

Most of our climate problems could be repaired by cleaning up the excess CO₂ in the air and so cooling things off. However, because of abrupt climate flips, the cleanup must be big, quick, and secure. Doubling all forests might satisfy the first two but it would be quite insecure—currently even rain forests are burning and rotting, releasing additional CO₂.

However, our escape route is not yet closed off. We can still do the equivalent of plowing under a cover crop, using perhaps one percent of the ocean surface for the next twenty years. A sustained bloom of algae is fertilized by pumping up seawater from the depths—whereupon another wind-driven pump flushes the surface water back into even deeper depths before its new biomass becomes CO₂ again. When the sunken biomass does decompose, its CO₂ is smeared out over 6,000 years. Such a slow return of excess CO₂ can be countered by forestry practices.

Putting current and past emissions back into secure storage would lower the global overheating, relieve deluge and drought, reverse ocean acidification, reverse half of sea level rise as the oceans cool, and reduce the chance of abrupt climate shifts. The plankton plantations could then be kept in readiness for cooling the planet in a methane emergency.

Books by WILLIAM H. CALVIN

The Great CO₂ Cleanup

The Great Climate Leap

Global Fever

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*with Derek Bickerton

**with George A. Ojemann

THE GREAT CO₂ CLEANUP

Backing Out of the Danger Zone

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In memory of climate scientist
STEPHEN H. SCHNEIDER
(1945-2010)

Preface

In searching for an effective intervention for global warming, I found that existing ideas for recapturing the excess CO₂ from the air do not meet the test of being sufficiently big, quick, and secure. Here I sketch out a novel approach to ocean fertilization that appears to pass this triple test.

It mimics natural up- and down-welling processes using push-pull ocean pumps powered by the wind to pull sunken nutrients back up to fertilize the ocean surface—but then immediately pushes the new plankton production down to the slow-moving depths before it can revert to CO₂. Such a plankton plantation flushes not only the living biomass but also the hundred-fold larger amounts of dissolved organic carbon from feces and suspended debris.

Finally I discuss the looming methane problem and the emergency cooling of the planet that it will require. This too is urgent if we are to take effective action before being weakened by resource wars and economic collapse.

1

The Emergency CO₂ Cleanup

"How did you go bankrupt?" one of the characters is asked in Ernest Hemingway's *The Sun Also Rises*.

"Two ways," he said. "Gradually and then suddenly."

Climate creep's gradual deterioration of our planet is bad enough. But it's those half-dozen climate leaps since 1976 (and a similar number of near misses, discussed in my prior book, *The Great Climate Leap*) that tell us we have an emergency¹, that we are already in danger of a serious blow from which we might not be able to recover in time—with civilization collapsing and the human population crashing within, say, the next twenty years.

Abrupt climate shifts can be like heart attacks: some are minor, others catastrophic. There is no predicting which. And there is no predicting when. Only prevention works.

To back out of this danger zone for climate surprises, we must quickly recapture past CO₂ emissions from fossil fuels, currently totaling 1,300 gigatonnes—though usually we talk instead of the 350 gigatonnes of carbon in that excess CO₂. (GtC = 10¹⁵g of Carbon = PgC.) Note how different this is from proposals² to merely capture some of the smokestack CO₂ and store it. Cleaning up the excess CO₂ in the air should minimize the abrupt climate shifts by reducing the major intermediate cause: the land

is heating up twice as fast as the ocean surface, setting up sudden circulation shifts.

As we try to remove the excess CO₂ over the next twenty years, another 250 GtC are likely be emitted, judging from the 3% annual growth in the use of fossil fuels. That's 600 GtC total that we need to take back³. It's comparable to four piles of coal as high as Mount Rainier. That's also about how much carbon that is held above ground in the remaining forests of the world. So the size of the twenty year cleanup job is equivalent to quickly doubling the forests of the world using fast-growing trees.

But in addition to being big and quick, our cleanup method must securely store that excess carbon so that it cannot get back into the air anytime soon. Given that the climate forecast is for drier droughts and stronger winds, forests will be very vulnerable to fire.

And if the fire doesn't get them, the rotting of dead trees will produce the CO₂ instead, taking a decade rather than a year. Even rain forests are currently burning and rotting, so doubling forests is not secure enough for our purpose. What is?

Chemically scrubbing the CO₂ from the air is expensive⁴ and requires a lot of new electrical power from clean sources, not likely to arrive quickly enough. One cannot merely scale up what suffices on submarines.

That pretty much leaves us stuck with finding new ways of doing the 30 GtC/year cleanup with biology, where—like the new forests—CO₂ is captured by photosynthesis, the oxygen liberated, and the carbon incorporated into an organic carbon molecule

such as sugar⁵. Then, to take it out of circulation, it must be buried.

Burying keeps organic carbon from decomposing or, if it does, keeps decomposition CO₂ from returning to the air. (Fans of big words call this ‘sequestration’ but ‘burial’ will do here.)

One could, for example, bundle up all of the crop residue (half of the biomass grown each year is cornstalks, inedible leaves, shells, etc.) and sink the weighted bales to the ocean floor⁶. It will decompose there but it will be a thousand years before its CO₂ can be carried back up to the ocean surface and into the air. Alas, this project, even when done on a global scale, will yield only a few percent of what we need to remove each year, which is 30 GtC.

And if crop residue represents half of the yearly agricultural biomass, this also tells you that additional land-based photosynthesis, competing for space and water with human uses, can’t do the job in time. At best, it can only double the numbers for crop residue—and that’s an order of magnitude short of what we need.

Miraculous new technology might come along but basically we must look to the oceans for the new photosynthesis and for the long-term storage of the CO₂ thus captured.

Algal blooms are temporary increases in biological productivity when the ocean surface is provided with fertilizer containing missing nutrients such as nitrogen and phosphorus.

The bloom comes from a window of opportunity. It takes a week for the primary consumers of the new algae, the little animals called zooplankton, to catch up in sheer numbers, as they cannot reproduce every 11 hours like the algae can. Grazing reduces the algal population numbers over the following weeks, even though there is no shortage of nutrients.

Most of this bloom biomass turns right back into CO₂ via respiration and rotting. Aided by winds that stir the surface layers, this CO₂ escapes back into the air. Only one captured carbon in every four manages to settle into deeper waters, where it doesn't have a chance to mix with the atmosphere for another thousand years or so.

And only one sunken carbon atom in a thousand manages to become sediment on the ocean floor, taken out of circulation for a hundred million years. Half of the rest turns into CO₂ that rejoins the atmosphere when the deep water is first upwelled ("ventilated" in oceanspeak).

Recently the chemical oceanographers have learned that the other half of the dissolved organic carbon (called refractory DOC) is somehow protected from becoming CO₂ for about 6,000 years⁷. Despite being upwelled multiple times, it doesn't become atmospheric CO₂ for a while. That's good news.

In addition to the heavier biomass (the larger fecal pellets and shells) that can settle into the depths before becoming CO₂, there is an express route to the depths: surface waters are flushed via whirlpools into the depths of the Greenland Sea and the Labrador Sea.

Bulk flow is the difference between having a thin pill dissolve on your tongue and knocking back a fistful of pills using a gulp of water to carry them down. Whirlpools carry down the living biomass (from fish to bacteria) as well as the dissolved organic carbon (from feces and smaller cell debris—think of it as carbon soup).

The major attempt to fertilize new plankton growth has been sprinkling the ocean surface with iron filings⁸. In many areas of ocean, this promptly causes a bloom. But the amount of new growth that actually settles into the depths has been discouraging.

Fertilizing near the downwelling whirlpools sounded like a good way of sinking much more—but then I recalled that, since 1978, each of the two biggest downwelling sites had shut down for a decade. (Fortunately, they didn't both fail at the same time. See the near-miss section of *The Great Climate Leap*.) Cross off one more carbon storage scheme that isn't secure enough, though conceivably big enough and fast enough.

So let us consider floating windmills (or equivalent wave-powered pumps, powered by the wind at one remove). They could pump up the nutrients that accumulate in the ocean depths⁹. A second set of pumps could carry the enriched carbon soup down

into the thousand-year depths, perhaps with some compressed air to prevent anoxia in the depths from the carbon soup's decomposition.

Those dissolved feces and such contain hundreds of times more organic carbon than does the living biomass—which is what makes downwelling surface water such a big deal compared to merely settling out the larger debris and fecal pellets.

In my preliminary estimates based on algal growth rates in algaculture¹⁰, the plankton plantations would need to cover about 0.8% of the ocean surface, an area equal to that of the Caribbean. The push-pull pumps would likely be scattered around the outer continental shelves in prime fishing grounds belonging to well-developed countries that can afford it. Since the fish and fishermen will love a plankton plantation, there's a cognitive carrot: a yearly payoff in fish catch while growing the climate fix with its payoffs for everyone.

Just as farmers grow a nitrogen-fixing crop of legumes and then plow it under, we would be growing a carbon-fixing crop of plankton and then pumping it under.

This bears a resemblance to what an artificial kidney does for the patient in chronic renal failure: cleaning up the accumulating toxins. Indeed, dialysis is an excellent analogy for both climate creep and climate leap. Dialysis machines are also used to prevent heart attacks in aspirin overdose patients, who have a one-in-four chance of suffering a heart attack unless the excess aspirin is promptly removed from the blood stream.

Like the terminal kidney patients I saw in the 1960s, back before dialysis became more widely available, our civilization is starting to look like a goner—apt to trip into a vicious downsizing cycle of resource war, famine, pestilence, and genocide.

All it takes is a big climate leap that cripples agriculture long enough for big cities to crash. (And, before someone objects that big cities have survived big droughts before, note that this hypothetical famine is global in extent, so that food cannot be imported and emigration attempts are usually fatal.)

Push-pull pumping looks to be big, quick, and secure. It illustrates that there is still at least one escape route open to us that might cool things down, reverse ocean acidification, reverse the part of sea level rise that is due to the thermal expansion of the oceans, and likely back us out of the danger zone for climate leaps.

From concept to proof of principle, to demonstration project and then deployment often takes more than a decade—though with wartime priorities, World War II history shows that several years may suffice when multiple solutions are pursued simultaneously.

2

Flying without a Safety Factor

A long-term perspective may come from environmental and ethical concerns. Many people can achieve it without any specialty training. But scientists are often the only ones who can add up the numbers and attach them to a timeline, saying where water shortages will happen, what areas will become deserts, and how much sea level will surely rise.

For any given element needed by an ecosystem—say carbon, nitrogen, or phosphorus—we use an accounting procedure that looks like balancing a checking account’s deposits and withdrawals, looking at whether the balance falls over time. If a mix of elements is needed to make photosynthesizing cells such as algae, and there is a scarcity issue for one component, then the situation is much like a production line shut down by a tardy supplier of a critical part. Anyone with a spreadsheet can now make a working model of such a construction process, tweaking the supply rate and the backup inventory to keep the production line going during brief supply disruptions—just as you would want immediately available cash on hand in case a sick relative needed a quick visit.

