Climate Shock

BY GERNOT WAGNER AND MARTIN L. WEITZMAN

*Climate Shock: The Economic Consequences of a Hotter Planet** is the last word (at least for now) on this increasingly alarming subject. No surprise there. Gernot Wagner is the lead senior economist for the Environmental Defense Fund and a former editorial writer for the *Financial Times*. Martin Weitzman, a professor at Harvard, has been at the forefront of environmental economics research for the past two decades. (Before that, he dazzled with a remarkably original framework for conquering stagflation, the economic catastrophe du jour in the 1970s and 1980s.) ¶ The chapter adapted here is on geoengineering – proposals for quarantining carbon dioxide emissions or altering the atmosphere to reduce the penetration of sunlight. Once thought the stuff of science fiction (check out *The Mars Trilogy* by Kim Stanley Robinson), geoengineering may be the last, best hope for containing global warming in a world that cannot seem to get its act together on the climate front. Wagner and Weitzman offer an accessible, clear-eyed analysis of the subject that will immunize readers from the Chicken Littles, conspiracy theorists and snake oil salesmen who tend to dominate the nascent debate over the benefits and costs of engineering away the impact of greenhouse emissions.

— *Peter Passell*

In June 1991 and with a year to go, preparations for the Rio Earth Summit were in full swing. "Sustainability" was in vogue.

Who could disagree that humanity ought to "ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs"?

The excitement was palpable. It might still be possible to achieve sustainable development "by the year 2000 and beyond," as the UN General Assembly had called for. There was only one problem: the Earth's atmosphere had already warmed by more than 0.5°C (0.9°F) since the Industrial Revolution, with all trends pointing higher still.

China had just emerged from a decade of market-based economic reforms and was on the cusp of pulling hundreds of millions of its citizens out of abject poverty. The best technologies available at the time meant that China would spend the next decade largely duplicating what the United States, Europe and others had done: burn coal, oil and natural gas – mostly coal – and dump the resulting carbon dioxide into the air, further heating the planet. There was only so much President George H. W. Bush could do by signing the 1992 Earth Summit declaration "Agenda 21," other than give heartburn and a rallying cry to future generations of right-wing conspiracy theorists. But all that was still a year out. President Bush and over a hundred fellow heads of state would not fly to Rio until June 1992.

Meanwhile, Mount Pinatubo, a volcano in the Philippines that had been dormant for over 400 years, began to rumble on April 2, 1991. Two months later, volcanic activity went into overdrive, culminating in a final explosion on June 15. Ash, rocks and lava buried the surrounding area. To make things worse, Typhoon Yunya slammed the area that very same day. The resulting floods, combined with the effects of the explosion, displaced more than 200,000 Filipinos; more than 300 died.

The costs were all too real. But so were the benefits: as a direct result of the volcanic eruption, global temperatures temporarily decreased by about 0.5°C (0.9°F), wiping out the entire temperature effects of human-caused global warming up to that point. The reduction in temperatures hit its peak just around the time of the Rio Earth Summit a year later.

Mount Pinatubo did all that by spewing some 20 million tons of sulfur dioxide into the stratosphere. That amount counteracted the global warming effect of around 585 billion tons of carbon dioxide that humans had managed to put into the atmosphere by then. (Now, more than two decades later, the total tonnage of carbon dioxide added to the atmosphere is around 940 billion, and still climbing.)

The leverage ratio of sulfur to carbon dioxide in terms of what's called "geoengineering" is enormous. The sulfur dioxide released by Mount Pinatubo reduced temperatures by about the same amount as 30,000 times as much carbon dioxide increased them. It's tempting to draw a link to nuclear technology: Little Boy, the atomic bomb dropped over Hiroshima, had roughly 5,000 times as much power as the same mass of traditional explosives.

