ocean

In 2010, the Arctic Council convened a meeting to discuss potential OA impacts in the Arctic, and in 2012, the Arctic Marine Assessment Project (AMAP), a working group of the Arctic Council, published an assessment of Arctic OA science and recommendations (AMAP, 2013). Climate change and OA are tightly linked in the Arctic. As summer sea ice cover declines with increasing temperatures, newly open cold surface water takes up additional CO_2, enhancing OA (AMAP, 2013). However, AMAP found a dearth of quantitative data on OA for the Arctic region. The teleconnections (spatially and temporally separate but significantly correlated large-scale weather events) and the drivers of change in the Arctic system are not adequately understood, so the interaction of climate change and OA in the region is not easy to forecast.

The AMAP (2013) recommendations call for enhanced research and monitoring efforts to expand understanding of acidification processes and their effects on Arctic marine ecosystems and northern societies that depend on them. AMAP also urges member states to implement adaptation strategies to address OA, tailored to local and societal needs (AMAP, 2013). The key findings of the AMAP OA assessment and recommendations of the AMAP working group have since been used to draft the 2013 Kiruna Declaration, signed by ministers representing the Arctic States, which calls for a reduction in CO_2 emissions and enhanced research and monitoring efforts. The Arctic Council also urged members to implement adaptation strategies for aspects of change, including OA.

The AMAP OA Assessment and report are a scientific "push" process that is carefully constructed to align with pre-identified regional priorities concerning natural resource preservation and use. The short time between the completion of the AMAP OA report and the signing of the Kiruna Declaration suggests that because other climate-oriented studies had already identified regional policy priorities, the findings of this OA assessment contributed to policy development more readily than if existing policy priorities were undeveloped, vague, or irrelevant to OA. Note, however, that the agreements of the Kiruna Declaration are only the first step. More basic research is absolutely needed in the region to address the dearth of OA data and to enhance our knowledge of the drivers and processes of OA for adequate and effective prevention and remediation actions. Developing the practical, actionable adaptation plans called for by the declaration will require a great deal more collaboration and synthesis among scientists, decision makers, and resource users.

Global-Scale CO_2 Mitigation Decision Making

The UN Framework Convention on Climate Change provides a process through which countries agree to mitigation targets for CO_2 (and other greenhouse gases) on a global scale. While it is currently uncertain whether information pushed about OA has significantly increased momentum toward carbon mitigation, the answer may become evident when new mitigation targets are agreed upon by the 21st Conference of the Parties in December 2015.

The IPCC acts as the authoritative scientific body and source of scientific information for UNFCCC negotiation and implementation. The IPCC Second Assessment Report (IPCC, 1995) provided important foundational scientific material that negotiators used to generate the landmark Kyoto Protocol in 1997 at the fourth annual UNFCCC Conference of the Parties (COP). At the 2014 UNFCCC COP 20, in Lima, Peru, the Subsidiary Body for Scientific and Technological Advice (Session 41; Agenda 8a) officially recognized that the IPCC Fifth Assessment Report (AR5), released in 2013 and 2014, will act as "the scientific foundation for the Ad Hoc Working Group on the Durban Platform for Enhanced Action." (The Durban Platform is the precursor process to a COP 21[2015] carbon mitigation agreement.) Information about OA was included more thoroughly in the IPCC AR5 than in any previous assessment, primarily because lead authors with OA expertise pushed to do so. The IPCC AR5 Synthesis Report (IPCC, 2014) included both graphics and written information about OA based on information in the IPCC Working Group II report that illustrated the combined, synergistic impacts of warming and acidification on marine species. Because the IPCC and the UNFCCC process are currently focused on keeping the average global temperature rise below 2°C, and not on CO_2 targets, work is still needed to translate CO_2 mitigation targets into avoided marine impacts with estimates of uncertainty (Herr et al., 2014). In other words, the scientific community needs to define clearly what the ramifications for marine life will be if certain atmospheric CO_2 levels are exceeded. The CO_2 targets that keep average global temperature rise below 2°C may lead to loss of marine life that is unacceptable to the global community (Steinacher at al., 2013). Although IPCC information, in general, is now being formally requested and affirmed by COP parties, OA was included in the AR5 because the scientific community recognized its importance and pushed it forward, not because governments were requesting that information.

DISCUSSION: LESSONS LEARNED FROM CASE STUDIES

The pace of decision making partly depends on whether the type or abundance of information being offered from the bottom up matches what is being sought from the top down (Figure 2). When OA research is newly established in a region or nation, offering information on a bottom-up or push basis will likely be the first step. However, in sudden crises where decision makers ask questions that can be answered using existing knowledge or a little additional information, decisions about appropriate adaptation strategies and research areas can proceed quickly; one example is the Pacific Northwest states' implementation of oyster hatchery monitoring for upwelling and water quality to avoid the use of low pH water in oyster larvae rearing tanks. When the answers to decision makers' questions are not available because questions are complex and transdisciplinary (Yates et al., 2015, in this issue), such as concerning the adequacy of the states' existing CWA water quality standards to address OA-driven water quality impairments, decision making tends to slow.

