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*Photo: Dave Burdick*

# ACID TEST:

CAN WE SAVE OUR OCEANS FROM CO<sub>2</sub>?

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# Acknowledgements

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## EXECUTIVE SUMMARY

### Introduction

Climate change is now widely recognized as the most significant environmental challenge of our time. This does not just mean that the environment or 'nature' is in danger. We too will suffer the consequences. We are inherently inseparable from the environment around us and are reliant upon the services it provides, from the air we breathe and the climates we inhabit, to the fertilized crops we consume. We are exquisitely adapted to the Earth as we know it. Unfortunately, our activities are now altering the balance of gases in the atmosphere—the very gases that help regulate the temperature and climate.

Our ever-growing greenhouse gas emissions, predominantly carbon dioxide, are trapping more heat in the atmosphere, causing the temperature of the Earth's surface to rise. The result? Melting ice caps, sea level rise, hotter average temperatures, shifting wildlife populations, changing disease patterns, and more severe droughts and storms.

The disrupted climate system will dramatically change the way people live on this planet. We can expect to see more heat-related sickness and death, and food supplies and food prices disrupted by more severe droughts. There will likely be widespread hunger in some countries and perhaps even famine. Rising sea levels will flood huge swaths of coastline. Within the coming centuries some of the world's largest and most important cities—including New York City, Bangkok and London—will be at risk of flooding and even total immersion. Entire countries such as Bangladesh and most small island nations will lose significant land area forcing millions of climate refugees to flee the rising seas.

*"Not only are the oceans warming and rising, but they are also becoming more acidic."*

Along with a disrupted climate system, our emissions of carbon dioxide are having a severe, but more insidious, impact on the oceans. The oceans absorb roughly 30 percent of global carbon emissions and 80 percent of the heat generated by increased levels of greenhouse gases, thereby mitigating some of the climate change that would otherwise occur.<sup>1,2</sup> However, this relief comes at a great cost. Not only are the oceans warming and rising, but they are also becoming more acidic.

The increasing amount of carbon dioxide in the oceans results in reactions that are changing the chemistry of the oceans, through a process known as ocean acidification. This threatens marine organisms like hard corals, clams and crabs that create calcium carbonate shells and skeletons. The acid created by excess carbon dioxide in the oceans takes the materials these organisms would otherwise use to create shells and skeletons, and makes it unavailable. This makes it increasingly difficult for corals and other marine animals to strengthen existing structures and build new ones. If ocean acidification continues, the very water that these organisms live in could become so corrosive that it would dissolve their shells and skeletons directly.

While the chemical processes making the oceans more acidic are well understood and accepted, we are just beginning to understand the wide-ranging effects acidification is likely to have on marine wildlife. Increased acidity may not directly kill non-calcifying organisms, but many are likely to be harmed in ways that reduce their overall fitness and ability to survive. These impacts could include decreased growth rate, reduced reproduction, disrupted respiratory and nervous system function and increased susceptibility to predators and disease, all of which could produce ripple effects through food webs and ecosystems. Ultimately, ocean acidification could transform the oceans, leaving them far less diverse and productive and making the lives and livelihoods of those who depend on them far more uncertain.

According to Stanford University oceanographer Ken Caldeira and his colleagues:

*"[The] chemical effects of CO<sub>2</sub> on the marine environment may be as great a cause for concern as the radiative effects of CO<sub>2</sub> on Earth's climate."<sup>3</sup>*



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*"The longer we wait to act the more difficult averting catastrophe becomes"*

## Reaching the Limits

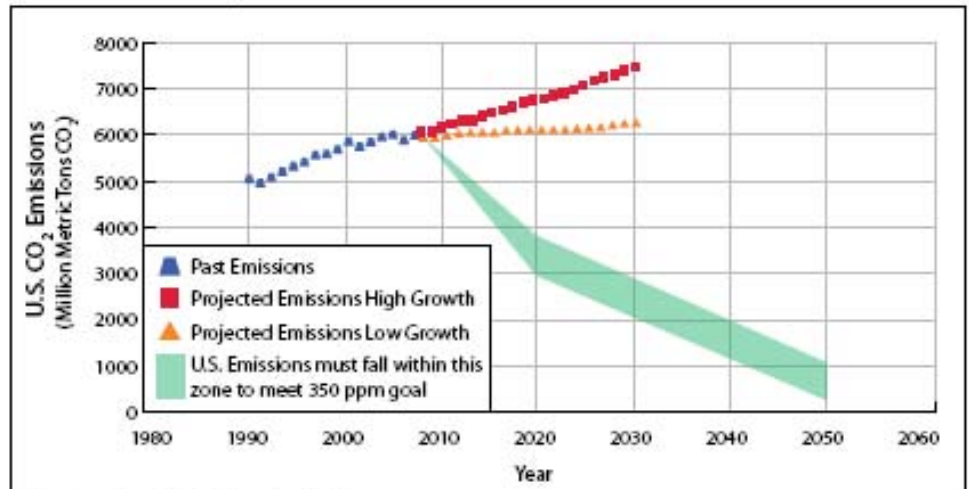
Current atmospheric carbon dioxide concentrations are already above safe levels. As a result, significant changes are already taking place throughout the oceans, from decreasing growth rates of corals on the Great Barrier Reef to massive coral bleaching events across the tropics. Coral reefs provide important habitat to a quarter of all marine species and are critical to the lives and livelihoods of many humans. Allowing coral reefs to disappear would result in intolerable changes throughout the oceans and to the lives of hundreds of millions of humans. What happens to coral reefs will foreshadow other catastrophic changes that are likely to take place around the world due to ocean acidification and climate change.

To prevent the loss of coral reefs, and ultimately avert a climate crisis, we must reduce atmospheric carbon dioxide levels below 350 parts per million (ppm).<sup>4</sup> Unfortunately, carbon dioxide in the atmosphere has already reached 385 part per million and is still climbing.<sup>5</sup> This current level is also much higher than it has been at any time over the course of human civilization.<sup>6</sup>

In today's society carbon dioxide emissions are directly tied to our continually growing need for energy. Recent figures released by the U.S. Energy and Information Administration (EIA) suggest that staying on the current business-as-usual (BAU) path, where current laws and policies remain unchanged, will result in world energy consumption in 2030 that is 50 percent above 2005 levels.<sup>7</sup> This would result in an atmospheric carbon dioxide concentration of over 570 ppm.<sup>8</sup>

If we continue along our current emissions path reefs will continue to degrade and could be pushed passed a tipping point, which is likely to occur at an atmospheric carbon dioxide level of around 450 ppm. At this point, reefs as we know them would be threatened with extinction. Once we surpass this tipping point coral reefs will shrink rapidly,<sup>9</sup> at least half of coral-associated wildlife will become rare or extinct. Shortly after that, coral reef ecosystems will likely be reduced to crumbling frameworks with few calcareous corals remaining.<sup>10</sup> Since coral reefs take

## Projected U.S. CO<sub>2</sub> Emissions vs. Emissions Trajectory for 350 ppm



Source: Oceana, based on EIA (2008) and IPCC (2007)

decades or even centuries to form, once such damage is done, the impacts will be irreversible for generations.

To save coral reefs from ocean acidification, we must stabilize atmospheric carbon dioxide at or below a concentration of 350 ppm. By doing so, we will also prevent other climate-related catastrophes. Current atmospheric carbon dioxide levels already exceed this amount, and with a projected increase over the coming decades it is vital to get on the right trajectory within the next few years and to make sure that carbon emissions peak and begin to decline within a decade.

The Intergovernmental Panel on Climate Change (IPCC) concluded that in order to stabilize carbon dioxide in the atmosphere at 350 ppm, global carbon dioxide emissions would need to be cut 85 percent below 2000 levels by 2050,<sup>11</sup> and in order to achieve this Annex I countries (industrialized countries and countries with economies in transition, such as the Russian Federation) would need to reduce their carbon emissions by 25 to 40 percent below 1990 levels by 2020 and 80 to 95 percent by 2050. Because these are not easy goals to achieve, countries and the international community must take action now to meet them. Our ability to set and meet short-term goals over the coming years will determine how successful we will be at safely stabilizing the climate. The longer we wait to act the more difficult averting catastrophe becomes.





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## Findings

This report highlights the following recent findings demonstrating that ocean acidification is already occurring and threatening the oceans. It also identifies the likely consequences of continued carbon dioxide emissions for oceans and marine ecosystems.

- Carbon dioxide in the atmosphere is higher than it has been for 800,000 years and probably for much longer.<sup>12</sup>
- The acidity of the ocean surface has increased 30 percent since before the Industrial Revolution.<sup>13</sup> If current trends continue, it could rise by another 100 percent by the end of this century<sup>14</sup>, exceeding the levels of the past 20 million years.<sup>15</sup>
- The increased amount of carbon dioxide the oceans are absorbing alters the movement of nutrients and chemicals in the oceans and has wide-ranging effects on ecosystems and marine life.<sup>16</sup>
- The higher acidity will also affect growth, reproduction, disease resistance and other biological and physiological processes in many species.<sup>21</sup>
- Many species will be unable to adapt to the rapid changes in ocean acidity and carbonate concentrations, especially those that build calcium carbonate shells and skeletons. This may lead to population crashes in many species, including oysters, mussels, crabs and lobsters.<sup>17, 18, 19, 20</sup>
- Impacts on carbonate-dependent species like corals and pteropods could cause major ripple effects throughout ecosystems and food webs ultimately affecting even the largest animals in the oceans, as well as many commercial fisheries.<sup>22</sup>
- Nearly 30 percent of the world's tropical corals have vanished since 1980, mainly due to warming events. At the current rate of emission growth, tropical corals could be gone by the middle to the end of this century.<sup>23, 24</sup>
- If current emission trends continue, cold-water corals will be severely stressed by 2040, and two-thirds of them could be in a corrosive environment by the century's end.<sup>25</sup>
- The disappearance of coral reefs would cost society billions of dollars annually due to losses in fishing, tourism and coastal protection services.<sup>26</sup>
- Over 100 million people depend on coral reefs economically,<sup>27</sup> and subsistence communities may experience health consequences and lack of food security due to the loss of protein associated with coral reefs.<sup>28</sup>
- Many commercial fisheries depend on reefs which provide food and shelter for fish.<sup>29, 30</sup> The loss of reefs may further destabilize already depressed commercial fish populations.
- To protect coral reefs and the ecosystems that depend on them, we must stabilize carbon dioxide in the atmosphere at or below 350 ppm. To achieve this, global emissions must be reduced to 85 percent below 2000 levels by 2050, which will require industrialized nations to reduce their emissions 25 to 40 percent below 1990 levels by 2020 and 80 to 95 percent by 2050.<sup>31, 32, 33</sup>



## Solutions

A variety of solutions will be needed to reduce levels of carbon dioxide in the atmosphere to 350 ppm. These include: (1) a shift away from our carbon-based energy economy, which can be done by building an infrastructure for energy alternatives such as solar, wind and hydrogen, and scaling back the use of coal unless carbon capture is effectively employed; (2) increasing energy efficiency in cars, trucks, trains, planes and ships, as well as in homes, office buildings, power generation and the industrial sector; and (3) reducing deforestation while also planting more forest land to help “draw down” carbon dioxide levels. If we want to save our coral reefs and shellfish fisheries, the ecosystems that depend on them and the values that we derive from them, we need to start now. With a 25-to-40 percent reduction needed by the industrialized countries of the world by 2020, there is no time to waste.

## Recommendations

### *Adopt a Policy of Stabilizing Atmospheric Carbon Dioxide at 350 ppm*

Governments must commit to stabilizing the levels of carbon dioxide in the atmosphere at 350 ppm or below. To achieve this, serious strides need to be taken within the next five years to set society on a path to zero net carbon emissions within the coming decades.

### *Promote Energy Efficiency and Low Carbon Fuels*

Energy should be conserved at every opportunity, including through improved fuel efficiency of cars, trucks, airplanes and ships, provision of cleaner fuels, investment in efficient mass transit, and individual, institutional and corporate actions to reduce energy use.

### *Shift to Alternative Energy Sources*

New or expanded coal-fired power plants and other expanded uses of coal should be prohibited until global warming pollution can be trapped and safely stored. In their place, governments and the private sector should implement programs to stimulate the development and use of renewable energy options such as wind and solar, and invest in upgrading the national power transmission grid so that energy produced from alternative sources can be cost-effectively moved to markets. Governments should immediately eliminate any and all subsidies that encourage the use of fossil fuels. Fossil fuels currently in the ground in sensitive ecosystems such as the Arctic and offshore should stay in the ground.

### *Regulate Carbon Releases*

Governments should immediately begin regulating carbon releases using a system that internalizes emissions costs and prevents continued releases that harm the oceans. Under-regulated sources of carbon dioxide emissions, such as those from shipping and aircraft should be included in a post-Kyoto Agreement and regulated by the appropriate international bodies, such as the International Maritime Organization and the International Civil Aviation Organization.

### *Preserve Natural Resilience*

The natural resilience of marine ecosystem should be maintained by curtailing other human caused threats, such as overfishing and pollution. Ocean acidification and climate change are not isolated threats, but act in concert with other impacts on ecosystems and species. Ocean ecosystems will have the best chance of surviving the pressures of ocean acidification if they are not simultaneously struggling to survive in the face of other threats.



## INTRODUCTION

Our continued burning of fossil fuels is increasing the levels of carbon dioxide in the atmosphere, and what goes into the atmosphere eventually ends up in the oceans. Consequently, the oceans have been absorbing large amounts of carbon dioxide since the Industrial Revolution (approximately 1750). It is this increasing amount of carbon dioxide in the oceans that is causing ocean acidification.

When carbon dioxide enters the ocean it combines with seawater to produce carbonic acid, which increases the acidity of the water, lowering its pH.<sup>35</sup> Although it is unlikely that the ocean will ever become actual acid (i.e. fall below a pH of 7.0), the term acidification refers to the process of the oceans becoming more acidic.

A major consequence of increasing ocean acidity is a reduction in the amount of carbonate available for use by marine animals. One of the most important uses of carbonate in the ocean is in the formation of calcium carbonate or limestone structures like coral skeletons, shells and pearls, and the tests (shells) of some marine plankton. Ocean acidification will severely impact the ability of these creatures to create their protective calcium carbonate structures, and will likely disrupt some of the most important chemical and biological functions of the oceans.<sup>36</sup>



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## WHAT IS OCEAN ACIDIFICATION?

