Statement of

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Introduction

I thank Chairman Markey, Ranking Member Sensenbrenner, and the other Members of the Select Committee for the opportunity to speak with you today about global climate change and its effects on our oceans. My name is Joan Kleypas. I am a Scientist at the National Center for Atmospheric Research in Boulder, Colorado. My research has focused on the interactions between marine ecosystems and climate change, with particular emphasis on the impacts of climate change on coral reef ecosystems. I have authored or co-authored more than 40 peer-reviewed scientific journal articles, book chapters, and technical documents, and have presented more than 40 invited talks worldwide. I have co-organized several international workshops on issues related to climate change and marine ecosystems. I currently serve on three committees related to carbon and the oceans: the Ocean Carbon and Biogeochemistry Scientific Steering Committee, the European CarboOcean International Advisory Board, and the European Program on Ocean Acidification (EPOCA). You have asked me to provide insights on issues related to the impacts of climate change on coral reefs. My testimony will focus on two major factors that affect coral reefs: ocean warming and the emerging problem of ocean acidification. I have worked on these issues for more than 10 years, and on coral reefs for more than 20 years.

Background

What are coral reefs? Coral reefs are geological structures built by biological communities dominated by corals. Coral reefs are quite unique in that they are literally defined by the rock – calcium carbonate – that the organisms produce during skeleton and shell building. A coral reef can be 30 meters thick and cover many square kilometers, essentially built over time by the thin veneer of organisms that live on the reef surface. The main organisms that build coral reefs are corals, animals related to sea anemones but which secrete skeletons. Many other organisms are also important in reef building: certain algae that secrete calcium carbonate, as well as mollusks, echinoderms, and many lesser-known groups of organisms. Even though corals are animals, their ability to grow quickly and build reefs is due to their symbiotic relationship with microscopic algae ("zooxanthellae") that live in their tissues. The symbiotic algae produce nutrients and energy via photosynthesis, which allows the corals to live in rather nutrient-poor regions.

Corals and reef-building algae thus require light to grow and are usually limited to waters less than 30m in depth; as such they are subject to atmospheric disturbances such as storms and hurricanes. The shallow-water restriction usually places them near land as well, and thus coral reefs occur at the triple-intersection of atmosphere-land-ocean. Most reefs therefore are quite accessible to man and have sustained human cultures for thousands of years, but they are also subject to multiple stressors from the nearby land, atmosphere, and the ocean.

Reefs in the U.S. and its territories. Coral reefs in the U.S. and its territories extend well beyond the familiar reefs of Hawaii, Florida, and Texas. Extensive coral reefs also exist in Puerto Rico, U.S. Virgin Islands, and in the Pacific: The Northern Mariana Islands, Saipan, Guam, Wake Island, Johnston Atoll, Kingman and Palmyra Atolls, Howland and Baker Islands, and Jarvis Island. The U.S. values its coral reefs and has a history of protecting them. In 1998, President Clinton issued an Executive Order establishing the U.S. Coral Reef Task Force, and in 2000 he issued an Executive Order to establish the Northwestern Hawaiian Island Coral Reef Ecosystem Reserve.

The value of coral reefs. Coral reefs occupy only about 1% of continental shelves, yet they support an estimated 25% of marine species. Coral reefs have the obvious economic value derived through fishing, tourism, the aquarium industry, etc. However, they also provide many hidden values that are often overlooked. Some of these include: 1) shoreline protection; 2) fish habitat; 3) beach sand supply; 4) potential pharmaceuticals and 5) biodiversity. Global economic valuations of coral reefs calculate the net economic benefit from reefs at about US$30 billion per year[1]. The economies of four Florida counties alone (Palm Beach, Broward, Miami-Dade, and Monroe) receive some US$4.3 billion in sales and $2 billion in annual income[2].

