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Understanding, Characterizing, and Communicating Responses to Ocean Acidification

CHALLENGES AND UNCERTAINTIES

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ABSTRACT. Over the past decade, ocean acidification (OA) has emerged as a major concern in ocean science. The field of OA is based on certainties—uptake of carbon dioxide into the global ocean alters its carbon chemistry, and many marine organisms, especially calcifiers, are sensitive to this change. However, the field must accommodate uncertainties about the seriousness of these impacts as it synthesizes and draws conclusions from multiple disciplines. There is pressure from stakeholders to expeditiously inform society about the extent to which OA will impact marine ecosystems and the people who depend on them. Ultimately, decisions about actions related to OA require evaluating risks about the likelihood and magnitude of these impacts. As the scientific literature accumulates, some of the uncertainty related to single-species sensitivity to OA is diminishing. Difficulties remain in scaling laboratory results to species and ecosystem responses in nature, though modeling exercises provide useful insight. As recognition of OA grows, scientists' ability to communicate the certainties and uncertainties of our knowledge on OA is crucial for interaction with decision makers. In this regard, there are a number of valuable practices that can be drawn from other fields, especially the global climate change community. A generally accepted set of best practices that scientists follow in their discussions of uncertainty would be helpful for the community engaged in ocean acidification.

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INTRODUCTION

Ocean acidification (OA) has leapt from obscurity to a major point of concern within ocean science. Over the past several decades, researchers have identified effects of anthropogenic CO_2 on the carbon system in the ocean (Feely et al., 2004) along with evidence that these chemical changes may alter marine ecosystems (Raven et al., 2005; Hall-Spencer et al., 2008; Fabricius et al., 2011; Kroeker et al., 2013). Early research results captured some societal attention, leading to international initiatives (e.g., the European Project on Ocean Acidification) and legislative mandates (e.g., the Federal Ocean Acidification Research and Monitoring Act, Washington State Executive Order 12-07) to support science efforts (Yates et al., 2015, in this issue).

Early on, scientists were challenged by nearly complete uncertainty about how and where OA impacts might occur; the clear prescription for this uncertainty was more research (Figure 1). This period was followed by a relatively high sense of certainty about potential adverse impacts of OA based on a small number of publications on very few species. We have now moved to a third stage of more nuanced knowledge and research targeting larger conceptual questions. These developments present new challenges as we reduce, quantify, and communicate the uncertainty around our knowledge. We must couple knowledge and language within and between disciplines to address the fundamental question that drives the field: to what extent will changes in ocean carbon chemistry alter marine ecosystems and harm people who depend on them?

Our theories about OA and their supporting evidence provide compelling information to apprise society about future challenges to ecosystems, in much the same way that our understanding of climate change may permit ecological forecasting (e.g., Clark et al., 2001). In many respects, uncertainties about the consequences of OA are no different from any other rapidly advancing field, such as epidemiology or macroeconomics, where decision makers may be called to take action based on a consensus of predictions about the future. In this respect, the field has much to learn from these other, more mature disciplines. Major issues, such as how and to what extent carbon chemistry will change in a specific location and how this change will influence populations and ecosystem structure, are questions clouded by uncertainty at a number of levels. The ability to predict changes in the natural environment suffers from two major sources of uncertainty: the imperfection of our knowledge (otherwise known as reducible uncertainty or estimation error) and the complexity of natural systems (otherwise known as irreducible uncertainty or process error). Each source of uncertainty is addressed with different strategies in terms of how science is conducted and how the resulting information is communicated to stakeholders and decision makers to influence societal decisions.

Within the scientific endeavor, uncertainty is unavoidable because research projects must be bounded due to constraints of time, space, and funding. No matter how carefully an experiment is set up, there is always some concern that the observed result is simply a chance event, a fear that is typically allayed by assessment with statistical tests. No matter how well a computer model is parameterized, all modelers know the shortfalls of their mathematical characterization of complex phenomena. How scientific projects are designed and how their data are analyzed and interpreted all influence the level of uncertainty in the results and extrapolations based on them (Glover et al., 2011). These issues are of great importance in OA research, but not uniquely so.

Careful study design cannot eliminate uncertainty from our understanding of natural phenomena. Many processes in nature vary in space and time in nonlinear fashions that challenge precise prediction. In the context of OA, this complexity makes predicting the exact biogeochemical conditions at a particular location or time extraordinarily difficult. When dealing with biological systems, we must also contend with the reality that each individual is unique and may respond differently to its environment. A number of strategies can increase understanding of natural variability, including collecting data for extended lengths of time, building observing systems with proper resolution to characterize variation, carefully cataloging communities experiencing naturally high CO_2 conditions over ecological time scales, and developing models with adequate resolution to capture small-scale phenomena.

All scientific disciplines seek to detect real patterns from noise; each discipline has its own standards that determine how these signal detection processes should work. Interdisciplinary research fields, like OA, can suffer disconnects where

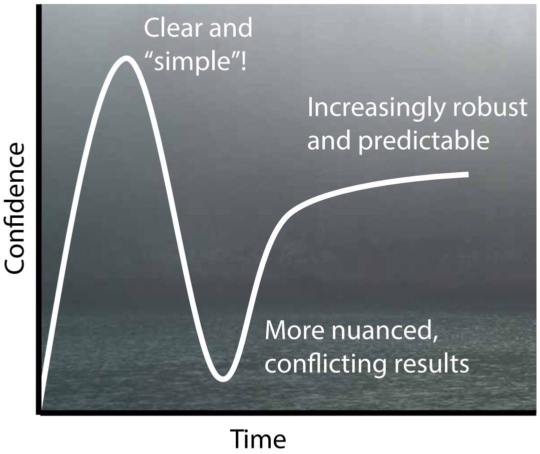


FIGURE 1. Schematic of the procession of confidence in understanding of ocean acidification (OA) through time. With only a few studies early in the field, things appear quite clear and simple, but this impression declines as more information adds to the paradigm. Eventually, the level of confidence stabilizes as more lines of evidence point to the bounds of what is known well versus what is not easily predictable. In addition to improved predictions, more robust estimates of error are gained through time.

evidence commonly accepted as strong in one field (e.g., community ecology) looks wildly uncertain to others (e.g., analytical chemistry). To decision makers, debates among disciplines can make even the best science seem too unsettled to warrant timely action. To maintain credibility and advance the uptake of its findings, the OA community must be clear and transparent as it evaluates sources of uncertainty. Tackling issues of communicating uncertainty among fields and with external audiences is a challenging but valuable opportunity for shaping how scientists design, analyze, and present their results.

From a communications standpoint, there is value in focusing not on uncertainty—the degree to which our information is imperfect—but rather on those aspects of the system that are supported by strong evidence (things that are more on the "certain" end of the spectrum, as in Box 1). Decades of research have resulted in many concepts that are known with a high degree of certainty across chemistry, biology, ecology, and social sciences (Figure 2). While many factors remain poorly understood, these core concepts provide an intellectual framework that can serve to guide future research and make predictions about the future impacts of current actions. The preferred approaches for communication will vary by target audience, which will range from schoolchildren to policymakers at national and international levels.