The absorption of carbon dioxide by the oceans moderates the impacts of climate change on terrestrial life. Since the Industrial Revolution the oceans have been acting as a "carbon sink" for carbon dioxide emissions, thereby lessening the extent of climate change. Without the oceans playing this role, the concentration of carbon dioxide in the atmosphere would have risen an additional 55 percent more than it has over the last 250 years.<sup>37</sup>

Prior to the Industrial Revolution the oceans were in relative equilibrium with the atmosphere, absorbing about the same amount of carbon dioxide each year as they released (2.15 billion metric tons of CO<sub>2</sub>).<sup>38</sup> However, as the concentration of carbon dioxide in the atmosphere has increased, due mainly to the burning of fossil fuels, the amount of carbon dioxide the oceans have been absorbing has also increased. The oceans will continue to absorb carbon dioxide from the atmosphere as long as the concentration of carbon dioxide in the surface waters is less than that in the atmosphere.<sup>39</sup>

The pH of the ocean surface has already fallen 0.1 units, representing a 30 percent increase in acidity.<sup>40</sup> By the end of this century, if current emission trends continue, it could fall by another 0.3 units, an almost 100 percent increase in acidity.<sup>41</sup> The pH scale can be misleading because it is logarithmic, so its units may seem incremental, when in fact, they represent major changes in acidity. For example, a seemingly small drop of 0.4 units in pH actually represents more than a doubling (an almost 150 percent increase) in the acidity of the ocean.<sup>42</sup> In the last 300 million years or more, ocean pH has never fallen to more than 0.6 units below the level of 1750,<sup>43</sup> however if fossil fuel use continues unabated over the next couple of centuries, ocean pH could fall more than 0.7 units below the 1750 level (see Table 1).<sup>44</sup>

The oceans are the largest repository, or carbon sink, for anthropogenic carbon dioxide on earth.<sup>45</sup> Since the Industrial Revolution the oceans have absorbed over 480 billion metric tons of carbon dioxide,<sup>47</sup> which represents almost half of the carbon dioxide emissions from the burning of fossil fuels, or approximately 30 percent of all human-caused carbon dioxide emissions.<sup>48</sup> The oceans are currently taking up some 30 million metric tons of carbon dioxide daily,<sup>49</sup> nearly twice the amount of carbon dioxide emitted by the U.S. each day.<sup>50</sup>



The current concentration of carbon dioxide in the atmosphere is much higher than it has been at any time over the course of human civilization – in fact, as far back as scientists have currently determined (800,000 years), the natural range has not exceeded 300 ppm.<sup>51</sup> If we continue on our current emissions trajectory, by 2050 ocean pH will be lower than at any point in the last 20 million years.<sup>52</sup>

Even more significant is the rate at which ocean chemistry is changing. The current rate of acidification is at least 100 times faster than the maximum rate over hundreds of thousands of years.<sup>53,54</sup> Carbon dioxide is being absorbed so rapidly that it is unlikely the buffering capacity of the surface waters of the oceans will be able to prevent a substantial lowering of ocean pH.<sup>55</sup>

**Table 1: Current and expected changes in ocean pH<sup>55</sup>**

	CHANGE FROM PRE-INDUSTRIAL pH		pH CONDITIONS HAVE NOT BEEN EXPERIENCED FOR
	pH UNITS	PERCENTAGE	
Today	-0.1	30	800,000 years
Business-as-Usual at 2050	-0.2	60	20 million years
Business-as-Usual at 2250	-0.7	210	300 million years

**Table 2: Past and future chemistry of surface sea water under a “Business-as-Usual” emissions scenario<sup>56</sup>**

YEAR	ATMOSPHERIC CO <sub>2</sub> CONCENTRATION (ppm)	SURFACE OCEAN pH
1750	280	8.19
2008	365	8.09
2020	440	8.03
2040	510	7.97
2060	600	7.91
2080	700	7.85
2100	850	7.78

Based on geologic history, marine calcifiers and the natural biogeochemical cycles of the ocean could be adversely affected by even small changes in the concentrations of carbon dioxide in the surface waters of the oceans.<sup>57,58</sup> Past mass extinctions and reef gaps (periods of time, on the order of millions of years, that reefs have taken to recover from mass extinctions) can likely be attributed to ocean acidification.<sup>59</sup> An acidification event that occurred fifty-five million years ago at the Paleocene-Eocene Thermal Maximum (PETM) caused the extinction of a significant proportion of benthic calcifiers.<sup>60</sup> We are currently on a path to equal or surpass the PETM acidification event. If the entire fossil fuel reservoir is exploited, similar amounts of carbon dioxide will be absorbed by the oceans as at the PETM, however the rate at which current emissions are occurring is much faster (over the space of decades to hundreds of years, as opposed to thousands), so it is likely that the consequences of current ocean acidification could be even more catastrophic than the PETM event. This means another mass extinction may be looming.<sup>61,62</sup>

*“It is likely that a continuation of current trends in carbon dioxide emissions will lead to an extinction of corals and may lead to the extinction of other marine species.”<sup>64</sup>*

— Dr. Ken Caldeira

## How Does the pH Scale Work?

Chemists identify an acid or base by the concentration of hydrogen ions (H<sup>+</sup>) present, which is expressed using the pH scale. The scale runs from 0 (a highly acidic solution, with high concentration of H<sup>+</sup>) to 14 (a highly basic solution, with a low concentration of H<sup>+</sup>). The pH of battery acid, for example is about 0, and drain cleaner, on the other hand, is about 14. A neutral solution has a pH of 7 and pristine sea water has a pH ranging from 8 to 8.3. A change of 1 unit represents a 10 fold increase in the concentration of hydrogen ions and therefore acidity. For example, pH 5 is 10 times more acidic than pH 6 and 100 times more acidic than pH 7.

Concentrations of Hydrogen ions compared to distilled water (pH)		Examples of solutions and their respective pH
10,000,000	0	Battery Acid
1,000,000	1	Hydrochloric Acid
100,000	2	Lemon Juice, Vinegar
10,000	3	Orange Juice, Soda
1,000	4	Tomato Juice
100	5	Black Coffee, Acid Rain
10	6	Urine, Saliva
1	7	“Pure” Water
1/10	8	Sea Water
1/100	9	Baking Soda, Toothpaste
1/1,000	10	Milk of Magnesium
1/10,000	11	Household Ammonia
1/100,000	12	Soapy Water
1/1,000,000	13	Bleach, Oven Cleaner
1/10,000,000	14	Liquid Drain Cleaner

Source: Richmond River County Council  
[www.rcc.nsw.gov.au](http://www.rcc.nsw.gov.au)

# OCEAN CHEMISTRY

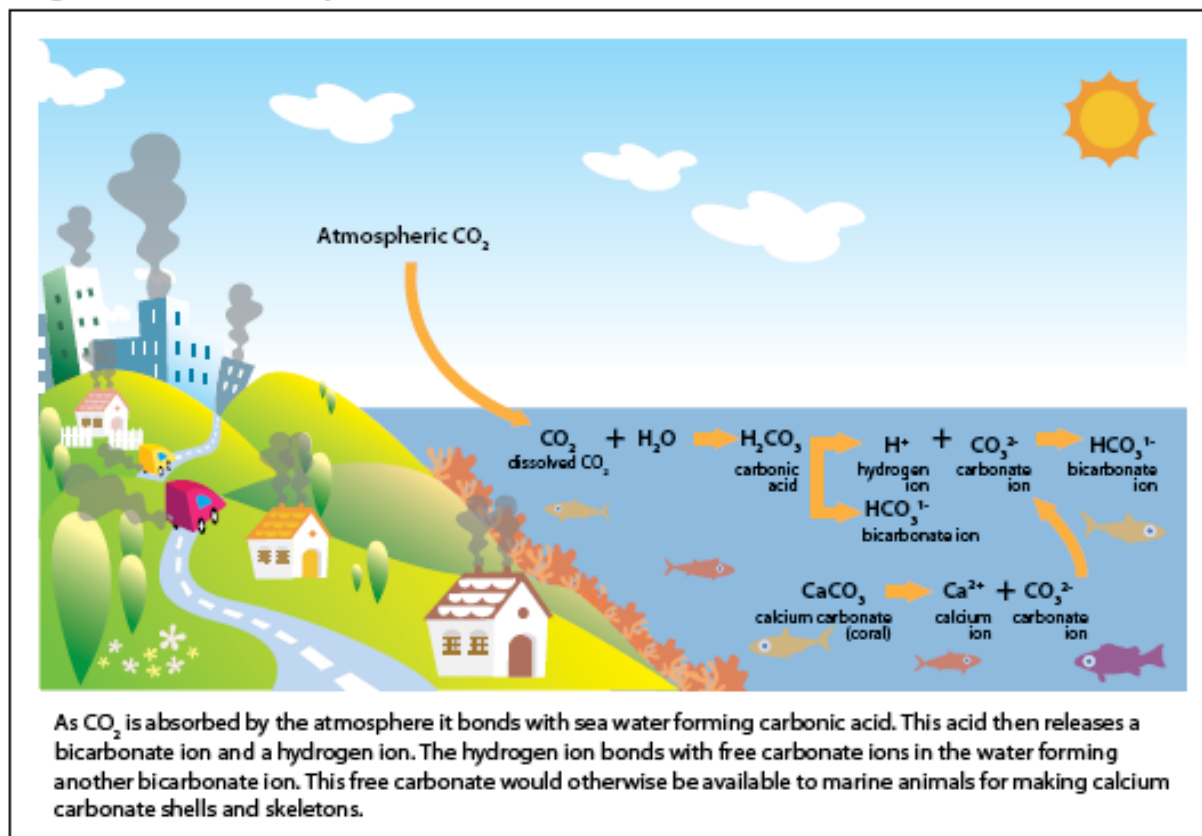
The chemical composition of seawater buffers against large shifts in pH. However, large additions of carbon dioxide can reduce the availability of carbonate, and even make the seawater corrosive to calcium carbonate structures.

## High Levels of Carbon Dioxide in Seawater Lowers Carbonate Availability

Water reacts with carbon dioxide absorbed from the atmosphere to form bicarbonate ions and, in the process, depletes carbonate ions. Carbonate and bicarbonate are in equilibrium with one another in the oceans, so an increase in the abundance of one causes a decrease in the abundance of the other. Carbonate is needed by marine animals to make their calcium carbonate shells and skeletons. At typical pH levels, most of the ocean's inorganic carbon is stored in the form of bicarbonate ions but there is still enough carbonate available for the formation of calcium carbonate. When carbon dioxide absorbed by the oceans reacts with water, it forms a bicarbonate ion and a hydrogen ion. This hydrogen ion can then bind with a carbonate molecule that would otherwise be available to make calcium carbonate (see Figure 1). This tips the balance of the system away from carbonate ions, reducing the availability of this important molecule, which is vital to sea life.

Some of the species that will likely be affected by a decrease in the availability of carbonate ions include; corals, starfish, oysters, crabs, shrimp, mussels, lobsters, coccolithophores (a type of phytoplankton), pteropods (sea snails) and foraminifera (plankton related to amoebas).

**Figure 1: The Chemistry of Ocean Acidification**





### Seawater Becomes Corrosive

In some acidified waters, the reduction of carbonate is so significant that calcium carbonate structures can start dissolving. Since calcium carbonate structures only exist in waters where sufficient levels of carbonate ions are available, the addition of hydrogen ions to waters that already have low concentrations of carbonate ions further decreases the availability of carbonate and can actually cause existing calcium carbonate structures to begin to dissolve. With the accumulation of enough carbon dioxide, regions of the oceans that already have low enough pH to be corrosive to calcium carbonate structures will expand and more such areas are likely to develop.

Since it is the concentration of hydrogen ions that actually defines the ocean's level of acidity, the binding of hydrogen ions with carbonate ions is a buffering process against the oceans becoming more acidic. However, since such large amounts of carbon dioxide are being absorbed, the dissolution of calcium carbonate structures is the only way to return the ocean to its pre-industrial acidity levels. However, this is a slow process, which will take thousands of years to complete. In the meantime, it is currently being outpaced by the influx of carbon dioxide<sup>63</sup> and many vitally important calcium carbonate structures such as coral reefs and shellfish may begin to dissolve.



Photo: A. Bristien

The skeleton of this *Oculina patagonica*, a hard coral found in the Mediterranean, completely dissolved after being in acidified waters for 6 months, only the soft anemone-like polyps were left.

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### The Role of Calcite and Aragonite

While the dissolution of calcium carbonate is primarily driven by the availability of carbonate ions, it is also affected by other factors, such as the chemical structure of calcium carbonate. Calcium carbonate is commonly found in two forms: calcite and aragonite. Organisms will generally create one form or the other, and some also add magnesium to their calcite structures. Aragonite and magnesium calcite are at least 50 percent more soluble than calcite and are therefore more vulnerable to the effects of increasing acidity.<sup>64</sup> As a result of their greater sensitivity to acidic conditions, organisms such as corals and pteropods that build their skeletons and shells out of aragonite, and coralline algae that produce magnesium calcite are particularly threatened by ocean acidification.<sup>65</sup>

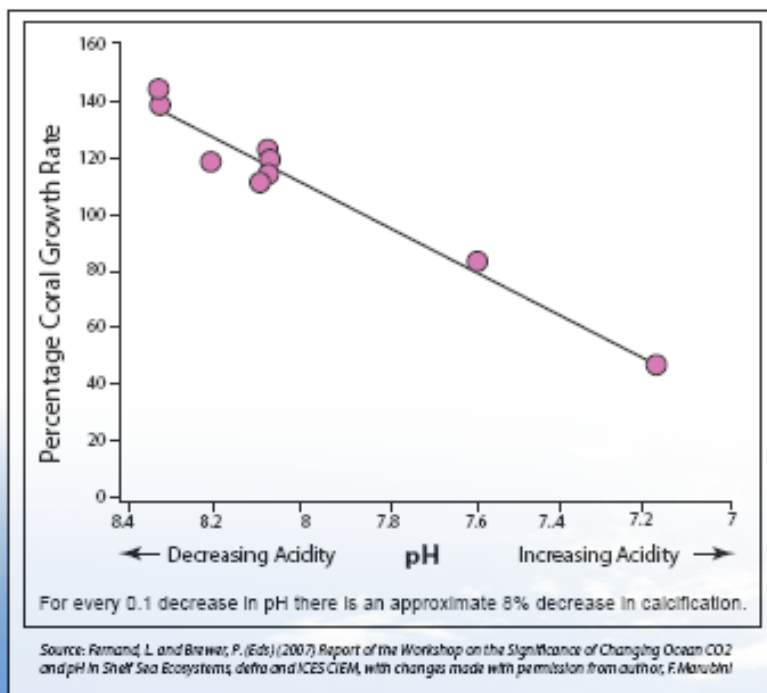
Calcification strongly depends on the "saturation state" of the surrounding water. This depends on a variety of factors including water temperature and pressure.<sup>66</sup> Currently, seawater near the surface is "super-saturated" with respect to all forms of calcium carbonate (i.e., the carbonate ion concentration is so high that calcium carbonate is easily created) so surface waters are therefore the most calcium carbonate "friendly" areas of the oceans<sup>67</sup>. Cold and deep waters hold higher levels of carbon dioxide and therefore are naturally more acidic and less calcium carbonate friendly than warm surface waters. Calcification rates, which are a measure of the ability of an animal to build a calcium carbonate structure, are higher when the pH is higher and water is "saturated" with respect to carbonate ions. As the saturation level decreases, as it does in deeper water, the growth of these species declines (see Figure 2).<sup>68</sup> Once "under-saturation" is reached, calcium carbonate will begin to dissolve. However, calcification rates can decline long before under-saturation is reached so some calcifiers may not even survive to reach the point of under-saturation.<sup>69</sup>

As more carbon dioxide enters the oceans, the saturation horizons (the boundary between saturated and under-saturated waters) for both aragonite and calcite move closer to the surface, thereby shrinking the area in which calcification can take place.<sup>70</sup> The amount of carbon dioxide already absorbed by the oceans has caused the saturation horizons to rise between 50 and 200 meters closer to the surface than they were before the Industrial Revolution.<sup>71</sup>

The Southern Ocean, due to its cold water, has the lowest concentrations of carbonate of all the world's oceans, and is the least hospitable to calcium carbonate structures, even near the surface.<sup>72</sup> As a result, the calcifiers of the Southern Ocean are most at risk from increasing carbon dioxide levels.

