CITATION

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Characterizing the Natural System

Toward Sustained, Integrated Coastal Ocean Acidification Observing Networks to Facilitate Resource Management and Decision Support

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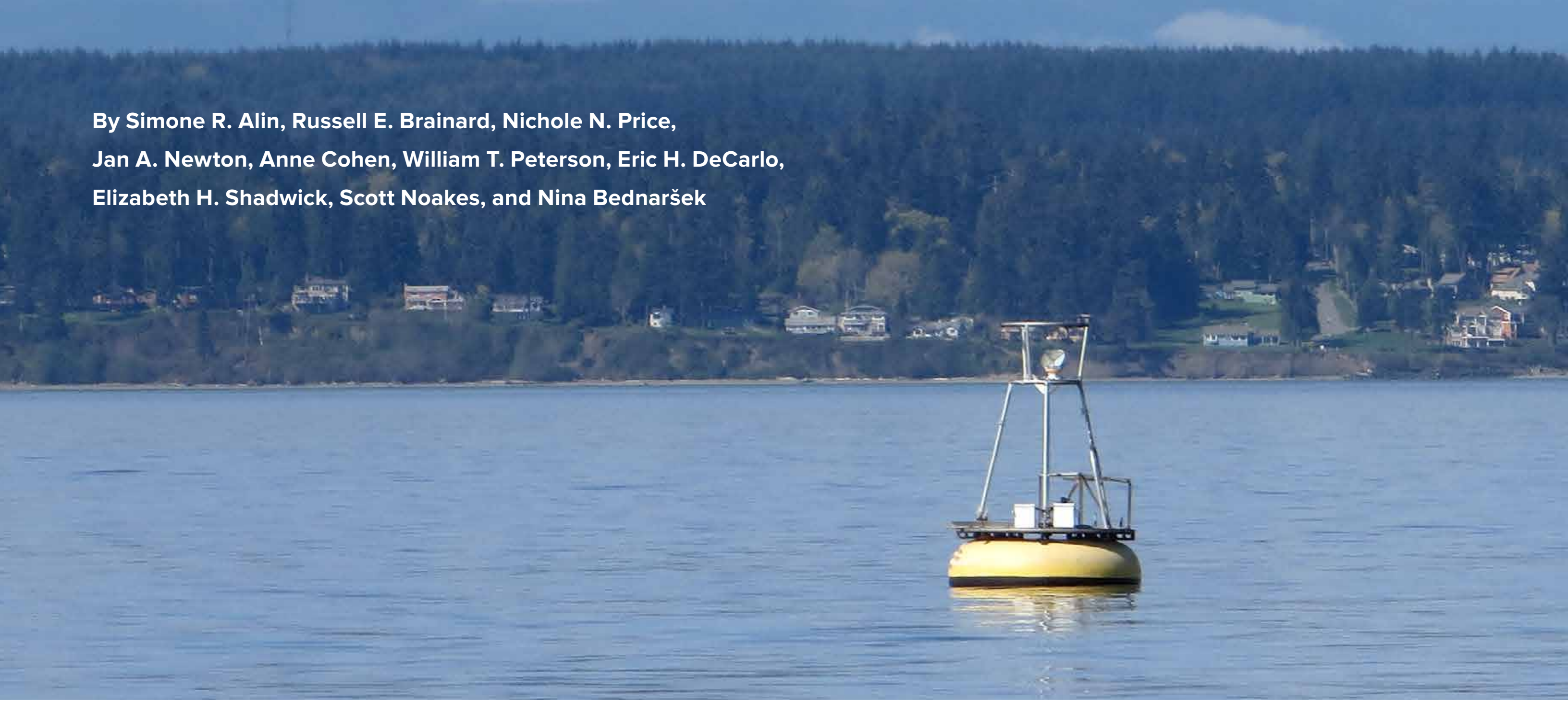

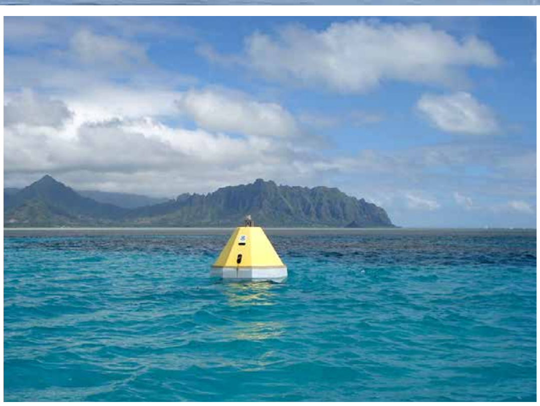

> "The long-term sustainability of these critical observing networks will rely on leveraging of resources and the strength of partnerships across the consortium of stakeholders and those implementing coastal ocean health observing networks."

ABSTRACT. Coastal ocean ecosystems have always served human populations—they provide food security, livelihoods, coastal protection, and defense. Ocean acidification is a global threat to these ecosystem services, particularly when other local and regional stressors combine with it to jeopardize coastal health. Monitoring efforts call for a coordinated global approach toward sustained, integrated coastal ocean health observing networks to address the region-specific mix of factors while also adhering to global ocean acidification observing network principles to facilitate comparison among regions for increased utility and understanding. Here, we generalize guidelines for scoping and designing regional coastal ocean acidification observing networks and provide examples of existing efforts. While challenging in the early stages of coordinating the design and prioritizing the implementation of these observing networks, it is essential to actively engage all of the relevant stakeholder groups from the outset, including private industries, public agencies, regulatory bodies, decision makers, and the general public. The long-term sustainability of these critical observing networks will rely on leveraging of resources and the strength of partnerships across the consortium of stakeholders and those implementing coastal ocean health observing networks.

INTRODUCTION

Ocean acidification is expected to progressively impact marine ecosystems, biodiversity, fisheries, and societies at scales ranging from local to regional to global through the twenty-first century and beyond. In order to best inform and prepare coastal stakeholders and decision makers across these scales, it is critical to develop an integrated, interdisciplinary biogeochemical and ecological observing network capable of robustly detecting and attributing changes in ocean chemistry to changes in indicators of ecosystem condition (i.e., structure and function) and human well-being. Time-series observations are needed to concurrently characterize variability in time and space of both biogeochemical conditions and ecological processes to better understand biological tolerances and societal responses to ocean acidification, as outlined in the vision statement of the Global Ocean Acidification Observing Network (GOA-ON; Newton et al., 2014).

As part of GOA-ON, scientists, stakeholders, and resource managers at international, national, regional, and local levels are jointly planning ocean acidification observing networks that will leverage existing programs and assets to: (1) provide a suite of consistent observations across scales, from open ocean to coastal and estuarine ecosystems, for detection of trends and associated ecological responses to ocean acidification (Figure 1, Level 1 of Goals 1 and 2); (2) provide a framework for process and attribution studies relevant to individual regions (Figure 1, Level 2 of Goals 1 and 2); (3) improve predictive models for ocean biogeochemistry and ecosystem responses (Figure 1, Goal 3); and (4) share data with indicators of the level of quality among all stakeholders at useful temporal and spatial scales (Figure 1, outer circles; Newton et al., 2014). Here, we discuss how the conceptual consensus recommendations for the coastal components of GOA-ON (Table 1, Figure 1) might be implemented in regional coastal areas where they will directly support effective decision making to address the most pressing societal challenges, such as fisheries for food security and livelihoods, community resilience, and coastal protection. We use examples from a few types of continental and island coastal ecosystems.

Coastal oceans are biogeochemically and physically dynamic environments characterized by strong spatial and temporal variability; consequently, coastal zone habitats are exceptionally diverse. Coastal ecosystems are also among the most productive in the world, hosting 15–30% of oceanic primary production (Gattuso et al., 1998), producing 87% of the world's fish catch (FAO, 2014), and providing essential habitats for much of the diversity of marine life. For example, while coral reef ecosystems comprise less than 0.25% of seafloor area, they are home to over 25% of marine species (Knowlton et al., 2010), with a recent estimate of 550,000–1,330,000 species on coral reefs worldwide (Fisher et al., 2015). With greater than 50% of the world's human population living within 50 km of a coastline, coastal ecosystems are particularly vulnerable to impacts from human activities that result in habitat degradation and losses of biodiversity. In addition to local anthropogenic stressors such as coastal development and fishing, climate change and ocean acidification are affecting coastal ecosystems. Sustainable ecosystem-based management of human interactions with coastal ecosystems and the ability to develop effective mitigation and adaptation strategies depends on reliable and timely observations for decision support. Among many needs, coastal observations must detect ecological responses as well as facilitate attribution of observed shifts to climate variability or trends, ocean acidification, other human activities, or natural processes.

Biogeochemical and ecological dynamics across various coastal ecosystems may be dominated by a range of influences, such as seasonal changes in winds, light, or temperature; inputs of freshwater, nutrients, or organic matter from land; and geomorphic factors (e.g., shelf width, bathymetric or coastline features). Thus, to be effective, a regional, integrated coastal ocean acidification observing network should be sufficiently consistent to facilitate comparison and improved understanding of biogeochemical processes and ecological responses across ecosystem types, as outlined by GOA-ON, yet must be sufficiently tailored to the dominant processes within each ecosystem type to allow for attribution of local observations to the underlying processes in that region (Figure 2). Overall, regional observing networks should be capable of making environmental and ecological measurements at temporal and spatial scales sufficient to: (1) establish spatial patterns and magnitudes of variability, (2) detect long-term changes from these envelopes of variability, (3) attribute ecological responses to environmental changes, (4) facilitate projections of future conditions, and (5) evaluate validity of models and hindcasts. In addition, observing assets within a regional network should be configured to address short-term regional stakeholder priorities.

Cognizant of diverse local to regional stressors for each ecosystem (see Breitburg et al., 2015, in this issue), as well as multiple compelling needs for long-term observations, regional observing networks are best framed when addressing coastal ocean health in an integrated, interdisciplinary manner, rather than solely based on carbonate chemistry and its impacts. Here, we delineate general guidelines for designing and implementing regional coastal ocean acidification observing networks that: (1) conform to GOA-ON principles for comparability, (2) are responsive to regional and local stakeholder needs, and (3) characterize critical attributes on local to regional scales. We offer examples highlighting key characteristics and needs for a few ecosystem types, stressing important scoping considerations (Table 2). These general guidelines and considerations apply, with some modifications, to other ecosystem types and locations.

