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# Introduction to this Special Issue on Ocean Acidification

## THE PATHWAY FROM SCIENCE TO POLICY

By Jeremy T. Mathis, Sarah R. Cooley, Kimberly K. Yates, and Phillip Williamson

Ocean acidification (OA) is a progressive decrease in the pH of seawater over decades, caused primarily by uptake of excess atmospheric $CO_2$ and accompanied by changes in seawater carbonate chemistry. Scientific studies designed to examine the effects of anthropogenic carbon dioxide ($CO_2$) emissions on global carbon fluxes have also led to the detection of OA. During the last decade, this phenomenon has surged to the attention of not only scientists but also policymakers and the public.

OA chemistry is well understood and follows first principles of acid-base chemistry (e.g., Gattuso and Hansson, 2011; Box 1 in **McLaughlin et al.**). Today, total anthropogenic release of $CO_2$ exceeds nine petagrams of carbon annually, with ~85% coming directly from industrial sources and ~15% from changes in land use. The three major sinks for this $CO_2$ are: ~46% of $CO_2$ emitted remains in the atmosphere, ~29% is absorbed by the terrestrial biosphere, and the ocean absorbs the remaining ~26% (Le Quéré et al., 2014), resulting in OA. Since the Industrial Revolution, global average surface ocean pH has dropped 0.1 unit (about a 30% increase in acidity; IPCC, 2013), and it is expected to drop another 0.3 to 0.4 units by 2100 (100–150% increase in acidity) if $CO_2$ emissions continue in a business-as-usual scenario (Orr et al., 2005; IPCC, 2013). Some areas of the ocean, such as coastal regions, upwelling zones, and polar seas, may be subjected to much greater chemical perturbations from OA than indicated by such globally averaged values (e.g., Feely et al., 2008; **Mathis et al.**).

### A NEW AREA OF INQUIRY EMERGES

While OA may appear to be a relatively "new" issue given the last decade of intense research activity, it has been expected for some time. As early as the 1940s and 1950s, some ocean researchers postulated that rising atmospheric $CO_2$ concentrations could decrease ocean pH and alter carbonate ion concentrations (e.g., Callendar, 1938; Bolin and Eriksson, 1959). However, such ideas were largely ignored on the premise that the ocean's size would render these pH changes small and thus biological impacts would be unlikely. By the 1970s, numerous researchers had published calculations showing that $CO_2$ emissions would eventually cause calcite and aragonite mineral undersaturation, but estimates of exactly when this would happen varied widely due to uncertainty about the current status of the ocean carbonate system (as reviewed by Doney et al., 2009a and 2009b).

Perception of risks associated with OA began to change in the 1990s as researchers conducted rigorous global ocean surveys that measured significant changes in seawater carbonate chemistry, improved their models, and carried out experimental studies simulating future conditions (e.g., Smith and Buddemeier, 1992; Gattuso et al., 1998). Research results indicated that a range of marine calcified organisms, both animals and plants, were potentially at risk (Royal Society, 2005; Kleypas et al., 2006). OA effects on tropical corals, and their ecosystems were of particular concern because rising ocean temperatures were already causing coral bleaching events in many areas. An early study showed a precipitous and potentially catastrophic decline in calcification for some tropical coral species at atmospheric $CO_2$ levels likely to occur by the end of this century, if current emission trends continue (Langdon et al., 2000). Other researchers studying the distribution of Antarctic pteropods found that $CO_2$ from the respiration of captive individuals caused their aragonite shells to dissolve (Orr et al., 2005), and coccolithophorids (calcareous phytoplankton) also seemed especially sensitive (Riebesell et al., 2000). These findings kicked off a flurry of follow-up experimental studies on other species, showing that responses could be highly variable (e.g., Doney et al., 2009b). Later, meta-analysis of

> “Despite the rapid growth in [ocean acidification] research, there are still many unanswered scientific questions as well as the societal questions posed by coastal resource users and decision makers.”

hundreds of such studies confirmed this variability and also demonstrated statistically significant decreases in survival, calcification, growth, photosynthesis, and abundance for certain calcifying taxa, as well as significant increases in growth and photosynthesis of non-calcifying taxa (Kroeker et al., 2013).

