2. Open Ocean Region Acidification Research

Richard A. Feely[1], Simone Alin[1], Brendan Carter[2], John P. Dunne[3], Dwight K. Gledhill[4], Liqing Jiang[5], Veronica Lance[5], Carol Stepien[1], Adrienne Sutton[1], and Rik Wanninkhof[6]

[1]NOAA/OAR, Pacific Marine Environmental Laboratory, NOAA, Seattle, WA

[2]NOAA/OAR, Cooperative Institute for Climate, Ocean, and Ecosystem Studies, University of Washington, Seattle, WA

[3]NOAA/OAR, Geophysical Fluid Dynamics Laboratory, NOAA, Princeton, NJ

[4]NOAA/OAR, Ocean Acidification Program, NOAA, Silver Spring, MD

[5]NOAA/NESDIS, CoastWatch/OceanWatch/PolarWatch Program, NOAA, College Park, MD

[6]NOAA/OAR, Atlantic Oceanographic and Meteorological Laboratory, NOAA, Miami, FL

Technical Contributors: Nina Bednaršek[1], Maria Kavanaugh[2], Jan Newton[3], Joseph Salisbury[4], Samantha Siedlecki[5]

[1]Southern California Coastal Water Research Project, Costa Mesa, CA

[2]College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, OR

[3]NANOOS, Applied Physics Laboratory, University of Washington, Seattle, WA

[4]School of Marine Science and Ocean Engineering, University of New Hampshire, Durham, NH

[5]Department of Marine Sciences, University of Connecticut, Groton, CT

Abstract

The primary goals of the open ocean research plan are to determine how anthropogenic carbon and pH changes interact with natural variability to collectively act on ocean carbonate chemistry and biology, and to continue to support and enhance the NOAA contribution to the Global Ocean Acidification Observing Network (GOA-ON) with new sensors, autonomous platforms, and biological measurements to be co-located with the physical and chemical studies. The observations will be utilized to validate models and calibrate satellite data synthesis products. Global maps and data synthesis products will be developed to provide information for national and international policy and adaptive actions, food security, fisheries and aquaculture practices, protection of coral reefs, shore protection, cultural identity, and tourism. The Open Ocean Region's research goals are to:

- Maintain existing observations and continue developing and deploying autonomous vehicles and biogeochemical (BGC) Argo floats to measure surface and water column carbon parameters, nutrients, and other Essential Ocean Variables (EOVs);
- Conduct biological sampling (e.g., Bongo net tows) during GO-SHIP cruises to determine the biological impacts of OA and other stressors on planktonic communities;

- Develop data management systems and synthesis products including visualizations of key chemical and biological parameters to quantify anthropogenic carbon dioxide (CO_2) buildup, rates of change of global ocean OA conditions, and biological rate processes; and
- Support data synthesis activities to provide validation of biogeochemical models.

Ocean Acidification in the Open Ocean Region

This chapter evaluates how anthropogenic changes and natural variability collectively act on ocean carbonate chemistry and determine the vulnerability to future ocean acidification (OA) conditions within the open ocean regions in deep waters beyond the continental shelf. Natural carbonate chemistry variability results from the combined actions and interactions among many different processes (e.g., air-sea exchange, circulation and transport, upwelling, production, remineralization, carbonate mineral dissolution, etc.). OA is an anthropogenic process, rooted in natural seawater carbonate chemistry, but is also influenced by regional and temporal variations and processes. Natural variability in carbonate chemistry is compounded by OA changes that have the capacity to create particularly extreme conditions in some regions of the global ocean. For example, high latitudes are particularly vulnerable to decreasing aragonite state conditions because of the combined effects of the anthropogenic CO_2 input, low temperature, and lower buffer capacity (Hauri et al., 2015; Zhang et al., 2020).

Models indicate that with continued atmospheric CO_2 absorption, the ocean is likely to undergo rapid changes in calcium carbonate saturation state, affecting calcifying organisms and leading to large-scale ecological and socioeconomic impacts (Feely et al., 2009; Orr et al., 2005; Steinacher et al., 2009;

