

***“ACID TEST: THE GLOBAL CHALLENGE OF OCEAN  
ACIDIFICATION”*** – A NEW PROPAGANDA FILM BY  
**THE NATIONAL RESOURCES DEFENSE COUNCIL**  
**FAILS THE ACID TEST OF REAL WORLD DATA**

*A critique by the Science and Public Policy Institute and the  
Center for the Study of Carbon Dioxide and Global Change*



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## FOREWORD

### “OCEAN ACIDIFICATION” – THE EXTREMISTS’ FALLBACK SCARE

First, they called it “global warming”. Then they noticed there had been no warming for 15 years, and cooling for 9, so they hastily renamed it “climate change”. Then they noticed the climate was changing no more than it ever had, so they tried “energy security”, and even named a Congressional Bill after it. Then they noticed that most Western nations already had bountiful energy security, in the form of vast, untapped domestic supplies of oil, gas, coal, or all three, so they switched to “ocean acidification”.

This is the new phantasmagoric for the tired, old scare whipped up by the NRDC and the environmental extremist movement for their own profit at our expense. The world’s corals, they tell us, will be eaten away by the acidified ocean within not more than ten years hence. Shellfish will be no more, their calcified carapaces and exoskeletons dissolved by the carbonic acid caused by our burning of fossil fuels. The oceans will die. Sound familiar?

Yet, as the indefatigable Craig Idso here demonstrates, the scientific consensus – if science were done by consensus at all, which it is not – is that the rising “ocean acidification” scare is just more piffle.

Our harmless emissions of trifling quantities of carbon dioxide cannot possibly acidify the oceans. Paper after paper after learned paper in the peer-reviewed literature makes that quite plain. Idso cites some 150 scientific sources, nearly all of them providing hard evidence, by measurement and experiment, that there is no basis for imagining that we can acidify the oceans to any extent large enough to be measured even by the most sensitive instruments. And, as Richard Feynman used to say, no matter how elegant your theory, no matter how smart you are, if experiment proves you wrong then you need another theory.

Why can’t rising atmospheric CO<sub>2</sub> acidify the oceans?

First, because it has not done so before. During the Cambrian era, 550 million years ago, there was 20 times as much CO<sub>2</sub> in the atmosphere as there is today: yet that is when the calcite corals first achieved algal symbiosis. During the Jurassic era, 175 million years ago, there was again 20 times as much CO<sub>2</sub> as there is today: yet that is when the delicate aragonite corals first came into being.

Secondly, ocean acidification, as a notion, suffers from the same problem of scale as “global warming”. Just as the doubling of CO<sub>2</sub> concentration expected this century will scarcely change global mean surface temperature because there is so little CO<sub>2</sub> in the atmosphere in the first place, so it will scarcely change the acid-base balance of the ocean, because there is already 70 times as much CO<sub>2</sub> in solution in the oceans as there is in the atmosphere. Even if all of the additional CO<sub>2</sub> we emit were to end up not in the atmosphere (where it might in theory cause a

very little warming) but in the ocean (where it would cause none), the quantity of CO<sub>2</sub> in the oceans would rise by little more than 1%, a trivial and entirely harmless change.

Thirdly, to imagine that CO<sub>2</sub> causes “ocean acidification” is to ignore the elementary chemistry of bicarbonate ions. Quantitatively, CO<sub>2</sub> is only the seventh-largest of the substances in the oceans that could in theory alter the acid-base balance, so that in any event its effect on that balance would be minuscule. Qualitatively, however, CO<sub>2</sub> is different from all the other substances in that it acts as the buffering mechanism for all of them, so that it does not itself alter the acid-base balance of the oceans at all.

Fourthly, as Professor Ian Plimer points out in his excellent book *Heaven and Earth* (Quartet, London, 2009), the oceans slosh around over vast acreages of rock, and rocks are pronouncedly alkaline. Seen in a geological perspective, therefore, acidification of the oceans is impossible.

For these and many other powerful *scientific* reasons, compellingly explained in great detail in Craig Idso’s masterly review of the scientific literature in this field, the acid-base balance of the oceans will remain in the future much as it has been in the past and, even if it were to change by the maximum quantity imagined by the most lurid of the scientists who have tried to foster this particular scare, the sea creatures that it is supposed to damage would either be unaffected by it or *thrive* on it.

Craig Idso’s monograph is not necessarily an easy read. The sheer quantity of evidence that he presents stands in powerful contrast to the empty catchiness of the message of the environmentalist extremists whose sun is now setting.

This is not an entertaining paper. Instead, it is true. In the words of the father of the scientific method, Ibn Al-Haytham, writing 1000 years ago in the Iraq of the early Middle Ages, “The road to the truth is perforce long and hard, but that is the road that we must follow.”

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January 5, 2010

# A NEW PROPAGANDA FILM BY THE NRDC FAILS THE ACID TEST OF REAL WORLD DATA

by Dr. Craig D. Idso | January 5, 2010

## SUMMARY FOR POLICY MAKERS

In late 2009, the National Resources Defense Council (NRDC) released a short 21-minute film entitled *Acid Test: The Global Challenge of Ocean Acidification*. Featuring Sigourney Weaver as its narrator, the film highlights the views of a handful of scientists, a commercial fisherman, and two employees of the NRDC, as they discuss what they claim is a mega disaster-in-the-making for Earth's marine life.

The villain of the story is *industrial man*, who has "altered the course of nature" by releasing large quantities of carbon dioxide or CO<sub>2</sub> into the air via the burning of the coal, gas and oil that has historically fueled the engines of modern society. Once emitted into the atmosphere, a portion of that CO<sub>2</sub> dissolves into the surface of the world's oceans, where subsequent chemical reactions, according to the NRDC, are lowering the pH status of their waters. This phenomenon, they theorize, is reducing marine calcification rates; and if left unchecked, they claim it will become so corrosive that it "will cause sea shells to dissolve" and drive coral reefs to extinction "within 20 to 30 years."

*Even a cursory review of the peer-reviewed scientific literature reveals that an equally strong case – if not a more persuasive one – can be made for the proposition that the ongoing rise in atmospheric CO<sub>2</sub> concentration will actually prove a boon to calcifying marine life.*

So what's the story here? Are coral reefs really in their last decades of existence? Will the shells of other calcifying marine life also dissolve away during our lifetimes? The NRDC film certainly makes it *appear* that such is the case; but a little scientific sleuthing reveals nothing of substance in this regard. In fact, even a *cursory* review of the peer-reviewed scientific literature reveals that an equally strong case – if not a more persuasive one – can be made for the proposition that the ongoing rise in atmospheric CO<sub>2</sub> concentration will actually prove a *boon* to calcifying marine life. Sadly, however, the NRDC chose to present an extreme one-sided, propagandized view of ocean acidification; and in this critique we present the part of the story that they clearly don't want you to know.

## OCEAN ACIDIFICATION – THE THEORETICAL SCARE

The rate of deposition of calcium carbonate by marine organisms is controlled at the cellular level by the saturation state of calcium carbonate in seawater; and oceanic surface waters have likely been saturated or supersaturated in this regard – providing a good environment for calcification – since early Precambrian times (Holland, 1984). Currently, however, as the air's CO<sub>2</sub> content rises in response to ever-increasing anthropogenic CO<sub>2</sub> emissions, and as more and more carbon dioxide therefore dissolves in the surface waters of the world's oceans, the pH values of the planet's oceanic waters should be gradually dropping – according to climate-alarmist *theory* – leading to a reduction in the calcium carbonate saturation state of seawater. It has been estimated, for example, that the globe's seawater has been *acidified* (actually made *less basic*) by about 0.1 pH unit relative to what it was in pre-industrial times; and model calculations imply an additional 0.7-unit drop by the year 2300 (Caldeira and Wickett, 2003), which decline is hypothesized to cause great harm to calcifying marine life such as corals.

As indicated in the NRDC movie, this phenomenon has been theorized to lead to a corresponding reduction in the calcification rates of marine organisms. Kleypas *et al.* (1999), for example, calculated that calcification rates of tropical corals should already have declined by 6 to 11% since 1880, as a result of the concomitant increase in atmospheric CO<sub>2</sub> concentration; and they predicted that the reductions could reach 17 to 35% by 2100, as a result of expected increases in the air's CO<sub>2</sub> content over the current century. Likewise, Langdon *et al.* (2000) calculated a decrease in coral calcification rate of up to 40% between 1880 and 2065. Based upon these and other such calculations, the NRDC movie opines that by mid-century, "entire vast areas of both the Southern Ocean and the Arctic Ocean will be so corrosive that it will cause sea shells to dissolve," and that "we're really in the last decades of coral reefs on this planet for at least the next, let's say million plus years."

*These considerations even suggest that the rising CO<sub>2</sub> content of Earth's atmosphere may well be a positive phenomenon, enhancing the growth rates of corals and helping them to better withstand the many environmental stresses that truly are inimical to their well-being.*

The ocean chemistry aspect of this theory is rather straightforward; but it is not as solid as model projections or the NRDC make it out to be. In another evaluation of the consequences of atmospheric CO<sub>2</sub> enrichment for seawater acidity, for example, Loaiciga (2006) found that a doubling of CO<sub>2</sub> from 380 to 760 ppm would increase seawater acidity by lowering its pH by only 0.19 unit. Thus, Loaiciga concluded that on a global scale and over the time scale considered (hundreds of years), there should *not* be "accentuated changes in seawater acidity" as a result of projected increases in the air's CO<sub>2</sub> concentration. In addition, with more CO<sub>2</sub> in the air,

additional weathering of terrestrial carbonates is likely to occur, which would increase delivery of Ca<sup>2+</sup> to the oceans and partly compensate for the CO<sub>2</sub>-induced decrease in oceanic calcium carbonate saturation state (Riding, 1996). And as with all phenomena involving *living*

organisms, the introduction of life into the ocean acidification picture greatly complicates things. A number of interrelated biological phenomena, for example, must also be considered; and when they are, it becomes much more difficult to draw such sweeping negative conclusions as portrayed by the NRDC in their film. In fact, as demonstrated in the following paragraphs, these considerations even suggest that the rising CO<sub>2</sub> content of Earth's atmosphere may well be a *positive* phenomenon, *enhancing* the growth rates of corals and helping them to *better withstand* the many environmental stresses that truly *are* inimical to their well-being, such as storm damage, sea-level rise, extreme temperatures, human-induced damage resulting from mining, dredging, fishing and tourism, as well as intensified pollution due to an over-abundance of nutrients, pesticides, herbicides and particulates arising from agricultural and other enterprises.

### **OCEAN ACIDIFICATION AND CORAL CALCIFICATION: LIFE FINDS A WAY**

Over sixty years ago, Kawaguti and Sakumoto (1948) illustrated the importance of photosynthesis in the construction of coral reefs. Specifically, they analyzed numerous data sets recorded in earlier publications, demonstrating that coral calcification rates are considerably higher in the daylight (when photosynthesis by coral symbionts occurs) than they are in the dark (when the symbionts lose carbon via respiration). A number of more modern studies have also demonstrated that symbiont photosynthesis enhances coral calcification (Barnes and Chalker, 1990; Yamashiro, 1995); and they have further demonstrated that long-term reef calcification rates generally rise in direct proportion to increases in rates of reef primary production (Frankignoulle *et al.*, 1996; Gattuso *et al.*, 1996, 1999). In fact, the work of Muscatine (1990) suggests that "the photosynthetic activity of zooxanthellae is the chief source of energy for the energetically expensive process of calcification" (Hoegh-Guldberg, 1999). Consequently, if an anthropogenic-induced increase in the transfer of CO<sub>2</sub> from the atmosphere to the world's oceans, i.e., *hydrospheric* CO<sub>2</sub> enrichment, were to lead to increases in coral symbiont photosynthesis – as atmospheric CO<sub>2</sub> enrichment does for essentially all terrestrial plants (Kimball, 1983; Idso, 1992; Idso and Idso, 1994) – it is likely that coral calcification rates would also increase.

Another consequence of this phenomenon is that more robustly growing zooxanthellae may take up more of the metabolic waste products of the coral host, which, if present in too great quantities, can prove detrimental to the health of the host, as well as the health of the entire coral plant-animal assemblage (Yonge, 1968; Crossland and Barnes, 1974). There are also a number of other substances that are known to directly interfere with calcium carbonate precipitation; and they too can be actively removed from the water by coral symbionts in much the same way that symbionts remove host waste products (Simkiss, 1964). More importantly, perhaps, a greater amount of symbiont-produced photosynthates may provide more "fuel" for the active transport processes involved in coral calcification (Chalker and Taylor, 1975), as well as more raw materials for the synthesis of the coral organic matrix (Wainwright, 1963; Muscatine, 1967; Battey and Patton, 1984). Finally, the photosynthetic process helps to maintain a healthy aerobic or oxic environment for the optimal growth of the coral animals (Rinkevich and Loya, 1984; Rands *et al.*, 1992); and greater CO<sub>2</sub>-induced rates of symbiont photosynthesis would enhance this important "environmental protection" activity.

In light of these several observations and their logical implications, with ever more CO<sub>2</sub> going into the air, driving ever more CO<sub>2</sub> into the oceans, increasingly *greater* rates of coral symbiont photosynthesis would be expected to be observed, all else being equal. And this phenomenon, in turn, should increasingly enhance all of the many positive photosynthetic-dependent phenomena described above and thereby increase coral calcification rates. Furthermore, it should increase these rates well beyond the point of overpowering the modest negative effect of the purely chemical consequences of elevated dissolved CO<sub>2</sub> on ocean pH and calcium carbonate saturation state. However, arriving at these conclusions is not as simple as it sounds.

For one thing, although many types of marine plant life do indeed respond to hydrospheric CO<sub>2</sub> enrichment (Raven *et al.*, 1985) – including seagrasses (Zimmerman *et al.*, 1997), certain diatoms (Riebesell *et al.*, 1993; Chen and Gao, 2004; Sobrino *et al.*, 2008), macroalgae (Borowitzka and Larkum, 1976; Gao *et al.*, 1993), and microalgae or phytoplankton (Raven, 1991; Nimer and Merrett, 1993) – the photosynthesis of many marine autotrophs is normally not considered to be carbon-limited, because of the large supply of bicarbonate in the world's oceans (Raven, 1997). However, as Gattuso *et al.* (1999) explain, this situation is only true for autotrophs that possess an effective carbon-concentrating mechanism; but to swing once again in the other direction, it is also believed that many coral symbionts are of this type (Burriss *et al.*, 1983; Al-Moghrabi *et al.*, 1996; Goiran *et al.*, 1996).

Nevertheless, Gattuso *et al.* (1999) reported that coral zooxanthellae – in a grand example of adaptation – are able to change their mechanism of carbon supply in response to various environmental stimuli. Furthermore, Beardall *et al.* (1998) suggest that an increased concentration of dissolved CO<sub>2</sub>, together with an increase in the rate of CO<sub>2</sub> generation by bicarbonate dehydration in host cells, may favor a transition to the diffusional mode of carbon supply, which is sensitive to hydrospheric CO<sub>2</sub> concentration. Consequently, if such a change in mode of carbon supply were to occur – prompted, perhaps, by hydrospheric CO<sub>2</sub> enrichment itself – this shift in CO<sub>2</sub> fixation strategy would indeed allow the several biological mechanisms described above to operate to enhance reef calcification rates in response to a rise in the air's CO<sub>2</sub> content.

*Long-term reef calcification rates have generally been observed to rise in direct proportion to increases in rates of reef primary production, which they say may well be enhanced by increases in the air's CO<sub>2</sub> concentration.*

In one final example that demonstrates the importance of biology in driving the physical-chemical process of coral calcification, Muscatine *et al.* (2005) note that the "photosynthetic activity of zooxanthellae is the chief source of energy for the energetically-expensive process of calcification," and that long-term reef calcification rates have generally been observed to rise in direct proportion to increases in rates of reef primary production, which they say may well be enhanced by increases in the air's CO<sub>2</sub> concentration.

Muscatine *et al.* began the report of their investigation of this subject by stating much the same thing, i.e., that endosymbiotic algae "release products of photosynthesis to animal cells ... and augment the rate of skeletal calcification." Then, noting that the "natural abundance of stable isotopes ( $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ ) has answered paleobiological and modern questions about the effect of photosymbiosis on sources of carbon and oxygen in coral skeletal calcium carbonate," they go on to investigate the natural abundance of these isotopes in another coral skeletal compartment – the skeletal organic matrix (OM) – in 17 species of modern scleractinian corals, after which they compare the results for symbiotic and nonsymbiotic forms to determine the role played by algae in OM development.

The significance of this study, in the words of Muscatine *et al.*, derives from the fact that "the scleractinian coral skeleton is a two-phase composite structure consisting of fiber-like crystals of aragonitic calcium carbonate intimately associated with an intrinsic OM," and although the OM generally comprises less than 0.1% of the total weight of the coral skeleton, it is, in their words, "believed to initiate nucleation of calcium carbonate and provide a framework for crystallographic orientation and species-specific architecture." In fact, they say that inhibition of OM synthesis "brings coral calcification to a halt."

In commenting on what was learned from their experiments, the researchers say their "most striking observation is the significant difference in mean OM  $\delta^{15}\text{N}$  between symbiotic and nonsymbiotic corals," which makes OM  $\delta^{15}\text{N}$  an important proxy for photosymbiosis. As an example of its usefulness, they applied the technique to a fossil coral (*Pachytheclis major*) from the Triassic (which prevailed some 240 million years ago), finding that the ancient coral was indeed photosymbiotic. Even more importantly, however, they conclude in the final sentence of their paper that "it now seems that symbiotic algae may control calcification by both modification of physico-chemical parameters within the coral polyps (Gautret *et al.*, 1997; Cuif *et al.*, 1999) and augmenting the synthesis of OM (Allemand *et al.*, 1998)."

*It has been clearly demonstrated, for example, that corals can grow quite well in aquariums containing water of very high dissolved CO<sub>2</sub> concentration.*

Although lacking the research to absolutely identify the "what" and definitively describe the "how" of the hypothesis of hydrospheric CO<sub>2</sub> enhancement of coral calcification, it is likely that something of the nature described above can indeed act to overcome the negative effect of the high-CO<sub>2</sub>-induced decrease in calcium carbonate saturation state on coral calcification rate. It has been clearly demonstrated, for example, that corals can grow quite well in aquariums containing water of very high dissolved CO<sub>2</sub> concentration (Atkinson *et al.*, 1995); and Carlson (1999) has stated that the fact that corals often *thrive* in such water "seems to

contradict conclusions ... that high CO<sub>2</sub> may inhibit calcification." And there are numerous other examples of such phenomena in the real world of nature, all of which are ignored by the NRDC film, but which we examine in what follows.