Climate modeling has focused on the averages and how temperatures ramp up. The state of the art is very good there and getting better, with a dozen groups around the world competing to do a good job of incorporating carbon cycle feedbacks—such as

when melting the Arctic tundra adds additional CO₂ and methane to the air, making it warmer still.

Note that warming the Arctic causes a chain reaction. Indeed, the process itself is much like the one for nuclear fission, where a uranium nucleus captures a slow neutron, becomes unstable enough to split into two lighter elements, and throws off two free neutrons to continue the mischief nearby (usually the packing density isn't high enough to keep the chain going). In the Arctic, we see excess CO₂ creating even more excess CO₂.

There are similar self-fulfilling contingencies such as rain forests burning down. The excess CO₂ has already caused enough overheating to create additional CO₂ via burning and rotting. (However "natural" this heating bonus, it is triggered by anthropogenic overheating.) Should chance create a long-lasting drought, half of the Amazon biomass' carbon could end up as atmospheric CO₂ within a few years. It's like a fatal heart attack occurring before gradual heart failure can cause death.

Because of such things happening along the way, a temperature ramp rising to a tipping point seriously overestimates the time remaining. Brief peaks usually do the damage, long before changes in the average get around to it—as in heat waves or when the inundation from mean sea level rise is preceded by that from stronger storm surges.

Yet even the slowly escalating aspect of the threat has been repeatedly obscured by the way we talk at several removes from the core problem. Over the years, our CO₂ action plans have shifted focus in a way that has diverted us from the excess 240

GtC of CO₂ currently in the air (what actually drives ocean acidity and overheating). Instead we merely talk about slowing the rate of increasing the problem.

Our excess CO₂ problem somehow became ‘stabilizing’ CO₂ concentration—though a high (but unchanging) CO₂ concentration still results in an unstable climate that spins off surprises.

A commonly-heard opinion is that we should “Let the climate heal itself after cutting emissions.” Framing our climate response solely in terms of gradually reducing emissions has caused a tendency—even among climate scientists—to treat carbon cleanup as a mere contingency plan should emission reductions fail (“Techniques for extracting atmospheric CO₂ ... might eventually prove necessary”) rather than as a parallel approach of great value.

Many now think that taking the growth out of emissions is an adequate goal for responding to climate change. Or that achieving zero emissions sometime later this century will do the job. Either would be a significant achievement but neither would get rid of the excess CO₂ quickly enough, or in a way which avoids dangerous acidification of the surface ocean.

Our current climate response is mostly a re-emphasis of the old virtues, such as “use less.” They do not constitute adequate treatment for the climate disease we already have. As when chemotherapy supplements tumor surgery, emissions reduction is merely an adjuvant (valuable to supplement another therapy but insufficient by itself). Our climate response must focus on

forestalling catastrophic developments, so that old virtues will have time to work and innovations will have time to prosper.

Emission reductions will remain important for climate action, as they hasten the day and lower the needed pumping capacity. If we instantly stopped burning coal and forests, it would eliminate 100 GtC of the 250 GtC emissions estimated for the next 20 years, reducing the size of the needed fix from 600 to 500 GtC.

We need a safety factor proportional to the hazard: if we can overbuild stadiums by a factor of four in strength, surely preventing a collapse of civilization warrants an even larger safety factor. For such reasons we must front-load our climate response, much as a course of antibiotics may include a double dose the first day.

3

Sketching Out a Climate Fix

By 2003, even the holdouts among the climate scientists were becoming convinced that something serious was afoot. It was no longer merely a matter of a prediction that global warming would occur—and it wasn't just heat waves. The domino-effect consequences of overheating were showing up in too many places, such as the increasing numbers of forest fires, deluge, and drought. Glaciers in Greenland were surging.

And most of them realized that even if the data or mechanistic explanation turned out to be wrong for one indicator of overheating, that wasn't going to make the others go away. You couldn't just use uncertainties in thermometer readings to put concerns on the back burner again.

Yet most of public climate discussion remains at the level of what scientists were discussing fifty years ago. The questions policymakers are asking now were valid concerns back then but they have since been answered—though you'd never know this to hear the radio loudmouths, who ceaselessly flog the old uncertainties to gain attention to themselves (and thus their advertisers). They are making millions in advertising dollars by exploiting the ignorance of science in much of their audience.

While deforestation and fossil fuel emissions got us into trouble, *it does not follow that fixing them will get us out of trouble*. Emission reductions would only scale down the future CO₂ additions—they do not subtract from the CO₂ that has

already accumulated. Though such reductions might suffice in the case of methane because so much naturally disappears in a decade, the natural drawdown mechanisms for CO₂ take ten times longer¹, with a stubborn one-fourth still hanging around a thousand years later.

Because abrupt climate shifts have already begun surprising us, gradual overheating is no longer the correct focus for understanding the risk we now face, where fast tracks to disaster must be forestalled.

Can we back out of the danger zone for abrupt shifts, climate's version of a heart attack? In addition to a low-carbon diet, we need emergency repairs—an intervention analogous to dialysis, one that quickly cleans out the toxic substance. Judging from the rate at which climate surprises have been occurring, we may only have several decades remaining for an effective intervention. That is the time for completing the repairs, not that for getting started.

Indeed, our current plans for climate action look more like a buying-time therapy for late-stage cancer than like a physiological fix such as the dialysis for kidney failure that makes possible a near-normal patient. Here I ask what a “climate fix” might look like, one that relieves many of the ocean acidification and climate problems and makes possible a near-normal planet.

Considering the rate of abrupt shifts so far, it would be prudent to expect additional surprises soon. Any one of them might close off our escape route, so that we spiral up to

catastrophic climate change. Most, however, could be avoided by taking the excess CO₂ out of circulation.

To back out of the danger zone for abrupt climate shifts, an appropriate goal would be to remove nearly all of the excess CO₂ over the next twenty years and put it back into long-term storage. About 30 GtC/yr must be taken out of circulation, one-third going to simply counteracting the out-of-control fossil fuel emissions that continue. And continue they will, especially in developing countries that will burn their own fossil fuels in order to modernize, their governments even less effective than the United States in implementing treaties.

The CO₂ cleanup would be an emergency repair, not a substitute for a low-carbon energy diet. Chemically scrubbing the atmosphere is unlikely to scale up fast enough. Though large enough, doubling forests² is not secure enough, given the trends in fire and drought. To avoid competing with the world's food production, most of any sequestered organic carbon must come from new biomass grown in new places.

Unless we quickly develop far more efficient methods for sequestering circulating carbon, we could see our escape route closed off.

4

Put the Genie Back in the Bottle?

Nearly all of the excess CO₂ is anthropogenic, an unintended byproduct of industrialization and such old technologies as cutting down trees and burning coal and oil. Unlike such threats to civilization as nuclear warfare, the climate crisis comes from very primitive, pickaxe-level technology.

Excess CO₂ is that above 280 parts per million in the air, the old maximum concentration for the last several million years of ice age fluctuations between 180 and 280 ppm. It is currently above 390 ppm and its increase since 1750 has been exponential.

The current 110 ppm excess puts us well into dangerous territory for climate surprises. At the 1976 sudden shifts, the excess was only 51 ppm, showing that a 350 ppm target¹, allowing for a 70 ppm anthropogenic excess, is not low enough. We hit 350 ppm back about 1988, well after the sudden shifts that began in 1976.

An appropriate goal for our emergency repair would be to “Put the genie back in the bottle”—to remove nearly all of the excess CO₂ and put it back into long-term storage—and to finish retiring this carbon debt within the next twenty years. It would be like drawing down a reservoir to keep a leaking dam from collapsing.

This emergency repair would need to recapture most of the 350 GtC fossil emissions between 1750 and 2009. On top of that, extrapolating the emissions trend since 2003 for two more decades suggests we should allow for capturing another 250 GtC to counteract out-of-control fossil fuel use.

If we could remove 30 Gt of circulating carbon each year, then in twenty years we could recapture an amount equal to all 600 GtC of the fossil fuels burned. Another 25 percent will be needed to offset deforestation. Additional amounts could offset such CO₂ heating equivalents as methane leaks and brightness reductions.

Large, swift, and sure. If *how quick* is twenty years and *how big* is equivalent to doubling all land vegetation, then most carbon removal schemes² are too little, too late, or too insecure. Many such schemes can still be part of longer-term solutions. What we need in the near term, however, is a climate fix, an emergency repair to make the long-term solutions relevant.

Though there are schemes for scrubbing CO₂ with proprietary chemicals³, time is too short to rely on finding the power to run such a giant new industry. But it is not necessary to remove CO₂ directly from the air to reduce its concentration there. Photosynthesis already removes about 210 GtC each year⁴ to create organic carbon molecules such as sugar. For atmospheric CO₂ to remain unchanged, we would expect 210 GtC/yr to be released as CO₂ by cell respiration and decomposition (burning, rotting).

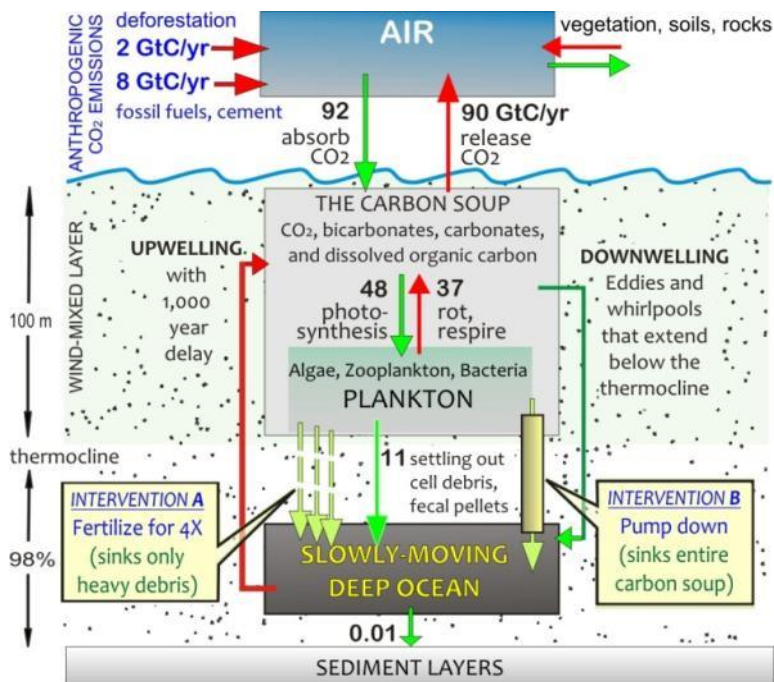
If we intercept some of the decomposition carbon before it reaches its usual atmospheric destination, the carbon cycle will become unbalanced, taking out more CO₂ from the air than it returns to it. This draws down atmospheric CO₂; it is the principle underlying most carbon removal schemes. But sea floor burial of crop residue⁵ and sewage⁶ would amount to less than 0.8 GtC/yr, not even able to counter the 2 GtC annually produced by continuing deforestation and quite inadequate for hiding 30 GtC/yr.