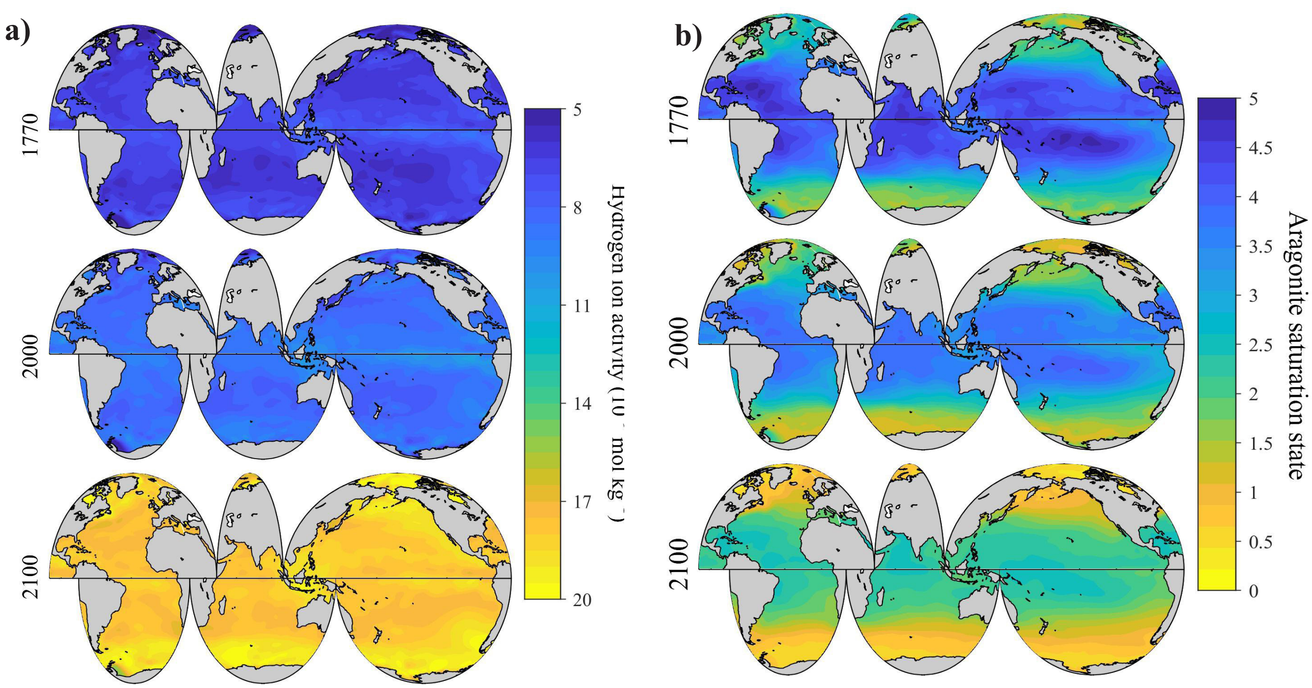


Figure 2.1. Model output of past, present, and future: a) hydrogen ion activity changes and b) aragonite saturation state based on global surface ocean pCO_2 observations normalized to the year 2000. The hydrogen ion activity distributions for 1770 and 2100 are reconstructed by extracting the temporal changes of pCO_2 and SST at individual locations of the global ocean from the Geophysical Fluid Dynamics Laboratory (GFDL)'s ESM2M Model and converting the data to hydrogen ion activity using CO2SYS. This provides a regionally varying view of the historical and future surface ocean H^+ simulations given by the Intergovernmental Panel on Climate Change (IPCC) Assessment Report (AR5) for the Representative Concentration Pathway 8.5 scenario (adapted from Jiang et al., 2019).

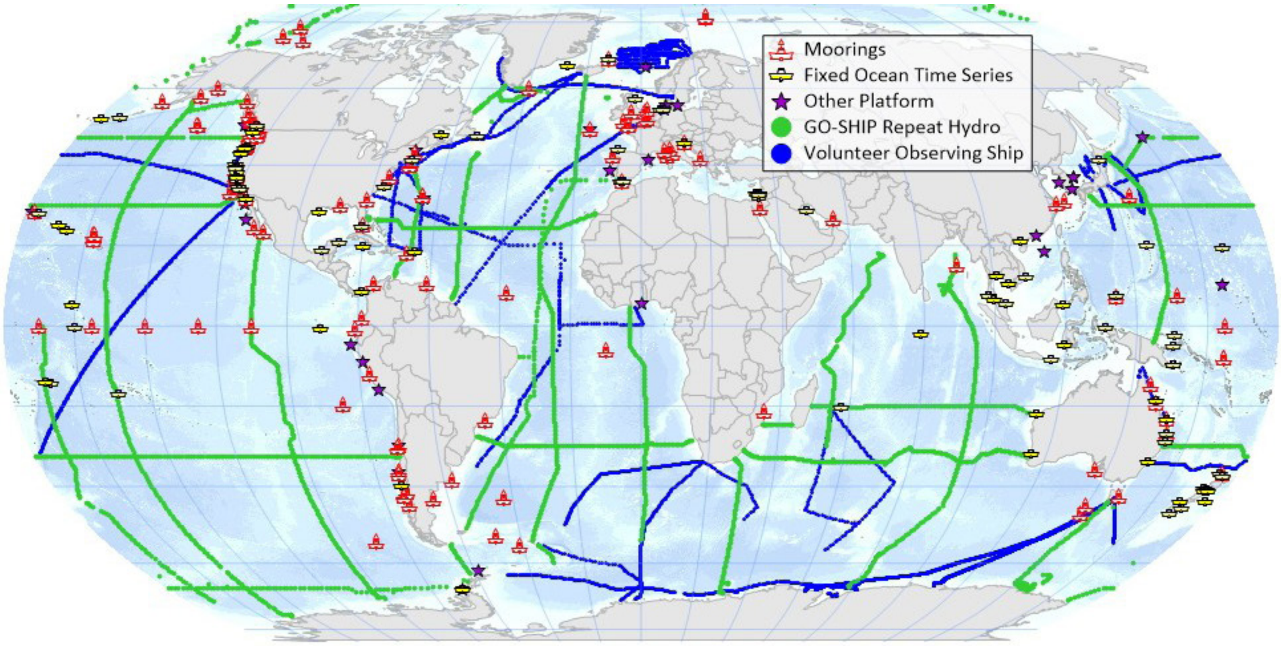


Figure 2.2. Present-day Global Ocean Acidification Observing Network, which is collaborative with the Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP) surveys, the Surface Ocean CO_2 Observing NETwork (SOCONET), the Ship of Opportunity Program (SOOP) volunteer observing ships, and the Ocean Sustained Interdisciplinary Time-series Environment observation System (OceanSITES) , and other open ocean and coastal observing networks (after Tilbrook et al., 2019).