As understanding grew about the potential impacts of rising $CO_2$ levels on the ocean and marine life, scientists began to look for analogous events in the geological record to gather clues about the long-term consequences of acidification events. The last large-scale OA event occurred during the Paleocene-Eocene Thermal Maximum, approximately 55 million years ago when $CO_2$ levels increased markedly in the atmosphere (Zachos et al., 2005). Although this increase occurred abruptly in geological terms, it was still an order of magnitude slower than the current rate. Sedimentary records showed that this global OA event was accompanied by surface ocean warming of 3–5°C (Aze et al., 2014), and together those changes led to mass extinctions, high rates of species turnover, and a complete loss of calcified fossils in at least some parts of the ocean. At many sites, the reappearance of calcified fossils in marine sediments took more than 100,000 years (Zachos et al., 2005). Recent studies also found strong evidence for OA causing marine mass extinctions at the Permo-Triassic boundary, around 252 million years ago (Clarkson et al., 2015).

## OCEAN ACIDIFICATION BECOMES A REAL-WORLD CONCERN

While scientists’ concerns about OA have mounted, evidence also emerged of its “real-world” impacts on human communities (Figure 1). In the mid to late part of the first decade of this century, shellfish growers in the Pacific Northwest United States noted massive die-offs of oyster larvae in hatcheries not due to any known problems such as disease or harmful algal blooms. Hatchery owners and scientists collaborated to diagnose the problem, finding that upwelled water with naturally low pH, further acidified by OA, was responsible (**Barton et al.**). Continued fact-finding by a team of specialists convened to study the problem found that in Washington State alone, OA threatened 3,200 jobs and $270 million a year due to its potential impacts on the state’s Pacific oyster aquaculture industry (Washington State Blue Ribbon Panel on Ocean Acidification, 2012). However, the problem goes far beyond just one state, because Pacific Northwest hatcheries represent a “bottleneck” for the entire Pacific oyster aquaculture industry: most Pacific oyster seed stock reared around the nation comes from hatcheries located in the region (Washington State Blue Ribbon Panel on Ocean Acidification, 2012).

Given these real-world impacts of OA, researchers have started to assess what socioeconomic impacts may result from OA in the future (Turley and Gattuso, 2012). Early socioeconomic modeling studies assumed specific $CO_2$ emissions scenarios and damage functions that related OA to economically valuable marine resources (Cooley and Doney, 2009; Brander et al., 2012; Narita et al., 2012). Later modeling studies simulated ecosystem responses to the combined effects of OA, temperature, and harvests (Kaplan et al., 2010). Risk assessment approaches are also used to examine the vulnerability of human communities to OA’s hypothesized impacts on marine harvests (Cooley et al., 2012; Mathis et al., 2014; Ekstrom et al., 2015). Modeling and observational studies are now being combined to inform species-specific OA response models that include population dynamics and socioeconomic relationships (Punt et al., 2014; Voss et al., 2015; Cooley et al., 2015). Although these papers foster a vigorous academic discussion of opportunities for adaptive resource management in the face of OA (Kelly et al., 2011; Billé et al., 2013; Kelly and Caldwell, 2013; Strong et al., 2014), true adaptation is advancing more slowly:

fisheries management has not yet begun to plan for OA in the future, and coastal managers and the US Environmental Protection Agency (US EPA) are just beginning to identify how existing activities, like reduction of nutrient pollution, also help reduce OA (**Cooley et al.**). Adaptation is advancing fastest in the industrial sector, where shellfish hatchery owners are implementing monitoring and new culturing techniques to safeguard their businesses (**Barton et al.**).

The research community has been extremely active in the past decade in the wider communication of its findings. Although "ocean acidification" is not yet a household phrase around the world, in just a decade, the issue has gone from a specialists' topic to a regionally relevant issue frequently discussed by popular media outlets (e.g., the "Sea Change: The Pacific's Perilous Turn" series by Craig Welch, formerly of the *Seattle Times*). In other regions like Alaska, residents now have a basic awareness of OA (Frisch et al., 2014)—even though their fisheries are not the ones experiencing current impacts—suggesting that science communicators' efforts to disseminate research findings, together with media attention, are effective.