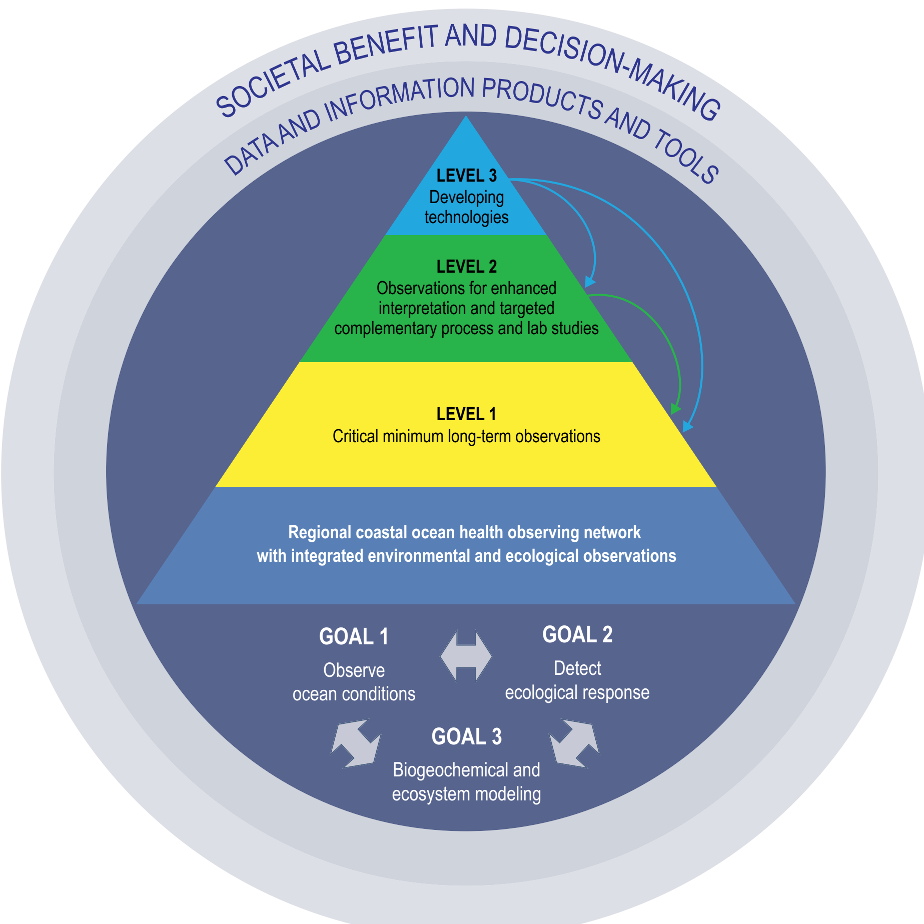

FIGURE 1. Schematic diagram of the parts of the Global Ocean Acidification Observing Network (GOA-ON), showing the core goals of GOA-ON, the levels at which various activities address the core goals in the pyramid above, and in the outer rings, the ultimate societal needs that the activities fulfilling the coastal observing network goals are designed to address. Connections between the societal drivers and coastal GOA-ON activities are particularly strong in coastal systems due to the reliance of human populations on coastal resources worldwide. *Courtesy of Amanda Dillon*

GOA-ON AND REGIONAL COASTAL OBSERVING EFFORTS

In any nation, region, or area, a diversity of organizations and institutions may contribute to observations, long-term monitoring, and research on ocean acidification under various legal authorities or management mandates. The core goals of GOA-ON outlined above facilitate diagnosis of spatial patterns and temporal trends in ocean acidification across regions, attribution of processes and drivers behind these patterns and trends,

TABLE 1. Global Ocean Acidification Observing Network (GOA-ON) requirements for environmental and ecological observations (consolidated from Newton et al. 2014). Requirements are broken down by priority parameters, patterns, or processes to constrain.[1]

GOAL 1: IMPROVE OUR UNDERSTANDING OF GLOBAL OCEAN ACIDIFICATION CONDITIONS.

Level 1: Critical minimum measurements, applied to document ocean acidification dynamics.

Parameters: Temperature, salinity, pressure (≈ water depth at which measurement is made), oxygen concentration, carbon-system constraint (including direct measurements and other means of estimating parameters[2]), and where feasible, fluorescence and irradiance should also be measured.

Patterns: Where photosynthetic calcifiers dominate, some measure of biomass of biota (corals, coralline algae, other photosynthesizers).

Processes: Where photosynthetic calcifiers dominate, constraining net ecosystem processes (net ecosystem calcification and net ecosystem production) is necessary.

Level 2: An enhanced suite of measurements that promote understanding of the primary mechanisms (including biologically mediated mechanisms) that govern ocean acidification dynamics; measurements applied toward understanding those dynamic processes. Dependent on site location, season, hydrographic conditions, and question, but recommendations include:

Parameters: Nutrients, bio-optical parameters, currents, meteorology, particulate organic and inorganic carbon, and atmospheric pCO_2.

Patterns: Phytoplankton species.

Processes: Net community metabolism and/or export production. In some warm-water coral habitats, freshwater, nutrient, and/or sediment inputs should also be measured.

Level 3: Opportunistic or experimental measurements that may offer enhanced insights into ocean acidification dynamics and impacts. Measurements under development that may later be adapted to Level 1 or 2.

Parameters: This category may include many parameters from Levels 1 and 2 for which autonomous sensors do not yet exist or require significant improvements or commercialization to be widely available and reliable for use in GOA-ON deployments.

GOAL 2: IMPROVE OUR UNDERSTANDING OF ECOSYSTEM RESPONSE TO OCEAN ACIDIFICATION. Many of these measurements will be specific to broad climate regions or ecosystem types. The level of granularity used in the GOA-ON framing document is polar, temperate, tropical, and nearshore, and is indicated below where recommendations are not universal.

Level 1:

Parameters: Photosynthetically active radiation, turbidity/total suspended solids (tropical, nearshore), particulate inorganic carbon (polar, temperate), colored dissolved organic matter (tropical, nearshore), nutrients (nearshore). For warm- and cold-water coral habitats, further characterization of chemical environment, including sediment mineralogy/composition, organism mineral content, alkalinity anomalies, and vertical profiles of saturation state over time (cold-water corals).

Patterns: Biomass/abundance of phytoplankton, zooplankton (micro- and meso-), and benthic producers and consumers; biomass of calcified vs. non-calcified species; timing of changes in abundance (e.g., blooms, community shifts, pigment changes); phytoplankton functional types (polar, temperate); calcified to non-calcified plankton abundance (temperate, nearshore); and calcified to non-calcified benthos abundance (nearshore). For warm- and cold-water coral habitats, population structure of corals and macroalgae; biomass, population, and trophic structure of cryptobiota; population structure of urchins; and architectural complexity.

Processes: Ratio of net ecosystem production to net ecosystem calcification, food supply rate and quality, bioerosion rates at specific sites.

Level 2:
Where not already included above.

Parameters: Chemical speciation (e.g., abundance of specific forms of carbon, nitrogen, phosphorus), transparent exopolymeric particles, fatty acid measurements (food quality), nutrient ratios, algal pigments, currents.

Patterns: Taxonomy, sea algae, satellite imagery (tropical), community structure (nearshore), trophic interactions (nearshore), disease (nearshore), phytoplankton species (nearshore).

Processes: Phytoplankton primary production; net community production; export flux; net community calcification; nutrient uptake; dissolution; zooplankton vertical/spatial, temporal variation; zooplankton grazing rates. Benthic habitats: burial, deposition, respiration, calcification, production.

GOAL 3: ACQUIRE AND EXCHANGE DATA AND KNOWLEDGE NECESSARY TO OPTIMIZE MODELING OF OCEAN ACIDIFICATION AND ITS IMPACTS.

Parameters: Bio-optical and chemical sensors (e.g., nitrate, oxygen, pH) on Argo floats, develop ocean acidification indicators for key locations, models for key benthic and pelagic organisms to link habitat and ocean acidification conditions and connect to integrated ecosystem assessments.

Patterns: Large-scale surveys to constrain models, better spatial coverage of moorings linked to targeted process studies, extended spatial coverage of gliders, evaluate ocean acidification monitoring networks using observing system simulation experiments (OSSEs), integrate water quality and plankton community information into physical-biogeochemical models for three-dimensional distributions on dominant temporal scales.

Processes: Model-data comparison to determine coastal impacts on open ocean biogeochemistry/ecology, short-term forecasts to evaluate model performance at ocean acidification network locations, improve linkages with physical modeling capabilities within regions, high-resolution circulation and wave models for coral reefs and extreme weather events.

[1] For present purposes, parameters are terms we measure with sensors or lab analyses; patterns require abundance, area, or mass estimation; and processes require biogeochemical or hydrological rate estimates.
[2] Including via empirical relationships, as in Juranek et al. (2009) and Alin et al. (2012).

prediction of future patterns and impacts, and support for informed and timely policy and management decisions (Table 1).

The US National Oceanic and Atmospheric Administration (NOAA) Ocean Acidification Observing Network (NOA-ON), with many partners, is consistent with GOA-ON design principles (NOAA Ocean Acidification Steering Committee, 2010; Interagency Working Group on Ocean Acidification, 2014). It provides an initial framework to guide the regional ocean acidification observing networks that have started to materialize through US Integrated Ocean Observing System (IOOS) regional associations. These regional observing networks provide data on regional trends and drivers related to ocean acidification and the associated ecosystem responses, thereby providing a foundation into which more detailed mechanistic process studies or ecosystem-specific observations of impacts can be integrated (e.g., Pfister et al., 2014).

The GOA-ON plan is a key aide for designing regional observing systems that are responsive to both long-term scientific and short-term stakeholder needs. GOA-ON delineates two respective levels of observational quality (1) "climate"-quality observations, which require the lowest uncertainty and highest confidence levels to detect long-term anthropogenic trends in carbon chemistry and related physical and chemical parameters, such as temperature, salinity, and nutrients, and (2) "weather"-quality observations to identify "relative spatial patterns and short-term variability" (Newton et al., 2014). In dynamic coastal ecosystems, a mechanistic interpretation of ecosystem changes attributable to ocean acidification and other interacting drivers requires climate-quality observations as well as high-resolution models to resolve signals with acceptable uncertainty. For many stakeholder and management needs, weather-quality measurements may suffice for correlation of environmental observations with ecosystem response data.

While detecting long-term global trends in ocean biogeochemistry is important, ecological responses tend to manifest primarily at local to regional scales due to the complexities of interactions across taxa "from the genes within species to biologically created habitats within ecosystems" (Duffy et al., 2013) and varying ecological community structure. Biogeochemical processes often vary over specific narrow frequencies (e.g., tidal, diel, seasonal), whereas organisms and communities within ecosystems reflect an integrated response to environmental variation over an even broader range of time scales due to varying life histories of each species. These considerations make broad partnerships and integration across complementary efforts (e.g., Duffy et al., 2013) important.