## CORAL CALCIFICATION MEASUREMENTS

According to one scientist appearing in the NRDC film, "coral reefs are particularly sensitive to ocean acidification," and in a dire prediction he further opines that we are presently in "the last decade in which we can do something about this problem." As ever more pertinent evidence accumulates, however, the *true* story appears to be just the *opposite* of this prediction.

Herfort *et al.* (2008), for example, note that an increase in atmospheric CO<sub>2</sub> will cause an increase in the abundance of HCO<sub>3</sub><sup>-</sup> (bicarbonate) ions and dissolved CO<sub>2</sub>; and they report that several studies on marine plants have observed "increased photosynthesis with higher than ambient DIC [dissolved inorganic carbon] concentrations," citing the works of Gao *et al.* (1993), Weis (1993), Beer and Rehnberg (1997), Marubini and Thake (1998), Mercado *et al.* (2001, 2003), Herfort *et al.* (2002) and Zou *et al.* (2003).

To further explore this subject, and to see what it might imply for coral calcification, the three researchers employed a wide range of bicarbonate concentrations "to monitor the kinetics of bicarbonate use in both photosynthesis and calcification in two reef-building corals, *Porites porites* and *Acropora* sp." This work revealed that additions of HCO<sub>3</sub><sup>-</sup> to synthetic seawater continued to increase the calcification rate of *Porites porites* until the bicarbonate concentration *exceeded three times that of seawater*, while photosynthetic rates of the coral's symbiotic algae were stimulated by HCO<sub>3</sub><sup>-</sup> addition until they became saturated at *twice* the normal HCO<sub>3</sub><sup>-</sup> concentration of seawater.

Similar experiments conducted on Indo-Pacific *Acropora* sp. showed that calcification and photosynthetic rates in these corals were enhanced to an even greater extent, with calcification continuing to increase above a *quadrupling* of the HCO<sub>3</sub><sup>-</sup> concentration and photosynthesis saturating at *triple* the concentration of seawater. In addition, they monitored calcification rates of the *Acropora* sp. in the dark; and, in their words, "although these were lower than in the light for a given HCO<sub>3</sub><sup>-</sup> concentration, they still increased dramatically with HCO<sub>3</sub><sup>-</sup> addition, showing that calcification in this coral is light stimulated but not light dependent."

In discussing the significance of their findings, Herfort *et al.* suggest that "hermatypic corals incubated in the light achieve high rates of calcification by the synergistic action of photosynthesis," which, as they demonstrated, is enhanced by elevated concentrations of HCO<sub>3</sub><sup>-</sup> ions that come courtesy of the ongoing rise in the air's CO<sub>2</sub> content. As for the real-world implications of their work, the three researchers note that over the next century the predicted increase in atmospheric CO<sub>2</sub> concentration will result in about a 15% increase in oceanic HCO<sub>3</sub><sup>-</sup>, and they say that this development "could stimulate photosynthesis and calcification in a wide variety of hermatypic corals."

In another study, Pelejero *et al.* (2005) developed a reconstruction of seawater pH spanning the period 1708-1988, based on the boron isotopic composition ( $\delta^{11}\text{B}$ ) of a long-lived massive *Porites* coral from Flinders Reef in the western Coral Sea of the southwestern Pacific. Their results indicated there was "no notable trend toward lower  $\delta^{11}\text{B}$  values" over the 300-year period investigated. Instead, they say that "the dominant feature of the coral  $\delta^{11}\text{B}$  record is a clear interdecadal oscillation of pH, with  $\delta^{11}\text{B}$  values ranging between 23 and 25 per mil (7.9

and 8.2 pH units)," which "is synchronous with the Interdecadal Pacific Oscillation." Furthermore, they calculated changes in aragonite saturation state from the Flinders pH record that varied between about 3 and 4.5, which values encompass "the lower and upper limits of aragonite saturation state within which corals can survive." But in spite this fact, they report that "skeletal extension and calcification rates for the Flinders Reef coral fall within the normal range for *Porites* and are not correlated with aragonite saturation state or pH."

Thus, contrary to claims that historical anthropogenic CO<sub>2</sub> emissions have already resulted in a significant decline in ocean water pH and aragonite saturation state, Pelejero *et al.*'s 300-year record of these parameters (which, in their words, began "well before the start of the Industrial Revolution") provides no evidence of such a decline. What is more, and also contrary to claims of how sensitive coral calcification rate is to changes in pH and aragonite saturation state, they found that huge cyclical changes in these parameters had essentially no detectable effect on either coral calcification or skeletal extension rates.

***Contrary to claims that historical anthropogenic CO<sub>2</sub> emissions have already resulted in a significant decline in ocean water pH and aragonite saturation state, Pelejero et al.'s 300-year record of these parameters provides no evidence of such a decline.***

In another study of historical calcification rates determined from coral cores retrieved from 35 sites on the Great Barrier Reef, Lough and Barnes (1997) observed a statistically significant correlation between coral calcification rate and local water temperature, such that a 1°C increase in mean annual water temperature *increased* mean annual coral calcification rate by about 3.5%. Nevertheless, they report there were "declines in calcification in *Porites* on the Great Barrier Reef over recent decades." They point out, however, that their data depict *several* extended periods of time when coral growth rates were either *above or below* the long-term mean, cautioning that "it would be unwise to rely on short-term values (say averages over less than 30 years) to assess mean conditions."

As an example of this fact, the two researchers report that "a decline in calcification equivalent to the recent decline occurred earlier this century and much greater declines occurred in the 18th and 19th centuries," long before anthropogenic CO<sub>2</sub> emissions made much of an impact on the air's CO<sub>2</sub> concentration. In fact, over the entire expanse of their data set, Lough and Barnes determined that "the 20th century has witnessed the second highest period of above average calcification in the past 237 years," which is not exactly what one would expect in light of (1) how dangerous high water temperatures are often said to be for corals, (2) the claim that earth is currently warmer than it has been at any other time during the entire past millennium, and (3) the fact that the air's CO<sub>2</sub> content is currently *much* higher than it has been for a *vastly* longer time.

Similar findings were reported by Bessat and Buigues (2001), who derived a history of coral calcification rates from a core extracted from a massive *Porites* coral head on the French Polynesian island of Moorea that covered the period 1801-1990. They performed this work, they say, because "recent coral-growth models highlight the enhanced greenhouse effect on the decrease of calcification rate," and rather than relying on *theoretical calculations*, they wanted to work with *real-world data*, stating that the records preserved in ancient corals "may provide information about long-term variability in the performance of coral reefs, allowing unnatural changes to be distinguished from natural variability."

The results of the two researchers' study indicated that a 1°C increase in water temperature *increased* coral calcification rate at the site they studied by 4.5%. Thus, they found that "instead of a 6-14% decline in calcification over the past 100 years computed by the Kleypas group, the calcification has increased, in accordance with [the results of] Australian scientists Lough and Barnes." They also observed patterns of "jumps or stages" in the record, which were characterized by an increase in the annual rate of calcification, particularly at the beginning of the past century "and in a more marked way around 1940, 1960 and 1976," stating once again that their results "do not confirm those predicted by the Kleypas *et al.* (1999) model."

Additional observation evidence that contradicts the Kleypas *et al.* model was provided by the work of Lough and Barnes (2000), who assembled and analyzed the calcification characteristics of 245 similar-sized massive colonies of *Porites* corals obtained from 29 reef sites located along the length, and across the breadth, of Australia's Great Barrier Reef (GBR), which data spanned a latitudinal range of approximately 9° and an annual average sea surface temperature (SST) range of 25-27°C. To these data they added other published data from the Hawaiian Archipelago (Grigg, 1981, 1997) and Phuket, Thailand (Scoffin *et al.*, 1992), thereby extending the latitudinal range of the expanded data set to 20° and the annual average SST range to 23-29°C.

This analysis revealed that the GBR calcification data were linearly related to the average annual SST data, such that "a 1°C rise in average annual SST increased average annual calcification by 0.39 g cm<sup>-2</sup> year<sup>-1</sup>." Results were much the same for the extended data set, as Lough and Barnes report that "the regression equation [calcification = 0.33(SST) - 7.07] explained 83.6% of the variance in average annual calcification (F = 213.59, p less than 0.001)," noting that "this equation provides for a change in calcification rate of 0.33 g cm<sup>-2</sup> year<sup>-1</sup> for each 1°C change in average annual SST."

With respect to the significance of their findings, Lough and Barnes say they "allow assessment of possible impacts of global climate change on coral reef ecosystems," and between the two 50-year periods 1880-1929 and 1930-1979, they calculate a calcification increase of 0.06 g cm<sup>-2</sup> year<sup>-1</sup>, noting that "this increase of approximately 4% in calcification rate conflicts with the estimated decrease in coral calcification rate of 6-14% over the same time period suggested by Kleypas *et al.* (1999) as a response to changes in ocean chemistry." What is more, the authors report that between the two 20-year periods 1903-1922 and 1979-1998, "the SST-associated increase in calcification is estimated to be less than 5% in the northern GBR, approximately 12% in the central GBR, approximately 20% in the southern GBR and to increase dramatically (up to approximately 50%) to the south of the GBR."

***In light of these real-world observations, Lough and Barnes concluded that coral calcification rates "may have already significantly increased along the GBR in response to global climate change."***

In light of these real-world observations, Lough and Barnes concluded that coral calcification rates "may have already significantly increased along the GBR in response to global climate change." Yet in spite of this compelling evidence, as well as the similar findings of others, claims of impending coral demise caused by rising air temperatures and CO<sub>2</sub> concentrations have continued to surface, including the study of Caldeira and Wickett (2003).

Based on a geochemical *model*, an ocean general-circulation *model*, an IPCC CO<sub>2</sub> emissions *scenario* for the 21st century, and a *logistic function* for the burning of earth's post-21st century fossil-fuel

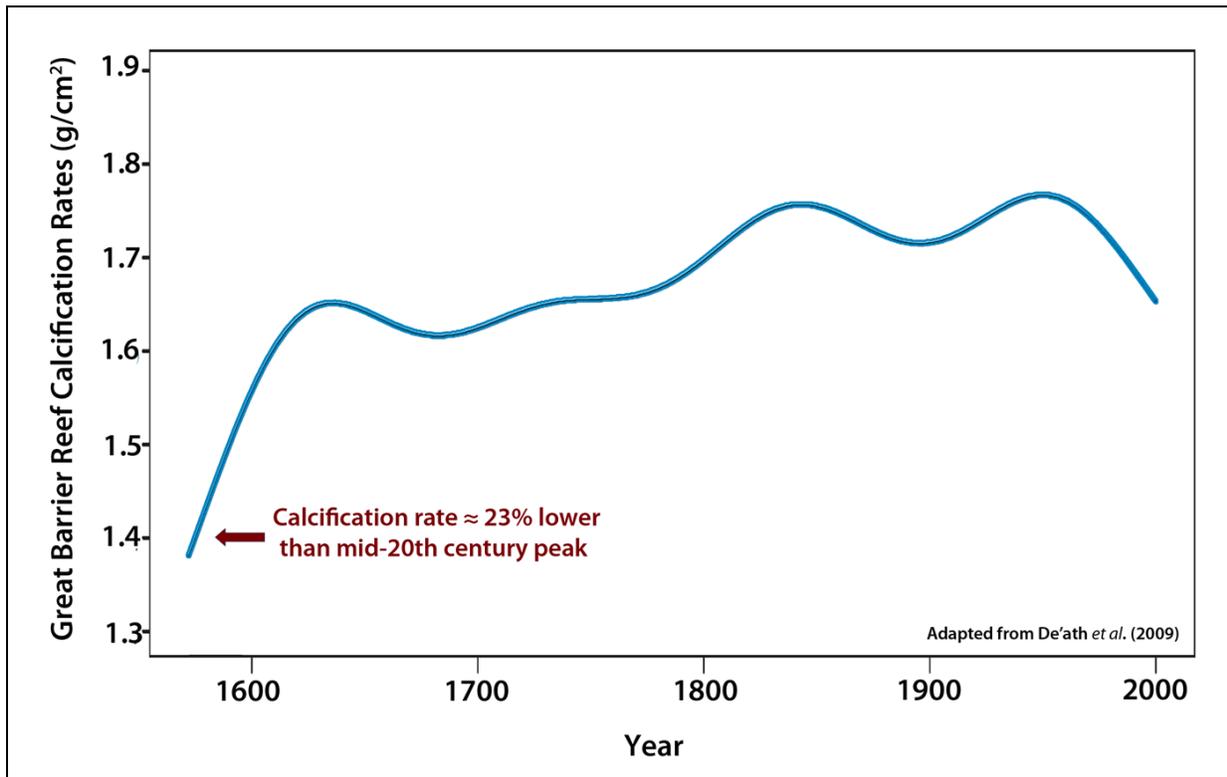
reserves, they *calculated* three important numbers: the maximum level to which the air's CO<sub>2</sub> concentration might rise, the point in time when that might happen, and the related decline that might be expected to occur in ocean-surface pH. These calculations indicated that earth's atmospheric CO<sub>2</sub> concentration could approach 2000 ppm around the year 2300, leading to an ocean-surface pH reduction of 0.7 unit, a change described by Caldeira and Wickett as being much more rapid and considerably greater "than any experienced in the past 300 million years," which proves deadly for earth's corals in their *scenario*.

The following year, similar concerns were raised in a report prepared for the Pew Center on Global Climate Change, which was released to the public on 13 February 2004 at the annual meeting of the *American Association for the Advancement of Science*. In that document, Buddemeier *et al.* (2004) claimed that the projected increase in the air's CO<sub>2</sub> content and the simulated decline in ocean-surface pH would dramatically decrease coral calcification rates, which were predicted to lead to "a slow-down or reversal of reef-building and the potential loss of reef structures."

Nevertheless, and because of all the contrary evidence, much of which we have cited above, Buddemeier *et al.* (2004) acknowledged that "calcification rates of large heads of the massive coral *Porites* increased rather than decreased over the latter half of the 20th century," further noting that "temperature and calcification rates are correlated, and these corals have so far responded more to increases in water temperature (growing faster through increased metabolism and the increased photosynthetic rates of their zooxanthellae) than to decreases in carbonate ion concentration."

One of the more recent claims of impending coral demise is based on the study of De'ath *et al.* (2009), who examined coral calcification rates on the Great Barrier Reef over the past 400 years. Results of their analysis indicate there was a 14% decline in *Porites* calcification rate between 1990 and 2005, which De'ath *et al.* claimed to be "unprecedented in at least the past 400 years." But if De'ath *et al.*'s calcification history is followed back in time a mere 33 more years, from 1605 to 1572, that claim is no longer true, because the coral calcification rate during that earlier time – when the air's CO<sub>2</sub> concentration was more than 100 ppm less than

what it is today and, according to climate alarmists, so much more *healthier* for earth's corals – was approximately 23% *lower* than what it was at its 20<sup>th</sup>-century peak.



A second way of looking at De'ath *et al.*'s data is to realize that from 1572 to the 20th century peak, *Porites* calcification rates on the Great Barrier Reef rose by about 29%, as the atmospheric CO<sub>2</sub> concentration and air temperature rose concurrently, after which calcification rates declined, but by a smaller 14%, as these same air temperature and CO<sub>2</sub> trends continued, further obfuscating the issue. With respect to the *reason* for the recent decline, De'ath *et al.* thus properly admit that "the causes for the Great Barrier Reef-wide decline in coral calcification of massive *Porites* remain unknown."

Another reason why the ongoing rise in the air's CO<sub>2</sub> content may not lead to reduced oceanic pH and, therefore, lower calcification rates in the world's coral reefs, is that the same phenomenon that powers the twin processes of coral calcification and phytoplanktonic growth (photosynthesis) tends to increase the pH of marine waters (Gnaiger *et al.*, 1978; Santhanam *et al.*, 1994; Brussaard *et al.*, 1996; Lindholm and Nummelin, 1999; Macedo *et al.*, 2001; Hansen, 2002); and this phenomenon has been shown to have the ability to dramatically increase the pH of marine bays, lagoons and tidal pools (Gnaiger *et al.*, 1978; Macedo *et al.*, 2001; Hansen, 2002) as well as to significantly enhance the surface water pH of areas as large as the North Sea (Brussaard *et al.*, 1996).

In one example, Middelboe and Hansen (2007) studied the pH of a wave-exposed boulder reef in Aalsgaarde on the northern coast of Zealand, Denmark, and a sheltered shallow-water area in Kildebakkerne in the estuary Roskilde Fjord, Denmark, reporting that, in line with what one would expect if photosynthesis tends to increase surface-water pH, (1) "daytime pH was

significantly higher in spring, summer and autumn than in winter at both study sites," often reaching values of 9 or more during peak summer growth periods vs. 8 or less in winter, that (2) "diurnal measurements at the most exposed site showed significantly higher pH during the day than during the night," reaching values that sometimes exceeded 9 during daylight hours but that typically dipped below 8 at night, and (3) that "diurnal variations were largest in the shallow water and decreased with increasing water depth."

In addition to their own findings, Middelboe and Hansen cite those of (1) Pearson *et al.* (1998), who found that pH averaged about 9 during the summer in populations of *Fucus vesiculosus* in the Baltic Sea, (2) Menendez *et al.* (2001), who found that maximum pH was 9 to 9.5 in dense floating macroalgae in a brackish coastal lagoon in the Ebro River Delta, and (3) Bjork *et al.* (2004), who found pH values as high as 9.8 to 10.1 in isolated rock pools in Sweden. Noting that "pH in the sea is usually considered to be stable at around 8 to 8.2," the two Danish researchers thus concluded that "pH is higher in natural shallow-water habitats than previously thought."

In a more recent example of this phenomena, Semesi *et al.* (2009) investigated whether diel variations in seawater pH caused by the photosynthetic activity of seagrass meadows within Chwaka Bay (Zanzibar, Tanzania) could affect the calcification and photosynthesis rates of calcareous red algae (*Hydrolithon* sp. and *Mesophyllum* sp.) and green algae (*Halimeda renschii*) growing within the marine meadows. This feat was accomplished by measuring rates of calcification and *relative photosynthetic electron transport* (rETR) of the algae *in situ* in open-bottom incubation cylinders either in the natural presence of the rooted seagrasses or after their leaves had been removed.

