5. West Coast Region Acidification Research

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Abstract

The West Coast Region includes the U.S. coastal waters off of Washington, Oregon, and California including the continental shelf and inland seas. These waters are influenced by adjacent regions and are collectively referred to as the California Current Large Marine Ecosystem (CCLME). This region is an eastern boundary current system marked by seasonal upwelling, which brings old, cold, and low-pH, carbon-rich subsurface waters to the ocean surface and drives significant regional pH and temperature variability. The CCLME is home to a highly productive ecosystem yielding economically and culturally significant fisheries including salmon and Dungeness crab. NOAA's West Coast Region research goals are to:

- Sustain and develop time-series that integrate carbonate chemistry and biological observations in habitats that are critical to commercially and ecologically important species, and use this knowledge to improve high-resolution regional models;
- Characterize species sensitivity to direct and indirect impacts of ocean acidification (OA) and evaluate the potential for species adaptation and acclimation; and
- Improve the understanding of the socioeconomic risk and vulnerability of fishing and coastal communities to OA in order to develop informed adaptation strategies.

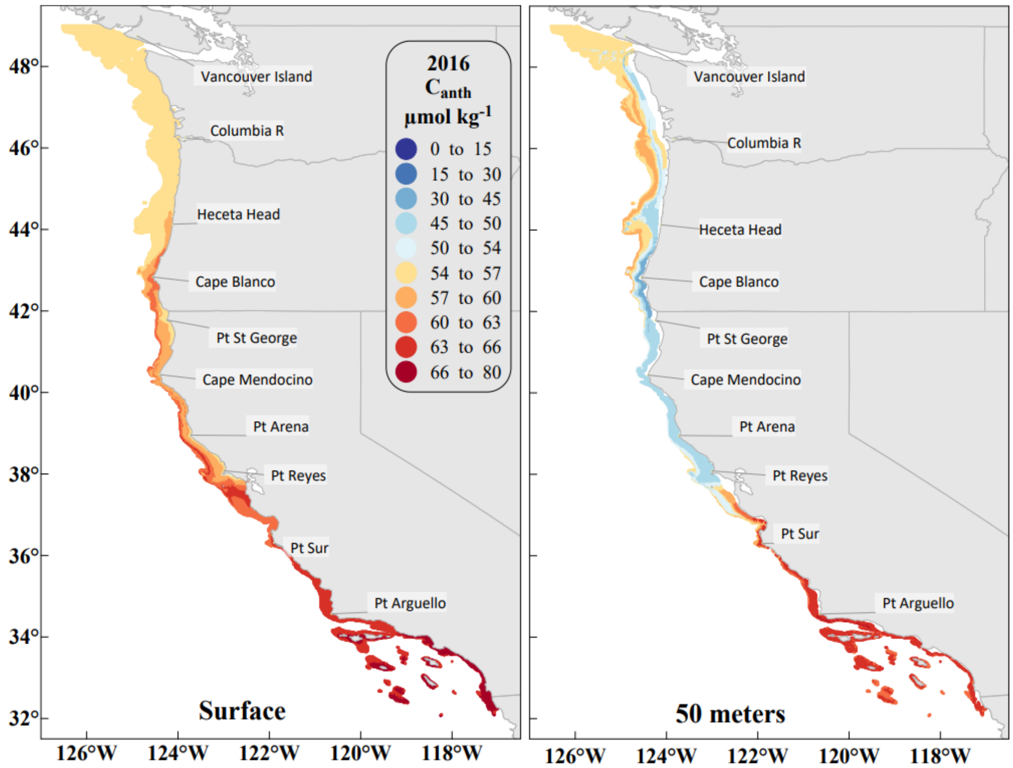


Figure 5.1. Distribution of anthropogenic carbon in surface and 50 m depth ocean waters in May-June 2016 based on the West Coast Ocean Acidification cruise. Credit: NOAA

Acidification in the West Coast Region

The North American Pacific coast from Vancouver Island to Baja California is a classic eastern boundary current upwelling region, termed the California Current Large Marine Ecosystem (CCLME) (Hickey, 1998; Chavez et al., 2017). In the CCLME, natural oceanographic processes combine with nutrient additions in some coastal areas and climate change-induced processes (i.e., enhanced upwelling); together these lead to a more rapid rate of acidification than in many other regions (Rykaczewski & Dunne, 2010; Turi et al., 2016; Carter et al., 2019a). This rapid acidification has raised concerns by people reliant on its productive living marine resources.