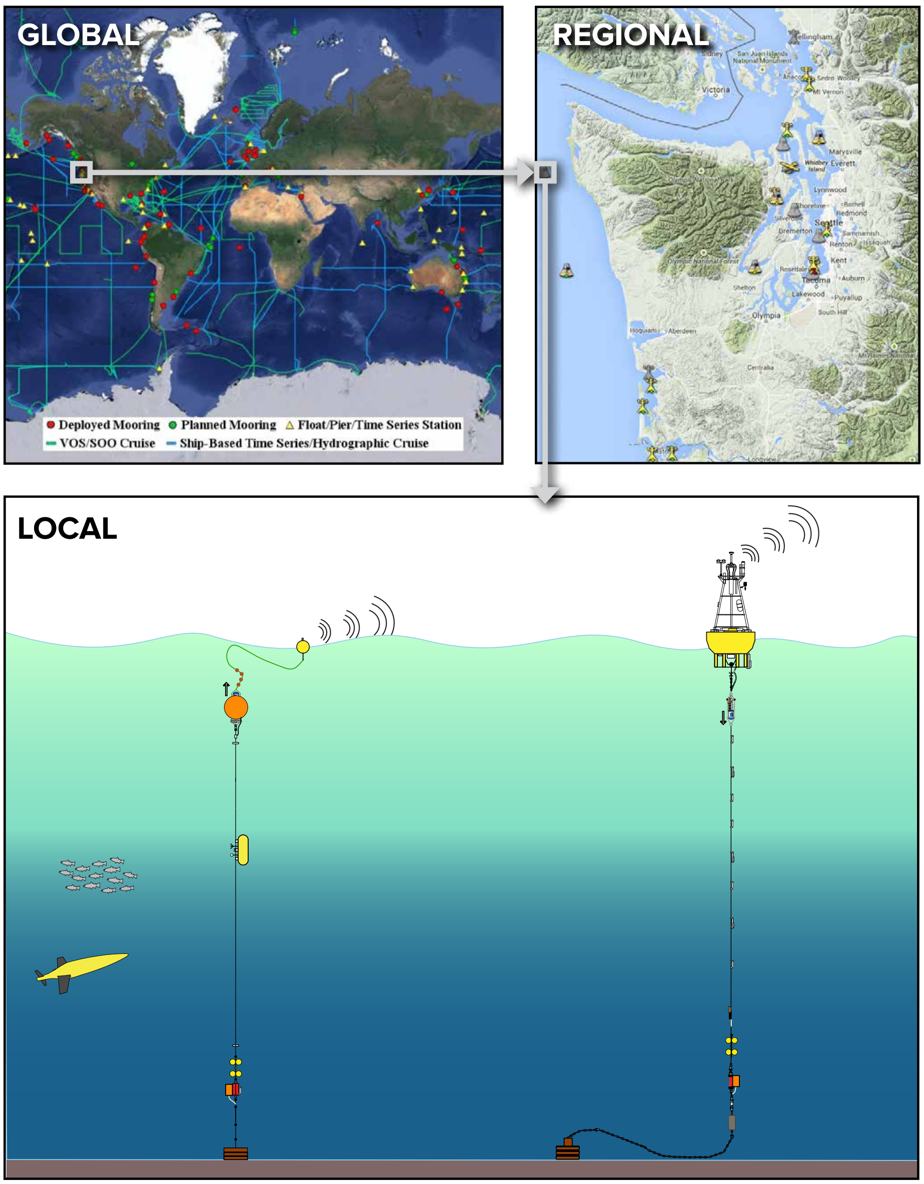

FIGURE 2. The nested scales of ocean acidification observing. Globally (top left), GOA-ON encompasses observing assets that meet consensus requirements. *Map courtesy of Cathy Cosca* A regional network (top right) encompasses assets designed and implemented by a consortium of stakeholders to address regional societal needs (e.g., the Northwest Association of Networked Ocean Observing Systems [NANOOS] for Washington State; http://nvs.nanoos.org). On the local scale (bottom), assets are targeted at understanding specific physical and biogeochemical processes within that particular ecosystem (e.g., moored and mobile assets off La Push, WA). *Modified from Alford et al. (2012), courtesy of John Mickett*

RECOMMENDATIONS FOR ESTABLISHING LONG-TERM, INTEGRATED COASTAL OCEAN HEALTH OBSERVATIONS

We make the following recommendations to facilitate more efficient planning and implementation for integrated coastal ocean acidification observing networks to maximize leveraging of existing institutional capabilities, resources, and other assets.

Recommendation 1

Identify and engage regional stakeholders with diverse interests in coastal resources, economic drivers, or uses that might be impacted by ocean acidification at the outset of the regional network design process. Stakeholders include researchers (observations, experiments, models, social science), resource managers, water and air quality monitoring agencies, tribal nations, industries relying on the marine environment or resources (capture fisheries, aquaculture, tourism), policymakers, organizations with outreach and education missions (schools, aquariums, zoos, visitors centers, media), and others. We provide a set of questions that can be applied across ecosystem types and that may help identify and engage stakeholders who may ultimately become strong partners in designing, planning, implementing, and sustaining regional interdisciplinary coastal ocean acidification observing networks (Table 2).

TABLE 2. Scoping questions to help identify key stakeholders and important knowledge gaps within an ecosystem for coastal ocean acidification observing network.

1. Are there any species or groups of species that play a dominant role in structuring ecological or biogeochemical processes within this ecosystem, including keystone species?
2. What are the most ecologically and economically important marine species, communities, or ecosystem functions in the region?
3. What is their regional societal and economic relevance (ecosystem goods and services)?
4. What are the ecological or trophic linkages among species in the ecosystem?
5. What vulnerability do these species and ecosystems have to ocean acidification?
6. What are the dominant temporal and spatial scales of variability that affect this ecosystem?
7. What are the necessary and appropriate levels of sampling resolution for tracking changes in ecological composition and abundance through time and across the ecosystem (e.g., species vs. functional taxonomic groups, numerical abundance vs. biomass vs. percent cover)?
8. What are the dominant processes influencing variation in biogeochemistry and ecology?
9. What additional stressors are important in the region or ecosystem, and are there existing monitoring efforts relevant to these?
10. What are the key indicators of ecosystem or organismal health, disease, or toxicity risks within the ecosystem or region, and what metrics, surveys, or assays can be used to track them?
11. What are the information needs and applications of key stakeholders?
12. What are the gaps in understanding within the region or ecosystem type that need to be surmounted to provide the needed information to benefit society?

Recommendation 2

Identify existing observing or monitoring activities, assets, and programs, particularly those with ongoing time-series measurements. A detailed gap analysis may be beyond the feasible or desired level of effort for this, but identifying relevant efforts that can be integrated to form a more comprehensive coastal ocean health observing network that includes partners who monitor ecological impacts attributable to ocean acidification should be identified across the region.

For the key species and ecosystems identified through the stakeholder engagement process, it is helpful to identify key environmental drivers, which may vary by ecosystem type within the region and may represent either natural processes or additional human pressures on these coastal ecosystems (see Breitburg et al., 2015, in this issue). Leveraging existing activities to the extent appropriate will enhance regional observing networks and assist in efforts to attribute patterns across multiple drivers. IOOS regional associations are examples of organizing bodies that cut across and unite diverse sectors such as academia, government, and industry. Leveraging may provide opportunities to develop insights into the historical progression of ocean acidification and related patterns or trends in ecological communities. Through judicious application of historical and proxy data sets (Juranek et al., 2009; Alin et al., 2012), estimates of historical ocean acidification trajectories might be reconstructed for comparison with biological and ecological time series, paleoenvironmental records, or hindcast models. As an example of leveraging opportunities, it would be beneficial to couple ocean acidification observing efforts to the nascent marine Biodiversity Observation Network (Duffy et al., 2013).

Recommendation 3

Design, prioritize, and implement elements of regional observing networks to fill key gaps in understanding that will best enable the region to mitigate and/or adapt to impacts of ocean acidification and interacting environmental stressors. Integrate new observations into existing programs wherever reasonable in order to maximize leveraging and engagement of all relevant stakeholders. Stakeholders should play a key role in prioritizing components of the regional network.

To contribute to global understanding of relative rates of change and the roles of interacting drivers across regions, the regional observing network should be capable of discerning long-term trends, dominant frequencies and spatial scales of variability, and ecosystem responses to changing environmental conditions. Other assets within a region should be targeted at shorter-term management applications or acquiring process-level understanding.

Recommendation 4

Develop and disseminate key data and information products needed by stakeholders. For some stakeholders, such as shellfish aquaculture managers, the needed data product is real-time or near-real-time data about ocean conditions; leveraging existing resources, such as data portals provided by regional associations of IOOS, is a cost-effective and timely means of disseminating this information. Fisheries and coastal resource managers often need information about recent changes in and future predictions for the ecosystem that require different data products. Support is needed to develop and sustain key data products and appropriate information delivery conduits to ensure timely availability to decision makers.

Recommendation 5

Regularly re-engage stakeholders to assess the utility of observations and information products, and employ adaptive strategies to better support changing societal requirements. As new impacts become known and technologies to facilitate more efficient monitoring become available, the network will benefit from periodic, systematic evaluation and identification of remaining (or new) knowledge gaps. New sensors and methods for making environmental and ecological observations may provide opportunities to improve quality and cost effectiveness (Figure 1, Level 3 of Goals 1 and 2; e.g., Byrne, 2014; Pfister et al., 2014). Stakeholder groups should carefully consider the critical importance of sustained, consistent, long-term time-series observations of both environmental and ecological conditions when deliberating whether to continue or alter the methods or locations of observations. Long-term climate monitoring principles provide a useful framework for evaluating such decisions (Karl et al., 1995; Trenberth et al., 2002).