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The comparison to nuclear technology also suggests the possible path ahead. The Titan II intercontinental ballistic missile was developed just 15 years after Little Boy was dropped. It could carry a warhead with more explosive power than all the bombs dropped in World War II combined, including Little Boy. If geoengineering advanced even a fraction as quickly, it's hard to imagine the technologies that could become available to counteract atmospheric warming by carbon dioxide. Even using today's technology, a more targeted geoengineering intervention could possibly achieve leverage ratios near a million-to-one – that is, 1 ton of cooling material could offset the warming caused by one million tons of carbon dioxide.

Both nuclear and conventional explosives destroy, whereas geoengineering has the potential to do immense good.

The similarities to the leverage of nuclear bombs are striking. But there's an important difference: both nuclear and conventional explosives destroy, whereas geoengineering has the potential to do immense good.

THE PROMISE AND PROBLEMS OF GEOENGINEERING

Without considering the costs and lives lost, Mount Pinatubo's effect on global temperature was presumably a good thing. If we could wipe out two centuries of accumulated, human-caused global warming by turning a knob, why not go for it?

There are a few problems with that simple picture. Mount Pinatubo decreased the indirect, if all-too-real, effects of carbon dioxide in the atmosphere: the 20 million tons of sulfur dioxide created a sunshade that dimmed the radiation from the sun by about 2 to 3 percent throughout the following year. But the eruption did nothing to counteract the direct effects of carbon pollution, like turning the oceans more acidic as they absorbed added carbon dioxide.

Moreover, as much as participants in the 1992 Earth Summit were presumably heartened by the cooling impact of Mount Pinatubo, they must have been distraught by the accompanying decrease in stratospheric ozone that protects us from ultraviolet light. Combine the volcano's sulfur dioxide and other gunk with certain types of pollution that we humans send into the atmosphere, and you may get ozone depletion of the type that gave us the ozone hole over the South Pole – but now the depletion could occur over the tropics as well.

If that weren't enough, Mount Pinatubo is also invariably blamed for weather extremes – flooding along the Mississippi River in 1993 and for droughts elsewhere. The volcanic eruption coincided with the beginning of a global dry spell lasting about a year. Direct links are difficult to establish, but that only makes it more problematic. If we could draw a direct line from Mount Pinatubo to sub-Saharan African droughts, we'd at least know what to hold responsible. Without that link, speculation runs rampant.

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What if, instead of a volcano, the cause of the climate change had been a group of scientists launching an experiment to counteract two centuries of global warming just in time for the Rio Earth Summit?

One can assume that such an experiment could have been designed in a way to avoid the 200,000 evacuations and 300 deaths. But even without those all-too-direct effects of the eruption, it would have been hard to imagine a university's institutional review board, the group charged with overseeing the safety of research, approving the experiment. It's often hard enough to get approval for a simple e-mail survey, asking test subjects to deploy their computer mice and answer a few benign questions. Now imagine intentionally injecting the stratosphere with tiny, custom-designed particles to mimic the effects of Mount Pinatubo, with the express purpose of altering the global climate.

Forget institutional review boards. The public might have a word or two to say here – as it should. Even if the only effect of releasing particles into the atmosphere were to cool the atmosphere with no regional difference whatsoever – an implausible outcome – it would still be hard to agree on the "right" amount of temperature lowering.

If you live at higher latitudes, a few degrees of warming might not be all that bad for you personally. Why dial that back? On the other hand, if you live in Cape Town, San Francisco or along the Mediterranean, you pretty much enjoy the most stable, ideal climate anywhere on Earth. Why change that?

And if we did dial it back, where should we stop? Pre-industrial levels seem like a reasonable target. But today seems fine, too.

There is no right answer to any of these questions, other than to say that we would need strong, global institutions and well-formed governance processes to make these decisions in a way that considers a breadth of voices in a democratic, well-informed way.