Current state of coral reefs worldwide and in the Caribbean. By several measures, the condition of coral reef ecosystems has declined worldwide. Two recent studies document large declines in the percent coral cover on coral reefs. Since the 1970's, the percent coral cover (the percentage of reef surface area occupied by corals) has declined from about 50% to 25%[3]; in the Caribbean, the decline has been from about 50% coral cover to 10%[4]. Worldwide, about one-fifth of all reefs have already been destroyed with low prospects for recovery[5]; about half of this is due to the phenomenon called "coral

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[1] Cesar H, Burke L, Pet-Soede L. 2003 *The Economics of Worldwide Coral Reef Degradation*, 6828GH Arnhem, The Netherlands

[2] Johns GM, Leeworth VR, Bell FW, Bonn MA. 2003. *Socioeconomic Study of Reefs in Southeast Florida. Final Report submitted to Broward County, Palm Beach County, Miami-Dade County, Monroe County, Florida Fish and Wildlife Conservation Commission, and NOAA, as revised April 18, 2003*

[3] Bruno JF, Selig ER. 2007. Regional decline of coral cover in the Indo-Pacific: Timing, extent, and subregional comparisons. *PLoS ONE* 2: e711. doi:10.1371/journal.pone.0000711

[4] Gardner TA, Côté IM, Gill JA, Grant A, Watkinson AR. 2003. Long-term region-wide declines in Caribbean corals. *Science* 301: 958-60

[5] Wilkinson C, ed. 2004. *Status of Coral Reefs of the World: 2004*, Vols. 1. Townsville, Queensland: Australian Institute of Marine Science

bleaching" (described below). Of the remaining reefs, about half are considered critically threatened (24%) to threatened (26%)[6].

How climate change affects coral reefs. Coral reefs are particularly vulnerable to climate change because they already suffer multiple direct impacts from human activities such as overfishing and poor land-use practices. Climate change encompasses an array of changes that can directly or indirectly affect the coral reef environment, e.g., global warming, sea level rise, changes in storm intensity or storm tracks, changes in river runoff from land, etc. The root cause of climate change – increases in atmospheric CO_2 – also causes "ocean acidification," which presents an additional health challenge to coral reef ecosystems. I address below the two main challenges facing coral reefs today: ocean warming and ocean acidification.

Ocean warming

Coral bleaching. Coral bleaching is a phenomenon whereby a coral expels the algal symbionts that live within its tissues. This can occur when a coral becomes stressed by one of more of a number of factors such as sudden changes in salinity, disease, or changes in temperature. Coral bleaching incidents were relatively rare and local until the 1980s, when large-scale "mass bleaching" events were first identified in association with anomalously warm waters during warm-phase years of the El Niño-Southern Oscillation (ENSO). Coral bleaching has become increasingly common and widespread since then, with almost all events linked warmer than normal ocean temperatures, regardless of the ENSO state[7].

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[6] Ibid.

[7] Hoegh-Guldberg O, Mumby PJ, Hooten AJ, Steneck RS, Greenfield P, et al. 2007. Coral reefs under rapid

The tropical oceans have warmed an average of 0.3-0.4ºC since the 1950s[8]; in many regions, temperatures have occasionally spiked by 1-2ºC or more above the normal maximum temperature in that region. On average, corals will bleach if temperatures exceed the normal maximum by 1-2ºC, even if for only a few weeks, but the temperature tolerance varies with region, species, and the baseline health of the corals.

The level of coral mortality following a bleaching event varies greatly with the severity and duration of the warming. In some regions, the corals have recovered completely (e.g., the Great Barrier Reef) while in others the entire coral community has died (e.g., Maldive Islands). Bleaching also increases vulnerability to diseases that contribute to coral mortality[9-10].

In 2005, a large-scale bleaching event in the Caribbean affected many reefs, particularly in the southern half of the basin and including reefs in Puerto Rico and the U.S. Virgin Islands. The same, unusually warm waters that fueled Hurricanes Katrina and Rita caused this mortality.