If we continue burning fossil fuels at the current rate, the entire Southern Ocean could become under-saturated with aragonite by the middle to the end of this century.<sup>73</sup> With an atmospheric carbon dioxide concentration of 450 ppm, 7 percent of the Southern Ocean, below 80°S, would be under-saturated with respect to aragonite.<sup>74</sup> With a carbon dioxide concentration of 560 ppm, aragonite, under-saturation will spread through the polar oceans, the sub-polar Southern Ocean and portions of the sub-Arctic North Pacific<sup>75</sup> making it almost impossible for aragonite structures to exist in these areas, which would have devastating consequences for cold-water corals, pteropods and other organisms that create their shells and skeletons out of aragonite or magnesium calcite.

**Figure 2: Tropical Coral Calcification (growth rate) Decreases as Acidity Increases**





# EFFECTS OF OCEAN ACIDIFICATION

The biological and physiological processes of many organisms will be challenged by increasingly acidic conditions<sup>76</sup> which, in turn, will result in changes to many marine ecosystems. According to The Royal Society's report on ocean acidification, the impacts on ecosystems could be severe and long lasting.

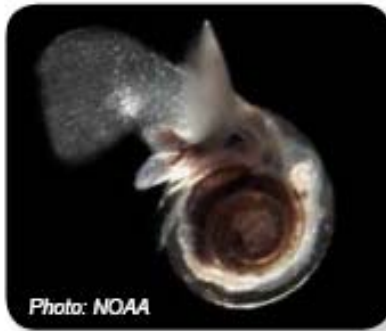


Photo: NOAA

A swimming pteropod  
(*Limacina helicina*)

## Calcification

Calcifying organisms are found throughout the oceans in shallow, deep and open-water ecosystems. Calcification is the physiological process by which organisms create structures, such as shells and skeletons, out of calcium carbonate. Some calcifiers build large structures, such as coral reefs, while others are minute, like coccolithophore tests that can only be seen with a microscope. Calcifying organisms include some of the most abundant and important species in the oceans including shallow and deep water corals; clams, oysters, pteropods and other mollusks; crustaceans, including lobsters and crabs; echinoderms like starfish; and even some types of phytoplankton.<sup>77,78</sup>

These organisms create calcium carbonate structures by taking calcium ( $\text{Ca}^{2+}$ ) and carbonate ( $\text{CO}_3^{2-}$ ) ions from the surrounding water. Calcium ions are generally abundant throughout the oceans, so they are not a limiting factor for growth. Carbonate ion availability, on the other hand, is more variable and scarce and therefore can limit calcification.<sup>79</sup> As mentioned earlier, increasing levels of carbon dioxide cause a decrease in carbonate ions which can slow or stop calcification altogether.<sup>80,81</sup>

Marine organisms produce calcium carbonate structures for various reasons at different stages of their lives. Corals, for example, produce calcium carbonate skeletons not only as an anchor and protective housing, but also to elevate their polyps toward the light and into the flowing currents. This allows them to more easily obtain the light, nutrients and minerals they need for growth.<sup>82</sup> It has also been suggested that some life phases, such as reproductive maturity, are triggered by the ability to calcify. Reproductive maturity in the coral, *Goniastrea aspera*, for example, is reached when the animal grows to a certain size which depends on its ability to calcify.<sup>83</sup> As a result, the inability of many organisms to calcify could affect their fitness and survivorship,<sup>84</sup> which could trigger significant secondary effects throughout marine ecosystems and food webs.<sup>85</sup>



Photo: Blaire Beavers

Oyster and Pearl



Photo: © OCEANA / ZOEAL

Spotted Spiny Lobster (*Panulirus guttatus*)



Photo: © OCEANA / Juan Cuevas

Smooth-skinned Red Starfish (*Hacelia attenuata*)

### Tropical Corals

A 20 percent increase above current carbon dioxide levels, which could occur within the next two decades, could significantly reduce the ability of corals to build their skeletons and some could become functionally extinct within this same timeframe.<sup>86</sup> According to Dr. Ken Caldeira:

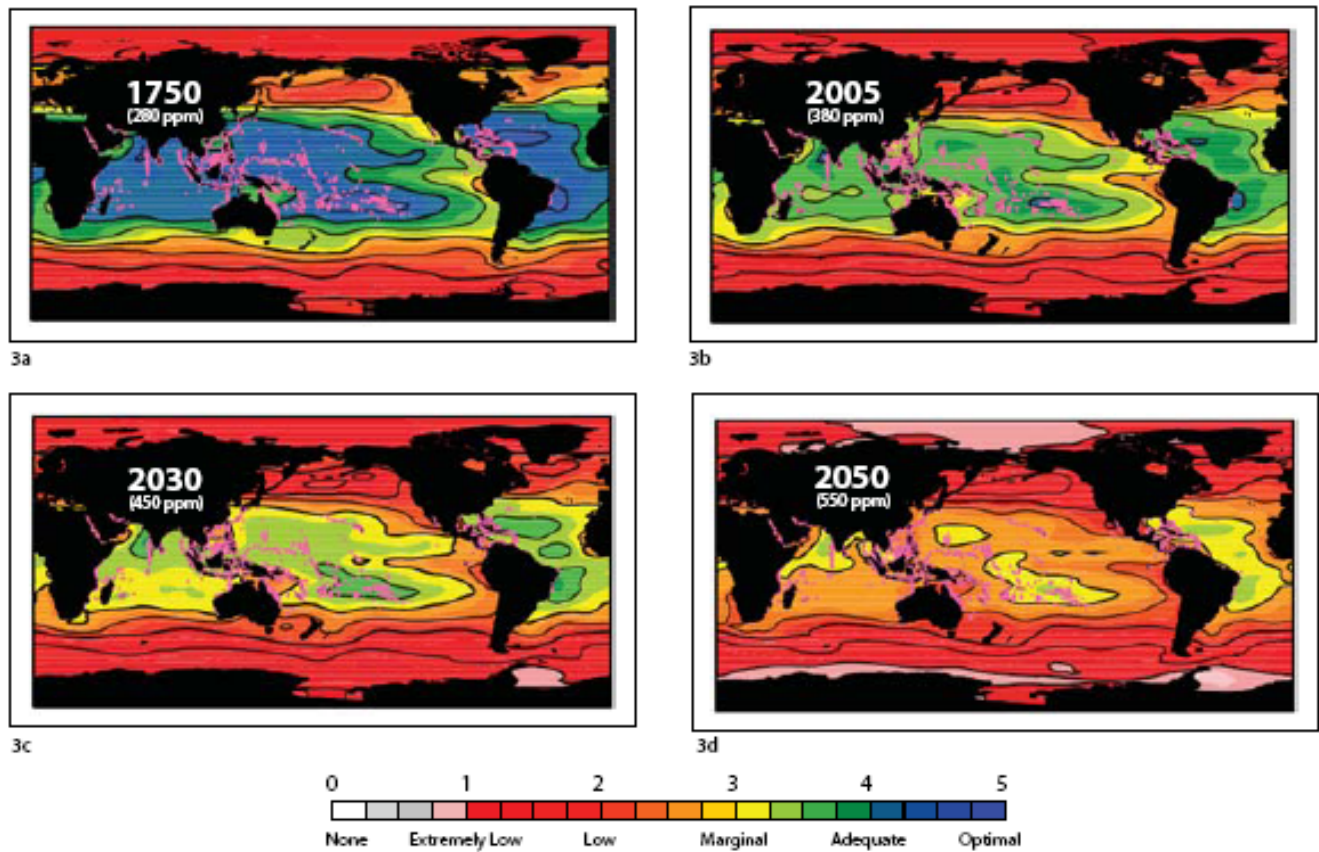
*"There is at least a reasonable expectation that if current carbon dioxide emission trends continue, corals will not survive this century."<sup>87</sup>*

Experiments on shallow water corals found that concentrations of carbon dioxide of 560 ppm (twice pre-industrial levels) reduced calcification up to 66 percent.<sup>88</sup> On a business-as-usual emissions path, this level of atmospheric carbon dioxide can be expected around the middle of this century.

In real terms this does not just mean corals grow more slowly, but also that they will be less able to overcome typical pressures. Coral reefs are constantly engaging in a battle to grow. Many reef dwellers actually break apart pieces of the corals' skeletons, either to feed upon or to create homes. This process is known as bioerosion. Even the healthiest reefs are constantly trying to grow faster than they are being eroded.<sup>89</sup> In a high carbon dioxide world not only is coral growth slower, it is also less robust, so the skeletons that are produced are weaker.<sup>90</sup> Consequently, coral reefs in more acidic conditions may not be able to overcome the typical amount of destruction and may start to shrink much earlier than otherwise predicted.

Prior to the Industrial Revolution around 98 percent of coral reefs were surrounded by waters with adequate or optimal aragonite saturation states (see Figure 3a), however this has rapidly changed with increasing ocean acidification. At today's carbon dioxide concentrations about 60 percent of coral reefs are surrounded by waters that have less than adequate saturation states (see Figure 3b) and if carbon dioxide concentrations increase to 450 ppm, more than 90 percent of coral reefs will be surrounded by such waters (see Figure 3c). No corals that exist today will be near waters with adequate saturation states if carbon dioxide concentrations are allowed to reach 550 ppm (see Figure 3d).<sup>91</sup>

**Figure 3: Aragonite Saturation State of the Ocean and Adequacy for Coral Growth**



Source: Adapted from: Cao L., & Caldeira K. (2008) Atmospheric CO<sub>2</sub> stabilization and ocean acidification. *Geophysical Research Letters*, in press, with permission from the authors.



In fact, an atmospheric carbon dioxide concentration of 560 ppm could produce ocean conditions so inhospitable to corals that almost all of the sites where corals grow today will be under-saturated with respect to aragonite causing the corals to dissolve.<sup>92</sup> However, coral calcification could virtually end before we reach 560 ppm because aragonite structures will likely be eroding due to acidification once carbon dioxide concentrations reach 480 ppm (see Table 3).<sup>93</sup> It is likely that under a business-as-usual scenario, only a few tiny areas in the oceans will remain optimal for coral growth by 2040, and by the end of this century no adequate conditions will remain.<sup>94</sup> It is for this reason that scientists have recommended that carbon dioxide concentrations in the atmosphere be stabilized at 350 ppm or below to maintain the coral dominated ecosystems we know today.<sup>95</sup>

**Table 3: Coral Reef Devastation has Begun and will Worsen as CO<sub>2</sub> Concentrations Increase<sup>96</sup>**

CO <sub>2</sub> CONCENTRATION (ppm)	CONDITION OF CORAL REEFS
360	Reefs will change due to ocean acidification, however they will remain coral dominated.
450	Density and diversity of corals on reefs will decline, including the loss of coral associated fish and invertebrates.
450-500	Reefs will likely become "rapidly eroding rubble banks". This may be seen as the tipping point for corals, beyond which reefs as we know them would be extremely rare, if not non-existent. It would be millions of years before coral reefs returned to their former diversity and density.

The loss of coral reefs would mean a loss of habitat and services for many millions of species. Reefs provide homes, nurseries, feeding grounds and spawning sites to a diversity of life that is virtually unparalleled anywhere else in the world. Unfortunately, due to the threats of ocean acidification and climate change, coral reef communities will become much less common.<sup>97</sup> Without reefs, severe consequences would result for as many as nine million species (including four thousand species of fish) that rely on reefs for shelter and nourishment.<sup>98</sup>

The chemistry of the oceans is changing so quickly it is unlikely that corals will be able to adapt to these new conditions.<sup>99</sup> Already, almost 30 percent of the world's tropical corals have vanished since 1980, predominantly due to ocean warming events.<sup>100</sup> If reefs continue to disappear at this rate, by the middle to end of this century no warm-water corals will remain.<sup>101</sup>

### Cold-Water Corals

While tropical corals are probably the best known and most widely loved calcifiers in the oceans, they are not the only type of corals that will be hit hard by ocean acidification. Cold-water or deep sea calcifying corals are possibly the most vulnerable marine ecosystems when it comes to anthropogenic carbon dioxide emissions.<sup>102</sup>

Although cold-water corals have been known to exist for more than two hundred years, most of what we know today we have learned only over the last few decades.<sup>103</sup> Cold-water, reef-forming corals have extremely high biodiversity and provide habitat and nursery areas for many deep-sea organisms, including several commercially important fish species.<sup>104</sup> There is still much that we do not know about these organisms and yet with the current rate of ocean acidification we may cause their disappearance before we even fully appreciate their true beauty and importance.<sup>105</sup>

Cold-water corals, sponges and their associated ecosystems have been recognized as important sources of new medical treatments for diseases as varied as cancer, arthritis, Alzheimer's and skin conditions.<sup>106</sup> For example, bamboo corals, a type of sea fan, have been used to synthesize human bone analogs for grafting, and may provide a model for artificial synthesis for collagen.<sup>107</sup>

There are six species of cold-water, reef building, stony corals that create calcium carbonate skeletons out of aragonite.<sup>108</sup> As some of the slowest growing corals on earth, acidification poses a real and immediate threat to these species.<sup>109</sup>



Photo: Jan Helge Fossa

Stony cold-water corals, such as *Lophelia*, rely on their hard skeletons to support their polyps so that they can capture food and nutrients from the surrounding water.



Photo: NOAA/MBARI

Deep-sea sponges along with corals provide important habitat for crabs and many other species.

