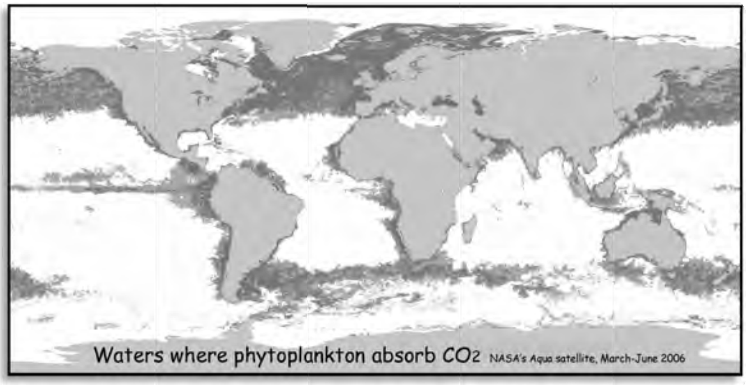
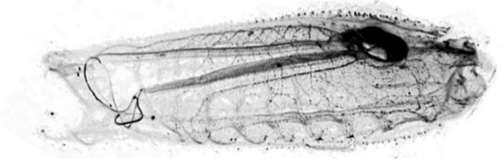
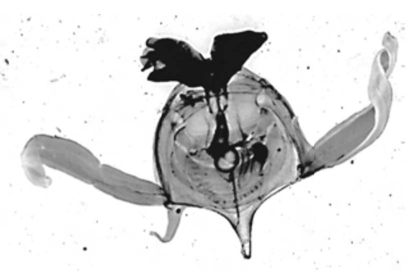


Waters where phytoplankton absorb CO_2 NASA's Aqua satellite, March-June 2006

The oceans have tiny algae called phytoplankton that remove CO_2 from the air and release oxygen. The darkened areas show the March-to-June amounts of chlorophyll in surface waters.



The phytoplankton feed the microscopic zooplankton and the larger salps. The jelly-like *Salpa aspera* above consumes large quantities of phytoplankton (the dot is the stomach) and excretes (black lines) large carbon pellets that sink quickly. Ocean carbon sinking is the primary way in which excess carbon is taken out of circulation for a million years. Some goes on to become limestone.



The microsnails above, both pteropods ("winged feet"), have a shell. When they die, that sinks some more carbon. Several decades ago, Victoria Fabry discovered that the pteropods do poorly in excess CO_2.

14

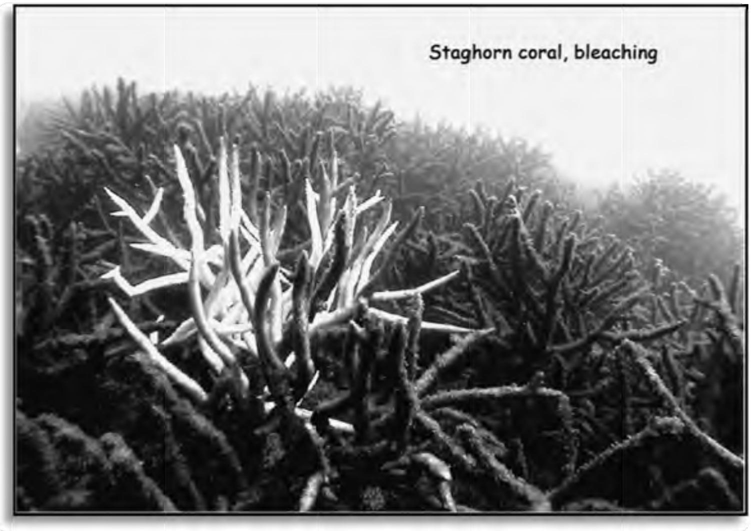
A Sea of CO2

It's even worse than "You don't know the half of it," at least when it comes to climate change. *An Inconvenient Truth* may have prepared you for the bad news about what's happening on land. But the other half of the bad news is what happens at sea.

I was shocked when I went directly from the bird-rich Galapagos Islands down to Easter Island, and discovered there were few shore birds and not much there that they could have fed on. I asked the Chilean archaeologist who was showing me around the island. He said the algae had been killed off by the warmer ocean, and with them the zooplankton that eat algae, next the fish, and then the birds farther up the food chain.

The big El Niño episodes had done this and water temperature has remained warm enough to inhibit recovery. The local fishermen have been reduced to seeking deep water fish, not very common, difficult to hook, and requiring expensive gear.