But we don't have a global government. Instead, we need to work with what we have. That's a fragmented global governance complex with imperfect representation and even more imperfect decision processes. Decision making in Washington, D.C., may be at a standstill, but at least there is a formal process for making decisions. On a global level, we have yet to create the institutions that would allow us to even have the conversation.

Fortunately, we are still far from having to make decisions about deploying geoengineering. Unfortunately, the failure to deal with global warming now is pushing us relentlessly in that direction.

FREE RIDERS, MEET THE FREE DRIVERS OF GLOBAL WARMING

Climate change is a problem because too few of us consider it one. And those of us who do can do little about it unless we get everyone

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else to act. Either we solve this problem for everyone, or we solve it for no one.

That, in a nutshell, is what makes the problem of anthropomorphic climate change so difficult to solve. You alone can do little beyond scream to get the right policies in place, which could then guide the rest of us in the right direction. Meanwhile, the overwhelming majority of the seven billion of us on this planet are "free riders." We don't pay for the full cost of our actions.

Worse, polluting is subsidized worldwide to the tune of some $500 billion annually. That averages out to a subsidy of around $15 per ton of carbon dioxide emitted, much of it in oil-rich, less-developed countries including Venezuela, Saudi Arabia and Nigeria that sell fuel at home below the world market price, as well as in China and India. Every one of these dollars is a step away from creating the right incentives. That is, instead of paying for the privilege of polluting, we are paid to pollute. Meanwhile, carbon dioxide "prices" in most of the United States, with the notable exception of California, are close to zero. That estimate assumes subsidies of around $3 per ton of carbon dioxide roughly balanced by direct and indirect measures such as energy efficiency standards and renewables mandates.

Every time you fly from New York to San Francisco and back you put roughly a ton of carbon dioxide into the air, some of which will stay there for decades or even centuries after your trip. That's you personally, not the whole plane, which emits proportionately more. And that ton will cause at least $40 worth of damage to the economy, to ecosystems and to health.

Assume, for argument's sake, that all seven billion humans board planes once every year. Also assume that each flight creates about one ton of carbon dioxide pollution per passenger.

If all seven billion of us flew, we'd collectively cause seven billion times $40 in damage. Divided by seven billion, we'd get back to each person facing a price of $40. But no one is facing the "right" $40 in terms of incentives.

That's the crux of the problem. Every person faces the same choice set: "my benefit, seven billion people's cost." As a result, we largely ignore the consequences of our actions, collectively flying too much and saddling society with enormous costs. But no one has the right financial incentives to try to do something about it. Voluntary coordination is a nonstarter: getting seven people to agree on anything is tough; getting seven billion to agree is impossible. That's where governments need to come in, and even there we find global cooperation very difficult.

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So far, not so good. But free riding is only half the problem. "Free driving" may be just as important. That's where geoengineering gets behind the wheel, and we end up back at Mount Pinatubo. About 20 million tons of sulfur dioxide managed to wipe out the global warming effects of 585 billion tons of carbon dioxide in the atmosphere. That's leverage. It's also another way of saying that it would probably be cheap to duplicate the cooling effects of Mount Pinatubo intentionally – "cheap," that is, in the narrow sense of the direct engineering costs of injecting 20 million tons of material to the stratosphere.

We may hate the idea of countering amazing amounts of pollution with yet more pollution of a different type. But the option is simply too cheap to ignore.

It's not like anyone would literally mimic Mount Pinatubo by pumping 20 million tons of sulfur dioxide into the stratosphere. At the very least, given current technology and knowledge, the sulfur would likely be delivered in the form of sulfuric acid vapor. Sooner rather than later, we may be looking at particles specifically engineered to reflect as much solar radiation back into space as possible, maximizing the leverage.

It may only take a fleet of a few dozen planes flying 24/7 to deliver the desired amount. Some have gone as far as to calculate how many Gulfstream G650 jets it would take to haul the necessary materials. But such specifics are indeed too specific. What matters is that the total costs would apparently be low compared to both the damage carbon dioxide causes and the cost of avoiding that damage by reducing carbon emissions.