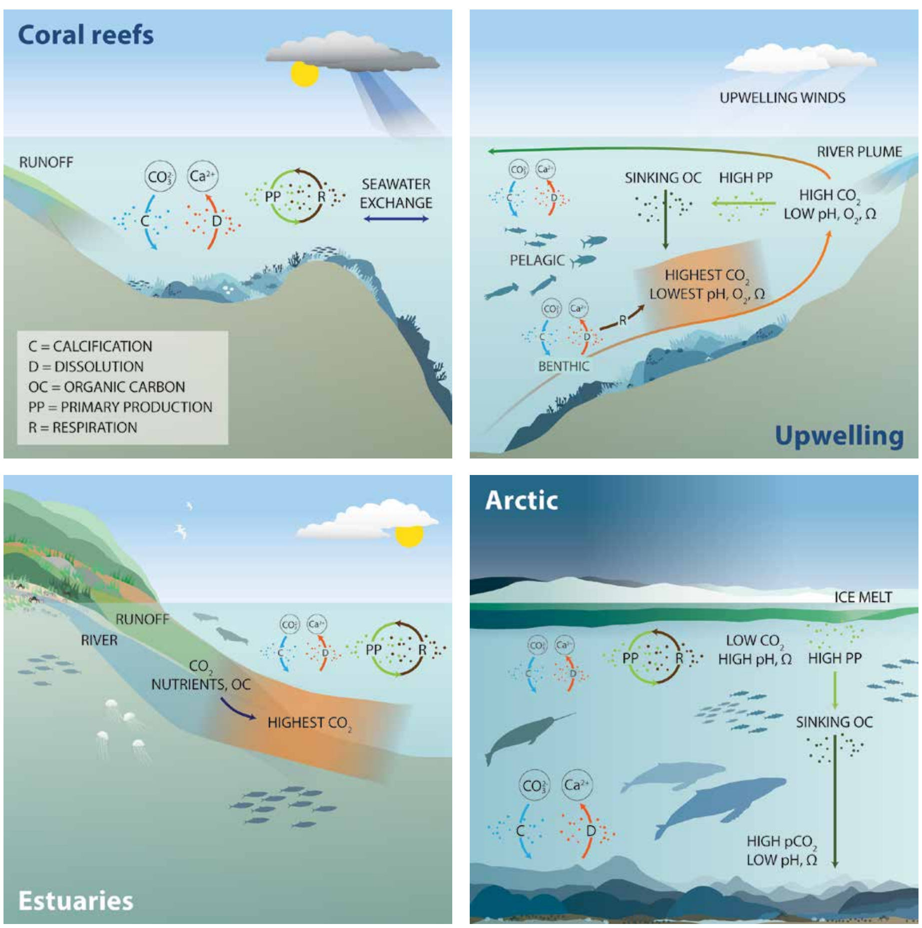

FIGURE 3. Schematic diagram of coastal ecosystem types described in the text, illustrating some key biogeochemical processes, ecosystem structures, and species. Coral reef (upper left), upwelling (upper right), estuaries (lower left), and Arctic (lower right). *Courtesy of Amanda Dillon*

KEY CONSIDERATIONS FOR REGIONAL OBSERVING NETWORKS IN A RANGE OF ECOSYSTEM TYPES

While GOA-ON guidance helps set first-order requirements, and our recommendations above and questions in Table 2 can refine them for specific regions, deciding on the key metrics of ecological variability within a given ecosystem is a very complex task, given the infinite range of possibilities for combinations of species (and higher taxonomic levels), genotypes, and functional groups within communities. Through the use of a few examples from ecosystem types with existing regional coastal ocean acidification observing networks (Figure 3), we demonstrate how an observing network can be designed to be responsive to regional stakeholder needs. These summaries focus on key characteristics of the ecosystems that did or should guide the design and implementation of regional coastal ocean health observing networks, highlighting some of the distinct challenges, stakeholder groups, and leveraging opportunities (Table 3). The myriad additional stressors affecting the four focal ecosystems are highlighted elsewhere in this issue (Breitburg et al., 2015). For other regions and ecosystem types, we highlight key attributes in Table 3, acknowledging the distinct management purviews and practices associated with each.

Coral Reefs (Pacific Islands)

Healthy coral reefs are among the most economically valuable ecosystems on Earth, providing vital ecosystem goods and services estimated to total between \$29.8 billion and >\$1 trillion annually, depending on the study methods (e.g., Cesar et al., 2003; Brander et al.,

TABLE 3. Nested levels of observing network requirements for global versus regional to local types of ocean acidification observing networks. Needs listed at international and national scales should apply to some extent to all ecosystems listed in the coastal and estuarine regional ecosystems section below, where a greater level of detail is given, although some details are specific to the US context of these guidelines.

Scale or ecosystem type	Key stakeholders	Key societal information or decision support needs	Key environmental processes driving variation	Key ecosystem resources, species, or conservation mandates	Key gaps in understanding
GLOBAL					
Open ocean	International science and policy communities.	Climate-quality observations for trend and variability in OA conditions. Models provide higher spatial resolution, predictions at decade-to-century scales, and attribution of impacts of climate change vs. ocean acidification on marine ecosystems at largest scale.	Interannual to decadal climate variability, global ocean uptake of CO_2 emissions, anthropogenic climate change, large-scale circulation of the ocean, wind patterns.	Open-ocean fisheries, ocean carbon sink.	Impacts of ocean acidification on lower trophic level species that may have globally significant feedback on biogeochemical cycles. Tipping points.
NATIONAL					
Coastal oceans, estuaries, Great Lakes (generally)	Federal (Environmental Protection Agency, NOAA, US Fish and Wildlife Service), state, and local agencies with water quality or coastal resource management mandates; Integrated Ocean Observing System and its regional associations; indigenous cultures; scientists.	Climate-quality water quality data and models that can estimate human contribution to changes in pH, oxygen, and related parameters (related to potential for regulation of CO_2 emissions under the US Clean Air Act and Clean Water Act).	Coastal circulation, land-water interactions, seasonality, extreme events.	Fisheries health protected by Magnuson-Stevens Act, endangered or threatened species protected by the Endangered Species Act.	Seasonal to decadal variability in coastal and estuarine biogeochemistry in most places.
COASTAL/ESTUARINE ECOSYSTEMS					
Nearshore/ intertidal	Public (recreation, food harvest), tourism industry, shellfish industry, shellfish/ fisheries managers, public health agencies (e.g., potential for increased shellfishery closures due to ocean acidification-related harmful algal bloom [HAB] intensification), local- to state-scale management.	Projected impacts on shellfish closures due to direct and indirect impacts of ocean acidification (e.g., impacts to viability of shellfish populations or HABs).	Tidal cycle, extreme events, other natural (or human) disturbance.	Shellfish, benthic fish, nursery for many pelagic fish species, seagrasses, kelps.	Expected impacts on ecological communities due to differential susceptibility to OA and other stressors; trophic or competitive interactions among species.
Aquaculture	Industry, public (consumers, environmental concerns about aquaculture).	Early warning observational and forecast systems for carbonate system variability on various time scales.	Storm-driven mixing, river inputs, upwelling.	Shellfish, finfish, kelp, and seaweed.	Sensitivity of many affected species.
Coral reefs	Local land/ocean managers, policymakers, indigenous people, tourism/ecotourism industry, shellfish (pearl oyster) industry, public (recreation, food harvesting).	Climate-quality observations to understand long-term impacts of ocean acidification. Weather-quality observations to assess local-regional multistressor impacts. Local/state managers need information for land-use decisions and coastal resource management. Biological monitoring to assess changes in key reef builders.	Global change; El Niño; storms or extreme events; nutrient, sediment, or sewage runoff or spills; coastal development and eutrophication; overfishing/harmful fishing practices; disease; ecological processes (production, respiration, calcification, dissolution).	Tropical coral reef and associated finfish. Coral species listed under the Endangered Species Act; stability of carbonate reef framework; net accretion vs. sea level rise rates for low-lying atolls.	Interplay of water residence time and biogeochemical processes driven by land-derived inputs remain only qualitatively known; contribution of microbial component to carbon cycling.

Table 3. Continued next page...

TABLE 3. Continued...

Scale or ecosystem type	Key stakeholders	Key societal information or decision support needs	Key environmental processes driving variation	Key ecosystem resources, species, or conservation mandates	Key gaps in understanding
COASTAL/ESTUARINE ECOSYSTEMS, continued...					
Upwelling/ shelf to upper slope ecosystems	Benthic and pelagic fisheries industry and managers, national environmental agencies with offshore management mandate, state agencies with nearshore management responsibility (where shelf is narrow).	Increased real-time information about water-column and benthic environmental conditions and biological response; seasonal to event-scale forecasts; develop ecosystem indicators, including health and food quality metrics (e.g., HABs toxin production metrics).	Upwelling, river plumes, and in situ metabolism, which can exacerbate or mitigate acidification in coastal waters; seasonal to long-term climate drivers; ocean circulation changes; ocean CO_2 uptake.	Benthic shellfish, pelagic life stages of nearshore shellfish, finfish, and species protected by Marine Mammal Protection Act and Endangered Species Act.	Impacts of changes in strength of any drivers (e.g., upwelling, ocean circulation, river runoff) on environmental condition; sensitivity or ability to adapt of many species; trophic plasticity of key species; ecosystem impacts due to food quality or health challenges driven by climate change or ocean acidification (e.g., sea star wasting disease).
Arctic	Indigenous populations, fisheries managers, scientists.	Weather-quality observations to assess local and regional variations relevant to Arctic fishery, land and ocean management; effects of short-term physical variability on biogeochemistry (glaciers, ice seasonality).	Sea-ice changes (freshening, decreased saturation state), enhanced surface ocean uptake of CO_2 (longer open water season), changes in wind forcing and water temperature, longer growing season (for primary producers), stratification (impacts nutrient supply).	Commercial species—salmon, pollock, Bering Sea crab. Shellfish and copepods support higher trophic levels (e.g., walrus, fish, seabirds, seals, whales).	Seasonality, interannual variability, winter dynamics, under-ice dynamics.
Antarctic	International organizations (e.g., Commission for the Conservation of Antarctic Marine Living Resources), nations with commercial fisheries (krill), conservation groups.	Weather-quality observations to assess role of short-term changes in the physical system on the biogeochemistry (ice-shelf collapse, glacier calving events, changes in seasonal ice retreat/ reformation).	Uptake of atmospheric CO_2, sea-ice melt in some regions, sea-ice gains in others, wind forcing (upwelling of CO_2-rich water onto continental shelves), Southern Ocean Oscillation (dominant climate mode for changes in wind), Southern Ocean is a large reservoir for anthropogenic CO_2.	Krill: not commercially important in the U.S., but supports higher trophic levels of international conservation concern (penguins, seals, whales).	Seasonality, interannual variability, winter dynamics, under-ice dynamics.

2014). Warm-water coral reef ecosystems are structurally defined by their reef-building corals and crustose coralline algae whose three-dimensional habitats support the highest levels of biodiversity of any marine ecosystem (Knowlton et al., 2010). From a human well-being perspective, coral reef ecosystems provide fisheries-related food security and livelihoods to hundreds of millions of people worldwide, with an estimated economic value of $5.7 billion; tourism-related livelihoods and revenue estimated at $9.6 billion; and protection to coastal communities from storm-induced waves, storm surges, tsunamis, and, when reef accretion rates suffice, some of the impacts of sea level rise. In addition, long-standing cultural practices and the livelihoods of indigenous populations around the world have evolved around these reefs over millennia (Bunce et al., 2000).

Major stakeholders include people living in "small island developing states" whose existence and subsistence depend on healthy coral reef resources; natural resource managers at various community, state, and federal levels; ecotourism and tourism industries; pearl oyster and aquarium trade industries; and nonprofit organizations with reef conservation missions. Stakeholder and decision-maker information needs vary widely from long-term (decadal and longer) projections of reef health and stability to immediate concerns about selecting sites for sustainable economic (e.g., fisheries and tourism) and cultural uses.