The researchers' indicated that "seagrass photosynthesis increased the seawater pH within the cylinders from 8.3-8.4 to 8.6-8.9 after 2.5 hours (largely in conformity with that of the surrounding seawater), which, in turn, enhanced the rates of calcification 5.8-fold for *Hydrolithon* sp. and 1.6-fold for the other 2 species," while "the rETRs of all algae largely followed the irradiance throughout the day and were (in *Mesophyllum* sp.) significantly higher in the presence of seagrasses." Thus, the three researchers concluded that "algal calcification within seagrass meadows such as those of Chwaka Bay is considerably enhanced by the photosynthetic activity of the seagrasses, which in turn increases the seawater pH." In fact, they note that the high pH values that were created by seagrass photosynthesis are what actually *caused* the elevated calcification rates of the macroalgae; and this observation supports the thesis that the lowering of seawater pH caused by higher atmospheric CO<sub>2</sub> concentrations may well be *counteracted* by CO<sub>2</sub>-induced increases in the photosynthetic activity of the symbiotic zooxanthellae of earth's corals, which phenomenon may boost the pH of seawater *in intimate contact with the coral host*, allowing the host to actually *increase* its calcification rate in CO<sub>2</sub>-enriched seawater (or to at least not suffer a major reduction in calcification), which end result is what has generally been observed in the real world over the course of the increase in the air's CO<sub>2</sub> concentration that has been experienced since the inception of the Industrial Revolution.

Returning back to calcification studies, Reynaud *et al.* (2004) grew nubbins of the branching zooxanthellate scleractinian coral *Acropora verweyi* in aquariums maintained at 20, 25 and

29°C, while weighing them once a week over a period of four weeks. This exercise revealed that coral calcification rates increased in nearly perfect linear fashion with increasing water temperature, yielding values of 0.06, 0.22 and 0.35% per day at 20, 25 and 29°C, respectively. These data reveal an approximate 480% increase in calcification rate in response to a 9°C increase in water temperature and a 160% increase in response to a 3°C increase in temperature, the latter of which temperature increases is somewhere in the low to midrange of global warming that the IPCC claims will result from a 300 ppm increase in the air's CO<sub>2</sub> concentration; and this positive temperature effect *far* outweighs the negative effect of rising CO<sub>2</sub> concentrations on coral calcification via ocean acidification.

*These data reveal an approximate 480% increase in calcification rate in response to a 9°C increase in water temperature and a 160% increase in response to a 3°C increase in temperature.*

Working in the ocean, Carricart-Ganivet (2004) developed relationships between coral calcification rate and annual average SST based on data collected from colonies of the reef-building coral *Montastraea annularis* at twelve localities in the Gulf of Mexico and the Caribbean Sea, finding that calcification rate in the Gulf of Mexico increased 0.55 g cm<sup>-2</sup> year<sup>-1</sup> for each 1°C increase, while in the Caribbean Sea it increased 0.58 g cm<sup>-2</sup> year<sup>-1</sup> for each 1°C increase. Pooling these data with those of *M. annularis* and *M. faveolata* growing to a depth of 10 m at Carrie Bow Cay, Belize, those from reefs at St. Croix in the US Virgin Islands, and those of *M. faveolata* growing to a depth of 10 m at Curacao, Antilles, Carricart-Ganivet reports he obtained a mean increase in calcification rate of approximately 0.5 g cm<sup>-2</sup> year<sup>-1</sup> for each 1°C increase in annual average SST, which is even greater than what was found by Lough and Barnes for *Porites* corals.

Some new and updated real-world assessments of coral growth were also provided by Lough (2008), who reported that "average linear extension and calcification rates in Indo-Pacific *Porites* are linearly [and positively] related to average water temperatures through 23 to 30°C," based on data obtained from 49 different reefs. She also reports, however, that "coral growth characteristics at 2 of 3 reefs in the central Great Barrier Reef provide evidence of a recent decline," but she adds that "the exact causes of these declines cannot be identified at present nor can they, at present, be directly related to lower aragonite saturation state."

In another study, McNeil *et al.* (2004) used a coupled atmosphere-ice-ocean carbon cycle model to calculate annual mean SST increases within the world's current coral reef habitat from 1995 to 2100 for increases in the air's CO<sub>2</sub> concentration specified by the IPCC's IS92a scenario, after which concomitant changes in coral reef calcification rates were estimated by combining the output of the climate model with empirical relationships between coral calcification rate and (1) aragonite saturation state (the negative CO<sub>2</sub> effect) and (2) annual SST (the positive temperature effect). Their choice for the first of these two relationships was that derived by Langdon *et al.* (2000), which leads to an even greater reduction in calcification than was predicted in the study of Kleypas *et al.* Their choice for the second relationship was that

derived by Lough and Barnes (2000), which leads to an increase in calcification that is only half as large as that derived by Carricart-Ganivet (2004). As a result, the net result of the two phenomena was doubly weighted in favor of reduced coral calcification. Nevertheless, McNeil *et al.* found that the increase in coral reef calcification associated with ocean warming *far* outweighed the decrease associated with the CO<sub>2</sub>-induced decrease in aragonite saturate state. In fact, they calculated that coral calcification in 2100 would be 35% higher than what it was in pre-industrial times *at the very least*. And they found that the area of coral reef habitat expands in association with the projected ocean warming.

In a study devoted to corals that involved a much longer time period than all of the studies previously discussed, Crabbe *et al.* (2006) determined the ancient growth rates of long-dead Quaternary corals found in limestone deposits of islands in the Wakatobi Marine National Park of Indonesia, after which they compared them to the growth rates of present-day corals of the same genera living in the same area. This work revealed that the Quaternary corals grew “in a comparable environment to modern reefs” – except for the air’s CO<sub>2</sub> concentration, which is currently higher than it has been at any other time throughout the entire Quaternary, which spans the past 1.8 million years – and their measurements indicated that the radial growth rates of the modern corals were 31% greater than those of their ancient predecessors in the case of *Porites* species, and 34% greater in the case of *Favites* species.

Many other papers also depict increasing rates of coral calcification in the face of rising temperatures and atmospheric CO<sub>2</sub> concentrations (Clausen and Roth, 1975; Coles and Jokiel, 1977; Kajiwara *et al.*, 1995; Nie *et al.*, 1997; Reynaud-Vaganay *et al.*, 1999; Reynaud *et al.*, 2007); and the studies they describe clearly indicate that 20<sup>th</sup>-century increases in atmospheric CO<sub>2</sub> and temperature have not been anywhere near as catastrophically disruptive to earth’s corals as theoretical calculations suggest they should have been. Rather, the observational data suggest that the temperature and CO<sub>2</sub> increases appear to have been *helpful* to Earth’s corals, supporting the thesis that *living entities* can often overcome *physical-chemical limitations*, which in the *absence* of life would not have been possible. In any event, and whatever the reason, one thing is sure: claims made by participants in the NRDC film that coral reefs will suffer extinction in the next two to three decades are soundly rebutted by literally *reams* of real-world data.

But what about *other* calcifying – and non-calcifying – marine organisms? How might *they* fare in a CO<sub>2</sub>-enriched and warmer world?

## **OCEAN ACIDIFICATION EFFECTS ON OTHER MARINE ORGANISMS**

According to the NRDC, most shellfish, various plankton and other marine species are all vulnerable to CO<sub>2</sub>-induced ocean acidification. Yet, once again, a vast array of data suggests that most of these other marine organisms will also adapt quite well to any human-induced change in oceanic pH.

Kurihara *et al.* (2007), for example, extracted sedimentary mud containing meiofauna – small benthic invertebrates that can pass through a 0.5 - 1 mm mesh but are retained by a 30 - 45 µm mesh – from the seafloor of Tanabe Bay on the Kii Peninsula of Japan and incubated it in marine

microcosms that were continuously aerated for 56 days with air of either 360 or 2,360 ppm CO<sub>2</sub> -- the latter of which concentrations has been predicted by some to be characteristic of the Earth in the year 2300 -- while they periodically measured the abundance and biomass of different members of the meiobenthic community contained in the sediments.

The researchers' observations revealed "no significant differences in the abundance of total meiofauna, nematodes, harpacticoid copepods (including adults and copepodites) and nauplii by the end of the experiment." In addition, they say there "may have been successful recruitments under elevated CO<sub>2</sub> conditions," and, therefore, that "elevated CO<sub>2</sub> had not impacted the reproduction of nematodes and harpacticoid copepods." Thus, the three researchers concluded that their results suggest that "the projected atmospheric CO<sub>2</sub> concentration in the year 2300 does not have acute effects on the meiofauna."

In another paper, Kranz *et al.* (2009) write that "marine phytoplankton contribute up to 50% of global primary production (Falkowski *et al.*, 1998) and influence earth's climate by altering various biogeochemical cycles (Schlesinger, 2005)." They also note, with respect to the latter subject and, more specifically, the marine nitrogen (N) cycle, that among diazotrophic cyanobacteria (dinitrogen-fixers), the species *Trichodesmium* "contributes about half of all marine N<sub>2</sub> fixation (Mahaffey *et al.*, 2005)," supporting "a large fraction of biological productivity in tropical and subtropical areas" and exerting, "over long timescales, a significant influence on global carbon cycles by providing a major source of reactive N to the water column (Falkowski and Raven, 2007)." Thus, to see how the ongoing and projected increase in the air's CO<sub>2</sub> concentration may impact one of the global ocean's most important diazotrophic cyanobacteria (*Trichodesmium erythraeum* IMS101), Kranz *et al.* (2009) grew the ubiquitous marine N<sub>2</sub>-fixer in semicontinuous batch cultures through which they bubbled air with CO<sub>2</sub> concentrations of either 370 or 1000 ppm. Then, after the cultures were acclimated to their respective CO<sub>2</sub> concentrations for at least 14 days (more than 5 generations), they measured rates of *particulate organic carbon* (POC) and *particulate organic nitrogen* (PON) fixation.

The team's results indicated there was "a strong increase in photosynthesis and N<sub>2</sub> fixation under elevated CO<sub>2</sub> levels," such that POC and PON production rates rose "by almost 40%." In discussing the generality of their findings, the German scientists noted that -- working with the same *Trichodesmium* species -- "Ramos *et al.* (2007) and Levitan *et al.* (2007) observed stimulation in N<sub>2</sub> fixation by approximately 40% and even up to 400%, while Hutchins *et al.* (2007) obtained stimulation by up to 35% over the respective CO<sub>2</sub> range." And in discussing the significance of these findings, they state that "the observed increase in photosynthesis and N<sub>2</sub> fixation could have potential [global] biogeochemical implications, as it may stimulate productivity in N-limited oligotrophic regions and thus provide a negative feedback on rising atmospheric CO<sub>2</sub> levels," slowing the rate of CO<sub>2</sub> rise and reducing the degree of CO<sub>2</sub>-induced global warming. And, of course, the CO<sub>2</sub>-induced stimulation of phytoplanktonic N<sub>2</sub> fixation enhances ocean fertility, while the increase in phytoplanktonic productivity increases the food base for zooplankton and higher faunal trophic levels.

In a similar vein, employing semi-continuous culturing methods that used filtered, microwave-sterilized surface Sargasso seawater that was enriched with phosphate and trace nutrients, Fu *et al.* (2008) "examined the physiological responses of steady-state iron (Fe)-replete and Fe-

limited cultures of the biogeochemically critical marine unicellular diazotrophic cyanobacterium *Crocospaera [watsonii]* at glacial (190 ppm), current (380 ppm), and projected year 2100 (750 ppm) CO<sub>2</sub> levels.” The results of this experiment indicated that when the seawater was *replete* with iron, daily primary production at 750 ppm CO<sub>2</sub> was 21% greater than it was at 380 ppm, while at 190 ppm CO<sub>2</sub> it was 38% lower than it was at 380 ppm. When the seawater was iron-*limited*, however, daily primary production at 750 ppm CO<sub>2</sub> was 150% greater than it was at 380 ppm, while at 190 ppm CO<sub>2</sub> it was 22% lower than it was at 380 ppm. With respect to N<sub>2</sub> fixation, rates varied little among the three CO<sub>2</sub> treatments when the seawater was iron-*limited*; but when the seawater was *replete* with iron, N<sub>2</sub> fixation at 750 ppm CO<sub>2</sub> was 60% greater than it was at 380 ppm, while at 190 ppm CO<sub>2</sub> it was 33% lower than it was at 380 ppm.

In discussing their findings, Fu *et al.* note that “several studies examining the marine diazotrophic cyanobacterium *Trichodesmium* have shown significant increases in N<sub>2</sub> fixation and photosynthesis in response to elevated CO<sub>2</sub> concentration (Hutchins *et al.*, 2007; Levitan *et al.*, 2007; Ramos *et al.*, 2007),” and they say their data “extend these findings to encompass the

***They conclude that “anthropogenic CO<sub>2</sub> enrichment could substantially increase global oceanic N<sub>2</sub> and CO<sub>2</sub> fixation,” which two-pronged phenomenon would be a tremendous boon to the marine biosphere.***

marine unicellular N<sub>2</sub>-fixing cyanobacterium *Crocospaera*,” which group, they add, “is now recognized as being perhaps equally as important as *Trichodesmium* to the ocean nitrogen cycle (Montoya *et al.*, 2004).” Consequently, they conclude that “anthropogenic CO<sub>2</sub> enrichment could substantially increase global oceanic N<sub>2</sub> and CO<sub>2</sub> fixation,” which two-pronged phenomenon would be a tremendous boon to the marine biosphere.

In another study, Bernhard *et al.* (2009) grew the marine foraminiferal protist *Allogromia laticollaris* – which they describe as “a ubiquitous protistan constituent of marine microbial systems” and “an important link in the marine food web” – in a mixture of 32‰ seawater and Alga-Gro seawater

medium in 20-ml glass culture tubes, while examining its response to a number of super-high atmospheric CO<sub>2</sub> concentrations to which the tubes were exposed: 15,000, 30,000, 60,000, 90,000 and 200,000 ppm, which values were compared to the study’s atmospheric control concentration of 375 ppm CO<sub>2</sub>. This work revealed, in their words, that the protist “is able to survive 10-14-day exposure to elevated CO<sub>2</sub> as high as 200,000 ppm.” In fact, they say that “both ATP [Adenosine Triphosphate, an indicator of cellular energy] data and microscopic examination indicate that considerable populations of *A. laticollaris* survived exposure to all experimental treatments of elevated CO<sub>2</sub>, even both replicates of the 200,000-ppm CO<sub>2</sub> experiments.” And they found that “at least three specimens reproduced during exposure to either 90,000 ppm or 200,000 ppm CO<sub>2</sub>,” while “such reproduction was observed only once in an atmospheric [375-ppm CO<sub>2</sub>] treatment.”

With respect to the significance of their findings, the four researchers first note that “*A. laticollaris* is an appropriate species to predict the response of shallow-water thecate

Foraminifera to predicted increases in atmospheric CO<sub>2</sub>, given its isolation [i.e., acquisition] from a shallow-water semi-tropical setting.” Hence, they go on to say their results indicate that “at least some foraminiferal species will tolerate CO<sub>2</sub> values that are one to two orders of magnitude higher than those predicted for the next few centuries.” And, last of all, they say that *A. laticollaris* will also tolerate CO<sub>2</sub> values that are one to two orders of magnitude greater than those predicted to occur for the “extreme case” of burning all fossil fuels in the crust of the earth.

In a review of what is known about the effects of a CO<sub>2</sub>-enriched atmosphere on micro- and macro-algae living in the world’s oceans, Wu *et al.* (2008) write that “enriched CO<sub>2</sub> up to several times the present atmospheric level has been shown to enhance photosynthesis and growth of both phytoplanktonic and macro-species that have less capacity of CCMs [CO<sub>2</sub>-concentrating mechanisms],” adding that “even for species that operate active CCMs and those whose photosynthesis is not limited by CO<sub>2</sub> in seawater, increased CO<sub>2</sub> levels can down-regulate their CCMs and therefore enhance their growth under light-limiting conditions,” because “at higher CO<sub>2</sub> levels, less light energy is required to drive CCM.” In addition, they report that enhanced CO<sub>2</sub> levels have been found to enhance the activity of nitrogen reductase in several marine plants, and that this phenomenon “would support enhanced growth rate by providing adequate nitrogen required for the metabolism under the high CO<sub>2</sub> level.” Last of all, they say that “altered physiological performances under high-CO<sub>2</sub> conditions may cause genetic alteration in view of adaptation over long time scales,” and that “marine algae may adapt to a high CO<sub>2</sub> oceanic environment so that evolved communities in [the] future are likely to be genetically different from contemporary communities.”

*With respect to their many findings, therefore, the eight researchers say their observations suggest that "the system under study was surprisingly resilient to abrupt and large pH changes."*

The findings described by the three researchers represent good news for the biosphere, since “marine phytoplankton contribute to about half of the global primary productivity,” and this phenomenon, in their words, “promotes the absorption of CO<sub>2</sub> from the atmosphere.” Consequently, both the micro- and macro-algae of the world’s oceans should be able to do an even more robust job of performing these vital functions in a CO<sub>2</sub>-enriched world of the future.

In another study, Vogt *et al.* (2008) examined the effects of atmospheric CO<sub>2</sub> enrichment on various marine microorganisms in nine marine mesocosms in a fjord adjacent to the Large-Scale Facilities of the Biological Station of the University of Bergen in Espeland, Norway. Three of the mesocosms were maintained at ambient levels of CO<sub>2</sub> (375 ppm), three were maintained at levels expected to prevail at the end of the current century (760 ppm or 2x CO<sub>2</sub>), and three were maintained at levels predicted for the middle of the next century (1150 ppm or 3x CO<sub>2</sub>), while measurements of numerous ecosystem parameters were made over a period of 24 days.

The results of this analysis showed no significant phytoplankton species shifts between treatments, and indicated that "the ecosystem composition, bacterial and phytoplankton abundances and productivity, grazing rates and total grazer abundance and reproduction were not significantly affected by CO<sub>2</sub> induced effects," citing in support of this statement the work of Riebesell *et al.* (2007), Riebesell *et al.* (2008), Egge *et al.* (2007), Paulino *et al.* (2007), Larsen *et al.* (2007), Suffrian *et al.* (2008) and Carotenuto *et al.* (2007). With respect to their many findings, therefore, the eight researchers say their observations suggest that "the system under study was surprisingly resilient to abrupt and large pH changes."

