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Ocean Carbon
& Biogeochemistry
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Frequently asked questions about **ocean acidification**



UK Ocean Acidification
Research Programme

www.oceanacidification.org

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Introduction

Over the past five years, no other issue has received more attention in the marine science community than ocean acidification. Ocean acidification is a multi-disciplinary research area that encompasses topics such as chemistry, paleontology, biology, ecology, biogeochemistry, modeling, social sciences and economics.

With this complexity and the continued development of our understanding in mind, the U.S. Ocean Carbon and Biogeochemistry (OCB; www.us-ocb.org) program, with support from the UK Ocean Acidification Research Programme (UKOA; <http://www.oceanacidification.org.uk/>), has updated and expanded a list of frequently asked questions (FAQs) that were developed in 2010 by OCB, the European Project on Ocean Acidification (EPOCA), and UKOA. Equipped with the most up-to-date information, the global ocean acidification research community has drafted concise, understandable summaries of the current knowledge. The responses were carefully vetted during an open peer-review and revision process to ensure readability without any loss of scientific accuracy. This effort was international in scale, with 63 scientists from 47 institutions and 12 countries contributing to the process.

We hope that this updated FAQ list will prove useful and would like to point out that it is an on-going process. Anyone is invited to seek clarification or send comments to Sarah Cooley (scooley@whoi.edu). The list will be revised periodically using this input and maintained at www.whoi.edu/OCB-OA/FAQs. More detailed information and references to the primary literature are also available on the website.

— *Jeremy Mathis and Kim Yates (OCB), and Carol Turley (UKOA)*

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OA Primer

Introduction to OA

What is ocean acidification?

International experts define ocean acidification (OA) as a decrease in ocean pH over decades or more that is caused primarily by uptake of CO₂ from the atmosphere. Because human activities are releasing CO₂ into the atmosphere very quickly, the ocean is taking up CO₂ faster today than it has in the past. This is causing global ocean chemistry to change more quickly than ocean systems can handle.

—R. Feely

What is the difference between pH and acidity?

“Acidity” is the concentration of hydrogen ions (H⁺) in a liquid, and pH is the scale on which this concentration is generally measured. The amount of hydrogen ions in a liquid determines how acidic the liquid is. Some common examples are shown in Figure 1a. The concentration of hydrogen ions can vary across many multiples of ten, or “orders of magnitude”—from 1 to 0.000000000000001 moles per liter. Because it is difficult to write down all the zeros accurately, we express acidity on a logarithmic scale called the pH scale. Because the pH scale is logarithmic (pH = -log[H⁺]), one step up or down on the pH scale corresponds to multiplying or dividing by ten on the hydrogen ion scale (Figure 1b).

—S. Alin, H. Findlay

Why are scientists concerned about such a seemingly small change in ocean pH?

Many organisms are very sensitive to seemingly small changes in pH. For example, in humans, arterial blood pH normally falls within the range 7.35–7.45. A drop of 0.2–0.3 pH units in human blood pH can result in rather profound health consequences, including seizures, heart arrhythmia, or even coma (a process called “acidosis”). Similarly, many marine organisms are very sensitive to either direct or indirect effects of the change in acidity (or H⁺ concentration) in the marine environment. Fundamental physiological processes such as respiration, calcification (shell/skeleton building), photosynthesis, and reproduction respond to the magnitude of changes in CO₂ concentrations in seawater, along with the resultant changes in pH and carbonate ion concentrations that are expected over the next century.

—S. Alin

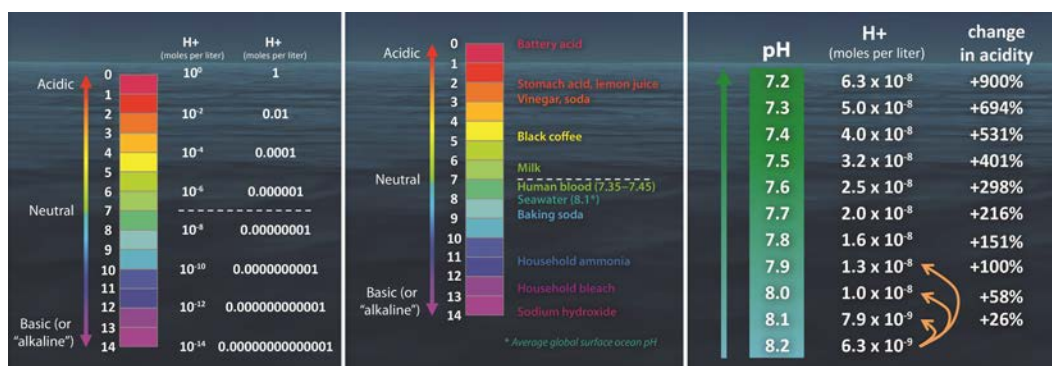


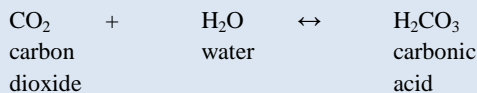
Figure 1: pH measures the acidity of a liquid. (a) The pH scale, with examples of common solutions and their pH values. (b) The pH scale is logarithmic, meaning that a change of one pH unit represents an order of magnitude change in the hydrogen ion (H⁺) concentration. Here the hydrogen ion concentrations are shown in both scientific notation and decimal form. (c) The percent change in acidity with falling pH values is calculated as the percent change in hydrogen ion (H⁺) concentration relative to the starting concentration. In this figure, the concentrations of H⁺ ions are shown in decimal notation (middle column) for every tenth of a pH unit from 8.2 down to 7.2. The numbers in the percent change in acidity column reflect the percent increase in H⁺ concentrations between the starting point (8.2) and each successive number. Average global surface ocean pH has already fallen from a pre-industrial value of 8.21 to 8.10, corresponding to an increase in acidity of 28.8%. Values of 7.8–7.9 are expected by 2100, representing a 100–150% increase in acidity.

Ocean acidification chemistry 101

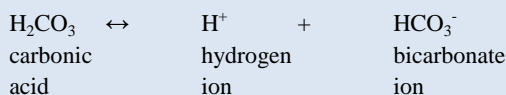
Carbon dioxide (CO₂) naturally exchanges between the atmosphere and the surface of the ocean. The CO₂ content of the upper ocean has been increasing in parallel with the CO₂ in the atmosphere since the Industrial Revolution, with the rate of increase becoming more rapid over the last half century as human-caused CO₂ emissions have accelerated.

When CO₂ dissolves in seawater, it has several consequences for the chemistry of the seawater. Some of the CO₂ that dissolves in seawater will remain in the form of a dissolved gas that can freely exchange with the atmosphere and be taken up directly by marine plants and phytoplankton. This fraction is usually referred to as dissolved or aqueous carbon dioxide, and it is typically expressed as the partial pressure of CO₂ [abbreviated pCO₂, in units of microatmospheres (µatm)].

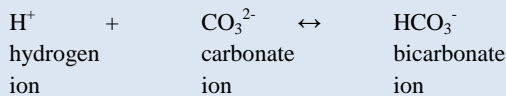
Some of the molecules of CO₂ dissolved in seawater combine with molecules of water (H₂O) to form a weak acid, called carbonic acid (H₂CO₃), the same acid that is in carbonated beverages like soda pop (Figure 2). This reaction can be depicted as:



When acids are dissolved in water, they “dissociate,” which means that they break apart into their constituent ions, in this case a hydrogen ion (H⁺) and a bicarbonate ion (HCO₃⁻), as is found in baking soda).



At typical seawater pH values, some of the hydrogen ions will remain as hydrogen ions, thus increasing the acidity and lowering the pH of the seawater. However, most of the hydrogen ions created through the previous reaction will subsequently combine with carbonate ions (CO₃²⁻) to form additional bicarbonate ions, thereby reducing the pool of carbonate ions.



In summary, the chemical changes in seawater resulting from increased atmospheric CO₂ concentrations include *increases* in the concentrations of dissolved (or aqueous) carbon dioxide, hydrogen ions, and bicarbonate ions, and *decreases* in the carbonate ion concentration and pH.

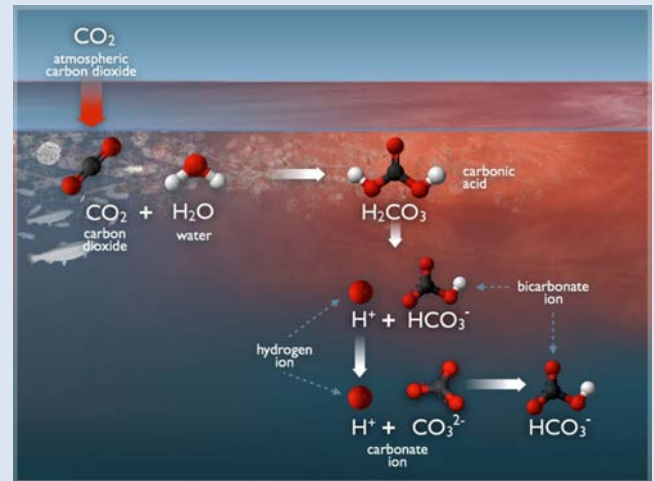
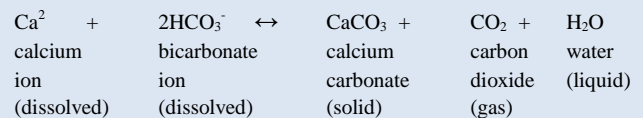


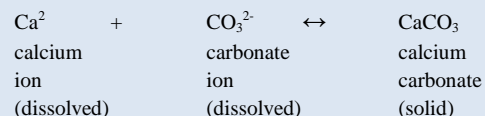
Figure 2: Chemistry of ocean acidification. As carbon dioxide (CO₂) dissolves into seawater (left), it creates carbonic acid (right). Through a series of chemical reactions, carbonic acid releases hydrogen ions (H⁺), which decreases seawater pH, and decreases the concentration of carbonate ions (CO₃²⁻), which provide chemical building blocks for marine organisms’ shells and skeletons.