Estimates are all over the place, but most put the direct engineering costs of getting temperatures back down to pre-industrial levels on the order of $1-to-$10 billion a year. Now, $1-to-$10 billion is not nothing, but it's well within the reach of many countries and maybe even the odd billionaire.

If a ton of carbon dioxide emitted today generates $40 in damage, we are talking fractions of a penny for the sulfur to offset it. That's three orders of magnitude lower, and it creates circumstances that are exactly parallel to the free-rider misincentives that have caused the problem in the first place. Instead of one person enjoying all the benefits of that cross-country round-trip and the other seven billion paying fractions of a penny each for the climate damage that one ton of carbon dioxide causes, here it's one person or (more likely) one country being able to pay the costs of geoengineering the entire planet – and potentially without consulting the other seven billion people.

Welcome to the free-driver problem. If climate change is the mother of all "externalities," as economists like to call it, geoengineering is the father, and the world is the child stuck in the middle. If mom says "no," go to dad and see whether he says "yes." The chance is pretty good, seeing as he's facing the exact opposite incentives from mom: a game of good-cop/bad-cop on a planetary scale.

Geoengineering is too cheap to dismiss as a fringe strategy developed by sinister scientists looking for attention and grant money, as some pundits would have it. If anything, it's the most experienced climate scientists who take the issue most seriously. And not because they want to.

OF SEAT BELTS AND SPEED LIMITS

In February 1975, a who's who in biomedical research descended on the Asilomar Conference Facilities, a small seaside resort in Pacific Grove, California, to discuss laboratory safety standards for the burgeoning discipline of recombinant DNA research. There was lots of promise to the research, but also significant danger – not least that the science would get ahead of public understanding and evoke a backlash that could result in defunded labs and shuttered science programs.

By all accounts, Asilomar, as the meeting came to be known, was a success. Research had, in fact, been halted ahead of the meeting because of public outcries over its possible dangers. Since then, recombinant DNA research has given us, among many other things, the hepatitis B vaccine, new forms of insulin, and gene therapy – not to mention a Nobel Prize in chemistry for Paul Berg, the co-organizer of the 1975 meeting.

That meeting also provided a model for how scientists can and should engage the public when their research hits particularly touchy subjects. Ahead of Asilomar, even Berg's own co-investigators had asked him to stop his research because of fears of biohazards that could lead to cancer in lab technicians or worse. The "Asilomar Process" assured scientists and helped guide science policy for decades to come.

It's almost comical to believe nowadays that a single meeting like that, assembling a few dozen biologists, a handful of physicians and the occasional lawyer, could assuage the public and policymakers alike in order to do what's right for science. You can already imagine the conspiracy theories swarming around. The newspaper editorial headlines practically write themselves:

How Far Is Too Far? Should Scientists Decide Their Own Limits?... The Brave New World of Hacking Your Genes… Hacking the Planet: Who Decides?...

The last of these headlines was, in fact, a real one. *The New Scientist* used it for an editorial entitled "Asilomar 2.0." That's at least how the organizers wanted it to be known. In March 2010, prominent climate scientists, budding geoengineers, a few journalists and the odd diplomat and environmentalist descended on the Asilomar facilities to try to rekindle the spirit of 1975. It was a gathering of the who's who in another burgeoning area of research with a lot of promise and quite a bit of potential for public backlash: geoengineering.

The opening line from a co-organizer set the tone: "Many of us wished we wouldn't be here." Most scientists wished instead that the world had heeded their advice and done something about global warming pollution decades ago. Steve Schneider, who has since died, spoke passionately about his climate research that had raised some of the first alarms, going back even before 1975. He had just written his own firsthand account, *Science as a Contact Sport: Inside the Battle to Save Earth's Climate*. But he wasn't there to sell or sign books. He came to lament the fact that it had come to this. Every scientist who spoke prefaced his or her words by saying that the "told-you-so's" were bittersweet.