Even if the land and water could be found⁷ to double forests, the climate forecast is for hotter summers, more droughts, and stronger winds. In some years, Amazonia already releases more CO₂ than it absorbs. Planting trees simply does not qualify as a climate fix; they are insufficiently secure against fire and rot.

To avoid competing with the world's food production, most of any sequestered organic carbon must come from new biomass grown in new places—for example, sinking additional cell debris into ocean depths via fertilizing the algae⁸.

In order to understand my suggestion that we sink the carbon in surface waters beneath the thermocline via bulk flow⁹, we must first examine how 140 GtC worth of excess CO₂ has already been absorbed by the oceans and how little of it is in thousand-year storage.

Figure 1



The Organic Carbon Soup

The ocean's carbon budget and how to keep 30 GtC/yr from becoming atmospheric CO₂. Iron fertilization experiments have been aimed at settling more cell debris into the depths (*Intervention A*) but 30 GtC/yr would require 4X the natural settling worldwide, as would achieving fertilization by pumping nutrients up to the surface. Pumping down (*Intervention B*) can be done at many sites and sinks the entire “organic carbon soup” of surface waters—unlike *A*, where only the larger particulate matter settles quickly enough for its pending CO₂ to be sequestered. (Source for fluxes: Houghton, 2007)

5

The CO₂ Cache and the Conveyor Belt

Wind-driven waves serve to subdivide most areas of the ocean into a wind-mixed surface layer and the slowly-moving ocean depths. Excess CO₂ in the air dissolves in the surface layer as waves bury air, forming bubbles with much more surface area. This creates a short-term easy-in-easy-out CO₂ cache on top plus an out-of-contact storage loop through the depths.

Any CO₂ produced by respiration and decomposition in the mixed layer will make it into the air. The bottom of the wind-mixed surface layer—about 100 meters down in open ocean but more like 30 m over a continental shelf—is marked by a decline in temperature. This “thermocline” depth deepens as winter winds stir things more vigorously, bringing up some of the nutrients that sank. That means that, after the thermocline returns to 100 meters, the surface layers are richer in nutrients for a while.

About 92 GtC is annually absorbed^{1,4} into this wind-mixed layer as dissolved CO₂, with about 90 GtC being released into the air. Most of the 2 GtC net gain in dissolved CO₂ is then buffered as bicarbonate (together, called total CO₂). Any attempt to draw down atmospheric CO₂ by, say, planting more trees will be slowed by the release of the bicarbonate cache’s excess (that’s why I speak of recapturing past emissions rather than just countering the excess CO₂ in the air).

From this 92 GtC annual supply of CO₂, 48 GtC is captured by algal photosynthesis to make organic carbon molecules such as sugar. Respiration and decomposition, however, soon makes CO₂ out of 37 GtC of it. About 11 GtC is heavy enough to settle below the thermocline before decomposing. Once in the depths, the decomposition CO₂ cannot easily reach the atmosphere. Most efforts to increase ocean sequestration, such as iron fertilization, have focused on settling additional dead biomass into the slowly circulating depths².

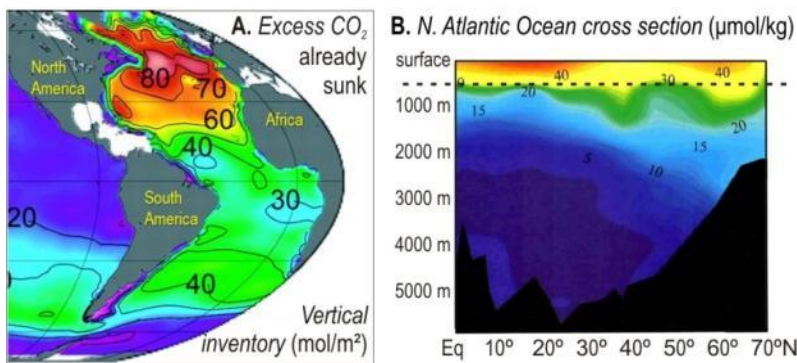
Algae are quickly grazed by zooplankton, which then respire and rot. The larger fecal pellets and the hard parts of plankton may sink through the thermocline before decomposing but smaller fecal pellets dissolve in the mixed layer. Dissolved organic carbon can survive in the mixed layer for a month³ before bacteria consume it and, via their respiration, turn it back into CO₂.

In addition to settling out 11 GtC/yr of debris and fecal pellets, there is that carried down in whirlpools. That biomass (algae, zooplankton, bacteria, exudates, debris, feces, and dissolved organic carbon) is hundreds of times larger than what succeeds in settling out. But this bulk flow into the depths only happens in a few places: small amounts in the Mediterranean Sea, more near the shores of Antarctica, most offshore of Greenland.

Because 200-km eddies and 20-km whirlpools carry surface waters far below the local thermocline, much of the anthropogenic CO₂ sunk thus far into millennial depths is in the North Atlantic Ocean.⁴ The “conveyor belt” that carries deep

waters south has not been strong enough to keep it from accumulating in the North Atlantic.

Figure 2



Excess CO₂ in the oceans

A. In terms of water column inventory⁵, the highest values are in the North Atlantic Ocean. Adapted from Sabine et al (2004).

B. The cross-section⁶ for concentrations shows it is not due to mixed layer differences but to the amount sunk below 500 m (dashed line) by vertical convection. Adapted from Feely et al (2001).

While we usually think of the sunken debris as settling out on the ocean floor to become limestone or coal, nearly all circulates back up to the surface. A mere 0.02% stays behind as sediments. Most becomes dissolved “total CO₂” in the slowly moving deep ocean.

Much of it resurfaces in the high southern latitudes, pumped up by the strong westerlies that circle the globe, pushing surface waters aside. Estimates for the delay until the flushed surface

water resurfaces range from 400 to 1,600 years⁷. Excess carbon sunk to just below the winter thermocline is likely to resurface sooner. It may take a sinking depth of more than 1,000 m to achieve millennial-scale storage.

In the cold depths, about half of the new dissolved organic carbon from the upper ocean is promptly converted into total CO₂. But it has recently been shown that the rest has a 6,000 year residence time⁸. Since the reason for this postponed oxidation into CO₂ is not yet clear, one cannot say that half of the carbon debt, if sunk within twenty years, would also stay out of the atmospheric circulation for an extra 5,000 years. But it seems a good bet, one we should take.

If the 600 Gt carbon debt were sunk, this range of resurfacing delays would smear it out over more than 6,000 years, with release averaging 0.1 GtC/yr. This annuity-like pattern (an early lump-sum deposit with a delayed and distributed payout) can avoid the sharp peaks of temperature and acidity that cause the most harm. Surfacing CO₂ at 0.1 GtC/yr is also well within the range that even forestry management could counteract.

Our emergency repair, then, involves both efficiently creating new ocean biomass and efficiently sinking it into thousand-year depths before it reverts to CO₂.

In the Greenland Sea, the limiting nutrient is nitrate; winter deepening of the wind-mixed layer brings some to the surface. However, spring algal blooms can exhaust this new supply within

several months. Summer algal population is then limited by what nitrate can be quickly recycled within the mixed layer.

Dust storms often fertilize offshore blooms; the iron fertilization experiments that they inspired do increase ocean productivity⁹ but often do not settle out large quantities. Blooms are also triggered when a strong wind pushes around surface waters, thereby upwelling nutrients. This led to more recent suggestions¹⁰ that vertical “ocean pipes” with a mechanical pump could similarly fertilize algal production with locally relevant nutrients, a continuous version of what winter winds bring up.

Fertilization alone can prove quite inefficient at sequestering carbon. To sink the needed 30 GtC/yr via settling out debris, we would need to quadruple primary production in all of the global oceans.

Clearly, boosting ocean productivity is not, by itself, the way to put the CO₂ genie back in the bottle. Unless we quickly develop a far more efficient method for sequestering the excess circulating carbon, we could see our escape route closed off. That’s how far we have already come in exceeding a safety margin.

The example in the next chapter shows a cleanup scheme that might suffice. It’s not a ready-to-roll proposal so much as a challenge to the real experts, something to improve or replace in a solution space constrained by the need to be Big (600 GtC), Quick (20 yr), and Secure (for 1,000 yr). It shows a major recovery is still possible.

6

Plowing Under a Carbon-fixing Crop

To avoid competing with the world's food production and supplies of fresh water, most sequestered carbon must come from new biomass grown in new places. Here I explore how paired ocean pumps might uplift nutrients and then sink the new organic carbon back into the ocean depths.

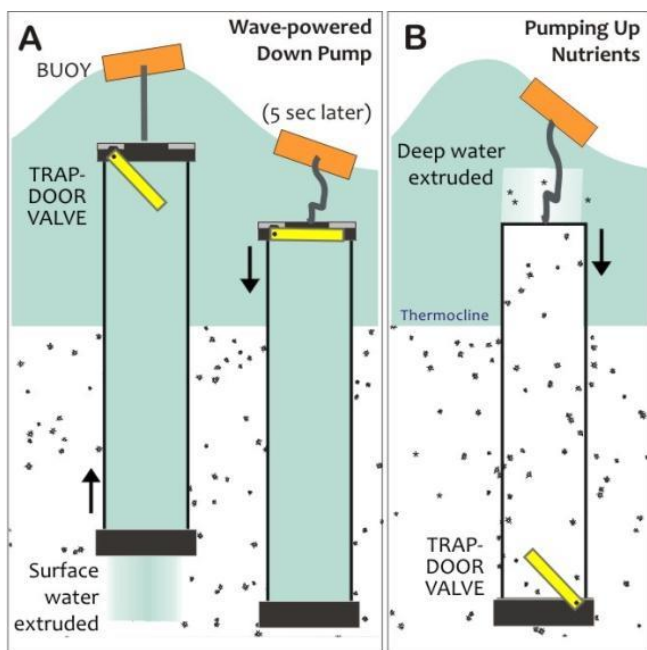
Instead of sinking only the debris that is heavy enough to settle out, as in iron fertilization, we would be using bulk flow to sink the entire organic carbon soup of the wind-mixed layer (organisms plus the hundred-fold larger amounts of dissolved organic carbon) before its carbon reverts to CO₂ and equilibrates with the atmosphere.

The CO₂ later produced in the depths by the sunken carbon soup will reach the surface 400–6,000 years later. Smearing it out over that period greatly reduces the damaging peaks in ocean acidification and global fever.

Without fertilization, there is about one gram of organic-bound carbon in a cubic meter of seawater¹ in the North Atlantic. The North Atlantic's meridional overturning circulation thus sinks about 0.6 GtC/yr of organic carbon. That suggests that local concentrations about fifty-fold larger might sink our needed 30 GtC/yr—were we to rely only on the whirlpools.