Impacts of changes in seawater chemistry on biology

Organisms may be affected directly or indirectly by changes in the concentrations of any of the forms of inorganic carbon (CO₂, HCO₃⁻, CO₃²⁻) discussed above, as well as by acidity levels. However, most research to date has focused on characterizing the response of organisms that build hard parts out of calcium carbonate—such as shells, skeletons, or tests—to decreases in the abundance of carbonate ions. Many organisms synthesize hard structures out of various forms of the biomineral calcium carbonate, including aragonite, calcite, and amorphous calcium carbonate. To build these solid structures, they must extract dissolved calcium and bicarbonate ions from seawater:



The net effect of forming calcium carbonate is to emit more carbon dioxide into the water, which creates carbonic acid and reduces the pool of carbonate ions as described above. For simplicity, many chemists sum together the above chemical reactions and write the formation of calcium carbonate as:



Ocean acidification chemistry 101 (continued)

To compare how easy or difficult it should be for organisms to build their calcium carbonate hard parts in waters with different chemistries, scientists use calcium carbonate saturation states (represented by the symbol Ω (omega)) as an index:

$$\Omega_{\text{form}} = \frac{[\text{Ca}^{2+}] \times [\text{CO}_3^{2-}]}{K_{\text{sp}'}}$$

saturation state for a specific form of CaCO ₃	=	[Ca ²⁺]	x	[CO ₃ ²⁻]	÷	K _{sp} '
		calcium ion concentration		carbonate ion concentration		solubility factor under environmental conditions

In the above equation, *form* refers to the specific crystal type of calcium carbonate the organism makes. Different crystal forms include aragonite, calcite, or amorphous calcium carbonate. The term $K_{\text{sp}'}$ is the “apparent solubility product.” This simply indicates the solubility of that type of calcium carbonate at the actual temperature, salinity, and depth of interest. At omega values greater than one, calcium carbonate is supersaturated, meaning that shell-building should be relatively easy and calcium carbonate structures will stay intact. At omega values below one, conditions are undersaturated, meaning that shell-building would be more difficult and the seawater would naturally break down that type of solid calcium carbonate. A value of one for omega indicates that the saturation state is at a threshold between solid calcium carbonate being favored (above one) and dissolved ions being favored (below one).

However, it is critical to note that saturation state is a chemical index, and different organisms have a wide range of tolerances to saturation states. Scientists are just beginning to learn more about the biological thresholds of different species. Although knowing the exact value of the saturation state will not necessarily help predict how a particular organism will respond, saturation state is a helpful chemical measure that can allow scientists to compare sensitivity across species and in varied environments. Having such a universal measure is key for letting us understand and predict how species that are ecologically or economically important will be affected by ocean acidification. —S. Alin

Common misunderstandings about pH and ocean acidification

Misunderstanding: Percent change in acidity isn't the same as percent change in pH.

When acid is added to a solution, the concentration of hydrogen ions (acidity) increases, and the pH decreases. People frequently confuse pH with acidity—pH is the scale on which acidity is expressed, but it is not the same as acidity. We can correctly compare the acidity at two different pH values by expressing the relative percentage change of the H⁺ concentration between the two pH levels, as in Figure 1c. For example, the present pH decrease of 0.11 from ocean acidification equals a 28.8% change in acidity (H⁺ concentration) when calculated in this way.

Misunderstanding: Liquids with high pH values don't have acidity; they only have alkalinity.

pH values above 7 are commonly referred to as “basic” or “alkaline.” These common terms can be confusing, because pH values do not directly measure the concentration of bases in the solution. pH values above 7 still measure the *acidity* of that liquid, but in that case, the liquid's acidity (H⁺ concentration) is very, very low (less than 10⁻⁷ (or 0.0000001) moles per liter, to be specific). High pH values also do not measure *alkalinity*. Alkalinity actually measures the acid neutralization capacity of seawater. To determine the alkalinity of a solution, a separate, detailed laboratory analysis must be done. It is incorrect to characterize the change in hydrogen ion concentration as a decrease in alkalinity.

Misunderstanding: Calling this phenomenon “ocean acidification” when surface seawater will remain “basic” under future emissions scenarios is alarmist.

Just as we describe an increase in temperature from -20°C to 0°C as warming, even though neither the starting nor the ending temperature is “warm,” the term “acidification” describes the increase in the level of acidity in the global oceans. Both “warming” and “acidification” do not refer to absolute end points. When CO₂ is added to seawater, it reacts with water to form carbonic acid (H₂CO₃). Therefore, acid is being added to seawater, which is acidifying it.

Misunderstanding: Because natural pH variability is greater than long-term pH change, ocean acidification is nothing to worry about.

Many scientists have observed that natural variability in seawater acidity (and thus pH) over days, weeks, and months is strong. This short-term variability can be much larger than the recent and forecasted changes in acidity that will take place over decades to centuries because of ocean acidification. The reason that scientists are concerned about this slow, long-term change is that it changes the environmental baseline. This means that the natural variability in acidity due to photosynthesis, respiration, upwelling, and many other processes will be overlaid on an ever-increasing average concentration of H⁺. Even though this change in the baseline is slow and steady relative to human time scales, this change is very fast relative to geological time scales. Ocean acidification is more rapid than any change in ocean acidity documented over the last 300 million years, so organisms that tolerate a certain narrow range of conditions may encounter increasingly stressful, or even lethal, conditions in the coming decades. (Also see Individuals and Ecosystems section.) —S. Alin

The name “ocean acidification”

Why call it ocean acidification, when the ocean is not acidic?

Ocean acidification refers to the process of lowering the oceans’ pH (that is, increasing the concentration of hydrogen ions) by dissolving additional carbon dioxide in seawater from the atmosphere, or by other chemical additions either caused by natural processes or human activity. The word “acidification” refers to lowering pH from any starting point to any end point on the pH scale. This term is used in many other scientific areas (including medicine and food science) to refer to the addition of an acid to a solution, regardless of the solution’s pH value. For example, even though seawater’s pH is greater than 7.0 (and therefore considered “basic” in terms of the pH scale), increasing atmospheric CO₂ levels are still raising the ocean’s acidity and lowering its pH. In comparison, this language is similar to the words we use when we talk about temperature. If the air temperature moves from -20°C to -0°C (-4°F to 32°F), it is still cold, but we call it “warming.”

— J. Orr, C.L. Sabine, R. Key

Is ocean acidification the same as climate change?

No. While ocean acidification and climate change share a common cause (increases in CO₂ in the atmosphere), climate change encompasses the effects associated with changes in the Earth’s heat budget (due to the greenhouse effect of CO₂ and to a lesser extent other climate reactive gases), which cause global warming and changes in weather patterns. Ocean acidification specifically refers to the lowering of ocean pH resulting from its absorption of human-released CO₂ from the atmosphere or by other chemical additions either caused by natural processes or human activity. Ocean acidification does not include the warming of the ocean.

— C.L. Sabine

The chemistry of ocean acidification

Concentrations of carbonate system species in seawater

	Preindustrial atmospheric CO ₂	2 x Preindustrial CO ₂
Atmospheric CO ₂ (µatm)	280	560
Carbonic acid H ₂ CO ₃ (µmol/kg seawater)	9	18
Bicarbonate HCO ₃ (µmol/kg seawater)	1757	1975
Carbonate CO ₃ ²⁻ (µmol/kg seawater)	239	151
Total carbon species TCO ₂ (µmol/kg seawater)	2005	2144
Total alkalinity TA (µmol/kg seawater)	2345	2345
pH	8.18	7.93
Ω-aragonite	3.72	2.35

These values were calculated using the “Mehrbach refit” carbonate system constants (Dickson and Millero, 1987, Deep-Sea Research), KSO₄ dissociation constant from Dickson (1990, Journal of Chemical Thermodynamics), and the total pH scale.

—J. Kleypas, A. Dickson, D. McCorkle

The chemistry of ocean acidification (continued)

How much has CO₂ already decreased pH and how much change is expected?

Scientists estimate that surface ocean pH has fallen by about 0.11 pH units from preindustrial times to today. Because pH is a measure of hydrogen ion concentration and the pH scale is logarithmic — for a decrease of 1 pH unit, the hydrogen ion concentration increases by a factor of 10 — a 0.11-unit pH decrease is equivalent to about a 29% increase in the ocean hydrogen ion concentration. If we continue on the expected trajectory for fossil-fuel use and rising atmospheric CO₂, pH is likely to drop by 0.3-0.4 units by the end of the 21st century and increase ocean hydrogen ion concentration (or acidity) by 100-150% above what it was in preindustrial times.

— S. Doney

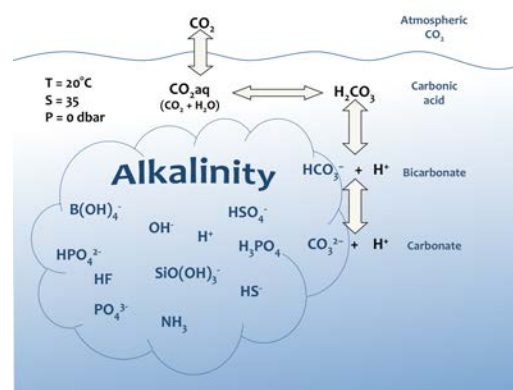


Figure 3: Carbonate chemistry and seawater alkalinity. Schematic of the carbonate system species in seawater and some of the equilibrium reactions that occur among them. Seawater total alkalinity (TA) is commonly defined as “the excess base” in seawater, or the sum of excess proton acceptors, and its component ions are illustrated in light blue. Seawater TA slows down, or buffers, changes in ocean pH because it includes so many different acid-base pairs. TA stays constant even when CO₂ is added to seawater because the charge balance of the solution stays the same, meaning that the number of positive ions generated equals the number of negative ions generated by these reactions.

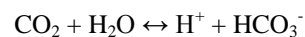
Why doesn't ocean salt buffer away ocean acidification?

When acids and bases neutralize each other in a laboratory experiment, salt and water form. But in the ocean, the major ions that make seawater “salty” (like sodium, chloride, and magnesium) are derived from rock weathering, which provides a balanced amount of positive and negative ions to the seas over many millennia. Weak acids and bases, like bicarbonate or borate, control variations in ocean pH on shorter time scales of decades to centuries. Of these weak acids and bases, the dissolved inorganic carbon species — carbonic acid (H₂CO₃), bicarbonate (HCO₃⁻), and carbonate (CO₃²⁻) — have the largest impact on global ocean pH variations because their concentrations are changing quickly relative to other chemical species in the ocean.

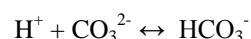
— C.L. Sabine

How does ocean acidification decrease the amount of carbonate ions in seawater?

When CO₂ dissolves in seawater it combines with water to form hydrogen (H⁺) and bicarbonate (HCO₃⁻) ions:



Some of the hydrogen ions combine with carbonate (CO₃²⁻) ions to form additional bicarbonate ions resulting in a decrease in the former and an increase in the latter:



Thus, the net effect when CO₂ is added to seawater is for the concentrations of H⁺, CO₂, and HCO₃⁻ to increase, and the concentration of CO₃²⁻ to decrease.

— A. Dickson

Will melting ice caps dilute the acidity by adding freshwater to the ocean?

