CLIMATE CHANGE AND ACIDIFICATION ARE AFFECTING OUR OCEANS

Written testimony by
Ken Caldeira

Carnegie Institution of Washington, Department of Global Ecology
260 Panama Street, Stanford, CA 94305 USA
and
Stanford University, Department of Geological and Environmental Sciences
450 Serra Mall, Braun Hall, Building 320, Stanford, CA 94305 USA

+1 650 704 7212; fax: +1 650 462 5968
kcaldeira@globalecology.stanford.edu

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INTRODUCTION

Climate change and acidification are both affecting our oceans. These are two different phenomena but both are primarily caused by carbon dioxide emissions to the atmosphere associated with the burning of coal, oil, and gas.

Carbon dioxide and other greenhouse gases cause the atmosphere to trap heat that would otherwise escape to space. The result in the atmosphere is changes in temperature, winds, precipitation, and evaporation. These changes in the atmosphere affect the oceans, causing changes in sea-level and ocean circulation, ultimately impacting coastal communities, fisheries, and natural ecosystems.

Nearly all of the carbon dioxide we emit to the atmosphere is ultimately absorbed by the oceans. Today, each American emits about 120 pounds of carbon dioxide into the atmosphere each day, and already about 1/3 of this is being absorbed by the ocean. Unfortunately, when carbon dioxide reacts with seawater it becomes carbonic acid. Carbonic acid, in high enough concentrations, is corrosive to the shells and skeletons of many marine organisms. Over the next decades, continued carbon dioxide emissions have the potential to create chemical conditions in the ocean that have not occurred since the dinosaurs became extinct. Such chemical conditions could cause the extinction of corals and threaten other marine ecosystems.

The solution of these problems lies in developing and deploying energy technologies that allow for economic growth and development without emitting greenhouse gases to the atmosphere. However, there are at least three other areas in which action is warranted:

(1) Climate change and acidification both act as additional stresses on marine ecosystems. Other stresses include over-fishing, coastal pollution, and introduced species. Efforts to reduce other stresses on marine ecosystems can help make marine ecosystems more resilient to the stresses posed by climate change and ocean acidification.

(2) Sea-level rise will be flooding coastal ecosystems and wetlands. These areas often act as hatcheries for commercially important fish. With sea-level rise, in the absence of coastal development, these coastal ecosystems would tend to shift towards what are now inland areas. However, if these areas are carelessly developed, such adaptive migration of these valuable ecosystems will be impossible. Management of our coastal environment and its development should take into account both future sea level rise and the welfare of coastal ecosystems, beaches, and wetlands.

(3) While the physics of climate change is reasonably well understood and the chemistry of ocean acidification is very well understood, we are just beginning to learn about the consequences of climate change and ocean acidification for marine ecosystems. Especially in the case of ocean acidification, a focused research effort could help us to understand the magnitude of the threat to marine ecosystems generally and economically important resources specifically.

CLIMATE CHANGE

By this time, the fact that greenhouse gases such as carbon dioxide cause climate change is well established. The basic physics of the greenhouse effect has now been understood for over 150 years. There are still uncertainties in the exact amount of warming that might result from an increase in greenhouse gases and even greater uncertainty in regional predictions of temperature and precipitation changes. Nevertheless, the sign of the change is clear: The Earth is getting hotter.

As the Earth heats, winds will change and areas of precipitation and evaporation will shift. All of these factors will affect ocean circulation.

Sea-level Rise

The simplest prediction is sea-level rise that results from the heating of the ocean. As the seawater warms, it expands. This thermal expansion of seawater is expected to increase sea level by about one foot during this century, if current trends in greenhouse gas emissions continue. Adding to this sea-level rise from thermal expansion is the sea-level rise from the melting of ice sheets. The amount of sea-level rise from the melting of ice sheets is far less certain, and could be anywhere from nearly zero to a couple of feet this century.

A sea-level rise of one or more feet this century means that coastal zones can expect floods that are one or more feet deeper than floods previously experienced. Beach erosion will increase. Much of the damage from sea-level rise is expected to occur during extreme conditions such as storm floods, and not during normal conditions.

A two-foot rise in sea level would eliminate about 10,000 square miles of land in the United States, an area equivalent to the size of Massachusetts and Delaware (EPA, 1989).