Coral disease. Coral disease has also increased in the last few decades, and dramatically so in the Caribbean[11]. The two most important Caribbean reef-building species (*Acropora palmata*, Elkhorn coral; and *Acropora cervicornis*, Staghorn coral) have been particularly affected by disease. These two species have declined dramatically, and in 2006 both were listed as “Vulnerable” under the Endangered Species

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climate change and ocean acidification. *Science* 318: 1737-42

[8] Kleypas JA, Danabasoglu G, Lough JM. 2008. Potential role of the ocean thermostat in determining regional differences in coral reef bleaching events. *Geophysical Research Letters* 35: L03613, doi:10.1029/2007GL032257

[9] Harvell CD, Mitchell CE, Ward JR, Altizer S, Dobson AR, et al. 2002. Climate warming and disease risks for terrestrial and marine biota. *Science* 296: 2158-62

[10] Wilkinson C, Souter D. 2008. *Status of Caribbean coral reefs after bleaching and hurricanes in 2005*. Townsville: Global Coral Reef Monitoring Network, and Reef and Rainforest Research Centre

[11] Porter JW, Dustan P, Jaap WC, Patterson KL, Kosmynin V, et al. 2001. Patterns of spread of coral disease in the Florida Keys. *Hydrobiologia* 460: 1-24

Act. Increasing ocean temperatures are hypothesized to increase disease by decreasing host resistance, and/or by increasing pathogen ranges, growth, virulence, or infectivity[12].

Ocean acidification

What causes ocean acidification? A large proportion of the carbon dioxide (CO_2) released to the atmosphere is absorbed by the ocean. A recent inventory of carbon in the oceans estimates that by mid-1990s, the oceans had already taken up nearly half of the total carbon dioxide released by human activities between 1800 and 1994[13]. Without this process, the atmospheric concentration of carbon dioxide would have risen from 280 ppmv (pars per million volume) to about 435 ppmv rather than the current concentration of 380 ppmv. The natural sequestration of carbon dioxide by the oceans thus slows down the build-up of greenhouse gases in the atmosphere.

However, the additional CO_2 in the water column is resulting in "ocean acidification," the progressive shift of ocean pH toward more acidic conditions. This shift is occurring because carbon dioxide combines with seawater to form carbonic acid, which lowers the pH. Once the concentration of carbon dioxide in the atmosphere reaches twice that of preindustrial times (560 ppmv), the pH of the surface ocean will have decreased from a preindustrial average of about 8.16 to about 7.91[14]. Because pH is reported on a logarithmic scale, this small change in pH represents a rather large increase (78%) in hydrogen ion concentration, with clear implications for biological processes. These

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[12] Harvell CD, Mitchell CE, Ward JR, Altizer S, Dobson AR, et al. 2002. Climate warming and disease risks for terrestrial and marine biota. *Science* 296: 2158-62

[13] Sabine CL, Feely RA, Gruber N, Key RM, Lee K, et al. 2004. The oceanic sink for anthropogenic CO_2. Ibid.305: 367-71

[14] Kleypas JA, Feely RA, Fabry VJ, C. Langdon CL, Sabine CL, L.L. Robbins. 2006. *Impacts of Increasing Ocean Acidification on Coral Reefs and Other Marine Calcifiers: A Guide for Future Research, report of a workshop held 18–20 April 2005, St. Petersburg, FL*: sponsored by NSF, NOAA, and the U.S. Geological Survey. 88 pp. http://www.isse.ucar.edu/florida/

changes will also cause shifts in the relative concentrations of other dissolved carbon species in the ocean. Notably, the concentration of the carbonate ion, which is a major building block for the skeletons and shells of many marine organisms, will decrease by about 34%[15]. Ocean acidification leads to slower and/or weaker coral reef growth. The consequences of this are analogous to severe osteoporosis in humans, and are described in detail below under "*Effects of ocean acidification on marine biota.*"