Informing the policy and management arenas about OA requires greater clarity about how to synthesize disparate lines of evidence and explain what OA means to particular species, ecosystems, or communities. The clearest example of how OA has already contributed to such conversations is the US Northwest shellfish industry (Barton et al., 2012). This example links change in ocean carbon chemistry to its effects on a commercially cultivated species to how the loss of oyster larvae affects the viability of the shellfish industry in the region (Kelly et al., 2013a). Multiple lines of evidence together present a powerful story about the potential serious impacts of OA. For other systems, links between OA and species response are currently understood as generalities. For example, if OA affects a particular species in the laboratory, will its response be the same in the field, where environmental conditions vary more and in different ways and ecological interactions occur? If so, will the effects on the species cascade throughout its food web? These questions become more complicated when we consider OA as just one of a host of co-occurring and interacting environmental changes that impact ecosystems simultaneously (Breitburg et al., 2015, in this issue).

In this article, we discuss several aspects of uncertainty in the science of ocean acidification, and outline some options and cautions for accommodating them. We then offer strategies for communicating the uncertain science of ocean acidification, drawing on lessons learned from the global climate change community. We must recognize that some, and possibly much, current uncertainty around the ecosystem consequences of OA will persist. Those working on OA from a policy or management perspective will likely be required to make decisions long before science can advance to the point where ecological and human consequences of OA can be projected with high accuracy. As such, developing

Box 1. Ocean Acidification Is a "Certainty"

The underlying process of OA is relatively simple and well-understood chemistry, but the field draws its sense of urgency because these chemical phenomena interact with other aspects of marine systems. The potential biological, ecological, and socio-economic impacts of OA are of far greater societal concern than the shifts in seawater ion concentrations. While we have much to learn about the progression of OA and how it will affect marine species and ecosystems, the field relies on several facts that are well supported by decades of experimental evidence:

1. The concentration of carbon dioxide in the atmosphere equilibrates with the concentration of carbon dioxide in the surface ocean (e.g., Henry's Law).

2. Carbon dioxide is an acid gas, forming carbonic acid when dissolved in water.

3. Increasing the amount of carbon dioxide dissolved in seawater decreases the saturation state for calcium carbonate minerals, which has consequences for the many species that grow and maintain calcium carbonate structures (Feely et al., 2004; Kleypas et al., 2006; Fabricius et al., 2011; Kroeker et al., 2013).

4. Numerous physiological processes are sensitive to alterations in concentrations of hydrogen, bicarbonate, and carbonate ions in seawater, and, therefore, OA may result in significant changes at the levels of organisms, populations, and ecosystems (Gattuso and Hansson, 2011; Kroeker et al., 2013).

5. Substantial changes are observed in some present-day coral reef and temperate benthic communities exposed to elevated CO_2 at ocean CO_2 seeps (e.g., Fabricius et al., 2011; see Box 2). Past OA episodes in the geological record are often marked by major extinction events of marine species, though OA typically occurred in conjunction with other major environmental changes, including climate change (Hönisch et al., 2012; Clarkson et al., 2015).

such precise predictions may not be the most effective priority for the research community. The more salient challenge is how best to provide useful information on the range of possible outcomes of OA that incorporates both experimental and natural uncertainty.

UNCERTAINTIES ASSOCIATED WITH BRIDGING BETWEEN DISCIPLINES

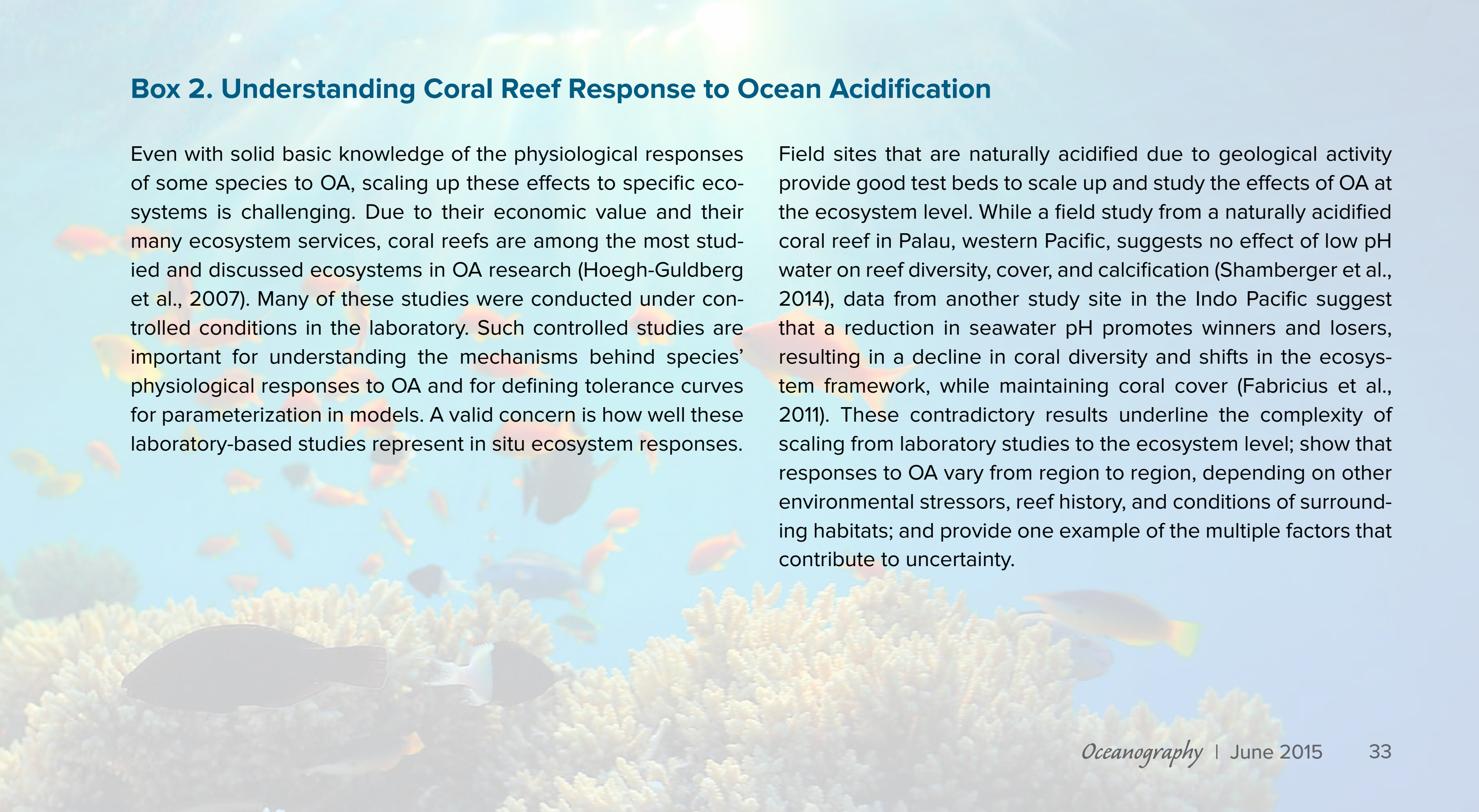
Uncertainty enters into OA research in different ways from different lines of investigation. In order to make predictions about complex coupled physical-chemical-biological systems, inferences must be drawn from multiple disciplines. This creates many avenues where lack of clarity about confidence in evidence can lead to false impressions of certainty. Appropriately propagating uncertainty is critical for sound synthesis of research findings. Statistical techniques for such error propagation are well accepted within formal analyses. The same care must be observed in cases where explanations are more conceptual.