Ongoing collaboration from the earliest stages will help prioritize research and increase the likelihood of pushing information in the most useful format possible. Until decision makers are fully engaged, efforts to scope research involving stakeholders (Figure 3) may only involve select industry representatives or multidisciplinary scientists. In early stages, local to regional state-of-the-science assessments help synthesize and distill disparate science information in order to respond to the needs of decision makers outside the research community. Keeping in mind the typical needs of decision makers (Table 1) will help scope the research in these early stages. Ultimately, a team of specialists from science, policy, and stakeholder communities must collaborate to identify regionally appropriate and feasible actions.

Synthesis and distillation of research findings is not enough, however, to provide fully decision-relevant information. Multi-specialist task forces are also needed to help scope and analyze possible adaptation plans, as in the West Coast OAH Panel, the Blue Ribbon Panel, and the Maine state commission (Maryland has also recently initiated a commission that is not described in this paper). In Maine and Washington, this work has resulted in proposal or passage of bills to provide ongoing funding or create state-based adaptation activities. As much as possible, this work should be aligned with needs and adaptation plans that have already been defined. As in the Arctic example, when information "push lines up with pull" because of pre-existing priorities, decision making can accelerate.

It also appears that local-scale decision making and action are happening faster than global-scale work, but this is motivating decision makers who operate at larger scales (e.g., West Coast state action is evolving into region-wide activity). Cases where OA has not become an agenda item could be due to a disconnect between research and the needs of stakeholders. For instance, OA remains difficult to incorporate into 303(d) listing decisions because the science does not squarely align with the strict requirements of this decision framework. In some places, other urgent priorities outcompete an issue that has not yet occurred locally. Unfortunately, the longer it takes to gather actionable information or identify where actual impacts are playing out, the more likely resources for studying the issue will dwindle.

The incremental nature of scientific research will never be able to answer decision makers' questions completely

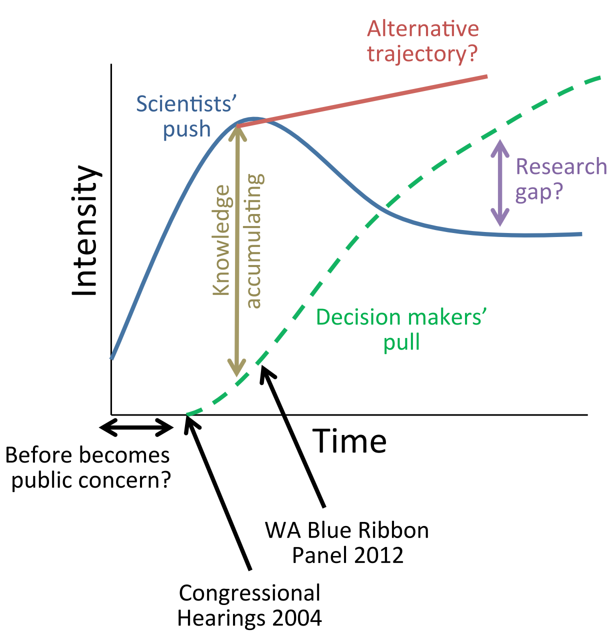

FIGURE 2. Schematic showing the accumulation of science information (blue curve) compared to the intensity of decision makers' needs (green curve). Once decision makers' needs accelerate and they begin to request specialized, synthesized information, a research gap (purple) is likely to emerge. Congressional hearings on OA in 2004 and the Washington State Blue Ribbon Panel in 2012 occurred at early and intermediate phases, when information requests by decision makers were just beginning to grow.

in a one-way, one-time knowledge transfer. Instead, it is useful to imagine a cyclic process (Figure 3), where the questions of all partners, including resource users, policy specialists, and scientists, help scope the direction of inquiry. For example, if OA researchers simply reported aragonite saturation states of US coastal waters without consulting natural resource managers, their findings could be incompatible with water quality standards expressed in pH units. A cyclic process allows decision makers to communicate their specific needs to researchers, who can then design studies to produce data and information that will fill those needs. Synthesized information products can be planned early on by all parties to support broad decision making that respects the limit of science knowledge.