Seasonal winds drive a coastal upwelling circulation characterized by equatorward flow in the CCLME, with coastal jets, associated eddies, and fronts that extend offshore, particularly in the central CCLME. Climate-driven alterations in upwelling circulation result in changes in coastal acidification and spatial gradients in anthropogenic carbon (greater surface accumulation in the south than the north due to the fact that the upwelled waters more prevalent in the north do not reflect current atmospheric carbon dioxide (CO_2) concentrations, **Figure 5.1**; deeper penetration in the north), particularly with recently intensified coastal winds (Feely et al., 2016, 2018; García-Reyes et al., 2015; Jacox et al., 2014; Rykaczewski et al., 2015; Sydeman et al., 2014). Upwelling supplies deep water to the shelf, which is rich in dissolved inorganic carbon and nutrients, but oxygen-poor. OA and hypoxia are stressors that are often found together because low-oxygen and high-CO_2 conditions both result from microbial respiration of organic matter (Chan et al., 2017; Feely et al., 2016, 2018). Models project that 50% of shelf waters in the central CCLME will experience year-long undersaturation by 2050 (Gruber et al., 2012; Hauri et al., 2013; Turi et al., 2016). In addition to upwelling stress, the northern CCLME experiences strong freshwater influences, associated with large outflows from the Columbia and Fraser rivers, as well as numerous smaller mountainous rivers with more episodic discharge. This riverine input leads to both lower buffering capacity and nutrient loading in local waters.

Knowledge of marine species' OA sensitivities has substantially increased since the early recognition of the role of changing seawater carbonate chemistry in oyster hatchery production problems in the Pacific Northwest (Barton et al., 2012, 2015). Laboratory work has revealed that some West Coast species including Dungeness crabs (Miller et al., 2016), Coho salmon (Williams et al., 2019), krill (McLaskey et al., 2016), and pteropods (Busch et al., 2014) are sensitive to OA conditions. Field evidence on Dungeness crabs, pteropods, foraminifera, and copepods, important prey in food webs for finfish including salmon, supports these conclusions (Bednaršek et al., 2014, 2016, 2017a,b, 2018, 2019, 2020; Bednaršek & Ohman, 2015; Feely et al., 2016; Osborne et al., 2016, 2019; Engström-Öst et al., 2019; **Figure 5.2**). West Coast-focused meta-analyses and synthesis work suggest that sensitivity research on a broader range of species and ways to infer both sensitivity among related species and species risk are needed to effectively project OA impacts on marine ecosystems (Busch & McElhany, 2016, 2017; Davis et al., 2017; Hodgson et al., 2016; Jones et al., 2018; Bednaršek et al., 2019).

The West Coast has many ecologically, economically, and culturally significant species with important life stages that inhabit depths below the productive, sunlit surface. While the surface ocean contains the highest anthropogenic CO_2 concentration from air-sea exchange processes, the subsurface environment is subject to considerably greater stress due to the combined effects of natural and anthropogenic CO_2 sources (**Figure 5.1**; Feely et al., 2008, 2010, 2012, 2016, 2018; Bednaršek et al., 2014; Siedlecki et al., 2016). Many regionally important species, like Dungeness crab, which generated $3.6 billion in commercial landings from 1950 to 2017, occupy a variety of habitats throughout their life cycles from the coast to the shelf and from benthic to surface waters. There are five National Marine Sanctuaries and numerous Essential Fish Habitats along the West Coast, which protect water quality and benthic habitats and fishes. Better characterization of pelagic and benthic habitat conditions across these continental shelf habitats is critical to inform fisheries and sanctuaries managers about OA exposure.

Output from OA scenarios in ecosystem models of the West Coast suggests more resilience to OA than might be inferred from sensitivity studies, although notable potential impacts are projected for Dungeness crab and the human communities economically and culturally dependent on its fishery (Ainsworth