Gattuso et al., 2015; see also Chapter 6; **Figure 2.1**). Quantifying the relative magnitude of natural variations provides useful context for determining the tolerance levels of organisms, which evolved before the influence of human-caused CO_2 emissions. The most important indicators for OA are pH (-log $a(H^+)$), pCO_2, carbonate ion concentrations ($[CO_3^{2-}]$), and calcium carbonate mineral saturation states, with significant increases in surface ocean pH and downward trajectories of surface ocean $[CO_3^{2-}]$ and carbonate saturation states expected throughout this century with increasing atmospheric CO_2 (e.g., **Figure 2.1**). However, attempts to synthesize pH and other carbonate data for the open ocean have largely been limited by available high-quality data, since pH and other carbonate parameter measurements require great care, calibration, and metadata validation (Feely et al., 2009; Takahashi et al., 2014; Jiang et al., 2015; Olsen et al., 2016; Carter et al., 2017; Gruber et al., 2019a,b; see also **Figure 6.2** in Chapter 6: U.S. Pacific Islands Region). In this chapter we recommend future research objectives, activities, and priorities for the open oceans for the next decade of NOAA OA research.

Environmental Change in the Open Ocean Region

After launching the GOA-ON in 2013, the current observing network is comprised of several observing networks deployed around the world—including moorings, repeat hydrography lines, ships of opportunity, and fixed ocean time-series (**Figure 2.2**). The existing large-scale global oceanic carbon observatory network, supported by the NOAA Global Ocean Monitoring and Observing (GOMO) Program, which includes the Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP) surveys, the Surface Ocean CO_2 Observing Network (SOCONET), the Ship of Opportunity Program (SOOP) volunteer observing ships, and the Ocean Sustained Interdisciplinary Time-series Environment Observation System (OceanSITES) time-series stations in the Atlantic, Pacific, and Indian oceans have provided a backbone of carbonate chemistry observations needed to understand OA (**Figure 2.2**). Indeed, much of the present understanding about long-term changes in the carbonate system is derived from these repeat surveys and time-series measurements in the open ocean (Feely et al., 2004, Sabine et al., 2004; Carter et al., 2017, 2019a; Sutton et al., 2019; Gruber et al., 2019b). At present, many of the existing moored carbon observatories only measure pCO_2 in surface waters, which is insufficient to effectively monitor and forecast OA conditions and concomitant biological effects. Future efforts will require additional platforms with an enhanced suite of physical, chemical, and biological sensors in the ocean interior.

Efforts to observe and predict the impact of OA on marine ecosystems must be integrated with an understanding of both the natural and anthropogenic processes that control the ocean carbonate system (**Figure 2.3**). Biogeochemical cycling leads to remarkable temporal and spatial variability of carbon in the open ocean. Long-term, high-quality observations are critical records for distinguishing natural cycles from climate change. There are several methods by which anthropogenic carbon can be distinguished from natural carbon, but all rely on the repeated, high-quality, spatially dense, synoptic, coast-to-coast records of nutrients, ventilation tracers, carbonate system measurements, dissolved gases, and physical properties provided by the GO-SHIP cruises (e.g., Sabine et al., 2004; Khatiwala et al., 2013; Carter et al., 2017, 2019a; DeVries, 2014; Gruber et al., 2019b). Recent research has shown that there are significant regional and decadal variations in anthropogenic CO_2 storage (e.g., Landschützer et al., 2016; DeVries et al., 2017; Gruber et al., 2019a,b), indicating that repeat hydrographic surveys will remain critical for quantifying ocean carbon storage in the coming decades. Feely et al. (2016) extended the open ocean anthropogenic carbon estimates to the California Current Large Marine Ecosystem, allowing the impacts of OA to be separated from natural processes over a two-decade-long time span. This is a critical application for anthropogenic carbon estimates that should be applied in other regions, as coastal regions play disproportionate roles in fisheries and ocean primary production compared to their small (~8% of total) ocean area, and because theseregions with air-sea pCO_2 disequilibria typically lack means to directly quantify the overall anthropogenic impact.

