Term Paper Peer Review

Effects of Ocean Acidification on Coccolithophores

Clarity:

This was a fairly easy read and understandable for the layman. All concepts were clearly described and defined in a way that an educated person could understand. Structurally this paper was organized well enough so that each concept built on the last giving a clear direction of the ideas and science that the author was trying to get across to the reader. In other words, it kept my attention, I was able to follow the concepts, and I had a clear understanding of where the author was leading me.

Suitability:

The paper's subject was well suited for the task given in the assignment. The paper followed the assignment guild lines and most concepts in the paper were briefly discussed in class with a few discussed at length.

Significance:

This paper was informative and understandable for the layman. I was able to understand how climate change is affecting the chemistry of the oceans and in turn coccolithophores. The author was unbiased in stating the facts, showing how science is not completely in agreement with outcomes in future predictability. Getting opposing results from different research was not confusing to the reader because the author clearly described both outcomes and gave reasons for both.

Accuracy:

The paper was accurate scientifically, or at least as well as I can understand. It appears that the research was thorough and comprehensive for the summative nature of the paper.

Contribution:

From a reader's point of view, it appears that the author has some experience and knowledge in the field. The author's unique contribution of pluralistic evolution was very insightful and gave a good twist at the end keeping the reader's attention.

This was a very well written summary of how climate change is affecting a coccolithophores by changing chemistry of the oceans.

Meteorology 504: Global Change
Spring 2009
Term Paper

Effects of Ocean Acidification on Coccolithophores

Abstract

The environmental changes currently underway on the planet in response to global climate change rival some significant geological events of the past. Considerable attention is given to the changes over land-surfaces, but much less is known about the effects higher atmospheric CO_2 levels will have on the world's oceans. This paper examines the relationship between atmospheric CO_2 levels and ocean pH values, the historical variation of this relationship as well as projections of future changes in pH values. Findings indicate that the decreasing pH values relative to increasing CO_2 levels, or "acidification," have deleterious effects on some phytoplankton species, particularly coccolithophores, the most abundant photosynthesizing organisms in the ocean. This reveals there may be a slow down of the ocean's biological pump. Other studies indicate that some species actually thrive in lower oceanic pH conditions, which reveals that research in the area of biological responses to global climate change is barely in its beginnings, especially with respect to the evolutionary responses of marine organisms. Such a drastic alteration of the planet with potential to change the ecological balance of the ocean behooves more research in these areas to fully understand the possible consequences of human alteration of atmospheric chemistry.

Introduction

In the past it has taken meteorite impacts or large increases in volcanism to produce the changes humans are projected to produce in our atmosphere by the end of the century. Not only are humans matching some of the most dramatic changes of Earth history, they are doing it at rates that are much faster than those seen through natural forces (even the extinction of the dinosaurs may have occurred over millions of years). The Earth's atmosphere is now at carbon dioxide (CO_2) levels that the world has not seen in over 20 million years (Rost and Riebesell 2004). The role CO_2 plays in the atmosphere is pretty well understood in regard to how it impacts the greenhouse effect, though there are some uncertainties in other factors' effects on the climate system in response to increased CO_2, such as water vapor. The changing atmosphere indicates there might be conditions on Earth that could change drastically from what some species have adapted to in the past 20 million years.

Higher atmospheric CO_2 levels have little direct effect on non-photosynthesizing life, the dangers of higher CO_2 lie in the change in climate. This is not the case in the ocean, as higher atmospheric CO_2 leads to a direct decrease in the pH level of the ocean. This issue has significant implications for human populations. For example, the decreasing pH levels of the ocean has led to a decline in coral reef ecosystems and the Intergovernmental Panel on Climate Change (IPCC) projections of CO_2 indicate that by the end of the century there may be no ocean environments left that could support reef ecosystems (Henderson, 2006). Estimates indicate that perhaps over 1/12th of the global population, or 500,000,000 people, are dependent on coral reef ecosystems through things like fishing or tourism (Global Coral Reef Monitoring Network, 2004).