Below, we address issues of uncertainty in species-response experiments, modeling responses of ecological communities to OA, and characterization of local and global biogeochemistry under OA. We see these avenues of research as both highly uncertain and essential for answering societal concerns about OA.

Species-Response Experiments

Much of the concern about OA impacts arises from reports in the literature regarding physiological responses of organisms subjected to elevated CO_2 conditions (summarized by Kroeker et al., 2010, 2013). This literature is based on a limited number of studies on a small fraction of marine species, mostly over relatively short time scales. Many believe that the antidote to this type of uncertainty is gaining additional knowledge through more research, but, in a field as immature as OA, new information often expands the universe of potential unknowns before reducing uncertainty. This presents a communication challenge, for discovery of new information can reveal a lack of understanding of fundamental physiological processes or phenomena, and it may appear that we know less as we learn more (Figure 1). For instance, species response studies have produced varying and contradictory results on impacts to growth and survival not only among closely related species (Miller et al., 2009) but even within the same species (Kelly et al., 2013b). This type of uncertainty is expected in the developmental stages of a field as studies illuminate deficiencies in knowledge about biochemical pathways, adaptive strategies, genetic variations, or even natural history unappreciated at the start of an experiment. Future research can delve into causes of these uncertainties (e.g., possible effects of genetic differences).

Characteristic of a young research field, OA experiments and observations began by testing relatively simple hypotheses, which have become more complex with additional knowledge. To date, most experiments addressing OA have focused on individual species' responses to just OA over relatively short durations. While these simple studies are needed to set the bounds of understanding of how sensitive species may be to OA, short-term, single-stressor studies on individual species provide a limited basis for understanding ecosystem responses to future change in a



Box 2. Understanding Coral Reef Response to Ocean Acidification

Even with solid basic knowledge of the physiological responses of some species to OA, scaling up these effects to specific ecosystems is challenging. Due to their economic value and their many ecosystem services, coral reefs are among the most studied and discussed ecosystems in OA research (Hoegh-Guldberg et al., 2007). Many of these studies were conducted under controlled conditions in the laboratory. Such controlled studies are important for understanding the mechanisms behind species' physiological responses to OA and for defining tolerance curves for parameterization in models. A valid concern is how well these laboratory-based studies represent in situ ecosystem responses.

Field sites that are naturally acidified due to geological activity provide good test beds to scale up and study the effects of OA at the ecosystem level. While a field study from a naturally acidified coral reef in Palau, western Pacific, suggests no effect of low pH water on reef diversity, cover, and calcification (Shamberger et al., 2014), data from another study site in the Indo Pacific suggest that a reduction in seawater pH promotes winners and losers, resulting in a decline in coral diversity and shifts in the ecosystem framework, while maintaining coral cover (Fabricius et al., 2011). These contradictory results underline the complexity of scaling from laboratory studies to the ecosystem level; show that responses to OA vary from region to region, depending on other environmental stressors, reef history, and conditions of surrounding habitats; and provide one example of the multiple factors that contribute to uncertainty.

world where OA is one of many environmental shifts. To this end, multi-species studies that expose organisms to multiple, simultaneous stressors for many generations are needed. Such work acknowledges that species response to OA may change when other stressors are added, and that interactions with other species influence responses to the physical environment (Rosa and Seibel, 2008; Kroeker et al., 2013; Roberts et al., 2013; Sanford et al., 2014). However, increasing experimental complexity infinitely is not practical, or necessarily desirable. General natural history and ecological knowledge can be used to define parameters most important to consider and what ecological interactions most strongly influence the focal species. Capacity for conducting experiments over several generations must be expanded to properly address uncertainty about species adaptation. At present, the question of the adaptive potential of species to respond to OA remains one of the most exciting avenues of research, but also one of the greatest sources of uncertainty. Research studies that show adaptive potential exists are very recent (e.g., Collins, 2011; Sunday et al., 2012; Pespeni et al., 2013; Tatters et al., 2013).

Meta-analysis provides a tool for exploring the generality of experimental results by identifying patterns from large swaths of research (e.g., Harvey et al., 2013; Kroeker et al., 2013; Wittmann and Portner, 2013). However, these syntheses are vulnerable to preferences in the research community for publishing studies that demonstrate negative effects of OA conditions on focal species. Researchers express a concern that "no-effect" papers do not fare well in the peer-review and manuscript selection process (Franco et al., 2014). To prevent these summarizing analyses from inadvertently biasing the literature and hiding an important metric of uncertainty, the research community, from editors to reviewers to publishing scientists, must commit to publishing the full range of responses to OA, including null responses. Alternate publication strategies—such as community data archives—may alleviate the burden on scientists of searching for venues for less "exciting" results.

Scaling Up to Ecological Communities

The complexity of the natural world limits the extent to which carefully controlled, single-species laboratory studies can ever mimic the natural variability of the chemical habitat, the influence of multiple stressors, and the species interactions that characterize marine habitats (Andersson et al., 2015, in this issue). Modeling and synthesis studies build on knowledge gained at the individual scale to project outcomes at much larger or longer scales. "Modeling" takes numerous forms; the simplest are conceptual models—"what if" exercises that can make connections between short-term, single-species studies and what might happen in the natural world. These simple models often feature in the discussion sections of research studies, extrapolating the results from a short test while accounting for unaddressed uncertainties and factors poorly, if at all. More complicated modeling forms, such as meta-analyses, empirical statistical models, or mechanistic numerical models, have more robust procedures for evaluating uncertainty, but, again, typically