Even though the process of ocean acidification was predicted since the 1970s, only recently has this process been verified by large-scale measurements of carbon in the ocean through programs such as the World Ocean Circulation Experiment and the Joint Global Ocean Flux Survey. Based on what we know about ocean pH in the past, the seawater chemistry of the surface ocean is already altered to a state that is considerably outside the range of conditions of the past several hundred thousand years and possibly twenty million years. The surface ocean is everywhere experiencing a decline in pH ("acidification"), which is causing changes in associated seawater properties such as the calcium carbonate saturation state. Today, the surface ocean remains saturated with the calcium carbonate minerals aragonite and calcite. The "saturation horizons," below which these minerals will dissolve, are becoming shallower as the oceans take up more CO_2. Within this century, it is predicted that the saturation horizon for aragonite will reach the surface near the poles, particularly in Antarctica and the North Pacific Ocean. Those organisms that secrete aragonite shells will thus be subject to undersaturated waters, which will restrict their ability to maintain shell building. It is unlikely that tropical surface waters will be become undersaturated in the future. However, many corals and coral communities appear to shift from net calcification to net dissolution at

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[15] Ibid.

values well above aragonite saturation[16-17]; that is, these systems may experience net decline even in waters that remain saturated.

Effects of ocean acidification on marine biota. The potential effects of ocean acidification on marine biota were not recognized until about a decade ago, when experiments indicated that changes in ocean pH could cause significant responses in major groups of marine organisms. Ocean pH is a fundamental property of seawater that affects almost every aspect of biochemistry. It can affect organisms physiologically; that is, such basic life functions such as photosynthesis, respiration, growth, etc.; but it also affects the ability of "marine calcifiers" to form their calcium carbonate shells or skeletons. The latter is particularly important to coral reef ecosystems, and for this testimony, I will concentrate on the impacts of ocean acidification on corals, coral communities, and coral reef structures. Most of the information I present here draws from a U.S. report jointly funded by the National Science Foundation, the National Oceanic and Atmospheric Administration, and U.S. Geological Survey[18].

Effects on reef calcifiers. So far, experiments have been conducted on at least six major groups of calcifying organisms: coccolithophores (microscopic algae); foraminifera (microscopic protozoans); coralline algae (benthic algae); echinoderms (sea urchins and starfish); mollusks (snails, clams, and squid); and corals. While the responses vary both between and within these groups, nearly all experiments on corals

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[16] Yates KK, Halley RB. 2006. CO_3^{2-} concentration and pCO_2 thresholds for calcification and dissolution on the Molokai reef flat, Hawaii. *Biogeosciences* 3: 357-69

[17] Langdon C, Takahashi T, Sweeney C, Chipman D, Goddard J, et al. 2000. Effect of calcium carbonate saturation state on the calcification rate of an experimental coral reef. *Global Biogeochemical Cycles* 14: 639-54

[18] Kleypas JA, Feely RA, Fabry VJ, C. Langdon CL, Sabine CL, L.L. Robbins. 2006. *Impacts of Increasing Ocean Acidification on Coral Reefs and Other Marine Calcifiers: A Guide for Future Research, report of a workshop held 18–20 April 2005, St. Petersburg, FL*: sponsored by NSF, NOAA, and the U.S. Geological Survey. 88 pp. http://www.isse.ucar.edu/florida/

show a decrease in calcification rate under lower pH conditions, indicating that calcification rates will decline by 10–50% if atmospheric CO_2 concentrations reach double the preindustrial concentrations[19-20]. Calcification rates in multiple massive coral colonies of the Great Barrier Reef show that calcification rates declined 21% between 1988–2003[21]; this decrease exceeds that expected from lowered saturation state alone, and probably reflects the composite effects of a suite of changing environmental conditions (e.g., saturation state, temperature, water quality).