Fresh water from melting ice caps dilutes the concentrations of all the various components of the carbonate system in seawater (described above), as well as the total alkalinity and salinity (both of which affect pH). For example, a liter of “typical” Arctic seawater (temperature, 5°C; salinity, 35; total alkalinity, 2244 micromoles per kilogram of seawater) that is exposed to today’s atmospheric CO₂ level of 390 ppm has a total carbon content of 2100 micromoles per kilogram of seawater and a pH of 8.04 (total scale, here and below). Adding a kilogram of freshwater to the kilogram of seawater would dilute the salinity, alkalinity, and carbon content to half of what they were, and the initial pH would increase to 8.21. However, this mixed seawater will now be out of equilibrium with the atmosphere, with a pCO₂ of 151 ppm, while the pCO₂ level of the overlying atmosphere is 390 ppm. Therefore, it will absorb CO₂ until the seawater pCO₂ also equals 390 ppm, at which point the pH will be 7.83.

— R.A. Feely, J. Kleypas

The chemistry of ocean acidification (continued)

Will CO₂ outgas as the oceans warm and decrease ocean acidification?

The CO₂ content of the surface waters of the oceans responds to both changes in CO₂ content of the atmosphere and changes in temperature. For example, if ocean temperatures were not changing, a doubling of preindustrial CO₂ levels (from 280 to 560 ppm) would cause an increase in the total amount of dissolved inorganic carbon in the surface ocean from about 2002 to 2131 micromoles per kilogram of seawater (assuming salinity = 35, temperature = 15°C, and alkalinity = 2300 micromoles per kilogram of seawater). If ocean temperatures warmed by 2°C over that period, then less carbon would be taken up (the increase would be from 2002 to 2117 micromoles per kilogram of seawater). Thus, a 2°C increase in temperature results in about a 10% decrease in carbon uptake in surface waters. The expected warming of the oceans also may alter ocean circulation, further reducing their capacity to absorb CO₂ from the atmosphere, but the excess CO₂ will still remain in the atmosphere and drive further acidification (and atmospheric warming). For pH, the net effects of climate warming on atmospheric CO₂, CO₂ solubility, and chemical speciation approximately cancel out.

— S. Doney, J. Kleypas

OA and the Earth System

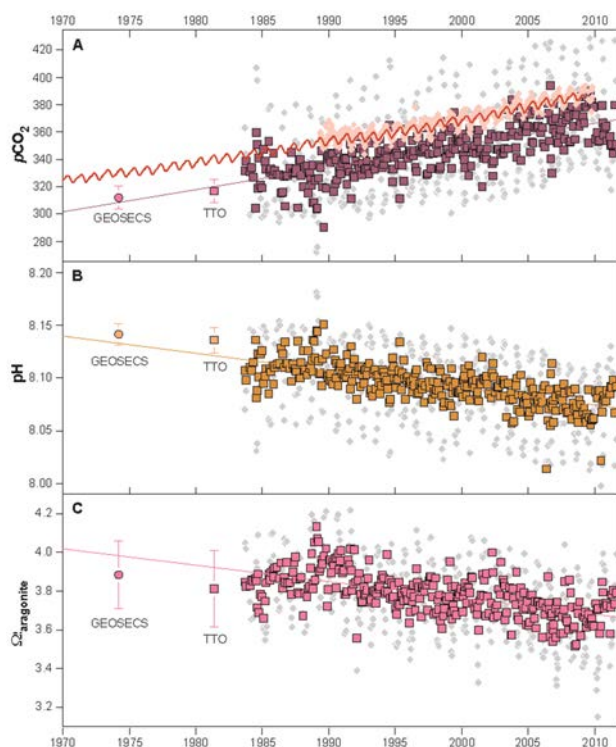
Measurements and observations

What evidence suggests that OA is happening and results from human activity?

Semi-continuous measurements of surface seawater acidity have been made in the Pacific and Atlantic Oceans for the past 20-30 years. These datasets have shown that the hydrogen ion concentration has been increasing. The observed increase in acidity agrees with estimates of the oceanic uptake of CO₂ that comes from human activities.

—C. Turley, J. Kleypas, N. Bates

Figure 4: Time series data from the surface ocean. Time-series of atmospheric and ocean pCO₂, pH and aragonite saturation states from Bates et al., 2012, *Biogeosciences*, doi:10.5194/bg-9-2509-2012. (a) Time-series of atmospheric pCO₂ (ppm) from Mauna Loa, Hawaii (red line), and Bermuda (pink symbols), and surface ocean seawater pCO₂ (µatm) at the Bermuda Atlantic Time-series Study (BATS) site off Bermuda. Observed (grey) and seasonally detrended (purple) surface ocean seawater pCO₂ levels are shown. Earlier seawater data from the GEOSECS (Geochemical Sections) and TTO (Transient Tracers in the Ocean) expeditions in the North Atlantic Ocean are also shown in this and following panels. (b) Time-series of surface ocean seawater pH at the BATS site off Bermuda. Observed (grey) and seasonally detrended (orange) seawater pH are shown. (c) Time-series of surface ocean aragonite saturation state ($\Omega_{\text{aragonite}}$) for calcium carbonate at the BATS site off Bermuda. Observed (purple) and seasonally detrended (purple line) seawater $\Omega_{\text{aragonite}}$ are shown.



Measurements and observations (continued)

How do OA's effects relate to those of other human activities?

Other human activities certainly are affecting seawater chemistry and the ocean's acid-base balance, but not nearly to the extent of atmospheric CO₂-driven acidification. Acid rain, which contains sulfuric and nitric acids originally derived from fossil fuel combustion, falls on the coastal oceans. The impact of acid rain on surface ocean chemistry may be important locally and regionally, but it is small globally and its total effects equal only a few percent of the changes driven by rising atmospheric CO₂. Coastal waters are also affected by excess nutrient inputs, mostly nitrogen, from agriculture, fertilizers and sewage. The resulting chemical changes lead to large plankton blooms, and when these blooms collapse and sink below the surface layer the resulting respiration from bacteria leads to a drawdown in seawater oxygen and an increase in CO₂, which decreases pH and calcium carbonate saturation state even more in subsurface coastal waters.

One of the major differences between OA and these types of human effects is that OA's influence is truly global in scale, affecting pH-sensitive and calcifying organisms in every ocean basin from the equator to the poles. At present, the effects are restricted primarily to the upper 200-500m of the ocean, but every year the effects penetrate to deeper depths. Many of the other impacts of human activities are more local in nature.

—S. Doney, C. Langdon, J. Mathis, R. Feely

Why is the current rate of change in pH concerning?

The current rate of decrease in pH is thought to be ten to a hundred times faster than anytime in the past 50 million years, and it may be unprecedented in Earth's history. Marine life that exists today has never experienced such a rapid change in average pH, and many important species like corals, oysters, mussels, clams, crabs and plankton may be adversely impacted and may not have sufficient time to evolve mechanisms to cope with this changing chemistry. During a much slower acidification event that occurred 55 million years ago (the Paleocene-Eocene Thermal Maximum), there was a mass extinction of marine life, especially in benthic species.

—S. Alin

How certain are we about OA?

There is no argument that seawater chemistry is changing. The root cause is rising atmospheric CO₂ released by human combustion of fossil fuels and deforestation. These changes are well documented by observations from repeat research cruises conducted throughout the world oceans over several decades, and from a number of time series data collection stations in the major ocean basins. There is less certainty about the possible biological impacts of ocean acidification, but this primarily is because different groups of marine organisms express a wide range of sensitivity to changing seawater chemistry. Some of the different responses exhibited by members of the same species in lab studies may simply reflect the natural variability in wild populations, because specimens have been collected from different areas, populations, or strains. Nevertheless, there is broad agreement among the scientific community that ocean acidification is occurring and that it likely will have significant effects, some positive and some negative, on a large number of marine organisms.

—S. Doney, S. Widdicombe, J. Mathis, R. Feely

Does "ocean" acidification also affect bodies of fresh water, like lakes?

Fresh water takes up carbon dioxide from the atmosphere through the same mechanism as seawater, and carbon dioxide in fresh water reacts with water molecules in the same chemical reactions as in seawater. But fresh water alkalinity tends to be much lower than that of seawater, so pH changes in bodies of fresh water tend to be greater, because the newly released H⁺ ions are not being buffered by as many bicarbonate ions. Therefore, aquatic life in fresh water can sometimes be more accustomed to wider pH changes than organisms in salt water. However, the examples of damage to fresh water lakes in the 1980s because of acid rain (caused by deposition of nitrogen and sulfur from fossil fuel use and industry) showed that bodies of fresh water can become progressively acidified and this process damages aquatic ecosystems. Fresh water ecosystems may also be experiencing nutrient loading that increases the rates of photosynthesis and respiration there, magnifying CO₂ drawdown and release. Local acidification from these other large-amplitude processes may mask atmospheric CO₂-driven acidification until longer time-series records are collected.

—S. Alin

Geological processes & history

How do we know what ocean pH was in the past?

Studying past marine environmental conditions is the focus of paleoceanography, a field that uses stand-ins or “proxies” for parameters that can no longer be measured, but that hold a close relationship to another measurable quantity. For the last 800,000 years, scientists have calculated ocean pH using the CO₂ concentration of air bubbles trapped in glaciers during ice sheet formation. In pre-industrial times the CO₂ concentration of the atmosphere followed the CO₂ concentration of the world surface ocean because of Henry’s law. We can then calculate the ocean CO₂ content from these air bubbles using the same relationship and then estimate ocean pH from that number. In fact, the ice core record shows that the atmospheric CO₂ concentration has never been higher than about 280 ppm during the last 800,000 years, creating conditions leading to an average preindustrial surface ocean pH of ca. 8.2.

To determine what ocean pH was more than 800,000 years ago, paleoceanographers use other proxies, such as the chemical and isotopic composition of fossil carbonate shells. In particular, the uptake of boron and its isotopes into foraminifer (microplankton that produce calcite shells) shells and coral skeletons are indicators for past seawater pH: Because the relative abundance of two dissolved species of boron in seawater, boric acid and borate, depend on seawater pH and because the relative abundance of boric acid increases at lower pH, marine carbonates incorporate relatively less boron and with a lower isotopic composition under low-pH conditions. Other proxies for marine carbonate chemistry include U/Ca ratios, and in shells of benthic foraminifers, also Zn/Ca and Cd/Ca ratios. All these chemical and isotopic proxies provide independent evidence for changes in seawater acidity in the growth environment of marine calcifiers. Using just the presence or absence of calcifying marine organisms in the geological record is not a good indicator for ocean acidification because the absence of carbonaceous remnants at the seafloor does not necessarily mean that the organisms did not live in the surface (calcifying planktonic organisms) or even the deep ocean (calcifying benthic organisms). Calcium carbonate structures could just have been dissolved at the sea floor as a consequence of the mineral’s solubility, which is determined by the seawater’s temperature, pressure, and amount of dissolved CO₂.