But this too fails the *secure-enough* test. Each of the two major sinking sites has failed for a decade, just since 1978. Thus we need an estimate for plankton plantations that do their own sinking of surface waters.

Figure 3



Push-Pull Pumps

A. An inexpensive wave-powered pump can push the surface's organic carbon soup below the thermocline. After a design by Philip Kithil, atmocean.com.

B. By reversing the trap-door valve, nutrient-laden cold water can be pulled to the surface. Schematics omit streamlining and ballast. For further discussion, see William H. Calvin (2008) *Global Fever: How to Treat Climate Change*. London and Chicago: University of Chicago Press.

If we fertilize via pumping up and sink nearby via bulk flow (a push-pull pump), we are essentially burying a carbon-fixing crop, much as farmers plow under a nitrogen-fixing cover crop of legumes to fertilize the soil. Instead of sinking only the debris that is heavy enough, we would be sinking the entire organic carbon soup of the wind-mixed layer.

Algaculture minimizes respiration CO₂ from higher up the food chain and so allows a preliminary estimate of the size of our undertaking. Suppose that a midrange 50 g (as dry weight) of algae can be grown each day under a square meter of sunlit surface, and that half is carbon. Thus it takes about $1 \times 10^{-4} \text{ m}^2$ to grow 1 gC each year. To produce our $30 \times 10^{15} \text{ gC/yr}$ drawdown would require $30 \times 10^{11} \text{ m}^2$ (0.8% of the ocean surface, about the size of the Caribbean).

But because we pump the surface waters down, not dried algae, we would also be sinking the entire organic carbon soup of the wind-mixed surface layer: the carbon in living cells plus the hundred-fold larger amounts in the surface DOC. Thus the plankton plantations might require only $30 \times 10^9 \text{ m}^2$ (closer to the size of Lake Michigan).

The space requirement will be more because downpumps will not capture all of the new plankton; it might be less because the relevant algaculture focuses on oil-containing algal species and on harvesting a biofuel crop, not on plowing under the local species as quickly as possible. The ocean pipe spacing, and the volume pumped down, will depend on the outflow needed to optimize the organic carbon production². Only field trials are likely to provide a better estimate for the needed size of sink-on-the-spot plankton plantations, pump numbers, and project costs.

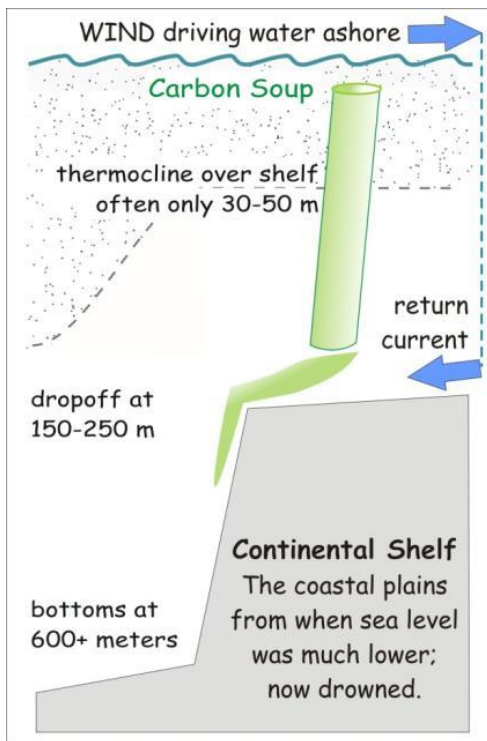
Though ocean fertilization is usually proposed for low productivity regions where iron is the limiting nutrient, another strategy is to boost the shoulder seasons in regions of seasonally high ocean productivity. For example, ocean primary productivity northeast of Iceland drops to half by June as the nutrients upwelled by winter winds are depleted. Continuing production then depends on recycling nutrients within the wind-mixed layer. However, to the southwest of Iceland, productivity stays high all summer.

Because not all of the new plankton will be successfully captured and sunk, fertilization will stimulate the marine food chain locally. Most major fisheries have declined in recent decades and, even where sustainable harvesting is practiced, it still results in fish biomass 73% below natural levels³. At least for fish of harvestable size, there is niche space going unused.

Locating the new plankton plantations over the outer continental shelves is more likely to supply a complete niche for many fish species, whereas deep-water plantations will lack variety. (The main commercial catch in deep water is tuna.) Also, down-pumping near the shelf edge would deposit the organic carbon in the bottom's offshore "undertow" stream, carrying it over the cliff onto the Continental Slope into deeper ocean.

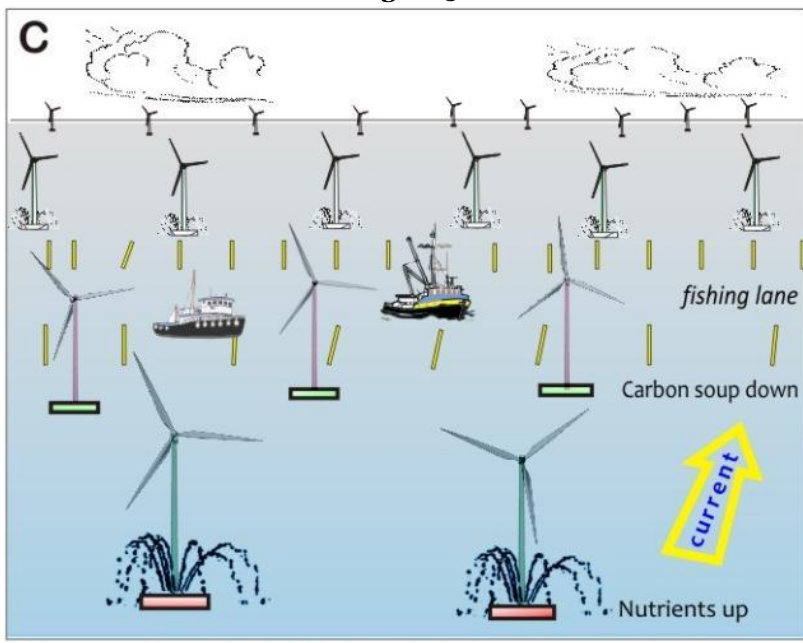
Note that pumps would be tethered to the bottom so that the ocean currents are always creating a plume downstream: a plume of fertilizer near the surface and a second plume of carbon soup in the depths. (Pumping up from a different depth than pumping

down will prevent the interaction that characterizes the oceanographers' box models.) While the water might come back around in a thousand years, the plumes for the clean-up will only be about twenty years long and well diluted by that time.

Figure 4

Augmenting the Continental Shelf Pump

for carrying bottom water over the edge of the continental shelf and, if dense enough⁴, into the ocean depths. Like the “carbon pump,” it’s only a metaphorical pump but it could be enhanced (green pipe) with a real pump, pushing carbon soup down to the bottom near the edge of the shelf. There it would be entrained by the return current from the wind-driven onshore current and carried down the continental slope into slowly circulating depths. Besides the shorter trip to the bottom, continental shelf siting also avoids international treaty complications, enabling fast action by a single nation.

Figure 5

A plankton plantation

A design using windmill pumps, including a fishing lane free of anchor cables. From Calvin (2008) *Global Fever*.

Figure 6**Test bed possibility**

Existing drilling platforms in the Gulf of Mexico could support a field trial for pump and plantation design. Map (adapted from NOAA.gov) shows about 4,000 active platforms; there are another 3,000 inactive. A similar opportunity exists in the North Sea.

7

Pro and Con

Here we have a candidate for removing 600 Gt of excess carbon from the air: the sink-on-the-spot plankton plantation that moves decomposition into the thousand-year depths. Push-pull pumping for fertilization and sequestration is relatively low-tech and merely augments natural up- and downwelling processes.

It has some unique advantages compared to current climate strategies:

- It is big, quick, and secure.
- It does not hinge on improbable self-denial by developing countries, treaties that take longer to negotiate than to ignore, or on finding a solution to the tragedy of the commons.
- It is impervious to drought and holdout governments.
- It does not compete for land, fresh water, fuel, or electricity.
- There is a “cognitive carrot,” an immediate payoff every year (fish catch) while growing the climate fix (the 600 GtC emergency draw down).

It is against such advantages that we must judge the potential downsides. Concerns voiced thus far include:

1. *Could we get international agreement fast enough?*
Continental shelves are within the Exclusive Economic Zone of the adjacent nation, which will have a strong interest in the restored fisheries. Shelves in the most productive latitudes belong to relatively wealthy countries. Their independent initiatives could quickly establish many plankton plantations without new treaties.
2. *Expensive?* If a pipe pump were to cost a thousand dollars in mass production, even a million of them would cost no more than the billion dollars spent in a single month on dog food in the U.S. But we cannot rely on any single method to work well, so we must budget on the thousand-fold-larger scale of what an unbudgeted bank bailout costs.
3. *Operating costs?* Wind and wave are free. Unlike fishing and farming, nothing about sink-on-the-spot plankton plantations will necessarily require handling, transport, or processing. Continuing costs would primarily be for maintenance and monitoring. Commercial fishing fees could provide significant income.
4. *Won't it pollute?* Perhaps not as proposed here, using local algae and nutrients in a vertical loop, but the usual considerations would apply should we want to introduce exotic or modified algal species to achieve even higher rates of sinking potential CO₂. Toxic blooms are possible during productivity transitions.
5. *Won't anoxic "dead zones" form?* Shallow continental shelf sites might have to be thinly utilized because hypoxia would

otherwise occur from the decomposition of the downwelled carbon soup in a restricted volume. Fish kills will occur when anoxia initially develops and fish cannot find their way out of the anoxic zone in time. However, a maintained anoxic zone will mostly repel fish from entering the problematic plume. One advantage of windmill pumps is that compressed air could be bubbled into the Archimedes screw chamber so that sufficient oxygen would be available for the new CO₂ production in the depths.

6. *We don't know what will happen.* The novelty here is minimal, even less than for iron fertilization. Fertilizing and sinking surface waters merely mimics, albeit in new locations or new seasons, those natural processes seen on a large scale in winter mixing and in ocean up- and downwelling. There is also historical precedent. The 80 ppm drawdown of atmospheric CO₂ in the last four ice ages is thought to have occurred via enhanced surface productivity, aided by a major change in Antarctic offshore downwelling.
7. *Won't this just move the ocean acidification problem into the depths?* There are already massive downwells of surface waters with their 30% acidity increase. Since the depths are 98% of ocean volume, there is a fifty-fold dilution of this acidity. Sinking 600 GtC would add only several percent to the deep-ocean inorganic carbon concentration—but that also means that we cannot keep up a 30 GtC/yr sinking rate for centuries without risking more serious impacts. After twenty years, we should be pumping only enough to offset any remaining out-of-control emissions. Another 2 GtC/yr may be needed to offset continuing deforestation. Additional amounts might offset such CO₂ heating equivalents as

methane leaks and the loss of surface brightness from ice melting.