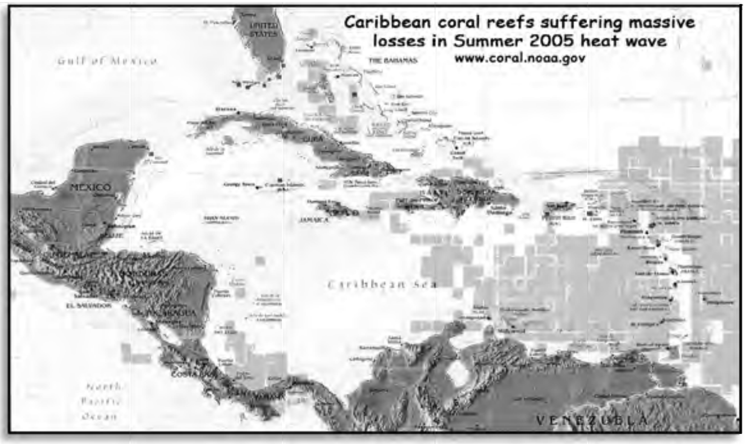
Jim Hansen and colleagues reported in 2006 that warming over the past century has been greater in the western Pacific than in the eastern. They suggest that the increased west-east temperature difference may have increased the likelihood of strong El Niños, such as those of 1983 and 1998.



A coral reef beginning to "bleach" (the plant part is ejected from the animal part) following environmental stress, such as overheating for too long.

Episodes of excessively warm water are also what have been killing off the coral reefs in many places. Vast areas of coral shed their gaudy coloration, turn bone white, and die if the heat continues for weeks. The 1983 El Niño was the first large-scale bleaching event in at least 300 years. The one in 1998 destroyed 16 percent of the world's coral reefs.

The hot summer of 2005 raised water temperatures all along the typical hurricane tracks into the Caribbean and the Gulf of Mexico. Besides paving the way for such devastating hurricanes as Katrina and Rita, the hot water directly affected many coral reefs. Marine biologists in Puerto Rico reported that 42 coral species on some reefs had bleached (areas of mere bleaching are not shown on the map). Coral colonies more than 800 years old died in a matter of weeks. It was worse farther east in the Virgin Islands. Coral that survives initially may die from subsequent disease; divers later saw die-offs as far down as 90 ft (27 m).



Caribbean coral reefs suffering massive losses in Summer 2005 heat wave
www.coral.noaa.gov

The shaded areas above show the areas where it remained hot enough for long enough to bleach and then kill corals. Many other areas (not shown) bleached.

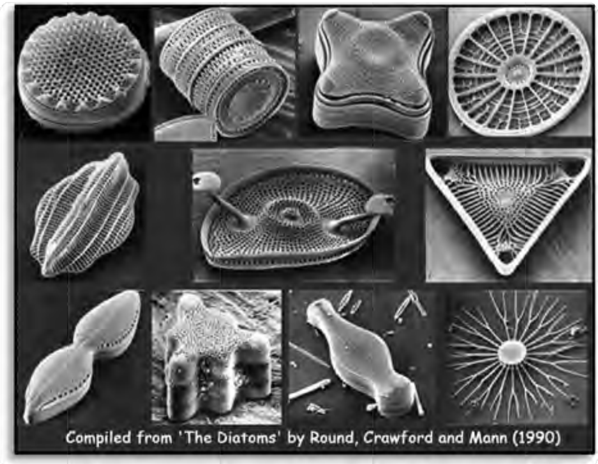
The Great Barrier Reef off Australia is already in serious trouble. The twenty-first century may well see the world's last coral reef die, say some of the experts.

Atmospheric CO2 has two parallel effects, global warming and ocean acidification. From each, there is a fan-out of impacts. In the atmosphere, elevated CO2 produces warming—and warming in turn may kill people (35,000 Europeans died in the heat wave of 2003), diminish cereal crops, expand the subtropical deserts, set up long-lasting droughts elsewhere, and cause the largest species extinction event since the demise of the dinosaurs.

In the ocean, it may be even worse, though the science is much less well established than on land. It wasn't until about 2003 that the magnitude of the ocean problems began to alarm scientists. My colleague Ed Miles said, "We are making changes in ocean ecosystems—changes not seen for millions of years—and we don't know what will happen. We just don't know."