This paper will investigate how higher atmospheric CO_2 concentrations alter the chemistry of the ocean. Additionally, it will investigate the response of one important group of phytoplankton, coccolithophores, to the changing oceanic conditions and what this means for the future of the oceans from an evolutionary perspective. Considerable attention will also be paid to the interrelationship of the ocean and atmosphere, specifically with the cycling of carbon through the contribution of coccolithophores to the ocean's "biological pump," which serves to sequester CO_2 into the ocean bottom through biological processes. Of note is that if a higher CO_2 atmosphere leads to oceanic conditions that lead to more or less productivity of these organisms, the amount of anthropogenic CO_2 emissions that are absorbed by natural factors (~~right now at~~ about 50% of emissions) would substantially increase or decrease, respectively, as the biological pump is a very significant natural carbon sink (Hofmann and Schellnhuber, 2009; Sarmiento and Gruber, 2006; Sabine et al., 2004).

Findings

Ocean Acidification

The addition of carbon dioxide to the atmosphere has multiple effects on the planet. The atmospheric response, an increase in the greenhouse effect, seems to get the most attention but other very serious effects can occur in the ocean as well. The increased concentration of atmospheric carbon dioxide (CO_2) produces a greater partial pressure of CO_2 (p_{CO2}) in the atmosphere. By increasing p_{CO2} in the atmosphere, it becomes a lot easier for the ocean to dissolve CO_2 in areas that the ocean is fresher (less saline) and/or colder. The ocean has long been an output for atmospheric CO_2, but with the addition of anthropogenic CO_2 to the atmosphere, the rate of dissolution has increased for the past 200 years (Feely et. al. 2006). The process of ocean dissolution of CO_2 and the consequences for ocean pH are given in figures 1 and 2 and further discussed below.

$$\text{(a)} \quad CO_2 + H_2O \leftrightarrow H_2CO_3$$

$$\text{(b)} \quad 2H_2CO_3 \leftrightarrow 3H^+ + HCO_3^- + CO_3^{2-}$$

Figure 1—Chemical reactions that occur as CO_2 is dissolved into ocean water. (a) The dissolution of CO_2 into ocean water creates H_2CO_3 (carbonic acid). (b) Carbonic acid releases hydrogen ions into solution with bicarbonate (HCO_3^-) and a lesser amount of carbonate (CO_3^{2-}) ions. Adapted from Burns (2008).

The dissolution of CO_2 in the ocean, the potential for which increases as pCO_2 increases, creates the weak carbonic acid (H_2CO_3—see Fig. 1a). Carbonic acid then gives off hydrogen ions (Fig. 1b) to the ocean, a process undertaken by all acids (Kurihara et. al., 2007). ~~This~~ release of hydrogen ions is what directly decreases ~~the~~ pH values in the ocean~~:~~ pH refers to the amount of hydrogen in an aqueous solution~~…p~~ denotes -log and H~~,~~ the activity of hydrogen ions. As pH values increase, the amount of hydrogen ions in dissolution decreases and as pH values decrease, the amount of hydrogen ions in dissolution increases, this is why low pH values (1-7) are considered acidic, and high values (7-14) are considered basic. In addition to giving off hydrogen ions, carbonic acid also forms bicarbonate and a lesser amount of carbonate (Fig. 1b) (Doney, 2006). It is important to note that the term "acidification" refers only to a decrease in pH levels, it does not indicate that the ocean is acidic. The ocean is actually alkaline with a current pH value around 8.1, though there are natural variations of +/- 0.3 units depending on region and season. The ocean will likely remain alkaline (pH level above 7) even with the projected human addition of CO_2 to the atmosphere (Burns, 2008).