Cold-water corals are found in oceans around the world, some at depths of more than five and a half kilometers below the ocean's surface. Cold-water corals live in cold, often deep areas that are generally less favorable to calcification.<sup>110</sup> The maximum depth for the cold-water corals that create aragonite skeletons appears to coincide with the depth of the aragonite saturation horizon.<sup>111</sup> While some species of reef-forming corals are found in the North Pacific, the reefs they create are not, which could be due to the shallow depth of the aragonite saturation horizon in this area.<sup>112</sup> The continued reduction in aragonite saturation state will likely affect cold water corals before shallow water reef builders.<sup>113,114</sup> Cold-water corals probably have such slow growth and calcification rates, at least in part, because of the low aragonite conditions in which they live.<sup>115</sup>

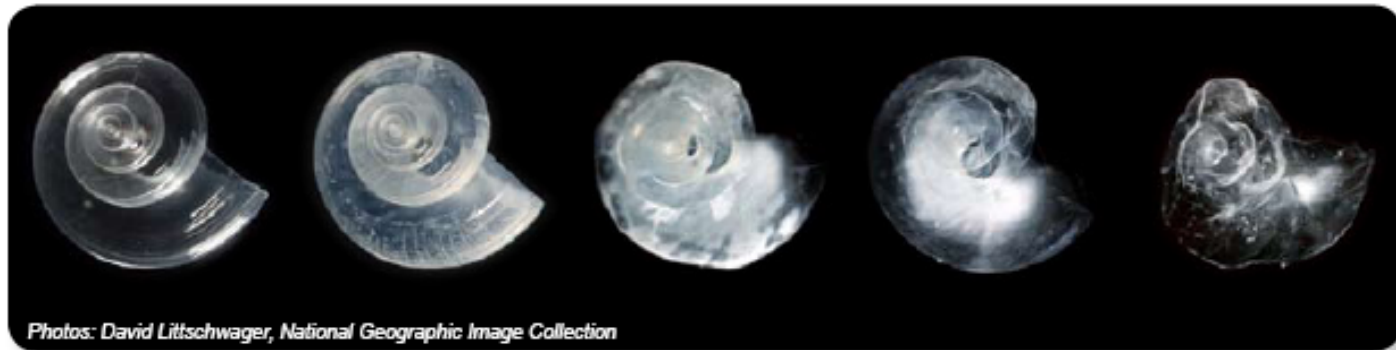
The aragonite saturation state could decrease enough to be too low to support the deepest cold water corals within a decade or less.<sup>118,117</sup> Assuming they react to lowered pH in the same way as shallow-water corals, cold-water corals could be facing significant reduction in growth rates well before 2020.<sup>118</sup> By 2040 all cold-water corals that we currently know to exist could be located in marginal growing conditions or worse,<sup>119</sup> and by the end of the century at least two-thirds of all cold-water corals could be in waters that are corrosive to aragonite.<sup>120</sup> Before the end of this century if we continue emitting carbon dioxide at current levels, it is likely that most of the world's oceans will be "completely uninhabitable" for these corals.<sup>121,122</sup>

#### Other Critical Calcifiers

It is not only corals that are going to be severely affected, and possibly eliminated, by ocean acidification. For example, mollusks, oysters, crustose coralline algae and huge numbers of planktonic calcifiers create skeletons, shells and tests out of calcium carbonate. Some of these organisms may be tiny, but they play very important roles in the ocean and in marine food webs.<sup>123</sup>

#### Crustose Coralline Algae

Crustose coralline algae are the primary calcifiers on coral reefs and play an important role in the growth and stabilization of these reefs, make significant contributions to reef sediments and serve as an important food source for sea urchins, parrot fish and several species of mollusks.<sup>124,125</sup> One recent study found an 86 percent reduction in the growth of crustose algae in acidified waters.<sup>126</sup> These algae make their skeletons out of magnesium calcite and are therefore likely to be among the first organisms on coral reefs to be affected by acidification.<sup>127</sup> Decreases in their ability to calcify and grow could severely impact the stability and diversity of coral reefs.



Photos: David Litschwager, National Geographic Image Collection

Dissolution of pteropod shell in acidified water

#### Pteropods

Pteropods, or swimming sea snails, are an integral part of the base of the polar and sub-polar food webs, where they serve as important prey for much of the ecosystem, including whales and top predators.<sup>128</sup> For instance, they account for up to 45 percent of the diet of Alaskan pink salmon.<sup>129</sup> Some preliminary studies suggest that a 10 percent reduction in pteropod production could result in a 20 percent reduction in mature pink salmon body weight.<sup>130</sup> Since their shells are made of aragonite and they are found in the cooler high-latitudes which will be among the first areas to become under-saturated, pteropods may be one of the first calcifiers to be threatened by acidification.<sup>131</sup> In a series of experiments, live pteropods were exposed to the level of aragonite under-saturation expected in the Southern Ocean by 2100. Within 48 hours their shells began to dissolve, despite the animal itself still being alive.<sup>132</sup> Increasing acidity could result in lower calcification rates in pteropods, which could produce a disruption near the base of ocean food webs causing major ecosystem shifts and a decoupling of predator-prey interactions. This could ultimately affect even the largest of top predators in the oceans along with many commercial fisheries.<sup>133</sup>



### ***Coccolithophores***

Coccolithophores are single-celled algae encased in calcite layers. Studies in some species have found declines in calcification when exposed to acidified waters, while others have not. One species actually increased its rates of calcification in higher carbon dioxide conditions.<sup>134</sup> However, a decrease in the calcification of even some species of coccolithophores could amplify climate change. Coccolithophores create massive algal blooms that have a lighter coloration than the surrounding water due to their chalky tests. This increases the amount of sunlight reflected back to the atmosphere and not absorbed by the oceans. Without these lighter shells to reflect sunlight, the Earth's albedo (reflectivity) could decrease by 0.13 percent.<sup>135</sup> In this way, a reduction in coccolithophore calcification could act to accelerate climate change.

Coccolithophores also produce dimethylsulfide (DMS), which reacts in the atmosphere to stimulate the development of clouds. It is possible that production of DMS by coccolithophores may be disrupted by ocean acidification. This could greatly reduce atmospheric concentrations of DMS, decreasing cloud cover over the oceans that reflects sunlight back to space, and resulting in even further warming of the planet.<sup>136,137</sup> Reductions in DMS could also have wide ranging ecosystem effects, as this compound is an important signal used by many animals such as seabirds,<sup>138</sup> reef fish<sup>139</sup> and seals<sup>140</sup> to navigate toward feeding grounds. Reductions in DMS could cause disruptions in the feeding patterns and ability of these animals to find adequate food.

### ***Planktonic Calcifiers***

Many species produce calcium carbonate during their larval phases, so increasing ocean acidification may also affect species that are not likely to be affected as adults. The larvae of two sea urchins, for example, showed decreased calcification and decreased developmental rate when exposed to increased carbon dioxide.<sup>141</sup> Other species, such as mussels, oysters, sea stars, brittle stars and crustaceans have shown decreases in larval phase calcification rates in elevated carbon dioxide conditions.<sup>142,143</sup> Disruption of the early development and life history of marine organisms will likely result in reduced fitness and survivorship, with potentially serious consequences for marine ecosystems.

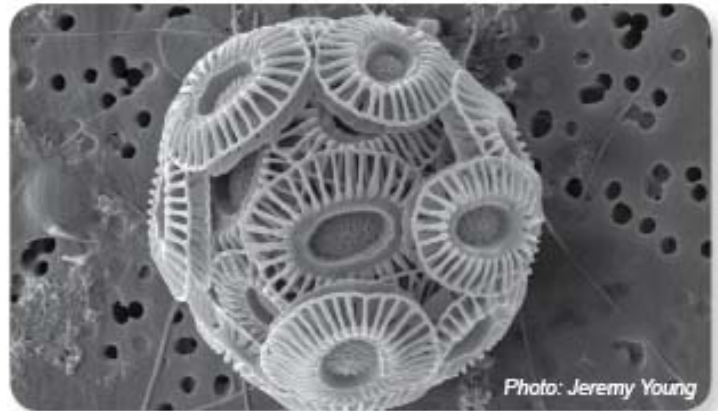


Photo: Jeremy Young

**Coccolithophores surround themselves in layers of tiny calcium carbonate plates called tests.**



Photo: Steve Groom, Plymouth Marine Laboratories

**Massive, lightly colored coccolithophore blooms reflect light back to space and have a cooling effect.**



Photo: Dave Burdick

**Brittle stars have shown decreases in larval phase calcification under high CO<sub>2</sub> conditions.**

## PHYSIOLOGICAL EFFECTS ON MARINE LIFE



Purple Sea Urchin  
(*Heliocidaris erythrogramma*)



Squid  
(*Sepioteuthis* sp.)



Photo: Kwansai Shell Database

Common Periwinkle  
(*Littorina littorea*)

Along with a decrease in the ability to calcify, many other biological and physiological processes will be disrupted by ocean acidification.<sup>144</sup> These impacts could include decreased growth rates,<sup>145</sup> reduced reproduction<sup>146</sup> and increased susceptibility to disease,<sup>147,148</sup> all of which could produce ripple effects through food webs and ecosystems.<sup>149</sup> Fundamental physiological functions, such as respiratory and nervous system functions could also be disrupted by ocean acidification.<sup>150</sup> In addition, ocean acidification may result in behavioral changes in some species.<sup>151</sup>

### Effects on Reproduction

Larvae and juveniles are often most sensitive to increased acidity. For example, the fertilization rate of two species of sea urchin eggs (*Hemicentrotus pulcherrimus* and *Echiometra mathaei*) decreased with increasing ocean acidification. They also had malformed skeletons caused by the increased levels of carbon dioxide.<sup>152</sup> Another species of sea urchin, *Heliocidaris erythrogramma*, had a 25 percent reduction in fertilization success at acidification levels that are expected by the year 2100 on a "business-as-usual" emission path.<sup>153</sup> High levels of carbon dioxide caused a number of other reproductive effects including declines in the sperm motility of Pacific oysters, reduced numbers of hatchlings of a species of sea snail (*Babylonia areolata*), and a lowered number of eggs produced by copepods.<sup>154,155,156</sup> If ocean acidification impacts reproduction, reductions in community size would likely follow.<sup>157</sup>

### Effects on Respiration

Ocean acidification in conjunction with climate change may cause oxygen stress in many marine organisms. As the oceans become warmer they will hold less oxygen, and this low oxygen along with the higher levels of carbon dioxide may cause the oxygen transport mechanisms in some species (like hemoglobin in humans) to bind more readily with carbon dioxide than with oxygen, making it difficult for the animals to breathe.<sup>158</sup> Squid are especially sensitive to oxygen stress since they require high levels of oxygen for their energy intensive form of swimming.<sup>159</sup> Inability to swim adequately could have severe consequences for individual fitness and ability to survive. Along with oxygen stress the metabolic functions of many organisms may be altered as they attempt to adapt to new acidity levels around them.<sup>160</sup> While this may not always kill individuals, it could impact growth and reproduction rates, which may result in harmful consequences at the population and species scales.<sup>161</sup>

### Effects on Behavior

With increasing acidity and its consequent changes to the physiological and biological processes in some species, resultant changes in behavior may occur to compensate for depressed functions. For example, a recent study showed that the common periwinkle (*Littorina littorea*) increased its avoidance behavior in response to the presence of crabs in high carbon dioxide conditions.<sup>162</sup> Under normal conditions this species relies on the ability to thicken its calcium carbonate shell when it senses crabs. However, when high acidity levels prevented the periwinkles from thickening their shells, they compensated by increasing their avoidance behavior.<sup>163</sup> While it is difficult to predict the effects such a change in behavior could have, it could plausibly compromise the fitness of the individuals that may now spend more time avoiding predators than feeding or performing other important tasks, and it could also have other unforeseen consequences for predators and ecosystems.

Some organisms will scale back important activities in order to maintain calcification when carbonate is scarce. For example, a type of brittlestar, *Amphiura filiformis*, spent less time ventilating its burrow and feeding in order to focus on regenerating lost arms. The brittlestars in more acidified waters also had smaller arm muscles as they were converting muscle mass into energy.<sup>164</sup> In this case ocean acidification prompted these animals to increase their rates of calcification in order to keep pace with decreasing availability of carbonate ions. But these actions came at a cost, one that may also reduce fitness and survival of the species.



## EFFECTS ON ECOSYSTEMS

It is currently unclear how acidification will affect community structure and ecosystem functioning; however, as a report of the Royal Society stated:

*"Without significant action to reduce carbon dioxide emissions into the atmosphere, this may mean that there will be no place in the future oceans for many of the species and ecosystems that we know today."<sup>165</sup>*

The reduction in planktonic calcifiers is likely to result in changes in the species composition within communities, which could have ripple effects throughout food webs.<sup>166</sup> Planktonic calcifiers form an important part of the base of many food webs in the oceans. If these species shift, become less nutritious, or disappear as a result of ocean acidification, the species that rely on them, including whales, turtles, and commercial fish species, could suffer from a lack of adequate prey. This could result in massive changes in the way that organisms interact throughout the oceans.

Even if the adults of some species are more resistant to the effects of ocean acidification, the heightened sensitivity of larvae and young will likely have significant impacts throughout populations and on ecosystem structure.<sup>167</sup> The impacts of ocean acidification will be varied among species, with many being chronically affected by increases in acidity.<sup>168</sup> Even species not directly affected biologically or physiologically are likely to be adversely affected by changes in food webs and ecosystem structure.



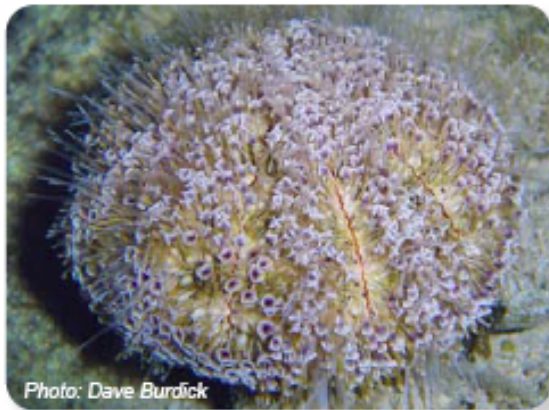


Photo: Dave Burdick

Poisonous Sea Urchin (*Toxopneustes pileolus*)

Many calcifiers play important ecosystem roles, such as sea stars that act as keystone predators, balancing community diversity by feeding on species that would otherwise out-compete other species in the community. Other examples include urchins which are important grazers and oysters and mussels which are vital ecosystem engineers since they create or modify the habitats they live in.

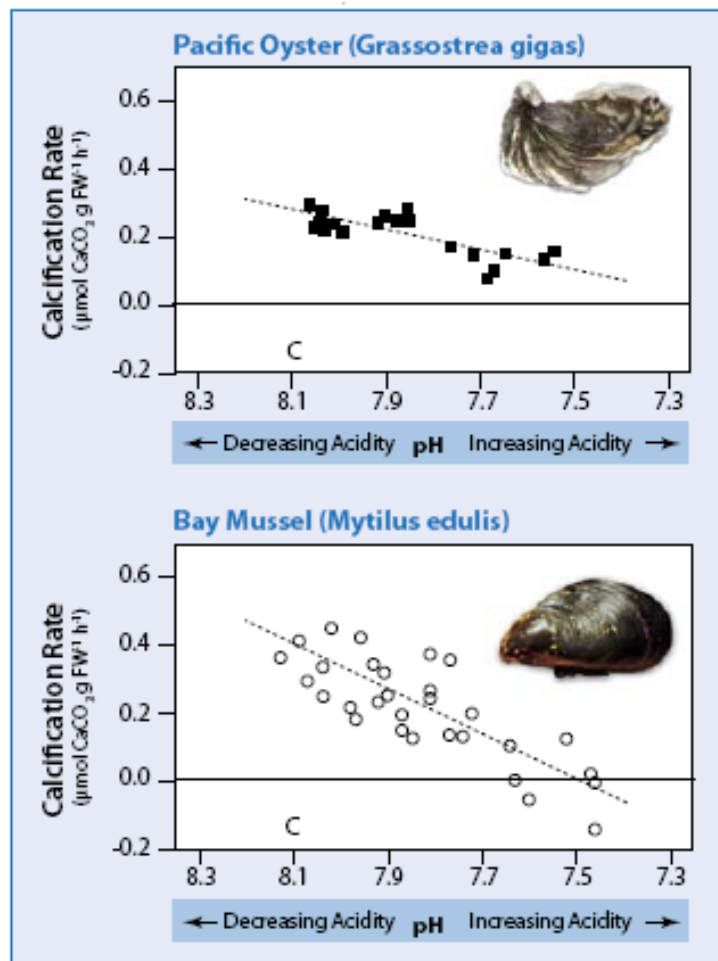
With increasing levels of carbon dioxide the calcification rates of Pacific oysters (*Crassostrea gigas*) and bay mussels (*Mytilus edulis*) decreased linearly (see Figure 4).<sup>169</sup> If atmospheric concentrations of carbon dioxide reach 740 ppm, which could happen before 2100, the calcification rates in these species are expected to decline 10 and 25 percent, respectively.<sup>170</sup> The loss of oysters and mussels could be quite severe since they are vitally important to the ecosystems they live in and make up significant proportions of global aquaculture production.<sup>171</sup>



Photo: © 2005 David Monniaux

Oyster (*Crassostrea gigas*)

Figure 4: Decreasing Acidity Decreases Calcification Rates



Source: Adapted from Gazeau, Frederic et al. (2007) Impact of Elevated CO<sub>2</sub> on Shellfish Calcification, *Geophysical Research Letters*, 34, with changes made by permission from author.