We do know part of what is already happening. About 85 percent of all the extra heat captured by the CO_2 blanket has been taken up by the oceans. It is reported that the southern oceans may have absorbed about as much CO_2 as they can.

More than half of the oxygen we breathe comes from photosynthesis by the near-surface phytoplankton and microalgae. Some of the microscopic animals in the sea (zooplankton, such as the diatoms pictured) that eat them grow tiny exoskeletons, taking up the carbon from the CO_2. When they die (and this happens quickly because of "bloom and bust"), these "shells" sink to the ocean depths. Some become limestone. Other zooplankton excrete carbon pellets which sink. This "biological pump" is presently the major pathway for taking excess carbon out of circulation for millions of years. As such, it is far more reliable than growing forests that can burn down, quickly putting the captured carbon back into the air.

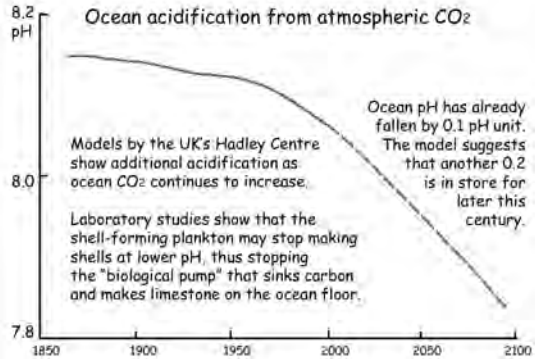


Diatoms and coccolithophores also sink carbon when they die.

Waves carry air bubbles down into the surface waters. Before a bubble rises to the surface and pops, its CO2 starts influencing the carbon chemistry in the ocean around it. A sea of CO2 not only reduces pH ("ocean acidification") but diminishes this "carbon pump" in more direct ways. It cuts the supply of the carbonate ions that combine with calcium ions to form the compound calcium carbonate, used for building shells and coral—and then limestone.

Normally the sea water has more than enough carbonate but when the elevated CO2 drives the carbonate equilibrium far enough out of balance, this starts pulling calcium carbonate out of shells and coral—tearing down rather than building up. The zooplankton then start looking malformed and dysfunctional. Both the coral and the calcite glue that holds a reef together get into similar trouble, dissolving like a cube of sugar. By dissolving coral reefs, the CO_2 adds to more global warming by removing an important carbon sink.

On land, some additional CO_2 in the air can serve as a fertilizer for some crops. But in the ocean, high CO_2 acts as an herbicide (indeed, it is used to kill all of the plankton in a tanker's ballast water before it is dumped, to avoid introducing new species in distant places).



Ocean acidification from atmospheric CO_2

Ocean pH has already fallen by 0.1 pH unit. The model suggests that another 0.2 is in store for later this century.

Models by the UK's Hadley Centre show additional acidification as ocean CO_2 continues to increase.

Laboratory studies show that the shell-forming plankton may stop making shells at lower pH, thus stopping the "biological pump" that sinks carbon and makes limestone on the ocean floor.

The important conclusions already reached by the researchers in the field: we must cut carbon emissions and pump down the CO_2 concentrations in the atmosphere, not merely cool down the earth by some geo-engineering project. Our fossil CO_2 is hitting at the bottom of the ocean food chain. And it is diminishing our most important carbon sink, just the sort of thing that could produce a runaway warming condition.

Acidification of seawater can cause high mortality rates in a variety of fish species when they are in their larval stage and part of the zooplankton. Bad as these effects of CO2 are, there is an even more serious one. The total number of phytoplankton ("primary production") in the world's oceans have been on a decline.

> I think there's a whole category of organisms that have been around for hundreds of millions of years which are at risk of extinction—namely, things that build calcium-carbonate shells or skeletons. To a first approximation, if we cut our emissions in half it will take us twice as long to create the damage. But we'll get to more or less the same place. We really need an order-of-magnitude reduction in order to avoid it.
>
> —climate modeler Ken Caldiera, 2006

A "bloom" of phytoplankton occurs when sufficient nutrients are brought together, say near a river mouth or sewage outfall. But winds may suffice. A steady wind that pushes aside the surface waters can bring cool underlying waters to the surface, carrying along sunken nutrients from the depths.