— J. Bijma, B. Hönisch, J. Mathis, R. Feely

If rock weathering increases, will this offset OA somewhat?

Over thousands of years, the weathering of continental rocks does increase the alkalinity of seawater and increases its ability to counteract pH decreases, but neutralizing all of the CO₂ from human activity that is entering the oceans with this process alone would take tens of thousands of years. Therefore, on the time scales of importance to humankind (decades to centuries), these processes are not fast enough to significantly buffer ocean acidification.

—F. Mackenzie, B. Hönisch, R. Zeebe, R. Feely, J. Bijma

As ocean acidity rises, will minerals underwater dissolve and offset ocean acidification?

Some minerals, in particular calcium carbonate (CaCO₃) minerals, will tend to dissolve under progressively more acidified conditions. In general, this source of neutralization will be too slow to offset ocean acidification, except to drive a global recovery of ocean pH over thousands of years.

—A. Andersson, D. Archer, R. Feely, B. Hönisch

Why would OA cause extinctions if species have survived changes throughout geological history?

The danger from ocean acidification is related to the current rate of change, the concentration of atmospheric CO₂ expected, and the magnitude of change of atmospheric CO₂ forecast if we keep emitting CO₂ at the same rate. Additionally, one must consider how rapid environmental change can affect organisms and species diversity. Today’s rate of CO₂ increase in the atmosphere is approximately 100 times greater than most changes that have occurred previously in Earth’s history. Other than at times of the great mass extinctions, there is no evidence in the geologic record for sustained rates of change in atmospheric CO₂ that have been as great or greater than today’s. During mass extinction events that have occurred periodically in geologic history due to climate change, the diversity of marine species was severely reduced. The number of surviving species represents only a fraction of the diversity of organisms that was present before the change. Recovery of species from these events is due to adaptation of the few existing species and evolution of new species. However, it takes several million years to achieve pre-extinction levels of biodiversity.

—J. Barry, D. Schmidt, K. Caldeira, P. Hallock Muller

Geological processes & history (continued)

How is today's change in ocean chemistry different from those in the past?

CO₂ is currently being added to the surface ocean much more quickly than geological processes can remove it. On timescales of about a thousand years, ocean currents mix and dilute the CO₂ added to the surface of the ocean with the much larger volume of water in the deep ocean. On timescales of several thousand years, CO₂ is removed by reaction with sediments made of calcium carbonate. In the past, CO₂ was typically added to the ocean surface (for instance by volcanoes) at about the same rate that the processes above removed it. Today the rate of CO₂ addition by humans is about 100 times faster, so CO₂ is being concentrated in surface waters, causing a larger and more rapid change in ocean pH.

—J. Rae, C. Langdon, A. Ridgwell, R. Zeebe, D. Schmidt

How will OA affect the particles reaching the seafloor and the geological record?

If OA persists long enough, the overall accumulation of CaCO₃ on the sea floor will be reduced because of decreasing rates of calcification by marine calcifiers living in the water column and on the bottom, but also due to increasing dissolution of CaCO₃ in the sediments. At locations on the seafloor where CaCO₃ dissolves faster than new CaCO₃ is added, a sediment core in the future will likely display a dark brown layer for this time period (Figure 5). Such a layer is found associated with the Paleocene Eocene thermal maximum (PETM), 55 million years ago, which was caused by a release of carbon analogous to fossil fuel CO₂. Calcified nanofossils in the geological record from before the PETM show fine structures, but the same fossil during the PETM is degraded (Figure 6).

—F. Mackenzie, D. Archer

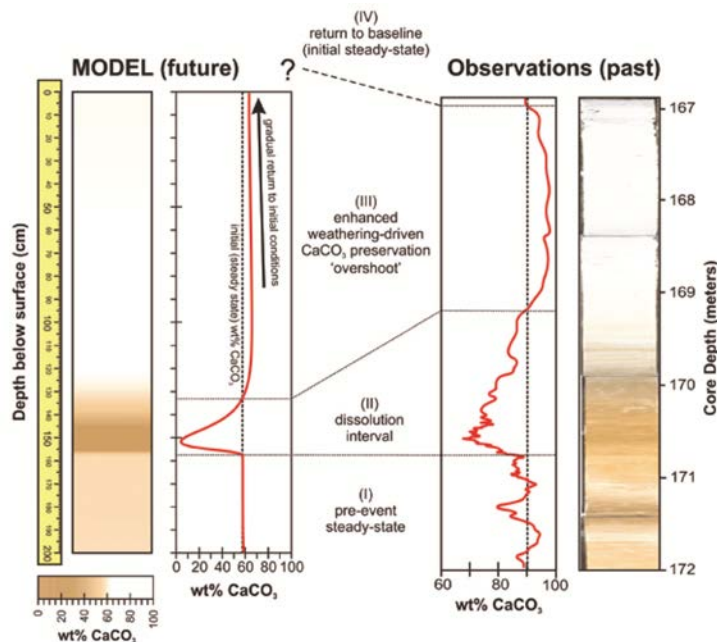


Figure 5: Ocean acidification in sediment cores. The marine geological signature of an ocean acidification event as it might get recorded in a sediment core. The figure shows both results from a model simulation and data from the Paleocene-Eocene Thermal Maximum. From Kump et al., 2009, *Oceanography*.

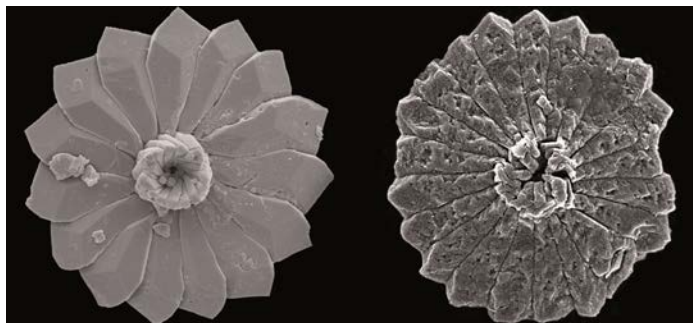


Figure 6: Calcium carbonate nanofossils before and during an OA event. Scanning electron micrograph (SEM) images of a calcareous nannofossil (*Discoaster*) (a) before and (b) during the Paleocene-Eocene Thermal Maximum, which was a period of ocean acidification in geological history. Images courtesy of P. Ziveri.

Physical circulation

Are all upwelling regions going to be ocean acidification hotspots?

Upwelling areas are indeed regions of low pH. However, their water chemistry is set primarily by the rise of old deeper water, and not by anthropogenic CO₂-driven ocean acidification. Deep water has naturally lower pH due to respiration of organic matter falling from the surface ocean. In some locations, such as off the west coast of North America, water upwelling from mid-depths contains a great deal of CO₂ from respiration as well as from anthropogenic CO₂, owing to local circulation, so that these locations demonstrate much lower pH and carbonate ion concentrations than are expected from upwelling or atmospheric CO₂ invasion alone. Seasonal upwelling happens in many locations worldwide. Upward movement of lower-pH, low-saturation state waters has been reported in the northeast Pacific Ocean and the Chukchi Sea in the Arctic Ocean as well.

— *S. Sundby, K.Y. Børshheim, S. Cooley*

If climate change slows ocean circulation, will that change ocean acidification?

If thermohaline ocean circulation slows because climate change increases the temperature of the surface ocean, the water column will become more stratified. This will slow mixing of carbon dioxide down into the upper ocean, although the surface layer will take up a great deal of CO₂. Nutrients also will not be mixed into the upper ocean from below as rapidly, decreasing primary production. This decreases the “biological pump” that carries organic carbon into the deep ocean by way of sinking particles. At the same time, slowing the formation of deep water in high latitudes will decrease the amount of CO₂ that penetrates the deep ocean basins.

— *S. Sundby, K.Y. Børshheim, S. Cooley*

Is ocean acidification the same in the surface and deep oceans?

No. The surface ocean is directly influenced by the entry of anthropogenic CO₂ from the atmosphere. This causes a decrease in marine pH and a subsequent reduction in carbonate ions that are essential for shell building organisms. Ocean acidification is penetrating downward in the ocean from the surface, and most of its impacts are seen in the upper 200-500m of the ocean. Elsewhere, CO₂ accumulates differently. Deep ocean water is “formed” when it cools and sinks in the high latitudes after being in contact with the atmosphere for some time, which sets the basic chemical content of deep water. After that, the deep ocean does not directly interact with the atmosphere. Additional CO₂ accumulation in the deep ocean happens because of the accumulation of respired organic products that have sunk down from the surface (marine snow). Because ocean circulation and mixing are relatively slow (on the order of a thousand years or more) compared to the relatively well-mixed atmosphere, it will take several more generations before we see the penetration of anthropogenic CO₂ spread throughout all of the deep ocean. However, repeat research cruises show that anthropogenic CO₂ is entering the ocean from the surface at the same time as it slowly spreads through the deep ocean. Ultimately OA will decrease the pH of all the water to levels lower than today.

—*S. Doney, C. Langdon, J. Mathis, R. Feely, S. Cooley*

Forecasts

Why wasn't this 'Ocean Acidification' problem predicted earlier?'

The ocean acidification problem was first predicted explicitly in the early 1970s when it was recognized that continued burning of fossil fuels would cause higher concentrations of CO₂ in the mixed layer of the ocean and decrease carbonate mineral saturation states. In the paper of Fairhall and in a paper written criticizing it the key concern articulated by these geochemists was to ask if and when the surface oceans might become undersaturated with respect to CaCO₃. There was discussion as to the likely ocean pCO₂ in the 21st century and some skepticism as to the likely consequences. Scientists emphasized the potential biological consequences for CaCO₃-forming organisms, recognizing **that** the consequences of ocean acidification would drastically affect organisms that build their skeletons and shells from calcium carbonate minerals and create disturbances in ecological systems in the sea. It is interesting to note that these concerns were not really followed up on until the 1980's when field observations were first used to calculate the effect of uptake of excess CO₂ in the northeast Pacific Ocean on carbonate chemistry, and calcite and aragonite saturation horizons. In the 1990s coral reef biologists started to test the hypothesis that saturation state controls calcification in corals and marine calcareous algae (rather than it depending simply on whether the waters were under- or oversaturated with respect to CaCO₃).

