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Coupling Chemical and Biological Monitoring to Understand

the Impact of Ocean Acidification on Coral Reef Ecosystems

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An emerging theme in ocean acidification (OA) science is the importance of coupling chemical, biological, and ecological research and monitoring to better understand the fate of marine ecosystems. This approach has been applied to several coral reefs to document the impact of intensifying OA on these biologically diverse and economically valuable ecosystems. Coupling sustained observations of both environmental conditions and living marine resources allows establishment of a historical baseline, sets the stage for tracking the long-term impacts of global change amid large natural variability, and provides the observational backbone to support process studies, manipulative experiments, and diagnostic and forecast modeling.

The long-term monitoring strategy developed in the United States for tropical shallow-water coral reefs is to measure conditions at several spatial and temporal scales in coral ecosystems of American Samoa, the Commonwealth of the Northern Mariana Islands, Florida, Flower Garden Banks, Guam, Hawai'i, Pacific Remote Island Areas, Puerto Rico, and the US Virgin Islands (Gledhill and Tomczuk, 2012; NCRMP, 2014). The monitoring efforts include (1) surveys across all sites to improve understanding of broad spatial patterns of change, and (2) higher frequency sampling at a limited number of sites to resolve fine-scale temporal patterns in biogeochemical conditions. Critical indicators measured include: temperature and vertical thermal structure; carbonate chemistry; coral growth rate; bioerosion rate; coral and fish abundance, size structure, and key species; coral condition (e.g., bleaching, disease, mortality); benthic percent cover; and rugosity (surface roughness). These measurements establish baseline temporal (diurnal to interannual) and spatial (centimeters to kilometers) variability in coral reef ecosystems, and they will, eventually, characterize change over time.

Some of the first baseline, high-frequency time series measurements of seawater partial pressure of CO_2 (pCO_2) in coral reef ecosystems were collected in the mid- to late 2000s (Figure 1). Moored autonomous pCO_2 ($MAPCO_2$) systems deployed at these locations measure surface seawater and air CO_2 every three hours and are often paired with autonomous pH sensors to constrain the carbonate system. While the time series locations shown in Figure 1 cross large latitudinal gradients, there are no clear spatial patterns. Any latitudinal pattern is masked by local conditions, which vary considerably in terms of physical characteristics and human impacts. For example, the greater environmental variability observed on average at lagoonal sites compared to barrier reef sites likely results from the enhanced influence of reef biology on seawater chemistry during longer residence times of shallow, lagoonal systems (e.g., Drupp et al., 2013). These pCO_2 time series also show that most of the monitored coral ecosystems are weak sources of CO_2 to the atmosphere, suggesting net calcification, and at most mooring locations, the seasonal cycle tends to dominate the natural variability signal (Figure 1).

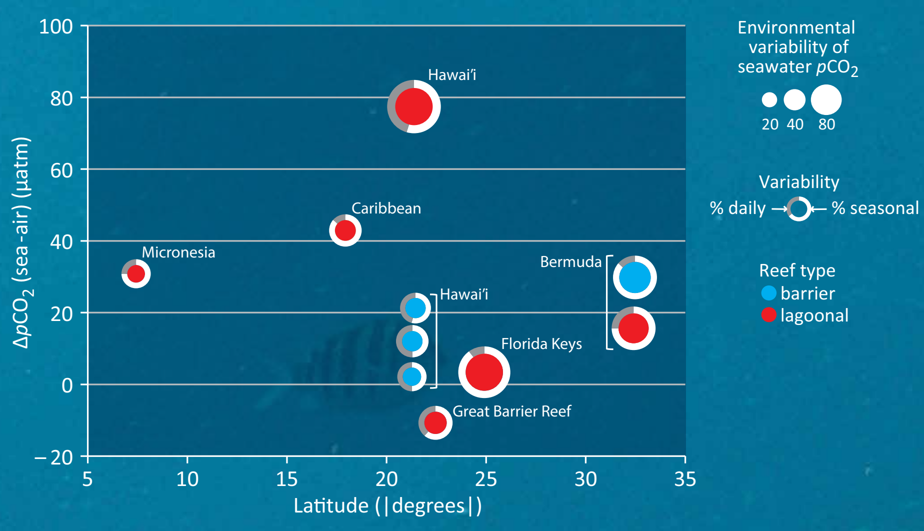

FIGURE 1. Mean ΔpCO_2 of surface seawater at coral reefs measured by autonomous $MAPCO_2$ systems. Inner circle colors illustrate reef types. Barrier reefs are subject to the most wave energy and are most exposed to offshore conditions. Lagoonal reefs occur shoreward of the offshore reef. Inner circle sizes are relative to the variability in the time series, defined here as the standard deviation of mean pCO_2. Outer rings show the proportion of variability in seawater pCO_2 due to the seasonal cycle (defined as the mean seasonal peak amplitude) and daily variability (defined as the mean daily peak amplitude). Detailed information on each site, including finalized data, is available at http://www.pmel.noaa.gov/co2.