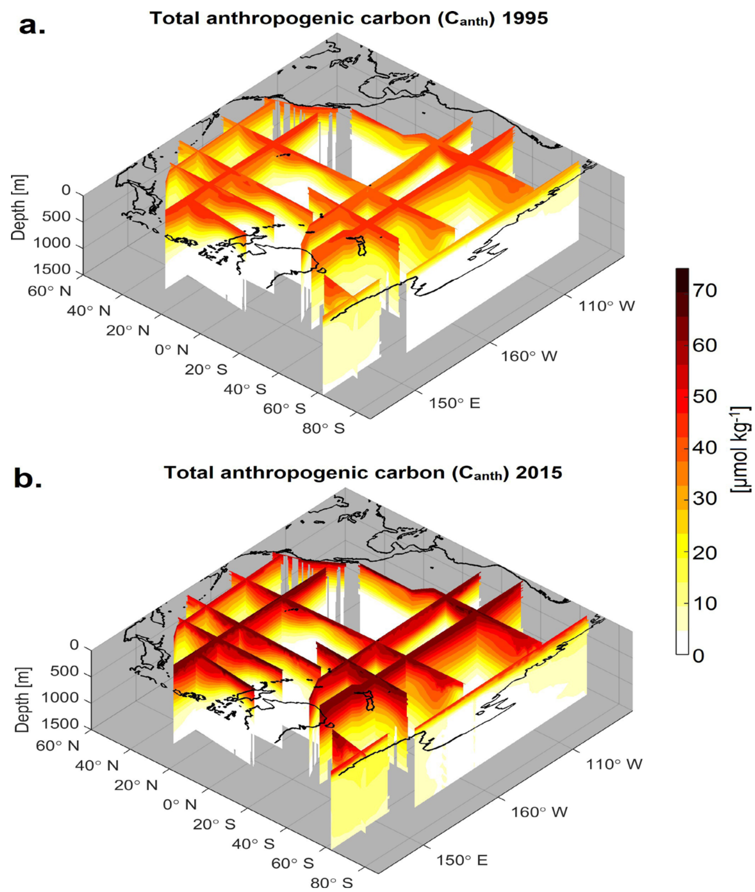


Figure 2.3. Anthropogenic dissolved inorganic carbon concentrations in µmol kg-1 along Pacific Ocean repeat hydrographic sections, estimated for (a) 1995 and (b) 2015. Darker colors indicate that higher concentrations are found near the surface, and extend deeper into the water column in the subtropical gyres. This figure is adapted from Carter et al. (2019a).

Open ocean time-series observations now exist in nearly all oceanic regions and show that the inorganic carbon chemistry of the surface ocean is currently changing at a mean rate consistent with the atmospheric CO_2 increase of approximately 2.0 μatm yr-1 (Bates et al., 2014a; Sutton et al., 2017, 2019). However, enhanced variability in high-latitude regions can complicate and, at times, obscure detection and attribution of longer-term ocean carbon changes. Recent work suggests it will require decades of observations to detect an anthropogenic signal at many coastal time-series stations (Carter et al., 2019a; Sutton et al., 2019; Turk et al., 2019). High-quality, open ocean time-series observations represent critical components of GOA-ON and provide a critical constraint of offshore processes influencing coastal systems, and we recommend their adoption at a larger scale. Open ocean time-series are a powerful way to quantify the United Nations Sustainable Development Goal 14.3 to minimize and address the impacts of OA, including tracking rates of change of OA globally.

Autonomous platforms have demonstrated their potential for revolutionizing the quantity and coverage of OA-related information retrievable from remote regions in all seasons (Bushinsky et al., 2019; Meinig et al., 2015). These surface vehicles and profiling floats possess the capacity to quantify OA and biogeochemical seasonal cycling across traditionally inaccessible regions and timescales. The advent of BGC-Argo profiling floats, with pH as one of the six BGC sensors, offers enormous opportunity to obtain greatly expanded datasets in the open ocean that will provide seasonal resolution of trends and processes that lead to a better understanding of the evolution of marine chemistry and biology conditions as they pertain to OA (**Figure 2.4**). Aside from directly determining OA parameters and processes from these programs, the data are increasingly used