Those earlier studies led scientists to test a wider variety of organisms where it was felt that ocean acidification-induced changes in seawater chemistry might play a role. As more and more organisms are studied, it is apparent that many do not take well to life in higher CO₂ waters. Nevertheless, even now there are cautions. First, in early experiments there was often a mismatch between the exposure conditions in laboratory experiments and those (typically more variable) conditions that are expected to occur in nature. More recent experiments more closely mimic the changes expected to occur in the future. However, only few species and ecosystems have been examined. Second, scientists are uncertain as to which species, if any, will be able to adapt to changing atmospheric and ocean chemistry conditions.

Finally, it is also uncertain as to how the species composition of whole ecosystems will change as individual organisms find life more stressful than they had in the past. There is still much that we don't know about the effects of ocean acidification, and it remains unclear as to how to manage for resulting changes in the future.

It is really unknown as to why these early warnings from the 1970s—in many ways prescient, in others simplistic—were essentially ignored even by marine chemists and modelers. It is perhaps indicative of the significant disciplinary boundaries that existed between marine chemistry and marine biology and which even now are only slowly being broken down as we develop multidisciplinary research projects to assess the likely consequences of ocean acidification. The complexities of understanding OA are indicative of the significant disciplinary boundaries that existed between marine chemistry and marine biology and which even now are only slowly being broken down as we develop multidisciplinary research projects to assess the likely consequences of ocean acidification.

—A. Dickson, K. Yates

Would seawater ever become acidic, even if all the world's fossil fuel reserves were burned?

Probably not. If all of the known recoverable reserves of coal, oil and natural gas are burned over the next two centuries it still does not release enough carbon dioxide to make the surface oceans become acidic. Moreover, the fundamental chemistry of the ocean carbon system, including the presence of calcium carbonate minerals on the ocean shelf and slope floor that can slowly dissolve and help neutralize some of the CO₂, prevents the oceans from becoming acidic on a global scale. However, if we also consider the vast stores of methane hydrates in ocean sediments, which can become unstable as ocean temperatures warm, the picture may change. If there were to be a massive release of methane from these sedimentary hydrates, the oxidation and subsequent production of CO₂ could be enough for some regions of the ocean to actually become acidic

—C.L. Sabine, J. Mathis, R. Feely

Forecasts (continued)

Which affects ocean acidification more, the rate or the amount of carbon dioxide released?

This is a complex question because both are important in determining the extent of ocean acidification over the next few centuries. Model projections show very little difference in the rate of CO₂ emission under differing scenarios for the next 50 years. However, after that there is a considerable divergence in the model outputs that show an order of magnitude difference in the amount of CO₂ released based on different emission scenarios. This is when we would expect to see the greatest differences in the overall ocean acidification effects. In the near term, the rate of emission will likely have the greatest impacts on those organisms that are forced to adapt to a quickening change in their environment. In the long run though, the total volume of CO₂ emitted is what will ultimately determine how low ocean pH drops and how long these changes will persist in the environment.

—*J. Mathis, R. Feely*

How strong is OA in my region and how might it develop in the future?

While ocean acidification is a global problem that will affect every single region at some point, there are places that are more sensitive and susceptible to its effects in the near term. For example, regions where there is natural upwelling of deep water onto the continental shelves, such as the west coast of North America, will be particularly vulnerable to ocean acidification. Other hot spots exist in the high latitude oceans near both poles. These regions are colder, which means higher concentrations of CO₂ and in most cases they are naturally preconditioned to have lower pH due to ocean mixing patterns or unique physical and chemical processes. If you live in a region where one or more of these processes exacerbate the ocean acidification effect then the impacts will likely be sooner rather than later.

—*J. Mathis, R. Feely*

How long it will take the ocean to recover from recent ocean acidification?

The increased levels of seawater CO₂ from human emissions (anthropogenic CO₂), which causes ocean acidification, builds up in the upper portions of the ocean and is slowly transported to deeper depths via mixing and convective processes as part of the global circulation “conveyor belt.” These CO₂-enriched waters must eventually react with calcium carbonate minerals in sediments in order for the excess CO₂ to be neutralized and carbonate alkalinity restored back into the water column. Ocean surface waters are not in contact with enough carbonate minerals in shallow sediments to allow total equilibration; thus equilibration of the ocean with carbonate minerals in deep-sea sediments necessarily involves deep-ocean circulation processes that take thousands of years to occur. Reaction of anthropogenic CO₂ with carbonate minerals will ultimately cause the average ocean alkalinity to get back into balance; however, full recovery of the oceans will require tens to hundreds of thousands of years.

—*R. Feely*

OA and Marine Life

OA and Photosynthesis

If photosynthesis increases with ocean CO₂ levels, can we expect algae and seagrass to benefit from increasing CO₂?

The form of carbon that phytoplankton, macroalgae, and seagrass use can vary depending upon the species as well as the habitat. As CO₂ increases and seawater pH continues to decrease, bicarbonate will become slightly more available while carbonate is less available. Those species that can effectively use increased CO₂ or bicarbonate might benefit and become competitive ‘winners’. It is thought that algal groups whose photosynthesis is currently limited or “undersaturated” by CO₂ or bicarbonate may grow faster in acidic seawater, while others whose photosynthesis is already saturated may not. However, many algae also precipitate calcium carbonate as part of their tissue and these species will not benefit from increasing CO₂. As a result, future acidification is expected to cause major

shifts in the species composition of ocean phytoplankton and plant communities. For example, studies of algal communities near volcanic CO₂ vents show that biodiversity can be lost due to the loss of carbonate-containing species such as crustose coralline algae, a worldwide group of red algae in coastal environments. Other studies show that the mixture of winning phytoplankton species in a future high-CO₂ ocean could be less able to support the productive food chains that support healthy ocean ecosystems and fisheries resources. Although particular photosynthetic groups will certainly thrive under acidified conditions, these are likely to be different than the dominant species today, and the resulting changes in biological community structure may very well not be positive ones in human terms.

— J. Hall-Spencer, D. Hutchins, C. Pfister

Will corals that contain photosynthesizing algae benefit from rising CO₂?

The photosynthesis of some, but not all, algae increases when CO₂ rises to levels projected for the end of this century (700-800 μatm). The single-celled algae called zooxanthellae (ZOH-zan-THELL-ee) that live within coral animals’ cells are some of the algae whose photosynthesis does not significantly increase at projected future CO₂ levels. Normally, zooxanthellae and corals maintain a delicately balanced symbiosis, in which the zooxanthellae transfer photosynthetically formed carbon-based nutrition to the coral host and provide an important source of carbon for the coral and for coral calcification (skeleton building). If the algae within the corals’ cells do too well and their numbers greatly increase, the transfer of nutrition to the coral host can be disrupted. So even if zooxanthellae photosynthesis were to increase under high CO₂, this does not necessarily benefit the corals. In the great majority of experiments, coral calcification rate decreases when the CO₂ level increases, so it is clear that the rise in CO₂ is decreasing the corals’ ability to build their skeletons rather than protecting them by altering zooxanthellae photosynthesis.

— C. Langdon, A. Cohen

OA and calcification

Why does adding CO₂ plus CaCO₃ benefit corals in saltwater aquaria, but not those in the ocean?

In saltwater aquaria, corals and fish require a narrowly balanced pH and owners often add carbonate “hardeners” to increase the water’s alkalinity and maintain the pH between 8.0 and 8.4. Devices called “calcium reactors” bubble CO₂ gas through crushed calcium carbonate (usually crushed coral), which releases calcium and carbonate ions into the salt water, providing the high-alkalinity, calcium-rich waters that aquarium corals and other calcifying organisms need to continue healthy growth. Unfortunately, these types of devices cannot be used to solve ocean acidification on a global scale, because of the vast amounts of crushed calcium carbonate that would be required to carry out the process in the world’s oceans. It has been suggested that buffering the global ocean with calcium carbonate would require an annual application of at least 30 times as much limestone as is mined by humans today (largely for cement production)- and this would have to be somehow distributed more or less evenly across all of the ocean basins.

— H. Findlay, J. Kleypas, M. Holcomb, D. Hutchins

OA and calcification (continued)

Why does ocean acidification affect shell building in marine organisms?

Dissolving CO₂ in seawater causes a suite of changes in the carbonate system in seawater: the concentrations of dissolved CO₂, total dissolved inorganic carbon, and the bicarbonate ion increase, while pH, carbonate ion concentration, and calcium carbonate saturation state decrease. One or several of these changes may affect shell building in marine organisms. The formation of skeletons or shells in most marine organisms is an internal process where most organisms appear to convert bicarbonate to carbonate to form calcium carbonate. But because this conversion creates protons (hydrogen ions), the organisms must exert energy to transport the hydrogen ions into the external environment (seawater). One hypothesis as to why ocean acidification can cause slower calcification rates (and there are several) is that as seawater pH decreases (leading to protons building up in the external environment), the organisms must exert more energy to rid themselves of the protons

— *H. Findlay, A. Cohen, J. Kleypas*

produced internally by calcification --- they are simply working against a steeper proton gradient. It takes energy to pump ions against their concentration gradients. This explains why many calcifying organisms have lower calcification rates when they are physiologically taxed by other stresses (e.g. lack of food); that is, the added stress leaves the organisms with less energy for calcification. Ocean acidification can also indirectly affect shell formation through physiological impacts, such as changes in an organism's respiration rate and aerobic metabolism, which can impact energy budgets and thus alter the animal's ability to produce shell material. While some organisms may grow their shells at normal rates under ocean acidification, the exposed parts of the shell may dissolve more quickly, so that the organism may need to spend more energy in shell maintenance, and less in reproduction or other important life activities like growth and stress tolerance.

Do crustaceans suffer from ocean acidification also?

Crustaceans form a very large group, which includes such familiar animals as copepods, crabs, lobsters, crayfish, shrimp, krill and barnacles. Compared to other marine calcifiers, crustaceans appear to be relatively tolerant to near-future ocean acidification. However, some direct negative effects, including changes in health, growth, reproduction, and survival have been documented in several key species. Other species experience indirect negative effects when their food supplies are altered.

—*S. Dupont, M. Collard*

Individuals & ecosystems

Why is the long-term change in average seawater pH of concern, when short-term fluctuations regularly exceed these limits?