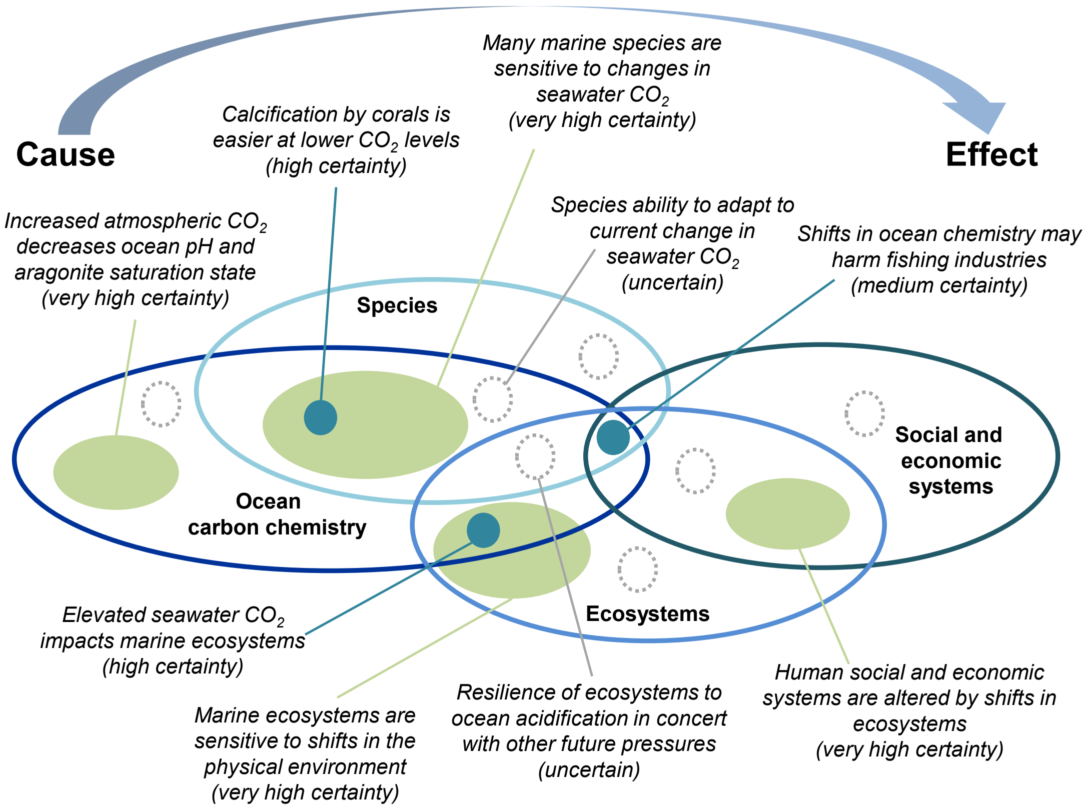


FIGURE 2. Knowledge of ocean acidification includes a number of concepts that are known with high level of certainty. The large circles represent general categories of knowledge. Within these fields are core concepts known with certainty (green shaded ovals) supported by specific pieces of evidence (blue circles) and other issues that are uncertain (dashed circles). The broad categories of knowledge are connected to each other, and the interfaces (for instance, between impacts to species, ecosystems, and social and economic systems) constitute the areas where synthetic knowledge is generated by interdisciplinary work and understanding is most likely to inform society about the impacts of ocean acidification.

cannot reflect factors that were not captured in the original experimental or field data or the theoretical framework used in model design and validation.

The validity of hypotheses generated from simple models linking experimental results to marine species in nature depends on the certainty and generality of the underlying results. Natural conditions may exacerbate or ameliorate impacts observed in the laboratory. For example, food supply in the laboratory environment is not provided at the same levels as in nature and may influence response to experimental chemistry conditions. Field studies in environments naturally experiencing wide swings in OA parameters (e.g., eutrophic coastal systems, upwelling regions) can give insight into whether and how species employ adaptive strategies. Studies of CO_2 vent systems can elucidate some indirect effects of acidification on community members (Garrard et al., 2014). Ecological interactions may also exacerbate the potential impacts of OA on a population (Cohen and Holcomb, 2009; Hettinger et al., 2013; Sanford et al., 2014). Research into underlying biochemical and evolutionary mechanisms linked to OA responses may provide important context for shaping conceptual models, a concept counterintuitive to the idea that such "basic" research has a limited place in applied research fields. In fact, mechanistic understanding of responses to environmental conditions is foundational for developing models and parameterizing scenarios projecting population or ecosystem responses to OA.

Detailed numerical models offer insight into ecological and economic consequences of OA that are not tractable to direct experimentation. Such models can be built from simple sets of rules, applying them to higher levels of organization to allow exploration of emergent behavior and thresholds for groups of species (e.g., Kaplan et al., 2010; Griffith et al., 2011; Busch et al., 2013) that can be verified by comparison with field data. Despite their promise, such models are not a panacea; it is fair to raise the question of whether the ocean acidification field is really ready to link simple experiments and observations with detailed predictions about future ecosystems. Improperly reported models can suggest an overly confident assessment of potential outcomes. When well designed, however, modeling studies can help to explore different scenarios and enhance our understanding about the likelihood and certainty of potential outcomes. Careful and explicit treatment of uncertainty will help researchers and nonscientists alike appreciate the opportunities and limitations of knowledge gained from numerical models. Reporting model output with an emphasis on likelihood and uncertainty and discussing how model results provide hypotheses for future studies will advance these priorities.

Characterizing Local and Global Biogeochemistry

Dynamic ocean processes that contribute to the observed natural variation in the chemical habitat of organisms operate over time and space in ways that are too broad for manipulative experiments; their investigation is best accomplished with models. Although researchers are highly certain about the broad-scale effects of increased atmospheric CO_2 levels on ocean carbon chemistry, making specific predictions about individual locations is not straightforward. The ocean carbon system is driven by a dynamic interplay of physical and biological factors, especially in coastal areas with complex circulation and additional interactions among atmospheric, land-based, and biological activities (Feely et al., 2010; Cai et al., 2011). Earth system models include representations of the atmosphere, the land surface, the ocean, and sea ice as well as coarse depictions of the lower trophic levels of ecosystems (Bopp et al., 2013), all of which influence the global carbon cycle and marine carbon chemistry.

Currently, due to computational constraints, global models are run at a resolution too coarse to represent many mesoscale physical oceanic features (e.g., coastal upwelling zones and eddies), which may have large effects on local carbon chemistry dynamics. Highly resolved regional biogeochemical models (${}^{1}/_{6}{}^{\circ}$ to ${}^{1}/_{12}{}^{\circ}$) are more likely to represent these features, but they currently fail to incorporate interactions of all critical components and remain too coarse for application to some systems (e.g., nearshore waters, estuaries, coral reefs). In this realm, future developments in modeling capability, such as nested regional and global Earth system models may reduce the uncertainty of predictions based on these tools.

Biogeochemical models are often forced with satellite and in situ atmosphere and ocean data. The degree of uncertainty in the model output therefore strongly depends on how well the available observations represent the system. Dynamic regions are often undersampled in certain seasons (e.g., polar systems in winter), which introduces measurement uncertainty that directly constrains certainty of model output. Various techniques (e.g., hindcast simulations [Stow et al., 2009], comparisons of present-day simulations) exist to evaluate model effectiveness, and they should be employed. It is important to recognize that future simulations include additional, unquantifiable uncertainty associated with assumptions that parameterizations valid under present-day conditions (e.g., Redfield ratios) will still apply in future oceans.

End users of projections from complex suites of coupled models must recognize that these tools propagate errors that decrease the confidence of predictions based upon them. Techniques such as integrating across multiple models can highlight the underlying strength of understanding. As models become more complex, using scenarios to estimate uncertainty becomes ever more important so that uncertainty can be incorporated into risk analysis frameworks. Events that may or may not happen (low likelihood with high uncertainty) may still deserve inclusion in risk analysis if the consequences of those events are high. Such analyses are well accepted in management processes where the emphasis is often on preventing dire consequences (e.g., tsunami and oil spill planning exercises).

Projections about future oceans developed with coupled biogeochemical, ecological, and human system models (e.g., California Current Atlantis ecosystem model) give valuable insights into the ecological and societal impacts of OA. They can help direct research activities, highlight consequences, and may be the most useful way to transfer knowledge from research circles to policy action (Boehm et al., 2015, in this issue).