8. *Isn't that a lot of water to flush through the depths?* The obvious test beds are the North Sea and Gulf of Mexico where thousands of existing drilling platforms could be used to support appended pipes and pumps. Without waiting for floating pumps, we could quickly test for impacts as well as efficient plantation layouts.
9. *What side effects might the pumps have on the North Atlantic's overturning circulation?* The two major downwelling sites are already wildly fluctuating, suggesting that a major component of current climate is quite unstable. Pumping up deep water in the right places might strengthen the whirlpools and help stabilize flushing's climate contribution. Such denser water should prime the surface waters to spiral down, thereby entraining less dense water for a net gain.
10. *Why not do it on land?* We could indeed do some of the algaculture in better-controlled conditions on coastal plains, with windmill pumps bringing up nutrient-laden water from just below the thermocline and then returning it enriched with organic carbon soup to deeper ocean.
11. *Won't this take the pressure off the fossil fuel users?* This climate fix is an emergency repair analogous to drawing down a reservoir behind a leaking dam, not a model for how to do things in the future. The emissions-reduction agenda is still essential for life after the repair. In the same 20 years,

we would need to stop the 3 GtC annual hit from burning coal and the 2 GtC from deforestation.

And three from the chemical oceanographers:

12. *Pumping up will just bring up water with higher CO₂ than in the surface waters.* Vertical mixing, for example, causes the shallow southern part of the North Sea to export CO₂ to the atmosphere in the summer¹. In stratified North Atlantic waters, annual mean concentrations of inorganic carbon are about 2,170 $\mu\text{mol/kg}$ in the 1500 m depths, 2,130 at 500 m, but with surface waters dropping as low as 1,970 in the northern North Sea². A 40 $\mu\text{mol/kg}$ difference means that upwelling brings up 0.48 gC m^{-3} of inorganic carbon. Settling new biomass below the thermocline may yield less organic carbon, causing reasonable skepticism about up-only fertilization per se.

In any event, this objection can be overcome by pairing down-pumps with up-pumps. Pumping down the same volume of *unfertilized* surface water would sink 1.0 gC m^{-3} in the North Atlantic³ as dissolved organic carbon (99%) and living biomass (1%), which will become CO₂ in the depths over 6,000 years.

The 0.48 gC m^{-3} “cost” (for a 40 $\mu\text{mol/kg}$ depth-to-surface difference) is then subtracted from the gross 1.0 gC m^{-3} sunk, yielding a net sinking of 0.52 gC m^{-3} even with no fertilization. With fertilization creating a many-fold increase in dissolved organic carbon locally, the uplift cost is unlikely to overtake the potential CO₂ sunk.

13. *But nutrient depletion of surface water says that one cannot do something that big without an external source of*

essential nutrients. Indeed, the 80 ppm CO₂ drawdown at the beginning of each of the last four glacial periods was initially attributed to continental dust storms fertilizing offshore waters⁴.

There are several ways in which the usual box-model reasoning may not apply here. Plumes (the water moves but pumps are tethered) prevent the box-model-style mixing of up- and down-flows for millennia. Thus you continue to pump up deep water with pre-project levels of nutrients and inorganic carbon. This fertilizer spreads in a surface plume that widens out downstream of the tethered up-pump. Similarly a down-pump creates a plume in the depths that, because of differing pipe lengths, has little opportunity to feed back into the intake of the up pumps downstream. So instead of a box model and long-term thinking, we need a Heraclitus framing of the problem (“You cannot step twice into the same river”) and a shorter-term focus to appreciate this opportunity for major carbon sequestration.

14. *Even so, aren't you going to run out of phosphate, what currently limits the global ocean productivity to a fraction of its capacity?* If not enough phosphate is recycled by the push-pull pumps, up-pump pipes could be sited to bring up bottom waters from the southern oceans that are currently rich in phosphate.

This brings up another big and secure (but not quick) carbon sequestration possibility—mimicking the ice age drawdown of 80 ppm CO₂. It was analyzed by Princeton's Robbie Toggweiler and colleagues⁵.

Some essential background: deep water production near the Antarctic coastline works differently than do the deep whirlpools of the North Atlantic Ocean. In the Antarctic seas, there are holes in the pack ice where the downwelling takes place, particularly in the winter when fierce mistral-like downslope winds off the land keep a polynya open. (A polynya is an area of open water in otherwise closed pack ice.)

The intense evaporation at an opening leaves behind a lot of salt, creating exceptionally dense cold water that sinks and then slides down the continental slope to create Antarctic Bottom Water. This dense pool spreads north through the abyss as far as Chesapeake Bay.

Farther out from the Antarctic shores, westerly winds circle the continent without being slowed down via running into land. This pushes water ahead and to the sides, creating the Antarctic Circumpolar Current. The water pushed aside creates eddies and the upwelling of deep water: this is the major return path for the conveyor belt whose downwelling end is in the Greenland and Labrador Seas.

This southern ring of eddies is the major place where nutrients such as phosphate are moved from the deep ocean to the surface. They then are carried worldwide by the conveyor belt and serve to fertilize plankton growth.

But the nearshore Antarctic path back down into the abyss sinks a significant fraction of this recently upwelled phosphate before it can participate in photosynthesis. This shunt is not thought to operate in glacial times (the deep phosphate concentration drops

then), presumably because more extensive pack ice seals over the polynyas to close off the shunt.

Making the currently shunted phosphate available to the ocean surface globally, so the story goes, would boost worldwide ocean productivity, drawing down CO₂ in the same way as it did at the end of the last warm interval in the ice ages.

My speculation is that switching off this shunt pathway could be done by anchoring balloons to ice upwind of an offshore polynya, so the offshore wind drags it into the opening and closes it. For a coastal polynya⁶ where there is no upwind ice to drag, a high shoreline berm or sea wall might be constructed to deflect the valley downslope wind from the nearshore ice edge, allowing ice to form near the shore and anchor itself on a frozen bottom.

Unfortunately, given those thousand-year ocean circulation paths, there is little reason to think that this would be quick enough for a climate fix—though it is possible that the increased fertilization of the Southern Oceans might produce quicker results. Modifying the existing polynya shunt could, however, be useful for the long-term regulation of climate. (Regulating the plankton plantations and augmenting the northern whirlpools are my other two candidates.)

The fate of most such proposals is, of course, that good reasons arise for not implementing them *as proposed*. My push-pull ocean pumps proposal is meant to serve primarily as an easy-to-remember target that defines the response ballpark by being big, quick, secure, powered by clean sources, and inexpensive enough so that a highly-developed country can

implement it on its own continental shelf without endless international conferences. Any alternative scheme must pass those same tests.

Now it is time to distinguish between *reversal*, *relief*, *reduction*, and *restoration* outcomes.

Sufficient CO₂ *reduction* should *relieve* heat waves and many of overheating's knock-on consequences such as deluge and drought; it should *reduce* the danger of abrupt climate shifts.

In the case of acidification and the thermal expansion of the oceans, we can talk of *reversal*.

But in many state-dependent systems, history also matters. Destabilized ice sheets may continue to slide downhill, increasing sea level long after the temperature trend is reversed. Many ecosystems exhibit regime shifts and some may prove difficult to *restore*; once the Amazon's rain forests are destroyed, its unusual regenerative rainfall cycle will collapse, and therefore plant succession may stay stuck for a very long time at the stage of fire-prone grasslands, with little biomass accumulation to counter that which was lost to fire and rot of the present rain forest.

8

Countering a Methane Burp

The plankton plantations might also prove relevant for countering the effects of methane, so let me outline the various methane threats as they are currently understood.

By now you have probably heard about one or more of the following;

- Natural gas is mostly methane. Gas pipelines leak 1-4% of what they carry. Neighborhood pipes and gas meter seals leak as well. Every time a gas furnace or hot water heater cycles off, some of its dead space methane is vented unburned. (Turning the flame up and down, in the manner of gas stoves, would make more sense than the current use of on-or-off cycling to adjust heat production.)
- Grazing animals have extra stomachs for the slow digestion of grass, and so they burp methane, CH₄, as well as CO₂. That much is “natural.” What is anthropogenic has to do with the number of animals. The more grazing animals, the more methane production.
- Methane is what causes mine explosions and, more commonly, the asphyxiation of coal miners. Much makes it into the atmosphere unburned. A century ago, “coal gas” was piped around cities for lighting purposes.

- The frozen Arctic tundra will, as it thaws, produce a lot of methane and release it into the air. There is already a steady leakage of methane from flooded permafrost deposits on Siberia's continental shelf¹. As the Arctic Ocean warms, there will be more.
- Besides such sources of steady leakage of methane into the air, there can be large releases of methane from the sea floor as methane hydrates break loose from the continental slope during an earthquake. They float to the sea surface and melt, delivering the methane to the atmosphere.

First, the methane basics². Molecule for molecule, CH₄ is about a hundred times more potent as an atmospheric heat-trapping gas than is a molecule of CO₂ on the time scale of decades. The amount of methane in the air has doubled in the last fifty years. Methane now produces 14 percent of the total greenhouse gas contribution to global warming, almost as much as deforestation's 18 percent.

The "natural gas" that comes up a well is mostly methane, with variable amounts of water vapor and CO₂ that must be removed before it will burn reliably.

When organic carbon is digested by bacteria, both CH₄ and CO₂ are released. But the proportion depends on the availability of oxygen. When little O₂ is available (hypoxic and anoxic conditions), little CO₂ can be formed—and so decomposition proceeds more slowly via the methane route.

If there is a lot of O_2 available, decomposition is quicker and it is mostly CO_2 that is produced. There are additional decomposition routes as well; the primary treatment of sewage involves bubbling a lot of air (20% O_2) through the raw sewage, trying to produce a lot of CO_2 before the other decomposition routes can make gases with offensive smells. (Both CO_2 and CH_4 are odorless.)

Let us now imagine that some brief event—something like the 2010 Gulf of Mexico disaster where it took six months to stop the release of crude oil and natural gas from a deep drilling blowout—were to double the amount of methane in the atmosphere. How long would this excess endure?

Much of the new methane from the six-month blip would be removed in ten years by natural processes. (In contrast, a CO_2 blip takes about ten times longer to fall as far—and maybe 25% would still be around a thousand years later.)

A big blip could get us into serious problems, especially via triggering abrupt climate shifts. And a big sustained leak is the leading candidate for some of the mass extinctions in the fossil record³.

Where might a methane leak come from? Most obviously, from the legacy of our addiction to petroleum: many, many wells have been drilled into depths, looking for oil or natural gas. Most have been abandoned as unpromising, the pipe being capped at the surface or on the ocean floor. South of Houston and New Orleans in the Gulf of Mexico, 7,000 wells were promising enough to construct a platform on stilts, though 3,000 of them

have since been abandoned. The length of the pipes connecting them to shore would, laid end to end, reach around the world.

