

Climate Change and Coral Bleaching
Eric Chan

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In the past few decades, the emerging problem of climate change has garnered much attention from the scientific community and public. It is widely accepted that global climate change has—and will have—an undeniable impact on human life. The effects of this change have already been felt agriculturally, through increasing natural disasters, availability of natural resources, and the spread of disease; however, these issues are not simply human concerns. Global climate change can also alter the delicate physiological balance of sensitive species such as corals, which serve as an integral component of many marine ecosystems. Coral reefs provide ecological services by maintaining vast biodiversity within ecosystems, its framework providing and regulating a habitat for the spawning, nursery, breeding and feeding of many other organisms. They also provide ecological services between adjacent ecosystems—providing homes for “mobile links” and exporting organic production and plankton to pelagic food webs. Meanwhile, the reefs provide physical structure services by buffering waves and currents, protecting shorelines from erosion, and building up land (Moberg 1999). Humans can utilize coral reefs, which are long-lived yet sensitive to changes in environment, to record pollution and climate trends (Eakin 1997). They are also important for sustaining the livelihood of coastal communities by attracting tourism and by providing raw materials and seafood products (Moberg 1999). Thus, it is imperative not only to study climate change through its direct impacts on human beings, but also through the lens of its ramifications for specific marine ecosystems—with consequent effects on larger systems and human life.

There are many factors that have contributed to changes in the Earth’s climate over the planet’s history. Natural processes, such as fluctuating intensity of the sun, changes in planetary orbit, ocean circulation, and volcanic activity can cause significant alteration in

climate measures. However, over the past 200 years, human activities such as burning of fossil fuels, deforestation, and agriculture have substantially contributed to climate change by significantly increasing greenhouse gas emissions into the atmosphere. Increased amounts of carbon dioxide, methane, ozone, and other gases subsequently contribute to the trapping of heat in the atmosphere by absorbing infrared radiation emitted by the Earth (<http://www.epa.gov>). These gases are then able to emit the longwave radiation back toward the surface, resulting in the so-called “greenhouse effect” (though this term is a misnomer—as greenhouses work by the suppression of convection, while greenhouse gases reduce radiation loss) (IPCC 2001).

Recent increases in greenhouse gas emissions has been implicated in patterns of global warming, with records indicating that the Earth’s surface has warmed by 0.7 and 1.5°F since the 20th century (NRC 2006). Furthermore, if concentrations of greenhouse gases continue to increase at current rates, it has been estimated that the average surface temperature of the Earth will increase by 2.5 to 10.4°F by 2100—a rate of warming that is two to ten times greater than that observed during the 20th century. This projected temperature increase is not likely to be evenly distributed around the globe, with winters expected to be warming more than summers (IPCC 2001). Change in sea level is expected to correlate with increased temperatures, as higher surface temperatures will expand ocean water, melt glaciers and ice caps, and cause portions of coastal Greenland and Antarctic ice sheets to melt or fall into the ocean. The Intergovernmental Panel on Climate Change (IPCC) states that the West Antarctic ice sheet and Greenland ice sheet both contain enough ice to raise sea levels by approximately 6 meters, respectively (IPCC 2001). It is projected that global average sea level will rise by 0.09 to 0.88m by 2100 though regional variations are expected.

El Niño even frequencies are also predicted to increase with future greenhouse warming. These El Niño/Southern Oscillation (ENSO) events are natural climate fluctuations that originate in the tropical Pacific Ocean, and can influence the climate of the entire planet. ENSO events consist of an irregular alternation between warm and cold (El Niño and La Niña, respectively) climate states. By coupling a global ocean general circulation and sea ice model to an atmospheric general circulation model known as ECHAM4, scientists have been able to simulate interannual variability in the tropical Pacific (Bacher 1997). This coupled model, which has been “flux corrected” to account for heat and freshwater variations, can simulate and predict ENSO periods. Two simulation experiments were then conducted to observe El Niño future conditions, one using fixed present-day atmospheric greenhouse gas concentrations, and the other using a model with increasing levels of greenhouse gases (in correspondence with the model proposed by the IPCC). Comparison between the two simulations indicated that the frequency of El Niño-like conditions—as well as enhanced year-to-year variability in sea surface temperature (SST) anomalies—will increase in the tropical Pacific Ocean through 2100, corresponding with predicted increases in greenhouse gases (Timmermann 1999). If these predictions are correct, it could have significant implications for marine organisms—such as corals and their symbionts—that are particularly sensitive to ENSO-related climate shifts.

