ISRS BRIEFING PAPER 5

CORAL REEFS AND OCEAN ACIDIFICATION

SYNOPSIS

This briefing paper summarizes the current knowledge of ocean acidification and how it will affect coral reefs, identifies future research needs, and addresses how ocean acidification should be included in overall coral reef management strategies.

Coral reef organisms and the structures that they build will be increasingly exposed in the coming decades to progressive decreases in seawater pH, associated with the oceanic uptake of carbon dioxide produced by fossil fuel burning, deforestation, cement production, and other human activities. These changes in seawater chemistry, popularly termed "ocean acidification", have been correlated with decreased production of calcium carbonate by organisms, along with increased calcium carbonate dissolution rates. The evidence that increased carbon dioxide in the atmosphere can have such direct effects on marine ecosystems is compelling but recent. While the calcification[1] response of some calcifying organisms is well characterized, the overall effects of reduced calcification rates on coral reef ecosystems have been barely investigated. Nonetheless, the potential negative consequences of ocean acidification on coral reefs argue strongly for measures to mitigate further increases in atmospheric carbon dioxide concentrations.

- Calcification rates in corals, which are the best studied coral reef organisms, will decrease by 30±18% by the time atmospheric carbon dioxide concentrations reach twice the preindustrial level in 30–50 years. Fewer studies have been conducted on coralline algae, *Halimeda*, and other calcifying algae that contribute to reef sediments, but for reasons both biological and geochemical, their calcification rates are expected also to decrease with ocean acidification.

- The effects of reduced skeletal growth on the survival and fitness of corals, algae and other calcifying organisms will depend on the function or functions of the skeleton. For example, weaker skeletons will probably afford less protection to coral polyps, while slower growth rates will probably decrease the ability of species to compete for space, and prolong sexual maturity; but these assumptions have not been tested. The effects of reduced skeletal growth on juvenile stages, settlement, and recruitment of calcifying organisms are essentially unknown.

- Most experiments have not indicated negative impacts on coral tissue growth under elevated carbon dioxide. Indeed, recent experiments have shown that some species cultured under high carbon dioxide concentrations can lose their skeletons altogether without apparent physiological stress or reductions in growth, and then resume skeletal building once carbon dioxide levels are returned to normal.

[1] Calcification refers to the process by which organisms secrete calcium carbonate to build their skeletons or shells.

- Dissolution rates of calcium carbonate rock and sediments on coral reefs will increase in the future. Coupled with reduced biological calcification rates, the net calcium carbonate production rates on coral reefs will decrease; that is, reef building will decrease.

INTRODUCTION

Ocean acidification has only recently been recognized as an important consequence of increasing atmospheric carbon dioxide concentrations. In the last 20–30 years, the understanding of the carbonate system in seawater has improved greatly, and studies of how the carbonate system affects marine biogeochemistry have also increased. As with any new "discovery" – in this case, that increasing levels of carbon dioxide are causing shifts in ocean pH[2] that can affect marine organisms – we begin with more questions than answers. The balance of scientific evidence, however, indicates that corals, coral reefs, and cold-water coral ecosystems will be significantly affected by future changes in the carbonate system in seawater.

CHEMICAL CHANGES IN THE OCEAN

The carbonate system in seawater plays an effective role in the ocean's buffering capacity – that is, the capacity of seawater to maintain a relatively stable pH. However, the current rate of atmospheric carbon dioxide increase (occurring over decades to centuries) is exceeding the rate at which the carbonate system can act to maintain a stable pH (requiring many millennia). If the increase in atmospheric carbon dioxide was much slower, then feedback mechanisms such as weathering of rocks would act to keep the system in balance. This explains why corals and coral reefs flourished millions of years ago when atmospheric carbon dioxide concentrations were much higher than today.

The process by which increasing carbon dioxide is causing ocean acidification is well understood and predictable, but the chemistry is somewhat complicated. The carbonate system in seawater involves three main carbon components: carbon dioxide (CO_2), bicarbonate (HCO_3^-), and carbonate (CO_3^{2-}). Based on our knowledge of preindustrial carbon dioxide concentrations, the proportions of carbonate and bicarbonate ions in surface tropical seawater are calculated to

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[2] pH is the "potential for hydrogen ions" in water, and is measured on the logarithmic scale; the lower the pH the higher the concentration of hydrogen ions, and the greater the acidity. A pH of 7 is neutral. pH of preindustrial tropical surface seawater was about 8.2 (on the "seawater pH scale"), but has decreased to about 8.1 today. This 0.1 pH change represents a nearly 30% increase in hydrogen ion concentration. The term 'ocean acidification' refers to the process of decreasing pH, but the tropical oceans are not expected to become technically acidic (< 7) in the future.

have been CO_3^{2-} (11%), HCO_3^- (88%), with the remainder existing as a combination of dissolved CO_2 and carbonic acid.