The overall pH level in the oceans (see Fig. 2) has decreased by 0.12 pH units from preindustrial values (Riebesell, 2004; Feely 2006). Though on a scale of 1-14, 0.12 units may seem inconsequential~~, because~~ the pH scale is logarithmic, this decrease accounts for an increase of hydrogen ions in solution by over 30%. Even though 0.12 pH units since 1850 is considerable, by the year 2100 “middle of the road” IPCC

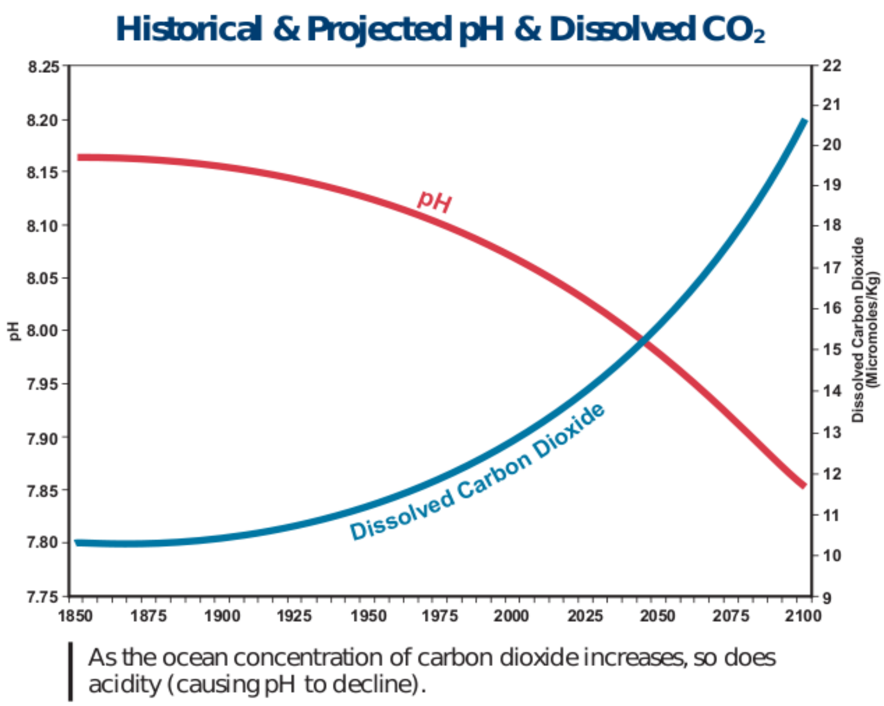

Figure 2—Feely et. al.'s (2006) figure showing 250 year representation of historical CO_2 dissolution and ocean pH as well as projected values.

projections indicate that ocean pH will drop by a further 0.3-0.4 units. Projections also show ocean pH decreasing by 0.77 units by the year 2300, which are levels that do not appear to have existed on earth for most of the last 300 million years (Burns, 2008). The human caused alteration of ocean pH levels is thus a much more drastic shift from the geological norm as compared to atmospheric CO_2 levels which have varied above projected values more recently in geologic time. This indicates that marine life is experiencing a substantial (and perhaps the most substantial) change in its environment in the face of global climate change.

The effect of coccolithophores on the biological pump

Coccolithophores are the most abundant calcifying phytoplankton in the ocean and are primarily responsible for the alkaline conditions in the ocean (Rost and Riebesell, 2004).   They form shell plates in a spherical shape that some hypothesize might be a defense mechanism to to protect them from grazers in the ocean, such as zooplankton species (Young, 1994). There seems to be greater support for the idea that the plates formed by coccolithophores, which are composed of calcium carbonate, are a byproduct of the process of ocean photosynthesis in which bicarbonate is used (See Rost and Riebesell for details of this process, 2004, pp. 109-114). As long as the coccolithophore is alive it remains in ocean surface waters, but upon death the abundance of $CaCO_3$ in its shell acts as a ballast that causes the coccolithophore's body parts to descend through the water column.

The decent of the calcium carbonate shells as well as the soft tissues of the organism within the shell delivers carbon from the ocean surface to the ocean bottom. This decent of planktonic organisms also delivers a food supply to benthic or bottom dwelling organisms and much of the carbon content in the descending material gets dissolved, or remineralized, in bottom ocean water. This draw down of atmospheric CO_2 to deep ocean through coccolithophores contributes to the *biological pump* (Fig. 3).

