THE OFFICIAL MAGAZINE OF THE OCEANOGRAPHY SOCIETY

Oceanography

CITATION

Doney, S.C. 2012. Review of *Ocean Acidification*, edited by J.-P. Gattuso and L. Hansson. *Oceanography* 25(1):301–303, http://dx.doi.org/10.5670/oceanog.2012.33.

DOI

http://dx.doi.org/10.5670/oceanog.2012.33

Ocean Acidification

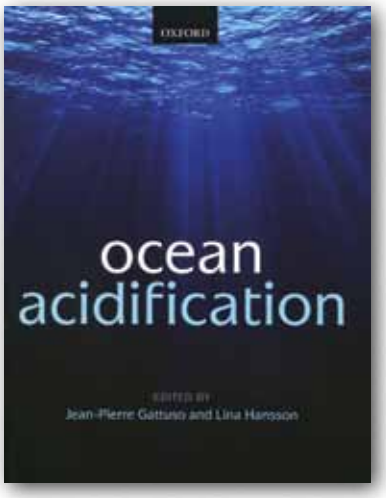
Edited by Jean-Pierre Gattuso and Lina Hansson, Oxford University Press, 2011, 326 pages, ISBN 978-0-19-959108, $67.95 US Paperback, $135 US Hardcover

REVIEWED BY SCOTT C. DONEY

This new book edited by Jean-Pierre Gattuso and Lina Hansson is a timely, interdisciplinary look at the phenomenon of ocean acidification, which refers broadly to changes in seawater chemistry caused by rising atmospheric carbon dioxide (CO_2) and the resulting effects on marine life and biogeochemistry. Atmospheric CO_2 has increased almost 40% above pre-industrial levels, and the ocean removes roughly a quarter of current human CO_2 emissions, driven mostly by the burning of fossil fuels. The topic of ocean acidification was brought to wide attention of the research community only recently with the publication of an influential Royal Society report in 2005. Since then, the scientific literature on acidification has virtually exploded, and targeted national and international research programs are blossoming. While many useful review articles, planning documents, and special volumes exist on the subject, a good example being the *Oceanography* special issue on "The Future of Ocean Biogeochemistry in a High CO_2 World" (volume 22[4], December 2009, http://www.tos.org/oceanography/archive/22-4.html), until the publication of this book, the community lacked a single, authoritative source spanning the full disciplinary breadth of the topic.

Ocean Acidification covers the basics and some advanced material in 15 well-written chapters that range from the chemical and biological impacts to social and economic implications. The authors are leading scientists in the field, many of whom participated in the European Program on Ocean Acidification (EPOCA). Unlike some edited books, the quality of the chapters is nearly universally high, and care was taken to standardize notation and connect ideas across chapters. The book's level is appropriate for a graduate student or marine scientist, with most chapters containing an accessible introduction to each subtopic; given the breadth of material, however, even readers with a good general oceanographic background may find some of the in-depth discussions challenging to follow in places. The chapters are written in the style of review articles, rather than in textbook style, and many contain extensive references to the current literature and detailed tables compiling literature results for elevated CO_2 experiments. The book also contains a mixture of nicely laid out color and black and white graphics, though the small font size for the figure captions and tables is somewhat eye straining.

Chapter 1 serves as a brief introduction to ocean acidification and covers the essential background on the seawater inorganic carbon system. The chemical shifts caused by adding CO_2 to seawater—declines in surface ocean pH, carbonate ion concentration, and the saturation state of calcium carbonate minerals (Ω)—are presented in a useful sidebar that is referenced throughout the rest of the book. Calcium carbonate is an important component of the shells and skeletons of many marine organisms, and lower saturation states suggest



that it may be harder for organisms to form or maintain these structures under higher CO_2. The chapter proceeds through an intriguing digression on the historical and modern path of acidification research. By the late 1950s, scientists predicted rising CO_2 would lead to substantial shifts in ocean chemistry, but it was not until the late 1990s and early 2000s when a series of seminal papers started indicating potentially large and disturbing negative impacts of elevated CO_2 on many calcifying species—corals, mollusks, coccolithophorids (calcifying phytoplankton), and pteropods (planktonic snails). Chapter 1 concludes with an illuminating bibliographic analysis, the bulk of the papers published in the last two decades. The subsequent chapters are essentially stand-alone articles and, for the most part, can be read in any order, except as noted below.