At some point growth is slowed to the point where a marine animal may no longer be able to maintain its skeleton, and the skeletal material will dissolve. This has been demonstrated in both mollusks and corals. A dramatic example of this is the work by Fine and Tchernov[22] in which two species of corals that were cultured in highly acidified water (equivalent to atmospheric CO_2 levels around 1200 ppmv) completely lost their skeletons; then re-grew them after being returned to seawater of normal pH. These species may not be typical of most reef-building corals, and indeed appear to be closely related to those few species that survived the Cretaceous-Tertiary extinction (65 million years ago) and later gave rise to modern-day corals (over time spans of millions of years). Nonetheless, the experiment highlighted three important points: (1) coral calcification rates can essentially stop or reverse in lowered ocean pH conditions; (2) the naked, anemone-like coral polyps remained healthy, but the fitness of the organisms overall

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[19] Langdon C. 2002. Review of experimental evidence for effects of CO_2 on calcification of reef builders. *Proceedings of the 9th International Coral Reef Symposium* 2: 1091-8

[20] Langdon C, Atkinson MJ. 2005. Effect of elevated pCO_2 on photosynthesis and calcification of corals and interactions with seasonal change in temperature/irradiance and nutrient enrichment. *Journal Of Geophysical Research-Oceans* 110: art. no. C09S7

[21] Cooper TF, De 'Ath G, Fabricius KE, Lough JM. 2008. Declining coral calcification in massive *Porites* in two nearshore regions of the northern Great Barrier Reef. *Global Change Biology* 14: 529-38

[22] Fine M, Tchernov D. 2007. Scleractinian coral species survive and recover from decalcification. *Science* 315: 1811

would change because of the loss of the protective skeleton; and (3) reversing the acidification process results in a reversal of the skeletal loss.

Fewer studies have been conducted on coralline algae, another major reef-builder. Certain species of coralline algae are able to calcify under extreme conditions, such as in the polar regions. However, recent studies conducted with Hawaiian crustose coralline algae showed that under acidified conditions they calcify more slowly and their larvae have lower settlement rates on reef surfaces[23]. The latter is important because coralline algae are an important colonizer of damaged reef surfaces and prepare the surface for later colonization by corals. Indeed, the effects of ocean acidification on other life stages of reef organisms are still minimally researched and poorly known.

Ocean acidification will not likely affect all species equally – indeed, as with most environmental changes, there will be winners and losers. For example, a recent study on microscopic plankton suggests that some species may have the capacity to adapt to ocean acidification. Studies on corals have not illustrated this capacity; corals and coralline algae that have been grown under decreased pH conditions for a year or more do not show signs of adapting[24].

Effects on organism survival and ecosystem functioning. There is essentially no information regarding how changes in calcification rate will affect the ability of organisms to survive in nature, and most of what we know is based on assumptions that organisms grow shells and skeletons for a variety of reasons, such as: protection, gathering light for photosynthesis, competing for space, anchoring to the substrate, and

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[23] Kuffner IB, Andersson AJ, Jokiel PL, Rodgers KS, Mackenzie FT. 2008. Decreased abundance of crustose coralline algae due to ocean acidification. *Nature Geoscience* 1: 77-140

[24] Langdon C, Broecker WS, Hammond DE, Glenn E, Fitzsimmons K, et al. 2003. Effect of elevated CO_2 on the community metabolism of an experimental coral reef. *Global Biogeochemical Cycles* 17: art. no. 1011

reproduction. Just as bone loss affects human fitness, it is likely that suppressing skeletal growth in a marine organism will affect its fitness and ability to function within its ecological community. Also, the function of the calcium carbonate may change over the lifetime of an organism. For example, calcium carbonate in a larval echinoderm provides the ballast that allows the larvae to settle onto suitable substrate, but later provides its protective exoskeleton.

Changes in the physiology and calcification rates of reef organisms will undoubtedly affect reef ecosystems and food chains. Non-calcifying species, such as fleshy macroalgae, may become more competitive for space if corals can no longer ‘hold their ground’ through calcification. Many species live directly within coral skeletons, and some of these in turn protect the corals from predators (e.g., feather duster worms that live in massive corals have been known to dissuade predation on their host by crown-of-thorns starfish). There have been several recent calls to reef researchers to take up the task to understand how reduced calcification on coral reefs will affect reef ecosystem functioning and reef ecosystem services, because there has yet been little research on this.