According to a broad range of species response experiments under different CO_2 emissions scenarios, coral reef communities will likely undergo significant ecological phase shifts this century as calcification of reef-building corals and crustose coralline algae is unable to keep pace with bioerosion and, potentially, dissolution processes (reviewed in Brainard et al., 2012). As this occurs, many of

TABLE 4. Triennial coral sampling scheme used by NOAA's Pacific Reef Assessment and Monitoring Program (Pacific RAMP) across the US-affiliated Pacific Islands.[1] All measurements taken at lower Class levels are taken at all higher Class sites as well.

Measurements[2]	Number of locations per island or group of islands	Depths	Duration of time measured or represented	Purpose	Date measurements started
Class 0 — Measurements done at most islands in each archipelagic region[3]					
Stratified random water sampling for carbonate chemistry (DIC, TA, S, T, nutrients; Newton et al., 2014)	~10 samples/island	Near-benthos	3–4 day snapshot every three years	To characterize long-term secular changes in nearshore seawater chemistry	Initiated in 2006, shifted to stratified random in ~2012
Classes 1 and 1.5 — Measurements done at four to eight islands in each archipelagic region					
Subsurface temperature recorders (STR)	4 cardinal direction transects	1–2, 5, 15, and 25 m	Every 30 min through 2012, then every 5 min	To characterize long-term secular changes in near-surface temperature	Initiated in 2001, standard depths since 2012
Site-specific and stratified random water sampling for carbonate chemistry (DIC, TA, S, T, nutrients)	~25 samples/island	1 km offshore surface, at site surface and near-benthos	3–4 day snapshot every three years	To characterize long-term secular changes in nearshore seawater chemistry	Initiated in 2006, shifted to stratified random in ~2012
Deploy 5 calcification accretion units (CAUs) (Price et al., 2011)	Four at each 15 m STR site	Benthos	Cumulative through triennial cycle	To measure rates of net accretion or new production of calcium carbonate, primarily in the form of crustose coralline algae	Initiated in 2010
Rugosity (30 vertical measurements along a 15 m long photo transect)	"	"	Snapshot every three years	To characterize topographic complexity	Initiated in 2013
Photo quadrat or photomosaic surveys	"	"	"	To assess benthic taxonomic composition	Initiated in 2013
Microbial water sampling	"	"	"	To characterize microbial diversity of reef environments	Initiated in 2010
Class 2 — Measurements done at four islands in each archipelagic region.					
Deploy three autonomous reef monitoring structures (ARMS)	At each 15 m STR site	Benthos	Cumulative measurement through triennial cycle between visits	To systematically monitor the biodiversity of the cryptic understudied organisms living within the reef matrix	Initiated in 2010
Deploy five bioerosion measurements units (BMUs)	"	"	"	To quantify rates of bioerosion of previously scanned calcium carbonate blocks	Initiated in 2013
Deploy SeaFET pH sensors and automated water samplers during 3–4 day visits	Opportunistic, subset of Class 2 sites	Near-benthos	1–3 days continuous for SeaFET, every 3–4 hours through a diel cycle for water samplers	To characterize diel cycle of carbonate chemistry	Initiated in 2015
Collect coral cores	"	5–15 m depending on availability of massive coral heads	Every third triennium, decadal-scale observations	To measure changes in calcification rates of massive reef-building corals, primarily *Porites* in recent decades	Initiated in 2010
Class 3 — Measurements done at one island in each archipelagic region.					
Deploy high-resolution moored carbonate system sensors (e.g., MAPCO$_2$ sensors)	Locations must be accessible for biweekly water sampling and routine maintenance	Near surface only	Every three hours, daily telemetry, biweekly water sampling for DIC, TA, S	To document diel and seasonal variability in seawater carbonate chemistry	Kaneohe Bay initiated in 2012, others sites not yet established

[1] Pacific RAMP is supported jointly by NOAA's Coral Reef Conservation Program and NOAA's Ocean Acidification Program as the Pacific Islands component of NOAA's National Coral Reef Monitoring Program.
[2] DIC = dissolved inorganic carbon. TA = total alkalinity. S = salinity. T = temperature.
[3] Archipelagic regions are the Main Hawaiian Islands, Northwest Hawaiian Islands, American Samoa, Marianas, and Pacific Remote Islands Marine National Monument

the ecological, economic, cultural, and coastal protection values that coral reefs provide to tropical coastal communities could be devastatingly impacted. Coral reefs are also subject to myriad other human-related pressures that range in scale from local to global (Brainard et al., 2012; Breitburg et al., 2015, in this issue). At present, 22 coral species are protected in US waters through the US Endangered Species Act because of their vulnerability to the combined effects of these global and local stressors.

Under the National Coral Reef Monitoring Program (NCRMP), NOAA operates an integrated interdisciplinary regional coastal ocean acidification observing network for coral reefs, the Pacific Reef Assessment and Monitoring Program (Pacific RAMP) that encompasses the US-affiliated Pacific Islands. Pacific RAMP was initiated in 2000 to begin establishing baseline conditions and monitoring the status and trends of coral reef ecosystems in the Pacific Islands (Figure 4). Standard Pacific RAMP surveys monitor the diversity, distribution, abundance, and condition of reef fishes, corals, other macro-invertebrates, and benthic algae in the context of their surrounding habitats and varying oceanographic conditions (Table 4). As awareness and concerns about the potential impacts of ocean acidification on coral reefs grew and new stakeholders came to the table, additional approaches and methods to specifically monitor the ecological impacts of ocean acidification were discussed, developed, adapted, and incorporated into Pacific RAMP surveys over the period since 2005. In order to address concerns about potential losses of biodiversity and resilience due to ocean acidification, and considering the results of species response experiments on corals and crustose coralline algae, observations of seawater carbonate chemistry, cryptobiota and microbial diversity, and rates of calcification, calcium carbonate accretion, bioerosion, and coral growth have been added to Pacific RAMP surveys to better assess, monitor, and attribute the ecological impacts of ocean acidification on coral reefs (Figure 4). Because of financial constraints and the vastness of the region, the observing network was designed in a hierarchical manner with four levels of observations ("Classes" in Table 4 and Figure 4) spatially distributed across the Pacific Islands region. Incorporation of existing complementary research has helped maximize the use of limited financial resources (e.g., NOAA's Coral Reef Instrumented Monitoring Platform [CRIMP] buoy program). Under NCRMP, the coral monitoring approach and methods outlined are also used throughout the US coral reef ecosystems in the western Atlantic/Caribbean.

Design and implementation of the Pacific RAMP/NCRMP ocean acidification observing network required many discussions and decisions about what metrics to measure, what methods to use, spatial scales and temporal frequencies of sampling, and how well observations represent the ecosystem. Likewise, many resulting decisions required prioritizing the primary questions; leveraging institutional resources, finances, and expertise;

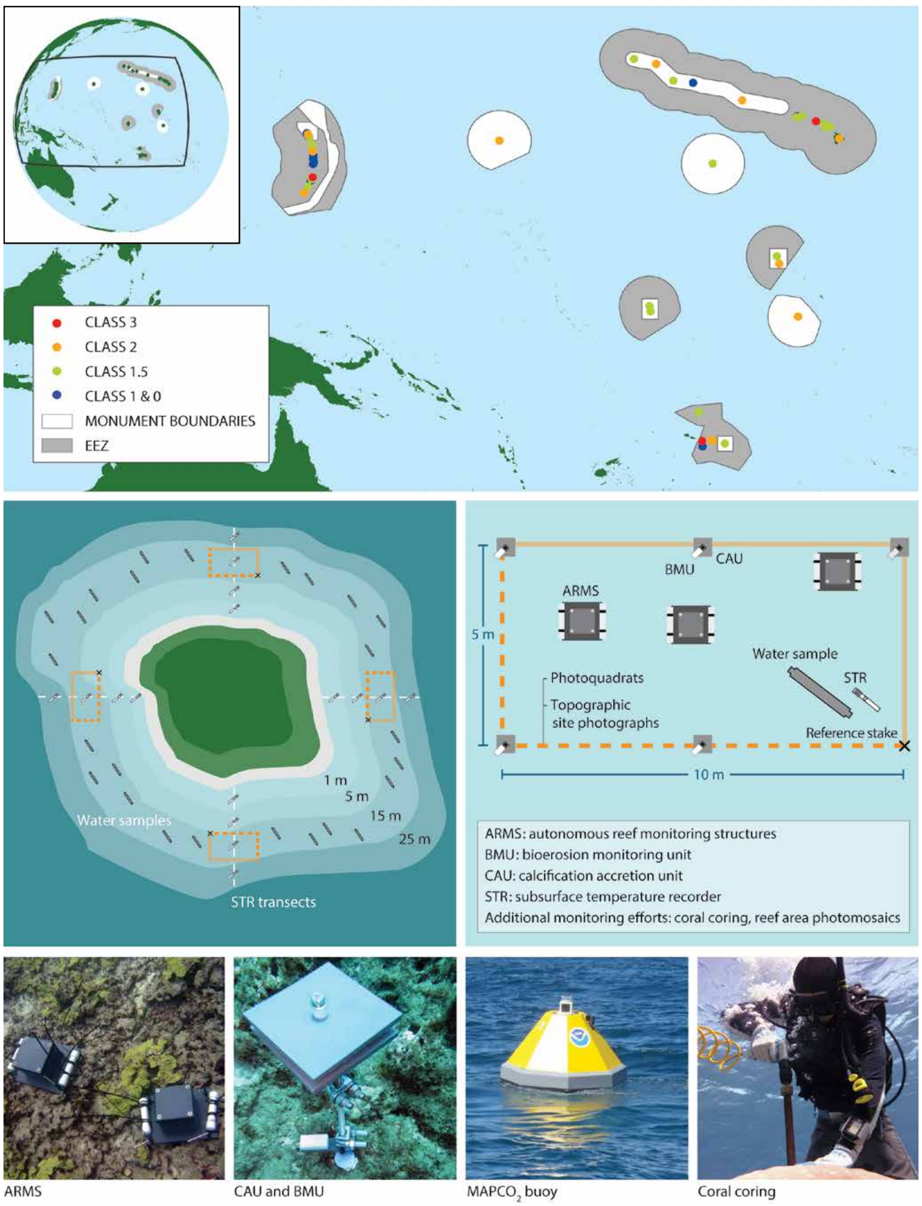

FIGURE 4. Schematic diagram of the hierarchical coral reef sampling scheme occupied on a triennial basis by the Pacific Reef Assessment and Monitoring Program (Pacific RAMP) and NOAA's National Coral Reef Monitoring Program. *Courtesy of Amanda Dillon*

and balancing and compromising around logistical and operational constraints. In this case, the ocean acidification observations were primarily developed to align with and complement ongoing status and trends monitoring of Pacific RAMP/NCRMP, which in turn was designed to monitor all of the coral reef ecosystems of the US Pacific Islands to meet requirements of the Coral Reef Conservation Act of 2000. The vastness and remoteness of the US Pacific Islands and budget realities constrain accessibility via relatively large ocean-going research vessels and limit surveys to a repeated three-year cycle of surveying the coral reefs of the main and Northwestern Hawaiian Islands in the first year; Commonwealth of Northern Mariana Islands, Guam, and Wake Atoll in year two; and American Samoa and Pacific Remote Islands Marine National Monument in year three.