Interagency coordination that will mesh information pushes and pulls is under way in the United States, helping to create a structure that supports and prioritizes action efficiently. Overarching research priorities already focus on vulnerabilities associated with carbon cycle changes, mitigation and adaptation possibilities, and emerging opportunities associated with global change (NRC, 2009), as well as asking how natural and human processes affect the carbon cycle, how policy and management decisions affect the levels of atmospheric CO_2 and methane, and how changes and management impact ecosystems, species, and natural resources (Michalak et al., 2011). The US National Research Council Committee on the Development of an Integrated Science Strategy for Ocean Acidification Monitoring, Research, and Impacts Assessment (NRC, 2010) identified key gaps in information needed to help federal agencies develop a program to improve understanding and address the consequences of OA. All of these statements have resulted in high-level intra- and intergovernmental entities and partnerships that seek national and international synergies in OA research, science funding, and decision-making processes. US federal scientific agencies working on OA are part of the Interagency Working Group on Ocean Acidification (IWG-OA), chaired by NOAA, which recently released a federal research strategy for OA (IWG-OA, 2014). IWG-OA partners coordinate research and support activities (e.g., the Ocean Carbon and Biogeochemistry Program's Ocean Acidification Subcommittee, which organized the meeting that gave rise to this paper). In the Arctic, beginning in 2015, US leadership of the Arctic Council has prioritized climate change issues and OA. Other Arctic research coordination activities such as the US Interagency Arctic Research Policy Committee and other OA adaptation, mitigation, and decision support activities will also be needed to implement some of the AMAP (2013) recommendations effectively at local to international scales. Although initial outcomes have primarily provided support for science via funding and coordination, these are precursor steps designed to inform specific national-level actions that federal agencies will take to enhance resilience of communities against OA, among other environmental changes (NRC, 2013). The emerging OA coordination activities build on existing foundations and bring information pushes and pulls closer together, and they pave the way for specific measurable outcomes beyond research in the future.

CONCLUSIONS

Getting OA on decision makers' to-do lists can result from (1) pushes of broad-based information that suddenly become relevant when a crisis intervenes; (2) requests for information targeted to respond to specific questions related to "upstream" issues, such as coastal communities' economic well-being or maintenance of water quality; or (3) provision of information that feeds into precautionary planning efforts or that is aligned with pre-existing priorities related to climate or regional development. Big picture questions regarding CO_2 reduction and widespread adaptation are particularly relevant in geopolitically significant international settings, whereas smaller-scale questions about local monitoring

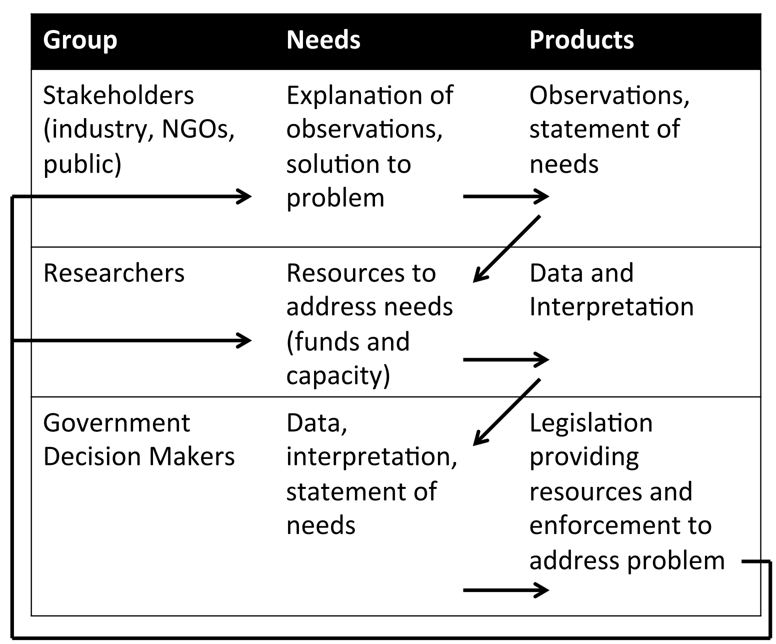

FIGURE 3. Cyclic flow of decision making. (top left) Questions from stakeholders, including industrial, scientific, and coastal users, drive research, whose interpreted results (middle row, right) are transmitted to decision makers (bottom row). This, in turn, generates more questions from decision makers, which drive the cycle again (middle and right columns). At every step of the cycle, needs and products differ.

and adaptation are important in local to regional environments. Nevertheless, the need to make OA a priority for decision makers is strong. Closing gaps between information pushes and pulls will support robust decision making, actionable policy making, and formulation of effective OA reduction plans and implementation strategies to address scientific gaps that hamper these actions.

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AUTHORS. **Sarah R. Cooley** (scooley@oceanconservancy.org) is Science Outreach Manager, Ocean Conservancy, Washington, DC, USA. **Elizabeth B. Jewett** is Director, Ocean Acidification Program, National Oceanographic and Atmospheric Administration (NOAA), Silver Spring, MD, USA. **Julie Reichert** is Fisheries Scientist, Oyster Recovery Partnership, Annapolis, MD, USA. **Lisa Robbins** is Research Oceanographer, US Geological Survey, Coastal and Marine Science Center, St. Petersburg, FL, USA. **Gyami Shrestha** is Director, US Carbon Cycle Science Program Office, US Global Change Research Program, Washington, DC, USA. **Dan Wieczorek** is Physical Science Technician, NOAA, National Marine Fisheries Service, Sandy Hook, NJ, USA. **Stephen B. Weisberg** is Executive Director, Southern California Coastal Water Research Project Authority, Costa Mesa, CA, USA.

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