In another study, Langer *et al.* (2006) conducted batch-culture experiments on two coccolithophores, *Calcidiscus leptoporus* and *Coccolithus pelagicus*, in which they observed a "deterioration of coccolith production above as well as below present-day CO<sub>2</sub> concentrations in *C. leptoporus*," and a "lack of a CO<sub>2</sub> sensitivity of calcification in *C. pelagicus*" over an atmospheric CO<sub>2</sub> concentration range of 98-915 ppm. Both of these observations, in their words, "refute the notion of a linear relationship of calcification with the carbonate ion concentration and carbonate saturation state." In an apparent negative finding, however, particularly in the case of *C. leptoporus*, Langer *et al.* observed that although their experiments revealed that "at 360 ppm CO<sub>2</sub> most coccoliths show normal morphology," at both "higher and lower CO<sub>2</sub> concentrations the proportion of coccoliths showing incomplete growth and malformation increases notably."

To determine if such deleterious responses might have also occurred in the real world at different times in the past, the researchers studied coccolith morphologies in six sediment cores obtained along a range of latitudes in the Atlantic Ocean. As they describe it, this work revealed that changes in coccolith morphology similar to those "occurring in response to the abrupt CO<sub>2</sub> perturbation applied in experimental treatments are not mirrored in the sedimentary record." This finding indicates, as they suggest, that "in the natural environment *C. leptoporus* has adjusted to the 80-ppm CO<sub>2</sub> and 180-ppm CO<sub>2</sub> difference between present [and] preindustrial and glacial times, respectively."

In further discussing these observations, Langer *et al.* say "it is reasonable to assume that *C. leptoporus* has adapted its calcification mechanism to the change in carbonate chemistry having occurred since the last glacial maximum," suggesting as a possible explanation for this phenomenon that "the population is genetically diverse, containing strains with diverse physiological and genetic traits, as already demonstrated for *E. huxleyi* (Brand, 1981, 1982, 1984; Conte *et al.*, 1998; Medlin *et al.*, 1996; Paasche, 2002; Stolte *et al.*, 2000)." They also state that this adaptive ability "is not likely to be confined to *C. leptoporus* but can be assumed to play a role in other coccolithophore species as well," which leads them to conclude that such populations "may be able to evolve so that the optimal CO<sub>2</sub> level for calcification of the species tracks the environmental value." With respect to the future, therefore, Langer *et al.* end by stating that "genetic diversity, both between and within species, may allow calcifying organisms to prevail in a high CO<sub>2</sub> ocean."

Focusing on another coccolithophore species, Riebesell (2004) noted that "a moderate increase in CO<sub>2</sub> facilitates photosynthetic carbon fixation of some phytoplankton groups," including "the coccolithophorids *Emiliania huxleyi* and *Gephyrocapsa oceanica*." Hence, in a major challenge

to the claim that atmospheric CO<sub>2</sub> enrichment will definitely harm such marine organisms, Riebesell suggests that "CO<sub>2</sub>-sensitive taxa, such as the calcifying coccolithophorids, should therefore benefit more from the present increase in atmospheric CO<sub>2</sub> compared to the non-calcifying diatoms."

In support of this suggestion, Riebesell describes the results of some CO<sub>2</sub> perturbation experiments conducted south of Bergen, Norway, where nine 11-m<sup>3</sup> enclosures moored to a floating raft were aerated in triplicate with CO<sub>2</sub>-depleted, normal and CO<sub>2</sub>-enriched air to achieve CO<sub>2</sub> levels of 190, 370 and 710 ppm, simulating glacial, present-day and predicted conditions for the end of the century, respectively. In the course of the study, a bloom consisting of a mixed phytoplankton community developed, and, in Riebesell's words, "significantly higher net community production was observed under elevated CO<sub>2</sub> levels during the build-up of the bloom." He further reports that "CO<sub>2</sub>-related differences in primary production continued after nutrient exhaustion, leading to higher production of transparent exopolymer particles under high CO<sub>2</sub> conditions," something that has also been observed by Engel (2002) in a natural plankton assemblage and by Heemann (2002) in monospecific cultures of both diatoms and coccolithophores.

Another significant finding of this experiment was that the community that developed under the high CO<sub>2</sub> conditions expected for the end of this century was dominated by *Emiliana huxleyi*. Consequently, Riebesell finds even more reason to believe that "coccolithophores may benefit from the present increase in atmospheric CO<sub>2</sub> and related changes in seawater carbonate chemistry," in contrast to the many negative predictions that have been made about rising atmospheric CO<sub>2</sub> concentrations in this regard. Finally, in further commentary on the topic, Riebesell states that "increasing CO<sub>2</sub> availability may improve the overall resource utilization of *E. huxleyi* and possibly of other fast-growing coccolithophore species," concluding that "if this provides an ecological advantage for coccolithophores, rising atmospheric CO<sub>2</sub> could potentially increase the contribution of calcifying phytoplankton to overall primary production." In fact, noting that "a moderate increase in CO<sub>2</sub> facilitates photosynthetic carbon fixation of some phytoplankton groups," including "the coccolithophorids *Emiliana huxleyi* and *Gephyrocapsa oceanica*" – and in a major challenge to the claim that atmospheric CO<sub>2</sub> enrichment will harm such marine organisms – Riebesell suggests that "CO<sub>2</sub>-sensitive taxa, such as the calcifying coccolithophorids, should therefore benefit more from the present increase in atmospheric CO<sub>2</sub> compared to the non-calcifying diatoms."

Support for Riebesell's findings was provided by an international team of thirteen researchers (Iglesias-Rodriguez *et al.*, 2008), who bubbled air of a number of different atmospheric CO<sub>2</sub> concentrations through culture media containing the phytoplanktonic coccolithophore species *Emiliana huxleyi*, while determining the amounts of particulate organic and inorganic carbon they produced. In addition, they determined the real-world change in average coccolithophore mass over the past 220 years in the subpolar North Atlantic Ocean, based on data obtained from a sediment core, over which period of time the atmosphere's CO<sub>2</sub> concentration rose by approximately 90 ppm and the earth emerged from the frigid depths of the Little Ice Age to experience the supposedly unprecedented high temperatures of the Current Warm Period.

Results of their analysis revealed an approximate doubling of both particulate organic and inorganic carbon between the culture media in equilibrium with air of today's CO<sub>2</sub> concentration and the culture media in equilibrium with air of 750 ppm CO<sub>2</sub>. In addition, they say the field evidence they obtained from the deep-ocean sediment core they studied "is consistent with these laboratory conclusions," and that it indicates that "over the past 220 years there has been a 40% increase in average coccolith mass."

Working with materials derived from the same North Atlantic Ocean sediment core, Halloran *et al.* (2008) analyzed the size distribution of CaCO<sub>3</sub> particles in the less-than-10- $\mu$ m sediment fraction over the past quarter-century. This work revealed, in the researchers' words, "a changing particle volume since the late 20th century consistent with an increase in the mass of coccoliths produced by the larger coccolithophore species," which included *Oolithotus fragilis*, *Calcidicus leptoporus*, *Coccolithus pelagicus* var. *pelagicus*, and *Helicosphaera carteri*. Such findings, again in the researchers' words, suggest that "in the real ocean the larger coccolithophore species increase their calcification in response to anthropogenic CO<sub>2</sub> release," and that "such a calcification response could be attributed to an alleviation of CO<sub>2</sub> limitation in species that partly rely on the diffusive supply of dissolved carbon dioxide for photosynthesis, as demonstrated by a rise in photosynthetic efficiency with increasing carbon dioxide in cultures of *E. huxleyi* (Rost *et al.*, 2003)."

Focusing more on the future, an independent team of seven scientists (Feng *et al.*, 2008) studied *Emiliania huxleyi* coccoliths that they isolated from the Sargasso Sea, and which they grew in semi-continuous culture media at low and high light intensities, low and high temperatures (20 and 24°C), and low and high CO<sub>2</sub> concentrations (375 and 750 ppm). This work revealed that in the low-light environment, the maximum photosynthetic rate was lowest in the low-temperature, low-CO<sub>2</sub> or ambient treatment, but was increased by 55% by elevated temperature alone and by 95% by elevated CO<sub>2</sub> alone, while in the high-temperature, high-CO<sub>2</sub> or greenhouse treatment it was increased by 150% relative to the ambient treatment. Likewise, in the high-light environment, there were maximum photosynthetic rate increases of 58%, 67% and 92% for the elevated temperature alone, elevated CO<sub>2</sub> alone and greenhouse treatments, respectively. Consequently, the researchers concluded, in their words, that "future trends of CO<sub>2</sub> enrichment, sea-surface warming and exposure to higher mean irradiances from intensified stratification will have a large influence on the growth of *Emiliania huxleyi*," and that large influence will be *positive*.

In addressing the impacts of ocean acidification on *fish*, Ishimatsu *et al.* (2005) noted that "fish are important members of both freshwater and marine ecosystems and constitute a major protein source in many countries." Hence, they wrote that the "potential reduction of fish resources by high-CO<sub>2</sub> conditions due to the diffusion of atmospheric CO<sub>2</sub> into the surface waters ... can be considered as another potential threat to the future world population." In response to this concern, therefore, Ishimatsu *et al.* conducted a survey of the scientific literature with respect to the potential negative consequences of atmospheric CO<sub>2</sub> enrichment on the health of fish that could arise from continued anthropogenic CO<sub>2</sub> emissions, finding a number of *possible* dire consequences.

Focusing on hypercapnia – a condition characterized by an excessive amount of CO<sub>2</sub> in the blood that typically results in acidosis, a serious and sometimes fatal condition characterized in humans by headache, nausea and visual disturbances – they say their survey revealed that "hypercapnia acutely affects vital physiological functions such as respiration, circulation, and metabolism, and changes in these functions are likely to reduce growth rate and population size through reproduction failure."

Although this conclusion sounds dire indeed, it represents an egregious flight of the imagination in terms of what could realistically be expected to happen *anytime* in earth's future. Ishimatsu *et al.* report, for example, that "predicted future CO<sub>2</sub> concentrations in the atmosphere are lower than the known lethal concentrations for fish," noting that "the expected peak value is about 1.4 torr [just under 1850 ppm] around the year 2300 according to Caldeira and Wickett (2003)." And with regard to just how far below the lethal CO<sub>2</sub> concentration for fish 1.4 torr is, in the case of *short-term* exposures on the order of a few days, they cite a number of studies that yield median lethal concentrations ranging from 37 to 50 torr, which values are 26 and 36 times *greater* than the *maximum* CO<sub>2</sub> concentration expected some *300 years from now*! And in the case of long-term exposures, to cite just a few examples, Ishimatsu *et al.* report that Fivelstad *et al.* (1999) observed only 5 and 8% mortality at the end of 62 days

*The scientific literature review of Ishimatsu et al. suggests that earth's fish, both freshwater and marine, will likely never experience any discomfort or ill effects from the direct consequences of the elevated atmospheric CO<sub>2</sub> concentrations caused by human activities.*

of exposure to CO<sub>2</sub> concentrations of 5 and 9 torr, respectively, for freshwater Atlantic salmon smolts, while mere 1 and 5% mortalities were found for seawater postsmolts of the same species at 12 and 20 torr after 43 days (Fivelstad *et al.*, 1998). In addition, they say that Smart *et al.* (1979) found little difference in mortality for freshwater rainbow trout reared for 275 days at 4 to 17 torr, and that no mortality occurred by the tenth week of exposure of juvenile spotted wolf fish to 20 torr (Foss *et al.*, 2003).

Fish embryos and larvae, however, are often more vulnerable to environmental stresses than are adult fish. Yet even here, the authors report that the 24-hour median lethal concentration of CO<sub>2</sub> on both eggs and larvae of several marine fish studied by Kikkawa *et al.* (2003) "ranged widely from 10 torr to 70 torr among species,"

with the *smaller* of these two values being *over seven times greater* than the CO<sub>2</sub> concentration expected 300 years from now. Lastly, Ishimatsu *et al.*'s review reveals growth reductions of 24 to 48%; but, again, the CO<sub>2</sub> concentrations needed to induce these growth reductions ranged from 17 to 20 torr, or 12 to 14 times more than the CO<sub>2</sub> concentration expected 300 years from now. Clearly, therefore, the scientific literature review of Ishimatsu *et al.* suggests that earth's fish, both freshwater and marine, will likely *never* experience any discomfort or ill effects from the direct consequences of the elevated atmospheric CO<sub>2</sub> concentrations caused by human activities.

Also examining the effects of rising CO<sub>2</sub> on juvenile fish were authors Munday *et al.* (2009). Working with a 70,000-liter recirculating sea water system at James Cook University's experimental marine aquarium facility, Munday *et al.* grew wild-caught pairs of the orange clownfish (*Amphiprion percula*) in 70-liter tanks containing sea water simulating a range of ocean acidification scenarios for the next 50-100 years -- 390 (current day), 550, 750 and 1030 ppm atmospheric CO<sub>2</sub> -- while documenting various aspects of egg, embryo and larval development.

According to the four researchers, all from the School of Marine and Tropical Biology of Australia's James Cook University, their experimental results indicated that "CO<sub>2</sub> acidification had no detectable effect on embryonic duration, egg survival and size at hatching." In fact, they say that it actually "tended to *increase* [italics added] the growth rate of larvae." Eleven days after hatching, for example, they observed that "larvae from some parental pairs were 15 to 18 per cent longer and 47 to 52 per cent heavier in acidified water compared to controls," further noting there was a "*positive* [italics added] relationship between length and swimming speed," and that "large size is usually considered to be advantageous for larvae and newly settled juveniles."

Given these findings, and in discussing current concerns over potential effects of the ongoing rise in the air's CO<sub>2</sub> content on marine fish, Munday *et al.* state that "the most common *prediction* [italics added] is that ocean acidification could [negatively] affect individual performance (e.g. development, growth, survival, swimming ability)," especially during the early life history of such fish. *However*, they indicate that "contrary to expectations," their results indicated that "CO<sub>2</sub>-induced acidification up to the maximum values likely to be experienced over the next 100 years had no noticeable effect on embryonic duration, egg survivorship and size at hatching for *A. percula*, and tended to have a positive effect on the length and weight of larvae."

In another study examining the effects of ocean acidification on fish, Melzner *et al.* (2009) write with respect to earth's 30,000 species of *teleost fish*, which include virtually all of the world's important sport and commercial fishes, that several of them have previously been shown to be able to "fully compensate extra cellular fluid pH," as well as "maintain oxygen consumption rates and growth performance under ocean acidification conditions (e.g. Larsen *et al.*, 1997; Foss *et al.*, 2003; Fivelstad *et al.*, 1998, 2003; Deigweiher *et al.*, 2008)," but they note that there have been no studies of these phenomena that have lasted for more than a few days. To rectify this situation, Melzner *et al.* maintained a group of Atlantic Cod (*Gadus morhua*) for four months in a re-circulating aquaculture system of 15 cubic meters volume at an atmospheric CO<sub>2</sub> partial pressure of 0.3 kPa (about 3,000 ppm) and another group for twelve months at a CO<sub>2</sub> partial pressure of 0.6 kPa (about 6,000 ppm), after which the fishes' swimming metabolism was investigated in a swim-tunnel respirometer, and tissue samples of their gills were taken for various chemical analyses, including gill Na<sup>+</sup>/K<sup>+</sup>-ATPase capacity, which serves "as a general indicator for ion regulatory effort."

At the conclusion of the study, the six German scientists reported that "motor activity in adult Atlantic Cod is not compromised by long-term exposure to water P<sub>CO2</sub> levels of 0.3-0.6 kPa," which are "scenarios exceeding the 0.2 kPa value predicted for surface ocean waters around

the year 2300 (Calderia and Wickett, 2003).” In light of what they learned from their study, therefore, Melzner *et al.* concluded that “adults of active fish species with a high ion regulatory capacity [which is employed to eliminate metabolic CO<sub>2</sub>] are well equipped to cope with prospected scenarios of global climate change,” even those far beyond what could likely be produced by the burning of all fossil fuels in the crust of the earth.

In a separate paper, Kurihara (2008) focused on "the effects of ocean acidification on early developmental and reproductive stages of calcifiers, both of which are believed to be the most vulnerable stages to environmental change within a life cycle." In doing so, he noted that certain laboratory experiments suggest that "ocean acidification has negative impacts on the fertilization, cleavage, larva, settlement and reproductive stages of several marine calcifiers, including echinoderm, bivalve, coral and crustacean species," and he concluded that "future changes in ocean acidity will potentially impact the population size and dynamics, as well as the community structure of calcifiers, and will therefore have negative impacts on marine ecosystems." *However*, most of the studies Kurihara cited did not observe statistically-significant negative effects of atmospheric CO<sub>2</sub> enrichment until very large increases in the air's CO<sub>2</sub> content were employed. In studies of sea urchins, for example, statistically-significant reductions in egg fertilization rates did not occur in *Echinometra mathaei* until the atmospheric CO<sub>2</sub> concentration was raised a full 5,000 ppm above that of the ambient air; and in *Hemicentrotus pulcherrimus*, even a 10,000 ppm increase in the air's CO<sub>2</sub> concentration was insufficient to elicit a statistically-significant decline in egg fertilization rate. In addition, Kurihara himself suggests that the great degree of scatter in the data may reflect "a degree of genetic variation for CO<sub>2</sub> tolerance within populations," which may allow the species to readily adapt to a long-term upward trend in the air's CO<sub>2</sub> content. And in the conclusion to his review, he acknowledges that "recent research has revealed that organisms could evolve within decades in response to strong pressures, which Stockwell *et al.* (2003) termed 'contemporary evolution'," citing the work of Collins and Bell (2004), to which can also be added the studies of Collins and Bell (2006) and Collins *et al.* (2006).

In another study, Gooding *et al.* (2009) measured growth rates and feeding rates of juvenile sea stars (*Pisaster ochraceus*) maintained in 246-liter aquaria that were filled with re-circulating natural sea water maintained at temperatures ranging from 5 to 21°C, and which were constantly bubbled with either ambient air of 380 ppm CO<sub>2</sub> or CO<sub>2</sub>-enriched air of 780 ppm CO<sub>2</sub>. This study indicated that “the relative growth (change in wet mass/initial wet mass) of juvenile *P. ochraceus* increased linearly with temperature from 5°C to 21°C,” and that it also responded positively to atmospheric CO<sub>2</sub> enrichment. More specifically, the authors found that “relative to control treatments, high CO<sub>2</sub> alone increased relative growth by about 67% over 10 weeks, while a 3°C increase in temperature alone increased relative growth by 110%.” They also state that increased CO<sub>2</sub> “had a positive but non-significant effect on sea star feeding rates, suggesting CO<sub>2</sub> may be acting directly at the physiological level to increase growth rates.” Last of all, their data show that the percentage of calcified mass in the sea stars dropped from approximately 12% to 11% in response to atmospheric CO<sub>2</sub> enrichment at 12°C, but that it did not decline further in response to a subsequent 3°C warming at either ambient or elevated CO<sub>2</sub>. Based on these findings, the three Canadian researchers write that “increased CO<sub>2</sub> will not have direct negative effects on all marine invertebrates, suggesting that predictions of biotic

responses to climate should consider how different types of organisms will respond to changing climatic variables."