The fluctuation of pH in coastal waters can be caused by a number of different factors including the influence of freshwater from land, interaction of seawater with fringing coastal habitats, and from changes in seawater chemistry caused by the metabolism of seafloor flora and fauna. Diurnal and seasonal variations in coastal seawater chemistry such as pH typically increase and decrease relative to the chemical signature of offshore oceanic seawater that is generally stable and responds primarily to ocean scale changes in seawater chemistry such as those driven by climate change. Organisms that live in areas with highly variable pH values have developed physiological strategies that allow them to tolerate the fluctuations that are characteristic of coastal environments. The problem is that, as ocean acidification continues to lower ocean pH, the diurnal and seasonal variation will also shift, and the time that the organisms are exposed to unfavorable pH conditions will increase and can exceed their tolerance limits.

—H. Findlay, J. Kleypas, M. Holcomb, K. Yates

If ocean acidification varies regionally, can organisms just move to areas where conditions are more favorable?

Oceans are populated by many species, especially invertebrates, that have a limited ability to move and are very long-lived. Whether or not a species can move to new areas is dependent on many factors. One of the main factors relates to the question of mobility and dispersal: does a particular organism have the ability to physically get to new locations either as an adult or through its offspring? Furthermore, ocean acidification is only one aspect of the physical environment that defines where conditions are favorable for organisms to live. Certain sites may be relatively unaffected by ocean acidification, but also lack in necessary food sources, have different predators or parasites, be a different temperature, or otherwise be unfavorable for colonization.

—M.J. O'Donnell, S. Sundby, K. Y. Børshheim

Why can't organisms adapt to the new conditions?

It is true that organisms have demonstrated an incredible ability to adapt to a wide range of environmental conditions, including reduced pH. However, evolutionary adaptation is a slow process, requiring many generations, and ocean acidification is occurring at a rapid pace compared to the life history of some organisms. Evolution is also facilitated by very large population sizes that include a great deal of genetic diversity, and by the ability to exchange genetic material between individuals freely. For these reasons, microorganisms like bacteria and phytoplankton are much more likely to exhibit adaptive evolution in response to rapid ocean acidification compared to larger, rarer, and more slowly reproducing organisms like fish or marine mammals. The many years that elapse for larger organisms to reach adulthood and produce offspring of their own could mean it would take tens to hundreds of years before a species can alter its physiology at the genetic level to better cope with these new conditions. Even species that reproduce more quickly may not be able to adapt; for example, at the edges of regions with favorable temperatures and water chemistry, corals have been trying to adapt to lower carbonate ion concentrations for many millions of years, but they have not been able to succeed in outcompeting algae and other non-calcifying species there. It seems unlikely, therefore, that corals could succeed in adapting to new temperatures and water chemistry in a few decades to respond to OA. Thus, species will be affected differently by changing ocean chemistry, depending upon their existing tolerance for environmental change versus their potential for evolutionary change. We expect that those species with shorter generation times and broad genetic variation for coping with change will be able to adapt to these rapid environmental changes. Those organisms that are more tolerant of the new conditions are likely to increase in importance in their communities as they don't have to spend as much energy coping with the CO₂ acidified water and can spend more energy on important processes like growth and reproduction. This could lead to large shifts in the composition of the groups that live in a habitat. For instance, coral reefs might increase in algal cover as corals decline.

—M.J. O'Donnell, D. Hutchins, A. Todgham, K. Caldeira, C. Pfister

Individuals & ecosystems (continued)

Won't ecosystems adjust if a few calcifying species leave an area?

During profound rapid changes in ocean chemistry like present-day ocean acidification, organisms respond in one of 3 ways: acclimation, adaptation, or extinction. If most species acclimate rapidly, the biodiversity and function of marine ecosystems may be relatively unchanged.

Evolutionary adaptation, however, is linked to generation time, meaning that long-lived species that mature slowly will have fewer opportunities to produce offspring more resistant to the rapidly changing environmental conditions. If OA drives large shifts in the abundance of key organisms in food webs, or significant rates of extinction, we can expect important changes in the function of ecosystems--- how energy and material flow from primary producers like plankton to top predators like fish and mammals.

Ecosystems are complex networks of interactions among biological organisms and the environment, and it is difficult to predict the full ecological impacts of changing any of those links. We know from CO₂ vent studies that OA affects biological species differently and the mix of marine species shifts, leading to lowered biodiversity and a change in the overall functioning of ecosystems. We depend on a whole range of marine ecosystem services, including food from fisheries, income from tourism and recreation, and oxygen and nutrient recycling from biogeochemical processes; all of these services could be altered, and in many cases degraded, by ocean acidification. Imagine, for example, the economic effects of the disappearance of sea urchins from Japanese fisheries or the decline in fish larvae of commercially important species. Furthermore, decreasing or disappearing calcifying organisms will affect (1) the chemical environment, (2) other calcifying and non-calcifying organisms that may depend on them (e.g., many organisms and hundreds of millions of people depend on coral reefs), and (3) the reservoir of carbon on Earth (the "rock" produced by calcifying organisms falls on the ocean floor to form massive "chalky" deposits that lock away some carbon into geological structures). Just like a neglected aquarium that gives way from fish and shellfish to algae, marine ecosystems may adjust, but they might then be populated by species that are less useful or desirable to humans, making the traditional resources and services provided by the changed ecosystems unavailable, different from before, or unpredictable.

— *D. Iglesias-Rodriguez, S. Doney, S. Widdicombe, J. Barry, K. Caldeira, J. Hall-Spencer*

Will ocean acidification kill all ocean life?

No. However, many scientists think that ocean acidification will lead to important changes in marine ecosystems. This prediction is largely based on geologic history: millions of years ago, marine ecosystems experienced rapid changes during ocean acidification events, including some species extinctions (see "Geologic History" below). Today, some species and the ecosystems they sustain are threatened by ocean acidification, particularly in combination with other climate changes such as ocean warming. Examples include tropical corals, deep-sea corals, bivalves, and swimming snails. These species play key roles in the oceans either because they build three-dimensional structures, which host a considerable biodiversity, or because they are key components of the food chain. Some species that build calcium carbonate structures, such as coral reefs, also provide key services to humans by providing food, protecting shorelines, and supporting tourism. Evidence for the ecological effects of ocean acidification today can be found at "champagne sites," locations where volcanic CO₂ vents naturally acidify the water and small CO₂ bubbles rise through the water column. At one of these sites around the Island of Ischia (Italy), for example, biodiversity is reduced by 30% at the acidity level that matches the level expected globally in 2100. However, these sites aren't perfect analogs for future conditions since selection pressures are much lower at vents compared to in future oceans.

— *J.-P. Gattuso, J. Hall-Spencer*

Will warming and acidification balance out responses from organisms?

In principle, there may be some benefit from warming for the calcification process, because precipitation of calcium carbonate is enhanced by temperature up to a certain threshold. However, organisms are accustomed to living in a limited thermal range and are performing less well in temperatures outside of this range. In many marine areas, organisms (calcifiers and non-calcifiers alike) are already exposed to temperatures reaching the upper end of their thermal windows. Pilot studies on crab and fish have demonstrated that exposure to CO₂ levels expected if CO₂ emissions continue to increase reduces the animals' capacity to tolerate extreme temperatures. Studies on corals have also shown that CO₂ enhances thermal sensitivity. In this case it encourages the likelihood of bleaching events triggered by warming. Overall, it appears that ocean acidification may enhance the sensitivity of organisms to climate warming.

— *H.-O. Pörtner, U. Riebesell*

Individuals & ecosystems (continued)

Will adult organisms be safe if they survive the effects of OA when they are young?

For common marine organisms, the gametes, eggs, various larval stages, juveniles, and adults may be affected differently by ocean acidification because they have different tolerances and coping strategies to environmental stress. In some cases, the early life stages may be more susceptible to stress, while in other cases, the adults may be. Experiments are necessary on all life stages to understand the full effects on an organism and to highlight stages that represent weak links. It is also important to consider ocean acidification's lifelong impacts on survival and reproduction. In general, early life history phases (gametes, larvae, juveniles) are expected to be more sensitive to ocean acidification than adults. Sometimes, early exposure carries over to cause later effects; for example, exposure of adults can decrease reproduction, and exposure of larvae can impact them as juveniles. Furthermore, acclimation may offset these effects after long-term exposure. If fewer young organisms survive to adulthood, population size will clearly be reduced. Ongoing stress usually limits the success of organisms – for example, stressed organisms grow slower and smaller, stressed predators will be less effective, and stressed prey may be less able to avoid capture – and ultimately this stress will decrease survival, causing population size to suffer. For adults, stress caused by ocean acidification may not affect everyday activities, but it will ultimately reduce organisms' growth and reproduction rates. Decreased reproduction can also alter the entire population's size. Impacts at any life stage can reduce the potential for a population to grow or to recover from losses due to disturbance or stress.

—*J. Barry, H. Findlay, S. Dupont*

How can CO₂, a normal product of respiration, be toxic?

Just as in seawater, respiratory CO₂ reduces the pH within cells. Organisms have evolved mechanisms to buffer, transport, and remove CO₂ from their cells at the rate at which it is produced. Ocean acidification reduces the CO₂ difference between the inside and outside of an animal's body, thereby hindering CO₂ removal and causing “respiratory acidosis.” (This term is analogous to “ocean acidification” because normal bodily fluids are slightly basic.) Respiratory acidosis may lead to, among other things, reduced metabolism and reduced organism activity. Additionally, many cellular functions are pH sensitive and may respond negatively to respiratory acidosis. For example, respiratory proteins (e.g. hemoglobin) in the blood bind oxygen at high pH and release it at low pH, allowing oxygen uptake at the gills and release at the cells, where metabolically produced CO₂ has decreased local pH. Many organisms can compensate for respiratory acidosis by shifting the balance of ions in the body. However, it is unknown whether they can maintain such an ionic imbalance in the long term.

—*B. Seibel*

Has ocean acidification caused any impacts on marine life so far?

Yes. Chemical changes in the ocean have been part of the environmental template in which marine biota have evolved, and in the present changes are also modulating ecological processes of marine populations and ecosystems. Recent evidence demonstrates that several coastal ecosystems are characterized by naturally low pH levels due to increased levels of pCO₂. The evidence collected in these ecosystems demonstrates how low pH levels (accompanied by high pCO₂ and low Ω) may impact organisms, populations, and community structure and function. Three examples of these ecosystems are explored below. 1) Cold CO₂ vents off Ischia (Italy): Volcanic gas vents emit CO₂ from the sea floor at ambient seawater temperatures, which leads to a natural pH gradient that impacts the distribution and abundance of benthic calcifier invertebrates. A 30% reduction in species diversity in the areas near the CO₂ vents has been reported. 2) Eastern Boundary Upwelling Systems (EBUES): These regions have naturally lower pH and saturation state because upwelled waters are enriched with CO₂ from remineralization of organic matter in the deeper ocean. The impact of low pH levels and Ω of the upwelled waters has been recently reported as a primary cause of the oyster larvae die-offs in hatchery on the United States' Oregon coast. 3) Coastal environments functioning as sinks for atmospheric CO₂: Adverse carbonate system conditions also occur naturally in these regions. For instance, the cold water of the Chilean Patagonia is a net sink for CO₂, and contrary to the previous examples, where increased pCO₂ (and corresponding decrease in pH and Ω) is due to a natural process, the chemical changes occurring in CO₂-sink areas represent an example of anthropogenic OA. However, natural processes may also react synergistically with anthropogenic OA, exacerbating the biological impacts reported for those habitats.