There is also a fair amount of methane found in association with coal. It is what kills thousands of miners each year via explosions or asphyxiation (the methane dilutes the oxygen content of the air so much that you cannot breathe fast enough to get the minimum amount of oxygen). The slower seepage of methane mostly escapes unburned into the air. And since there are a lot of abandoned mine shafts and scalped mountain tops, it is small wonder that the highest concentrations of methane in the United States are found over states with a lot of mining, not over the states with a lot of livestock that burp methane.

Strip mines and mountain-top removals, while considerably safer for the coal workers, create many new paths for venting methane into the air. While we can imagine sealing up old mine shafts to reduce the rate of methane leakage, that's not going to work for such grand earth-removal operations that bleed methane everywhere.

Now we know enough to talk about what a big methane burp would do to change the climate. Initially it acts like even more CO₂ excess: it overheats the planet and sets us up for abrupt climate shifts. But we could counter its overheating effects by reducing the atmospheric CO₂ accumulation even more.

We probably would not need to build a methane-capture facility on the scale of the plankton plantations. Indeed, we could use plankton plantations to counter the methane's heating effects

by reducing the CO₂ heating effects to below the 280 ppm baseline. At least in the short run, the methane treatment would be the CO₂ treatment, intensified. That is to say, reducing heating via carbon sequestration or reflecting away sunlight would serve to counter methane's overheating effects.

The imperative is to have standby cooling capacity in case a giant burp of methane suddenly makes it into the air. To my mind, we would need plankton plantations even if we didn't have an excess CO₂ problem. We need them (or an equivalent), just sitting around with most of the windmills and wave-powered pumps turned off, ready to spring into action to counteract a methane burp.

The two big sources for a methane mega-burp—something far larger than what any malfunctioning well might contribute—are thawing tundra (containing frozen soil from ancient dust storms) and unstable continental slopes (where the continental shelf drops off to much deeper bottoms) in the Arctic and sub-Arctic latitudes.

Thawing allows the tundra's organic matter to be decomposed, producing CO₂ and CH₄. The Arctic Ocean, formerly roofed over by reflective ice and snow for most of the year, is now increasingly uncovered in the summertime, the dark surface waters absorbing sunlight around the clock. That warms the air above the surface. The winds then warm the surrounding land—which is where the tundra is. Melt ponds spring up like pox marks on a face. Once thawed, the buried organic matter can be

decomposed by the usual bacteria—but the buried oxygen quickly runs out, and so methane accumulates, percolating upward.

When the ice capping an Arctic pond starts to melt, eight months of trapped methane escapes into the air⁴. Tundra scientists amuse themselves by drilling a small fishing hole through the ice covering a pond. Enough methane comes whistling out to be set on fire, producing a fiery fountain.

The water in the pond, being denser than the underlying frozen tundra, cuts into the pond's bottom like a wedge, speeding up the thaw and methane production.

Offshore, earthquakes under the continental slope cause avalanches, allowing buried ice, with methane trapped in between the H₂O molecules in their icy matrix (called a methane hydrate or clathrate), to pop loose from the sea floor and rise to the sea surface. And to melt there, releasing the methane directly into the atmosphere.

This is already happening in the North Pacific Ocean offshore of British Columbia and in the Arctic Ocean offshore of Siberia. Fishermen amuse themselves by holding up a piece of ice and setting fire to it.

An excess of earthquakes is expected offshore because sea level is rising. The continental slopes are now under added hydrostatic pressure from above, and where the hillside is unstable, avalanches will occur (they are the common cause of

tsunamis). Some will let loose large amounts of “The ice that burns” to float to the surface and melt.

When you know that there are going to be more fires, you stockpile water for firefighting. We now know that methane burps are a serious global threat and so we must provide cooling capacity, held in a stand-by reserve. After the twenty-year cleanup of CO₂, the plankton plantation might serve nicely.

If you have read this far, you are now well-informed about the known climate threats, far better than your neighbors.

Consider sending your favorite chapter to a local newspaper editor as a suggestion for a feature article or editorial. Or post it to a blog to start a discussion. Send it to your lawmakers.

PDFs of individual chapters can be found at *WilliamCalvin.org/bk15*. Because of what I said on the copyright page, you don't need to seek permission for copying unless you are a book publisher. Just do it.

9

What Will the Greek Chorus Say?

In the drama of the ancient Greeks 2,500 years ago, a tragedy adhered to a certain form. The protagonist was always a good, respected man of great power, often a hero, who acted out of good intentions. Despite this, he had a tragic flaw, or made a tragic error, that put him on the road to catastrophe. He would eventually recognize his problem—but, at least in those classic tragedies, it was always too late to save him from the consequences of his actions¹.

The Greek Chorus stood around on stage, commenting on the dramatic action. Not only did they fill in the background story, but they had a point of view, often setting up an ethical framework by which the protagonist's action should be judged. The chorus helped to evoke the visionary experience that was “the very essence of tragedy.”

So what might a Greek chorus have to say someday about a looming climate tragedy?

(Scene: What appears to be the stage of an amphitheater, now washed by waves from the rising sea level. The backdrop shows a sandy beach and a full moon low in the sky, seen through sunset haze. Most actors except the politician are scantily clad, hoping to catch some cool breeze from off the ocean for evaporative cooling. If desired, the politician can be shown with an umbilical hose piping in cool

air to a pants leg from his vehicle at stage left. Vacuum-cleaner hose will suffice. It can be run up the actor's back so that his bouffant hairdo is made to stand up.)

Chorus (Prologue, chanted while coming onstage): Seven years of deluge here, drought there, hunger everywhere. Coastal cities hit by big waves and bigger hurricanes, New Orleans writ large.

And everywhere this heat wave, summer after summer. The death toll is high among infants and senior citizens. Our air conditioners cause the electrical grid to collapse. Then even our electric fans do not work. Buildings are uninhabitable if their windows cannot be opened. And even evaporative cooling doesn't work like it used to, because the humidity has become so high from global warming.

Chorus Leader: Who dares not stir by day must walk by night². Ghostly pale, we gather at the sea shore each evening, hoping for a breeze.

Water supplies frequently dry up, causing some cities to be abandoned. But because things are not much better elsewhere, half of the fleeing people die. Our neighboring countries are starving. Their militias raid our border states for food.

The people are bewildered and angry, half-crazy with suppressed rage from decades of being worried and challenged, repeatedly bitten from without and within³. The times are desperate.

It feels as if civilization were about to collapse. And without civilized behaviors, the life of man is solitary, poor, nasty, brutish, and short⁴ (*Pause, then repeat the last sentence.*)

Chorus Leader (turning to actors): Rumors fly around that it is now too late to fix our climate—that we are already doomed, stuck on the road to ruin, spiraling up into the hothouse. Is that true?

(*Three reporters wearing suits come alive as the Congressman begins to speak, take out their pens and raise their videocams.*)

Congressman Deny Delay: Of course not. Let's have no more of your unpatriotic climate nonsense—we've proved it's just another spell of bad weather. To get us through it, we're building more coal plants to run the extra air conditioners.

(*Reporters sit.*)

Physician (rolls eyes up): Just build more coal-fired plants, indeed! You apparently seem to think that fanning the flames is still a good idea. Don't you ever learn? (*Congressman acts as if he heard nothing.*)

ClimateGuy (looking at *Chorus Leader*): To answer your question about inevitability, about ten years ago I would have said no, that we could fix things. I thought then that, politics aside, that we were capable of repairing the climate, that it was both technologically and economically feasible.

But we've become much weaker economically since then. And we've added so much more to the CO₂ burden. Now I'm not so sure that we can get our act together, not as confident that we can clean up the CO₂ in time to save ourselves. For all I know, we're on the slippery slope already.

EconomicsGuy (turning toward *Congressman*): I hope you took in the implications of what he just said. That except for your brand of politics, we could have avoided this mess we're in.

Do you live in your own little world, where cause and effect somehow functions differently than it does for the rest of us? Where two plus two equals five? Where wishes somehow trump reality?

And it isn't that you were blind. Otherwise you and your buddies wouldn't have been so proactive for decades, trying to keep people confused.

Congressman Deny Delay: I resent that, sir! Let me remind you that we are duly elected and doing the will of the people. You lost the election, sir! Don't get in our way! (*Exits stage left, purposefully, followed by reporters.*)

EconomicsGuy (looking stage right and then turning to the others): I've known that guy for years and he didn't used to be like that. He was a good man, even if I didn't like the way he voted. You could speak frankly to him and he would listen. But then he got into the climate skeptic game for his fifteen minutes of fame. And that sort of thing spreads like a contagious disease, winning them elections.

Physician: When something interferes with our self-image, or when we are afraid, guilty, or confused, we tend to deny it. It only takes one of them to trigger denial. Climate change can invoke all four of them.

Chorus: Science, driven by a quest for truth, used to be the common touchstone of what is real and verifiable. But then the fans of business-as-usual spent millions on advertising, to make sure that people stayed confused about the causes of global warming and the consequences. Those manipulators made it seem reasonable to wait before acting.

Next they tried cutting back on funding for climate and alternative energy research.

When that failed to stop the bad news, they tried intimidating the climate scientists, calling for congressional investigations of those who spoke out. The deniers spammed the scientists with lawsuits, forcing the scientists to pay lawyers out of pocket and then take out second mortgages on their homes.

Now the deniers are even questioning the patriotism of those who keep pointing out that the emperor is naked.

EconomicsGuy (pointing at the departing congressman):
Suppose he's turned into a control freak? That bit about "We've proved it's just another spell of bad weather" implied that it's the ruling party's determination that is relevant, not that of the scientists.

Remember when the White House was caught, just after the turn of the century, letting an ex-oil-company lobbyist edit what the government scientists said about climate?

ClimateGuy: And to think that I once was so naïve as to believe that the facts spoke for themselves.

Reminds me of when the Vatican thought that Galileo was impinging on the church's prerogative to say what the heavens contained—such as the Earth being the center of the universe, around which other heavenly bodies rotated.

Physician: But still it moves. However, control issues don't explain very much. He reminds me more of a delusional patient.

EconomicsGuy: Delusional? Doesn't that mean he believes something that is false—despite incontrovertible evidence to the contrary? But unlike most people who believe impossible things, no amount of rational argument will budge him?

Chorus Leader: Alice in Wonderland laughed: "There's no use trying," she said; "one can't believe impossible things."

Said the Queen: "I daresay you haven't had much practice. When I was younger, I always did it for half an hour a day. Why, sometimes I've believed as many as six impossible things before breakfast."

Physician: Practice helps. But to qualify as a medically-interesting delusion, the belief also has to be contrary to what almost everybody else believes. Otherwise commonplace

superstitions and some venerated religious beliefs might qualify as delusions.