Upwelling Systems

Along the US West Coast, shellfish and finfish industries supported by the region's high ecosystem productivity are economically important, with $32.7 billion in sales impacts and roughly 220,000 jobs supported by the commercial seafood industry in 2012 (NMFS, 2014). Calcifying invertebrates with benthic life stages and limited mobility represent four of the 10 most valuable commercial fisheries on the West Coast (Table 5). Recreational fishing accounted for 7.4 million fishing trips in 2012, supporting 18,800 jobs and yielding another $2.5 billion in sales (NMFS, 2014). Shellfish and finfish represent highly valued tribal nation resources for both subsistence and ceremonial uses (i.e., non-commercial harvests; Radtke, 2011). Healthy marine ecosystems represent high aesthetic and economic value for tourism and non-extractive recreation (e.g., whale watching, tidepooling).

Stakeholders are diverse. The economic importance of shellfish and finfish to West Coast state economies make these fisheries (both wild and hatchery-spawned), as well as those tasked with observing, forecasting, and managing them, important stakeholders. Larval mortality events at Pacific Northwest shellfish hatcheries associated with corrosive water events galvanized regional shellfish and finfish industries in support of ocean acidification monitoring, research, and mitigation efforts (Barton et al., 2015, in this issue). Fisheries managers require reliable forecasts of fisheries production and stock that rely on understanding prey availability and the factors that influence it. Coastal and estuarine water quality managers are responsible for declaring water bodies impaired with respect to pH if values stray outside specified limits under the Clean Water Act. Organizations with marine conservation missions, such as West Coast aquariums, are also critical stakeholders for building an ocean acidification observing network and can help both generate new results and communicate their importance to public and policy audiences.

Eastern boundary current upwelling systems like the California Current Large Marine Ecosystem (CCLME) constitute natural laboratories for studying ocean acidification in the context of multiple stressors (see Breitburg et al., 2015, in this issue). In addition to ocean acidification, wind-driven upwelling, intense production and in situ respiration on the shelf, and river inputs of waters high in CO_2 and low in calcium result in a wide dynamic range of values for carbonate chemistry, oxygen, and nutrients, with strong spatial and temporal variability. Summertime conditions are frequently corrosive to calcium carbonate and become hypoxic (e.g., Grantham et al., 2004; Feely et al., 2008). A growing number of marine species exhibit reduced growth and survival when exposed to corrosive conditions, particularly when they are compounded by hypoxia. Observed sensitivity in economically or ecologically important species include early life stages of some oyster, mussel, scallop, and clam species under experimental conditions (Gobler et al., 2014; Waldbusser et al., 2014), as well as calcifying pelagic snails under in situ conditions (pteropods; Bednaršek et al., 2014). Mortality of Dungeness crabs and other benthic organisms has been observed due to hypoxia events (e.g., Grantham et al., 2004), broadening the stakeholder base and policy relevance. Forecasts of increasing intensity, extent, and duration of undersaturated conditions along the West Coast are concerning for the CCLME (Gruber et al., 2012; Hauri et al., 2013).

Efforts to monitor ocean acidification and hypoxic conditions and ecosystem impacts in the CCLME have taken advantage of several complementary platforms and programs, some new since 2005, others pre-existing. NOAA and many partners support a network of moored time-series stations along the West Coast that provide high-frequency ocean acidification-relevant measurements (Figure 5). Since 2009, efforts to integrate biogeochemical measurements into biological and fisheries survey cruises and vice versa have been initiated. Autonomous shipboard

TABLE 5. Commercial landings[1] for most economically valuable fisheries on the US West Coast (California, Oregon, Washington) from 2003 to 2012.[2] Gray shaded entries represent invertebrates with some calcium carbonate hard parts.

Species	Total value (2003–2012)
Dungeness crab	$1,312,233,926
California market squid	$417,528,455
Pacific oyster	$411,768,620
Pacific geoduck clam	$400,817,096
Pacific hake (whiting)	$334,971,917
Albacore tuna	$291,808,355
Sablefish	$271,104,039
Chinook salmon	$220,238,947
Manila clam	$199,346,707
Ocean shrimp	$152,899,359
Pacific sardine	$120,332,152
California spiny lobster	$86,553,611
Dover sole	$68,031,185
Sea urchin	$75,240,059

[1] Note: This database does not include the value of all aquaculture or of non-commercial tribal or recreational fisheries.
[2] Source: http://www.st.nmfs.noaa.gov/commercial-fisheries/commercial-landings/annual-landings/index.

analytical systems on NOAA Fisheries and other research vessels map relevant parameters at the surface. Water-column profiling surveys document subsurface conditions down to the depths of important demersal fisheries. Fisheries observations focused on quantifying phytoplankton and zooplankton, including ichthyoplankton, date back as far as the 1940s on the West Coast, but due to funding limitations, most only measure a subset of the chemical parameters needed to constrain ocean acidification and hypoxia conditions or only cover carbon measurements at a subset of stations. Although monitoring gaps abound, indicator species may provide insight into the time-integrated stresses on organisms that form the energetic basis of marine ecosystems and fisheries. Pteropods, which are sensitive to subtle changes in saturation state (Bednaršek et al., 2014), have been suggested as useful indicator taxa for monitoring ecological impacts of ocean acidification.

The first West Coast carbon cruise in 2007 and the contemporaneous shellfish hatchery seed crisis resulted in a very effective research partnership in the Pacific Northwest and boosted efforts to create an integrated ocean acidification observing network on the West Coast (Feely et al., 2008; Barton et al., 2015, in this issue). The California Current Acidification Network (C-CAN) emerged from this partnership among West Coast ocean acidification stakeholders in 2010, as did real-time monitoring of seawater in hatcheries supported by state and federal funds (Barton et al., 2015, in this issue). C-CAN facilitates communication on monitoring priorities and best practices, management needs, and mitigation and adaptation strategies to diverse partners. Regional IOOS associations have also played a key role in coordination and communication among ocean acidification stakeholders, are partners in the West Coast ocean acidification observing network, and provide invaluable access to real-time data through Web-based portals. Finally, the Washington State Blue Ribbon Panel on Ocean Acidification and the West Coast Ocean Acidification and Hypoxia Science Panel have provided venues for communicating cutting-edge understanding of West Coast ocean acidification conditions and ecological vulnerability across a diverse network of stakeholders, and in so doing, have mobilized funding and political progress on ocean acidification mitigation and adaptation in West Coast states.

Estuaries

Estuaries teem with life as a result of intense primary production at the land-ocean boundary. Here, organisms occupy a variety of muddy, sandy, or rocky substrates. Seagrass meadows, tidal wetlands, or mangrove forests provide habitat and food while sequestering CO_2 from the atmosphere or surface seawater. Estuaries act as nurseries for many species of fish and birds. Historically, estuaries and freshwater-influenced bays have been important sites for abundant oyster growth in the United States, with many East Coast estuaries having formerly extensive oyster shell reefs. Oysters and other shellfish provide a number of valued ecosystem services, including water column filtration and shoreline protection.

Historically, humans have settled around estuaries, and their exploitation of resources has resulted in overfishing, seafloor dredging, and eutrophication and pollution of the waters. Yet, myriad stakeholders still depend on estuarine services and products. Those involved with monitoring and managing estuaries—including marine labs and aquariums, shellfish growers, and tribal, state, and local governments—should be encouraged to monitor for ocean acidification along with their other mandates. Such partners present important leveraging opportunities for installing carbon sensors and collecting carbonate system water samples. Nationally, NOAA's National Estuarine Research Reserve System is a network of 28 estuaries

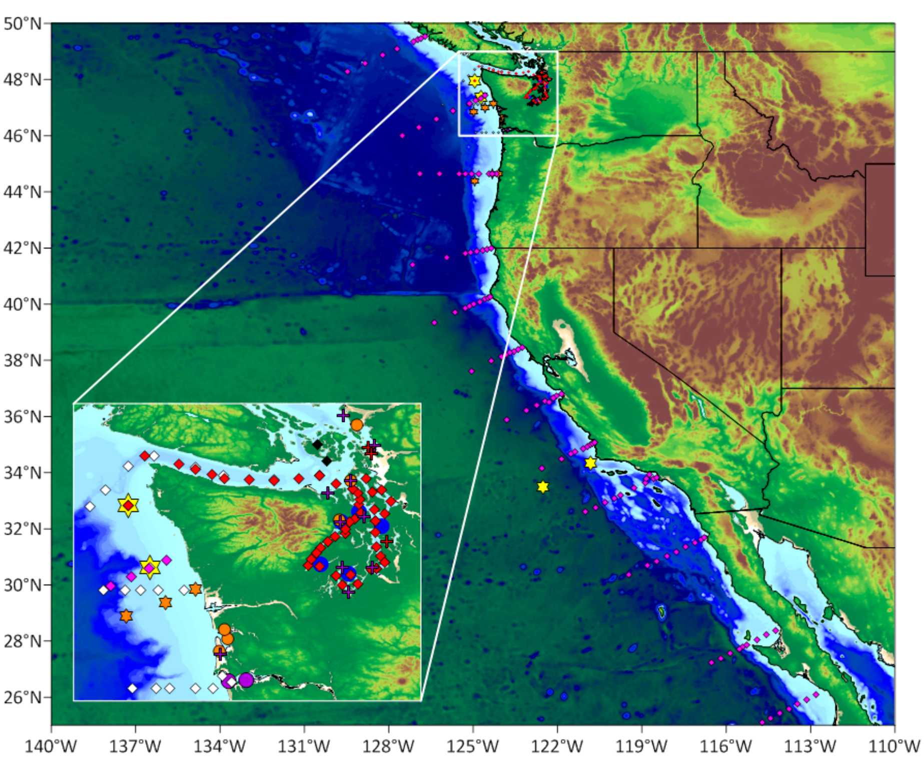

FIGURE 5. Ocean acidification observing assets in the California Current Large Marine Ecosystem and Puget Sound (inset), a large urbanized fjord estuary. Symbols represent sampling stations: moored time-series stations (yellow/orange stars on coast and blue circles in Puget Sound); time-series stations sampled by ship- or land-based researchers on a recurring basis (all other symbols). *Courtesy of Dana Greeley*

conducting extensive research and monitoring on climate change and resilience, habitat protection, and water quality, which would provide an excellent framework for added sensors and sampling.