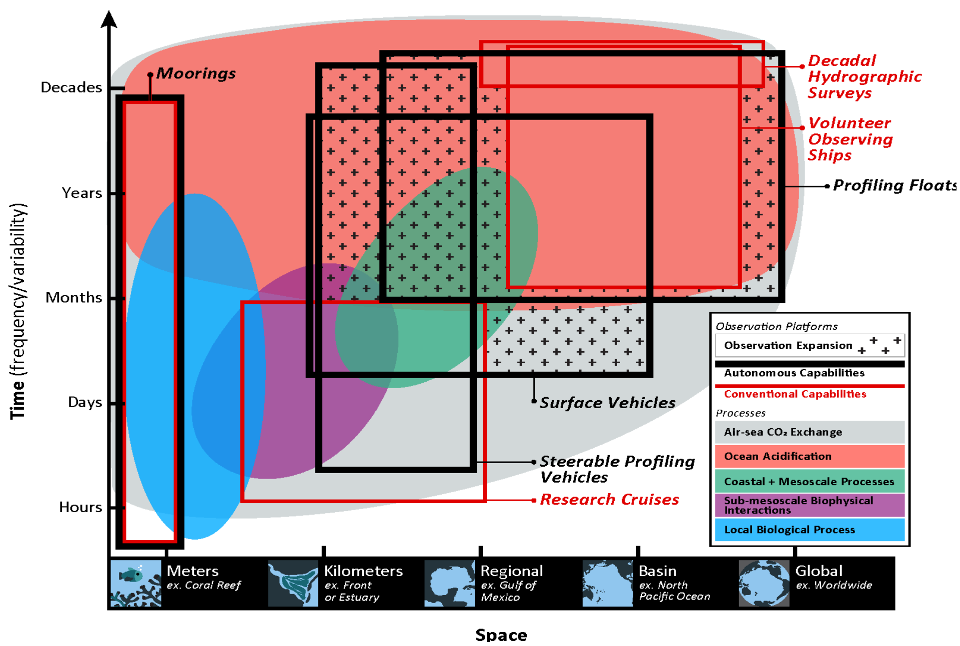


Figure 2.4. Carbonate system processes and autonomous vehicle observational capabilities as a function of time and space. Ocean processes that affect the carbonate system (solid colored ovals with labels in the legend) are depicted as a function of the temporal and spatial scales over which they must be observed to capture important scales of variability and/or long-term change. The ability of platforms, including conventional approaches (red boxes) and autonomous arrays (black), to capture carbonate system processes is superimposed over the characteristic time and space footprints of important carbon cycle processes. The mooring box includes both open-ocean observatories and compact, fixed observatories deployed in coastal and benthic regions. Box boundaries that are directly adjacent to one another (i.e., the upper boundaries of profiling floats, decadal hydrographic surveys, and ships of opportunity) indicate the same temporal or spatial boundary, but are offset for clarity (after Bushinsky et al., 2019). Satellite remotely sensed surface ocean observations (ranging from sub-km to global and from sub-days to decades in some cases) can be assimilated into carbonate and ocean physics models and used as validation for some model outputs.

to validate models including ingestion into novel assimilation schemes such as ocean state estimates. However, as an emergent autonomous technology, the uncertainties associated with their use and lack of *in situ* calibrations are still being quantified, and extensive work remains to be completed before the promise of this observation strategy can be fully realized (Johnson et al., 2017; Williams et al., 2017). On autonomous surface vehicles, seawater pCO_2, and pH can be directly measured, with *in situ* calibration of CO_2 providing high-quality data equivalent to moored pCO_2 time-series (e.g., Saildrone). However, even the highest-quality pCO_2 and pH sensors in combination do not meet GOA-ON climate-quality goals for tracking OA, and sensor development efforts must address this challenge. Research must continue to determine how best to implement new observing platforms and sensors, use the data they retrieve, and quality control and manage their sensor outputs.

Research Objective 2.1: Continue leadership and support for GOA-ON (coordinated with Pacific Islands Region Chapter 6 Research Objective 6.2)

GOA-ON provides a framework to knit together information from ship-based hydrography; time-series moorings, floats, and gliders with carbon system, pH, and oxygen sensors; and ecological surveys and associated biological responses. Support will assure continuation of the ongoing international observing programs, support augmentation of observation with key biological Essential Ocean Variables (EOVs) and encourage further development of novel platforms.

Action 2.1.1: Build upon the existing NOAA-supported GOA-ON activities and expand the global network with new sensors and observing platforms that provide important information on the changing physical, chemical, and biological conditions in open ocean environments.

Action 2.1.2: Ensure OA relevant measurements are included on all Surface Ocean CO_2 Observing Network (SOCONET) and Ship of Opportunity Program (SOOP) volunteer observing ships.

Action 2.1.3: Enable the development of globally accessible, high-quality data and data synthesis products, including assessments of OA status and trends, which facilitate research and new knowledge on OA, communicate the status of OA and biological response, and enable forecasting of OA conditions.

Research Objective 2.2: Separate natural and anthropogenic CO_2 signals and elucidate feedbacks on seasonal to decadal scales

Quantifying the vertical and horizontal distributions, temporal variability, and long-term trends of anthropogenic carbon will provide critical information for determining the biogenic responses of organisms and communities to OA.

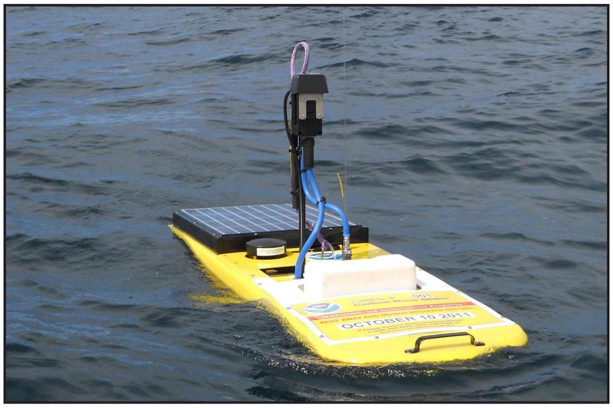
Action 2.2.1: Link open ocean and coastal cruises for tracking the distribution and trends of anthropogenic carbon increases in the ocean.

Action 2.2.2: Expand time-series observations in open ocean and coastal waters (see *Chapters 3–11*) to characterize rates of ocean carbon change over time, which is necessary to reduce uncertainties in future projections of OA.

Action 2.2.3: Continue the development of sensors on autonomous platforms that can measure carbon parameters, nutrients, and other biogeochemical EOVs, especially those meeting climate- quality standards of GOA-ON.