EconomicsGuy: There certainly is a vocal minority that goes along with climate denial—though there is some bullying involved. Remember back in 2010 when they first made climate denial a qualification to run for governor or for Congress—at least if you wanted campaign money?

They will force any politician who shows signs of doing actual hard thinking to walk a plank into a sea of craziness⁵.

Physician: They may have gone collectively mad, but it's not as if some antipsychotic medication could fix their problem. This is political pathology and, unlike most delusional behavior in individuals, it can be fatal to others.

Chorus Leader: In ancient Greece, should the ruling party harbor delusions about their own strength or cunning, they were likely to lose a war. The victors would usually slaughter the male half of their population, with the women marched off to be sold as slaves. The threat of that fate helped to keep delusional leaders from gaining power because the more pragmatic would be so wary of them.

Physician: I think that the climate delusions started out as that “see no evil, hear no evil” stance of people who want to avoid the subject.

Avoiders may accept the science, yet don't talk about the climate crisis because their personal ethics would then require them to take action. Actually doing something would conflict with their other priorities in life.

‘Just pretend it isn’t there and maybe it will go away.’ Best recipe for disaster ever invented.

But the scale of it! The deny- and delay-mongers have made disbelief in science into a ruling superstition, perhaps to cater to the anti-government business-as-usual crowd that finances them.

EconomicsGuy: There is a loud and intellectually corrupt segment of public life dedicated to fact-denial⁶. Decades ago, when they first became so bold about climate denial, climate change wasn’t yet a taboo subject. Now they’ve gotten coercive about it because they’re so afraid that the current banking system will collapse.

Physician: The deniers don’t worry any more about getting caught in their lies, having learned that so many voters simply don’t pay enough attention to connect the dots. Journalists can do it but their bosses often have firm orders to discourage it.

And so the deniers can keep using the climate skepticism of the 1970s over and over because, no matter how often you explain that those questions have long since been answered, the misrepresentation doesn’t catch up with the deniers.

Chorus Leader: Many people get their news only from the loudmouths of talk radio. And all the constant repetition of the lies indeed works just like Joseph Goebbels told Adolf Hitler it would. Even if someone watches the evening news, it may be a network whose owner has told the news department

to always report climate news as if it were still controversial, mere opinion⁷.

EconomicsGuy: Lies just lead to more lies. Now they have to lie to keep the economy from crashing. No one wants to lend money anymore, not even for five years, unless persuaded that business-as-usual will prevail and they will get their money back. So the ruling party sets out to fool them, all in the national interest.

Chorus: You can fool all the people some of the time, and some of the people all the time, but you cannot fool all the people all the time.⁸

Physician: Hey, they're channeling Abe Lincoln this time. But Lincoln left out something important.

The deny-delay crowd gets away with fooling folks because Lincoln's "all the time" assumes we have enough time left for the truth to sink in and for us to throw out the unscrupulous. But it's not happening and there's not enough time left.

ClimateGuy: Now if the ruling party was pragmatic, they would be making a big show of projects to repair the climate, burying all of that excess CO₂ and raising hope that way. But they're pretty stubborn.

[*Silent musing.*]

Chorus Leader: The Resurrection Project has now engraved most of the how-to manuals from the web onto the inside surfaces of aluminum beverage cans, one page per can. Half of college

textbooks are now engraved. Even if books were burned and digital records were lost, metal scavengers would discover the engravings when cutting cans open to flatten them into roof shingles. Some would piece books together and read them, speeding the resurrection of civilization.

But after analyses of recent political history were included, all such engraving was banned by the ruling party as defeatist propaganda.

ClimateGuy: And while all countries contributed to the CO₂ blanket, it's the politics of the U.S. that creates a global bottleneck. If you can't get the country that contributed the most to the CO₂ accumulation to start moving, then other countries are going to have trouble asking their own people to make sacrifices.

The U.S. used to have the reputation, left over from World War II and our brief Space Age, of being the can-do innovator that worked around problems. Just the kind of country that you'd expect to take the lead in solving the climate problem.

Chorus: If flying-saucer creatures or angels or whatever were to come here in a hundred years, say, and find us gone like the dinosaurs, what might be a good message for humanity to leave for them on the walls of the Grand Canyon? (*Unrolling banner*) **WE PROBABLY COULD HAVE SAVED OURSELVES, BUT WERE TOO DAMNED LAZY TO TRY VERY HARD.**—Kurt Vonnegut (1991)⁹

[*Silent musing.*]

Chorus Leader: This nation was built by men who took risks: pioneers who were not afraid of the wilderness, business men who were not afraid of failure, scientists who were not afraid of the truth, thinkers who were not afraid of progress, dreamers who were not afraid of action.¹⁰

EconomicsGuy: Right. And now we have leaders who stick their heads in the sand—and are proud of it. Now the rest of the world sees the United States as having gone collectively mad.

They remember the precedents. We prefer not to recall them, but foreign leaders likely remember those mass suicides of unbelievably gullible middle-class Americans. First there was the Jonestown Massacre in 1978, the mass suicide of 900 members of an American cult led by Jim Jones.

Then in 1989 near San Diego, Heaven's Gate members led by Marshall Applewhite—believing that the earth was about to be wiped clean and refurbished—committed mass suicide on the theory that they could thereby escape the fate of others via hitching a ride to heaven on the Hale-Bopp comet, passing by at that time in the night sky.

ClimateGuy: It's hard to blame the rest of the world for suspecting that we'll take the suicidal path for climate. For some reason, they resent the fact that we'll drag them along with us.

As an American, I get a lot of hateful looks from people on the streets when I travel abroad to climate science meetings. So I adopted a British accent and, while in London, bought

myself a complete outfit of clothing, shoes, sunglasses—even argyle socks.

[Silent musing.]

EconomicsGuy: At least those who continued to insist that the earth is flat never achieved such political power—nor did they threaten the rest of us with a chaotic collapse of civilization. And the disappearance of civilized behaviors.

Physician: Even worse than the suicidal fools are those proactive fans of Armageddon. They attempt mass murder, hoping to trigger the End of the World.

Remember the first one, Aum Shinrikyo, that got written up¹¹ in a medical journal as if it were an emerging infectious disease? That sect which attracted so many young graduates from Japan's major universities that it was dubbed a “religion for the elite”? Lots of members and a big bank account, with offices in the U.S., Russia, and Japan? They attracted audiences of 15,000 people even in Moscow.

Their leadership's 1995 nerve gas attacks on the Tokyo subway trains were said to be an attempt to provoke a war that would destroy everyone—except, of course, the faithful. The idea was to blame the attacks on the U.S., triggering a world war, which would then lead to Armageddon¹².

EconomicsGuy: Fools, maybe, but technically capable fools—they brewed their own nerve gases. They turned malicious under the leadership of a juvenile bully who later learned charisma

and thrived. But his second in command was a cardiologist and the other subway attackers had applied physics degrees.

It looks as if training in logical thinking isn't a reliable defense against delusional thinking.

[Silent musing.]

Chorus Leader: So are humans afflicted with some tragic flaw?

Physician: Such as susceptibility to delusional thoughts?

That might be because the structured thought which we need for planning ahead and for speaking long sentences—and reasoning about them—appear to have been invented rather recently in our evolutionary history⁷³. Maybe only 2,000 generations back, and that's not much time for natural selection to get the bugs out. Or at least, not well enough to withstand modern media onslaughts.

But otherwise, the psychological imperfections responsible for our plight seem pretty minor to me, just stuff that is unethical in many cultures— such as trolling for suckers. It doesn't take some urge to suicide or mass murder, triggered by the complexities of modern society.

EconomicsGuy: Yet the consequences of playing people for fools, with misrepresentations the mainstay of many a political ad campaign, are very different than in the days of trying to sell the Brooklyn Bridge to tourists.

Even when the deniers are caught lying, it doesn't seem to make any difference in the next election, what with all the

media obfuscation they can stir up. Which just encourages them to try it again and again.

[Silent musing.]

ClimateGuy: And to think that we started the climate damage with really low-tech means—just cutting down trees, then mining coal. That’s pickaxe-level technology.

But it led to the dry-rot of civilization where, even though various means to back out of the climate crisis were possible, we actively chose to pretend that the climate problem didn’t exist.

(Foreground stage lights begin dimming and then flickering. The Chorus briefly chants an exasperated “Not again.” The moonlit beach scene backdrop soon becomes the dominant stage lighting, the actors silhouetted.)

ClimateGuy: Let me quickly say, to end on a positive note, that there’s still some chance of hauling ourselves off this slippery slope by a crash effort to clean up the CO₂. Unlike when it was first proposed, back when the economy was good, we’ll now need four times as much technology as well as a far bigger dose of good luck.

If we make it, this will still be a very impoverished planet to live on. Those millions of species that recently went extinct won’t reappear. We already have major ecosystems to repair and the Amazon’s rain forests probably won’t ever come back.

EconomicsGuy: You know, that interminable opera of Wagner's, *Götterdämmerung*, is all about the end of the world. But remember what they say about it. "It ain't over until the fat lady sings." And that Brünhilde sure turned out to be pretty long-winded.

[Pause.]

Chorus Leader (repeated several times as they all slowly leave the stage to walk along the "beach" background):

Here, on the level sand,
Between the sea and land,
What shall I build or write
Against the fall of night?
Tell me of runes to grave
That hold the bursting wave,
Or bastions to design
For longer date than mine.¹⁴

10

The Great Use-It-or-Lose-It Intelligence Test

Most civilizations of the past have proven fragile¹, snuffing out their own candle. Climate change was usually the final blow, once they had made themselves vulnerable via explosions in population and resource consumption.

Thanks to both history and science, we're the first society to understand what's going on, both with resource issues and climate change.

But presently some political parties make one wonder if human intelligence is mature enough to avoid committing collective suicide—even though we're still technologically and economically capable of repairing the rot we have caused in the foundations. The problem is the political willpower to do it quickly enough.

My chapter title comes from a dinner lecture that I gave in Beijing to the people who created the green revolution in agriculture. (You can view the hour-long video on the World Bank's web site or at global-fever.org). In its written version, the pamphlet starts out this way:

To fit the magnificence of this setting in Beijing's Great Hall of the People, and the honor of giving the Sir John Crawford Memorial Lecture, it is well to have a subject of suitable proportions.

I have chosen one of global size and urgent time frame: our climate crisis. We only have one future and one global climate—and now it looks as if we only have one chance to rescue our civilization from collapse and prevent a mass extinction of species during the 21st century.

It is easy to appreciate that one more degree of global warming will seriously reduce crop yields in the tropics, but in the words of climate scientist Claudia Tebaldi², “It’s the extremes, not the averages, that cause the most damage to society and to many ecosystems.” Even if you live where the *average* rainfall stays the same, there will still be more extreme weather such as floods and droughts. That they “balance out” will comfort no one.