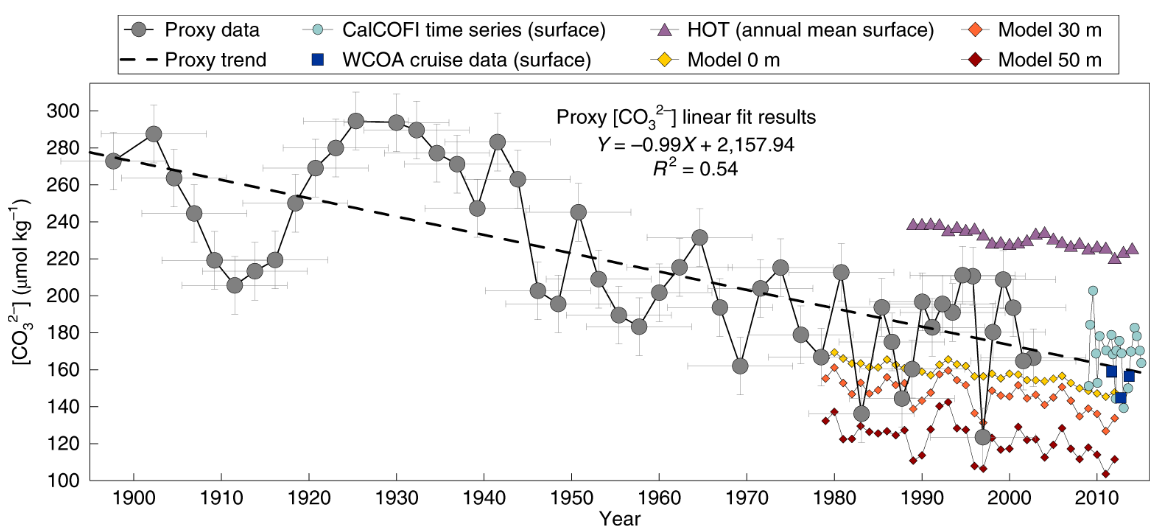


Figure 5.2. A twentieth-century proxy reconstruction of carbonate ion concentration ($[CO_3^{2-}]$) for the California Current Ecosystem (Santa Barbara Basin, CA). Proxy $[CO_3^{2-}]$ values are based on fossil planktonic foraminifera shell thickness and reveal an estimated 35% decrease in $[CO_3^{2-}]$ over the 20th century. The proxy-based $[CO_3^{2-}]$ compared to available *in situ* surface measurements and published hindcast biogeochemical model simulations and are in excellent agreement with the forward-projected trend, even if datasets do not temporally overlap. Modified from Osborne et al. (2019)

et al., 2011; Busch et al., 2013, 2014; Marshall et al., 2017; Hodgson et al., 2018). Increasingly, consideration of OA together with other stressors that co-occur with it in the region, such as hypoxia and warming, is seen as crucial for characterizing and understanding OA's influence on living marine resources in a way that is ecologically relevant to the CCLME (Bednaršek et al., 2018, 2019, 2020; Trigg et al., 2019; Reum et al., 2014, 2016).

Environmental Change in the West Coast Region

Since the publication of the 2010 NOAA Ocean, Coastal, and Great Lakes Acidification Research Plan, NOAA has supported a range of OA observations and monitoring efforts on existing and NOAA-developed platforms, which include moorings, cruises, ships of opportunity, gliders, and new autonomous platforms (**Figure 5.3**). Research cruises provide the highest quality physical and chemical measurements, particularly for subsurface observations, and yield both good estimates of cumulative OA exposure and anthropogenic CO_2 content; thus, cruises, including both coastal and open ocean repeat-hydrography cruises (GO-SHIP, Sloyan et al., 2019a), remain a strong research priority for OA (Carter et al., 2019a).

A researcher using an experimental system to study acidification impacts on marine species in the NOAA Mukilteo Research Station in Washington. Credit: Benjamin Drummond/bdsjs.com

On the other hand, sensors on time-series moorings or autonomous platforms can provide observations with high spatial and/or temporal resolution that capture the full range of carbonate chemistry variability (Carter et al., 2019b). Some sensors are mature and in regular use (e.g., Sutton et al., 2014a; Wanninkhof et al., 2019), while important work continues on improving and evaluating newer *in situ* sensors with respect to accuracy, precision, and data-processing methods for operational deployments (e.g., Bresnahan et al., 2014; Williams et al., 2017; Riser et al., 2018).

NOAA and academic scientists have partnered with shellfish growers on the West Coast to monitor OA conditions at hatcheries and grow-out sites via shore-based inorganic carbon systems and sensors in development, with real-time data accessibility (Barton et al., 2012, 2015). This has led to our ability to understand OA dynamics along a gradient from nearshore to offshore (Alin et al., 2015). West Coast environments experience a large range of marine environmental conditions over both space and time with respect to carbonate chemistry and benefit from excellent access to laboratory and ship facilities. Through partnership with the U.S. IOOS regional associations (NANOOS, CeNCOOS, and SCCOOS), OA sensors deployed on existing IOOS assets have increased West Coast observation capability substantially. National Ecosystem Research Reserves measure pH in estuaries throughout the region. In addition, National Marine Sanctuaries and areas designated as Essential Fish Habitat by NMFS provide key testbeds for ongoing assessment of the consistency, uncertainty, and reliability of new platforms and sensors, particularly those that provide insight into critical subsurface habitats and conditions. For instance, the benthic nearshore time-series observations from the Olympic Coast National Marine Sanctuary have been used with empirical relationships to calculate OA variables. Collectively, these nearshore observations show much more dynamic conditions than offshore, though seasonal upwelling is still the dominant signal. Nearshore data streams are critical for understanding impacts on coastal species and can benefit from partner platforms such as aquariums, industry, and other shoreside facilities with marine resource interests.