Developing global synthesis and modeling products and maps of OA indicators

Repeat coast-to-coast cruises are the chief means through which we understand rates of decadal ocean uptake of anthropogenic CO_2 and resulting global inventories (Sabine et al., 2004; Gruber et al., 2019b), as well as the ensuing ocean carbonate chemistry changes that are underway in the global ocean (e.g., Byrne et al., 2010; Feely et al., 2004, 2012; Carter et al., 2016, 2017; Jiang et al., 2015, 2019). Sustained support for decadal reoccupation of open ocean repeat hydrography lines is critical to ensure that we can continue to estimate ocean uptake and inventories of anthropogenic carbon into the future, as well as providing high-quality datasets for global ocean model validation. These in turn support accurate and reliable generation of boundary conditions for regional coastal models (e.g., Feely et al., 2016; Carter et al., 2017, 2019a).



A wave glider makes ocean carbon dioxide (pCO_2) measurements in Washington coastal waters while deployed by researchers aboard the R/V Wecoma. Credit: Richard Feely/NOAA

Open ocean transects provide valuable insight into source water evolution relevant to coastal acidification trajectories, although their decadal resolution provides infrequent snapshots of such conditions and must be cross-referenced to more frequent coastal observations to gain insight into rates of change in shelf environments (cf. Feely et al., 2012, 2016; McClatchie et al., 2016). Global Earth System Models of coupled carbon and climate are also key sources of information on past trends and future projections for OA. Currently available model data include a suite of simulations from the 5th Coupled Model Intercomparison Project (Taylor et al., 2012; https://esgf-node.llnl.gov/projects/cmip5/), including simulations from NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) with two state-of-the-art Earth System Models, GFDL-ESM2M and GFDL-ESM2G (Dunne et al., 2012a, 2013; ftp://nomads.gfdl.noaa.gov/CMIP5/output1/NOAA-GFDL/). The global modeling community continues to advance on this frontier and has commenced an ongoing 6th phase of the Coupled Model Intercomparison Project (Eyring et al., 2016), which includes a vastly more comprehensive suite of experiments, in which GFDL is fully engaged. Public access to the next-generation Earth System Models will be provided by the global modeling community over the coming years.

New autonomous platforms such as autonomous surface vehicles and profiling floats offer an enormous opportunity to obtain greatly expanded datasets that will provide daily to seasonal resolution of trends and processes, especially in traditionally inaccessible regions. However, there are considerable data management tools that must be developed before these observations can be integrated with established observations in global data synthesis products and used to validate models. Intercomparisons between established and new observations can help determine uncertainty of new technologies, but a data integration system is also critical to support these new approaches now and into the future. Research must continue to determine how best to implement these observing platforms, use the data they retrieve, and quality control and manage their sensor outputs. Support for the continuation of the ongoing observing programs, support augmentation of observations with key biological EOVs such as plankton, assure maintenance of the high quality of the data, and encourage further development of these new platforms.

Global seasonal-to-interannual prediction of acidification anomalies requires reliance on large- scale physical and biogeochemical data assimilation that is dependent on *Research Objective 2.2* above. These forecasts are in a state of development and require a better understanding of data assimilation methods, especially considering the new observational assets coming online in the next few years. Global historical and future scenarios of decadal to centennial acidification using fully coupled carbon-climate earth system models are in continued development as described in *Research Objective 2.3*. When run in physical data-assimilation mode, these models show much early promise with respect to predictability of carbon uptake and acidification (Li et al., 2016; Park et al., 2018) on seasonal to decadal timescales, and earth system prediction is possible using the GFDL MOM6 model. An essential part of this development on all timescales includes multi-decade retrospective analysis of acidification patterns compared with observations to test the skill and improve the forecast and projection systems. Key observations for this activity include those that characterize the ocean ecosystem and biogeochemical cycles at the process level and their sensitivity to multiple stressors including the physiological role of acidification on plankton growth and behavior and its consequences for biodiversity and controls on calcite, aragonite, and high Mg-calcite formation and dissolution. The cycling of calcium carbonate has been recently identified as a potentially important process that is not consistently simulated (Dunne et al., 2012b; Buitenhuis et al., 2019); and thus remains poorly constrained and requires further improvements in understanding.

Research Objective 2.3: Observe the evolution of marine chemistry and biology to provide model initial conditions and validation

Quantifying OA impacts requires the development of global and regional data products from observational data such as open ocean observations from GO-SHIP, BGC Argo, and SOCONET to provide initialization data for model runs and validation datasets for testing model predictive capabilities (*in coordination with Pacific Islands Region Chapter 6 Research Objective 6.3*).

Action 2.3.1: Develop synthesis products including maps and sections of key chemical and biological parameters to quantify the buildup of anthropogenic CO_2, rates of change in global ocean OA conditions, and impacts of OA on key species.

Action 2.3.2: Continue the development of data management and quality control systems for autonomous sensors on autonomous surface vehicles and biogeochemical (BGC) Argo profiling floats in order to incorporate these new observations in data products and validate models.

Action 2.3.3: Continue development of regional-to-global scale prediction BGC models focused on acidification extremes spanning timescales from seasonal to interannual to decadal.