Effects on coral reef structures. Coral reef ecosystems are defined by their ability to produce a net surplus of $CaCO_3$ that produces the reef structure. Under increasing ocean acidification not only will coral community calcification decrease, but dissolution rates will increase [25-26], with a net decrease in reef building and a probable shift toward net dissolution in those reefs that are already near the limit for reef growth (e.g. higher latitude reefs). Interestingly, even though global warming will probably allow corals to

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[25] Langdon C, Takahashi T, Sweeney C, Chipman D, Goddard J, et al. 2000. Effect of calcium carbonate saturation state on the calcification rate of an experimental coral reef. Ibid.14: 639-54

[26] Yates KK, Halley RB. 2006. CO_3^{2-} concentration and pCO_2 thresholds for calcification and dissolution on the Molokai reef flat, Hawaii. *Biogeosciences* 3: 357-69

inhabit higher latitudes[27], the decrease in reef $CaCO_3$ production is likely to shift the limit of reef development to lower latitudes[28-29].

Coral reefs exist simply because corals and other organisms secrete calcium carbonate faster than it is removed. During the repeated glacial to interglacial sea level transgressions of the past 3 my (million years), reef ecosystems thrived because their rapid accretion rates migrated the coral community upward and maintained them within the minimum light levels for continued growth. The structural complexity of coral reefs allows them to support high marine biodiversity. The structure also shapes and protects shorelines because it acts as a natural barrier to waves and currents. It is also the foundation for atoll and cay development. If calcium carbonate production decreases, then reef building and the constant supply of coral sediment will also decrease. Mass coral die offs in recent years has led to considerable erosion on some reefs; the Galápagos reefs, for example, were formed over several thousand years, but were eroded away within a decade following the 1982-1983 coral bleaching event that killed off 95% of the corals. Ocean acidification not only decreases calcification rates on reefs, it also increases dissolution rates, so that net reef building declines. Any reduction in calcium carbonate increases the potential for reef erosion, particularly in the face of rising sea level.

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[27] Precht WF, Aronson RB. 2004. Climate flickers and range shifts of reef corals. *Frontiers in Ecology and the Environment* 2: 307-14

[28] Kleypas JA, Buddemeier RW, Gattuso JP. 2001. The future of coral reefs in an age of global change. *International Journal of Earth Sciences* 90: 426-37

[29] Guinotte JM, Buddemeier RW, Kleypas JA. 2003. Future coral reef habitat marginality: temporal and spatial effects of climate change in the Pacific basin. *Coral Reefs* 22: 551-8

[30] Kleypas JA, Buddemeier RW, Gattuso JP. 2001. The future of coral reefs in an age of global change. *International Journal of Earth Sciences* 90: 426-37

Paleontological Perspective.

Periods of high atmospheric CO_2 concentrations are common throughout the geologic record. Some of these high-CO_2 periods, e.g. Cretaceous Period 65 million years ago, include massive shallow-water $CaCO_3$ deposits, including reef structures. Initially this appears to be a conundrum: if high atmospheric CO_2 concentration produces acidic seas, why was $CaCO_3$ production and preservation so prevalent in these earlier high-CO_2 periods? The short answer to this question is that the carbonate saturation states were almost certainly maintained during those periods despite the high pCO_2 levels. This is possible because, with increases in atmospheric CO_2 and decreases in ocean pH, another part of ocean chemistry, total alkalinity, will increase. This increase occurs because increased atmospheric CO_2 causes rainfall to be more acidic, and increases weathering rates on land; this increases the alkalinity of river runoff. Also, as ocean pH decreases, more deep-sea carbonate dissolves and adds alkalinity to the ocean. Both of these processes take thousands of years to bring the carbonate system back to equilibrium. Ocean acidification today is occurring because the rate of CO_2 increase in the atmosphere is much faster than the rates at which the negative feedbacks of weathering and carbonate dissolution act to restore ocean pH. Indeed, there is evidence of a sudden input of carbon into the atmosphere or ocean some 55 million years ago; concurrent with that is evidence that of a major marine carbonate dissolution event[31].