Economically, ecologically, and culturally important West Coast species such as Dungeness crab, geoduck, other harvested bivalves, salmon, and groundfish use a variety of different habitats throughout

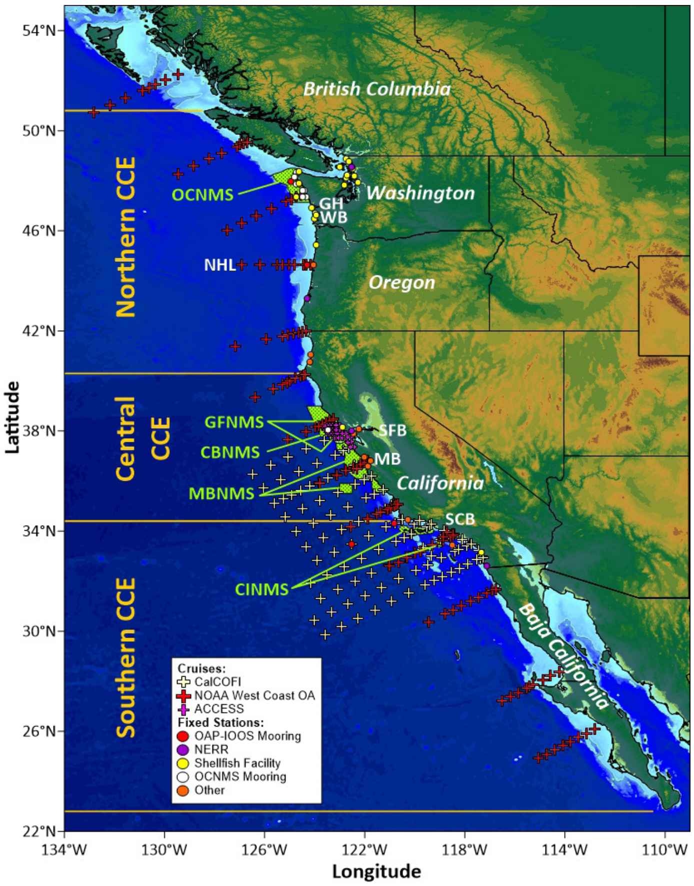


Figure 5.3. Map of the California Current Large Marine Ecosystem (CCLME) with National Marine Sanctuary boundaries (lime green) and long-term North American Pacific coast, NOAA-supported OA sampling platforms, as indicated in the legend. Abbreviations include: OCNMS = Olympic Coast National Marine Sanctuary, GH = Gray's Harbor, WB = Willapa Bay, NHL = Newport Hydrographic Line, OAP-IOOS = NOAA Ocean Acidification Program – Integrated Ocean Observing System, NERR = National Estuarine Research Reserve, GFNMS = Gulf of the Farallones National Marine Sanctuary, CBNMS = Cordell Bank National Marine Sanctuary, MBNMS = Monterey Bay National Marine Sanctuary, SFB = San Francisco Bay, MB = Monterey Bay, CINMS = Channel Islands National Marine Sanctuary, SCB = Southern California Bight. Credit: Dana Greeley/ NOAA

the water column and from the shoreline to the shelf-break, making OA monitoring in a diversity of habitats critical for fulfilling NOAA's OA-monitoring -related responsibilities. Different species are sensitive to different aspects of the carbonate system (i.e., pCO_2, pH, aragonite or calcite saturation; i.e., Waldbusser et al., 2015); thus, full delineation of the carbonate system is important at all locations. Such measurements have enabled shellfish growers to adjust culturing practices successfully (Barton et al., 2015). Characterizing the multiple aspects of change in the ocean environment, including increasing anthropogenic CO_2 concentrations, decreasing oxygen, warming, and changing nutrient availability, is required to tease out which changes drive marine ecosystem response (Feely et al., 2016, 2018; Pacella et al., 2018; Evans et al., 2019). Integrating physical and chemical time-series with time-series of species and ecosystem indicators is a priority for oceanographic research globally (Sloyan et al., 2019b) and for the West Coast specifically. In this region, the unusual environmental conditions that have occurred over the past decade have caused unprecedented harmful algal blooms (HABs) and mass mortality events of sea stars, seabirds, and kelp (Miner et al., 2018; Gibble et al., 2018; Harvell et al., 2019; Hohman et al., 2019). Some West Coast sanctuaries and regions, such as the Southern California Bight, have developed climate action plans, identified indicator species and habitats, and detailed monitoring strategies (Duncan et al., 2014; Hutto, 2016).

To provide decision support at relevant timescales for managers of West Coast species and protected areas, improved models are needed that provide skillful estimates of environmental conditions at daily to decadal timescales and beyond. Predictability of these model systems depends on the right resolution for habitats of interest, resolving processes with the appropriate skill and understanding, and predicting processes on the correct timescale. This underscores the need to sustain OA observations across spatial gradients from nearshore to offshore, in order to verify and provide input to models. On-going model development and evaluation are needed to improve parameterizations of important processes in simulations, including short-term and seasonal forecasts. Mechanisms driving predictability of carbon variables on various timescales require further investigation, especially on decadal timescales (Turi et al. 2016; Li & Ilyina, 2018; Li et al., 2019), to provide better forecasts and predictions. These mechanisms will require a more complete understanding of the processes responsible for communication across interfaces on these timescales within the upwelling regime – between the CCLME and the North Pacific Gyre, the shelf and offshore, and the estuaries and the shelf. These processes contribute to amplification of the OA signal within this system, but the degree to which they contribute inter-annual to decadal variability is not well constrained at present. West Coast models now are skillful enough that they can attribute coastal and estuarine acidification to the relevant driver, be it inputs from air-sea exchange, and/or nutrient inputs (e.g., Puget Sound, San Francisco Bay, southern California), rivers (Washington to northern California), changing ocean circulation (e.g., upwelling), and/or biological process rates (e.g., Halle & Largier, 2011). Live Ocean and J-SCOPE, two newer modeling systems in the Pacific Northwest, now provide forecasts and projections of ocean conditions relevant for marine resources, such as sardine and Dungeness Crab (Kaplan et al., 2016; Siedlecki et al., 2016). Other decision points that model simulations can support include timing of fishery openings relative to forecasted OA or hypoxia conditions and field out-planting of shellfish within optimal temperature and carbonate chemistry windows.