COMMUNICATING UNCERTAINTY

OA science is already demonstrating relevance outside the realm of research, and people are making policy and management decisions based on summary understanding (e.g., Washington State Executive Order of 12-07 based on Ruckelshaus et al. [2012] and Feely et al. (2013]). Decision makers in a variety of contexts, ranging from industry to ocean policy and management (e.g., Hoegh-Guldberg et al., 2014; Boehm et al., 2015, in this issue; Cooley et al., 2015, in this issue), can benefit from actionable information on what is known and what is not known. In this context of rapidly advancing policy-relevant science, approaches used in communicating the science of climate change over the past decades can suggest best practices for communicating OA research. For example, the broad, interdisciplinary implications of OA require insights and communication across disciplines. Both transparency and expert judgment about what fieldwork, experiments, and models suggest about responses to OA are essential. However, the concept of uncertainty presents a challenge to effective science communication (Fischhoff, 2013). Here, we discuss ways to handle this challenge.

A Challenge in Managing Risks

OA and climate change share some of the same complexities that pose challenges for decision making (Kandlikar et al., 2005; Jones and Preston, 2011; Jones et al., 2014). Most fundamentally, the uncertainties about future outcomes, which will unfold over many decades and have potentially large consequences, are persistent. The uncertainties range from future levels of carbon dioxide emissions to the ecological and socioeconomic consequences of OA acting in concert with other simultaneous stressors. Recognition that making decisions in a changing climate involves managing risks has increased (Jones and Preston, 2011; IPCC, 2014), where risk can be thought of as the potential for consequences when something of human value is at stake and the outcome is uncertain.

A strategy for communication of risks relies on assessing the widest possible range of potential impacts, including those with low probability but large consequences, and then summarizing knowledge of the likelihood and consequences of different outcomes. A focus on risk acknowledges that exact future outcomes will never be known with complete certainty and that uncertainty is therefore part of the decision-making context. Communicating risks often requires synthesis of scientific understanding across disciplines; it most usefully involves (1) characterizing the changing physical hazards, (2) identifying the species, ecosystems, and societies exposed to these changes, and (3) describing their vulnerabilities and sensitivities, including their abilities to adapt (Jones and Preston, 2011; Oppenheimer et al., 2014).

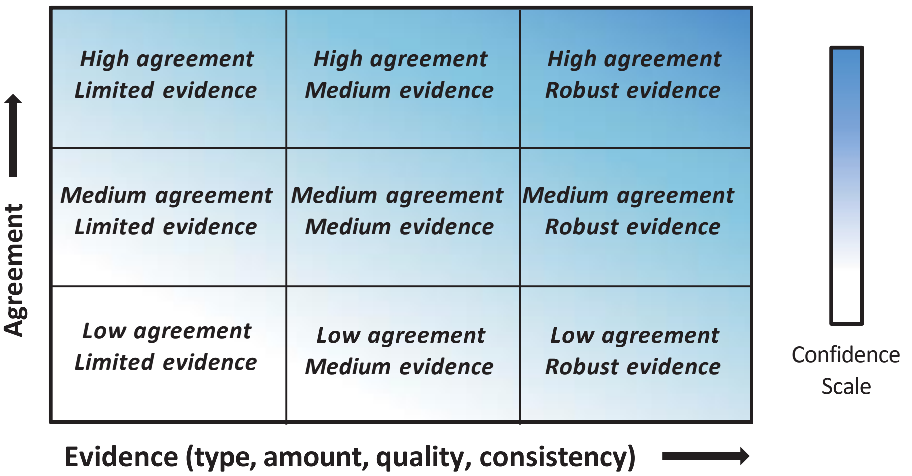
Evaluating the State of Knowledge

A first step in communicating current understanding of risk and uncertainty is evaluating the state of knowledge. Available tools include reviews of the literature; quantitative syntheses, including meta-analyses, expert surveys, and elicitations; and assessment. All of these techniques both enable and require explicit treatment of the uncertainty of their findings. Expert surveys and elicitations (e.g., Kriegler et al., 2009; Gattuso et al., 2013), which involve formal methods for gathering expert perspectives, are useful when policy-relevant questions cannot be fully answered by available scientific evidence. Here, "assessment" refers to a process of providing comprehensive evaluation of scientific knowledge to inform decision making on complex and broad issues. As examples, the Intergovernmental Panel on Climate Change (IPCC) and some US Integrated Ecosystem Assessments have provided periodic assessments of the impacts of climate change, which have included assessment of ocean acidification (e.g., Harvey et al., 2014; Hoegh-Guldberg et al., 2014; Pörtner et al., 2014). As is typical of large-scale assessment, IPCC reports involve multiple rounds of monitored scientific review to ensure the scientific rigor of conclusions. They also include participation by governments to make sure the topics addressed are relevant to decision makers and to ensure confidence among these decision makers that the conclusions have been developed through a transparent and fair process.

Communicating the State of Knowledge

Scientists working on ocean acidification are often asked for their expert opinion about how a species may respond to OA or what ecological changes we should expect in a specific location. Conceptual models are useful for communicating answers to these questions with individuals or groups outside of the scientific community. While they are not subject to the same level of scrutiny as computational models, they are influential and effective communication tools. Conceptual models can be communicated via words alone, though they are often well suited for graphical representation and even animations.

The process through which scientific information is evaluated and communicated can be as important to its usefulness as the credibility and rigor of the information itself (Cash et al., 2002; Jasanoff, 2010). Communicating scientific understanding effectively to decision makers is different from interacting with fellow scientists and is also different from advocacy. Informing decision making benefits from a non-persuasive approach, where uncertainties are acknowledged and the evidence speaks for itself (Pidgeon and Fischhoff, 2011). Policy choices and decisions informed by science often additionally entail value judgments that go beyond the science. Providing scientific information productively can thus mean characterizing possible outcomes and the consequences of different policy options, while recognizing the importance of values and goals in subsequent decisions (IPCC, 2014).



High agreement *Limited evidence*	*High agreement* *Medium evidence*	*High agreement* *Robust evidence*
Medium agreement *Limited evidence*	*Medium agreement* *Medium evidence*	*Medium agreement* *Robust evidence*
Low agreement *Limited evidence*	*Low agreement* *Medium evidence*	*Low agreement* *Robust evidence*

FIGURE 3. Defined approaches to evaluating and communicating the degree of certainty in scientific findings can improve their accessibility and traction. This figure shows, for example, different levels of evidence and agreement and their relationships to increasing confidence. Evidence is most robust when there are multiple lines of independent evidence. *Figure used with permission from Field et al. (2014)*

For researchers unfamiliar with policy nuance, yet tasked with communicating ocean acidification science to diverse audiences, designated terminology to describe levels of certainty about policy-relevant science can be used to communicate scientific understanding in a balanced and comprehensive way (Figure 3; Gattuso et al., 2014; Hoegh-Guldberg et al., 2014; IPCC, 2014; Pörtner et al., 2014). For example, since its Third Assessment Report, the IPCC has provided guidance on systematically communicating the degree of certainty in assessment findings, with the guidance iteratively updated and improved over time (Swart et al., 2009; Mastrandrea and Mach, 2011; Burkett et al., 2014). For each statement summarizing current scientific understanding, assessment authors base their assessment on the available scientific evidence, which can include the degree of agreement about this evidence (Mastrandrea et al., 2010, 2011; IPCC, 2014). Levels of confidence are then used to communicate judgments about the validity of assessment findings, and likelihood terms express the chance of specific outcomes occurring. Central to the guidance is the importance of communicating where multiple lines of independent evidence point to the same conclusion versus where competing explanations exist; characterizing the widest possible range of potential outcomes; providing information on the sources of uncertainties; and clearly linking each assessment finding and its uncertainty terminology to a traceable account of the evaluated literature (Mastrandrea et al., 2010, 2011). Expanding the use of calibrated language to the standard work of scientists studying OA and its potential effects would ease reporting challenges throughout the endeavor.