In response to the concerns of both researchers and the stakeholder community, funding agencies in the United States, Europe, and elsewhere began to dedicate resources to improve understanding of the processes controlling OA as well as its impacts on organisms and ecosystems. The European Project on Ocean Acidification, launched in 2008, was the first coordinated multi-institution, multi-national effort focused solely on OA. Soon afterwards, Germany and the United Kingdom launched national-level multiyear efforts (BIOACID and UKOA, respectively; **Yates et al.**). Subsequent efforts in Europe (e.g., MedSEA) have built on these very strong foundations for coordination and collaboration. In the United States, the Federal Ocean Acidification Research and Monitoring Act (FOARAM) of 2009 required federal agencies to form a comprehensive plan to monitor and research OA effects on organisms and ecosystems, establish an interagency research and monitoring program, assess the socioeconomic impacts of OA, and develop research adaptation strategies effective against OA. To date, numerous federal, state, private, and nongovernmental organizations in the United States have participated in researching OA impacts, involving the expenditure of more than $100 million. Other nations' scientific funding organizations are also strongly supporting ocean acidification research (e.g., Australia, Canada, Chile, China, Japan, New Zealand, Sweden, and South Korea), and the OA research community is now truly global.

The concerted worldwide effort to understand OA has exponentially increased the number of scientific publications (and investigators) addressing this issue. Between 2000 and 2013, the number of papers increased by 35% per year, compared with an increase of 4.8% for all scientific fields (Riebesell and Gattuso, 2015). Around 75% of the total OA literature has been published since the last *Oceanography* special issue on the topic in 2009 (http://tos.org/oceanography/archive/22-4.html). Lead authors for publications in the last decade have come from 37 nations (Ocean Acidification International Coordination Centre; *pers. comm.*, March 12, 2015). Although researchers in Europe and North America dominate the field, there is also strong OA publication output from Australia, China, and Japan, and there are recent increases in publications from South America and India (Figure 2).

The combination of OA's increasingly clear relevance for coastal communities, extensive communication on the topic, and burgeoning research have accelerated recognition of OA at international policy levels (IPCC, 2013; **Cooley et al.**). At the 2014 international "Our Ocean Conference" hosted by the US State Department, ocean acidification was one of the conference's three main focus issues. The main challenge to taking international action to address OA is that curbing its root cause, atmospheric $CO_2$ emissions, requires complex international cooperation. Nevertheless, local actions to protect against OA ("buying time") can be taken (Billé et al., 2013; **Barton et al.**) to complement

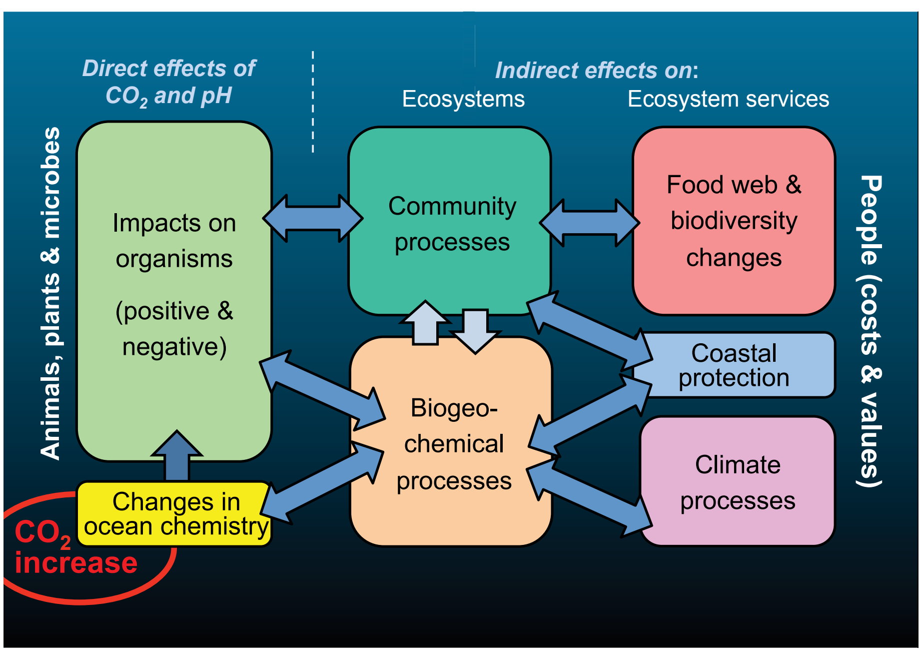


**FIGURE 1.** The direct (left side) and indirect (right side) effects of ocean acidification with their associated interactions shown with the blue arrows. *Adapted from Williamson and Turley (2012)*

ongoing efforts to cut $CO_2$ emissions through the UN Framework Convention on Climate Change.