The natural response of coastal ecosystems (and beaches) to sea level rise that has occurred at the end of the last ice age was for these ecosystems (and beaches) to move inland as land was lost to the sea. However, today, there is significant human development along the coasts. This human development can act as a barrier to the shoreward migration of coastal ecosystems. As a result, coral ecosystems, mangroves, wetlands, beaches, and other coastal environments can be threatened by sea-level rise.

Coastal ecosystems often act as hatcheries for commercially important fish stocks. Coastal systems such as coral reefs and beaches have high tourism value.

It is important that future coastal development consider the potential for future sea-level rise and the protection of coastal ecosystems.

Ocean Heating

The heating of the ocean contributes to sea-level rise, but it has other effects on the marine ecosystems. Perhaps the clearest case relates to coral reefs, where the bleaching of coral reefs has been closely related to changes in sea surface temperatures.

However, the warming of the oceans has more subtle effects on marine ecosystems. There has been extensive documentation of fish stocks moving poleward in response to warming of the North Atlantic ocean. There is no expectation that entire ecosystems are capable of migrating as a single unit. So, for example, fish species may migrate northward, but seabirds that feed on those fish have no way of knowing that the fish have migrated. Thus, the seabirds may seek food unsuccessfully in their traditional feeding grounds. Recent seabird deaths in northern California and Oregon have been associated with shifts in winds and resulting changes in ocean circulation and availability of food (Barth et al., 2007).

Clearly, polar ecosystems cannot move further poleward to maintain the temperatures these ecosystems need. Thus, polar marine ecosystems are particularly threatened.

Oxygen dissolves more easily in cold water than in warm water. Thus, fish can suffocate in warm water. Very active fish, like tuna, have a very high oxygen demand. This is a primary reason why adult tuna prefer to live in cold water environments where oxygen is plentiful. Warming of the ocean can be expected to increase the oxygen stress on marine ecosystems (Pörtner and Knust, 2007).

Stratification and Marine Productivity

Most life in the ocean lives near the surface where there is both light and food. The base of the food chain are typically tiny photosynthetic organisms that rely on nutrients (essentially fertilizer) mixed up from below.

Warm water floats on top of cold water. As the surface ocean heats, the contrast in temperature between the surface water and deeper water increases. This inhibits mixing between the surface ocean and deeper ocean waters.

Deeper ocean waters are enriched in nutrients. When mixing of this nutrient-rich water up to the surface is inhibited, less nutrients are supplied to the productive surface layers of the ocean. With a diminished nutrient supply, there will be less growth of the plants and algae that form the base of the food chain (Behrenfeld et al., 2006), and marine ecosystems can be expected to become less productive, impacting fisheries.

A relationship between increased sea-surface temperature and decreased biological productivity in the ocean has been confirmed for the tropics and mid-latitudes based on satellite observations of sea surface temperature and chlorophyll concentrations.

OCEAN ACIDIFICATION

Today, nearly 30 billion tons of carbon dioxide are released to the atmosphere from the burning of fossil fuels (and from secondary sources such as cement manufacture). About 10 billion tons of carbon dioxide are going into the ocean each year. The average American emit about five times as much carbon dioxide as the average person on this planet – the average American emits about 120 pounds of CO_2 each day, with about 40 pounds of this CO_2 going into the oceans each day for each American. It is unreasonable to expect that so much CO_2 could go into the ocean without having negative consequences for marine biota.

EPA Water Quality Standards

The U.S. Environmental Protection Agency (1976) Quality Criteria for Water state: “For open ocean waters where the depth is substantially greater than the euphotic zone, the pH should not be changed more than 0.2 units outside the range of naturally occurring variation … .” Atmospheric CO_2 concentrations would need to be stabilized at < 500 ppm for the ocean pH decrease to remain within the 0.2 limit set forth by the U.S. Environmental Protection Agency (1976).

A Personal History

The first paper quantifying the greenhouse effect was called “On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground” (Arhenius, 1896). Back then, the tern “carbonic acid” was used to refer to carbon dioxide, because carbon dioxide forms carbonic acid when it dissolves in water.

I began studying this issue when I worked for at a Department of Energy laboratory (Lawrence Livermore National Laboratory). I was also scientific co-director of the DOE Center for Research on Ocean Carbon Sequestration. We were researching the feasibility of slowing climate change by intentionally placing carbon in the ocean.