Photo: © Darkone

Mussel (*Mytilus edulis*)



Oysters provide important habitat for other benthic organisms and help to govern the flow of nutrients and energy in coastal ecosystems.<sup>172</sup> They are filter feeders, which means they filter their food out of the water they live in. This provides an added service by filtering out excess phytoplankton, along with chemicals and other pollutants that could otherwise cause harm in the surrounding water. If acidification results in a reduction in these important species, waterways can rapidly become polluted and unsafe and there could be significant changes in coastal biodiversity and ecosystem functioning.

Marine mussels provide habitat for smaller invertebrates, enhance sediment stability and serve as an important food source for many species, including sea birds and humans.<sup>173</sup> Increased acidification is expected to reduce mussel calcification,<sup>174</sup> reduce metabolic activity,<sup>175</sup> and growth rates,<sup>176</sup> and even suppress immune function.<sup>177</sup> If these species and others like them that provide important ecosystem services are severely affected by rising acidity levels, the loss of the benefits these species provide could be catastrophic to the wildlife and humans alike that depend upon them.



**Maxima clam  
(*Tridacna maxima*)**

Photo: © Christoph Specjalski

## IMPACTS OF OCEAN ACIDIFICATION ON HUMANS

Not only do the oceans govern some of the most important geochemical cycles that make the planet inhabitable, they also serve as an important provider of food, livelihood, recreation and rejuvenation for billions of people. Unfortunately, ocean acidification could completely change the oceans as we know them today. Less diverse and vibrant oceans could in various ways negatively impact life as we know it.

For example, more than 100 million people are economically dependent upon corals reefs, with many more reliant on reefs for protection, resources and pleasure.<sup>178</sup> The disappearance of coral reefs could result in the loss of many billions of dollars every year since the reefs provide some 30 billion dollars annually to the global economy through coastal protection, tourism, fishing and other goods and services.<sup>179</sup> Many subsistence fishing communities rely on the fish found in reef ecosystems for vital proteins,<sup>180</sup> the loss of which could result in serious health consequences and food security concerns for these communities.

### Coastal Protection

Coastal communities across the globe depend on the protection of reefs from storm surges, tsunamis and coastal erosion.<sup>181</sup> In the December 2004 tsunami, coastlines that had less robust coral reefs experienced greater loss of life and damage to infrastructure than those with well-developed reefs.<sup>182,183</sup> A scientific model developed by researchers at Princeton University showed that coasts with healthy reefs were at least twice as protected from tsunamis as coasts with dead reefs.<sup>184</sup> The loss of coral reefs due to ocean acidification could result in increased threats to the health, safety and well-being of many coastal communities.

### Tourism

Coastal communities will also suffer significant economic losses from the degradation of coral reefs. As reefs decline and their associated ecosystems become less diverse, many tourists will find new, less affected areas in which to spend their money. This will likely mean major losses to coastal communities that are dependent upon tourism for their incomes. The coastal reefs in Hawaii alone are estimated to generate 364 million dollars annually in net business revenues.<sup>185</sup> The loss of this income could severely harm the economy of Hawaii.





## Fisheries

In 2004, about 85.5 million metric tons of marine fish worth 76.4 billion dollars were caught globally.<sup>186</sup> While it is difficult to estimate the impact that increasing acidity will have on fish and shellfish populations, it is likely that many will be adversely affected.

As tropical coral reefs begin to disappear due to acidification, many commercially important fish species that rely upon these reefs for critical habitat could also be in danger since many species depend on coral reefs for shelter and food.<sup>187</sup> There have already been some examples of fish that have disappeared from reefs during bleaching events. In 1998, after a bleaching event on the Okinawan reefs, the orange-spotted filefish (*Oxymonacanthus longirostris*) was unable to survive without the living coral.<sup>188</sup> While this filefish was not particularly important commercially it provides an example of what could happen to important fish species as acidification worsens.

Deep-water reefs, like their shallow-water counterparts, are biodiversity hotspots providing important habitat to many species, including many commercially important species of fish like grouper.<sup>189,190</sup> More than half of the total U.S. fishery landings (an over 4 billion dollar per year industry) is derived from Alaskan waters.<sup>191</sup> Many of the commercially important species in this region rely upon the cold-water corals off the Alaskan Aleutian Islands.<sup>192</sup> These corals are likely to be severely affected and may even begin to dissolve before the end of this century, a situation that would undoubtedly harm their dependant fish populations and fisheries.<sup>193</sup> The cold-water coral reefs of the Atlantic coast of the United States also form a veritable oasis of corals, sponges, crabs, lobsters, sea stars and fish.

Many of the world's commercial fisheries are likely to be threatened by ocean acidification either directly, by biological and physiological changes due to increased acidity, or indirectly through changes in habitat and prey availability. Many of the areas where acidification is predicted to be most severe within the coming century are highly productive and support some of the world's most important commercial fisheries.<sup>194</sup>

The effects of ocean acidification on mollusks (e.g. clams, oysters and mussels) and crustaceans (e.g. lobsters, crabs, crayfish and shrimp) are likely to present great losses both economically and to ecosystem services. Shellfish farming has increased at around 8 percent per year over the last 30 years and in 2004 the market was worth over 9.8 billion dollars.<sup>195</sup> Crustaceans will be particularly vulnerable to ocean acidification as they require carbonate ions to harden their new shells after molting.<sup>196</sup> The calcification rates of both edible bay mussels (*Mytilus edulis*) and Pacific oysters (*Crassostrea gigas*) have been found to decrease with increasing acidity.<sup>197</sup> In 2005, U.S. fishermen captured over 330 thousand metric tons of crustaceans and over 877 thousand metric tons of mollusks.<sup>198</sup> The 2005 U.S. revenue from shellfish was close to 17 million dollars.<sup>199</sup> Decreases in these populations due to ocean acidification could have massive economic repercussions.



Photo: © OCEANA / ZOE A

Horse eyed jacks (*Caranx latus*)



Photo: Scott France

Cold-Water Coral Garden



Photo: Féron Benjamin

Common Cockle (*Cerastoderma edule*)



Photo: © OCEANA / ZOE A

Channel clinging crab (*Mithrax spinosissimus*)

## REACHING THE LIMITS

"If there's no action before 2012, that's too late. What we do in the next two to three years will determine our future. This is the defining moment." Dr. Rajendra Pachauri, scientist, economist and Chair of the IPCC. (2007)

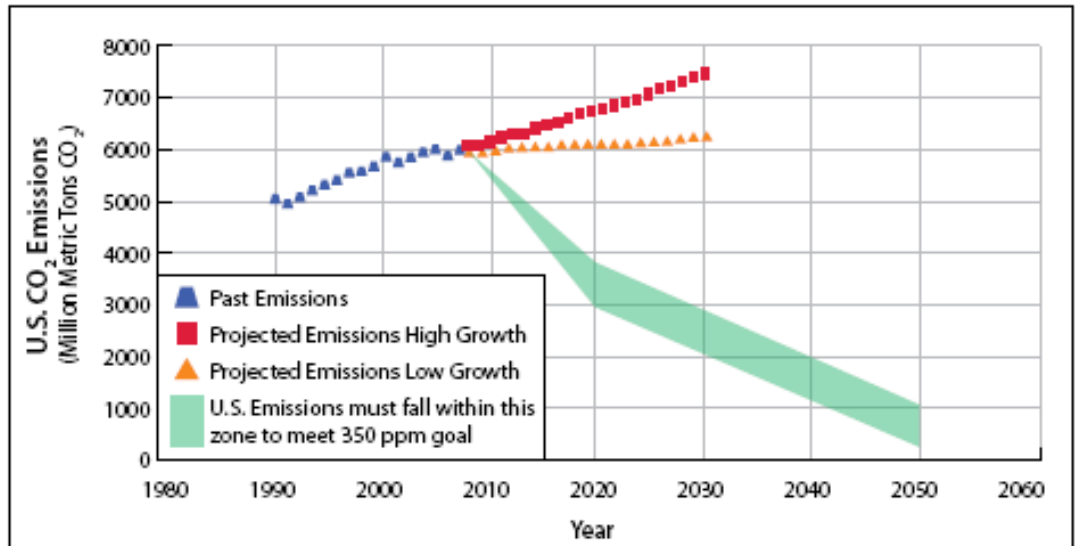
Current atmospheric carbon dioxide concentrations are already above safe levels and as a result we are seeing significant changes taking place throughout the oceans, from decreasing growth rates of corals on the Great Barrier Reef to massive coral bleaching events across the tropics. Coral reefs are acutely vulnerable to ocean acidification and climate change. They provide important habitat to a quarter of all marine species and are significant to the lives and livelihoods of many humans. Allowing coral reefs to disappear would result

in intolerable changes throughout the oceans as well as major disruptions in the lives of hundreds of millions of people. What happens to coral reefs will foreshadow other catastrophic changes that are likely to take place around the world due to ocean acidification and climate change.

To prevent the loss of coral reefs, and ultimately avert a climate crisis, we must reduce atmospheric carbon dioxide levels to below 350 ppm.<sup>200</sup> Unfortunately, carbon dioxide in the atmosphere has already exceeded this safe level, having reached 385 ppm and climbing.<sup>201</sup> Besides being too high to protect the planet's coral reefs, this current level is also much higher than it has been at any time over the course of human civilization.<sup>202</sup> In fact, as far back as scientists have currently determined (800,000 years), the natural range has not exceeded 300 ppm.<sup>203</sup>

If we stay on our current emissions trajectory we will far exceed the 350 ppm goal and we will not prevent the extinction of the corals. In today's society, carbon dioxide emissions are directly tied to our need for energy, and that need is growing. Recent figures released by the U.S. Energy and Information Administration (EIA) indicate that staying on the current business-as-usual path, where current laws and policies remain

**Figure 5: Projected U.S. CO<sub>2</sub> Emissions vs. Emissions Trajectory for 350 ppm**



Source: Oceana, based on EIA (2008) and IPCC (2007)

unchanged will result in world energy consumption in 2030 increasing by 50 percent above 2005 levels.<sup>204</sup> This will result in a steady increase in anthropogenic carbon dioxide emissions, with 51 percent more carbon dioxide in the atmosphere by 2030 than there was in 2005, resulting in an atmospheric carbon dioxide concentration of over 570 ppm.<sup>206</sup>

With carbon dioxide levels this high, ocean acidification will be extremely severe within the next few decades. We have already entered the danger zone and reefs are already starting to decline. It is unlikely that reefs will be able to sustain themselves for many decades at the currently high carbon dioxide conditions. However, if we continue along our current emissions path reefs could be pushed passed a tipping point, likely to occur around 450 ppm, at which point reefs as we know them would be extremely rare, if not non-existent. Once we surpass this tipping point coral reefs will shrink rapidly,<sup>206</sup> at least half of coral-associated wildlife will become rare or extinct, and the services reefs provide to millions of people will grind to a halt. Shortly after that, coral reef ecosystems will likely be reduced to crumbling frameworks with few calcareous corals remaining.<sup>207</sup> Since coral reefs take decades and even centuries to form, once such damage is done, the impacts will be irreversible for generations.



However, this does not have to be the future of the oceans. By making the correct choices we can save coral reefs, and the wildlife and humans that depend upon them, and ultimately the Earth as we currently know it, from ocean acidification and climate change. By choosing a low carbon future, atmospheric carbon dioxide concentrations can be stabilized at safe levels below 350 ppm.<sup>208</sup> At these levels changes will still take place across reef ecosystems; however, they will remain coral dominated and continue to create calcium carbonate.<sup>209</sup>

To save coral reefs from ocean acidification we must stabilize atmospheric carbon dioxide at or below 350 ppm. Scientists looking at other vulnerable ecosystems have identified similar limits beyond which positive feedback loops could prevent full recovery. By preventing ocean acidification and stabilizing the climate at safe levels we will also be preventing other climate-related catastrophes.

Since we can not expect to simply halt all emissions immediately we must expect there will be some overshoot of the ultimate 350 ppm stabilization goal.<sup>210</sup> However, remaining in the current danger zone we are in for longer than a couple of decades will result in intolerable changes taking place. This means that it is vital to get on the right trajectory within the next few years and to make sure that carbon emissions peak and begin to decline in less than a decade.

The Intergovernmental Panel on Climate Change (IPCC) concluded that in order to stabilize carbon dioxide in the atmosphere at 350 ppm by 2050 global carbon dioxide emissions would need to be cut by 85 percent below 2000 levels,<sup>211</sup> and in order to achieve this, Annex I countries (industrialized countries and countries with economies in transition, such as the Russian Federation) would need to reduce their carbon emissions by 25 to 40 percent below 1990 levels by 2020 and 80 to 95 percent by 2050. (see Figure 5). These are not easy goals to achieve and consequently, the United States and the international community must make immediate serious commitments to meet them.

Our ability to set and meet short-term goals over the coming years will determine how successful we will be at safely stabilizing the climate. In order to realize the greatly needed cuts of 25 to 40 percent by 2020 countries will need to act immediately. The longer we wait to act the more difficult averting catastrophe becomes.