Four chapters are devoted to past, present, and future trends in seawater carbonate chemistry. Using data from global ocean CO_2 surveys and time series beginning in the late 1980s, Chapter 3 presents the strong observational evidence for rising seawater CO_2 levels and dropping pH levels

with time, consistent with theory and models. Looking to the future, model projections indicate even more rapid changes over the twenty-first century, as atmospheric CO_2 levels continue to grow due to accelerated fossil-fuel burning and CO_2 accumulation. The chapter concludes with in-depth discussions on air-sea gas exchange timescales, thermodynamic relationships among ocean carbonate system variables, and previously unpublished model results for marginal seas. The somewhat misplaced Chapter 14 extends the analysis of future ocean CO_2 trends using model simulations to explore baseline "business as usual" and carbon mitigation scenarios out to the year 2500. This chapter is the most research-paper-like of all of them, concentrating primarily on the authors' own work, but it brings into focus that today's human CO_2 emissions will continue to alter ocean chemistry for many centuries into the future and the large reductions in CO_2 emissions required to stabilize atmospheric CO_2 and surface ocean pH.

The two paleo-chemistry/geology chapters are complementary and should be read in sequence. Chapter 2 discusses the controls on atmospheric CO_2 and ocean carbonate saturation state as a function of timescale, and Chapter 4 examines covariations in carbonate reef abundance and taxonomy, seawater chemistry, and CO_2 over the Phanerozoic (last ~ 540 million years) from an evolutionary perspective. Together, the chapters make three important points. First, geochemical mechanisms act to stabilize ocean carbonate saturation state on timescales longer than a few millennia such that high atmospheric CO_2 in the geological past does not necessarily imply low carbonate saturation state; pH and Ω can be decoupled. Second and related, the rate of change in CO_2 is the most important factor for biology, and the current rapid growth in CO_2 suggests that there may be few direct geological analogs to the present situation, with the exception perhaps of extreme events like the Palaeocene-Eocene Thermal Maximum ~ 55 million years ago. Third, acidification, warming, and low oxygen (anoxia) often occur in conjunction in the geological record, making it difficult to separate the effects of each stressor. Chapter 4 also presents an intriguing hypothesis linking episodic CO_2-induced acidification and long-term variations in ocean anoxia to explain trends in the abundance and diversity of hyper-calcifiers (corals and massively calcifying sponges), perhaps because of their limited ability to control the fluid composition at the site of calcification.

A block of chapters follows on the potential biological impacts of changing CO_2, pH, and saturation state, broken down into heterotrophic microorganisms (Chapter 5), pelagic organisms and ecosystems (Chapter 6), benthic systems (Chapter 7), nektonic organisms (Chapter 8), sediment fauna (Chapter 9), and biodiversity and ecosystem function (Chapter 10). Chapter 10 could be read first because it offers a nice overview of the observed responses of most taxonomic groups and then puts these observations in the context of different habitats. Coral reefs, the deep sea, polar oceans, and upwelling regions are called out as vulnerable systems. Overall, the discussion about acidification impacts on biodiversity and ecosystem function necessarily is more speculative, reflecting our current limited state of knowledge regarding effects on food-web dynamics and community structure. In fact, many of the chapters highlight that what we know at present about biological responses is often dwarfed by what we don't know, the latter offering a cornucopia of potential research and student thesis topics.