As part of this research effort, DOE funded investigation of the effect of carbon dioxide on marine organisms, including both primary research and synthesis of work funded by other organizations. It soon became apparent that CO_2 could threaten marine organisms not only at the high concentrations that might be relevant for an intentional ocean storage project but also at the lower concentrations expected to result from the oceanic uptake of carbon dioxide from the atmosphere.

I wrote the study that introduced the term "ocean acidification" (Caldeira and Wickett, 2003). When we first submitted this study for publication in Nature magazine, we compared the oceanic effects of releasing carbon dioxide into the deep ocean with the effects of releasing carbon dioxide into the atmosphere. The editors of Nature magazine felt that the effects of releasing carbon dioxide into the atmosphere were so alarming that it was unnecessary to show the effects of deep sea injection. Thus, the study as published focused on the effects of atmospheric release. In that study, we concluded that future carbon dioxide releases could produce chemical conditions in the oceans that have not been seen in the past 300 million years, with the exception of rare brief catastrophic events in Earth history.

Ocean Acidity, Biota, and the Geologic Record

Many marine organisms, including corals and clams, make their shells or skeletons out of calcium carbonate. The upper ocean is super-saturated with respect to calcium carbonate minerals, which means there is a chemical force helping these organisms to form and maintain their shells and skeletons. These organisms use both calcium and carbonate to form calcium carbonate. The ocean acidity produced by carbonic acid (carbon dioxide) attacks carbonate, removing one of the essential building blocks needs by corals and clams and many other marine organisms to build their shells and skeletons.

It is very easy to predict the future chemistry of the upper ocean. The chemistry is very well understood. You can take a bucket of seawater and put it under a bell jar with a different atmospheric CO_2 concentration, and then measure the chemistry of the water – and the measured chemistry will agree very closely with what would be predicted by calculations. This chemistry has been well understood for decades. (This chemistry is very similar to the chemistry of blood. In fact, the science of seawater chemistry was based on approaches developed to understand blood chemistry.)

If you take a bucket of seawater from the Southern Ocean or Arctic Ocean and place it under a bell jar with CO_2 concentrations expected later this century under "business-as-usual" scenarios, you will find that this water is able to dissolve the shells of some marine organism (see Figure). If you do the same thing with seawater from the tropics, you will find that you create the kind of chemistry in which no coral is found living in the real ocean today – it would be so difficult for the corals to produce their skeletons that they would be unlikely to compete successfully with sea grasses, algae, and other organisms seeking that ecological space.

The United States has funded project to drill into the ocean floor over the past few decades. From these drill holes cores are withdrawn. From the sediments in these cores we have gained an understanding of the changes in deep ocean chemistry over the past 50 million years. It is now clear that even if atmospheric CO_2 is stabilized at 450 ppm, the deep ocean will be more corrosive to carbonate minerals than at any time over the past 50 million years (Caldeira and Wickett, 2005; Tripati et al. 2005).

My PhD dissertation work was on what occurred to ocean chemistry when the dinosaurs became extinct some 65 million years ago. At that time, nearly every marine organism that made a shell or skeleton out of calcium carbonate disappeared from the geologic record. It took hundreds of thousands to millions of years for marine biology to recover. For example, some few coral individuals survived but it took 2 million years for them to repopulate the coasts of the tropical and subtropical oceans.

In the next decades, if CO_2 emissions are unabated, we may make the oceans more corrosive to carbonate minerals than at any time since the extinction of the dinosaurs. I personally believe that this will cause the extinction of corals, even though this cannot be proved conclusively.

Knowns, and Known and Unknown Unknowns

We know that our carbon dioxide emissions, if unabated, will produce chemical conditions in the oceans that have not been experienced for many millions of years. There is good reason to believe that this could “put the nail in the coffin” of the remaining coral reefs throughout the world. However, much is unknown.

Most experiments on the biological response of marine organisms to increased CO_2 have been conducted on relatively few organisms over relatively short periods in laboratory environments. Most of these experiments have focused on corals and other organisms with calcium carbonate shells or skeletons.

Nobody has yet looked at how ocean acidification might affect fish eggs or fish larvae. Nobody knows how ocean acidification impacts on the plankton that form the base of the food chain might affect the organisms at the top of the food chain.