(left) Collecting a coral core in the Galápagos. *Credit: Josh Feingold* (middle) Servicing trip to an ocean acidification buoy located on the southwestern coast of Puerto Rico in the La Parguera Natural Reserve. *Credit: Sylvia Musielewicz* (right) Storm approaching the Cheeca Rocks ocean acidification buoy located within the Florida Keys National Marine Sanctuary off Islamorada, Florida. *Credit: Lauren Valentino*

However, pCO_2 variability due to daily cycles in reef photosynthesis/respiration and calcification/dissolution is also significant in surface waters. While surface data allow us to understand how sea-air CO_2 flux influences the patterns and trends in these systems, connecting surface CO_2 flux to subsurface carbon chemistry dynamics and impacts on reef organisms requires subsurface time series that are more recent additions to the suite of observations at these sites.

One of the major challenges in attribution of OA in the modern world is that other stressors (e.g., increasing ocean temperature) impact rates of reef calcification, confounding our ability to detect the ecosystem impact of OA on coral reefs. For example, anomalously warm seawater temperatures in 2014 caused a mass coral bleaching event at Cheeca Rocks, a patch reef located along the Florida Keys Reef Tract (Figure 1, at 24.90°N, 80.62°W, characterized as lagoonal; Figure 2). The frequency and severity of warm-water coral bleaching events has increased dramatically over the past 30 years on a global scale and is expected to increase further with climate change (Hoegh-Guldberg et al., 2007). The depression in coral reef calcification associated with bleaching stress and any resultant mortality (Eakin, 1996) potentially confounds our ability to attribute declines in net ecosystem calcification (NEC) to OA. To control for this, we are utilizing high-resolution landscape mosaics to monitor key sites (Figure 2). Landscape mosaicking is an image-based mapping technology that provides comprehensive scientific information on benthic reef communities from rapid field surveys. Using these mosaics, we can normalize the measurement of NEC with important metrics of community structure, such as coral cover (to species level) and the presence of other calcifiers, such as crustose coralline algae. This technique allows us to determine the impact that acute disturbances, like coral bleaching, as well as more subtle shifts in community structure have on NEC. Because these measurements are coupled with high-frequency monitoring of physical and chemical parameters (Figure 2), the end result is a better ability to understand the effect of OA on NEC in real-world, dynamic coral reef ecosystems. In this case, preliminary observations do not show a clear impact of bleaching on carbon chemistry (Figure 2), and they will serve as important records of reef response to the impacts of warming and OA. Maintaining long-term, multidisciplinary monitoring of both coral reef change and the drivers of change while also integrating experimental and modeling studies at key locations will allow us to better understand how OA and other processes control the changes we observe in these ecosystems.

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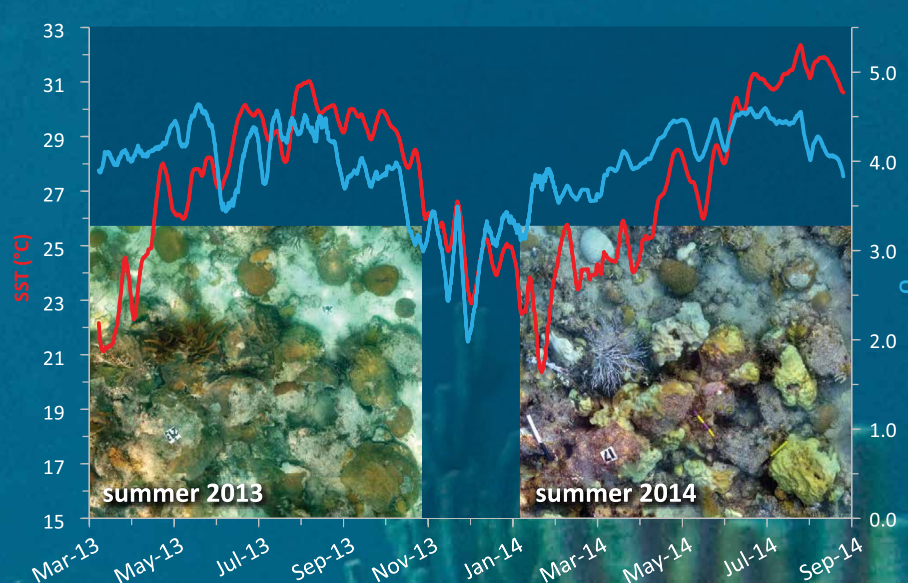

FIGURE 2. Weekly averaged measured sea surface temperature (SST) in red and estimated aragonite saturation state (Ω_{arag}) in blue at Cheeca Rocks in the Florida Keys, with Ω_{arag} estimated from seawater pCO_2 and pH observations. Side-by-side mosaic images show the same reef area at Cheeca Rocks in 2013 and 2014. The purple and yellow stick is 50 cm long. While the 2013 image shows normal pigmentation, the 2014 image shows widespread bleaching coincident with warm water stress.