## SOLUTIONS

Many of the foremost scientific thinkers on this issue have demonstrated that it is possible to prevent runaway climate change, though there is certainly no silver bullet and doing so will not be easy. James Hanson of NASA has argued that the critical 350 ppm target needed to protect corals is achievable. It should come as no surprise that this will require a concerted effort by individuals, companies and institutions throughout the world. In their study Pacala and Socolow propose a “wedge-based” approach involving some combination of fifteen viable solutions and concluded:

*“Humanity already possesses the fundamental scientific, technical, and industrial know-how to solve the carbon and climate problem for the next half-century.”<sup>212</sup>*

While our carbon dioxide reductions need to be significant and timely, there are many, varied options ranging from conservation and increasing energy efficiencies to advanced reduction technologies, the use of alternative energy options and renewable fuels. The diverse array of solutions available require our shifting to a less carbon dependent energy economy which means building an infrastructure for energy alternatives such as solar, wind, and hydrogen, and scaling back or even stopping the use of coal, unless carbon capture is effectively employed. They also include increasing energy efficiency efforts in cars, trucks, trains, planes and ships, as well as in homes, office buildings, power generation and industrial sectors; and cutting down on deforestation while also planting more forest land to help “draw down” carbon dioxide levels.

In the meantime, when the use of carbon fuels is unavoidable, technologies such as end of the pipe scrubbers and carbon capture devices would play an important role in reducing the amount of carbon dioxide released to the atmosphere. Placing a cost on carbon dioxide emissions would allow these alternatives to enter the market and be truly competitive.<sup>213</sup>

To prevent future ocean acidification we need to switch from a trajectory of rapidly increasing carbon dioxide emissions to one in which net emissions have been reduced to zero.<sup>214</sup> However, some alternative measures have been suggested to address ocean acidification, such as adding chemicals to ocean waters to lower their acidity. But these are at best short-term, local stop-gap measures, which will not prevent ocean acidification on a global scale.<sup>215</sup>

Furthermore, such geo-engineering solutions could wreak havoc on already fragile ecosystems causing a whole host of other unintended and unforeseen consequences.

Geo-engineering solutions have also been proposed to address carbon dioxide levels in the atmosphere. These include iron fertilization and deep ocean sequestration, both of which are likely to exacerbate ocean acidification.<sup>216,217,218</sup> These approaches should be viewed with caution and only employed if and when they are proven effective and their impacts on the oceans are understood and known to be negligible.

Unfortunately, the acidity of the oceans has already increased by 30 percent due to anthropogenic carbon dioxide released since the Industrial Revolution. There will be some lag time between the time when human emissions are reduced to appropriate levels and the point at which level of acidity of the ocean decreases. Therefore, it is vitally important that we cut emissions as soon as possible so that ocean conditions do not become unbearable for many marine animals. We must also do all we can to reduce other pressures on ocean ecosystems to ensure their resilience and give them every possible chance to survive. Threats such as overfishing and destructive fishing techniques, pollution and climate change all act in concert to weaken ocean ecosystems and make survival even more tenuous. By stopping these and other threats we can provide the ocean with a fighting chance to survive the looming dangers of ocean acidification.

Essentially, every decision we make from here on out must be influenced by the need to make these changes. Debate continues about whether and how market approaches will work, and how to place a price on carbon, but one thing is clear: If we want to save our coral reefs and shellfish fisheries, the ecosystems that depend on them and the values that we derive from them as humans, we need to start now. With a 25 to 40 percent reduction needed by the industrialized countries of the world by 2020, there is no time to waste.

At the same time, ocean acidification should not be seen as a reason to throw up our hands and cry that saving the oceans is hopeless; it is not. Rather we should realize the seriousness of this threat and take immediate appropriate actions to move society away from our dependence on carbon-based fossil fuels to a low carbon future in which coral reefs and other marine organisms will not be threatened by acidic waters.



Wind turbine.



# RECOMMENDATIONS

## *Adopt a Policy of Stabilizing Atmospheric Carbon Dioxide at 350 ppm*

Governments must commit to stabilizing the levels of carbon dioxide in the atmosphere at 350 ppm or below. To achieve this, serious strides need to be taken within the next five years to set society on a path to zero net carbon emissions within the coming decades.

## *Promote Energy Efficiency and Low Carbon Fuels*

Energy should be conserved at every opportunity, including through improved fuel efficiency of cars, trucks, airplanes and ships, provision of cleaner fuels, investment in efficient mass transit, and individual, institutional and corporate actions to reduce energy use.

## *Shift to Alternative Energy Sources*

New or expanded coal-fired power plants and other expanded uses of coal should be prohibited until global warming pollution can be trapped and safely stored. In their place, governments and the private sector should implement programs to stimulate the development and use of renewable energy options such as wind and solar, and invest in upgrading the national power transmission grid so that energy produced from alternative sources can be cost-effectively moved to markets. Governments should immediately eliminate any and all subsidies that encourage the use of fossil fuels. Fossil fuels currently in the ground in sensitive ecosystems such as the Arctic and offshore should stay in the ground.

## *Regulate Carbon Releases*

Governments should immediately begin regulating carbon releases using a system that internalizes emissions costs and prevents continued releases that harm the oceans. Under-regulated sources of carbon dioxide emissions, such as those from shipping and aircraft should be included in a post-Kyoto Agreement and regulated by the appropriate international bodies, such as the International Maritime Organization and the International Civil Aviation Organization.

## *Preserve Natural Resilience*

The natural resilience of marine ecosystem should be maintained by curtailing other human caused threats, such as overfishing and pollution. Ocean acidification and climate change are not isolated threats, but act in concert with other impacts on ecosystems and species. Ocean ecosystems will have the best chance of surviving the pressures of ocean acidification if they are not simultaneously struggling to survive in the face of other threats.

Photo: E. Harrould-Kolieb

## ENDNOTES

- 1 Sabine, C.L. et al. (2004) The Oceanic Sink for Anthropogenic CO<sub>2</sub>, *Science* 305:367-371
- 2 IPCC (2007) Summary for Policymakers. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*
- 3 Caldeira, Ken and Michael E. Wickett (2005) Ocean Model Predictions of Chemistry Changes from Carbon Dioxide Emissions to the Atmosphere and Ocean, *Journal of Geophysical Research*, Vol. 110
- 4 Hoegh-Guldberg, Ove et al. (2007) Coral Reefs Under Rapid Climate Change and Ocean Acidification, *Science*, 318:1737-1742
- 5 NASA Jet Propulsion Laboratory; Global Climate Change, NASA's Eyes on the Earth, <http://climate.jpl.nasa.gov/>
- 6 Luthi, Dieter et al. (2005) High-resolution in carbon dioxide concentration record 650,000-800,000 years before present, *Nature*, 433:379-382
- 7 Energy Information Administration (EIA) (2008) International Energy Outlook 2008, Highlights, <http://www.eia.doe.gov/total/energyhighlights.html>
- 8 Energy Information Administration (EIA) (2008) International Energy Outlook 2008, Highlights, <http://www.eia.doe.gov/total/energyhighlights.html>
- 9 Hoegh-Guldberg, Ove et al. (2007) Coral Reefs Under Rapid Climate Change and Ocean Acidification, *Science*, 318:1737-1742
- 10 Hoegh-Guldberg, Ove et al. (2007) Coral Reefs Under Rapid Climate Change and Ocean Acidification, *Science*, 318:1737-1742
- 11 IPCC (2007) Summary for Policymakers. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*
- 12 Luthi, Dieter et al. (2005) High-resolution in carbon dioxide concentration record 650,000-800,000 years before present, *Nature*, 433:379-382
- 13 Orr, James C. et al. (2005) Anthropogenic Ocean Acidification Over the Twenty-first Century and Its Impact on Calcifying Organisms, *Nature*, 437:681-686
- 14 Caldeira, K. and Wickett, M.E. (2005) Ocean model predictions of chemistry changes from carbon dioxide emissions to the atmosphere and ocean, *Journal of Geophysical Research*, 10: C09S04
- 15 Turley, C.M., J.M. Roberts and J.M. Guinotte (2007) Corals in deep-water: Will the unseen hand of ocean acidification destroy cold-water ecosystems? *Coral Reefs*, 26:445-448
- 16 Fabry, Victoria J. et al. (2008) Impacts of Ocean Acidification on Marine Fauna and Ecosystem Processes, *ICES Journal of Marine Science*, 65:414-432
- 17 Hoegh-Guldberg, Ove (2005) Low Coral Cover In a High-CO<sub>2</sub> World, *Journal of Geophysical Research*, 110:C09S06
- 18 Fabry, Victoria J. et al. (2008) Impacts of Ocean Acidification on Marine Fauna and Ecosystem Processes, *ICES Journal of Marine Science*, 65:414-432
- 19 Feely, Richard, et al. (2004) Impacts of Anthropogenic CO<sub>2</sub> on the CaCO<sub>3</sub> System in the Oceans, *Science*, 305:362-366
- 20 Gazeau, Frederic et al. (2007) Impact of Elevated CO<sub>2</sub> on Shellfish Calcification, *Geophysical Research Letters*, 34
- 21 For example: Blibby, R. et al. (2008) Effects of Ocean Acidification on the Immune Response of the Blue Mussel *Mytilus edulis*, *Aquatic Biology*, 2:67-74, Portner, Hans O., Martina Langenbuch and Anke Reipschläger (2004) Biological Impact of Elevated Carbon Dioxide Concentrations: Lessons from animal physiology and Earth History, *Journal of Oceanography*, 60:705-718, Kurihara, Haruko, Shinji Shimode and Yoshitaka Shrayama (2004) Sub-Lethal Effects of Elevated Concentration of CO<sub>2</sub> on Planktonic Copepods and Sea Urchins, *Journal of Oceanography*, 60:743-750, Castro, K. et al (2006) The Conceptual Approach to Lobster Shell Disease Revisited, *Journal of Crustacean Biology*, 26(4):646-660
- 22 Fabry, Victoria J. et al. (2008) Impacts of Ocean Acidification on Marine Fauna and Ecosystem Processes, *ICES Journal of Marine Science*, 65:414-432
- 23 Caldeira, Ken. (2007) What Corals are Dying to Tell Us: About CO<sub>2</sub> and Ocean Acidification, Roger Revelle Commemorative Lecture, *Oceanography*, 20(2):188-195
- 24 Hoegh-Guldberg, Ove et al. (2007) Coral Reefs Under Rapid Climate Change and Ocean Acidification, *Science*, 318:1737-1742
- 25 Guinotte, J.M. et al. (2006) Will human-induced changes in seawater chemistry alter the distribution of deep-sea corals? *Frontiers Ecol. Env.* 4:141-146
- 26 Hoegh-Guldberg, Ove (2005) Low Coral Cover in a High-CO<sub>2</sub> World, *Journal of Geophysical Research*, 110:C09S06
- 27 Hoegh-Guldberg, Ove (2005) Low Coral Cover in a High-CO<sub>2</sub> World, *Journal of Geophysical Research*, 110:C09S06
- 28 FAO (Food and Agriculture Organisation) (2004) *The State of the World Fisheries and Aquaculture 2004*, FAO, Rome
- 29 Ishimatsu, Atsushi et al. (2004) Effects of CO<sub>2</sub> on Marine Fish: Larvae and Adults, *Journal of Oceanography*, 60:731-741
- 30 Roberts, S. and Hirschfeld, M. (2004) Deep Sea Corals: Out of Sight, But no Longer out of Mind, *Front. Ecol. Environ.*, 3:123-130
- 31 IPCC (2007) Summary for Policymakers. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*
- 32 Hansen, J. et al. (2008) Target Atmospheric CO<sub>2</sub>: Where Should Humanity Aim?
- 33 Hoegh-Guldberg, Ove et al. (2007) Coral Reefs Under Rapid Climate Change and Ocean Acidification, *Science*, 318:1737-1742
- 34 Caldeira, Ken. (2007) What Corals are Dying to Tell Us: About CO<sub>2</sub> and Ocean Acidification, Roger Revelle Commemorative Lecture, *Oceanography*, 20(2):188-195
- 35 Caldeira, Ken and Michael E. Wickett (2005) Ocean Model Predictions of Chemistry Changes from Carbon Dioxide Emissions to the Atmosphere and Ocean, *Journal of Geophysical Research*, 110:C09S04
- 36 Fabry, Victoria J. et al. (2008) Impacts of Ocean Acidification on Marine Fauna and Ecosystem Processes, *ICES Journal of Marine Science*, 65:414-432
- 37 Sabine, C.L. et al. (2004) The Oceanic Sink for Anthropogenic CO<sub>2</sub>, *Science*, 305:367-371
- 38 Watson, A.J. and J.C. Orr (2003) "Carbon dioxide fluxes in the global ocean" In M.J.R. Fasham (Ed.) *Ocean Biogeochemistry*. The IGBP Series, Springer, New York
- 39 Schubert, R. et al. (2006) The Future Ocean – Warming Up, Rising High, Turning Sour: Special Report, German Advisory Council on Global Change (WBGU)
- 40 Orr, James C. et al. (2005) Anthropogenic Ocean Acidification Over the Twenty-first Century and Its Impact on Calcifying Organisms, *Nature*, 437:681-686
- 41 Caldeira, K. and Wickett, M.E. (2003) Anthropogenic Carbon and Ocean pH, *Nature* 425:365
- 42 Orr, James C. et al. (2005) Anthropogenic Ocean Acidification Over the Twenty-first Century and Its Impact on Calcifying Organisms, *Nature*, 437:681-686
- 43 Bindoff, N.L., et al. (2007) Observations: Oceanic Climate Change and Sea Level. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- 44 Caldeira, Ken and Michael E. Wickett (2005) Ocean Model Predictions of Chemistry Changes from Carbon Dioxide Emissions to the Atmosphere and Ocean, *Journal of Geophysical Research*, Vol. 110
- 45 Luthi, Dieter et al. (2005) High-resolution in carbon dioxide concentration record 650,000-800,000 years before present, *Nature*, 433:379-382 and Turley, C.M., J.M. Roberts and J.M. Guinotte (2007) Corals in deep-water: Will the unseen hand of ocean acidification destroy cold-water ecosystems? *Coral Reefs*, 26:445-448 and Bindoff, N.L., et al. (2007) Observations: Oceanic Climate Change and Sea Level. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- 46 Sabine, C.L. et al. (2004) The oceanic sink for anthropogenic CO<sub>2</sub>. *Science* 305: 367-371
- 47 Sabine, C.L. and R. Feely (2007) The Oceanic Sink for Carbon Dioxide In Greenhouse Gas Sinks, D. Reay et al. (Eds.) CABI Publishing, Oxfordshire, UK
- 48 Sabine, C.L. et al. (2004) The