AN EXAMPLE: CLIMATE CHANGE PLUS OCEAN ACIDIFICATION

It was mentioned above that seawater chemistry is very similar to blood chemistry. When we use our muscles, the CO_2 concentration in our blood increases, and our blood becomes more acidic, and this causes the hemoglobin in our blood to bind to the CO_2. When this CO_2-carrying-hemoglobin reaches our lungs, contact with the atmosphere in our lungs causes our blood to become less acidic, and this causes the hemoglobin in our blood to give up the CO_2 and bind instead to oxygen. In this way, the chemistry of our blood regulates oxygen transport and CO_2 removal.

Similar processes go on in organisms like fish and squid (Pörtner et al., 2005). But, as mentioned above, heating of the ocean will decrease the oxygen content of water. In addition, there will be much more carbon dioxide dissolved in the seawater. Thus, the ocean water will look a lot more like oxygen-depleted CO_2-rich blood in a muscle. It is expected that in this environment the hemoglobin (or its relative in other species) may not give up as much of its CO_2 or bind to as much oxygen. Thus, this can contribute to oxygen stress in marine organisms.

It is not known how important this type of effect might be, or at what atmospheric CO_2 levels this might to impact ecosystems, including economically valuable species. But this shows that climate change and ocean acidification have the potential to act synergistically to damage marine ecosystems.

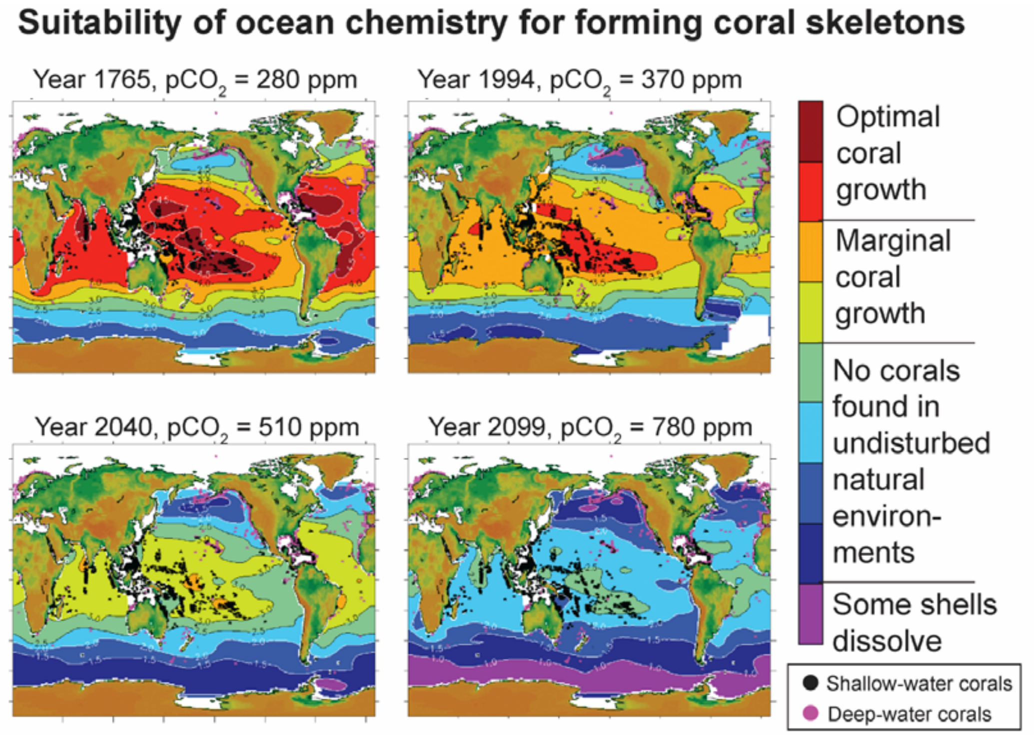
OBSERVATIONS

The clearest way to reduce the risks climate change and acidification pose for our oceans is to reduce carbon dioxide emissions.

Climate change and ocean acidification will stress ocean ecosystems. Reduction of other stresses on marine systems (e.g., overfishing, loss of wetlands) will make marine systems more resilient to climate change and ocean acidification.

The physics of climate change are fairly well understood and the chemistry of ocean acidification is very well understood. While there is enough information to be concerned and alarmed, there is still great uncertainty on the response of marine ecosystems to these stresses. More research could help inform sound policy development. Research on biotic effects of ocean acidification is especially lacking.