The current status of ocean acidification observing in estuaries varies greatly, but in general is underdeveloped. Estuarine ecosystems pose unique challenges for developing regional coastal ocean health observing networks to address stressors such as ocean acidification, eutrophication, and hypoxia. The high degree of spatial heteorogeneity and temporal variability of biogeochemical processes makes it difficult to adequately characterize the natural environment (e.g., Feely et al., 2010; Wallace et al., 2014). Freshwater runoff from land into estuaries is typically enriched in inorganic and organic carbon and nutrients relative to coastal waters, and this can fuel intense estuarine outgassing and in situ metabolism, driving CO_2, O_2, and nutrient content toward strong enrichment in some areas and depletion in other areas.

High-Latitude Systems

Together, climate change, ocean acidification, and potential species invasions pose grave threats to productive high-latitude ecosystems that support some of the world's most economically valuable fisheries (Table 6), as well as some of the world's most charismatic coastal fauna (e.g., polar bears and penguins). The polar oceans are essentially inverses of each other: the Arctic Ocean is surrounded by continents and receives abundant freshwater input to its shallow shelf ecosystems; in contrast, the deep Antarctic shelves surround a polar continent with little freshwater runoff (Aronson et al., 2011). Because of its oceanographic isolation, connection to the deep sea, and extreme cold, Antarctica's deep shelf ecosystems have 50–60% species-level endemism and lack the fast-moving, shell-crushing predators that dominate Arctic to sub-Antarctic benthic coastal food webs (Aronson et al., 2011). In contrast, seabirds, seals, whales, and walruses rely heavily on benthic invertebrates from shallow Arctic shelf ecosystems (Grebmeier, 2012).

The numerous stakeholders for polar ocean acidification include international science and policy communities, commercial fisheries, and indigenous populations (Arctic only). We include both Arctic and Antarctic marine ecosystems here because the United States plays a role in international monitoring of Antarctic coastal oceans.

The world's high-latitude oceans are productive marine ecosystems that harbor numerous endemic marine species and provide globally significant oceanic storage for anthropogenic CO_2 (Khatiwala et al., 2009). Calcium carbonate saturation states are expected to decline rapidly in high-latitude oceans as increased temperatures result in loss of sea ice that will affect net CO_2 uptake. Thus, the high-latitude oceans are projected to manifest some of the earliest and most persistent aragonite undersaturation in the world ocean (Steinacher et al., 2008; Feely et al., 2009). Because of short food chains and strong coupling between benthic and pelagic ecosystems, Arctic marine ecosystems are particularly prone to reorganization (Grebmeier, 2012). Some authors conjecture that ocean acidification will be the most significant habitat impact for Antarctic krill—which support penguins, whales, and other species of international conservation concern—and the deep-sea benthos (e.g., Constable et al., 2014).

Many profound knowledge gaps remain for both ecosystems, including the tolerances for changing temperature and ocean chemistry of many important prey species and the resilience of predator species to changing abundance and distribution of prey species (e.g., Fabry et al., 2009; Aronson et al., 2011; Constable et al., 2014). The impacts of multiple, simultaneous, and rapidly changing stressors on all trophic levels, many of which represent economically or ecologically important species, has only begun to be investigated (Breitburg et al., 2015, in this issue). Thus, high-latitude observing networks need to be well integrated to understand how physical changes in temperature, salinity, and ice dynamics due to warming, freshwater input, and ice melt, as well as biogeochemical changes due to ocean acidification and feedbacks from changing productivity, will affect high-latitude marine ecosystems.

There is a deficit in long-term observing resources in both polar oceans due in large part to the challenges of making observations under ice through the polar winters. Although a few exist in

TABLE 6. Commercial landings[1] for most economically valuable fisheries in Alaskan waters from 2003 to 2012.[2] Gray shaded entries represent invertebrates with some calcium carbonate hard parts.

Species	Total value (2003–2012)
Walleye pollock	$2,990,983,835
Sockeye salmon	$1,955,979,346
Pacific cod	$1,818,965,197
Pacific halibut	$1,808,993,643
Sablefish	$1,050,999,220
King crab	$985,257,530
Snow crab	$739,580,134
Pink salmon	$724,859,395
Chum salmon	$450,213,697
Yellowfin sole	$333,409,891
Coho salmon	$243,994,974
Chinook salmon	$190,385,230
Rock sole	$185,915,480
Atka mackerel	$171,048,155
Pacific herring	$165,626,187
Pacific Ocean perch rockfish	$104,547,205
Dungeness crab	$87,211,170
Rockfish	$75,053,374
Southern tanner crab	$67,113,266
Flathead sole	$58,321,427
Ten-year total, top species	**$14,208,458,356**
Ten-year total, all species	**$14,519,606,876**

[1] Note: This database does not include the value of all aquaculture or of non-commercial tribal or recreational fisheries.
[2] Source: http://www.st.nmfs.noaa.gov/commercial-fisheries/commercial-landings/annual-landings/index.

high-latitude locations, moored time-series stations equipped with carbon sensors are generally lacking in Arctic and Antarctic waters. International GO-SHIP/Repeat Hydrography cruises have made decadal surveys of physical and biogeochemical parameters in Southern Ocean waters since the 1980s, but 2015 will bring the first Arctic decadal cruises. In Pacific Arctic waters (Bering and Chukchi Seas), a large number of biophysical moorings have been deployed for various periods, starting in 1990, and carbon sensors (pCO_2 and pH) were added to the longest deployed of them, M2 in the southern Bering Sea. In Arctic waters of the North Atlantic, the Iceland Sea time-series station established in 1983 has included carbon sensors since 2013. Recurring biological surveys to detect changes in productivity and biodiversity commenced in Arctic waters of the North Pacific in 2010, and the partners involved have facilitated international data sharing by providing online data portals. Similarly, because of the unique biodiversity in Antarctic waters, special attention was focused on analyzing biodiversity in the Southern Ocean as part of the International Polar Year (2007–2009) and the Census of Marine Life (2000–2010) (DeBroyer et al., 2014). Early efforts to develop coastal ocean acidification observing networks in Arctic and Antarctic shelf waters have recognized the dearth of observing resources in high-latitude oceans, the importance of considering multiple stressors, and the need for integrating physical, chemical, and biological observations within existing monitoring frameworks to the extent possible in order to best address impacts of the many rapid changes occurring in polar marine ecosystems (NOAA Ocean Acidification Steering Committee, 2010; AMAP, 2013).

OBSERVING IN SUPPORT OF FORECASTING

As noted from goal 3 of GOA-ON, observations to support forecasts are a critical need for coastal stakeholders. Developing models, scaled by and tested with observational data, is an important scientific direction; synergies with observing network development should be pursued. Observations improve oceanographic and ecosystem models through model validation; in turn, model results inform the observing community about where additional observing assets or detailed process studies may be needed to further illuminate aspects of ocean acidification (e.g., Curchitser and Batchelder, 2013). Model development is needed on several scales: to project future conditions years out so coastal resource managers and decision makers can respond and to forecast conditions days out so that aquaculture and other fisheries can adapt their immediate practices.

CONCLUSIONS

Developing and sustaining a linked global network of integrated coastal ocean acidification observing networks is an overwhelming but critically important task in this era of rapid environmental change and decreasing funding for scientific research and long-term monitoring. Partnerships, stakeholder engagement, and institutional investment are imperative for the long-term sustainability of coastal ocean observing networks, but much of the needed growth in monitoring scope can be folded into existing water quality and natural resource monitoring efforts, requiring lower levels of funding than would be needed to implement completely new observing efforts. In addition to validation of predictive models, coastal ocean health observing networks will provide a long-term context for process studies (Pfister et al., 2014), will be a framework for assessing potential adaptation and mitigation strategies, and will keep society, stakeholders, and decision makers abreast of evolving conditions of our coastal oceans, the rich living resources they host, and the essential ecosystem goods and services they provide to coastal communities. Beyond simply gaining scientific understanding of these important and complex ecosystems, a sustained, long-term observing network that will allow regular assessment of coastal ecosystem ocean health and the efficacy of adaptation and mitigation efforts is needed (see Schindler and Hilborn, 2015).

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REFERENCES

Alford, M.H., J.B. Mickett, S. Zhang, P. MacCready, Z. Zhao, and J. Newton. 2012. Internal waves on the Washington continental shelf. *Oceanography* 25(2):66–79, http://dx.doi.org/10.5670/oceanog.2012.43.

Alin, S.R., R.A. Feely, A.G. Dickson, J.M. Hernández-Ayón, L.W. Juranek, M.D. Ohman, and R. Goericke. 2012. Robust empirical relationships for estimating the carbonate system in the southern California Current System and application to CalCOFI hydrographic cruise data (2005–2011). *Journal of Geophysical Research* 117, C05033, http://dx.doi.org/10.1029/2011JC007511.

AMAP. 2013. *AMAP Assessment 2013: Arctic Ocean Acidification*. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, 99 pp.

Aronson, R.B., S. Thatje, J.B. McClintock, and K.A. Hughes. 2011. Anthropogenic impacts on marine ecosystems in Antarctica. *Annals of the New York Academy of Sciences* 1,223:82–107, http://dx.doi.org/10.1111/j.1749-6632.2010.05926.x.

Barton, A., G.G. Waldbusser, R.A. Feely, S.B. Weisberg, J.A. Newton, B. Hales, S. Cudd, B. Eudeline, C.J. Langdon, I. Jefferds, and others. 2015. Impacts of coastal acidification on the Pacific Northwest shellfish industry and adaptation strategies implemented in response. *Oceanography* 28(2):146–159, http://dx.doi.org/10.5670/oceanog.2015.38.

Bednaršek, N., R.A. Feely, J.C.P. Reum, B. Peterson, J. Menkel, S.R. Alin, and B. Hales. 2014. *Limacina helicina* shell dissolution as an indicator of declining habitat suitability owing to ocean acidification in the California Current Ecosystem. *Proceedings of the Royal Society B* 281:20140123, http://dx.doi.org/10.1098/rspb.2014.0123.

Brainard, R.E., C. Birkeland, C.M. Eakin, P. McElhany, M.W. Miller, M. Patterson, and G.A. Piniak. 2012. *Status Review Report of 82 Candidate Coral Species Petitioned Under the U.S. Endangered Species Act*. NOAA Technical Memorandum. NOAA-TM-NMFS-PIFSC-27, Washington, DC, 533 pp.