CONCLUSIONS

Although the focus of this article has been *un*certainty related to OA, the questions that face decision makers are those of certainty. How certain are we that OA will affect marine ecosystems? What do we know about the scope of those impacts? Regardless of the levels of statistical confidence that emerge from experiments or models, researchers should keep in mind that decision makers are more interested in whether potential consequences are adverse enough or certain enough to justify the costs of action.

The political and social contexts in which the OA field has emerged have enhanced the influence of scientific information on societal action. We argue that scientists' ability to accurately assess and communicate the certainties and uncertainties of our knowledge on OA and its impacts will help retain this influence into the future. As OA gains wider recognition in the future, there is great value in nurturing open lines of communication among all stakeholders, from decision makers to industry leaders, regulators, resource managers, scientists, and the general public. Given that OA research is informing decisions at the same time as the field is developing, there is opportunity for two-way communication and allowing societal needs to shape the way the science is done and presented.

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REFERENCES

Andersson, A.J., D.I. Kline, P.J. Edmunds, S.D. Archer, N. Bednaršek, R.C. Carpenter, M. Chadsey, P. Goldstein, A.G. Grottoli, T.P. Hurst, and others. 2015. Understanding ocean acidification impacts on organismal to ecological scales. *Oceanography* 28(2):16–27, http://dx.doi.org/10.5670/oceanog.2015.27.

Barton, A., B. Hales, G.G. Waldbusser, C. Langdon, and R.A. Feely. 2012. The Pacific oyster, *Crassostrea gigas*, shows negative correlation to naturally elevated carbon dioxide levels: Implications for near-term ocean acidification effects. *Limnology and Oceanography* 57:698–710, http://dx.doi.org/10.4319/lo.2012.57.3.0698.

Boehm, A.B., M.Z. Jacobson, M.J. O'Donnell, M. Sutula, W.W. Wakefield, S.B. Weisberg, and E. Whiteman. 2015. Ocean acidification science needs for natural resource managers of the North American west coast. *Oceanography* 28(2):170–181, http://dx.doi.org/10.5670/oceanog.2015.40.

Bopp, L., L. Resplandy, J.C. Orr, S.C. Doney, J.P. Dunne, M. Gehlen, P. Halloran, C. Heinze, T. Ilyina, R. Séférian, and others. 2013. Multiple stressors of ocean ecosystems in the 21st century: Projections with CMIP5 models. *Biogeosciences* 10:6,225–6,245, http://dx.doi.org/10.5194/bg-10-6225-2013.

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

Burkett, V.R., A.G. Suarez, M. Bindi, C. Conde, R. Mukerji, M.J. Prather, A.L. St. Clair, and G.W. Yohe. 2014. Point of departure. Pp. 169–194 in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, and others, eds, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, http://dx.doi.org/10.1017/CBO9781107415379.006.

Busch, D.S., C.J. Harvey, and P. McElhany. 2013. Potential impacts of ocean acidification on the Puget Sound food web. *ICES Journal of Marine Science* 70:823–833, http://dx.doi.org/10.1093/icesjms/fst061.

Cai, W.-J., X. Hu, W.-J. Huang, M.C. Murrell, J.C. Lehrter, S.E. Lohrenz, W.-C. Chou, W. Zhai, J.T. Hollibaugh, Y. Wang, and others. 2011. Acidification of subsurface coastal waters enhanced by eutrophication. *Nature Geoscience* 4:766–770, http://dx.doi.org/10.1038/ngeo1297.

Cash, D., W. Clark, F. Alcock, N. Dickson, N. Eckley, and J. Jäger. 2002. *Salience, Credibility, Legitimacy, and Boundaries: Linking Research, Assessment, and Decision Making*. Faculty Research Working Papers Series RWP02-046, John F. Kennedy School of Government, Harvard University, Cambridge, MA, USA, 24 pp.

Clark, J.S., S.R. Carpenter, M. Barber, S. Collins, A. Dobson, J.A. Foley, D.M. Lodge, M. Pascual, R. Pielke Jr., W. Pizer, and others. 2001. Ecological forecasts: An emerging imperative. *Science* 293:657–660, http://dx.doi.org/10.1126/science.293.5530.657.

Clarkson, M.O., S.A. Kasemann, R.A. Wood, T.M. Lenton, S.J. Daines, S. Richoz, F. Ohnemueller, A. Meixner, S.W. Poulton, and E.T. Tipper. 2015. Ocean acidification and the Permo-Triassic mass extinction. *Science* 348:229–232, http://dx.doi.org/10.1126/science.aaa0193.

Cohen, A.L., and M. Holcomb. 2009. Why corals care about ocean acidification: Uncovering the mechanism. *Oceanography* 22(4):118–127, http://dx.doi.org/10.5670/oceanog.2009.102.

Collins, S. 2011. Competition limits adaptation and productivity in a photosynthetic alga at elevated CO_2. *Proceedings of the Royal Society B* 278:247–255, http://dx.doi.org/10.1098/rspb.2010.1173.

Cooley, S.R., E.B. Jewett, J. Reichert, L. Robbins, G. Shrestha, D. Wieczorek, and S.B. Weisberg. 2015. Getting ocean acidification on decision makers' to-do lists: Dissecting the process through case studies. *Oceanography* 28(2):198–211, http://dx.doi.org/10.5670/oceanog.2015.42.

Fabricius, K.E., C. Langdon, S. Uthicke, C. Humphrey, S. Noonan, G. De'ath, R. Okazaki, N. Muehllehner, M.S. Glas, and J.M. Lough. 2011. Losers and winners in coral reefs acclimatized to elevated carbon dioxide concentrations. *Nature Climate Change* 1:165–169, http://dx.doi.org/10.1038/nclimate1122.

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

Feely, R.A., T. Klinger, J. Newton, and M. Chadsey, eds. 2012. *Scientific Summary of Ocean Acidification in Washington State Marine Waters.* Washington Shellfish Initiative Blue Ribbon Panel on Ocean Acidification, NOAA Oceans and Atmospheric Research Special Report, 176 pp, https://fortress.wa.gov/ecy/publications/publications/1201016.pdf.

Feely, R.A., C.L. Sabine, K. Lee, W. Berelson, J. Kleypas, V.J. Fabry, and F.J. Millero. 2004. Impact of anthropogenic CO_2 on the $CaCO_3$ system in the oceans. *Science* 305:362–366, http://dx.doi.org/10.1126/science.1097329.