Corals often form vital (but sometimes tenuous symbiotic) relationships with photosynthetic dinoflagellate endosymbionts known as zooxanthellae. These algae provide their coral hosts with organic compounds that may contribute a substantial portion of the coral’s diet, and is also believed to provide much of the energy necessary for processes such as tissue and skeletal growth and reproduction (Szmant 1990). Coral “bleaching” is a process that occurs when corals expel their mesenterial zooxanthellae and/or their pigments (most often as a response to environmental or physiological stress), resulting in a marked whitening

of the coral host. A generally accepted bleaching “threshold” is approximately 1°C above mean summer maximum temperatures, which is expected to be increasingly exceeded according to projected climate change models (Hughes 2003). Rapid rises in sea level along with increased atmospheric CO₂ may also affect bleaching event frequencies, but to a lesser degree than temperature and SST changes. It has been suggested that rising sea level may increase coral distance from the photic zone enough that their photosynthetic zooxanthellae no longer provide adequate contribution—and are thus expelled. Meanwhile, increased concentrations of CO₂ can react with surface waters and increase its acidity, dissolving reef limestone and decreasing the deposition rate and strength of limestone by reef organisms (Hoegh-Guldberg 1999).

It is clear how ENSO events are strongly associated with coral bleaching events, as their warm cycles can cause prolonged rise in SST and subsequently stress corals into expelling their zooxanthellae. The effects of ENSO-related climate change on coral reefs is perhaps most evident in the 1997-1998 El Niño event, whose strength, coupled with abnormally high temperatures, caused massive worldwide bleaching of corals, and resulted in damage or death of an estimated 16% of the world’s coral reefs. Certain reefs were more affected than others by these events, with around 65% of Arabian and Persian reefs dead as a result of bleaching. In 2004, an estimated 20% of all coral reefs were regarded as effectively lost or damaged beyond repair, of which the wider Caribbean reefs are experiencing the most dire decline—with an 80% drop in live coral over a 25 year period—caused by bleaching and other stresses (Wilkinson 2002). But why does bleaching have such dire consequences on the livelihood of coral species? Scientists studied this issue using the Floridian reef coral, *Montastrea annularis*, conducting analysis of 2 such coral populations undergoing prolonged bleaching. The bleached corals observed were found to possess 30% less tissue carbon and 40% less tissue nitrogen biomass per skeletal surface area, and during the reproductive

season, were unable to initiate oogenesis. These observations indicated that bleached corals were able to survive prolonged bleaching by consuming their own structural materials, but then consequently lost the resources necessary for reproduction. Nearby normal and bleached corals that had repopulated themselves with zooxanthellae exhibited no loss of tissue biomass or impaired oogenesis (Szmant 1990). This finding indicates the importance of the symbiotic relationship between coral and zooxanthellae for the survival of the host species, and how devastating climate change-related coral bleaching can be for the survival of coral populations.

In an era of climate change, rising temperatures, and increasing ENSO events, devastation of coral reefs is becoming increasingly likely. However, there is the suggestion that long-term survival of coral reefs can be attained through association with new, more thermally tolerant zooxanthellae types. As of 2006, eight phylogenetic clades of zooxanthellae have been discovered and characterized by nuclear ribosomal and chloroplast DNA analysis. Each of these zooxanthellae clades (A through H) contains many species types, and some corals appear to associate with several different types at one time (Berkelmans 2006). Scientists set out to find if specific combinations of host corals and symbionts could provide ecological advantage with regard to increased thermal tolerance, designing experiments using the relatively bleaching sensitive, Indo-Pacific stony coral *Acropora millepora*. Experimental manipulations involved transplantation of *A. millepora* colonies to separate locations, recording the temperatures of these locations, and genotyping the zooxanthellae within them. Meanwhile, nubbins were removed from the colonies at each of the five populations and were subjected to four temperature treatments: 27.5°C for non-bleaching control, 30, 31, and 32°C—temperatures that theoretically exceed the “bleaching threshold.” Zooxanthellae extracted from extracted nubbins were subjected to counts and fluorescence measurements before and after fourteen months of coral exposure to both

laboratory and environmental temperatures. The experiments showed that some corals were able to increase their tolerance to temperature shifts by exchanging dominant type C zooxanthellae to type D, and that these new zooxanthellae types were likely subdominantly present in the corals—rather than exogenously acquired from the environment. Those corals that had taken up the most tolerant, D-type symbionts could raise their temperature tolerance by 1 to 1.5°C, and were thus more resistant to bleaching than type C dominant corals (Berkelmans 2006). The results of this research indicate that acclimatization mediated by zooxanthellae change is a naturally occurring process in coral reefs, and supports current hypotheses that bleaching is a mechanism for corals to obtain symbionts more suited for stressful environments. These findings also provide hope that corals may be able to withstand some forthcoming temperature shifts by exchanging zooxanthellae types, though the protection inferred by this mechanism may only buy corals a small window of time before climate change exceeds new bleaching “thresholds.” There is hope, however, that humans may be able to use this time to reduce greenhouse gases and other climate changing agents—slowing current climate trends (Berkelmans 2006).