Satellite Observations for Understanding Open Ocean Acidification

Satellite observations offer a powerful tool for studying surface ocean carbonate dynamics either by deriving CO_2 parameters via satellite sea surface temperature and salinity, or by inferring large-scale patterns from physical parameters that can be remotely-sensed and validated using observations obtained from *in situ* observing assets (e.g., ships and time-series stations). While satellite sensors are not capable of actual direct carbonate parameter measurements, they are able to sensibly detect a broad range of surface physical and biological phenomena that influence carbonate system dynamics (Salisbury et al., 2015; Shutler et al., 2020). By quantifying changes in parameters through time and space, satellite data together with *in situ* observations can provide reasonable rate proxies for the effects of mixing and community metabolism on the carbonate system (Hales et al., 2012). Beyond the direct study of OA, ocean satellite data can also support other activities detailed throughout this plan ranging from cruise planning to model validation. Robust, sustained, internally consistent access to ocean satellite products that are fit-for-purpose (e.g., near-real-time and delayed science quality products) remains a critical need.

Recognizing that many satellite-based empirical or semi-empirical algorithms relating observable parameters to OA are regionally specific (i.e., Gledhill et al., 2015), there remains a requirement to objectively establish discrete domains where uniquely defined algorithms can be robustly parameterized. One promising approach in recent years has been the development of dynamic seascape classification products (i.e., Kavanaugh et al., 2014, 2016). Thus, there is much opportunity for improvements that include, but are not limited to, the addition of new variables, methodological comparison, and global validation.

Surface ocean gridded data synthesis products of satellite remote sensing outputs can provide surface ocean-specific algorithms to be applied to remotely sensed products to produce gridded fields of monthly global sea surface $p\mathrm{CO_2}$. These fields can then be coupled to total alkalinity (TA) fields derived from salinity data (e.g., ESA- SMOS; NASA SMAP), which can be used in conjunction with $p\mathrm{CO_2}$ and temperature to derive monthly dynamics for global surface ocean carbonate saturation states and pH (e.g., Jiang et al., 2015, 2019).

Improved models for quantifying surface biological perturbations to the carbonate system from space are needed. The predominant perturbation arises from net community production (NCP), or the balance between gross primary production (GPP) and community respiration (CR). Several existing strategies for retrieving satellite-derived NCP include a space-time accounting of the change in organic carbon inventories (Jönsson et al., 2011; Jönsson & Salisbury, 2016), satellite estimates of organic carbon export (e.g., Siegel et al., 2014; Li et al., 2018), and satellite-derived NPP (e.g., Saba et al., 2011) versus CR (Zhai et al., 2010). To facilitate these efforts, repeated hydrographic surveys should facilitate *in situ* optical measurements that include apparent and inherent optical properties, particle-size distributions, and multispectral fluorescence, in conjunction with ship-based rate measurements (NPP, NCP, and CR). Additional measurements may be required to optimally relate optical data to rate estimates, including but not limited to chlorophyll (and associated pigments), particulate organic carbon, and phytoplankton functional-type enumerations.

Research Objective 2.4: Derive global statistical or quasi-mechanistic algorithms to infer surface ocean carbonate dynamics and underlying biological processes to be acquired from remotely sensed data

Satellite observations can be used to determine surface ocean carbon distribution either directly or by synoptically scaling up discrete surface observations obtained from *in situ* observing assets.

Action 2.4.1: Derive seascape-specific multivariate algorithms for predicting global surface ocean pCO_2 at suitable spatiotemporal scales (e.g., monthly, 0.5 degree).

Action 2.4.2: Incorporate measurements supporting satellite algorithm development and determination of net biological productivity into ongoing OA surveys.

Biological Sensitivity in the Open Ocean Region

Large-scale hydrographic studies crossing major biogeographical provinces are of fundamental importance for understanding short- and long-term biological and ecological responses associated with OA and other climate change-related stressors in the open ocean (e.g., Bednaršek et al., 2014, 2017a; Engström-Öst et al., 2019). Each province is characterized by a set of baseline conditions, and additionally is affected by seasonal and 'event-scale' variability. On large scales, the transitions between adjacent provinces are often characterized by strong OA gradients. When accompanied by gradients in other environmental factors, such as temperature, nutrients, dissolved oxygen, and food availability, they create the potential for multiple drivers to provoke strong biological responses (Bednaršek et al., 2018).

Planktonic communities likely are some of the most vulnerable to OA and comprise key prey items for larger pelagic and benthic invertebrates, fishes, and marine mammals. Plankton are unevenly distributed across oceanic ecosystems, with their numbers, composition, and survival being highly sensitive and responsive to environmental conditions. Related species often respond differently to OA and other stressors, and have different spatial and temporal dynamics that may substantially affect food availability for larger organisms, and in turn for ecosystem services and seafood resources. Changes in biodiversity and lower and higher trophic level species composition are ultimately dependent upon species vulnerability versus adaptation potential. So far, OA gradients have been used as natural laboratories for detection of sensitive responses across various levels of biological organization.

There is a fundamental need for integration of physical, chemical, and biological data into a biogeographic framework to be able to develop OA-related species-distribution models. The assessment of OA-related impacts is currently limited because synoptic information about species distributions, their physiological limitations, and the physical-chemical characterization of local environments are not always recorded together. More specifically, Habitat Suitability Indices (HSIs) can be used as statistical approaches using multiple regression methods to define an envelope of optimal conditions in which an organism may persist (Bednaršek et al., in review). Continuous Plankton Recorder (CPR) data have been collected over time, and some of them now represent unique time-series that could be used with gridded products generated by large hydrographic surveys to define species' niches and construct species-distribution models related to prognostic shifts in OA properties. Future CPR studies should add OA sensor measurements to the observational effort.