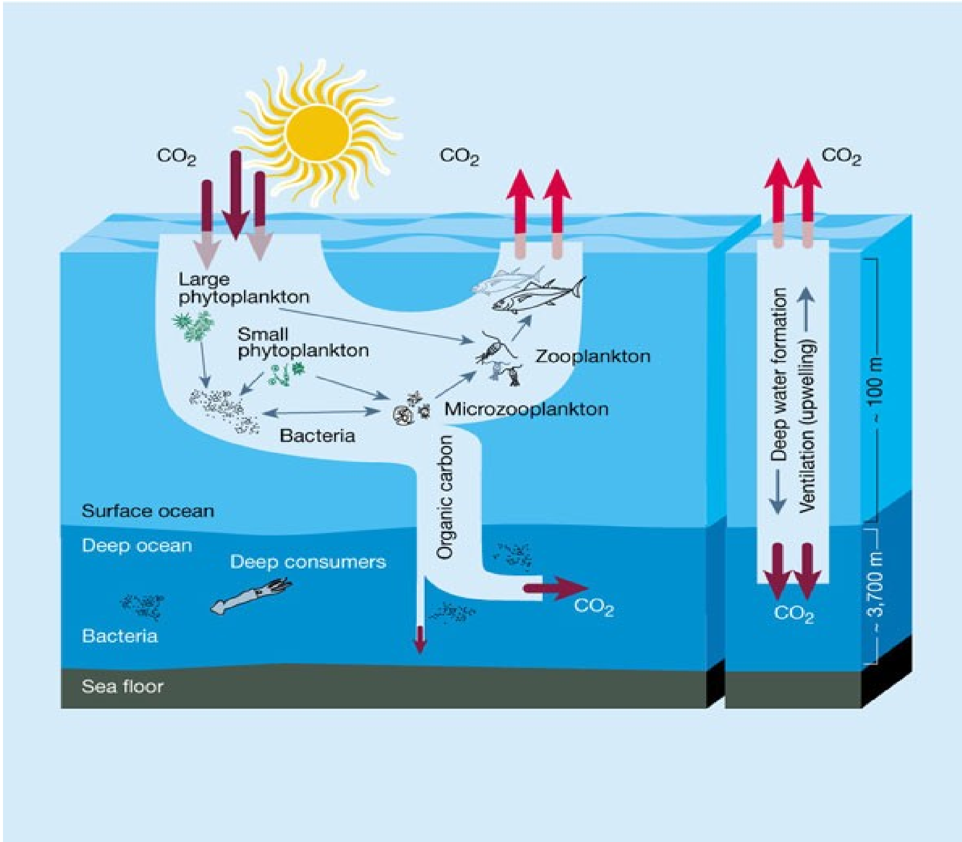

Figure 3—A simplified representation of the biological pump. From Chisholm (2000).

Figure 3 depicts a simplification of the intricacy of the biological pump and it is important to note that there are fluctuations of CO_2 in *and* out of the ocean. One flux of CO_2 back into the atmosphere from the ocean involves the formation of calcium carbonate by organisms such as coccolithophores and shell-forming zooplankton. The production of CO_2 in this process is given by the following chemical equation (from Rost and Riebesell, 2004):

$$Ca^{2+} + 2HCO_3^- \rightarrow \mathbf{CaCO_3} + H_2O + \mathit{CO_2}$$

The release of CO_2 back into the surface ocean, and subsequently the atmosphere when the surface ocean becomes supersaturated, acts to counter the draw down of carbon into the ocean. The net effect, however, has historically and prehistorically been an overall draw down of CO_2 from the atmosphere as the biological pump outweighs the "counter" biological pump (Rost and Riebesell, 2004).

Reduction in carbonate concentration

Recall that the presence of carbonic acid in the ocean releases hydrogen ions into solution. These hydrogen ions like to bond especially with the carbonate ion (CO_3^{2-}) thereby decreasing the concentration of carbonate in the ocean. The decrease in carbonate concentration has severe implications for organisms that produce calcium carbonate ($CaCO_3$) shells (like coccolithophores) because these shells are only sustainable with higher concentrations of carbonate and calcium ions (Henderson, 2006). Once carbonate concentrations fall, these shells start to dissolve, to the detriment of the organism. In addition, lower carbonate concentrations also cause the malformation of calcite shells by coccoliths as the supply of carbonate is decreased, making it harder for the production of calcium carbonate.