- Oceanic Sink for Anthropogenic CO<sub>2</sub>, *Science* 305:367-371
- 49 Feely, R.A. et al. (2008) Evidence for Upwelling of Corrosive "Acidified" Water onto the Continental Shelf, Report, Scienceexpress, 10:1126
- 50 Calculated from: EIA (2007) Emissions of Greenhouse Gases in the United States 2006, DOE/EIA-0573(2006)
- 51 Luthi, Dieter et al. (2005) High-resolution in carbon dioxide concentration record 650,000-800,000 years before present, *Nature*, 453:379-382
- 52 Turley, C.M., J.M. Roberts and J.M. Guinotte (2007) Corals in deep-water: Will the unseen hand of ocean acidification destroy cold-water ecosystems? *Coral Reefs*, 26:445-448
- 53 Raven, John et al. (2005) Ocean Acidification due to Increasing Atmospheric Carbon Dioxide, The Royal Society
- 54 Siegenthaler, U. et al. (2005) Stable carbon cycle-climate relationship during the late Pleistocene, *Science*, 310:1313-1317
- 55 Raven, John et al. (2005) Ocean Acidification due to Increasing Atmospheric Carbon Dioxide, The Royal Society
- 56 Adapted from: Fernand, L. and Brewer, P. (Eds) (2007) Report of the Workshop on the Significance of Changing Ocean CO<sub>2</sub> and pH in Shelf Sea Ecosystems, defra and ICES CIEM
- 57 Caldeira, K. and Wickett, M.E. (2003) Anthropogenic Carbon and Ocean pH, *Nature* 425:365
- 58 Feely, R.A. et al. (2004) Impact of Anthropogenic CO<sub>2</sub> on the CaCO<sub>3</sub> system in the oceans, *Science* 305:362-366
- 59 Veron, J.E.N. (2008) A Reef in Time: The Great Barrier Reef from Beginning to End, Harvard University Press, Sydney
- 60 Turley, C.M., J.M. Roberts and J.M. Guinotte (2007) Corals in deep-water: Will the unseen hand of ocean acidification destroy cold-water ecosystems? *Coral Reefs*, 26:445-448
- 61 Zachos, James, et al. (2005) Rapid Acidification of the Ocean During the Paleocene-Eocene Thermal Maximum, *Science*, 308:1611-1615
- 62 Caldeira, Ken. (2007) What Corals are Dying to Tell Us: About CO<sub>2</sub> and Ocean Acidification, Roger Revelle Commemorative Lecture, *Oceanography*, 20(2):188-195
- 63 Raven, John et al. (2005) Ocean Acidification due to Increasing Atmospheric Carbon Dioxide, The Royal Society
- 64 Feely, Richard, et al. (2004) Impacts of Anthropogenic CO<sub>2</sub> on the CaCO<sub>3</sub> System in the Oceans, *Science*, 305:362-366
- 65 Orr, James C. et al. (2005) Anthropogenic Ocean Acidification Over the Twenty-First Century and its Impacts on Calcifying Organisms, *Nature*, 437:681-686
- 66 Fabry, Victoria J. et al. (2008) Impacts of Ocean Acidification on Marine Fauna and Ecosystem Processes, *ICES Journal of Marine Science*, 65:414-432
- 67 Doney, Scott C. (2007) The Dangers of Ocean Acidification, *Scientific American*, 294:58-65
- 68 Gehlen, M. et al. (2007) The Fate of Pelagic CaCO<sub>3</sub> Production in a High-CO<sub>2</sub> Ocean: A model study, *Biogeosciences*, 5:505-519
- 69 Orr, James C. et al. (2005) Anthropogenic Ocean Acidification Over the Twenty-first Century and its Impact on Calcifying Organisms, *Nature*, 437:681-686
- 70 Gehlen, M. et al. (2007) The Fate of Pelagic CaCO<sub>3</sub> Production in a high CO<sub>2</sub> Ocean: A model study, *Biogeosciences*, 4:505-519
- 71 Orr, James C. et al. (2005) Anthropogenic Ocean Acidification Over the Twenty-first Century and its Impact on Calcifying Organisms, *Nature*, 437:681-686
- 72 Schubert, R. et al. (2006) The Future Ocean – Warming Up, Rising High, Turning Sour: Special Report, German Advisory Council on Global Change (WBGU)
- 73 Orr, James C. et al. (2005) Anthropogenic Ocean Acidification Over the Twenty-First Century and its Impacts on Calcifying Organisms, *Nature*, 437:681-686
- 74 Cao L., & Caldeira K. (2008) Atmospheric CO<sub>2</sub> stabilization and ocean acidification. *Geophysical Research Letters*, in press
- 75 Orr, James C. et al. (2006) Arctic Ocean Acidification, *EOS Transactions of the American Geophysical Union*, 87(36), Ocean Sciences Meeting Supplement, Abstract DS14B-01
- 76 Blibby, R. et al. (2008) Effects of Ocean Acidification on the Immune Response of the Blue Mussel *Mytilus edulis*, *Aquatic Biology*, 2:67-74
- 77 Raven, John et al. (2005) Ocean Acidification due to Increasing Atmospheric Carbon Dioxide, The Royal Society
- 78 Caldeira, Ken. (2007) What Corals are Dying to Tell Us: About CO<sub>2</sub> and Ocean Acidification, Roger Revelle Commemorative Lecture, *Oceanography*, 20(2):188-195
- 79 Kleypas, Joan and Chris Langdon (2000) Overview of CO<sub>2</sub>-Induced Changes in Seawater Chemistry, Proceedings of the 9th International Coral Reef Symposium, Bali, Indonesia, 2:1085-1089
- 80 Feely, Richard A. (2004) Impact of Anthropogenic CO<sub>2</sub> on the CaCO<sub>3</sub> System in the Oceans, *Science*, 305:362-266
- 81 Gehlen, M. et al. (2007) The Fate of Pelagic CaCO<sub>3</sub> Production in a high CO<sub>2</sub> Ocean: A model study, *Biogeosciences*, 4:505-519
- 82 Kleypas, J.A. et al. (2006) Impacts of Ocean Acidification on Coral Reefs and Other Marine Calcifiers: A guide for future research, Report on a workshop sponsored by NSF, NOAA, USGS
- 83 Sakai, K. (1998) Delayed maturation in the colonial coral *Goniastrea aspera* (Scleractinia): Whole-colony mortality, colony growth and polyp egg production, *Res. Popul. Ecol.*, 40:287-292
- 84 Kleypas, J.A. et al. (2006) Impacts of Ocean Acidification on Coral Reefs and Other Marine Calcifiers: A guide for future research, Report on a workshop sponsored by NSF, NOAA, USGS
- 85 Gehlen, M. et al. (2007) The Fate of Pelagic CaCO<sub>3</sub> Production in a high CO<sub>2</sub> Ocean: A model study, *Biogeosciences*, 4:505-519
- 86 Personal correspondence with Ove Hoegh-Guldberg, 24 October 2007
- 87 Caldeira, Ken. (2007) What Corals are Dying to Tell Us: About CO<sub>2</sub> and Ocean Acidification, Roger Revelle Commemorative Lecture, *Oceanography*, 20(2):188-195
- 88 Turley, C.M., J.M. Roberts and J.M. Guinotte (2007) Corals in deep-water: Will the unseen hand of ocean acidification destroy cold-water ecosystems? *Coral Reefs*, 26:445-448
- 89 Hoegh-Guldberg, Ove (2005) Low Coral Cover in a High-CO<sub>2</sub> World, *Journal of Geophysical Research*, 110:C09S06
- 90 Hoegh-Guldberg, Ove et al. (2007) Coral Reefs Under Rapid Climate Change and Ocean Acidification, *Science*, 318:1737-1742
- 91 Cao L., & Caldeira K. (2008) Atmospheric CO<sub>2</sub> stabilization and ocean acidification. *Geophysical Research Letters*, in press; and Personal correspondence with Ken Caldeira
- 92 Hoegh-Guldberg, Ove et al. (2007) Coral Reefs Under Rapid Climate Change and Ocean Acidification, *Science*, 318:1737-1742
- 93 Hoegh-Guldberg, Ove et al. (2007) Coral Reefs Under Rapid Climate Change and Ocean Acidification, *Science*, 318:1737-1742
- 94 Turley, C.M., J.M. Roberts and J.M. Guinotte (2007) Corals in deep-water: Will the unseen hand of ocean acidification destroy cold-water ecosystems? *Coral Reefs*, 26:445-448
- 95 Hoegh-Guldberg, Ove et al. (2007) Coral Reefs Under Rapid Climate Change and Ocean Acidification, *Science*, 318:1737-1742
- 96 Hoegh-Guldberg, Ove et al. (2007) Coral Reefs Under Rapid Climate Change and Ocean Acidification, *Science*, 318:1737-1742
- 97 Hoegh-Guldberg, Ove (2005) Low Coral Cover in a High-CO<sub>2</sub> World, *Journal of Geophysical Research*, 110
- 98 Stone, Richard (2007) A World Without Corals? *Science*, 316:678-681
- 99 Hoegh-Guldberg, Ove et al. (2007) Coral Reefs Under Rapid Climate Change and Ocean Acidification, *Science*, 318:1737-1742
- 100 Raven, John et al. (2005) Ocean Acidification due to Increasing Atmospheric Carbon Dioxide, The Royal Society
- 101 Caldeira, Ken. (2007) What Corals are Dying to Tell Us: About CO<sub>2</sub> and Ocean Acidification, Roger Revelle Commemorative Lecture, *Oceanography*, 20(2):188-195
- 102 Turley, C.M., J.M. Roberts and J.M. Guinotte (2007) Corals in Deep-Water: Will the unseen hand of ocean acidification destroy cold-water ecosystems? *Coral Reefs*, 26(3):445-448
- 103 Roberts, S. and Hirshfield, M. (2004) Deep Sea Corals: Out of Sight, But no Longer out of Mind, *Front. Ecol. Environ.*, 3:123-130
- 104 Husebo, A. et al. (2002) Distribution and abundance of fish in deep-sea coral habitats, *Hydrobiologia*, 471:91-99

- 105 Guinotte, John M. et al. (2006) Will Human-Induced Changes in Seawater Chemistry Alter the Distribution of Deep-Sea Scleractinian Corals? *Frontiers in Ecological Environment*, 4(3):141-146
- 106 Maxwell, S. (2005) An aquatic pharmacy: The biomedical potential of the deep sea. *Current: The Journal of Marine Education* 21(4):31-32
- 107 Erlich, H. et al. (2005) Deep-Sea Bamboo Corals: Living Bone Implants. 3rd International Symposium on Deep-Sea Corals: Science and Management
- 108 Guinotte, John M. and Victoria J. Fabry (2008) Ocean Acidification and its Potential Effects on Marine Ecosystems, *Annals of the New York Academy of Sciences*, 1134:320-342
- 109 Turley, C.M., J.M. Roberts and J.M. Guinotte (2007) Corals in deep-water: Will the unseen hand of ocean acidification destroy cold-water ecosystems? *Coral Reefs*, 26:445-448
- 110 Turley, C.M., J.M. Roberts and J.M. Guinotte (2007) Corals in Deep-Water: Will the unseen hand of ocean acidification destroy cold-water ecosystems? *Coral Reefs*, 26(3):445-448
- 111 Guinotte, J.M. et al. (2006) Will human-induced changes in seawater chemistry alter the distribution of deep-sea corals? *Frontiers Ecol. Env.* 4:141-146
- 112 Guinotte, J.M. et al. (2006) Will human-induced changes in seawater chemistry alter the distribution of deep-sea corals? *Frontiers Ecol. Env.* 4:141-146
- 113 Guinotte, John M. and Victoria J. Fabry (2008) Ocean Acidification and its Potential Effects on Marine Ecosystems, *Annals of the New York Academy of Sciences*, 1134:320-342
- 114 Roberts, J. Murray, et al. (2006) *Reefs of the Deep: The Biology and Geology of Cold-Water Coral Ecosystems*, Science, 312:543-547
- 115 Guinotte, John M. and Victoria J. Fabry (2008) Ocean Acidification and its Potential Effects on Marine Ecosystems, *Annals of the New York Academy of Sciences*, 1134:320-342
- 116 ISRS (2007) Coral Reefs and Ocean Acidification Briefing Paper 5, International Society for Reef Studies
- 117 Turley, C.M., J.M. Roberts and J.M. Guinotte (2007) Corals in deep-water: Will the unseen hand of ocean acidification destroy cold-water ecosystems? *Coral Reefs*, 26:445-448
- 118 Turley, C.M., J.M. Roberts and J.M. Guinotte (2007) Corals in deep-water: Will the unseen hand of ocean acidification destroy cold-water ecosystems? *Coral Reefs*, 26:445-448
- 119 Guinotte, J.M. et al. (2006) Will human-induced changes in seawater chemistry alter the distribution of deep-sea corals? *Frontiers Ecol. Env.* 4:141-146
- 120 Guinotte, J.M. et al. (2006) Will human-induced changes in seawater chemistry alter the distribution of deep-sea corals? *Frontiers Ecol. Env.* 4:141-146
- 121 Raven, John et al. (2005) Ocean Acidification due to Increasing Atmospheric Carbon Dioxide, *The Royal Society*
- 122 Caldeira, Ken and Michael E. Wickett (2003) Anthropogenic Carbon and Ocean pH: The coming centuries may see more ocean acidification than the past 300 million years, *Nature*, 425
- 123 Gehlen, M. et al. (2007) The Fate of Pelagic CaCO<sub>3</sub> Production in a high CO<sub>2</sub> Ocean: A model study, *Biogeosciences*, 4:505-519
- 124 Jokiel, P.L. et al. (2008) Ocean Acidification and Calcifying Reef Organisms: A mesocosm investigation, *Coral Reefs*, 27:473-483
- 125 Guinotte, John M. and Victoria J. Fabry (2008) Ocean Acidification and its Potential Effects on Marine Ecosystems, *Annals of the New York Academy of Sciences*, 1134:320-342
- 126 Jokiel, P.L. et al. (2008) Ocean Acidification and Calcifying Reef Organisms: A mesocosm investigation, *Coral Reefs*, 27:473-483
- 127 Jokiel, P.L. et al. (2008) Ocean Acidification and Calcifying Reef Organisms: A mesocosm investigation, *Coral Reefs*, 27:473-483
- 128 Orr, James C. et al. (2005) Anthropogenic Ocean Acidification Over the Twenty-First Century and its Impacts on Calcifying Organisms, *Nature*, 437:681-686
- 129 Aydin, Kerim Y. et al. (2005) Linking ocean food webs to coastal production and growth rates of Pacific Salmon (*Oncorhynchus* spp.), using models on three scales, *Deep Sea Research Part II: Tropical Studies in Oceanography*, 52(5-6):757-780
- 130 Fabry, Victoria J. et al. (2008) Impacts of Ocean Acidification on Marine Fauna and Ecosystem Processes, *ICES Journal of Marine Science*, 65:414-432
- 131 Guinotte, John M. and Victoria J. Fabry (2008) Ocean Acidification and its Potential Effects on Marine Ecosystems, *Annals of the New York Academy of Sciences*, 1134:320-342
- 132 Guinotte, John M. and Victoria J. Fabry (2008) Ocean Acidification and its Potential Effects on Marine Ecosystems, *Annals of the New York Academy of Sciences*, 1134:320-342
- 133 Gehlen, M. et al. (2007) The Fate of Pelagic CaCO<sub>3</sub> Production in a high CO<sub>2</sub> Ocean: A model study, *Biogeosciences*, 4:505-519
- 134 Iglesias-Rodriguez, M. Deborá et al. (2008) Phytoplankton Calcification in a High-CO<sub>2</sub> World, *Science*, 320:336-340
- 135 Tyrell, T. et al. (1999) Optical Impacts of Oceanic Coccolithophore Blooms. *Journal of Geophysical Research*, 104(C2):3323-3341
- 136 Vogt, M. et al. (2008) Dynamics of dimethylsulphoniopropionate and dimethylsulphide under different CO<sub>2</sub> concentrations during a mesocosm experiment, *Biogeosciences*, 5:407-419
- 137 Charlson, R., et al. (1987) Oceanic Phytoplankton, Atmospheric Sulphur, Cloud Albedo and Climate, *Nature*, 326:655-661
- 138 Nevitt, G. and Haberman, K. (2003) Behavioral attraction of Leach's storm-petrels (*Oceanodroma leucorhoa*) to dimethyl sulfide, *The Journal of Experimental Biology*, 206:1497-1501
- 139 DeBose, J, Lema, S. and Nevitt, G. (2008) Dimethylsulfoniopropionate as a Foraging Cue for Reef Fish, *Science*, 319:1356
- 140 Kowalewski, S. et al. (2006) High Olfactory Sensitivity for Dimethyl Sulphide in Harbor Seals, *Biology Letters*, 2:106-109
- 141 Shirayama, Y. and H. Thorton (2005) Effect of Increased Atmospheric CO<sub>2</sub> on Shallow Water Marine Benthos, *Journal of Geophysical Research*, 110:C09S08
- 142 Kleypas, JA et al. (2006) Impacts of Ocean Acidification on Coral Reefs and Other Marine Calcifiers: A guide for future research, Report on a workshop sponsored by NSF, NOAA, USGS
- 143 Raven, John et al. (2005) Ocean Acidification due to Increasing Atmospheric Carbon Dioxide, *The Royal Society*
- 144 Bibby, R. et al. (2008) Effects of Ocean Acidification on the Immune Response of the Blue Mussel *Mytilus edulis*, *Aquatic Biology*, 2:67-74
- 145 Portner, Hans O., Martina Langenbuch and Anke Relpschlager (2004) Biological Impact of Elevated Carbon Dioxide Concentrations: Lessons from animal physiology and Earth History, *Journal of Oceanography*, 60:705-718
- 146 Kurihara, Haruko, Shinji Shimode and Yoshihisa Shirayama (2004) Sub-Lethal Effects of Elevated Concentration of CO<sub>2</sub> on Planktonic Copepods and Sea Urchins, *Journal of Oceanography*, 60:743-750
- 147 Castro, K. et al. (2006) The Conceptual Approach to Lobster Shell Disease Revisited, *Journal of Crustacean Biology*, 26(4):646-660
- 148 Personal Communications with Dr. Robert Steneck
- 149 Portner, Hans O., Martina Langenbuch and Anke Relpschlager (2004) Biological Impact of Elevated Carbon Dioxide Concentrations: Lessons from animal physiology and Earth History, *Journal of Oceanography*, 60:705-718
- 150 Ishimatsu, Atsushi, et al. (2004) Effects of Carbon Dioxide on Marine Fish: Larvae and Adults, *Journal of Oceanography*, 60:731-741
- 151 Bibby, R. et al. (2007) Ocean Acidification Disrupts Induced Defences in the Intertidal Gastropod *Littorina littorea*, *Biology Letters*, 3:699-701
- 152 Kurihara, Haruko, Shinji Shimode and Yoshihisa Shirayama (2004) Sub-Lethal Effects of Elevated Concentration of CO<sub>2</sub> on Planktonic Copepods and Sea Urchins, *Journal of Oceanography*, 60:743-750
- 153 Havenhand, Jon. et al. (2008) Near-future levels of ocean acidification reduce fertilization success in a sea urchin, *Current Biology*, 18(5):651-652
- 154 Dong, Q.X. et al. (2002) Factors affecting sperm motility of tetraploid Pacific oysters, *Journal of Shellfish Research*, 21:719-723
- 155 Luo, J. et al. (2004) The Influence of pH and salinity in hatching rate of egg sac of *Babylonia areolata* and the effect of different diet on the development, survival rate of the larvae, *Marine Sciences/Haiyang Kexue* 28:6:5-9
- 156 Kurihara, H. et al. (2004) Effects of raised CO<sub>2</sub> concentration on the egg production rates and early development of two marine copepods (*Acartia* sp. and *Acartia erythraea*), *Marine Pollution Bulletin*, 49:721-727
- 157 Kurihara, Haruko and Atsushi Ishimatsu (2008) Effects of high CO<sub>2</sub> seawater on the copepod (*Acartia tsuensis*) through all life stages and subsequent generations, *Marine Pollution Bulletin*, 56(6):1086-1090
- 158 Written testimony of Ken Caldeira, Climate Change and Acidification are Affecting our Oceans; presented before the Subcommittee on Fisheries, Wildlife and Oceans House Committee on Natural Resources, "Wildlife and Oceans in a Changing Climate" hearing, 17 April 2007
- 159 Portner, Hans O. and S. Zielinsk (1998) Environmental Constraints and the Physiology of Performance in Squids, *South African Journal of Marine Science*, 20:207-221