Byrne *et al.* (2009) investigated the effects of ocean acidification state (pH values of 8.2-7.6, corresponding to atmospheric CO<sub>2</sub> concentrations of 230-690 ppm) and seawater temperature (20-26°C, where 20°C represents the recent thermal history of indigenous adults) on the fertilization of sea urchin (*Heliocidaris erythrogramma*) eggs and their subsequent development in what they call "the eastern Australia climate change hot spot," which is located near Sydney. Their results indicated that over the ranges of seawater pH and temperature they studied, there was "no effect of pH" and "no interaction between temperature and pH" on sea urchin egg fertilization. In addition, they report that "comparative data on the effect of increased CO<sub>2</sub> and decreased pH as a single stressor on sea urchin fertilization and development are available for five species," and that "these studies show that sea urchin fertilization and early development are only affected by pH < 7.4 (above 1000 ppm CO<sub>2</sub>)," citing the work of Bay *et al.* (1993), Kurihara and Shirayama (2004) and Carr *et al.* (2006).

Seawater pH also had no effect on the longer-term development of fertilized sea urchin eggs; but the six scientists say that warming led to "developmental failure at the upper warming (+4 to +6°C) level, regardless of pH." Even here, however, they appear quite hopeful, stating that "it is not known whether gametes from *H. erythrogramma* adults acclimated to 24°C would have successful development in a +4°C treatment," stating that their study "highlights the potentiality that adaptive phenotypic plasticity may help buffer the negative effects of warming, as suggested for corals." In fact, they note that "single stressor studies of thermotolerance in a diverse suite of tropical and temperate sea urchins show that fertilization and early development are robust to temperature well above ambient and the increases expected from climate change," citing the work of Farmanfarmaian and Giese (1963), Chen and Chen (1992) and Roller and Stickle (1993). Thus, all things considered, it would appear that sea urchins may be well equipped to deal with the challenges of projected ocean acidification and global warming, *and then some*, even if they were to occur simultaneously.

Citing a drop of 0.1 pH unit in the global ocean since the start of the Industrial Revolution, Richardson and Gibbons (2008) acknowledge that "such acidification of the ocean may make calcification more difficult for calcareous organisms," resulting in the "opening [of] ecological space for non-calcifying species." In line with this thinking, they report that Attrill *et al.* (2007) have argued that "jellyfish may take advantage of the vacant niches made available by the negative effects of acidification on calcifying plankton," causing jellyfish to become more abundant; and they note that the latter researchers provided some evidence for this effect in the west-central North Sea over the period 1971-1995. Hence, they undertook a study to see if Attrill *et al.*'s findings (which were claimed to be the first of their kind) could be replicated on a much larger scale.

Working with data from a larger portion of the North Sea, as well as throughout most of the much vaster Northeast Atlantic Ocean, Richardson and Gibbons used coelenterate (jellyfish) records from the Continuous Plankton Recorder (CPR) and pH data from the International Council for the Exploration of the Sea (ICES) for the period 1946-2003 to explore the possibility of a relationship between jellyfish abundance and acidic ocean conditions. This work revealed

that there were, as they describe it, "no significant relationships between jellyfish abundance and acidic conditions in any of the regions investigated." In harmony with their findings, the two researchers also note that "no observed declines in the abundance of calcifiers with lowering pH have yet been reported." In addition, they write that the "larvae of sea urchins form skeletal parts comprising magnesium-bearing calcite, which is 30 times more soluble than calcite without magnesium," and, therefore, that "lower ocean pH should drastically inhibit the formation of these soluble calcite precursors." Yet they report that "there is no observable negative effect of pH." In fact, they say that echinoderm larvae in the North Sea have actually exhibited "a 10-fold increase in recent times," which they say has been "linked predominantly to warming (Kirby *et al.*, 2007)." In light of this impressive body of real-world evidence, therefore, Richardson and Gibbons concluded that "the role of pH in structuring zooplankton communities in the North Sea and further afield at present is tenuous."

Gutowska *et al.* (2008) studied the cephalopod mollusk *Sepia officinalis* and found that it "is capable of not only maintaining calcification, but also growth rates and metabolism when exposed to elevated partial pressures of carbon dioxide." Over a six-week test period, for example, they found that "juvenile *S. officinalis* maintained calcification under 4000 and 6000 ppm CO<sub>2</sub>, and grew at the same rate with the same gross growth efficiency as did control animals," gaining approximately 4% body mass daily and increasing the mass of their calcified cuttlebone by over 500%. These findings thus led them to specifically conclude that "active cephalopods possess a certain level of pre-adaptation to long-term increments in carbon dioxide levels," and to generally conclude that our "understanding of the mechanistic processes that limit calcification must improve before we can begin to predict what effects future ocean acidification will have on calcifying marine invertebrates."

In another study, Berge *et al.* (2006) continuously supplied five 5-liter aquariums with low-food-content sea water that was extracted from the top meter of the Oslofjord outside the Marine Research Station Solbergstrand in Norway, while CO<sub>2</sub> was continuously added to the waters of the aquaria so as to maintain them at five different pH values (means of 8.1, 7.6, 7.4, 7.1 and 6.7) for a period of 44 days. Prior to the start of the study, blue mussels (*Mytilus edulis*) of two different size classes (mean lengths of either 11 or 21 mm) were collected from the outer part of the Oslofjord, and 50 of each size class were introduced into each aquarium, where they were examined close to daily for any deaths that may have occurred, after which shell lengths at either the time of death or at the end of the study were determined and compared to lengths measured at the start of the study. Simultaneously, water temperature rose slowly from 16 to 19°C during the initial 23 days of the experiment, but then declined slightly to day 31, after which it rose rapidly to attain a maximum value of 24°C on day 39.

A lack of mortality during the first 23 days of the study showed, in the words of the researchers, that "the increased concentration of CO<sub>2</sub> in the water and the correspondingly reduced pH had no acute effects on the mussels." Thereafter, however, some mortality was observed in the highest CO<sub>2</sub> (lowest pH) treatment from day 23 to day 37, after which deaths could also be observed in some of the other treatments, which mortality Berge *et al.* attributed to the rapid increase in water temperature that occurred between days 31 and 39.

With respect to growth, the Norwegian researchers report that "mean increments of shell length were much lower for the two largest CO<sub>2</sub> additions compared to the values in the controls, while for the two smallest doses the growth [was] about the same as in the control, or in one case even higher (small shells at pH = 7.6)," such that there were "no significant differences between the three aquaria within the pH range 7.4-8.1."

Berge *et al.* say their results suggest that "future reductions in pH caused by increased concentrations of anthropogenic CO<sub>2</sub> in the sea may have an impact on blue mussels," but that "comparison of estimates of future pH reduction in the sea (Caldeira and Wickett, 2003) and the observed threshold for negative effects on growth of blue mussels [which they determined to lie somewhere between a pH of 7.4 and 7.1] do however indicate that this will probably not happen in this century." Indeed, Caldeira and Wickett's calculation of the maximum level to which the air's CO<sub>2</sub> concentration might rise yields a value that approaches 2000 ppm around the year 2300, representing a surface oceanic pH reduction of 0.7 unit, which only drops the pH to the upper limit of the "threshold for negative effects on growth of blue mussels" found by Berge *et al.*, i.e., 7.4. Consequently, blue mussels will likely not be affected by the tendency for atmospheric CO<sub>2</sub> enrichment to lower oceanic pH values.

In another paper dealing with mussels, Tunnicliffe *et al.* (2009) discovered "dense clusters of the vent mussel *Bathymodiolus brevior* in natural conditions of pH values between 5.36 and 7.29 on the northwest Eifuku volcano, Mariana arc, where liquid carbon dioxide and hydrogen sulfide emerge in a hydrothermal setting," which they studied along with mussels from "two sites in the southwestern Pacific: Hine Hina in the Lau backarc basin and Monowai volcano on the Kermadec arc," where "the same mussel species nestles in cracks and rubble where weak fluid flow emerges." Accordingly, the authors identified four-decade-old mussels that had learned to cope with the extreme acidity of these hellish conditions, although their shell thickness and daily shell growth increments were "only about half those recorded from mussels living in water with pH > 7.8." Nevertheless, the mussels were alive and doing well in such conditions. And the six researchers note that the mussels were accompanied by "many other associated species," as reported in the study of Limen and Juniper (2006).

*There is ample reason to believe that even the worst case atmospheric CO<sub>2</sub>-induced acidification scenario that can possibly be conceived would not prove a major detriment to most calcifying sea life.*

These several findings, according to Tunnicliffe *et al.*, attest to "the extent to which long-term adaptation can develop tolerance to extreme conditions." And just how extreme were the conditions in which the mussels lived? Referring back to the study of Caldeira and Wickett (2003) who calculated a 0.7 unit pH decline from 8.1 to 7.4 by the year 2300, and considering the much *lower* pH range in which the mussels studied by Tunnicliffe *et al.* and the many species studied by Limen and Juniper were living (5.36 to 7.29), there is ample reason to believe

that even *the worst case atmospheric CO<sub>2</sub>-induced acidification scenario that can possibly be conceived* would not prove a major detriment to most calcifying sea life.

## CONCLUSION

In conclusion, based on the many *real-world observations* and *laboratory experiments* described above, it is clear that recent *theoretical claims* of impending marine species extinctions, due to increases in the atmosphere's CO<sub>2</sub> concentration, have no basis in empirical reality. In fact, these unsupportable contentions are typically *refuted* by demonstrable facts. As such, the NRDC's portrayal of CO<sub>2</sub>-induced ocean acidification as a *megadisaster-in-the-making* is seen, at best, to be a one-sided distortion of the truth or, at worst, a blatant attempt to deceive the public.

*The NRDC's portrayal of CO<sub>2</sub>-induced ocean acidification as a megadisaster-in-the-making is seen, at best, to be a one-sided distortion of the truth or, at worst, a blatant attempt to deceive the public.*

Surely, the NRDC and the scientists portrayed in their film should have been aware of at least *one* of the numerous peer-reviewed scientific journal articles that do not support a catastrophic – or even a problematic – view of the effect of ocean

acidification on calcifying marine organisms; and they should have shared that information with the public. If by some slim chance they were *not* aware, *shame on them* for not investing the time, energy, and resources needed to fully investigate an issue that has profound significance for the biosphere. And if they *did* know the results of the studies we have discussed, no one should ever believe a single word they may utter or write in the future.

Finally, if there is a lesson to be learned from the materials presented in this document, it is that far too many predictions of CO<sub>2</sub>-induced catastrophes are looked upon as sure-to-occur, when real-world observations show such doomsday scenarios to be highly unlikely or even virtual impossibilities. The phenomenon of CO<sub>2</sub>-induced ocean acidification is no different. Rising atmospheric CO<sub>2</sub> concentrations are not the *bane* of the biosphere; they are an invaluable *boon* to the planet's many life forms.

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## REFERENCES

- Al-Moghrabi, S., Goiran, C., Allemand, D., Speziale, N. and Jaubert, J. 1996. Inorganic carbon uptake for photosynthesis by the symbiotic coral-dinoflagellate association. 2. Mechanisms for bicarbonate uptake. *Journal of Experimental Marine Biology and Ecology* **199**: 227-248.
- Allemand, D., Tambutte, E., Girard, J.-P. and Jaubert, J. 1998. Organic matrix synthesis in the scleractinian coral *stylophora pistillata*: role in biomineralization and potential target of the organotin tributyltin. *Journal of Experimental Biology* **201**: 2001-2009.
- Atkinson, M.J., Carlson, B.A. and Crow, G.L. 1995. Coral growth in high-nutrient, low-pH seawater: A case study of corals cultured at the Waikiki Aquarium, Honolulu, Hawaii. *Coral Reefs* **14**: 215-223.
- Attrill, M.J., Wright, J. and Edwards, M. 2007. Climate-related increases in jellyfish frequency suggest a more gelatinous future for the North Sea. *Limnology and Oceanography* **52**: 480-485.
- Barnes, D.J. and Chalker, B.E. 1990. *Calcification and photosynthesis in reef-building corals and algae*. Dubinsky, Z, ed. Amsterdam, The Netherlands: Elsevier, 109-131.
- Battey, J.F. and Patton, J.S. 1984. A reevaluation of the role of glycerol in carbon translocation in zooxanthellae-coelenterate symbiosis. *Marine Biology* **79**: 27-38.
- Bay, S., Burgess, R. and Nacci, D. 1993. Status and applications of echinoid (phylum Echinodermata) toxicity test methods. In: Landis, W.B., Hughes, J.S. and Lewis, M.A., Eds. *Environmental Toxicology and Risk Assessment*. American Society of Testing and Materials, Philadelphia, Pennsylvania, USA, pp. 281-302.
- Beardall, J., Beer, S. and Raven, J.A. 1998. Biodiversity of marine plants in an era of climate change: Some predictions based on physiological performance. *Bot. Mar.* **41**: 113-123.
- Beer, S. and Rehnberg, J. 1997. The acquisition of inorganic carbon by the sea grass *Zostera marina*. *Aquatic Botany* **56**: 277-283.
- Berge, J.A., Bjerkeng, B., Pettersen, O., Schaanning, M.T. and Oxnevad, S. 2006. Effects of increased sea water concentrations of CO<sub>2</sub> on growth of the bivalve *Mytilus edulis* L. *Chemosphere* **62**: 681-687.
- Bernhard, J.M., Mollo-Christensen, E., Eisenkolb, N. and Starczak, V.R. 2009. Tolerance of allogromiid Foraminifera to severely elevated carbon dioxide concentrations: Implications to future ecosystem functioning and paleoceanographic interpretations. *Global and Planetary Change* **65**: 107-114.
- Bessat, F. and Buigues, D. 2001. Two centuries of variation in coral growth in a massive *Porites* colony from Moorea (French Polynesia): a response of ocean-atmosphere variability from south central Pacific. *Palaeogeography, Palaeoclimatology, Palaeoecology* **175**: 381-392.

- Bjork, M., Axelsson, L. and Beer, S. 2004. Why is *Ulva intestinalis* the only macroalga inhabiting isolated rockpools along the Swedish Atlantic coast? *Marine Ecology Progress Series* **284**: 109-116.
- Borowitzka, M.A. and Larkum, W.D. 1976. Calcification in the green alga *Halimeda*. III. The sources of inorganic carbon for photosynthesis and calcification and a model of the mechanisms of calcification. *Journal of Experimental Botany* **27**: 879-893.
- Brand, L.E. 1981. Genetic variability in reproduction rates in marine phytoplankton populations. *Evolution* **38**: 1117-1127.
- Brand, L.E. 1982. Genetic variability and spatial patterns of genetic differentiation in the reproductive rates of the marine coccolithophores *Emiliana huxleyi* and *Gephyrocapsa oceanica*. *Limnology and Oceanography* **27**: 236-245.
- Brand, L.E. 1984. The salinity tolerance of forty-six marine phytoplankton isolates. *Estuarine and Coastal Shelf Science* **18**: 543-556.
- Brussaard, C.P.D., Gast, G.J., van Duyl, F.C. and Riegman, R. 1996. Impact of phytoplankton bloom magnitude on a pelagic microbial food web. *Marine Ecology Progress Series* **144**: 211-221.
- Buddemeier, R.W., Kleypas, J.A. and Aronson, R.B. 2004. *Coral Reefs & Global Climate Change: Potential Contributions of Climate Change to Stresses on Coral Reef Ecosystems*. The Pew Center on Global Climate Change, Arlington, VA, USA.
- Burris, J.E., Porter, J.W. and Laing, W.A. 1983. Effects of carbon dioxide concentration on coral photosynthesis. *Marine Biology* **75**: 113-116.
- Byrne, M., Ho, M., Selvakumaraswamy, P., Nguyen, H.D., Dworjanyn, S.A. and Davis, A.R. 2009. Temperature, but not pH, compromises sea urchin fertilization and early development under near-future climate change scenarios. *Proceedings of the Royal Society B* **276**: 1883-1888.
- Caldeira, K. and Wickett, M.E. 2003. Anthropogenic carbon and ocean pH. *Nature* **425**: 365.
- Carlson, B.A. 1999. Organism responses to rapid change: What aquaria tell us about nature. *American Zoologist* **39**: 44-55.
- Carotenuto, Y., Putzeys, S., Simonelli, P., Paulino, A., Meyerhofer, M., Suffrian, K., Antia, A. and Nejstgaard, J.C. 2007. Copepod feeding and reproduction in relation to phytoplankton development during the PeECE III mesocosm experiment. *Biogeosciences Discussions* **4**: 3913-3936.