Research Objective 5.1: Improve characterization of OA parameters in subsurface environments that are critical habitats to commercially and ecologically important species

Better characterization of surface and subsurface carbonate chemistry conditions will improve understanding of the risk of species and ecosystems to OA and parameterization of models used to hindcast, describe current, and forecast conditions.

Action 5.1.1: Ensure that conditions and rates of environmental change of OA and interacting stressors—particularly temperature, carbon chemistry, oxygen, nutrients, and HABs—are assessed via co-located observations in critical habitats for key species at vulnerable life stages, as well as for their food resources.

Action 5.1.2: Enhance moorings and profiling platforms to include additional chemical and biological sensors for subsurface waters to delineate rates of change of critical parameters.

Action 5.1.3: Continue to quantify anthropogenic CO_2 concentrations through coastal and open ocean cruises, which collect the data needed to attribute carbonate chemistry change to anthropogenic acidification versus contributions from other processes.

Action 5.1.4: Provide measured and calculated OA products necessary for validation of underlying physical and biogeochemical processes in coupled physical-biogeochemical coastal models of acidification and model output.

Research Objective 5.2: Enhance understanding of the relationships between biological systems and chemical conditions, including effective indicators of change for various habitats

Tracking biological response to OA, other long-term secular ocean changes, unusual environmental events including marine heatwaves, HABs, and mass mortality events underlies the reason for developing integrated monitoring efforts, which can help tease out environmental drivers and identify cause and effect of unusual events.

Action 5.2.1: Incorporate biological observations into physical and chemical time-series (e.g., research cruises, long-term monitoring at sentinel sites such as National Marine Sanctuaries, shellfish hatcheries, underway sampling on ships, autonomous platforms).

Action 5.2.2: Develop procedures to utilize pteropods and other species as West Coast-specific indicators of species and ecosystem status and change across different habitats.

Research Objective 5.3: Advance analytical tools that can better describe ocean conditions in the past, present, and future

Model development is critical to providing skillful estimates of environmental conditions at daily to decadal timescales and beyond and at spatial scales that vary from regional to local. Development of past-to-future, high-resolution West Coast ocean models should continue in order to provide decision support at relevant timescales for managers of West Coast sanctuaries, Essential Fish Habitat, deep-sea coral and sponge habitats, and shellfish and finfish species.

Action 5.3.1: Develop models that can be validated, parameterized, and evaluated by observational data (e.g., moored time-series, nearshore stations) and that include chemical and biological rates key for understanding the progression of OA.

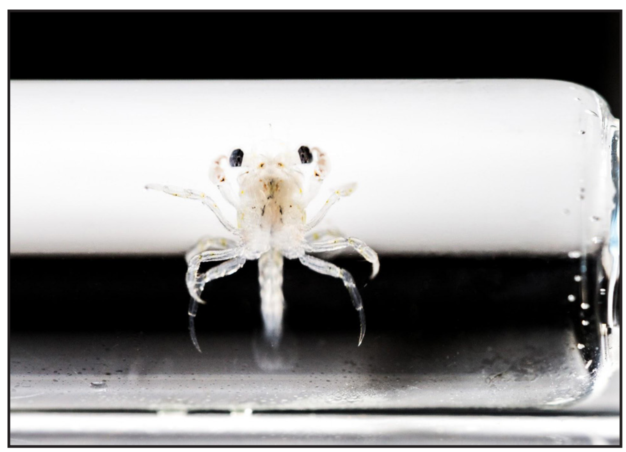
Action 5.3.2: Develop short-term and seasonal forecasts and synthesis products that can support annual industry, tribal, and management decision points and decadal predictions that support planning, policy, and adaptation among West Coast states, tribes, and stakeholders.

Action 5.3.3: Better utilize West Coast satellite observations and satellite-derived products to complement and provide independent estimates of spatially resolved current and upcoming ocean conditions from surface to benthic habitats.

Biological Sensitivity in the West Coast Region

West Coast ecosystems are highly productive and have economic and cultural value. The marine heatwave and El Niño events of 2014-2016 indicated how sensitive West Coast ecosystems and their marine resources are to the kinds of environmental conditions that are expected to become more frequent and intense in the future. The goal of this work is to project long-term ecological effects of OA to better understand the consequences of carbon emissions, provide managers the information needed to anticipate changes in marine resources, and inform potential mitigation and adaptation options.