The oceans have already absorbed about half of industrial-age emissions of carbon dioxide. The combination of carbon dioxide (CO_2) and water (H_2O) produces the weak acid carbonic acid (H_2CO_3) that causes a slight drop in ocean pH (hence the term "ocean acidification"). The carbonic acid rapidly dissociates to bicarbonate and then carbonate, but not completely, and the associated decrease in ocean pH causes the relative proportions of the carbonate ion species to shift. In tropical surface seawater today, the relative proportions of CO_3^{2-} and HCO_3^- have shifted to 9% and 90% respectively, and under doubled preindustrial CO_2 conditions, will shift further to 7% and 93%, respectively. This equates to a large (> 30%) decrease in the carbonate ion concentration once atmospheric CO_2 levels reach 560 ppmv.

The reduction in carbonate ion concentration is important because precipitation rates of calcium carbonate ($CaCO_3$), the material secreted by corals and other reef-building and reef-dwelling organisms, are directly correlated with carbonate ion concentration. Carbonate ion concentration largely determines calcium carbonate saturation state, which is the level of supersaturation of calcium carbonate in the water column and a logical measure of the relative tendency for a calcium carbonate mineral to precipitate (saturation state > 1) or dissolve (saturation state < 1). Lowering the saturation state reduces the ability of corals and other reef organisms to secrete calcium carbonate. Note that saturation states for aragonite (the form of calcium carbonate secreted by corals) are lower than those for calcite (a more stable form of calcium carbonate secreted by mollusks and many other organisms). Tropical coral reefs developed over thousands of years in waters that were highly super-saturated with respect to aragonite (4–5x saturation). Predictions are that by the end of this century, almost all reefs will be exposed to much lower saturation states (2–3x saturation) (see Figure). Cold water coral ecosystems appear to be even more threatened by ocean acidification, because many of these are perched on continental shelves and slopes just above the aragonite saturation horizon (depth between saturated and under-saturated waters). Recent studies show that ocean acidification is causing an upward migration of these saturation depths, so that the deeper cold water corals will be immersed in undersaturated waters (conditions corrosive to calcium carbonate) within a decade or less.

RESPONSES OF CORALS AND CORAL REEF MESOCOSMS TO OCEAN ACIDIFICATION

The current understanding of how corals and other reef organisms will respond to ocean acidification are almost entirely based on tank and mesocosm experiments, where organisms are grown under conditions where the carbonate system in seawater has been altered. Nearly all of these experiments show a significant positive relationship between calcification and calcium carbonate saturation state. The bulk of these studies indicate that coral calcification will decrease by 3–60%[3] under the doubled-CO_2 scenario that is expected to occur within three to five decades.

Most of these studies have not included the effects of other variables that also affect calcification rates, such as temperature, light, and nutrients. Temperature, for example, can strongly affect calcification rates. In a few species, there is some evidence that while declining saturation state may be suppressing calcification rates, increasing temperatures may be enhancing them. This is thought to be a short-term effect, because the coral calcification response to temperature is not linear; rather, it reaches a maximum near the coral's optimal temperature[4], and then decreases at temperatures higher than that optimum. Indeed, a recent study of massive corals from the Great Barrier Reef indicates that calcification rates there have declined by about 20% over the last 16 years, despite a temperature increase of 0.3–0.4ºC over the same period. In addition, any positive effect of increasing temperature on coral calcification rates is overridden by the current dramatic decreases in coral cover due to temperature-induced coral bleaching and disease.