A study carried out by Riebesell (2004) where coccolithophore cultures were subjected to different levels of CO_2 concentrations found that a doubling of atmospheric CO_2 would cause a calcification reduction of up to 40%. Malformed calcite shells of coccolithophores from similar studies are presented in Fig. 4. Not all calcifying organisms respond the same way as coccolithophores, studies show that some organisms actually increase calcification and thrive under elevated pCO_2 conditions (Gutowska et.

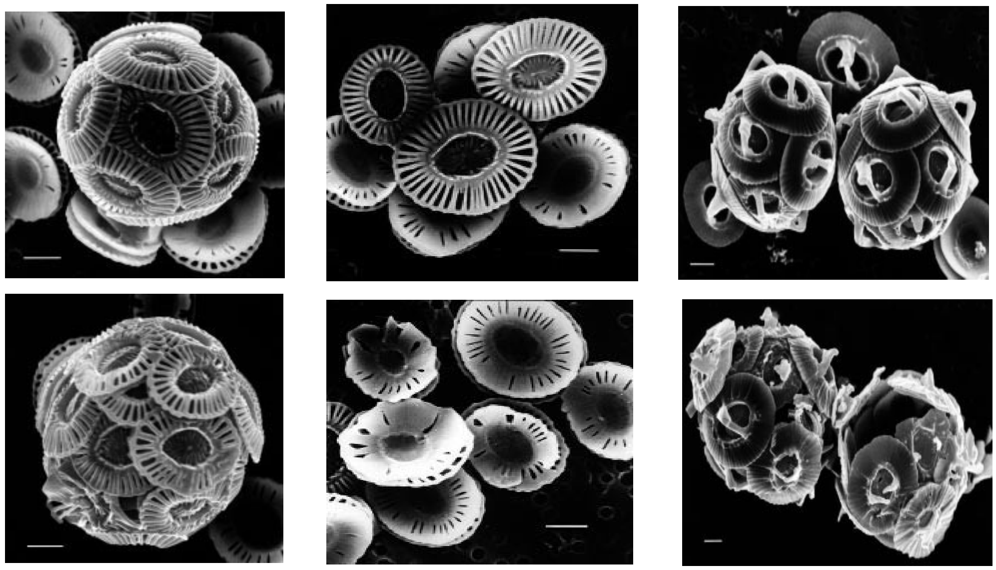

Figure 4—The very abundant coccolithophore Emiliana huxleyi (*left 2 columns*), Gephyrocapsa oceanica *(right column) and their degradation in a study simulating an acidic environment (bottom row). From Riebesell (2000).*

al., 2008). This differential response among marine calcifying species threatens to disturb the ecological balance of abundant organisms such as coccolithophores and less abundant organisms such as the cephalopod species studied by Gutowska et. al. (2008).

The changing marine environment has raised the attention of evolutionary biologists in trying to predict the evolutionary response of calcifying organisms to global climate change. It appears that knowledge of the adaptive capabilities of these organisms is not understood well enough to make such predictions. There are speculations that form a dichotomy as some say that calcifying organisms will respond to elevated CO_2 by degradation and decreasing photosynthetic productivity (Bell and Collins, 2008) while other organisms will become much more productive (Gutowska et. al., 2008). Collins and Bell are part of an extremely small group of researchers conducting studies in experimental evolution to better understand the biological response to global climate change. Their often-cited study in 2004 of the effects of elevated pCO_2 on green algae populations over a thousand generations is one of the very few of its kind.