—*N.A. Lagos, P. Manríquez*

Experimental methods

Does it make a difference when some scientists add acid while others add CO₂ in OA experiments on marine organisms?

Yes. Either CO₂ or a strong acid (such as hydrochloric acid, HCl) can be added to seawater to change the pH. However, even though the pH of the seawater manipulated using acid may be the same as the seawater manipulated by adding CO₂, the rest of the carbonate system parameters (such as total alkalinity, dissolved inorganic carbon, pCO₂, and carbonate mineral saturation state) are slightly different. For example, when pH is lowered in a closed system by 0.4 using only acid the other carbonate system parameters are approximately 8% lower than when CO₂ is added to lower pH. This result occurs because addition of CO₂ increases the dissolved inorganic carbon in seawater in addition to lowering the pH as occurs when CO₂ is added to seawater from the atmosphere. While this seems like a very small difference, there is evidence that such small variations in seawater chemistry may affect biological response experiments especially when they are scaled to natural systems (Yates in press). While no systematic difference has been found yet in the responses of calcifying organisms exposed to seawater acidified by mineral acid or through CO₂ aeration, caution should be used to “get the chemistry right” in ocean acidification experiments.

—U. Riebesell, K. Yates

Could short term lab experiments on marine organisms differ from the decades or centuries it takes to reach the expected changes?

In ocean acidification response experiments, animals are usually not placed immediately in CO₂-enriched waters, but instead they are kept in water that is then equilibrated with carefully controlled gas mixtures. Although it is impossible to perform experiments that simulate the rate of anthropogenic CO₂ accumulation in the atmosphere and the oceans, the CO₂ levels used are far below those that have been shown to cause shock. Nonetheless, these CO₂ levels may disturb physiological processes (acid-base regulation, development of larvae, growth) in ways that appear relatively mild on short time scales. Therefore, long-term exposures are usually needed to find out whether these levels are detrimental and cause fatalities. Sometimes, long-term exposures can identify capacities for acclimation as well. On long time scales, even small decreases in individual animals' health may harm a species, for example, in cases where species compete with others in ecosystems or when they are exposed to another stressor like extreme temperature.

—H.-O. Pörtner, J. Mathis, R. Feely

Fisheries

Why are people so concerned about larval organisms?

We are concerned with the larvae (and juveniles) because these are the life stages most critical to ultimately contributing to adult populations, and we know this is where the bottleneck in natural populations exists. In most natural bivalve species, as well as other benthic species, there is considerable mortality in these early stages, with only a fraction of the individuals surviving to larger sizes that generally allow them to escape predation and be more resilient to environmental parameters. In fact, year to year in some species there may be wide variability in how many individuals succeed, with some years showing no new individuals to the population. We therefore focus most efforts on understanding how the early life-history stages are impacted because that is often the bottleneck of population growth in bivalves.

—G. Waldbusser, M. Green, J. Salisbury

Will oysters, clams, and mussels that we eat for food no longer be available in future oceans?

It's not likely that all of these will be gone completely. We know that larval and juvenile stages are most susceptible, and that areas with favorable conditions will shrink because of the way that carbonate chemistry varies in the coastal oceans. There will probably always be some refuges where these organisms find favorable conditions. But we don't know how long the conditions will last, and whether those refuges will become so small that it becomes economically unfeasible to rely on bivalves as a food item. We also do not know how quickly some of these species may be able to adapt to lower pH conditions. There is some evidence sub-populations may be differentially sensitive, so it may be that genetic traits already exist to allow species to adapt. However, we do not know if any of those adaptations come at an expense of sensitivity to other stressors. At some point there will be limits to physiological compensation in species.

—G. Waldbusser, M. Green, J. Salisbury

OA and Humans

OA and human well being

What are some of the possible or actual societal impacts of OA?

Ocean acidification is expected to have negative overall effects on many marine species. This could alter marine food chains and food supply to humans. This could also decrease the storm protection that reefs provide, tourism opportunities, and other benefits (like biodiversity and habitat) that are difficult to value. Over one billion people around the world depend primarily on marine fisheries for most of their protein intake. Decreasing harvests could especially hurt the poorest people and the least developed nations that have the fewest agricultural alternatives. This could promote migration and pose security risks.

—C. St. John, K. Segarra, S. Cooley

How might OA affect international or national security?

Ocean acidification has the potential to create regional instability if it harms the health and availability of commercial fish stocks and other goods and services derived from the sea, like coastal protection by coral reefs from storms and tsunamis. These changes will impact the food supply and economic opportunities of vulnerable nations. Tensions within and between nations could develop as human communities seek alternative places to live, areas to fish, or ways to generate income. Ultimately, ocean acidification may contribute to widespread social and political instability by promoting human migration and competition for scarce natural resources.

—C. St. John, K. Segarra, S. Cooley

Ethics

Why is OA important enough to justify large government expenditures?

The oceans and their ecosystems are poorly understood compared to the terrestrial environment. Our knowledge is rapidly growing; however, we still have much to learn. Scientists need to give policymakers the best possible information so that they can make informed decisions regarding ocean acidification. That requires research, and in the open ocean, that research is expensive. Scientists have clear evidence that ocean acidification can impact marine species (including species extinction within decades) but most of the science is based on single-species experiments. How this translates at the ecosystem level is poorly understood and requires complex (and expensive) experimental design. However, it is the only way to answer the question and obtaining and distributing that knowledge takes considerable effort. Maintaining clear, open communication among researchers, leaders, and citizens is critical.

—J. Kleypas, C. Turley, R. Key, R. Feely, P. Williamson, S. Dupont

Scientists have answered the question “Is ocean acidification real?” with a definite “yes.” Now we must address the questions: “How bad will the consequences be?” and “What are the solutions?” The first of these is the most difficult question to answer, because we already know that CO₂ levels will continue to rise for the foreseeable future and consequently ocean acidification will increase. Because of the impacts of ocean acidification on marine species and ecosystems that provide food and other services, many scientists are focused on what CO₂ concentration is considered dangerous to the planet and to society. In answering the question “What are the solutions?” most scientists agree that reducing greenhouse gas emissions is the best solution. Yet because atmospheric CO₂ concentrations continue to rise, the emphasis on ocean acidification has necessarily shifted from what can be done about the cause of the problem (rising CO₂) to what can be done about its consequences. This is a huge challenge.

Ethics (continued)

Why shouldn't we let the oceans just continue taking up CO₂ and buffering climate?

Ocean acidification and climate change are two sides of the same coin. Both are direct consequences of anthropogenic CO₂ emissions and occur simultaneously. The oceans currently take up about one quarter of anthropogenic CO₂ emissions, and this service slows the rate of climate change. In the long term, on time scales of tens of thousands of years, the majority of anthropogenic CO₂ emissions (80–90%) will end up in the ocean, but over shorter time scales (centuries to several thousands of years), most of the CO₂ will remain in the atmosphere. It is also important to point out that impacts on the oceans affect the functioning of Earth's ecosystems. The oceans provide vital roles in biogeochemical cycles, not only in the regulation of CO₂, but in the production of oxygen, the cycling of nitrogen and other important nutrients, and the production of gases that affect such things as cloud formation. Many species use both land and ocean habitats, and many humans rely on healthy oceans for their food and livelihoods. The oceans are an integral, interconnected part of the Earth system, and cannot be realistically considered as a separate entity.

— U. Riebesell, J. Kleypas, C. Turley, M. O'Donnell

Management and mitigation options

Would adding antacids to the ocean be helpful?

Chemical bases are effective absorbers of CO₂ and carbonic acid. Indeed, CO₂ reactions with carbonate and silicate base minerals are the primary ways Nature naturally consumes excess atmospheric CO₂ and ocean acidity over geologic time scales. Methods that accelerate these natural reactions are therefore pertinent to CO₂ and OA mitigation. Prior to concerns over OA, Kheshgi proposed large-scale ocean addition of a base, calcined limestone (Ca(OH)₂), to accelerate the removal of CO₂ from the atmosphere. It was later proposed that limestone be directly added to carbonate-undersaturated depths in the ocean to increase alkalinity, effecting both carbonic acid neutralization and increased CO₂ uptake. For the same purpose, coastal addition of finely ground silicate minerals has been suggested. The local amendment of waste shell material (CaCO₃) to benthic sites has been shown to produce seawater chemistry beneficial for the recruitment of

calcifying marine bivalves. Land-based point-source or atmospheric CO₂ mitigation schemes using base minerals can generate alkaline solutions that, in addition to consuming CO₂, could be helpful in combating OA. Here, waste or air CO₂ is converted to dissolved alkaline bicarbonate, which when added to the ocean would help stabilize if not increase buffering capacity and calcium carbonate saturation state. The common use of CO₂/calcium carbonate alkalinity generators to maintain pH and carbonate saturation state for corals and shellfish in saltwater aquaria illustrates, on a small scale, the potential benefit of such an approach to combating local/regional OA. However, further research on the possible scale, safety, and cost-effectiveness of the preceding OA management/mitigation methods is needed.

—G. Rau

What are the options for mitigating the effects of elevated CO₂ on marine life?

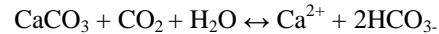
Thus far the primary OA management and mitigation actions proposed have focused on 1) reducing anthropogenic CO₂ emissions and hence stabilizing air and ocean CO₂ concentrations, and 2) maximizing biotic resilience and adaptation to elevated CO₂ using conventional marine management practices (MPAs, pollution and overfishing reduction, etc.). However, stabilization of atmospheric CO₂ below harmful levels may not be achieved, and conventional, passive management practices may not be effective against CO₂ impacts. Some alternative physical, biological, chemical, and hybrid conservation methods have been proposed, but research into their potential effectiveness, cost, safety, and scale of application has yet to be seriously undertaken. A broader and deeper search for and evaluation of new marine conservation practices is needed in the increasingly likely event that unsafe CO₂ and pH thresholds are surpassed.