The mechanisms underlying increased temperature tolerance of some zooxanthellae over others are an important area of study to find ways for preventing coral bleaching. By examining the thylakoid membranes (phospholipid bilayer membranes inside chloroplasts that play a significant role in photosynthesis) of zooxanthellae with different temperature tolerances, scientists are able to study key determinants of thermal stress tolerance on a molecular level. Experiments conducted on cultured zooxanthellae were performed to find a key determinant of thermal-stress sensitivity (Tchernov 2004). Researchers obtained cultures of various zooxanthellae, and subjected them to variable thermal tolerance tests (growing samples at 26°C and then subjecting them to 32°C water). Meanwhile, thylakoid membranes were observed through transmission electron micrography, while photochemical energy

conversion efficiency was observed through fast repetition-rate fluorometer measurements. The scientists observed that the thylakoid membranes of thermally tolerant zooxanthellae were unaffected by higher temperatures, while those membranes of thermally sensitive clones exhibited membranes with disrupted stacking patterns—interfering with photochemical energy transduction. This interference was confirmed by fluorometer measurements, as thermally sensitive zooxanthellae exhibited marked changes in electron-transfer times, with a 40% decrease in photochemical energy conversion efficiency during the photosynthetic absorption of light. Furthermore, through lipid analysis, thermally tolerant zooxanthellae isolates were found to have higher relative concentrations of saturated polyunsaturated fatty acid in thylakoid membranes (Tchernov 2004). These results indicate the importance of thylakoid membrane integrity as one possibly critical determinant of thermal stress tolerance in corals, and demonstrate the potential use of lipid analysis to provide a sensitive gauge of coral susceptibility to bleaching.

Though laboratory tests such as lipid analysis can be used as a predictor for local coral bleaching vulnerability, other technologies allow for more encompassing predictions of coral bleaching. The National Oceanic and Atmospheric Administration (NOAA) and National Environmental Satellite, Data and Information Service (NESDIS) have together developed a method to map SST “HotSpot” anomalies using 50km satellite imaging. HotSpots are defined as SSTs that are above the Maximum Monthly Mean (MMM) SST, and can be linked to coral bleaching, which can occur with a 1°C increase above the summer MMM SST. Scientists created a retrospective HotSpot map for 1998 using 9km resolution and 15 years of SST data, comparing it to 50km maps. The experiment showed that in situ temperatures could be accurately reproduced using 9km resolution (Toscano 2002). This is an important advance in imaging, as lower-resolution 50km mapping is sufficient for an event such as the 1998 ENSO event—due to the large areas affected—but is not refined enough to

represent temperatures near landmasses. The high-resolution HotSpot mapping allows for better spatial detail of thermal stress patterns, variabilities, and levels—with greater detail in and around particular reefs or within large reef complexes. In addition to aiding in prediction of coral bleaching events, researchers found 9km climatology map values were warmer and reduced the anomaly levels in the 50km product—indicating that perhaps coral bleaching is triggered by even less thermal stress than was originally thought (Toscano 2002).

In February 2000, more than 100 governments concluded that global climate change was the primary cause of the 1997-1998 mass bleaching events (Reaser 2000). The widespread acceptance of the fact that coral bleaching—and subsequent death—is a result of global climate change has led scientists to recommend policy changes to protect their livelihood. Such actions as emphasizing that coral bleaching can act as an indicator of the effects of global warming and collapse of coral reef ecosystems, encouraging development of approaches for assessment of coral reef vulnerability to global warming, building technology for monitoring and prediction of coral bleaching and its impacts, and identifying approaches for developing rapid response measures to bleaching events (Hughes 2003). Conservational biologists also recommend the building of stakeholder partnerships, community participation programs, and public education campaigns that will address causes and ramifications of coral bleaching, support research and support policy measures. Perhaps most universal, however, is the push for international integration to control greenhouse gas emissions, and upscaling of local, regional, and global reef management systems (Toscano 2002, Hughes 2003). With concerted effort, it is possible to protect coral reefs from climate change-related bleaching and other thermal stresses—and by doing so, protect the valuable diversity and vital systems the reefs support.

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