Discussion

Effects of lower calcification rates on Global Climate Change

Coccolithophores and other planktonic species account for nearly ¾ of the total amount of calcium carbonate precipitated in the ocean (Burns, 2008). A reduction of calcification by 40% could therefore have considerable effects on the CO_2 released back into the atmosphere through the counter biological pump. Lower production of $CaCO_3$ would also lower the byproducts of that process (CO_2), thereby enhancing the net flux of carbon into the ocean depths. This would seem to have a negative feedback effect on atmospheric CO_2 levels and would help further absorb human emissions. However, other factors beyond this initial counter-effect also come into play.

The reduced amount of $CaCO_3$, which also acts as a ballast, could slow the decent of organic material through the water column…this would also affect the balance of the biological pump and the counter biological pump, perhaps offsetting the initial changes described above. In addition, the increased time in suspension in the water column may result in less material arriving to the ocean bottom as undissolved $CaCO_3$, which may alter the rate of the current formation of limestone and chalk. This would mean that more carbon would be dissolved into the lower ocean which recycles itself on the order of centuries to millennia, as opposed to storage in rock that naturally recycles itself on the order of millions of years. The dissolved carbon in the world's oceans will eventually make its way back to the surface and then into the atmosphere to be dealt with by the descendants of today's population.

As is clearly evident in figure 4, the lowered calcium carbonate production considerably alters the shape of coccolithophores' calcite plates (or coccospheres). As the physiological functions of these coccospheres are poorly understood, there is large uncertainty in regard to how the activity of coccolithophores will change over the next century. Coccolithophores can form blooms that alter the planetary albedo; when blooming the abundance of coccolithophores is so great that hundreds of square kilometers of ocean are lightened to a bright green-blue. These patches of lightened ocean reflect light back into space, thereby reducing the amount of shortwave radiation absorbed by the earth. If lower calcium carbonate levels in their shells lead to decreased activity or an overall population reduction, this albedo effect could be diminished. Coccolithophores are apparently also responsible for the creation of sulphides that provide nuclei for cloud droplet formations, which also reflect sunlight (Burns, 2008).

Possible Evolutionary responses to Ocean Acidification

If indeed the function of the coccospheres of coccoliths are defense mechanisms against grazers (Young 1994), which is still viewed as a speculative hypothesis (Rost and Riebesell, 2004), then the alteration of coccospheres in response to increasing CO_2 levels could lead to a shift in the relative dominance of coccoliths in the ocean. The literature suggests that there is substantial lack in research in studying the effects of Global Climate Change on ocean biodiversity (Vézina and Hoegh-Guldberg, 2008). There is a potential with ocean acidification in changing the evolutionary paths of the oceanic ecosystems which support all levels of life, including humans.

Conclusion:

There is some debate among evolutionary biologists about the way that species evolve. Darwinian biologists usually think of evolution as a very gradual process that occurs over millennia, while other biologists adhere to the concept of punctuated equilibrium. The concept of punctuated equilibrium describes adaptations of species occurring as a rapid response to a changing environment. This may be supported by generalities in the fossil record, such as the many missing "transitional" species. If species do indeed undergo greatest morphological changes in bursts that parallel climatic or environmental changes, then one would expect that there would be many fewer chances for these transitional species to become preserved. In times when there are no drastic environmental changes occurring, punctuated equilibrium holds that species remain in a rather equilibrated state with very little change if any. As is often the case, what nature really does may actually lie somewhere in the middle ground of the Darwinian biologists and punctuated equilibrium.

With global climate change, ~~is~~ appears that humans are, for the first time, able to conduct an evolutionary experiment on a global scale that can test the evolutionary pathways organisms might take in response to rapid climatic changes. Evolutionary changes have previously only been observable through the largely incomplete fossil record or through artificial selection carried out by humans. Humans are now able to observe and test the evolutionary mechanism of punctuated equilibrium as opposed to gradualism, which is largely unobservable. It would seem that something so unprecedented would receive an overabundance of attention but as was discussed earlier, this is simply not the case. Clearly, the dangers potentially faced through ocean acidification need to be further assessed and presented to the public if concern is to be raised about the full deleterious effects of global climate change.