—G. Rau

Management and mitigation options (continued)

If we increase shellfish aquaculture, will the shells help remove carbon dioxide?

A common misconception in biogeochemistry is that formation of calcite removes carbon dioxide. As can be clearly seen in the reverse of the following equation the formation of calcite actually produces CO₂:



The calcification process does take up bicarbonate ion, but it causes shifts in the carbon system in seawater that result in a lower pH and an increase in pCO₂. Many organisms convert bicarbonate to the carbonate they use to build their shells, and this produces hydrogen ions, thus increasing acidification. Most coral reefs, for example, on the time scales we are interested in, are small sources of CO₂ to the atmosphere rather than sinks. From an ecosystems point of view, even well-intended aquaculture could cause unintentional harm by altering coastal landscapes, increasing pollution and disease, or releasing genetically altered or foreign species into the environment. Any activity aimed at reducing ocean acidification should be considered in a wider context to avoid replacing one environmental impact with another.

—A. Cohen, S. Widdicombe, C. Turley, R. Feely

Can geoengineering solutions for climate change also help OA?

Most proposed geoengineering approaches to limit climate change attempt to provide symptomatic relief from climate change without addressing the root cause of the problem — excess carbon dioxide in the environment. Most geoengineering proposals address the climate consequences of our carbon dioxide emissions but do not address the chemical consequences of these emissions. For example, strategies that seek to cool the Earth by reflecting additional sunlight to space would have little direct effect on ocean chemistry and therefore would not significantly diminish ocean acidification.

Some proposals have sought to diminish changes in ocean chemistry by adding compounds to the ocean that would chemically neutralize acids. However, reversing ocean acidification this way would require adding an amount of material much larger than the amount of carbon dioxide we are emitting to the atmosphere. Therefore, these proposed solutions would require a new mining and chemical processing infrastructure as large as our current energy system. It seems reasonable to suggest that this level of effort and spending would be better applied to transforming our energy system away from dependence on a finite pool of fossil fuel resources to use of renewable, infinite resources— which would also prevent carbon dioxide from entering the environment in the first place instead of requiring us to consider neutralizing its effects after it is already spreading through the atmosphere and oceans.

—K. Caldeira, C. Turley

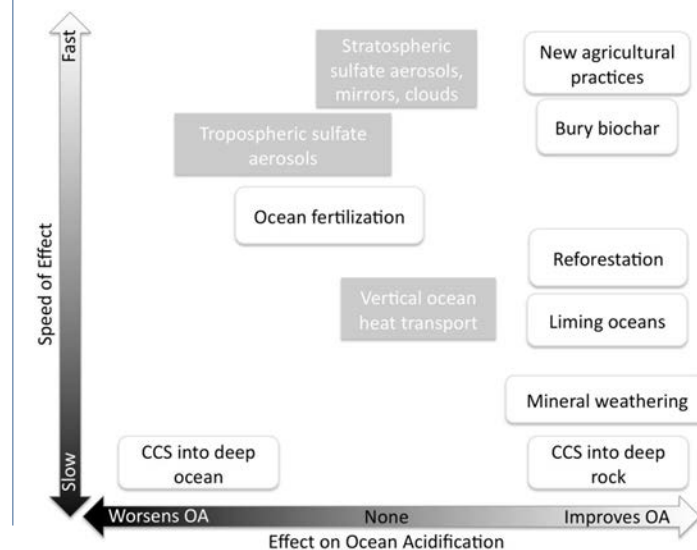


Figure 7: Geoengineering and ocean acidification.

Geoengineering measures that have been suggested to deal with climate change, their effect on ocean acidification, and their timetable for acting. Open boxes indicate strategies considered as “remediations,” or those that attempt to remove the causes of climate change, and gray boxes indicate “interventions,” or those that attempt to moderate the results of climate change. CCS stands for carbon capture and sequestration. From Cooley and Mathis, in revision, *Ocean Yearbook*.

Management and mitigation options (continued)

What can we do about ocean acidification on local and regional scales?

In areas with high levels of local pollution into a restricted environment (e.g., bays and estuaries), mitigation of these local sources of pollution may be able to help offset some of the local pH change caused by ocean acidification. However, local-scale mitigating or remediating action is likely to have only local-scale effects, and would only be relevant in locations in which non-CO₂ pollution exacerbates global CO₂-driven acidification. These small-scale actions are concrete steps that jurisdictions can take and may provide important local benefits, and in particular may serve to increase the resilience of coastal ecosystems in the context of multiple stressors to these environments. But ultimately any local-scale effort to control ocean acidification's effects probably buys only a small amount of time as national governments and international consortia struggle to control global CO₂. Because unilateral action by a small jurisdiction to address the root cause of ocean acidification (i.e., CO₂ emissions) would not substantially mitigate the problem at the scale of the jurisdiction, emissions reduction at the global scale remains the central policy goal for addressing ocean acidification.

—K. Caldeira, R. Kelly, C. Turley

Will CO₂ uptake by marine plants help stop climate change and ocean acidification?

Carbon stored in coastal environments like mangroves and seagrass meadows is called “blue carbon.” Like organic carbon on land stored in trees, this “blue carbon” is locked into organic matter that can be preserved on how large these environments are, and how much carbon they can store. It appears that these areas are natural hot spots for carbon sequestration. Moreover, seagrass beds often occur near coral reefs. Blue carbon may represent a way of offsetting some amount of ocean acidification locally. Future conservation efforts may target these environments to make the most of their ability to sequester carbon. (See also the *OA and Photosynthesis* section.)

—C. Turley, D. Herr, C. Duarte

Will capping atmospheric CO₂ at 350 or 400 ppm stop OA?

Atmospheric CO₂ is already at 392 ppm and is increasing at about 2 ppm per year. Without dramatic reductions in CO₂ emissions, atmospheric CO₂ will continue to rise, and most emission forecasts for the near future indicate a likely increase (rather than decrease) in atmospheric CO₂ growth rate. The first step in addressing ocean acidification, therefore, is to stabilize and eventually reduce CO₂ emissions. Atmospheric CO₂ almost certainly will peak well above 400 ppm, because we will not stop increasing emissions in the next 5 years. The impacts on marine life at the peak CO₂ level may be substantial. In the long run, it may be possible to reduce atmospheric CO₂ through natural and artificial uptake mechanisms. The chemistry of seawater is reversible, and returning to 350-400 ppm would return pH and carbonate saturation levels to approximately their current conditions. However, some research has suggested that even current-day conditions may be deleterious for some organisms, and it is even less clear if future biological impacts due to peak CO₂ will be reversible. Even if we stabilized CO₂ emissions, atmospheric fossil fuel CO₂ will continue to penetrate into the deep ocean for the next several centuries, which may impact deep-water organisms such as cold-water corals.

— S. Doney

Policy development & decision making

Are there any international agreements or regulations focused on mitigating OA?

To date there are no international policies put in place to stop ocean acidification. Nevertheless, OA is now being discussed by many global organizations like the United Nations General Assembly, specialized UN bodies, and the World Bank. Ocean acidification was recently identified as a priority topic by the Conference of the Parties (COP) to the Convention on Biological Diversity (CBD), and it was included in the outcome text of the June 2012 Conference on Sustainable Development (Rio+20) as a recognized threat to economically and ecologically important ecosystems and coastal communities.

—E. Harrould-Kolieb, G. Galland, C. Vivian

Policy development & decision making (continued)

Is it too late to do anything?

It is within our technical and economic means to modify our energy and transportation systems and land-use practices to largely eliminate carbon dioxide emissions from our economies by mid-century. It is thought that the cost of doing this — perhaps 2% of the worldwide economic production — would be small, yet at present it has proven difficult for societies to decide to undertake this conversion.

Every individual can take important steps that can help our societies to be carbon free. We can make changes in our own daily lives that will contribute to reducing carbon emissions, such as reducing our own energy usage and being more energy efficient. We can also ensure that we are utilizing our strength as consumers by purchasing products that have smaller carbon footprints and are less destructive to the ocean, for instance choosing locally caught, sustainable fish. This will not only send a message to industries that we are no longer interested in buying carbon intensive, unsustainable products, but will also help to protect vulnerable marine ecosystems and ensure they are more resilient to the changes likely to occur due to ocean acidification. But changes need to be society wide, so while individual action is incredibly important, it is also vital that we tell our leaders to make the right choices to transition our societies and eliminate carbon dioxide emissions. The more people that send our leaders this message the better. Tell your friends, family, community and anyone who will listen about ocean acidification and how they can help to prevent it. In the long run these steps will not only help to prevent future acidification of the ocean, but will also reduce climate change, make the oceans more resilient and healthy and in many cases save you money as well.

—K. Caldeira, E. Harrould-Kolieb

If OA is so potentially serious why isn't it included in the UNFCCC COP negotiations?

The chemistry of ocean acidification has been understood for a long time. More recently, scientists have found that a wide range of marine organisms could be affected. As our understanding of this has grown, international groups such as the United Nations have begun to include ocean acidification in current planning, for example, in the United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP) activities.

—J. Kleypas, C. Turley, E. Harrould-Kolieb

Should we place marine protected areas in areas less likely to suffer OA and other stressors?

Yes. If we can reduce the stresses to sensitive ecosystems that are within our control like land-based sources of pollution and overfishing, then this will give those ecosystems the best chance of dealing with additional stresses, such as those due to climate change that we can't control. Conversely, if we do nothing to manage the threats within our control, then the combined stress of pollution, overfishing, and ocean acidification makes it much more difficult for coral reef ecosystems to function with the added stress from climate change impacts. The threat of ocean acidification has only recently been brought to the forefront of our collective concern. There is still much that must be learned in regards to the threat of OA such as basic information on the spatial and temporal variability in carbonate chemistry, as well as the sensitivity of different species and taxa. This type of information is a critical for managers to make informed decisions on consideration of marine protected areas (MPAs). As such, only very recently have the discussions begun with regards to how to manage the threat of ocean acidification.

—D. Manzello, K. Yates, J. Hall-Spencer, D. Herr

Are governments or management agencies considering OA in the context of multiple stressors?

Governing bodies appear to be waiting to see what current studies show before taking specific actions. Several government-sponsored research projects and programs around the world are focusing on multiple stressors such as ocean acidification, warming, and deoxygenation on marine systems. These projects are finding that combined effects tend to be more severe than just one stressor alone, so communicating this research is critical to inform policy. Consequently, researchers around the world have collaborated to communicate their concerns about these three stressors to key stakeholders at national, international, and intergovernmental levels (see www.oceanunderstress.com).

—R. Feely, C. Turley, C. Vivian, S. Dupont

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