Unless you have been keeping up with climate science for the past twenty-five years, you likely do not know how serious the matter has become. The notion that we might slowly get into serious trouble by mid-century has been conveyed by the media and understood by at least some political leaders. But that scenario depends on somehow avoiding sudden shifts in climate in the meantime, instant setbacks at a time when we lack maneuvering room....

Preventing the 2° fever is the Great Use-it-or-lose-it Intelligence Test. And we are dealing with the time frame used centuries ago by Edmund Burke when he said, “The public interest requires doing today those things that men of intelligence and goodwill would wish, five or ten years hence, had been done.”

We are already in dangerous territory and have to act quickly to avoid triggering widespread catastrophes. The only good analogy is arming for a great war, doing what must be done regardless of cost and convenience.

We dare not wait until we are weakened before undertaking emergency climate repairs. Our ability to avoid a human population crash will be compromised if economies become fragile or if international cooperation is lost via conflicts. A serious jolt—say, a major rearrangement of the winds—could cause catastrophic crop failures and food riots within several years, creating global waves of climate refugees with the attendant famine, pestilence, war, and genocide.

At the beginning of World War II, Franklin D. Roosevelt used the metaphor of a “four alarm fire up the street” that had to be extinguished immediately, whatever the cost. Our need for fast action on climate deterioration requires devoting the resources necessary to radically shorten the developmental cycle for all carbon burial projects.

Acquiescing in a slower approach is, in effect, playing Russian roulette with the climate gun. The climate crisis needs wartime priorities.

Acknowledgements

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Explaining the Author

Given the topic of this book, normal people (not just those in the climate denial industry) are sure to ask: “How can a shrink know anything about climate science?”

It’s an understandable confusion. While I am a professor emeritus of psychiatry and behavioral sciences, I am not a psychiatrist. Not even an M.D.

However, that’s par for the course. More than half of the faculty at most research-oriented medical schools are Ph.D. types—and that’s even true of many clinical departments, certainly mine.

Most climate scientists reside in departments such as oceanography, atmospheric sciences, geophysics, and the earth sciences. How does a neurophysiologist find any overlap with them? The journey involved an improbable intermediate stop in anthropology—or at least that part of archeology and physical anthropology concerned with human evolution from the great apes.

I started out in physics. My Ph.D. was in Physiology and Biophysics. And that formal education was what made possible my forays into climate science over the last three decades. I could not have read and understood the research literature without that background.

Though I hadn’t thought much about respiration and digestion since my Ph.D. qualifying exams (after which brains became my specialty), the issues of climate science brought it all back. Whenever the oceanographers would mention *convection*, I’d mentally substitute the physiologists’ equivalent term, *bulk flow*. When they got off on the carbon cycle, I’d recall the lectures on the digestive

tract and ecology that I used to give when I taught Biology 100 for a few years.

Back in the late 1970s when I was wiretapping single nerve cells as an associate professor of neurological surgery, I took a sabbatical year as a visiting professor of neurobiology at the Hebrew University of Jerusalem and started thinking about the emergent properties of whole circuits of cells, one of which is more precise timing, much needed for accurate throwing and hammering. Someone had just shown that, if you gang together four times as many embryonic heart cells, the beat's irregularity was cut in half—a biological example of the Law of Large Numbers.

From that I inferred that throwing more accurately might involve assigning a lot more neurons to tell the muscles when to move. Maybe, I speculated, that's why humans need a bigger brain than, say, chimpanzees. A long 1986 report by Jane Goodall told me that Gombe chimps throw in ways that don't require much accuracy. (Throwing is mostly used as a threat. They don't bother to "get set" to throw. Or, for that matter, practice their throws.)

That's what got me to reading up on the 6 million years (Myr) of human evolution since a chimpanzeelike ancestor. It turns out that brain size didn't start to increase until about 2.5 Myr ago. That was also about the time that sharp-edged stone tools became much more prominent. And about that time, the ice ages began.

What did those three trends have to do with one another? Coincidence, or was there some cause-and-effect hiding in there? A brain tripling in size over a mere 2.5 Myr was an oddity, a fast track that needed explaining. I love piecing together multidisciplinary stories like that. (Prior examples: *The Cerebral Code*, *Lingua ex Machina*, my archaeological explanations for the Acheulian handaxe, and my 1975 article on trigeminal neuralgia.)

The big brain puzzle started taking over my life. I had to pay attention to climate change, as it is often the evolutionary driver that leads to a new species. I heard a lot of discussion of punctuated equilibrium, how “progress” is often compressed into brief periods. In between them, change was usually slow.

It turns out that climate change is similarly jerky.

Ice age climates are cool, dry, windy, and dusty—but the climate can flip into conditions that are relatively warm and wet. Back in the 1970s, brief warm-ups were thought to happen a few times within each 100,000 year glaciation cycle. But in 1984 came the ice core evidence. (See *The Great Climate Leap*.) It wasn't just a few events but more like a few *dozen* events, some flipping back and forth in only a few centuries, with abrupt transitions taking only five years or so. If the brain enlarged more easily during episodes of climate change, there were a lot of sudden shifts available for pumping it up. (See *A Brain for All Seasons*.)

So after 1984, I read everything I could find regarding abrupt climate change, for reasons that had little to do with global warming. But by the time of my 1998 cover story for *The Atlantic*, “The Great Climate Flip-flop,” I began to realize that triggering abrupt climate jerks via global overheating might prove to be more serious than the expected heat waves and droughts. Jared Diamond's 2005 book *Collapse* got me to thinking about our present civilization's vulnerability.

Once I discovered how bad the 2003 Greenland melting had been, I began to drop everything else and focus on how we might get ourselves out of this mess. I read up on global warming per se, whereas my earlier interest was mostly confined to the abrupt episodes. I wrote it all up in 2008 as *Global Fever*.

Then I started collecting modern examples of sudden shifts that were global in scale even though not as dramatic as the ancient flips.

I'd never heard anyone talk about the modern quick shifts but there they were, buried in the literature of oceanography, meteorology, and rain forest ecology.

It seemed obvious that we were going to have to clean up the excess CO₂ accumulation in the air, yet few were talking about it. No one seemed to realize that all of the good ideas for slowing CO₂ annual emissions were woefully inadequate for the bigger job of cleaning up the CO₂ accumulation. Examining their numbers is what led me to considering push-pull pumps (they are quite common around medical schools) in my search for solutions that were big, quick, and secure.

Almost no one was talking with a sense of urgency, perhaps because they didn't know about the sudden shifts and near misses since 1976, or didn't have much insight into the state transitions that cause instability in such nonlinear systems as heart, nerve, and climate.

Surely, I thought, there were a few climate scientists out there who knew all of what I knew—but I couldn't rely on them having enough experience in translating complicated science for general readers such as policy wonks and legislators. Or being able to spare the time from their heavy load of teaching, research, and evaluating the situation for the IPCC.

That's where this short book and *The Great Climate Leap* came from. Unlike all of my previous books, writing the pair was more a matter of civic responsibility than of choice.

W.H.C.
Seattle

Index

An index has been omitted; however, since the full text is available on the web via WilliamCalvin.org, a search engine can substitute.

Chapter Notes

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Chapter 4 *Put the Genie Back in the Bottle?*

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 - ⁶ Anderson PS (1993) Evidence for an Antarctic winter coastal polynya. *Antarctic Science* 5:221-226.

Chapter 8 Countering a Methane Burp

- ¹ Natalia Shakhova, Igor Semiletov, Anatoly Salyuk, Vladimir Yusupov, Denis Kosmach, Örjan Gustafsson (2010) Extensive Methane Venting to the Atmosphere from Sediments of the East Siberian Arctic Shelf. *Science* 327, 1246. DOI:10.1126/science.1182221
- ² Calvin WH (2008) *Global Fever: How to Treat Climate Change*. London and Chicago: University of Chicago Press. See Chapter 12, p.158. faculty.washington.edu/wcalvin/bk14
- ³ Peter D. Ward (2007) *Under a Green Sky: global warming, the mass extinctions of the past, and what they mean for our future*. Smithsonian/Collins.
- ⁴ Katey Walter et al (2006) Methane bubbling from Siberian thaw lakes as a positive feedback to climate warming. *Nature* 443, at DOI: 10.1038/nature05040.

David Archer (2007) Methane hydrates and anthropogenic climate change. *Biosci. Discuss.* 4 993–1057 and see RealClimate.org/index.php?p=227.

Chapter 9 What Will the Greek Chorus Say?

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- ¹ A modern example of a classic-style tragedy (though lacking a Greek chorus) is Arthur Miller's second play, *All My Sons* (1947). That the protagonist always understood too late doesn't make Greek tragedies pessimistic. I consider it a playwright's technique for conveying visionary insight in a manner more likely to stick permanently in memory and promote thinking ahead.
 - ² William Shakespeare (1581) *King John* I.i.172
 - ³ Adapted from a passage in Greg Bear's *Quantico* (2007).
 - ⁴ Thomas Hobbes (1651) *Leviathan*.
 - ⁵ Timothy Egan. opinionator.blogs.nytimes.com/2011/06/09/the-reluctant-mormon/?hp
 - ⁶ "Republicans in a congressional panel declared, by a majority vote, that climate change caused by humans does not exist. The majority of the House then voted to get rid of federal funding for the world's finest scientists in the field to study the changing earth, through the Intergovernmental Panel on Climate Change. Blink, blink, just like that — our representatives wished away the future." Timothy Egan (2011) *Twister's Tale*. *New York Times* at opinionator.blogs.nytimes.com/2011/05/26/twisters-tale/?hp.
 - ⁷ *Sent: Tue Dec 08 12:49:51 2009*
From: Sammon, Bill [Fox News Washington managing editor]
 "Given the controversy over the veracity of climate change data...we should refrain from asserting that the planet has warmed (or cooled) in any given period without IMMEDIATELY pointing out that such theories are based upon data that critics have called into question. It is not our place as journalists to assert such notions as facts, especially as this debate intensifies."
 See climateprogress.org/2010/12/15/leaked-email-fox-news-sammon-cast-doubt-on-climate-science/.
 - ⁸ Abraham Lincoln.
 - ⁹ Kurt Vonnegut (1990) *Fates Worse than Death: An Autobiographical Collage*.
 - ¹⁰ American theatre critic Brooks Atkinson.
 - ¹¹ www.cdc.gov/ncidod/eid/vol5no4/olson.htm

¹² See en.wikipedia.org/wiki/Aum_Shinrikyo.

¹³ Calvin WH (2004) *A Brief History of the Mind* (Oxford University Press).

¹⁴ A. E. Housman (1936) *Poems*.

Chapter 10 *The Great Use-It-or-Lose-It Intelligence Test*

¹ Diamond J. (2003) *Collapse: How Societies Choose to Succeed or Fail*. New York: Viking.

² Claudia Tebaldi et al, "Going to Extremes," *Climatic Change* (December 2006). See www.ucar.edu/news/releases/2006/wetterworld.shtml.