References

Bell G., Collins S. (2008). Adaptation, extinction and global change. *Evolutionary Applications*. Vol. 1 Issue 1 pp. 3-16.

Burns, W. C. G. (2008). Anthropogenic Carbon Dioxide Emissions and Ocean Acidification: The Potential Impacts on Biodiversity. In: Saving Biological Diversity... Springer, New York, NY. pp. 187-202

Chisholm, S. W. (2000). Oceanography, Stirring times in the Southern Ocean. *Nature*. Vol. 407. pp. 685-687.

Collins, S., Bell, G. (2004). Phenotypic consequences of 1,000 generations of selection at elevated CO_2 in a green alga. *Nature*. Vol. 431. pp. 566-569.

Doney, S.C. (2006). The Dangers of Ocean Acidification. *Scientific American*. Vol. 294 (3). pp. 58-65.

Feely, R. A., Sabine, C. L., Fabry, V. J. (2006). Carbon Dioxide and Our Ocean Legacy. NOAA. Pacific Marine Environmental Laboratory. Obtained from: <www.pmel.noaa.gov/pubs/PDF/feel2899/feel2899.pdf>

Global Coral Reef Monitoring Network (2004). Status of coral reefs of the world: 2004. Available at <http://www.gcrmn.org/status2004.aspx>

Gutowska, M. A., Pörtner, H. O., Melzner, F. (2008). Growth and calcification in the cephalopod *Sepia officinalis* under elevated seawater pCO_2. *Marine Ecology Progress Series*. Vol. 373. pp. 303-309.

Henderson, C. (2006). Paradise Lost. *New Scientist.* No. 2563 pp. 28-33.

Hofmann, M., Schellnhuber, H.-J. (2009). Ocean acidification affects marine carbon pump and triggers extended marine oxygen holes. *PNAS*. Vol. 106 (9) pp. 3017-3022.

Kurihara H. (2008) Effects of CO_2-driven ocean acidification on the early developmental stages of invertebrates. *Marine Ecology-Progress Series*. Vol. 373 pp. 275-284.

Kurihara, H., Kato, S., Ishimatsu, A. (2007). Effects of Increased Seawater pCO_2 on Early Development of the Oyster *Crassostrea Gigas. Aquatic Biology.* Vol. 1, pp. 91-98.

Riebesell, U., Zondervan, I., Rost, B., Tortell, P. D., Zeebe, R. E., Morel, F. M. M. (2000). Reduced calcification of marine plankton in response to increased atmospheric CO_2. *Nature.* Vol. 407, pp. 364-367.

Riebesell, U. (2004). Effects of CO_2 enrichment on Marine Phytoplankton. *Journal of Oceanography*. Vol. 60. pp. 719-729.

Rost B., Zondervan I., Wolf-Gladrow D. (2008) Sensitivity of phytoplankton to future changes in ocean carbonate chemistry: current knowledge, contradictions and research directions. *Marine Ecology-Progress Series.* Vol. 373 pp. 227-237

Rost, B., Riebesell, U. (2004) Coccolithophores and the biological pump: responses to environmental changes. In: Coccolithophores-From Molecular Changes to Global Impact. Springer, New York, NY. pp. 99-126.

Sabine, C.L., Feely, R.A., Gruber, N., Key, R.M., Lee, K., Bullister, J. L., Wanninkhof, R., Wong, C. S., Wallace, D.W.R., Tilbrook, B., Millero, F. J., Peng, T-H., Kozyr, A., Ono, T., Rios, A. F. (2004). The oceanic sink for anthropogenic CO2. *Science.* Vol. 305 (5682), pp. 367–371.

Sarmiento, J.L., Gruber, N. (2006) Ocean Biogeochemical Dynamics. Princeton University Press, Princeton, NJ, pp. 503.

Vézina, A. F., Hoegh-Guldberg, O. (2008). Effects of ocean acidification on marine ecosystems. *Marine Ecology Progress Series*. Vol. 373. pp. 199-201

Young, J. R. (1994). Function of Coccoliths. In: Coccolithophores. Cambridge University Press. Cambridge. pp. 63-82.