- 160 Portner, Hans O., Martina Langenbuch and Anke Reipschläger (2004) Biological Impact of Elevated Carbon Dioxide Concentrations: Lessons from animal physiology and Earth History, *Journal of Oceanography*, 60:705-718
- 161 Portner, Hans O., Martina Langenbuch and Anke Reipschläger (2004) Biological Impact of Elevated Carbon Dioxide Concentrations: Lessons from animal physiology and Earth History, *Journal of Oceanography*, 60:705-718
- 162 Bibby, R. et al... (2007) Ocean Acidification Disrupts Induced Defences in the Intertidal Gastropod *Littorina littorea*, *Biology Letters*, 3:699-701
- 163 Bibby, R. et al... (2007) Ocean Acidification Disrupts Induced Defences in the Intertidal Gastropod *Littorina littorea*, *Biology Letters*, 3:699-701
- 164 Wood, Hannah L. et al... (2008) Ocean acidification may increase calcification rates, but at a cost, *Proceedings of the Royal Society B*, 274(1644):1767-1773
- 165 Raven, John et al... (2005) Ocean Acidification due to Increasing Atmospheric Carbon Dioxide, *The Royal Society*
- 166 Fabry, Victoria J. et al... (2008) Impacts of Ocean Acidification on Marine Fauna and Ecosystem Processes, *ICES Journal of Marine Science*, 65:414-432
- 167 Ishimatsu, Atsushi, et al... (2004) Effects of Carbon Dioxide on Marine Fish: Larvae and Adults, *Journal of Oceanography*, 60: 731-741
- 168 Kurihara, Haruko, Shinji Shimode and Yoshihisa Shirayama (2004) Sub-Lethal Effects of Elevated Concentration of CO<sub>2</sub> on Planktonic Copepods and Sea Urchins, *Journal of Oceanography*, 60:743-750
- 169 Gazeau, Frederic et al... (2007) Impact of Elevated Carbon Dioxide on Shellfish Acidification, *Geophysical Research Letters*, Vol. 34
- 170 Gazeau, Frederic et al... (2007) Impact of Elevated Carbon Dioxide on Shellfish Acidification, *Geophysical Research Letters*, Vol. 34
- 171 Gazeau, Frederic et al... (2007) Impact of Elevated Carbon Dioxide on Shellfish Acidification, *Geophysical Research Letters*, Vol. 34
- 172 Gazeau, Frederic et al... (2007) Impact of Elevated CO<sub>2</sub> on Shellfish Calcification, *Geophysical Research Letters*, 34
- 173 Nagarajan, R., Lea, S., and Goss-Custard, J.D. (2006) Seasonal Variations in Mussel, *Mytilus edulis* L. Shell Thickness and Strength and Their Ecological Implications, *Journal of Experimental Marine Biology and Ecology*, 339:241-250
- 174 Gazeau, F. et al... (2007) Impact of Elevated CO<sub>2</sub> on Shellfish Calcification, *Geophysical Research Letters*, 34:L07603
- 175 Michaelidis, B. et al... (2005) Effects of Long-Term Moderate Hypercapnia on Acid-Base Balance and Growth Rate in Marine Mussels *Mytilus galloprovincialis*, *Marine Ecological Progress*, 293:109-118
- 176 Berge, J.A. et al... (2006) Effects of Increased Sea Water Concentrations of CO<sub>2</sub> on the Growth of the Bivalve *Mytilus edulis* L., *Chemosphere*, 62:681-687
- 177 Bibby, R. et al... (2007) Ocean Acidification Disrupts Induced Defences in the Intertidal Gastropod *Littorina littorea*, *Biology Letters*, 3:699-701
- 178 Hoegh-Guldberg, Ove (2005) Low Coral Cover in a High-CO<sub>2</sub> World, *Journal of Geophysical research*, 110:C09S06
- 179 Cesar, H. et al... (2003) The Economics of Worldwide Coral Reef Degradation, *Cesar Environmental Economics Consulting*
- 180 FAO (Food and Agriculture Organisation) (2004) *The State of the World Fisheries and Aquaculture 2004*, FAO, Rome
- 181 Cesar, H. et al... (2003) The Economics of Worldwide Coral Reef Degradation, *Cesar Environmental Economics Consulting*
- 182 Fernando, H. et al... (2005) Coral Poaching Worsens Tsunami Destruction in Sri Lanka, *EOS Trans. AGU*, 86:33
- 183 On Asia's Coasts, Progress destroys natural defenses, *The Wall Street Journal*, Dec 31, 2004, Reported by A. Brown
- 184 Kunkel, C. et al... (2006) Coral Reefs Reduce Tsunami Impact in Model Simulations, *Geophysical Research Letters*, 33:L23612
- 185 U.S. EPA; Region 9; Water Program; Oceans, Coasts and Estuaries; Coral Reefs, [www.epa.gov/region09/water/occe/coralreefs.html](http://www.epa.gov/region09/water/occe/coralreefs.html)
- 186 FAO (2007) *The State of World Fisheries and Aquaculture, 2006*, FAO Fisheries and Aquaculture Department
- 187 Ishimatsu, Atsushi et al... (2004) Effects of CO<sub>2</sub> on Marine Fish: Larvae and Adults, *Journal of Oceanography*, 60:731-741
- 188 Kokita, T. and A. Nakazono (2001) Rapid response of an obligately corallivorous flatfish *Oxymonacanthus longirostris* (Monacanthidae) to a mass coral bleaching event, *Coral Reefs*, 20:155-158
- 189 Turley, C.M., J.M. Roberts and J.M. Gulnotte (2007) Corals in Deep-Water: Will the unseen hand of ocean acidification destroy cold-water ecosystems? *Coral Reefs*, 26(3):445-448
- 190 Roberts, S. and Hirschfeld, M. (2004) Deep Sea Corals: Out of Sight, But no Longer out of Mind, *Front. Ecol. Environ.*, 3:123-130
- 191 Pritchard, E. S. (Ed) (2008) *Fisheries of the United States, 2007*, National Marine Fisheries Service, Office of Science and Technology, [http://www.st.nmfs.noaa.gov/st1/fus/fus07/fus\\_2007.pdf](http://www.st.nmfs.noaa.gov/st1/fus/fus07/fus_2007.pdf)
- 192 Portner, Hans O., Martina Langenbuch and Anke Reipschläger (2004) Biological Impact of Elevated CO<sub>2</sub> Concentrations: Lessons from animal physiology and Earth history, *Journal of Oceanography*, 60:705-718
- 193 Portner, Hans O., Martina Langenbuch and Anke Reipschläger (2004) Biological Impact of Elevated Carbon Dioxide Concentrations: Lessons from animal physiology and Earth History, *Journal of Oceanography*, 60:705-718
- 194 Gulnotte, John M. and Victoria J. Fabry (2008) Ocean Acidification and its Potential Effects on Marine Ecosystems, *Annals of the New York Academy of Sciences*, 1134:320-342
- 195 FAO (Food and Agriculture Organisation) (2004) *The State of the World Fisheries and Aquaculture 2004*, FAO, Rome
- 196 Raven, John et al... (2005) Ocean Acidification due to Increasing Atmospheric Carbon Dioxide, *The Royal Society*
- 197 Gazeau, Frederic et al... (2007) Impact of Elevated CO<sub>2</sub> on Shellfish Calcification, *Geophysical Research Letters*, 34
- 198 FIGIS: Global Production Statistics 1950-2005: [www.fao.org/figis](http://www.fao.org/figis)
- 199 NMFS: Annual Commercial Landing Statistics; [www.st.nmfs.noaa.gov/pls/webpls/FT\\_HELP.SPECIES](http://www.st.nmfs.noaa.gov/pls/webpls/FT_HELP.SPECIES)
- 200 Hoegh-Guldberg, Ove et al... (2007) Coral Reefs Under Rapid Climate Change and Ocean Acidification, *Science*, 318:1737-1742
- 201 NASA Jet Propulsion Laboratory; Global Climate Change, NASA's Eyes on the Earth, <http://climate.jpl.nasa.gov/>
- 202 Luthi, Dieter et al... (2005) High-resolution in carbon dioxide concentration record 650,000-800,000 years before present, *Nature*, 453:379-382
- 203 Luthi, Dieter et al... (2005) High-resolution in carbon dioxide concentration record 650,000-800,000 years before present, *Nature*, 453:379-382
- 204 Energy Information Administration (EIA) (2008) *International Energy Outlook 2008, Highlights*, <http://www.eia.doe.gov/oiat/leo/highlights.html>
- 205 Energy Information Administration (EIA) (2008) *International Energy Outlook 2008, Highlights*, <http://www.eia.doe.gov/oiat/leo/highlights.html>
- 206 Hoegh-Guldberg, Ove et al... (2007) Coral Reefs Under Rapid Climate Change and Ocean Acidification, *Science*, 318:1737-1742
- 207 Hoegh-Guldberg, Ove et al... (2007) Coral Reefs Under Rapid Climate Change and Ocean Acidification, *Science*, 318:1737-1742
- 208 Hansen, J. et al... (2008) Target Atmospheric CO<sub>2</sub>: Where Should Humanity Aim?
- 209 Hoegh-Guldberg, Ove et al... (2007) Coral Reefs Under Rapid Climate Change and Ocean Acidification, *Science*, 318:1737-1742
- 210 Hansen, J. et al... (2008) Target Atmospheric CO<sub>2</sub>: Where Should Humanity Aim?
- 211 IPCC (2007) Summary for Policymakers. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*
- 212 Pacala, S. and R. Socolow (2004) Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies, *Science*, 305:968-972
- 213 Energy Information Administration (EIA) (2008) *International Energy Outlook 2008, Highlights*, <http://www.eia.doe.gov/oiat/leo/highlights.html>
- 214 Matthews, H. Damon and Ken Caldeira (2008) Stabilizing climate requires near-zero emissions, *Geophysical Research Letters*, 35:L04705
- 215 Raven, John et al... (2005) Ocean Acidification due to Increasing Atmospheric Carbon Dioxide, *The Royal Society*
- 216 Hawkins, D.G. (2004) No Ext: Thinking about leakage from geologic carbon storage sites, *Energy*, 29:1571-1578
- 217 Raven, John et al... (2005) Ocean Acidification due to Increasing Atmospheric Carbon Dioxide, *The Royal Society*
- 218 Busseler, Ken O. et al... (2008) Ocean Iron Fertilization - Moving Forward in a Sea of Uncertainty, *Science*, 319:162

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