Studies that identify the sensitivities of ecologically and socioeconomically important species yield information useful for management of wild capture fisheries, ecosystems, and aquaculture now and in the future. Species sensitivity studies can be designed to build understanding of physiological mechanisms that underlie species' responses to OA; help characterize species vulnerability; and estimate OA risks to people and community well-being. Such information underpins modeling efforts that aim to project species response to OA progression and is important for extrapolating patterns of sensitivity in species not subject to experimentation or observation. Targeted output from experiments should include functional relationships 1) across a range of pH, pCO_2, or aragonite or calcite saturation state values, which can be used to identify response thresholds, and 2) with co-occurring environmental stressors projected to change with climate change, including temperature, oxygen concentration, and salinity. The experimental facilities at the Northwest Fisheries Science Center (NWFSC) have built in a multi-stressor (OA, dissolved oxygen, and temperature) and diurnal variability approach, and the new Mukilteo facility now under design will improve on those capabilities.



Dungeness crab megalops, a larval stage. Credit: Benjamin Drummond/bdsjs.com

The West Coast is exposed to variability in carbonate chemistry conditions over both space and time and can be used as a natural laboratory. Recently, OA events have co-occurred with marine heatwaves, hypoxic events, and HABs, exposing organisms to interactive effects of multiple stressors. Collection and analysis of field samples having defined chemical exposures, or conducting novel *in situ* experiments can inform understanding of the implications of OA under field conditions, with duration of exposure under acidified conditions longer than can usually be accomplished in the lab. In addition, experimentally derived thresholds related to species sensitivity can be tested in the field to improve the interpretation of species vulnerability in coastal environments.

To date, we have not yet been able to directly attribute population changes from existing time-series to OA, potentially due to the lack of available paired chemical and biological measurements (McElhany, 2016). However, physiological and organismal responses in field samples correlate with anthropogenic CO_2 content (Bednaršek et al., 2014, 2017a, 2020; Feely et al., 2016). As OA and co-stressors progressively increase, species tolerance thresholds will continue to be crossed, which will precipitate ecological change. Biological time-series collections, sample preservation and archival, and analyses are needed now to enable the detection and attribution of change; on-going West Coast time-series should be maintained, enhanced, and examined. Monitoring should focus on 'indicator species', selected by careful consideration of carbonate chemistry sensitivity, cost of observation, availability of existing data, likely changes in habitat conditions, ecological or economic importance, etc. Two candidate indicator taxa include foraminifera and pteropods, the latter of which is already used as indicator of OA in the Puget Sound and Southern California Bight regions.

A potential tool for defining how the natural environment may be becoming stressful to marine life is to develop habitat suitability indices (HSIs), which provide depth- and time-integrated metrics of species exposure to challenging environmental conditions, ideally based on rigorous laboratory experiments. These HSIs use sensitivity information developed in combination with the modeling efforts to give managers advance information about the likely condition or survival of marine species. It is critical to develop integrated ecosystem metrics like HSIs in partnership with states, tribes, industry, and other organizations to reflect environmental exposure of key species to multiple stressors relevant to forecast and decision-maker timescales. HSIs also provide valuable information for food web and ecosystem modeling (*Action 5.6.2*) and help guide efforts to detect biological effects of OA in the field (*Action 5.6.3*). HSI metrics need to be testable with observations and connected to monitoring activities. HSIs do not, in themselves, translate into species impact but rather serve as an indication of potential exposure.

Research Objective 5.4: Understand species sensitivity to OA and characterize underlying mechanisms

Species sensitivity studies yield information that underpins our understanding of the potential impacts of OA on human and natural systems.

Action 5.4.1: Conduct laboratory sensitivity studies on species harvested in federal, state, and tribal fisheries along the West Coast and the prey species that support them.

Action 5.4.2: Develop and implement methods to generate data on the mechanisms driving species sensitivity, including acid-base balance, 'omics approaches, and neural and behavioral functioning to elucidate sub-lethal effects of OA conditions and possible adaptation.

Action 5.4.3: Assess how knowledge of sensitivity based on laboratory studies translates to expressions of sensitivity to different carbonate chemistry conditions and multiple stressors in the field.

Research Objective 5.5: Investigate the potential for species to acclimate and/or adapt to OA

Studies that target information on species acclimation and acclimatization (i.e., recovery of function by individuals with prolonged exposure) or adaptation (i.e., genetic and epigenetic changes within a population or across populations) make possible long-term predictions for key ecologically and socioeconomically important species.

Action 5.5.1: Conduct multi-generational, complete life-cycle laboratory studies to characterize sensitivity to OA.

Action 5.5.2: Assess how OA sensitivity varies within and among individuals, strains, and populations of a species in field and aquaculture studies to improve understanding of intra- and inter-specific variance, which has enormous implications for understanding how to manage marine resources for OA

Action 5.5.3: Employ molecular techniques to better understand the influence of OA on individuals and populations.