- Carr, R.S., Biedenbach, J.M. and Nipper, M. 2006. Influence of potentially confounding factors on sea urchin porewater toxicity tests. *Archives of Environmental Contamination and Toxicology* **51**: 573-579.
- Carricart-Ganivet, J.P. 2004. Sea surface temperature and the growth of the West Atlantic reef-building coral *Montastraea annularis*. *Journal of Experimental Marine Biology and Ecology* **302**: 249-260.
- Chalker, B.E. and Taylor, D.L. 1975. Light-enhanced calcification and the role of oxidative phosphorylation in calcification of the coral *Acropora cervicornis*. *Proceedings of the Royal Society of London B* **190**: 323-331.
- Chen, C.P. and Chen, B.Y. 1992. Effects of high temperature on larval development and metamorphosis of *Arachnoides placenta* (Echinodermata Echinoidea). *Marine Biology* **112**: 445-449.
- Chen, X. and Gao, K. 2004. Characterization of diurnal photosynthetic rhythms in the marine diatom *Skeletonema costatum* grown in synchronous culture under ambient and elevated CO<sub>2</sub>. *Functional Plant Biology* **31**: 399-404.
- Clausen, C.D. and Roth, A.A. 1975. Effect of temperature and temperature adaptation on calcification rate in the hermatypic *Pocillopora damicornis*. *Marine Biology* **33**: 93-100.
- Coles, S.L. and Jokiel, P.L. 1977. Effects of temperature on photosynthesis and respiration in hermatypic corals. *Marine Biology* **43**: 209-216.
- Collins, S. and Bell, G. 2004. Phenotypic consequences of 1,000 generations of selection at elevated CO<sub>2</sub> in a green alga. *Nature* **431**:566-569.
- Collins, S. and Bell, G. 2006. Evolution of natural algal populations at elevated CO<sub>2</sub>. *Ecology Letters* **9**: 129-135.
- Collins, S., Sultemeyer, D. and Bell, G. 2006. Changes in C uptake in populations of *Chlamydomonas reinhardtii* selected at high CO<sub>2</sub>. *Plant, Cell and Environment* **29**: 1812-1819.
- Conte, M., Thompson, A., Lesley, D. and Harris, R.P. 1998. Genetic and physiological influences on the alkenone/alkenonate versus growth temperature relationship in *Emiliana huxleyi* and *Gephyrocapsa oceanica*. *Geochimica et Cosmochimica Acta* **62**: 51-68.
- Crabbe, M.J.C., Wilson, M.E.J. and Smith, D.J. 2006. Quaternary corals from reefs in the Wakatobi Marine National Park, SE Sulawesi, Indonesia, show similar growth rates to modern corals from the same area. *Journal of Quaternary Science* **21**: 803-809.
- Crossland, C.J. and Barnes, D.J. 1974. The role of metabolic nitrogen in coral calcification. *Marine Biology* **28**: 325-332.

- Cuif, J.-P., Dauphin, Y., Freiwald, A., Gautret, P. and Zibrowius, H. 1999. Biochemical markers of zooxanthellae symbiosis in soluble matrices of skeleton of 24 *Scleractinia* species. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology* **123**: 269-278.
- De'ath, G., Lough, J.M. and Fabricius, K.E. 2009. Declining coral calcification on the Great Barrier Reef. *Science* **323**: 116-119.
- Deigweiher, K., Koschnick, N., Portner, H.O. and Lucassen, M. 2008. Acclimation of ion regulatory capacities in gills of marine fish under environmental hypercapnia. *American Journal of Physiology-Regulatory Integrative and Comparative Physiology* **295**: R1660-R1670.
- Egge, J., Thingstad, F., Engel, A., Bellerby, R.G.J. and Riebesell, U. 2007. Primary production at elevated nutrient and pCO<sub>2</sub> levels. *Biogeosciences Discussions* **4**: 4385-4410.
- Engel, A. 2002. Direct relationship between CO<sub>2</sub> uptake and transparent exopolymer particles production in natural phytoplankton. *Journal of Plankton Research* **24**: 49-53.
- Falkowski, P.G., Barber, R. and Smetacek, V. 1998. Biogeochemical controls and feedbacks on ocean primary production. *Science* **281**: 200-206.
- Farmanfarmaian, A. and Giese, A.C. 1963. Thermal tolerance and acclimation in the western purple sea urchin, *Strongylocentrotus purpuratus*. *Physiol. Zool.* **36**: 237-343.
- Feng, Y., Warner, M.E., Zhang, Y., Sun, J., Fu, F.-X., Rose, J.M. and Hutchins, A. 2008. Interactive effects of increased pCO<sub>2</sub>, temperature and irradiance on the marine coccolithophore *Emiliana huxleyi* (Prymnesiophyceae). *European Journal of Phycology* **43**: 87-98.
- Fivelstad, S., Haavik, H., Lovik, G. and Olsen, A.B. 1998. Sublethal effects and safe levels of carbon dioxide in seawater for Atlantic salmon postsmolts (*Salmo salar* L.): Ion regulation and growth. *Aquaculture* **160**: 305-316.
- Fivelstad, S., Olsen, A.B., Asgard, T., Baeverfjord, G., Rasmussen, T., Vindhelm, T. and Stefansson, S. 2003. Long-term sublethal effects of carbon dioxide on Atlantic salmon smolts (*Salmo salar* L.): ion regulation, haematology, element composition, nephrocalcinosis and growth parameters. *Aquaculture* **215**: 301-319.
- Fivelstad, S., Olsen, A.B., Kloften, H., Ski, H. and Stefansson, S. 1999. Effects of carbon dioxide on Atlantic salmon (*Salmo salar* L.) smolts at constant pH in bicarbonate rich freshwater. *Aquaculture* **178**: 171-187.
- Foss, A., Rosnes, B.A. and Oiestad, V. 2003. Graded environmental hypercapnia in juvenile spotted wolffish (*Anarhichas minor* Olafsen): Effects on growth, food conversion efficiency and nephrocalcinosis. *Aquaculture* **220**: 607-617.

Frankignoulle, M., Gattuso, J.-P., Biondo, R., Bourge, I., Copin-Montegut, G. and Pichon, M. 1996. Carbon fluxes in coral reefs. II. Eulerian study of inorganic carbon dynamics and measurement of air-sea CO<sub>2</sub> exchanges. *Marine Ecology Progress Series* **145**: 123-132.

Fu, F.-X., Mulholland, M.R., Garcia, N.S., Beck, A., Bernhardt, P.W., Warner, M.E., Sanudo-Wilhelmy, S.A. and Hutchins, D.A. 2008. Interactions between changing pCO<sub>2</sub>, N<sub>2</sub> fixation, and Fe limitation in the marine unicellular cyanobacterium *Crocosphaera*. *Limnology and Oceanography* **53**: 2472-2484.

Gao, K., Aruga, Y., Asada, K., Ishihara, T., Akano, T. and Kiyohara, M. 1993. Calcification in the articulated coralline alga *Corallina pilulifera*, with special reference to the effect of elevated CO<sub>2</sub> concentration. *Marine Biology* **117**: 129-132.

Gao, K., Aruga, Y., Asada, K. and Kiyohara, M. 1993. Influence of enhanced CO<sub>2</sub> on growth and photosynthesis of the red algae *Gracilaria* sp. and *G chilensis*. *Journal of Applied Phycology* **5**: 563-571.

Gattuso, J.-P., Allemand, D. and Frankignoulle, M. 1999. Photosynthesis and calcification at cellular, organismal and community levels in coral reefs: A review on interactions and control by carbonate chemistry. *American Zoologist* **39**: 160-183.

Gattuso, J.-P., Pichon, M., Delesalle, B., Canon, C. and Frankignoulle, M. 1996. Carbon fluxes in coral reefs. I. Lagrangian measurement of community metabolism and resulting air-sea CO<sub>2</sub> disequilibrium. *Marine Ecology Progress Series* **145**: 109-121.

Gautret, P., Cuif, J.-P. and Freiwald, A. 1997. Composition of soluble mineralizing matrices in zooxanthellate and non-zooxanthellate scleractinian corals: Biochemical assessment of photosynthetic metabolism through the study of a skeletal feature. *Facies* **36**: 189-194.

Gnaiger, E., Gluth, G. and Weiser, W. 1978. pH fluctuations in an intertidal beach in Bermuda. *Limnology and Oceanography* **23**: 851-857.

Goiran, C., Al-Moghrabi, S., Allemand, D. and Jaubert, J. 1996. Inorganic carbon uptake for photosynthesis by the symbiotic coral/dinoflagellate association. 1. Photosynthetic performances of symbionts and dependence on sea water bicarbonate. *Journal of Experimental Marine Biology and Ecology* **199**: 207-225.

Gooding, R.A., Harley, C.D.G. and Tang, E. 2009. Elevated water temperature and carbon dioxide concentration increase the growth of a keystone echinoderm. *Proceedings of the National Academy of Sciences, USA*: 10.1073/pnas.0811143106.

Goreau, T.F. 1959. The physiology of skeleton formation in corals. I. A method for measuring the rate of calcium deposition by corals under different conditions. *Biological Bulletin* **116**: 59-75.

- Grigg, R.W. 1981. Coral reef development at high latitudes in Hawaii. In: *Proceedings of the Fourth International Coral Reef Symposium*, Manila, Vol. 1: 687-693.
- Grigg, R.W. 1997. Paleooceanography of coral reefs in the Hawaiian-Emperor Chain - revisited. *Coral Reefs* **16**: S33-S38.
- Gutowska, M.A., Pörtner, H.O. and Melzner, F. 2008. Growth and calcification in the cephalopod *Sepia officinalis* under elevated seawater pCO<sub>2</sub>. *Marine Ecology Progress Series* **373**: 303-309.
- Halloran, P.R., Hall, I.R., Colmenero-Hidalgo, E. and Rickaby, R.E.M. 2008. Evidence for a multi-species coccolith volume change over the past two centuries: understanding a potential ocean acidification response. *Biogeosciences* **5**: 1651-1655.
- Hansen, P.J. 2002. The effect of high pH on the growth and survival of marine phytoplankton: implications for species succession. *Aquatic Microbiology and Ecology* **28**: 279-288.
- Heemann, C. 2002. *Phytoplanktonexsudation in Abhängigkeit der Meerwasserkarbonatchemie*. Diplom. Thesis, ICBM, University of Oldenburg, Germany.
- Herfort, L., Thake, B. and Roberts, J. 2002. Acquisition and use of bicarbonate by *Emiliana huxleyi*. *New Phytologist* **156**: 427-36.
- Herfort, L., Thake, B. and Taubner, I. 2008. Bicarbonate stimulation of calcification and photosynthesis in two hermatypic corals. *Journal of Phycology* **44**: 91-98.
- Hoegh-Guldberg, O. 1999. Climate change, coral bleaching and the future of the world's coral reefs. *Marine and Freshwater Research* **50**: 839-866.
- Holland, H.D. 1984. *The chemical evolution of the atmosphere and oceans*. Princeton, NJ: Princeton University Press.
- Hutchins, D.A., Fu, F.-X., Zhang, Y., Warner, M.E., Feng, Y., Portune, K., Bernhardt, P.W. and Mulholland, M.R. 2007. CO<sub>2</sub> control of *Trichodesmium* N<sub>2</sub> fixation, photosynthesis, growth rates, and elemental ratios: Implications for past, present, and future ocean biogeochemistry. *Limnology and Oceanography* **52**: 1293-1304.
- Idso, K.E. 1992. Plant responses to rising levels of atmospheric carbon dioxide: A compilation and analysis of the results of a decade of international research into the direct biological effects of atmospheric CO<sub>2</sub> enrichment. Tempe, AZ: Office of Climatology, Arizona State University.
- Idso, K.E. and Idso, S.B. 1994. Plant responses to atmospheric CO<sub>2</sub> enrichment in the face of environmental constraints: A review of the past 10 years' research. *Agricultural and Forest Meteorology* **69**: 153-203.

- Iglesias-Rodriguez, M.D., Halloran, P.R., Rickaby, R.E.M., Hall, I.R., Colmenero-Hidalgo, E., Gittins, J.R., Green, D.R.H., Tyrrell, T., Gibbs, S.J., von Dassow, P., Rehm, E., Armbrust, E.V. and Boessenkool, K.P. 2008. Phytoplankton calcification in a high-CO<sub>2</sub> world. *Science* **320**: 336-340.
- Ishimatsu, A., Hayashi, M., Lee, K.-S., Kikkawa, T. and Kita, J. 2005. Physiological effects of fishes in a high-CO<sub>2</sub> world. *Journal of Geophysical Research* **110**: 10.1029/2004JC002564.
- Kajiwara, K., Nagai, A. and Ueno, S. 1995. Examination of the effect of temperature, light intensity and zooxanthellae concentration on calcification and photosynthesis of scleractinian coral *Acropora pulchra*. *J. School Mar. Sci. Technol.* **40**: 95-103.
- Kawaguti, S. and Sakumoto, D. 1948. The effects of light on the calcium deposition of corals. *Bulletin of the Oceanographic Institute of Taiwan* **4**: 65-70.
- Kikkawa, T., Ishimatsu, A. and Kita, J. 2003. Acute CO<sub>2</sub> tolerance during the early developmental stages of four marine teleosts. *Environmental Toxicology* **18**: 375-382.
- Kimball, B.A. 1983. Carbon dioxide and agricultural yield: An assemblage and analysis of 430 prior observations. *Agronomy Journal* **75**: 779-788.
- Kirby, R.R., Beaugrand, G., Lindley, J.A., Richardson, A.J., Edwards, M. and Reid, P.C. 2007. Climate effects and benthic-pelagic coupling in the North Sea. *Marine Ecology Progress Series* **330**: 31-38.
- Kleypas, J.A., Buddemeier, R.W., Archer, D., Gattuso, J.-P., Langdon, C. and Opdyke, B.N. 1999. Geochemical consequences of increased atmospheric carbon dioxide on coral reefs. *Science* **284**: 118-120.
- Kranz, S.A., Sultemeyer, D., Richter, K.-U. and Rost, B. 2009. Carbon acquisition by *Trichodesmium*: The effect of pCO<sub>2</sub> and diurnal changes. *Limnology and Oceanography* **54**: 548-559.
- Kurihara, H. 2008. Effects of CO<sub>2</sub>-driven ocean acidification on the early developmental stages of invertebrates. *Marine Ecology Progress Series* **373**: 275-284.
- Kurihara, H., Ishimatsu, A. and Shirayama, Y. 2007. Effects of elevated seawater CO<sub>2</sub> concentration of the meiofauna. *Journal of Marine Science and Technology* **15**: 17-22.
- Kurihara, H. and Shirayama, Y. 2004. Effects of increased atmospheric CO<sub>2</sub> on sea urchin early development. *Marine Ecology Progress Series* **274**: 161-169.
- Langdon, C., Takahashi, T., Sweeney, C., Chipman, D., Goddard, J., Marubini, F., Aceves, H., Barnett, H. and Atkinson, M.J. 2000. Effect of calcium carbonate saturation state on the calcification rate of an experimental coral reef. *Global Biogeochemical Cycles* **14**: 639-654.

- Langer, G. and Geisen, M., Baumann, K.-H., Klas, J., Riebesell, U., Thoms, S. and Young, J.R. 2006. Species-specific responses of calcifying algae to changing seawater carbonate chemistry. *Geochemistry, Geophysics, Geosystems* **7**: 10.1029/2005GC001227.
- Larsen, B.K., Portner, H.O. and Jensen, F.B. 1997. Extra- and intracellular acid-base balance and ionic regulation in cod (*Gadus morhua*) during combined and isolated exposures to hypercapnia and copper. *Marine Biology* **128**: 337-346.
- Larsen, J.B., Larsen, A., Thyraug, R., Bratbak, G. and Sandaa R.-A. 2007. Marine viral populations detected during a nutrient induced phytoplankton bloom at elevated pCO<sub>2</sub> levels. *Biogeosciences Discussions* **4**: 3961-3985.
- Levitan, O., Rosenberg, G., Setlik, I., Setlikova, E., Grigel, J., Klepetar, J., Prasil, O. and Berman-Frank, I. 2007. Elevated CO<sub>2</sub> enhances nitrogen fixation and growth in the marine cyanobacterium *Trichodesmium*. *Global Change Biology* **13**: 531-538.
- Limen, H. and Juniper, S.K. 2006. Habitat controls on vent food webs at NW Eifuku Volcano, Mariana Arc. *Cahiers de Biologie Marine* **47**: 449-455.
- Lindholm, T. and Nummelin, C. 1999. Red tide of the dinoflagellate *Heterocapsa triquetra* (Dinophyta) in a ferry-mixed coastal inlet. *Hydrobiologia* **393**: 245-251.
- Liu, Y., Liu, W., Peng, Z., Xiao, Y., Wei, G., Sun, W., He, J. Liu, G. and Chou, C.-L. 2009. Instability of seawater pH in the South China Sea during the mid-late Holocene: Evidence from boron isotopic composition of corals. *Geochimica et Cosmochimica Acta* **73**: 1264-1272.
- Loaiciga, H.A. 2006. Modern-age buildup of CO<sub>2</sub> and its effects on seawater acidity and salinity. *Geophysical Research Letters* **33**: 10.1029/2006GL026305.
- Lough, J.M. 2008. Coral calcification from skeletal records revisited. *Marine Ecology Progress Series* **373**: 257-264.
- Lough, J.M. and Barnes, D.J. 1997. Several centuries of variation in skeletal extension, density and calcification in massive *Porites* colonies from the Great Barrier Reef: A proxy for seawater temperature and a background of variability against which to identify unnatural change. *Journal of Experimental and Marine Biology and Ecology* **211**: 29-67.
- Lough, J.B. and Barnes, D.J. 2000. Environmental controls on growth of the massive coral *Porites*. *Journal of Experimental Marine Biology and Ecology* **245**: 225-243.
- Macedo, M.F., Duarte, P., Mendes, P. and Ferreira, G. 2001. Annual variation of environmental variables, phytoplankton species composition and photosynthetic parameters in a coastal lagoon. *Journal of Plankton Research* **23**: 719-732.
- Mahaffey, C., Michaels, A.F. and Capone, D.G. 2005. The conundrum of marine N<sub>2</sub> fixation. *American Journal of Science* **305**: 546-595.

- Marubini, F. and Thake, B. 1998. Coral calcification and photosynthesis: evidence for carbon limitation. In: *International Society for Reef Studies (ISRS), European Meeting*, Perpignan, September 1-4, 1998, p. 119.
- McNeil, B.I., Matear, R.J. and Barnes, D.J. 2004. Coral reef calcification and climate change: The effect of ocean warming. *Geophysical Research Letters* **31**: 10.1029/2004GL021541.
- Medlin, L.K., Barker, G.L.A., Green, J.C., Hayes, D.E., Marie, D., Wreiden, S. and Vaultot, D. 1996. Genetic characterization of *Emiliana huxleyi* (Haptophyta). *Journal of Marine Systems* **9**: 13-32.
- Melzner, F., Gobel, S., Langenbuch, M., Gutowska, M.A., Portner, H.-O. and Lucassen, M. 2009. Swimming performance in Atlantic Cod (*Gadus morhua*) following long-term (4-12 months) acclimation to elevated seawater  $P_{CO_2}$ . *Aquatic Toxicology* **92**: 30-37.
- Menendez, M., Martinez, M. and Comin, F.A. 2001. A comparative study of the effect of pH and inorganic carbon resources on the photosynthesis of three floating macroalgae species of a Mediterranean coastal lagoon. *Journal of Experimental Marine Biology and Ecology* **256**: 123-136.
- Mercado, J.M., Niell, F.X. and Gil-Rodriguez, M.C. 2001. Photosynthesis might be limited by light, not inorganic carbon availability, in three intertidal Gelidiales species. *New Phytologist* **149**: 431-439.
- Mercado, J.M., Niell, F.X., Silva, J. and Santos, R. 2003. Use of light and inorganic carbon acquisition by two morphotypes of *Zostera noltii* Hornem. *Journal of Experimental Marine Biology and Ecology* **297**: 71-84.
- Middelboe, A.L. and Hansen, P.J. 2007. High pH in shallow-water macroalgal habitats. *Marine Ecology Progress Series* **338**: 107-117.
- Montoya, J.P., Holl, C.M., Zehr, J.P., Hansen, A., Villareal, T.A. and Capone, D.G. 2004. High rates of  $N_2$  fixation by unicellular diazotrophs in the oligotrophic Pacific Ocean. *Nature* **430**: 1027-1031.
- Munday, P.L., Donelson, J.M., Dixon, D.L. and Endo, G.G.K. 2009. Effects of ocean acidification on the early life history of a tropical marine fish. *Proceedings of the Royal Society B* **276**: 3275-3283.
- Muscantine, L. 1967. Glycerol excretion by symbiotic algae from corals and *Tridacna* and its control by the host. *Science* **156**: 516-519.
- Muscantine, L. 1990. The role of symbiotic algae in carbon and energy flux in reef corals. *Coral Reefs* **25**: 1-29.