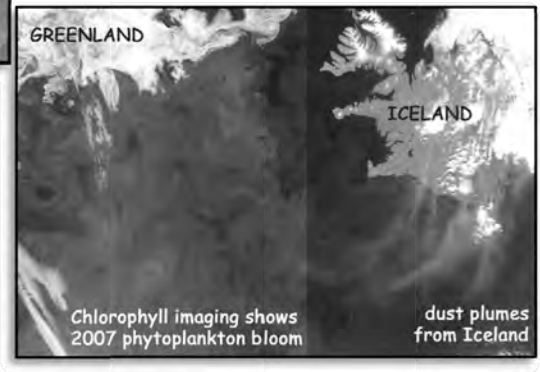
In many places, plankton's ability to pump down CO2 is limited by the loss of building materials. When the shell-forming zooplankton die and sink, they take with them the calcium, phosphates, and other nutrients needed by the next generation.

One theory for the widespread decline of plankton is a lack of fertilization by the iron that is carried off the red deserts by high winds. In the cool-dry-windy-dusty climate of the ice ages, the atmospheric CO2 drops down to its baseline, 180 ppm. This is widely attributed to iron fertilization.

Wind-driven upwelling of nutrients caused this large phytoplankton bloom offshore of Canada and the U.S. in 2006.

The westerlies in the southern oceans create an entire band of upwelling circling the globe. (See page 172.)

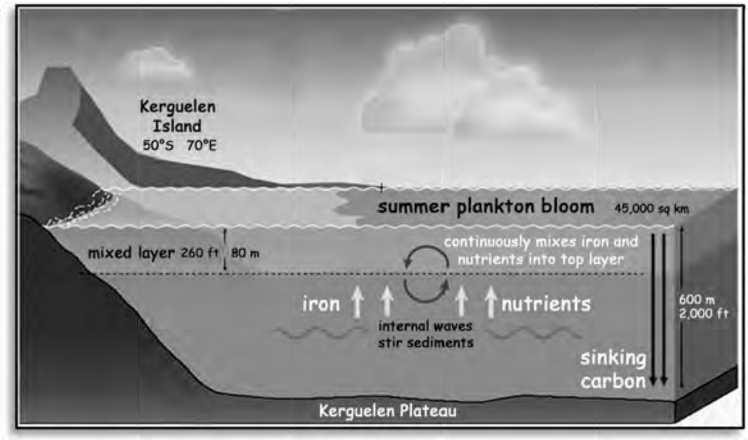
Large sand dunes along the coast of Angola and Namibia regularly fertilize the offshore blooms with iron dust carried by the winds. At Walvis Bay (beneath large plume at the bottom), there are sea lions everywhere, carpeting most of the beaches, attesting to the rich food supply for the top of the food chain.



Dust plumes from Iceland have been seen fertilizing large blooms of phytoplankton.

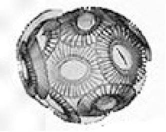
So, to naturally remove some fossil CO2, why not create a bloom on demand, simply by spreading around some iron dust? There have been a number of "iron-enrichment" experiments, yielding valuable data on single applications of iron to enhance phytoplankton production.

The zooplankton bloom usually doesn't occur until a week or so later. Not much research has yet addressed that follow-on bloom—indeed, it is only some of the zooplankton species which are relevant for long-term sinking of carbon. Fortunately, some French scientists have begun to study a "natural experiment" where iron enrichment continues for many months over an area the size of Switzerland.

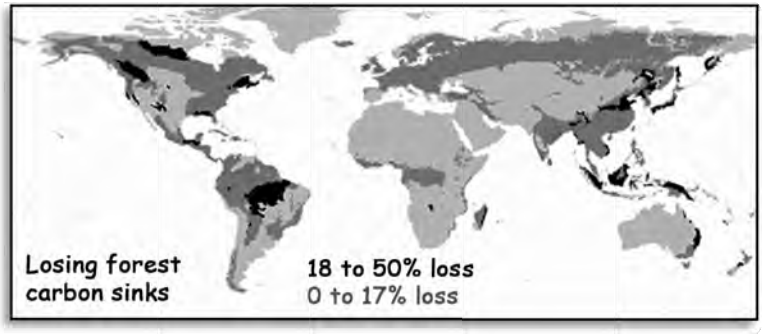


Kerguelen underwater plateau, to the southeast of the volcanic island in the Indian Ocean, has internal waves that stir up the iron in the sediments. This keeps the annual bloom going for a few months, sinking ten to a hundred times more carbon, per unit of iron, than was estimated during the previous single-application studies. The Kerguelen bloom quits when there is no longer enough iron.