Research Objective 5.6: Enable the detection and attribution of direct and indirect impacts of OA on managed species and ecosystems

While evidence from laboratory experiments indicates that many marine species are sensitive to OA conditions, limited understanding of how this sensitivity will influence populations or their distributions in the wild or alter food webs and ecosystems creates a critical gap in current research efforts and for sound resource management under changing ocean conditions.

Action 5.6.1: Develop Habitat Suitability Indices, which provide depth- and time-integrated metrics of species exposure to challenging environmental conditions and can be integrated into forecasts and predictions.

Action 5.6.2: Model species, food web, and ecosystem responses to OA to understand the consequences of OA and the success of management strategies for sustainable harvests and conservation. Intensive numerical models can join data and tools from various scientific disciplines in ways that conceptual models cannot.

Action 5.6.3: Conduct biological monitoring and data analysis at robust enough levels to detect species or ecosystem change attributable to OA, and specifically to anthropogenic carbon uptake.

Human Dimensions in the West Coast Region

The ocean, coasts, and estuaries of the CCLME hold vast economic, social, and cultural importance for more than 1,100 coastal and fishing communities, including tribes and indigenous communities, and other diverse populations in rural, suburban, and urban areas. Through fisheries landings data, and other data sources such as the U.S. Census, NOAA has developed some knowledge about commercial and recreational fishing activities, reliance on fishing and aquaculture, and other social and economic conditions linking people to marine systems (Harvey et al., 2018; ONMS, 2019).

Dungeness crab support an economically important West Coast fishery. Laboratory, field, and modeling studies suggest Dungeness crabs are negatively affected by acidified conditions. Credit: Benjamin Drummond/bdsjs.com

However, while it is generally acknowledged that healthy and productive marine ecosystems support human communities, the mechanisms that link marine species and habitats with the full array of human dimensions (e.g., livelihoods, nutritional needs, cultural heritage, and recreation benefits for coastal populations) are not well understood (Breslow et al., 2016; Kittinger et al., 2012). In addition, critical gaps exist in the quality, frequency, topical, and geographic breadth of available information. Underdeveloped conceptual models describing the relationships between various fishing and coastal communities and marine ecosystems, as well as the lack of sufficient and appropriate data to assess socioeconomic changes, create challenges to evaluating OA vulnerability of people in different places who have varied dependence on marine systems. Hence, to support decision-making at local to regional scales throughout the West Coast, there is a need to synthesize and collect new socioeconomic data in order to develop models and other tools that may be used to estimate the socioeconomic impacts of OA in the region. Improved understanding of OA risks to sociocultural and economic well-being of fishing and coastal communities are priorities for NOAA social science on the West Coast (NOAA Fisheries, 2016, 2019a).

Improved knowledge of the vulnerabilities of socioeconomic well-being to OA, and how these vary across populations, is critical to understand and develop strategies for mitigation and adaptation. A science-based framework to support planning, policy, and responses to OA by West Coast states, tribes, and stakeholders requires deeper knowledge of adaptive capacity. For example, how do community and fisheries characteristics (e.g., labor dynamics, social services, vessel mobility, species allocations, etc.) and perceptions of OA risks shape their response strategies? Research in support of adaptation depends on information about institutional structures and policy contexts (e.g., port infrastructure and fisheries permitting systems) that either help fisheries or communities perform well in the face of change or create barriers and challenges to their adaptation. Such focus on institutional and policy contexts creates the foundation for simulating scenarios and identifying alternative management actions, including those actions expected to generate benefits to communities and increase their adaptive capacity (Aguilera et al., 2015; Evans et al., 2013). Providing decision-relevant information to managers and industry, including developing technical tools for evaluating the socioeconomic consequences of potential management actions related to OA, is critical to effective management (**Figure 5.4**). In many cases, actions taken in response to OA will create synergistic benefits for a multitude of changes facing communities. The West Coast constitutes a dynamic social-ecological system with multiple and cumulative stressors arising from changes in the ocean such as temperature, OA, hypoxia, and HABs coupled with disruptions in conditions of fishing and coastal communities such as market prices, fishing access, labor shortages, and demographic changes (Bennett et al., 2016). More comprehensive and foundational human dimensions research can help decision-makers evaluate multiple objectives and outcomes (e.g., ecological, social, and economic benefits) and model future projections and uncertainties of the social-ecological impacts of ocean change in order to maintain thriving coastal communities and economies.

Research Objective 5.7: Improve understanding of the risks to social, cultural, and economic well-being of fishing and coastal communities that are dependent on OA-sensitive species, and the associated social and economic drivers of OA vulnerability

Human vulnerability to OA can be direct or indirect through impacts to important species and ecosystems, and compounded by other (non-OA) social and ecological stressors that human communities may face. Communities and decision-makers require better information about social-ecological relationships and mechanisms of impact in order to anticipate and understand OA risks to people.