Large-scale OA gradients in the open ocean represent transition zones where enhanced biodiversity potentially harbors important genetic variability. However, many taxa are difficult to distinguish and identify to the species level, and most can only be identified to higher taxonomic levels in their early life history stages (e.g., as eggs and larvae). Advances in new metagenomic technology (barcoding, eDNA, etc.) will allow for the evaluation of the relationships among community-level biological diversity and physical and chemical ocean parameters, in order to understand responses to OA and enable the establishment of linkages using molecular identification tools for rapid monitoring and assessment of climate change effects on pteropods and other planktonic species in the future (Stepien et al., 2019).

Research Objective 2.5: Research impacts on lower trophic levels in oligotrophic waters

Biological and biogeochemical studies on hydrographic surveys can delineate biological responses to OA gradients across biogeographic province boundaries in the open ocean (in coordination with *Pacific Islands Region Chapter 6 Research Objective 6.4*).

Action 2.5.1: Utilize Bongo and Continuous Plankton Recorder tows during OA cruises to determine the biological impacts of OA and other stressors on planktonic communities.

Action 2.5.2: Develop statistical tools for assessing the impacts of OA and other stressors on marine organisms.

Action 2.5.3: Develop biogeochemical and phylogenetic tools for assessing impacts of OA and other stressors on marine organisms.

Humpback whale fluke spotted off the northern California coast. Credit: Richard Feely/NOAA

Research Objective 2.6: Research impact of OA on highly migratory species

Migratory species, including fishes, squids, and marine mammals are dependent on some OA-sensitive species as food. Analyses of species compositions and their food chains *in situ* and in lab experiments will help predict OA effects (in coordination with *Pacific Islands Region Chapter 6 Research Objective 6.5*).

Action 2.6.1: Develop biogeochemical tools for assessing the impacts of OA and other stressors on higher-level taxonomic groups.

Human Dimensions in the Open Ocean Region

The impacts of OA on marine ecosystems in the open ocean will likely have negative effects on ecosystem services, marine resources, and the human communities that depend on them for their livelihoods, subsistence, and social and cultural continuity (Cooley & Doney, 2009; Cooley et al., 2012, 2016; Gattuso et al., 2015; Hoegh-Guldberg et al., 2017; Leong et al., 2019). A high priority in the open ocean is identifying and projecting the effects of OA on marine resource-reliant industries, local fisheries, and human communities, and developing ecosystem-based fisheries management systems that are driven by OA-informed environmental, ecological, and socioeconomic considerations.

Much of the focus of OA impacts are in coastal regions where humans directly rely on resources such as fisheries, and natural barriers such as reefs providing storm protection. However, open ocean forcing affects these coastal resources. For example, climate variability such as El Niño Southern Oscillation and large-scale extreme events such as the northeast Pacific marine heatwave of 2014-2016 have direct impacts on coastal resources and coral reefs (Di Lorenzo & Mantua, 2016; Kleypas et al., 2015; Peterson et al., 2017; Sanford et al., 2019). Improved global projections of OA combined with warming and sea level rise are also necessary for informing coastal zone managers and policymakers. The connections between open ocean events and the coastal zone must be better understood to project OA impacts.

Another critical open ocean process that could be impacted by OA is the biological pump (Passow & Carlson, 2012; Boyd et al., 2019). Additional research and model development are needed to understand how ocean warming and OA will affect the ability of the biological pump to sequester carbon, which is necessary for predicting future atmospheric CO_2 concentrations and the resulting carbon cycle changes.

An important objective to mitigating future OA impacts will be securing coordinated national and international investments to develop effective adaptation strategies and solutions for affected communities. Metrics of impact due to changes in open ocean forcing and processes will be required for decision-makers to understand how effective local adaptation strategies can be in the face of global ocean and climate change. These impacts must be effectively communicated to decision- makers and the public to describe potential OA impacts to environmental, biological, economic, and social systems. Open ocean researchers should pursue efforts to create visualization and educational products and outreach resources targeting diverse stakeholders to promote understanding and awareness of OA.

Research Objective 2.7: Assess direct and indirect effects of OA on communities

Coupling open ocean forcing, coastal environmental and ecological dynamics, and human-use sectors in ecosystem models will support assessment of OA impacts on marine resource-reliant industries and communities, including impacts to human well-being and ecosystem services (in coordination with *Pacific Islands Region Chapter 6 Research Objective 6.7*).

Action 2.7.1: Identify relationships among key social, cultural, and economic drivers to biophysical, fishery, and ecosystem parameters along the open ocean to coastal continuum to predict potential responses from future OA scenarios.

Action 2.7.2: Create regional economic impact and behavioral models for marine resource-reliant industries that include open ocean forcing to inform consideration of benefits and costs of alternative management strategies to mitigate impacts from OA.

Action 2.7.3: Develop management objectives related to human-use sectors, ecosystem services, and well-being, and derive indicators to monitor effectiveness of management strategies.

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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