- Muscatine, L., Goiran, C., Land, L., Jaubert, J., Cuif, J.-P. and Allemand, D. 2005. Stable isotopes ( $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ ) of organic matrix from coral skeleton. *Proceedings of the National Academy of Sciences USA* **102**: 1525-1530.
- Nie, B., Chen, T., Liang, M., Wang, Y., Zhong, J. and Zhu, Y. 1997. Relationship between coral growth rate and sea surface temperature in the northern part of South China Sea. *Sci. China Ser. D* **40**: 173-182.
- Nimer, N.A. and Merrett, M.J. 1993. Calcification rate in *Emiliana huxleyi* Lohmann in response to light, nitrate and availability of inorganic carbon. *New Phytologist* **123**: 673-677.
- Paasche, E. 2002. A review of the coccolithophorid *Emiliana huxleyi* (Prymnesiophyceae), with particular reference to growth, coccolith formation, and calcification-photosynthesis interactions. *Phycologia* **40**: 503-529.
- Paulino, A.I., Egge, J.K. and Larsen, A. 2007. Effects of increased atmospheric  $\text{CO}_2$  on small and intermediate sized osmotrophs during a nutrient induced phytoplankton bloom. *Biogeosciences Discussions* **4**: 4173-4195.
- Pearson, G.A., Serrao, E.A. and Brawley, S.H. 1998. Control of gamete release in fucoid algae: sensing hydrodynamic conditions via carbon acquisition. *Ecology* **79**: 1725-1739.
- Pelejero, C., Calvo, E., McCulloch, M.T., Marshall, J.F., Gagan, M.K., Lough, J.M. and Opdyke, B.N. 2005. Preindustrial to modern interdecadal variability in coral reef pH. *Science* **309**: 2204-2207.
- Ramos, J.B.E., Biswas, H., Schulz, K.G., Laroche, J. and Riebesell, U. 2007. Effect of rising atmospheric carbon dioxide on the marine nitrogen fixer *Trichodesmium*. *Global Biogeochemical Cycles* **21**: 10.1029/2006GB002898.
- Rands, M.L., Douglas, A.E., Loughman, B.C. and Ratcliffe, R.G. 1992. Avoidance of hypoxia in a cnidarian symbiosis by algal photosynthetic oxygen. *Biological Bulletin* **182**: 159-162.
- Raven, J.A. 1991. Physiology of inorganic C acquisition and implications for resource use efficiency by marine phytoplankton: Relation to increased  $\text{CO}_2$  and temperature. *Plant, Cell and Environment* **14**: 779-794.
- Raven, J.A. 1997. Inorganic carbon acquisition by marine autotrophs. *Advances in Botanical Research* **27**: 85-209.
- Raven, J.A., Osborne, B.A. and Johnston, A.M. 1985. Uptake of  $\text{CO}_2$  by aquatic vegetation. *Plant, Cell and Environment* **8**: 417-425.
- Reynaud, S., Ferrier-Pages, C., Boisson, F., Allemand, D. and Fairbanks, R.G. 2004. Effect of light and temperature on calcification and strontium uptake in the scleractinian coral *Acropora verweyi*. *Marine Ecology Progress Series* **279**: 105-112.

- Reynaud, S., Ferrier-Pages, C., Meibom, A., Mostefaoui, S., Mortlock, R., Fairbanks, R. and Allemand, D. 2007. Light and temperature effects on Sr/Ca and Mg/Ca ratios in the scleractinian coral *Acropora* sp. *Geochimica et Cosmochimica Acta* **71**: 354-362.
- Reynaud-Vaganay, S., Gattuso, J.P., Cuif, J.P., Jaubert, J. and Juillet-Leclerc, A. 1999. A novel culture technique for scleractinian corals: Application to investigate changes in skeletal  $\delta^{18}\text{O}$  as a function of temperature. *Marine Ecology Progress Series* **180**: 121-130.
- Riding, R. 1996. Long-term change in marine  $\text{CaCO}_3$  precipitation. *Mem. Soc. Geol. Fr.* **169**: 157-166.
- Riebesell, U. 2004. Effects of  $\text{CO}_2$  enrichment on marine phytoplankton. *Journal of Oceanography* **60**: 719-729.
- Riebesell, U., Bellerby, R.G.J., Grossart, H.-P. and Thingstad, F. 2008. Mesocosm  $\text{CO}_2$  perturbation studies: from organism to community level. *Biogeosciences Discussions* **5**: 641-659.
- Riebesell, U., Schulz, K., Bellerby, R., Botros, M., Fritsche, P., Meyerhofer, M., Neill, C., Nondal, G., Oschlies, A., Wohlers, J. and Zollner, E. 2007. Enhanced biological carbon consumption in a high  $\text{CO}_2$  ocean. *Nature* **450**: 10.1038/nature06267.
- Riebesell, U., Wolf-Gladrow, D.A. and Smetacek, V. 1993. Carbon dioxide limitation of marine phytoplankton growth rates. *Nature* **361**: 249-251.
- Richardson, A.J. and Gibbons, M.J. 2008. Are jellyfish increasing in response to ocean acidification? *Limnology and Oceanography* **53**: 2040-2045.
- Rinkevich, B. and Loya, Y. 1984. Does light enhance calcification in hermatypic corals? *Marine Biology* **80**: 1-6.
- Roller, R.A. and Stickle, W.B. 1993. Effects of temperature and salinity acclimations of adults on larval survival, physiology, and early development of *Lytechinus variegatus* (Echinodermata: Echinoidea). *Marine Biology* **116**: 583-591.
- Rost, B., Riebesell, U., Burkhart, S. and Sultemeyer, D. 2003. Carbon acquisition of bloom-forming marine phytoplankton. *Limnology and Oceanography* **48**: 55-67.
- Santhanam, R., Srinivasan, A., Ramadhas, V. and Devaraj, M. 1994. Impact of *Trichodesmium* bloom on the plankton and productivity in the Tuticorin bay, southeast coast of India. *Indian Journal of Marine Science* **23**: 27-30.
- Schlesinger, W.H. 2005. *Biogeochemistry*. Elsevier, Amsterdam.

- Scoffin, T.P., Tudhope, A.W., Brown, B.E., Chansang, H. and Cheeney, R.F. 1992. Patterns and possible environmental controls of skeletogenesis of *Porites lutea*, South Thailand. *Coral Reefs* **11**: 1-11.
- Semesi, I.S., Beer, S. and Bjork, M. 2009. Seagrass photosynthesis controls rates of calcification and photosynthesis of calcareous macroalgae in a tropical seagrass meadow. *Marine Ecology Progress Series* **382**: 41-47.
- Simkiss, K. 1964. Phosphates as crystal poisons of calcification. *Biological Review* **39**: 487-505.
- Smart, G.R., Knox, D., Harrison, J.G., Ralph, J.A., Richards, R.H. and Cowey, C.B. 1979. Nephrocalcinosis in rainbow trout *Salmo gairdneri* Richardson: The effect of exposure to elevated CO<sub>2</sub> concentrations. *Journal of Fish Diseases* **2**: 279-289.
- Sobrino, C., Ward, M.L. and Neale, P.J. 2008. Acclimation to elevated carbon dioxide and ultraviolet radiation in the diatom *Thalassiosira pseudonana*: Effects on growth, photosynthesis, and spectral sensitivity of photoinhibition. *Limnology and Oceanography* **53**: 494-505.
- Stockwell, C.A., Hendry, A.P. and Kinnison, M.T. 2003. Contemporary evolution meets conservation biology. *Trends in Ecology and Evolution* **18**: 94-101.
- Stolte, W., Kraay, G.W., Noordeloos, A.A.M. and Riegman, R. 2000. Genetic and physiological variation in pigment composition of *Emiliania huxleyi* (Prymnesiophyceae) and the potential use of its pigment ratios as a quantitative physiological marker. *Journal of Phycology* **96**: 529-589.
- Suffrian, K., Simonelli, P., Nejstgaard, J.C., Putzeys, S., Carotenuto, Y. and Antia, A.N. 2008. Microzooplankton grazing and phytoplankton growth in marine mesocosms with increased CO<sub>2</sub> levels. *Biogeosciences Discussions* **5**: 411-433.
- Tunncliffe, V., Davies, K.T.A., Butterfield, D.A., Embley, R.W., Rose, J.M. and Chadwick Jr., W.W. 2009. Survival of mussels in extremely acidic waters on a submarine volcano. *Nature Geoscience* 10.1038/NGEO500.
- Vogt, M., Steinke, M., Turner, S., Paulino, A., Meyerhofer, M., Riebesell, U., LeQuere, C. and Liss, P. 2008. Dynamics of dimethylsulphoniopropionate and dimethylsulphide under different CO<sub>2</sub> concentrations during a mesocosm experiment. *Biogeosciences* **5**: 407-419.
- Wainwright, S.A. 1963. Skeletal organization in the coral *Pocillopora damicornis*. *Quarterly Journal of Microscopic Science* **104**: 164-183.
- Wei, G., McCulloch, M.T., Mortimer, G., Deng, W. and Xie, L. 2009. Evidence for ocean acidification in the Great Barrier Reef of Australia. *Geochimica et Cosmochimica Acta* **73**: 2332-2346.

Weis, V.M. 1993. Effect of dissolved inorganic carbon concentration on the photosynthesis of the symbiotic sea anemone *Aiptasia pulchella* Carlgren: role of carbonic anhydrase. *Journal of Experimental Marine Biology and Ecology* **174**: 209-225.

Wu, H.-Y., Zou, D.-H. and Gao, K.-S. 2008. Impacts of increased atmospheric CO<sub>2</sub> concentration on photosynthesis and growth of micro- and macro-algae. *Science in China Series C: Life Sciences* **51**: 1-7.

Yamashiro, H. 1995. The effects of HEBP, an inhibitor of mineral deposition, upon photosynthesis and calcification in the scleractinian coral, *Stylophora pistillata*. *Journal of Experimental Marine Biology and Ecology* **191**: 57-63.

Yonge, C.M. 1968. Living corals. *Proceedings of the Royal Society of London B* **169**: 329-344.

Zimmerman, R.C., Kohrs, D.G., Steller, D.L. and Alberte, R.S. 1997. Impacts of CO<sub>2</sub> enrichment on productivity and light requirements of eelgrass. *Plant Physiology* **115**: 599-607.

Zou, D.H., Gao, K.S. and Xia, J.R. 2003. Photosynthetic utilization of inorganic carbon in the economic brown alga, *Hizikia fusiforme* (Sargassaceae) from the South China Sea. *Journal of Phycology* **39**: 1095-1100.

**Source:** [http://scienceandpublicpolicy.org/originals/acid\\_test.html](http://scienceandpublicpolicy.org/originals/acid_test.html).



## APPENDIX # 1 – NRDC FILM TEXT

### ACID TEST: THE GLOBAL CHALLENGE OF OCEAN ACIDIFICATION

NRDC's film Acid Test, featuring Sigourney Weaver, is now available online in its entirety.  
A Natural Resources Defense Council Production – Narrated by *Sigourney Weaver*.

**Source:** <http://www.nrdc.org/oceans/acidification/aboutthefilm.asp>.

### INTRODUCTION

**NARRATOR:**

*The ocean keeps secrets. Hidden beneath its waves are worlds within worlds. Over billions of years, the ocean has created endless varieties of life. Life that enchants us, that sustains us. And despite our science, life that mystifies us still.*

**STEVE PALUMBI:** (Ph.D., Stanford University)

*The oceans are an incredible place, full of the most amazing kinds of life. Life that you can never imagine really working. Things that if somebody just thought of them and showed them to you, you'd think 'That's ridiculous, nothing like that could ever live' – but it does.*

**BRUCE STEELE:** (Commercial Fisherman)

*In 35 years of diving, it's quite a picture. I've spent my life on the bottom of the ocean with black sea bass. I've seen white sharks underwater. I've been in schools of bait that would be so big that they will dark out the sun. I can only hope that the ocean maintains that vitality. It's an incredible place of mystery and it's something that's beautiful beyond description.*

**LISA SUATONI:** (Ph.D., Natural Resources Defense Council)

*People rely on the oceans in so many ways. Some ways are obvious, like food, recreation, transportation.*

**STEVE PALUMBI:**

*They clean our shores, they protect our coastlines from storms.*

**LISA SUATONI:**

*The oceans regulate climate and provide the world with most of its oxygen.*

**NARRATOR:**

*But we are now certain of one awesome fact. The oceans power to create life is rivaled by our own power to destroy it.*

## ACID TEST: THE GLOBAL CHALLENGE OF OCEAN ACIDIFICATION

**NARRATOR:**

Scientists refer to ocean acidification as the 'other carbon problem.' The first, of course, is global warming.

**LISA SUATONI:**

*People have heard about global warming for years, but it is only over the past five years that experts really understood that the carbon dioxide is causing a problem for the oceans as well. And what's worrisome, is that it hasn't even been on our radar.*

**NARRATOR:**

*Carbon dioxide pollution is transforming the chemistry of the ocean, rapidly making the water more acidic. In decades, rising ocean acidity may challenge life on a scale that has not occurred for tens of millions of years. So we confront an urgent choice, to move beyond fossil fuels, or to risk turning the ocean into a sea of weeds.*

**KEN CALDEIRA:** (Ph.D., Carnegie Institution)

*When we burn coal, oil or gas, we introduce carbon dioxide into the atmosphere. But the atmosphere touches the ocean over 70% of earth's surface. So, this carbon dioxide we're putting into the atmosphere, we are also putting into the ocean.*

**NARRATOR:**

*Carbon dioxide, or CO<sub>2</sub>, exists naturally in our atmosphere. Plants need it to grow, animals exhale it in every breath. But carbon dioxide is also a by-product of burning fossil fuels, and in large amounts, it is a dangerous pollutant. Since the industrial revolution, the ocean has absorbed roughly one quarter of the carbon dioxide produced by burning fuels. Scientists once thought this beneficial, after all, that carbon dioxide would otherwise accelerate global warming. But what happens when so much carbon dioxide, 22 million tons of it each day, mixes with ocean water? In terms of chemistry, the answer is simple: it becomes an acid.*

**LISA SUATONI:**

*Since the industrial revolution, the ocean acidity has increased by 30%. With mathematical models, scientists have demonstrated that if we continue to pollute as we are now, the ocean acidity will double by the end of the century, compared to pre-industrial times. That is a big problem.*

**NARRATOR:**

*Scientists only recently stopped to think about what this would mean for life in the ocean. Thousands of ocean species build protective shells to survive. Some are so prolific, they can be seen from space. These organisms create their shells, which can be paper-thin, by drawing certain molecules from the water around them. But rising acidity depletes those molecules.*

**KEN CALDEIRA:**

*So, by removing the essential building block for shell formation, it's making the organisms work a lot harder to build their shells, and that means they have less energy to get food. They have less energy to reproduce and eventually the organism can no longer compete ecologically. The surprise is how sensitive some marine organisms are to this increased acidity from carbon dioxide.*

**NARRATOR:**

*And when acidity gets too high, shells dissolve. [Graphic "Shell in polar water conditions predicted for 2100.]*

**STEVE PALUMBI:**

*We're changing the basic rules of everything, and because of that, a lot of organisms may not be able to survive.*

**KEN CALDEIRA:**

*Already, we've seen water showing up off the coast of northern California that's acidic enough to start actually dissolving sea shells. It's thought that this kind of corrosive water showing up will become more and more common.*

**BRUCE STEELE:**

*Most of the west coast and North America's shellfish - that's Dungeness crabs, lobsters, mussels, oysters, sea urchins, shrimp - all those life forms are at risk.*

**KEN CALDEIRA:**

*By mid-century, if we continue emitting carbon dioxide the way we have been, entire vast areas of both the southern ocean and the arctic ocean will be so corrosive that it will cause sea shells to dissolve.*

**NARRATOR:**

*Scientific models show that in just a few decades, we will profoundly alter the oceans chemistry. [Graphic: Ocean Corrosiveness to Aragonite. Red=Dissolving point. Year 2000-2100.] Such conditions haven't existed since the extinction of the dinosaurs. Recreating those conditions so quickly could leave many ocean animals unable to adapt. What if shellfish could no longer build shells? Would they cease to exist? Perhaps. Shelled creatures such as corals and plankton play a key role in the ocean food web. Teripods are a kind of plankton that live all around the world, and in great abundance in polar waters. Teripods are especially vulnerable.*

**VICTORIA FABRY:** (Ph.D., California State University San Marcos)

*We're looking at teripod shells, which are planktonic snails with a calcium carbonate shell, that we collected from Antarctica this past winter. And you can see, it looks like there is this lip, where it may have already started to dissolve and kind of curled over, cuz that's what it looks like when it dissolves, it kind of melts, almost like a candle and wax melting. The shell thickness along the leading edge right here is less than one micrometer thick. These are the thinnest teripod shells I've ever seen.*

**NARRATOR:**

*There's growing alarm that higher acidity will extinguish creatures like teripods, that are a basic food source for fish. In many parts of the world, fish are a basic food source for people.*

**STEVE PALUMBI:**

*So, you can't just worry about the big things in the ocean. You have to worry about what they eat and where their food comes from. If the smallest things in the ocean are affected by ocean acidification, then it ripples all the way up the food web, making the largest things in the ocean even more in danger.*