Managements of our coastal environments, both on land and in water, should take climate change, ocean acidification, and sea-level rise into consideration.



based on Feely et al. (2006) [NOAA}

Figure 1. Maps showing the distribution of ocean chemistry suitable for coral growth for different time periods, assuming “business-as-usual” CO_2 emissions. Colors represent the chemical force promoting the development of coral skeletons. Year 1765: Several hundred years ago, before the carbon dioxide emissions of the industrial revolution, nearly all coral reefs are found in the red-colored regions with a few in the orange and and very few in the yellow-green regions. No corals are found in the more blue and purple colored regions. Year 1994: Already, as a result of historical carbon dioxide emissions, the area that is most suitable for coral growth has retreated to the western Pacific Ocean (and a little bit of the Indian Ocean). Most existing corals are already in marginal environments for coral growth. Year 2040: Already, there is no place left in the ocean that is optimal for coral growth. In parts of the Southern Ocean, shells of some organisms, such as pteropods, are starting to dissolve. Year 2099: By the end of the century, there is no place left in the ocean with the kind of ocean chemistry where corals are found growing naturally. Shells of marine organisms are dissolving through most of the Southern Ocean.

SELECTED REFERENCES

Arrhenius, Svante, 1896, On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground, London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science (fifth series), April 1896. vol 41, pages 237–275.

Barth, John A., Bruce A. Menge, Jane Lubchenco, Francis Chan, John M. Bane, Anthony R. Kirincich, Margaret A. McManus, Karina J. Nielsen, Stephen D. Pierce, and Libe Washburn. Delayed upwelling alters nearshore coastal ocean ecosystems in the northern California current. PNAS 2007 104: 3719-3724; 10.1073/pnas.0700462104.

Behrenfeld, M. J., R. T. O'Malley, D. A. Siegel, C. R. McClain, J. L. Sarmiento, G. C. Feldman , J. Milligan, P. G. Falkowski, R. M. Letelier , and E. S. Boss, 2006: Climate-driven trends in contemporary ocean productivity. Nature, 444(7120), 752-755.

Caldeira, K., and M.E. Wickett, Anthropogenic carbon and ocean pH, Nature 425, 365-365, 2003.

Caldeira, K., and M.E. Wickett, Ocean model predictions of chemistry changes from carbon dioxide emissions to the atmosphere and ocean. Journal of Geophysical Research (Oceans) 110, C09S04, doi:10.1029/2004JC002671, 2005.

Caldeira, K., M. Akai, P. Brewer, B. Chen, P. Haugan, T. Iwama, P. Johnston, H. Kheshgi, Q. Li, T. Ohsumi, H. Poertner, C. Sabine, Y. Shirayama, J. Thomson. Ocean storage. In: IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp.

EPA, 1989: The Potential Effects of Global Climate Change on the United States. Report to Congress. Washington, D.C.: U.S. Environmental Protection Agency. EPA 230-05-89-052.

EPA,1976: Quality Criteria for Water, Washington, DC (http://www.epa.gov/waterscience/criteria/redbook.pdf)

Orr, J.C., et al., Anthropogenic Ocean Acidification over the Twenty-first Century and Its Impact on Calcifying Organisms, Nature 437:681-686 (2005).

Pörtner, H.O., M. Langenbuch, and B. Michaelidis (2005) Synergistic effects of temperature extremes, hypoxia, and increases in CO2 on marine animals: From Earth history to global change, J. Geophys. Res. 110, C09S10, doi:10.1029/2004JC002561.

Pörtner, H.O., Knust R. (2007) Climate change affects marine fishes through the oxygen limitation of thermal tolerance. Science 315, 95 - 97.

Raven, J. Caldeira, K. Elderfield, H. Hoegh-Guldberg, O. Liss, P. Riebesell, U. Shepherd, J. Turley, C. Watson, A. (2005) Acidification due to increasing carbon dioxide. In Report 12/05. London , T.R.S.o. (ed.) London : The Royal Society, pp. vii + 60.

Tripati, A., Backman, J., Elderfield, H., and Ferreti, P., 2005, Eocene bipolar glaciation associated with global carbon cycle changes. Nature, 436:341-345.