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[31] Zachos JC, Rohl U, Schellenberg SA, Sluijs A, Hodell DA, et al. 2005. Rapid acidification of the ocean during the Paleocene-Eocene thermal maximum. *Science* 308: 1611-5

Deep-water corals and carbonate mounds

Shallow-water tropical ecosystems are not the only coral community threatened by ocean acidification. Deep-water scleractinian corals lack the algal symbionts of their tropical counterparts, and thrive in the subphotic zone waters of continental slopes, usually in depths of 200–1000 m. They grow slowly and can live a long time, up to 1500 years old. The distribution and environmental needs of deep-water corals are quite poorly known, but they are of particular interest because of they support high biodiversity and fisheries. The maximum depth of these communities, particularly of the aragonitic scleractinians corals, appears to be limited to the depth of the aragonite saturation horizon[32], which reaches an average depth of > 2000 m in the North Atlantic, but can be as shallow as 200 m in the North Pacific ocean. Like their tropical counterparts, deep-water corals can produce large mounds of calcium carbonate, albeit much more slowly[33]. Nonetheless, these deep-water structures also support high biodiversity, and elevate the associated communities above the substrate. Similar to tropical coral reefs, ocean acidification is expected to contract the geographic range of deep-water coral communities, but in contrast to the equatorward contraction of tropical coral reefs, it is the depth distribution of deep water coral communities that will contract, with the deepest communities being the first to experience a shift from saturated to undersaturated conditions.

Both coral reefs and deep-water corals are the foundation of the productive coral communities they build. Just as a forest does not exist without trees, a coral reef cannot exist without corals. Tropical coral reefs are well known for the many symbiotic

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[32] Guinotte JM, Orr J, Cairns S, Freiwald A, Morgan L, George R. 2006. Will human-induced changes in seawater chemistry alter the distribution of deep-sea scleractinian corals? . *Frontiers in Ecology and the Environment* 4: 141-6

[33] Roberts JM, Wheeler AJ, Freiwald A. 2006. Reefs of the deep: The biology and geology of cold-water coral ecosystems. *Science* 312: 543-7

relationships that have developed between species, and given the relatively few years we have observed these underwater wonders (essentially since SCUBA was invented in the 1950s), there are many more such relationships are yet to be observed. The impacts of ocean acidification on coral reef food chains, biological and chemical cycles, and ultimately our fisheries are certain. The loss of the reef structure alone will have tremendous impacts on local shorelines, infrastructure and adjacent ecosystems, as well as on the economies and livelihoods of millions of people that are served both directly and indirectly by the reef.

Solutions and Future Research

Ocean acidification will be one of the greatest environmental risks we face if we continue to allow CO_2 to build up in the atmosphere. The obvious solution is to reduce CO_2 emissions; this will not only decrease ocean acidification, it will decrease many of the other problems associated with climate change. The positive news is that stabilizing atmospheric concentrations of carbon dioxide would halt further acidification almost immediately (compared to the considerable momentum in ocean warming). Furthermore, with new technologies to not only slow atmospheric CO_2 increases, but to actually remove CO_2 from the atmosphere, the current acidification of the upper ocean would be reversed. It is true that much of the carbon absorbed by the oceans will eventually be transported by ocean circulation to deeper depths, and will remain in the ocean for hundreds of years. The upper ocean, however, is in near equilibrium with the atmosphere, and removing CO_2 from either the ocean or the atmosphere causes CO_2 to diffuse across the air-sea interface (gas diffuses from the region of high concentration to low concentration). Thus, restoring the atmosphere to its preindustrial state would restore the surface ocean to its preindustrial pH.