## WHERE ARE WE NOW ON OA RESEARCH AND DECISION MAKING?

In the last decade, OA research has made strong progress in documenting the short-term physiological responses of single species or strains to pH decrease (or $CO_2$ increase) as a single driver. As noted above, major response patterns have been identified (Kroeker et al., 2013). Attributing coastal changes in acidity and ion balances to specific coastal processes (e.g., atmospheric $CO_2$ invasion, biological processing, or non-oceanic water runoff) is also becoming possible (e.g., Feely et al., 2010; Mathis et al., 2011; Evans et al., 2014). However, other environmental stressors (e.g., rising temperatures, eutrophication, and hypoxia) are likely to co-occur, complicating the predictability of biological responses, particularly in coastal zones (**Breitburg et al.**). Species-specific models that synthesize these data and attempt to project the effects of OA and other stressors on marine populations (Kaplan et al., 2010; Punt et al., 2014; Voss et al., 2015) are becoming available, but they are few in number compared to the vast need for information at population and ecosystem levels.

Despite the rapid growth in OA research, there are still many unanswered scientific questions as well as the societal questions posed by coastal resource users and decision makers. Both ecological and societal questions require information about the long-term, holistic responses of marine ecosystems to a multitude of overlapping environmental changes. OA research therefore needs to accelerate its transitions from (1) single stressors to multiple stressors (including rising temperature, decreasing oxygen, changes in nutrients or food supply, and interactions with pollutants); (2) physiological responses over time scales of weeks/months to population responses over years/decades, including the potential for genetic adaptation; (3) single species to communities, food webs, and ecosystems; and (4) carbon-cycle-focused oceanography and impact studies to a more transdisciplinary approach that includes the human perspective and explores both mitigation and human adaptation options. Although all these developments are important, the last is arguably the most challenging (**Yates et al.**) because it requires much stronger engagement with research users as well as those with expertise in other scientific areas.

This special issue contains papers assessing the state of OA research in the context of the four transitions described above. Seven papers arose from discussion groups at the 2013 Ocean Acidification Principal Investigators' Meeting organized by the US Ocean Carbon and Biogeochemistry (OCB) Program (http://www.us-ocb.org) and supported by the National Science Foundation, NOAA, and the National Aeronautics and Space Administration. Nine additional papers review the state of knowledge on ocean acidification from either topical or regional foci. Both kinds of papers provide forward-looking assessments that explore one or more of the transitions outlined above.

Several papers in this issue focus primarily on the first three transitions, including multiple stressors, longer time scales, and scaling up to ecosystems. For instance, **Breitburg et al.** explore the state of knowledge about multiple stressors, particularly in coastal regions. **Andersson et al.** discuss the need to scale up to ecosystem responses and perform experiments that will shed light on different time scales of response. **Mackey et al.** review OA influences on photosynthesis and present information relevant for multi-stressor, longer-term, and population-scale studies. Regionally focused papers explore the state of knowledge concerning OA impacts on the Arctic (**Mathis et al.**), the Great Lakes (**Phillips et al.**), and New England (**Gledhill et al.**), demonstrating the state of knowledge in those areas on multiple stressors, long-term responses, and ecosystem-scale responses. In reviews that are relevant to all four transitions, **Levin et al.** review geochemical proxies available to study organisms' exposure