Field, C.B., V.R. Barros, K.J. Mach, M.D. Mastrandrea, M. van Aalst, W.N. Adger, D.J. Arent, J. Barnett, R. Betts, T.E. Bilir, and others, eds. 2014. Technical summary. Pp. 35–94 in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, and others, eds, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, http://dx.doi.org/10.1017/CBO9781107415379.004.

Fischhoff, B. 2013. The sciences of science communication. *Proceedings of the National Academy of Sciences of the United States of America* 110:14,033–14,039, http://www.pnas.org/content/110/Supplement_3/14033.full.

Franco, A., N. Malhotra, and G. Simonovits. 2014. Publication bias in the social sciences: Unlocking the file drawer. *Science* 345:1,502–1,505, http://dx.doi.org/10.1126/science.1255484.

Garrard, S.L., M.C. Gambi, M.B. Scipione, F.P. Patti, M. Lorenti, V. Zupo, D.M. Paterson, and M.C. Buia. 2014. Indirect effects may buffer negative responses of seagrass invertebrate communities to ocean acidification. *Journal of Experimental Marine Biology and Ecology* 461: 31–38, http://dx.doi.org/10.1016/j.jembe.2014.07.011.

Gattuso, J.-P., P. Brewer, O. Hoegh-Guldberg, J.A. Kleypas, H.-O. Pörtner, and D. Schmidt. 2014. Ocean acidification: Cross-chapter box. Pp. 97–166 in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, and others, eds, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, http://dx.doi.org/10.1017/CBO9781107415379.005.

Gattuso, J.P., and L. Hansson, eds. 2011. *Ocean Acidification*. Oxford University Press, Oxford, UK, 326 pp.

Gattuso, J.-P., K.J. Mach, and G. Morgan. 2013. Ocean acidification and its impacts: An expert survey. *Climatic Change* 117:725–738, http://dx.doi.org/10.1007/s10584-012-0591-5.

Glover, D.M., W.J. Jenkins, and S.C. Doney. 2011. *Modeling Methods for Marine Science*. Cambridge University Press, Cambridge, UK, 592 pp.

Griffith, G.P., E.A. Fulton, and A.J. Richardson. 2011. Effects of fishing and acidification-related benthic mortality on the southeast Australian marine ecosystem. *Global Change Biology* 17:3,058–3,074, http://dx.doi.org/10.1111/j.1365-2486.2011.02453.x.

Hall-Spencer, J.M., R. Rodolfo-Metalpa, S. Martin, E. Ransome, M. Fine, S.M. Turner, S.J. Rowley, D. Tedesco, and M.-C. Buia. 2008. Volcanic carbon dioxide vents show ecosystem effects of ocean acidification. *Nature* 454:96–99, http://dx.doi.org/10.1038/nature07051.

Harvey, B.P., D. Gwynn-Jones, and P.J. Moore. 2013. Meta-analysis reveals complex marine biological responses to the interactive effects of ocean acidification and warming. *Ecology and Evolution* 3:1,016–1,030, http://dx.doi.org/10.1002/ece3.516.

Harvey, C.J., N. Garfield, E.L. Hazen, and G.D. Williams, eds. 2014. *The California Current Integrated Ecosystem Assessment: Phase III Report*. http://www.noaa.gov/iea/CCIEA-Report/pdf/index.html.

Hettinger, A., E. Sanford, T.M. Hill, J.D. Hosfelt, A.D. Russell, and B. Gaylord. 2013. The influence of food supply on the response of Olympia oyster larvae to ocean acidification. *Biogeosciences* 10:6,629–6,638, http://www.biogeosciences.net/10/6629/2013/bg-10-6629-2013.pdf.

Hoegh-Guldberg, O., R. Cai, P.G. Brewer, V.J. Fabry, K. Hilmi, S. Jung, E.S. Poloczanska, and S. Sundby. 2014. The Ocean. Pp. 1,655–1,731 in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. V.R. Barros, C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, and others, eds, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Hoegh-Guldberg, O., P.J. Mumby, A.J. Hooten, R.S. Steneck, P. Greenfield, E. Gomez, C.D. Harvell, P.F. Sale, A.J. Edwards, K. Caldeira, and others. 2007. Coral reefs under rapid climate change and ocean acidification. *Science* 318:1,737–1,742, http://dx.doi.org/10.1126/science.1152509.

Hönisch, B., A. Ridgwell, D.N. Schmidt, E. Thomas, S.J. Gibbs, A. Sluijs, R. Zeebe, L. Kump, R.C. Martindale, S.E. Greene, and others. 2012. The geological record of ocean acidification. *Science* 335:1,058–1,063, http://dx.doi.org/10.1126/science.1208277.

IPCC. 2014. Summary for policymakers. Pp. 1–32 in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, and others, eds, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, http://dx.doi.org/10.1017/CBO9781107415379.003

Jasanoff, S. 2010. Testing time for climate science. *Science* 328:695–696, http://dx.doi.org/10.1126/science.1189420.

Jones, R.N., A. Patwardhan, S.J. Cohen, S. Dessai, A. Lammel, R.J. Lempert, M.M.Q. Mirza, and H. von Storch. 2014. Foundations for decision making. Pp. 185–228 in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, and others, eds, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jones, R.N., and B.L. Preston. 2011. Adaptation and risk management. *WIREs Climate Change* 2:296–308, http://dx.doi.org/10.1002/wcc.97.

Kandlikar, M., J. Risbey, and S. Dessai. 2005. Representing and communicating deep uncertainty in climate-change assessments. *Comptes Rendus Geoscience* 337:443–455.

Kaplan, I.C., P.S. Levin, M. Burden, and E.A. Fulton. 2010. Fishing catch shares in the face of global change: A framework for integrating cumulative impacts and single species management. *Canadian Journal of Fisheries Science* 67:1,968–1,982, http://dx.doi.org/10.1139/F10-118.

Kelly, R.P., S.R. Cooley, and T. Klinger. 2013a. Narratives can motivate environmental action: The Whiskey Creek ocean acidification story. *Ambio* 43:592–599, http://dx.doi.org/10.1007/s13280-013-0442-2.

Kelly, M.W., J.L. Padilla-Gamiño, and G.E. Hofmann. 2013b. Natural variation, and the capacity to adapt to ocean acidification in the keystone sea urchin *Strongylocentrotus purpuratus*. *Global Change Biology* 19: 2536-2546, http://dx.doi.org/10.1111/gcb.12251.

Kleypas, J.A., R.A. Feely, V.J. Fabry, C. Langdon, C.L. Sabine, and L.L. Robbins. 2006. *Impacts of Ocean Acidification on Coral Reefs and Other Marine Calcifiers: A Guide for Future Research*. NSF, NOAA, and the US Geological Survey, St. Petersburg, FL, workshop report, April 18–20, 2005, 88 pp.

Kriegler, E., J.W. Hall, H. Held, R. Dawson, and H.J. Schellnhuber. 2009. Imprecise probability assessment of tipping points in the climate system. *Proceedings of the National Academy of Sciences of the United States of America* 106:5,041–5,046, http://dx.doi.org/10.1073/pnas.0809117106.