**NARRATOR:**

*As individual strands disappear, the entire food web becomes weaker, more vulnerable, less beneficial to humankind.*

**OVE HOEGH-GULDBERG:** (Ph.D., University of Queensland)

*And many of us are concerned about what that means for the earth's marine ecosystems, but also for the many millions of people that depend on these systems for their food and income.*

**NARRATOR:**

*Ocean acidity will rise most quickly in cold water regions, and areas where deep water wells up to the surface.*

**LISA SUATONI:**

*That is disconcerting because it coincides with the regions of the most productive fisheries in the world.*

**BRUCE STEELE:**

*I'm a fisherman. Every single day I have to make a prediction - where I'm going to go fishing, whether I'm going to find fish where I go. And every single day the decisions I make, make the difference between whether I stay a fisherman and make a profit. I can make predictions. I think these things are dire problems. Either we change what we're doing on land, or it will have profound effects on fisheries as we know it.*

**NARRATOR:**

*Marine life that might withstand warming temperatures, or rising acidity, may succumb when confronted by both. [Graphic: 2003 reef collapse from heat wave, Phoenix Islands.] Coral reefs already struggle to survive in warming waters. Rising ocean acidity puts them in double jeopardy.*

**OVE HOEGH-GULDBERG:**

*We know that coral reefs are particularly sensitive to ocean acidification. And the reason for that is that corals are unable to form their skeletons as quickly as they used to, and reefs are starting to crumble and disappear. We may lose those ecosystems within 20 or 30 years. And in those structures live an estimated million species. One in every four species in the ocean lives on a coral reef. We've got the last decade in which we can do something about this problem. But*

*it is very, very clear that if we don't start to deal with it right now, with very, very stern cuts to emissions, we are going to condemn oceans to an extremely uncertain future.*

**KEN CALDEIRA:**

*We're really in the last decades of coral reefs on this planet for at least the next, let's say million plus years, unless we do something very soon to reduce CO2 emissions. We're moving from a world of rich biological diversity into essentially a world of weeds.*

**STEVE PALUMBI:**

*Today we're in a really remarkable history of the ocean. A hundred years ago it was inexhaustible - we couldn't touch it, you couldn't harm it. In a hundred years, it might be dead.*

**KEN CALDEIRA:**

*When people say it was high CO2 a hundred million years ago, so we have nothing to worry about, that high CO2 was achieved over a slow process of millions of years. And if we achieve high CO2 over millions of years, the earth will be able to handle it. If we achieve high CO2 over decades, the ocean is in big trouble.*

**NARRATOR:**

*Earth is the only planet we know of where life exists. To understand our own actions, we sometimes need to view them in a larger context. Planet earth was formed four and a half billion years ago. Three and a half billion years ago, life began. Two hundred and fifty million years ago, dinosaurs appeared. And two hundred thousand years ago, homo sapiens. Within that framework, human civilization is brand new. Our industrial society, but an instant. Yet in that instant, we have altered the course of nature. We have heated the earth's surface, acidified it's oceans, and consumed much of its natural habitat. Now, something extraordinary looms. A mass extinction of animals and plants, caused not by volcanic eruption, or the collision of a meteor, but by the actions of one species - ours.*

**KEN CALDEIRA:**

*If we destroy these ecosystems it will take millions of years for them to recover. It's as if somebody, just because they had the ability to do it, decided to run through the metropolitan museum with a knife, slashing the great paintings of the world.*

**NARRATOR:**

*We have created this problem. We should be able to solve it. The ocean, after all, is resilient. Given the chance, and enough time, it can heal itself. So how can we give the ocean that chance? Marine protected areas, like national parks in the sea, shelter ocean life from industry and development. Sustainable fishing practices allow fish stocks to regenerate. The ocean can better defend itself against rising acidity and temperature if its systems are healthy.*

**LISA SUATONI:**

*To make the oceans more resilient to these changes, we need to do a better job of keeping the oceans healthy. That means restoring depleted fish populations. Establishing marine protected areas all around the globe. And reducing pollution, particularly nutrient pollution in the costal zones.*

**STEVE PALUMBI:**

*Solving those local problems gives those ecosystems a chance to survive, a chance to make it through while we solve the global problem. We know how to solve the local problems in marine ecosystem health. We know how to solve the global problem. The question is - will we?*

**NARRATOR:**

*The only way to stop acidification is to emit less carbon dioxide. Our industrial revolution began more than two centuries ago. Technology's advanced rapidly since then. But we still make energy as we have for hundreds of thousands of years - by setting things on fire. Often, we squander the energy we make, using more than necessary to accomplish our goals. But now we know how to use energy more efficiently. How to do more with less.*

**RALPH CAVANAGH:** (Co-Director, Energy Program, Natural Resources Defense Council)

*There was a time when people thought about energy efficiency and conservation as sacrifice, doing without, dark homes, shuttered economies. That is emphatically not what we're talking about. We're talking about getting dramatically more work out of less energy with better technology. Those energy efficiency solutions are particularly promising because the whole world will want to adopt them. If we take that initial step, we will also - in addition to reduction carbon pollution - have the very welcome dividend, in the form of economic stimulus because we'll be reducing energy bills.*

**NARRATOR:**

*We know how to capture energy cleanly from sunlight, wind, tides, and the heat of the earth's core.*

**RALPH CAVANAGH:**

*Imagine that you're living in a house that gets some of its electricity from its own solar panels, feeds some of that back into your own vehicle when it's plugged in at night, provides you with energy services, and maybe this is the most important single piece of it - at costs below those you're paying now. That double dividend was never more needed by the US and world economy as it is right now.*

**NARRATOR:**

*We are on the verge of a green industrial revolution. A revolution that will expand our economy, protect our resources, and give us real energy independence. There is much we don't know about how carbon pollution will affect our world. Still, we have to choose. We can go on as we have, forcing future generations to survive somehow without the vast ocean resources that have sustained us. Or, we can move beyond fossil fuels, securing a future that works for all of us - for all living things. What will we choose?*

*[It Can Be Done. [www.acidtestmovie.com](http://www.acidtestmovie.com).]*

*[Out-takes shown below on right half of screen, with credits rolling on left half of screen.]*

**KEN CALDEIRA:**

*You're not going to use this, but I'll just say it though. What makes a Greek tragedy a tragedy is that you can see it coming. Oedipus you know goes and marries his mother, and eventually tears his eyes out and you want to tell him - look, no, don't marry your mother, you can stop this, process now...*

**STEVE PALUMBI:**

*And you think if I could only go back and change that one little tiny instant, then things would have been different. I think we're in that instant right now.*

**KEN CALDEIRA:**

*We sit, feeling almost helpless, because we see this unraveling, leading to its tragic end.*

**LISA SUATONI:**

*Researchers are predicting significant and substantial changes in the next two decades, to our oceans. So it is not necessarily a problem we're passing off to future generations. It's a problem that we're generating for ourselves.*

**OVE HOEGH-GULDBERG:**

*I think that what gets me up in the morning is that I don't want to see coral reefs disappear on my watch. And I know that my fellow scientists feel this way as well. So, we feel compelled to communicate the message that this is a serious issue and that changes that haven't happened for millions of years are starting to happen right before our eyes. I think it's important to point out that it's not all over yet.*

**BRUCE STEELE:**

*I don't expect people to understand what teripods are, or what various forms of plankton are likely to survive or not survive, but I do expect our policy makers to take serious an issue that is so closely tied to life on this planet and the future of life on this planet. I have hope. You can't fish and not have hope.*

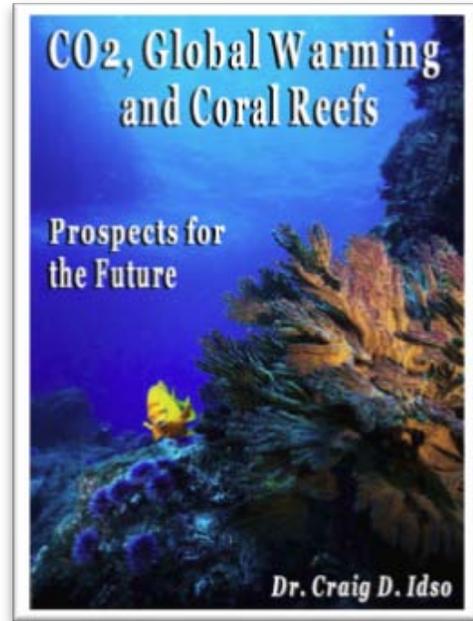
*[A Natural Resources Defense Council production - Made possible by a grant from the Entertainment Industry Foundation.]*

## APPENDIX # 2 – SPPI ADDITIONAL RESOURCES FOR THIS ISSUE

### BOOK – CO<sub>2</sub>, GLOBAL WARMING AND CORAL REEFS: PROSPECTS FOR THE FUTURE.

#### SUMMARY FOR POLICY MAKERS

One of the long-recognized potential consequences of the ongoing rise in the air's CO<sub>2</sub> content is CO<sub>2</sub>-induced global warming, which has been predicted to pose a number of problems for both natural and managed ecosystems in the years ahead. Of newer concern, in this regard, are the effects that the ongoing rise in the air's CO<sub>2</sub> content may have on coral reefs. It has been suggested, for example, that CO<sub>2</sub>-induced global warming will do great damage to corals by magnifying the intensity, frequency, and duration of a number of environmental stresses to which they are exposed. The predicted consequences of such phenomena include ever more cases of coral disease, bleaching, and death.



Increases in the atmosphere's CO<sub>2</sub> content have also been postulated to possess the potential to harm coral reefs *directly*. By inducing changes in ocean water chemistry that can lead to reductions in the calcium carbonate saturation state of seawater, it has been predicted that elevated levels of atmospheric CO<sub>2</sub> may reduce rates of coral calcification, possibly leading to slower-growing – and, therefore, weaker – coral skeletons, and in some cases, death.

Because of these many concerns, and the logical desire of individuals and governments to do something about what they perceive to be bona fide threats to the well-being of the biosphere, it is important to have a correct understanding of the scientific basis for the potential problems that have been predicted. Hence, in the following pages we review the scientific literature on CO<sub>2</sub>, global warming and coral reefs, in an effort to determine if the ongoing rise in the air's CO<sub>2</sub> content does indeed pose a threat to these incomparable underwater ecosystems. The key findings of this review are as follows:

- There is no simple linkage between high temperatures and coral bleaching.
- As living entities, corals are not only acted upon by the various elements of their environment, they also *react* or *respond* to them. And when changes in environmental factors pose a challenge to their continued existence, they sometimes take major defensive or adaptive actions to insure their survival.
- A particularly ingenious way by which almost any adaptive response to any type of environmental stress may be enhanced in the face of the occurrence of that stress would be to replace the zooxanthellae expelled by the coral host during a stress-induced

bleaching episode by one or more varieties of zooxanthellae that are more tolerant of the stress that caused the bleaching.

- The persistence of coral reefs through geologic time – when temperatures were as much as 10-15°C warmer than at present, and atmospheric CO<sub>2</sub> concentrations were 2 to 7 times higher than they are currently – provides substantive evidence that these marine entities can successfully adapt to a dramatically changing global environment. Thus, the recent die-off of many corals cannot be due solely, or even mostly, to global warming or the modest rise in atmospheric CO<sub>2</sub> concentration over the course of the Industrial Revolution.
- The 18- to 59-cm warming-induced sea level rise that is predicted for the coming century by the IPCC – which could be greatly exaggerated if predictions of CO<sub>2</sub>-induced global warming are wrong – falls well within the range (2 to 6 mm per year) of typical coral vertical extension rates, which exhibited a modal value of 7 to 8 mm per year during the Holocene and can be more than double that value in certain branching corals. Rising sea levels should therefore present no difficulties for coral reefs. In fact, rising sea levels may actually have a *positive* effect on reefs, permitting increased coral growth in areas that have already reached the upward limit imposed by current sea levels.
- The rising CO<sub>2</sub> content of the atmosphere may induce changes in ocean chemistry (pH) that could slightly reduce coral calcification rates; but potential positive effects of hydrospheric CO<sub>2</sub> enrichment may more than compensate for this modest negative phenomenon.
- Theoretical predictions indicate that coral calcification rates should decline as a result of increasing atmospheric CO<sub>2</sub> concentrations by as much as 40% by 2100. However, real-world observations indicate that elevated CO<sub>2</sub> and elevated temperatures are having just the *opposite* effect.

In light of the above observations, and in conjunction with all of the material presented in this review, it is clear that climate-alarmist claims of impending marine species extinctions due to increases in both temperature and atmospheric CO<sub>2</sub> concentration are not only *not supported* by real-world evidence, they are actually *refuted* by it.

### WHERE TO FIND THIS BOOK

**SPPI HOME PAGE:**

[http://scienceandpublicpolicy.org/originals/co2\\_coral\\_warming.html](http://scienceandpublicpolicy.org/originals/co2_coral_warming.html).

**AMAZON.COM:**

[http://www.amazon.com/CO2-Global-Warming-Coral-Reefs/dp/0971484589/ref=sr\\_1\\_2?ie=UTF8&s=books&qid=1262712271&sr=1-2](http://www.amazon.com/CO2-Global-Warming-Coral-Reefs/dp/0971484589/ref=sr_1_2?ie=UTF8&s=books&qid=1262712271&sr=1-2).

## EPA FILING: EFFECTS OF OCEAN ACIDIFICATION ON MARINE ECOSYSTEMS

**Source:** [http://scienceandpublicpolicy.org/originals/effects\\_of\\_ocean\\_acidification\\_on\\_marine\\_ecosystems.html](http://scienceandpublicpolicy.org/originals/effects_of_ocean_acidification_on_marine_ecosystems.html).

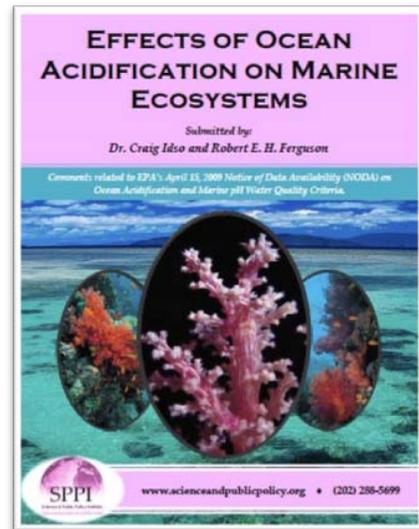
Comments related to EPA's April 15, 2009 Notice of Data Availability (NODA) on Ocean Acidification and Marine pH Water Quality Criteria. Submitted by Craig Idso and Robert Ferguson.

### SUMMARY

The EPA's Notice of Data Availability (NODA), Docket ID No. EPA-HQ-OW-2009 0224, solicited public comment on available scientific information pertaining to the effects of ocean acidification on marine ecosystems. This document, submitted as a public comment, reviews numerous peer-reviewed research papers that have investigated the phenomenon of ocean acidification. The key findings are as follows:

- There is nothing unnatural or unprecedented about current measurements of ocean water pH. Model-derived estimates of a CO<sub>2</sub>-induced 0.1 pH unit decline since the start of the Industrial Revolution cannot be validated in the historical record.
- Coral calcification is a biologically-driven process that will likely overcome physical-chemical limitations, which in the absence of life would not be possible.
- Observational data overwhelmingly demonstrate that rates of coral calcification have *increased* over the past century and beyond as temperatures and atmospheric CO<sub>2</sub> concentrations have risen.
- Potential future declines in oceanic pH will likely not prove to be a major detriment to corals and other sea life. For many such organisms, the future rise in *p*CO<sub>2</sub> will yield growth *benefits*.

Such findings contrast with statements made by the EPA in the NODA (see Part II. Background on Ocean Acidification), which consider the impact of ocean acidification on marine organisms to largely be negative.

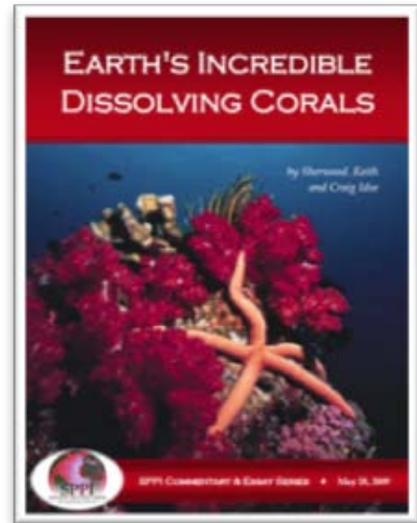


## EARTH'S INCREDIBLE DISSOLVING CORALS

**Source:** [http://scienceandpublicpolicy.org/commentaries\\_essays/earth\\_s\\_incredible\\_dissolving\\_corals.html](http://scienceandpublicpolicy.org/commentaries_essays/earth_s_incredible_dissolving_corals.html).

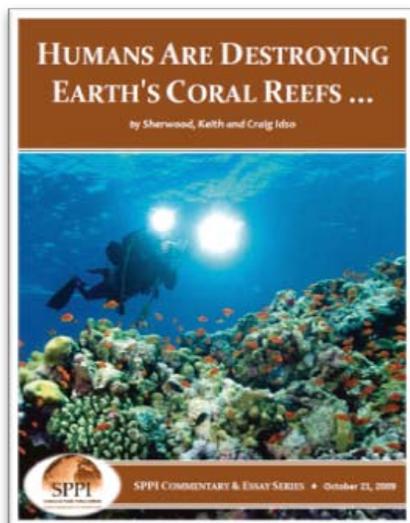
In a paper recently published in Geophysical Research Letters, Silverman et al. (2009) created a model of coral calcification based on field observations of gross community calcification as a function of aragonite saturation state ( $\Omega_{arag}$ ), sea surface temperature (SST) and live coral cover, after which they calculated calcification rates for more than 9,000 reef locations using model values of  $\Omega_{arag}$  and SST at different atmospheric CO<sub>2</sub> concentrations, which exercise led them to conclude that "by the time atmospheric partial pressure of CO<sub>2</sub> will reach 560 ppm, all coral reefs will cease to grow and start to dissolve."

*What's wrong with this picture?*



## HUMANS ARE DESTROYING EARTH'S CORAL REEFS ...

**Source:** [http://scienceandpublicpolicy.org/originals/acid\\_test.html](http://scienceandpublicpolicy.org/originals/acid_test.html).



Is it really the case that the burning of fossil fuels is responsible for the dire straits in which the world's coral reefs currently find themselves? If not, what then are the *real* threats to reefs?