Action 5.7.1: Collect new information (e.g., through the use of surveys and interviews) and synthesize existing information (e.g., commercial and recreational fisheries data, fishing community profiles, and traditional and local knowledge) to better characterize the interactions of humans and environments and the importance of OA-sensitive species and ecosystems to people across scales.

Action 5.7.2: Develop new OA-relevant social-ecological conceptual models and use these coupled models to estimate the risks to humans and community well-being (e.g., cultural, livelihood, and health) and the distribution of risks across sectors and social and demographic factors.

Action 5.7.3: Improve models to 1) provide necessary decision support for estimating income and employment impacts of OA on commercial fisheries, aquaculture, and coastal tourism and 2) relate the economic value of recreational crab and other shellfish harvesting to estimated changes in biomass.

Action 5.7.4: Examine the synergistic, antagonistic, and cascading effects of multiple and cumulative stressors on human vulnerability to address critical gaps in our knowledge of how OA-impacts interact with other environmental and socioeconomic stressors that communities must contend with.

Research Objective 5.8: Improve understanding and communication of adaptation strategies of fishing and coastal communities

Improved knowledge and communication of how communities can reduce vulnerability, including the barriers and capacities for coping with and adapting to OA and cumulative stressors, are critical to developing policies, tools, and strategies for mitigating socioeconomic risks (*Objective 5.7*) and identifying management actions that may result in more resilient communities.

Action 5.8.1: Develop information about adaptive capacity, and specifically evaluate institutional structures and policy contexts that either help or hinder fisheries and communities in the face of change.

Action 5.8.2: Identify alternative management actions to improve resilience of communities and ecosystems under OA conditions, for example by identifying resource management actions that generate indirect and co-benefit flows to communities, reflect community priorities, and reduce potential negative consequences from management decisions to communities.

Action 5.8.3: Provide decision-relevant information to managers and industry, including developing technical tools for simulating scenarios and evaluating the socioeconomic tradeoffs of potential management actions related to OA.

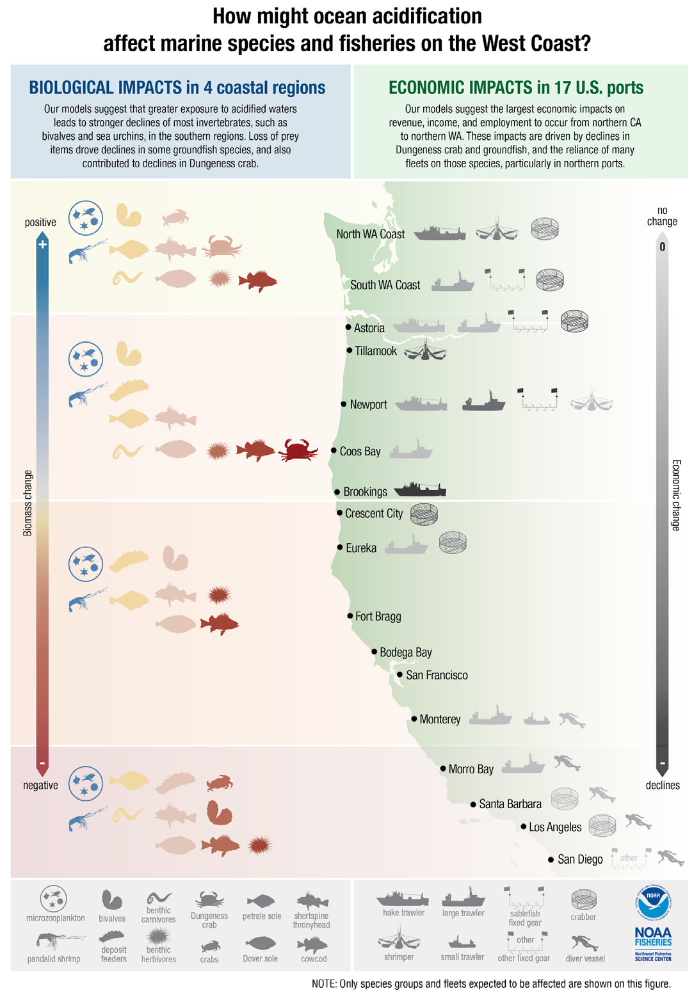


Figure 5.4. Infographic of model output on how OA could influence West Coast species and the economies of communities that participate in fisheries harvest. The infographic is based on work presented in Busch & McElhany (2016), Marshall et al. (2017), and Hodgson et al. (2018). Credit: Su Kim/NOAA

References

[INTRO] = Introduction;

[NAT] = National Ocean & Great Lakes;

[OO] = Open Ocean Region;

[AK] = Alaska Region;

[ARC] = Arctic Region;

[WC] = West Coast Region;

[PAC] = U.S. Pacific Islands Region;

[SAG] = Southeast Atlantic & Gulf of Mexico Region;

[FLC] = Florida Keys and Caribbean Region;

[MAB] = Mid-Atlantic Bight Region;

[NE] = New England Region;

[GL] = Great Lakes Region

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