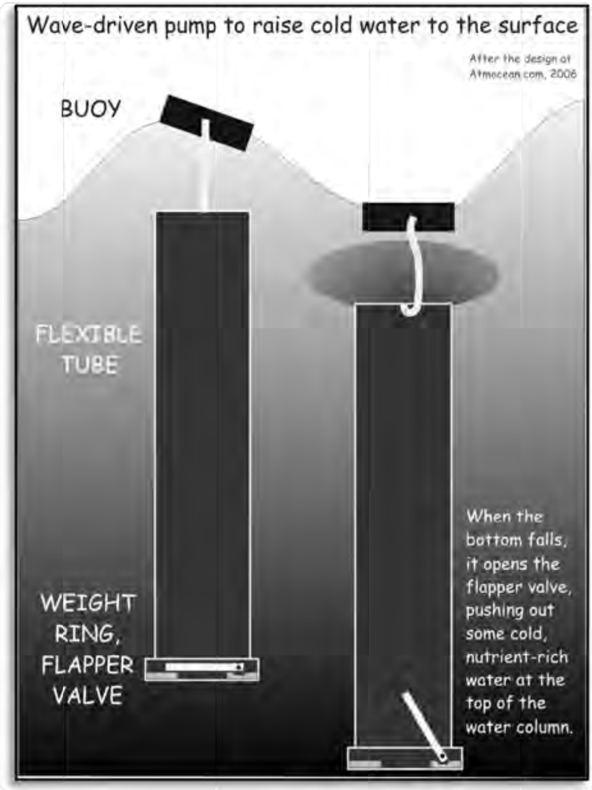
Iron fertilization around the edges of such a Switzerland-sized bloom would be an obvious strategy because such waters are near the threshold for a bloom already. Some coccolithophore species have even larger blooms. In 1991 south of Iceland, *Emiliania huxleyi* had a bloom three times the size of Iceland.



I suspect that terrestrial carbon sinks are going to prove unreliable because of drought, heat waves, and fire. We already have extensively cleared areas that were once forested. The largest such area is the southern Amazon Basin in Brazil, though Canada is similarly black in the diagram below.



Given that 70 percent of the earth's surface is water, we're likely to try out some schemes to solve our need for more carbon sinks. I intend the following scheme only as a brief hint at a plankton management technology, what we might see later in this century.



Technology can perhaps mimic the natural upwelling from the nutrient-rich depths in less well endowed regions of ocean surface. Inventors have been busy patenting schemes, despite the lack of money for demonstration projects. One patent is simple enough to explain in one page. I wish I'd thought of it myself. The diagram shows a simple scheme for using the ups and downs of waves to power the uplift of cold, nutrient-rich deep waters.

Coming down off the top of a wave, the tube falls with the flapper valve open. After some hours, deep water arrives at the top of the column. Now when the weighted column drops after a wave crest, deep water is forced out at the top of the column. The higher the wave, the greater the pump stroke.

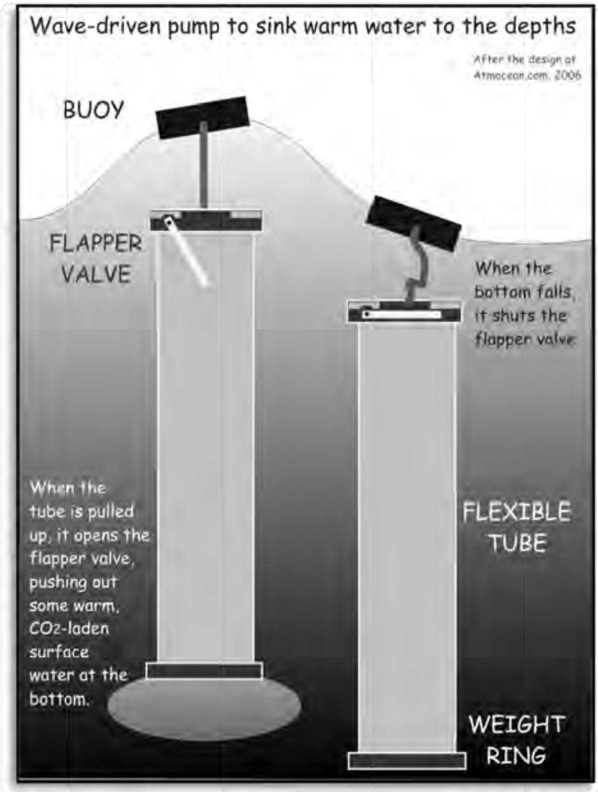
Imagine thousands of such columns around the edges of a natural bloom such as Kerguelen's, extending the bloom's area by providing extra nutrients from the deeper waters. And the waves are always high at Kerguelen.