Brander, L.M., D. Narita, K. Rehdanz, and R.S.J. Tol. 2014. The economic impacts of ocean acidification. Pages 1–18 in *Handbook on the Economics of Ecosystem Services and Biodiversity.* P.A.L.D. Nunes, P. Kumar, and T. Dedeurwaerdere, eds, Edward Elgar Publishing.

Breitburg, D.L., J. Salisbury, J.M. Bernhard, W.-J. Cai, S. Dupont, S.C. Doney, K.J. Kroeker, L.A. Levin, W.C. Long, L.M. Milke, and others. 2015. And on top of all that… Coping with ocean acidification in the midst of many stressors. *Oceanography* 28(2):48–61, http://dx.doi.org/10.5670/oceanog.2015.31.

Bunce, L., P. Townsley, R. Pomeroy, and R. Pollnac. 2000. *Socioeconomic Manual for Coral Reef Management*. Australian Institute of Marine Science, Townsville, Australia, 264 pp.

Byrne, R.H. 2014. Measuring ocean acidification: New technology for a new era of ocean chemistry. *Environmental Science and Technology* 48:5,352–5,360, http://dx.doi.org/10.1021/es405819p.

Cesar, H., L. Burke, and L. Pet-Soede. 2003. *The Economics of Worldwide Coral Reef Degradation.* Cesar Environmental Economics Consulting, Arnhem, The Netherlands.

Constable, A.J., J. Melbourne-Thomas, S.P. Corney, C. Barbraud, D.K.A. Barnes, N.L. Bindoff, P.W. Boyd, A. Brandt, D.P. Costa, A.T. Davidson, and others. 2014. Climate change and Southern Ocean ecosystems: Part I. How changes in physical habitats directly affect marine biota. *Global Change Biology* 20(10):3,004–3,025, http://dx.doi.org/10.1111/gcb.12623.

Curchitser, E.N., and H.P. Batchelder. 2013. Advances in physical, biological, and coupled ocean models during the US GLOBEC program. *Oceanography* 26(4):52–67, http://dx.doi.org/10.5670/oceanog.2013.75.

DeBroyer, C., P. Koubbi, H.J. Griffiths, B. Raymond, C. d'Udekem d'Acoz, A.P. Van de Putte, B. Danis, B. David, S. Grant, J. Gutt, and others, eds. 2014. *Biogeographic Atlas of the Southern Ocean*. Scientific Committee on Antarctic Research, Cambridge.

Duffy, J.E., L.A. Amaral-Zettler, D.G. Fautin, G. Paulay, A. Tatiana, H.M. Sosik, J.J. Stachowicz, and T.A. Rynearson. 2013. Envisioning a marine biodiversity observation network. *BioScience* 63:350–361, http://dx.doi.org/10.1525/bio.2013.63.5.8.

Fabry, V.J., J.B. McClintock, J.T. Mathis, and J.M. Grebmeier. 2009. Ocean acidification at high latitudes: The bellwether. *Oceanography* 22(4):160–171, http://dx.doi.org/10.5670/oceanog.2009.105.

Feely, R.A., S.R. Alin, J. Newton, C.L. Sabine, M. Warner, A. Devol, C. Krembs, and C. Maloy. 2010. The combined effects of ocean acidification, mixing, and respiration on pH and carbonate saturation in an urbanized estuary. *Estuarine, Coastal and Shelf Science* 88:442–449, http://dx.doi.org/10.1016/j.ecss.2010.05.004.

Feely, R.A., S.C. Doney, and S.R. Cooley. 2009. Ocean acidification: Present conditions and future changes in a high-CO_2 world. *Oceanography* 22(4):36–47, http://dx.doi.org/10.5670/oceanog.2009.95.

Feely, R.A., C.L. Sabine, J.M. Hernandez-Ayon, D. Ianson, and B. Hales. 2008. Evidence for upwelling of corrosive "acidified" water onto the continental shelf. *Science* 320:1,490–1,492, http://dx.doi.org/10.1126/science.1155676.

Fisher, R., R.A. O'Leary, S. Low-Choy, K. Mengersen, R.E. Brainard, and M.J. Caley. 2015. Species richness on coral reefs and the pursuit of convergent global estimates. *Current Biology* 4:500–505, http://dx.doi.org/10.1016/j.cub.2014.12.022.

FAO (Food and Agriculture Organization). 2014. *The State of World Fisheries and Aquaculture: Opportunities and Challenges*. Rome, http://www.fao.org/3/a-i3720e.pdf.

Gattuso, J.-P., M. Frankignoulle, and R. Wollast. 1998. Carbon and carbonate metabolism in coastal aquatic ecosystems. *Annual Review of Ecology and Systematics* 29:405–434, http://dx.doi.org/10.1146/annurev.ecolsys.29.1.405.

Gobler, C.J., E.L. DePasquale, A.W. Griffith, and H. Baumann. 2014. Hypoxia and acidification have additive and synergistic negative effects on the growth, survival, and metamorphosis of early life stage bivalves. *PLoS ONE* 9, http://dx.doi.org/10.1371/journal.pone.0083648.

Grantham, B.A., F. Chan, K.J. Nielsen, D.S. Fox, J.A. Barth, A. Huyer, J. Lubchenco, and B.A. Menge. 2004. Upwelling-driven nearshore hypoxia signals ecosystem and oceanographic changes in the northeast Pacific. *Nature* 429:749–754, http://dx.doi.org/10.1038/nature02605.

Grebmeier, J.M. 2012. Shifting patterns of life in the Pacific Arctic and sub-Arctic seas. *Annual Review of Marine Science* 4:63–78, http://dx.doi.org/10.1146/annurev-marine-120710-100926.

Gruber, N., C. Hauri, Z. Lachkar, D. Loher, T.L. Frölicher, and G.K. Plattner. 2012. Rapid progression of ocean acidification in the California Current System. *Science* 337:220–223, http://dx.doi.org/10.1126/science.1216773.

Hauri, C., N. Gruber, A.M.P. McDonnell, and M. Vogt. 2013. The intensity, duration, and severity of low aragonite saturation state events on the California continental shelf. *Geophysical Research Letters* 40:3,424–3,428, http://dx.doi.org/10.1002/grl.50618.

Interagency Working Group on Ocean Acidification. 2014. *Strategic Plan for Federal Research and Monitoring of Ocean Acidification*. Washington, DC, 84 pp., https://www.whitehouse.gov/sites/default/files/microsites/ostp/NSTC/iwg-oa_strategic_plan_march_2014.pdf.

Juranek, L.W., R.A. Feely, W.T. Peterson, S.R. Alin, B. Hales, K. Lee, C.L. Sabine, and J. Peterson. 2009. A novel method for determination of aragonite saturation state on the continental shelf of central Oregon using multi-parameter relationships with hydrographic data. *Geophysical Research Letters* 36, L24601, http://dx.doi.org/10.1029/2009GL040778.

Karl, T.R., V.E. Derr, D.R. Easterling, C.K. Folland, D.J. Hofmann, S. Levitus, N. Nicholls, D.E. Parker, and G.W. Withee. 1995. Critical issues for long-term climate monitoring. *Climatic Change* 31:185–221, http://dx.doi.org/10.1007/BF01095146.

Khatiwala, S., F. Primeau, and T. Hall. 2009. Reconstruction of the history of anthropogenic CO_2 concentrations in the ocean. *Nature* 462:346–349, http://dx.doi.org/10.1038/nature08526.

Knowlton, N., R.E. Brainard, R. Fisher, M. Moews, L. Plaisance, and M.J. Caley. 2010. Coral reef biodiversity. Pp. 65–78 in *Life in the World's Oceans: Diversity, Distribution, Abundance*. Wiley-Blackwell, Oxford, UK.

NMFS (National Marine Fisheries Service). 2014. *Fisheries Economics of the United States 2012.* Economics and Sociocultural Status and Trends Series, NOAA Technical Memorandum, NMFS-F/SPO-137, 183 pp., https://www.st.nmfs.noaa.gov/Assets/economics/documents/feus/2012/FEUS2012.pdf.

Newton, J.A., R.A. Feely, E.B. Jewett, P. Williamson, and J. Mathis. 2014. *Global Ocean Acidification Observing Network: Requirements and Governance Plan*. GOA-ON, 57 pp., http://goa-on.org/docs/GOA-ON_Plan_final_Sept_2014.pdf.

NOAA Ocean Acidification Steering Committee. 2010. *NOAA Ocean and Great Lakes Acidification Research Plan*. NOAA Special Report, National Oceanic and Atmospheric Administration, Washington, DC, 143 pp.

Pfister, C.A. A.J. Esbaugh, C.A. Frieder, H. Baumann, E.E. Bockmon, M.M. White, B.R. Carter, H.M. Benway, C.A. Blanchette, E. Carrington, and others. 2014. Detecting the unexpected: A research framework for ocean acidification. *Environmental Science & Technology* 48:9,982–9,994, http://dx.doi.org/10.1021/es501936p.

Radtke, H.D. 2011. *Washington State Commercial Fishing Industry: Total Economic Contribution*. Prepared by H. Radtke, Natural Resource Economist for Seattle Marine Business Coalition, Yachats, OR, 19 pp.

Schindler, D.E., and R. Hilborn. 2015. Prediction, precaution, and policy under global change: Emphasize robustness, monitoring, and flexibility. *Science* 347:953–954, http://dx.doi.org/10.1126/science.1261824.

Steinacher, M., F. Joos, T.L. Frölicher, G.-K. Plattner, and S.C. Doney. 2008. Imminent ocean acidification in the Arctic projected with the NCAR global coupled carbon cycle-climate model. *Biogeosciences* 6:515–533, http://dx.doi.org/10.5194/bg-6-515-2009.

Trenberth, K.E., T.R. Karl, and T.W. Spence. 2002. The need for a systems approach to climate observation. *Bulletin of the American Meteorological Society* 83:1,593–1,602, http://dx.doi.org/10.1175/BAMS-83-11-1593.

Waldbusser, G.G., B. Hales, C.J. Langdon, B.A. Haley, P. Schrader, E.L. Brunner, M.W. Gray, C.A. Miller, and I. Gimenez. 2014. Saturation-state sensitivity of marine bivalve larvae to ocean acidification. *Nature Climate Change* 5:273–280, http://dx.doi.org/10.1038/NCLIMATE2479.

Wallace, R.B., H. Baumann, J.S. Grear, R.C. Aller, and C.J. Gobler. 2014. Coastal ocean acidification: The other eutrophication problem. *Estuarine, Coastal and Shelf Science* 148:1–13, http://dx.doi.org/10.1016/j.ecss.2014.05.027.

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