Kroeker, K.J., R.L. Kordas, R. Crim, I.E. Hendriks, L. Ramajo, G.S. Singh, C.M. Duarte, and J.-P. Gattuso. 2013. Impacts of ocean acidification on marine organisms: Quantifying sensitivities and interaction with warming. *Global Change Biology* 19:1,884–1,896, http://dx.doi.org/10.1111/gcb.12179.

Kroeker, K.J., R.L. Kordas, R.N. Crim, and G.G. Singh. 2010. Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. *Ecology Letters* 13:1,419–1,434, http://dx.doi.org/10.1111/j.1461-0248.2010.01518.x.

Mastrandrea, M.D., C.B. Field, T.F. Stocker, O. Edenhofer, K.L. Ebi, D.J. Frame, H. Held, E. Kriegler, K.J. Mach, P.R. Matschoss, and others. 2010. *Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties*. Intergovernmental Panel on Climate Change (IPCC), 7 pp., https://www.ipcc.ch/pdf/supporting-material/uncertainty-guidance-note.pdf.

Mastrandrea, M.D., and K.J. Mach. 2011. Treatment of uncertainties in IPCC Assessment Reports: Past approaches and considerations for the Fifth Assessment Report. *Climatic Change* 108:659–673, http://dx.doi.org/10.1007/s10584-011-0177-7.

Mastrandrea, M.D., K.J. Mach, G.-K. Plattner, O. Edenhofer, T.F. Stocker, C.B. Field, K.L. Ebi, and P.R. Matschoss. 2011. The IPCC AR5 guidance note on consistent treatment of uncertainties: A common approach across the working groups. *Climatic Change* 108:675–691, http://dx.doi.org/10.1007/s10584-011-0178-6.

Miller, A.W., A.C. Reynolds, C. Sobrino, and G.F. Riedel. 2009. Shellfish face uncertain future in high CO_2 world: Influence of acidification on oyster larvae calcification and growth in estuaries. *PLoS ONE* 4:e5661, http://dx.doi.org/10.1371/journal.pone.0005661.

Oppenheimer, M., M. Campos, R. Warren, J. Birkmann, G. Luber, B. O'Neill, and K. Takahashi. 2014. Emergent risks and key vulnerabilities. Pp. 1,039–1,099 in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, and others, eds, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Pespeni, M.H., F. Chan, B.A. Menge, and S.R. Palumbi. 2013. Signs of adaptation to local pH conditions across an environmental mosaic in the California Current Ecosystem. *Integrative and Comparative Biology* 53:857–870, http://dx.doi.org/10.1093/icb/ict094.

Pidgeon, N., and B. Fischhoff. 2011. The role of social and decision sciences in communicating uncertain climate risks. *Nature Climate Change* 1:35–41, http://dx.doi.org/10.1038/nclimate1080.

Pörtner, H.-O., D. Karl, P.W. Boyd, W. Cheung, S.E. Lluch-Cota, Y. Nojiri, D.N. Schmidt, and P. Zavialov. 2014. Ocean systems. Pp. 411–484 in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, and others, eds, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Raven, J., K. Caldeira, H. Elderfield, O. Hoegh-Guldberg, P. Liss, U. Riebesell, J. Shepherd, C. Turley, and A. Watson, eds. 2005. *Ocean Acidification Due to Increasing Atmospheric Carbon Dioxide*. The Cloyvedon Press, Cardiff, 58 pp.

Roberts, D.A., S.N.R. Birchenough, C. Lewis, M.B. Sanders, T. Bolam, and D. Sheahan. 2013. Ocean acidification increases the toxicity of contaminated sediments. *Global Change Biology* 19:340–351, http://dx.doi.org/10.1111/gcb.12048.

Rosa, R., and B.A. Seibel. 2008. Synergistic effects of climate-related variables suggest future physiological impairment in a top oceanic predator. *Proceedings of the National Academy of Sciences of the United States of America* 105:20,776–20,780, http://dx.doi.org/10.1073/pnas.0806886105.

Ruckelshaus, W.D., J.J. Manning, L. Ayers, B. Blake, S. Bloomfield, D.S. Busch, C. Davis, B. Dewey, N. Dicks, R.A. Feely, and others. 2012. *Ocean Acidification: From Knowledge to Action. Washington State's Strategic Response*. H. Adelsman and L. Whitely Binder, eds, Washington State Blue Ribbon Panel on Ocean Acidification, Washington Department of Ecology, Olympia, Washington, Publication no. 12-01-015, 158 pp., https://fortress.wa.gov/ecy/publications/publications/1201015.pdf.

Sanford, E., B. Gaylord, A. Hettinger, E.A. Lenz, K. Meyer, and T.M. Hill. 2014. Ocean acidification increases the vulnerability of native oysters to predation by invasive snails. *Proceedings of the Royal Society B*, http://dx.doi.org/10.1098/rspb.2013.2681.

Shamberger, K.E.F., A.L. Cohen, Y. Golbuu, D.C. McCorkle, S.J. Lentz, and H.C. Barkley. 2014. Diverse coral communities in naturally acidified waters of a western Pacific reef. *Geophysical Research Letters* 41:499–504, http://dx.doi.org/10.1002/2013GL058489.

Stow, C.A., J. Jolliff, D.J. McGillicuddy Jr., S.C. Doney, J.I. Allen, M.A.M. Friedrichs, K.A. Rose, and P. Wallhead. 2009. Skill assessment for coupled biological/physical models of marine systems, *Journal of Marine Systems* 76:4–15, http://dx.doi.org/10.1016/j.jmarsys.2008.03.011.

Sunday, J.M., R.N. Crim, C.D.G. Harley, and M.W. Hart. 2012. Quantifying rates of evolutionary adaptation in response to ocean acidification. *PLoS ONE* 6:e22881, http://dx.doi.org/10.1371/journal.pone.0022881.

Swart, R., L. Bernstein, M. Ha-Duong, and A. Petersen. 2009. Agreeing to disagree: Uncertainty management in assessing climate change, impacts and responses by the IPCC. *Climatic Change* 92:1–29, http://dx.doi.org/10.1007/s10584-008-9444-7.

Tatters, A.O., A. Schnetzer, F. Fu, A.Y.A. Lie, D.A. Caron, and D.A. Hutchins. 2013. Short- versus long-term responses to changing CO_2 in a coastal dinoflagellate bloom: Implications for interspecific competitive interactions and community structure. *Evolution* 67:1,879–1,891, http://dx.doi.org/10.1111/evo.12029.

Wittmann, A.C., and H.-O. Pörtner. 2013. Sensitivities of extant animal taxa to ocean acidification. *Nature Climate Change* 3:995–1,001, http://dx.doi.org/10.1038/nclimate1982.

Yates, K.K., C. Turley, B.M. Hopkinson, A.E. Todgham, J.N. Cross, H. Greening, P. Williamson, R. Van Hooidonk, D.D. Deheyn, and Z. Johnson. 2015. Transdisciplinary science: A path to understanding the interactions among ocean acidification, ecosystems, and society. *Oceanography* 28(2):212–225, http://dx.doi.org/10.5670/oceanog.2015.43.

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