That's my speculative example for what might be in store, once we learn a lot more about safe plankton management. Because the flapper valve can always be latched closed, the managers of an anchored array of hundreds of such tubes could turn nutrient upwelling on and off. Near such managed arrays would become a good place to fish.

Its inventors point out that an array of up-tubes could cool surface water by a degree or so—which, if done in the typical hurricane/typhoon/cyclone tracks, could reduce wind strength before landfall.

Note that waves can also pump surface waters down. Just place the flapper valve at the top, facing down. Down-tubes provide another method of sinking the dissolved CO2 and carbon-laden nutrients in the surface waters, as well as some of the heat.

Serious scientific warnings about rising CO2 started in 1956, so we have a half century of history to illuminate why the societal response has been so sluggish. Science serves as our headlights and, if the applications of technology outdrive the headlight reach, it may prove impossible to stop in time. Most of our climate problem comes from very simple technologies (axe, plow, drill) but without the high-tech science satellites, we would be blind to major changes. Without the working models of climate, we would have little idea of how sensitive the climate mechanisms are to small changes.


Wave-driven pump to sink warm water to the depths

After the design of Atmocean.com, 2006

When the bottom falls, it shuts the flapper valve

When the tube is pulled up, it opens the flapper valve, pushing out some warm, CO2-laden surface water at the bottom.

William H. Calvin, GLOBAL FEVER (University of Chicago Press, 2008)

But even with good data on how global warming and its effects have been occurring for the last fifty years, even with good coupled circulation models for atmosphere and ocean to show us the consequences, society has mostly ignored the increasingly emphatic warnings. There are partial exceptions such as Europe and the state of California, but there are also many global actors trying to modernize rapidly. Some actors (U.S., Australia, Canada) are addicted to high-energy (and high-garbage) lifestyles and have been, despite their advanced technological abilities, unwilling to take even baby steps toward conservation or carbon-free ("C-free") energy.

Avoiding tipping points does not come for free. Civilizations have good reflexes only if they build them in. We have not.

Fatalism takes it for granted that we are not masters of our fate. But, while that is obviously true in some sense, it does not follow that god-will-provide is the correct attitude to adopt (what most people associate with fatalism). Our capabilities are quite different than when those predictable Greek tragedies were written 2,500 years ago.

Most civilizations in the past have proven fragile. We're the first one to understand what's going on. We're likely capable of repairing the rot we have caused in the foundations. But it takes a great deal more. People pay much more attention to political and religious leaders—and to actors—than they do to scientists, so much depends on whether they help to lead an effective response.

While denial and deception have played roles in our slow response, there is nothing here that seems peculiar to intelligent life on Earth. Explosions in population and consumption seem likely to be found in any society where intelligence is not mature enough to head off such problems. One suspects that, for every galactic society that solves its problems in time, there will be hundreds that snuff out their own candle.

> For decades, the U.S. has been the moral, economic, and military leader of the free world. What will happen when we end up in Planetary Purgatory, facing 20 or more feet of sea-level rise, and the rest of the world blames our inaction and obstructionism, blames the wealthiest nation on earth for refusing to embrace even cost-effective solutions that could spare the planet from millennia of misery? The indispensable nation will become a global pariah.
>
> —oceanographer Joseph Romm, 2007

> But these people [of hard-hit countries] may not be content to remain passive victims, for they will surely know that the world they inherit is not one that they have created. The resentment felt by Muslims towards Westerners will be tame by comparison. As social collapse accelerates, new political philosophies may emerge, philosophies which seek to lay blame where it truly belongs—on the rich countries which lit the fire that has now begun to consume the world.
>
> —the writer Mark Lynas, 2007

GLOBAL

How to Treat Climate Change

FEVER

WILLIAM H. CALVIN

THE UNIVERSITY OF CHICAGO PRESS
CHICAGO AND LONDON

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