CONSEQUENCES FOR REEF BUILDING AND ECOSYSTEM FUNCTIONING

Few studies have been conducted on the calcification responses of other reef organisms, and virtually no studies have looked at the effects of lowered calcification rates on organism survival. While coral polyps can survive without their skeletons in aquaria, it is doubtful that they would survive in a reef environment. This raises important questions about the function of coral skeletons; that is, how will reduced skeletal growth affect coral survival and ecological roles within the coral community? The benefits of $CaCO_3$ skeletons include protection, rigidity, competition for space, anchoring to substrate, reproduction, etc. The impact of slower skeletal

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[3] This range is based on results from 17 studies on coral and coral reef mesocosms that included a variety of experimental conditions.
[4] Usually the average summertime temperature that the coral normally experiences.

growth will likely vary among species, depending on how each benefit from skeletal growth, but it is likely that adaptation of many coral species to reduced skeletal growth will alter their ecological roles and species-species interactions.

In addition, some studies indicate that net calcification rates in coral reef environments are likely to decrease to values < 0; that is, dissolution rates of calcium carbonate will exceed gross calcification rates. This indicates that future reef-building will slow down progressively with increasing carbon dioxide concentrations; in some cases reef-building may reverse in the latter half of this century. Changes in the natural maintenance of reef structures has consequences not only for reef organisms and biodiversity, but also for associated environments, because coral reefs form barriers that protect coastlines and create conditions that benefit mangroves and seagrass beds.

RESEARCH NEEDS

Research needs extend into every arm of coral reef research, and include extremely basic data collection as well as sophisticated lab and modeling studies. Several recent publications have identified gaps in our understanding of how ocean acidification will affect coral reefs in the future. Listed below are research needs that address the most salient of these gaps. Because of the far-reaching aspects of this topic, an overarching need is to establish cross-disciplinary and cross-institutional collaborations that will minimize duplication of studies and allow efficient and creative research planning.

1. Measurements of the carbonate system, calcification, and dissolution across the suite of coral reef environments, over time-periods and scales necessary to understand the response of the system to continued increases in CO_2.
2. Quantification of the spatial and temporal variations in coral reef carbonate budgets.
3. Quantification of the relative and interactive effects of multiple variables that affect calcification and metabolism in coral reef organisms: e.g., saturation state, light, temperature, and nutrients.
4. Studies of the impacts of reduced calcification on organisms and ecological processes.
5. Determination of the calcification mechanisms across various calcifying taxa.

6. Standardization of seawater chemistry and calcification measurements on corals and reefs.

MANAGING CORAL REEFS FOR CHRONIC OCEAN ACIDIFICATION

The only effective way to prevent ocean acidification is to prevent carbon dioxide buildup in the atmosphere, either through reductions in fossil fuel emissions, or carbon sequestration technologies. Marine aquarists are familiar with the problem of acidification within their own micro and mesocosm coral communities. Over time, aquarium seawater becomes progressively acidic and coral growth slows. Additives (particularly calcium) are routinely used to raise the calcium carbonate saturation state, but in the real world, such solutions are neither feasible nor economical.

As with coral bleaching, since there are few measures for prevention, management strategies will need to focus on increasing coral reef resilience, usually by managing other stressors on reefs. Unfortunately, the science of ocean acidification and its impacts on coral reefs is too new to develop specific guidelines for increasing resilience to ocean acidification, but managers will certainly benefit from scientific research that specifically addresses resilience. Sediment dissolution rates are too slow to counter the effects of ocean acidification over large scales, but within the complex of an entire reef system, sediment dissolution in some environments may provide more buffering of the local water column than in others. This has not been tested, but if true, then corals are likely to grow better in these environments. Another example could consider coral cultivation on reefs: Are some species more resilient to ocean acidification than others? What environmental variables *can* be managed to promote robust calcification rates? Do macroalgae or coralline algae influence the local carbonate chemistry in ways that positively or negatively impact carbonate chemistry?

RECOMMENDATIONS

Ocean acidification is one of many global challenges to ensuring a viable ocean environment in which coral reefs can survive in the future. The ISRS calls on our world leaders to significantly reduce carbon dioxide emissions, on our fellow scientists to improve our understanding of the effects of ocean acidification, and on reef managers to maximize the conservation of reef ecosystems in the face of this environmental threat.

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Figure. Changes in aragonite saturation state of surface waters for the years 1765 (preindustrial) and 2100 (from Feely, et al. submitted), based on modeling results of Orr, et al. (2005) and a Business-as-usual CO_2 emissions scenario. Distributions of tropical coral reefs (black dots) and cold-water coral bioherms (pink dots) are from Guinotte, et al. (2006).