It is tempting to recommend some limit to how warm and/or acidic the ocean can get before irreparable damage will occur. The "safest" value would be the maximum values experienced during the glacial interglacial cycles (essentially the preindustrial levels). At the current atmospheric CO_2 concentration of 382 ppmv, coral reefs are already considered near their threshold for survival[34]. At CO_2 levels between 450 to 500 ppmv, coral reefs would experience significantly more bleaching events[35], and some reefs will begin to experience net dissolution[36]. At CO_2 levels above 500 ppmv, analyses indicate that coral bleaching and ocean acidification to be prohibitive to normal reef functioning[37]. However, for many other ocean ecosystems, the CO_2 threshold may be much lower. We do not have a good understanding of the CO_2 concentrations that will: 1) impact fish species or their food resources, 2) impact larval survival and recruitment of important species of fish and shellfish, and 3) cause changes in community composition in ways that affect the ability of the oceans to recycle important nutrients such as carbon, nitrogen, and phosphorus. In reality, there are likely to be a continuum of thresholds, and predicting these is complicated by the problem of "multiple stressors" on marine ecosystems, such as pollution, poor land-use practices, and overfishing.

In my opinion we know enough about the effects of ocean warming and ocean acidification to be extremely concerned about not only coral reef ecosystems, but all

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[34] Hoegh-Guldberg O, Mumby PJ, Hooten AJ, Steneck RS, Greenfield P, et al. 2007. Coral reefs under rapid climate change and ocean acidification. Ibid.318: 1737-42

[35] Hoegh-Guldberg O. 2005. Low coral cover in a high-CO_2 world. *Journal of Geophysical Research-Oceans* 110: C09S6

[36] Yates KK, Halley RB. 2006. CO_3^{2-} concentration and pCO_2 thresholds for calcification and dissolution on the Molokai reef flat, Hawaii. *Biogeosciences* 3: 357-69

[37] Hoegh-Guldberg O, Mumby PJ, Hooten AJ, Steneck RS, Greenfield P, et al. 2007. Coral reefs under rapid climate change and ocean acidification. *Science* 318: 1737-42

ocean ecosystems. Even at today's CO_2 concentrations, coral reefs will continue to experience bleaching for years to come. Corals and other reef organisms will almost certainly face the additional problems that ocean acidification poses for their ability to survive. And finally, coral reef structures themselves, which not only support coral reef biodiversity, but also protect shorelines and support valuable fisheries, are themselves threatened by ocean acidification.

It is urgent that we improve our understanding of how ocean acidification will affect all marine life across molecular to ecosystem scales. Given the multiple stressors in our environment, actions should be taken to minimize additional stresses to organisms or ecosystems that are particularly vulnerable to ocean acidification. Acquiring the information needed to advise policy makers on these issues will require coordinated research across multiple institutes and government agencies. In some cases, even basic information on the distribution patterns of major groups of marine organisms is lacking and such information would greatly inform our ability to predict future biological responses. Existing efforts by NOAA and NASA should be expanded to improve monitoring and observations; but much of the key needed research is at the cellular to ecosystem levels and requires basic academic research through both NSF and EPA. To support ocean acidification research, the U.S. Senate passed the *Federal Ocean Acidification Research and Monitoring Act of 2007 (FOARAM)* in December 2007. I urge the House of Representatives to pass the companion legislation that has been introduced by Representatives Tom Allen (D-ME), Jay Inslee (D-WA), Wayne Gilchrest (R-MD) and nine other co-sponsors.

Conclusions

Ocean warming and ocean acidification is affecting all oceans and the organisms that live in them. The pH of the surface ocean, where the bulk of ocean production and biodiversity exist, is changing in lock step with changes in atmospheric CO_2 concentration. Evidence from multiple scientific disciplines points to the same conclusion: ocean life is sensitive to changes in ocean pH, and will be increasingly affected by ocean acidification. This is particularly true of coral reefs, an ecosystem that is defined by the large calcium carbonate structures that they produce. Corals and many coral reef organisms will be affected by a decreased capacity to grow and maintain their shells and skeletons. This will affect their ability to survive, but it will also affect reef structures that offer many valuable ecosystems services to man. Because ocean acidification is likely to affect such a broad array of marine organisms, we can expect to see significant changes in marine ecosystems, including those that support commercial fishing.

Ocean acidification is an emerging scientific issue, but it is also one of high environmental risk. Because of this, I am deeply grateful for this opportunity to address the Select Committee, and I look forward to answering your questions.