Other common biological themes emerge. Most biological impacts are inferred from short-term manipulation experiments done at the organism level to examine the effects of step increases in CO_2, for example, lower calcification rates in benthic corals, higher photosynthesis rates for seagrasses and some phytoplankton groups, and increased nitrogen fixation by some cyanobacteria. Effects on natural populations and communities so far have been more difficult to detect, outside of a limited number of pelagic mesocosm experiments and some studies in isolated high-CO_2 environments, such as at shallow volcanic vents, which tend to support laboratory findings. In general though, the variability in responses within natural populations and the ability of organisms to acclimate or adapt to gradual CO_2 trends is mostly unknown. Organism responses may be modulated by life-history stage, with juveniles often more susceptible than adults, and organisms may be able to accommodate elevated CO_2 but at an additional energetic cost, with consequences for development, reproduction, and fitness. Synergistic interactions are observed or may be expected between acidification and other anthropogenic stressors—warming, reduced oxygen, and nutrient eutrophication. Species respond to different chemical aspects of acidification: for calcifiers, the key

may be declining carbonate ion levels; for autotrophs, increased aqueous CO_2; and for adult fish and cephalopods, the major issues are acid-base regulation and CO_2/O_2 transport and gas exchange. The sensitivity of many critical microbial processes is as yet unclear, besides a suggestion of reduced nitrification, but any substantial changes could have wholesale effects on biogeochemistry.

Two chapters directly tackle acidification impacts on biogeochemistry and climate feedbacks, one on reactive trace gases (Chapter 11) and the other on greenhouse gases CO_2 and N_2O (Chapter 12). Organohalogens can influence the oxidative capacity (ability to remove many pollutants) of the troposphere, but the present data on acidification effects is limited and contradictory. The case is somewhat better defined though still complex for dimethylsulfide (DMS), which when released to the atmosphere can form aerosols and cloud condensation nuclei; reduction in DMS flux to the atmosphere suggested by some studies could lead to less marine stratus cloud cover and additional warming. Ocean acidification may alter the ocean carbon cycle via impacts on the export flux and subsurface remineralization for either calcium carbonate or organic matter. The net effect on ocean carbon storage varies, with both positive and negative feedbacks, but is relatively small in current models. Increased carbon-to-nutrient ratios in sinking organic matter seen in some mesocosms exposed to high CO_2 could expand subsurface low-oxygen zones and increase N_2O production.

Chapter 13 asks about the implications for humans, looking at socio-economic impacts on fisheries, recreation, and tourism, and other ecosystem services. The chapter also addresses approaches for communicating science to the public and decision makers, describing the EPOCA Reference User Group model that attempts to bridge different stakeholder groups. Though this territory will be unfamiliar for many natural scientists, the questions raised are worth pondering. The book concludes with a wide-ranging summary of our current state of knowledge, the evidence, and our level of confidence (Chapter 15), encapsulated into 15 key statements on the "knowns" and "unknowns" of ocean acidification. Recommendations for future work and research challenges are also discussed.

Overall, I highly recommend this book for students and scientists interested in the topic of ocean acidification. There is no other single resource that covers so admirably the disciplinary breadth of the problem. Readers new to the field will come away with a solid foundation, and even those who are familiar with the topic will find interesting new nuggets of information. Ocean acidification is an emerging research field with a rapidly evolving knowledge base, and the snapshot of the literature captured in this book may need to be updated in the not too distant future with new discoveries and interpretations.

Scott C. Doney *(sdoney@whoi.edu) is Senior Scientist, Marine Chemistry and Geochemistry Department, Woods Hole Oceanographic Institution, Woods Hole, MA, USA.*

HANDS-ON OCEANOGRAPHY

www.tos.org/hands-on

Hands-On Oceanography provides an opportunity for you to publish teaching materials developed for undergraduate and/or graduate classes in oceanography. Activities include, but are not limited to, computer-based models and laboratory demonstrations that actively engage students (i.e., activities where students have to make decisions, record results, and interpret results). All submissions are peer reviewed. Publication of teaching materials may address the broader impacts criterion for NSF-funded research.

Visit *www.tos.org/hands-on* to download published activities or for more information on submitting an activity of your own for consideration.