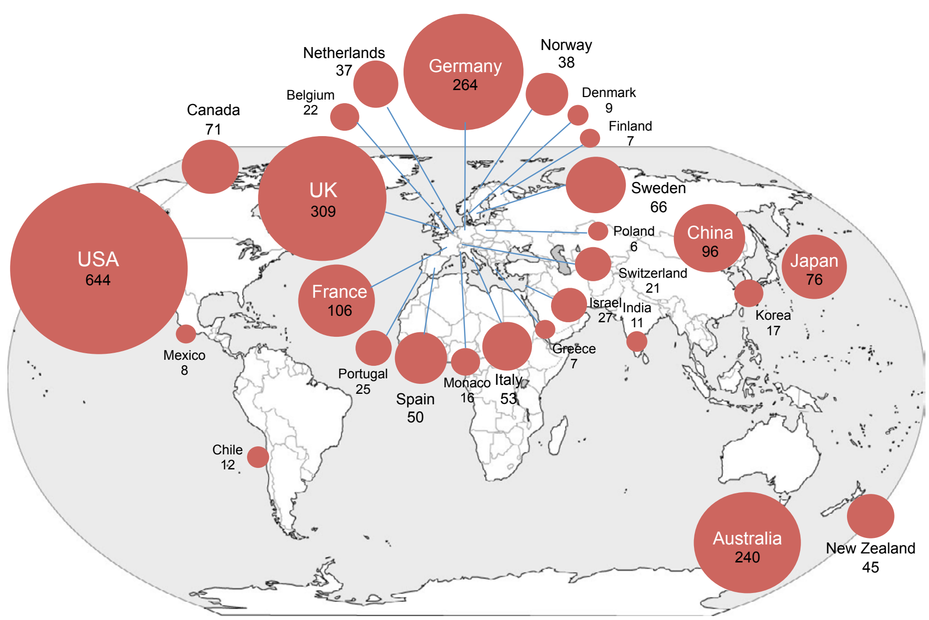


**FIGURE 2.** National involvement in ocean acidification research based on first authors' addresses for peer-reviewed papers published from 2005–2014 for countries with five or more ocean acidification publications. Data from Ocean Acidification International Coordination Centre; *pers. comm.*, March 12, 2015.

to OA, and **Salisbury et al.** review the present applications of satellite data for aspects of carbonate system studies related to OA.

Other papers in the issue focus on the fourth transition, the development of more integrated, interdisciplinary, and transdisciplinary approaches. These papers arose from discussions at the US principal investigators' meeting that also involved program managers, data managers, and international colleagues from multiple disciplines. Scientific needs for integrated monitoring (**Alin et al.**), ecosystem-focused monitoring (**Sutton et al.**), and technical developments (**Martz et al.**) are discussed, while **Garcia et al.** explore the critical issue of data management that involves collaboration and expertise beyond the ocean carbon cycle community. Several papers relate to human adaptation, addressing the intersection of OA research, monitoring, and regional decision making on the US West Coast (**Barton et al.**, **Boehm et al.**, **McLaughlin et al.**). In addition, papers consider research coordination in a societal context (**Yates et al.**), bringing research outcomes to policy attention (**Cooley et al.**), and the role of uncertainty in OA science, both in scientific studies and communicating results (**Busch et al.**). These papers all indicate strong energy within the OA research community to help take the field to the next level, to more directly answer societal as well as scientific questions.

## THE GREATER CONTEXT

The OA problem is not going away. Future increases in global population, which is expected to grow by 20–25% before stabilizing, and future economic growth will make increased demands on marine environmental resources. Current economic growth and resource use rates will also make it difficult to constrain, and subsequently reduce, our unsustainable dependence on fossil fuels, which leads to the $CO_2$ emissions that drive OA. The most optimistic IPCC scenario (RCP 2.6) would result in a further global pH decrease in the surface ocean of ~0.1 units by 2100; the most pessimistic is ~0.35 (Bopp et al., 2013). Even if all $CO_2$ emissions halted tomorrow, ocean chemistry would take thousands of years to fully recover to its pre-industrial state (Archer, 2005). However, with aggressive changes in national energy policies, achieved at the global scale, substantive increases in energy usage are still possible while also reducing $CO_2$ emissions (Climate-KIC and International Energy Agency, 2015) through the use of renewable energy sources (IPCC, 2012), carbon capture and storage (Rackley, 2009), and, potentially, carbon dioxide removal techniques (Williamson and Turley, 2012).

$CO_2$-driven OA is not the only threat to the ocean. Many other stressors on marine ecosystems increase the risk of interactive and synergistic impacts. Globally, the number of people living within 200 km of the coast is expected to double from 3 billion to 6 billion by 2030, while global consumption of seafood could triple in that period. Thus, it is necessary to address $CO_2$ emissions at all levels of governance, while also taking steps to prepare coastal communities for future ocean conditions—which will undoubtedly include warmer, more acidified, lower-oxygen water (e.g., Gruber, 2011).

Published OA research over the past decade has measurably advanced our knowledge of this issue. It has provided a strong foundation that has already supported evidence-based decision making, in particular by aiding Pacific Northwest hatcheries to stay in business and helping scientific programs to place new observational resources in strategic locations. Scientific findings to date have also underscored the need for more information about the mechanisms by which OA affects biological processes and leads to impacts on ecosystems and resources valued by humans. The scientific knowledge coming from OA studies is already becoming more closely aligned with the needs of decision makers, accelerating the science's usefulness in setting future policies and goals. OA science has begun to evolve into a transdisciplinary, ecosystem-focused field of study that takes full account of other anthropogenic stressors. This transition will aid the fair use of marine resources in the face of growing environmental pressures. In another decade, we are confident that OA research will not only have played an important role in the debate on climate change and energy policy but also will have contributed to robust local and regional decision making that is related to ocean resources, environmental health, and human well-being.

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