Geoengineering treats the symptoms without reducing the underlying problem. Pick your favorite analogy. It's like chemotherapy or a tracheostomy for the planet: a last-ditch effort to do what prevention failed to accomplish.

That's where we are now. Some of the most serious climate scientists are looking toward geoengineering as an option – not because they want to, but because it may well be our only hope for avoiding a climate catastrophe. Mount Pinatubo-style remedies have gotten significant attention of late for precisely that reason.

These scientists also highlight one of the key problems that comes up when discussing geoengineering. As we're sucked into the free-driver problem, we inevitably spend less time trying to solve the free-rider problem. Life comes with trade-offs. Spend the better part of your workday worrying about shooting tiny sulfur-based particles into the atmosphere, and you don't spend that time worrying about getting carbon out of it.

The same conundrum holds outside the lab: why reduce emissions if we know that the latest technological advance can solve the problem without changing our ways? The best response is simply that geoengineering treats the symptoms without reducing the underlying problem. Pick your favorite analogy. It's like chemotherapy or a tracheostomy for the planet: a last-ditch effort to do what prevention failed to accomplish.

For an analogy closer to the issue at hand, geoengineering is not unlike coping with higher temperatures and other climate impacts through adaptation. While no one nowadays would dispute the need to adapt to global warming already baked into the system, not too long ago environmentalists cautioned against even saying "adaptation" out loud. They were worried that doing so would distract from efforts to reduce carbon dioxide emissions in the first place.

Wearing seat belts makes some drivers feel so safe that they drive more recklessly. But that's hardly an argument against seat belt laws. It just means we need to set (and enforce) speed limits, too.

If the prospect of injecting millions of tons of tiny, artificially engineered particles into the planet's stratosphere to create a sunshield of sorts doesn't scare you, you haven't been paying attention. Not too surprisingly, it turns out that the vast majority of Americans haven't. Polling guru Tony Leiserowitz at Yale has asked Americans, "How much, if anything, have you read or heard about geoengineering as a possible response to climate change." The vast majority (74 percent) said: "Nothing." Of the other 26 percent who had heard the term, only 3 percent knew what it meant.

None of that means that we shouldn't take geoengineering seriously. We may be racing past so many climate change tipping points that this kind of planetary "chemotherapy" is already needed. But at the very least, we ought to find out the full implications. We can't wait and hope for the best; nor can we hope that the free-driver effect won't ever show its full force.

COOLING THE PLANET, FAST AND SLOW

Mount Pinatubo-inspired geoengineering has its appeal, largely because it purports to be fast, cheap and powerful. But it isn't the only geoengineering option. The basic idea is to reflect more solar radiation back into space. Injecting sulfur-based particles into the stratosphere is just one way, and one of the most daring. Painting roofs white is sometimes proposed as another.

The logic comes down to why winter coats tend to be black, and whites are in vogue between Memorial and Labor days. Black absorbs light; white radiates it back. This is one reason the melting of Arctic sea ice is so disconcerting. Instead of white surfaces radiating the sun's rays back into space, darker water tends to absorb it, feeding a vicious circle that accelerates planetary heating. Ubiquitous white roofs in some parts of the Mediterranean already contribute to pleasant local microclimates. Some would have us duplicate that effect in urban areas elsewhere.

It sounds pretty good, but there are at least three problems. For one, we'd need to know the total impact with much more certainty before we go down that path. White roofs reflect more light, but they do so from the earth's surface. The reflected sunlight doesn't escape neatly back into space. Rather, the light hits soot and all sorts of other air pollutants and particulates, possibly reacting with them to make local air pollution worse.

Second is scale. Painting all the roofs in the world white would only have about a tenth the impact of an annual Mount Pinatubo-size eruption.

That brings us to the third fundamental issue: convincing millions of people to do something that may benefit the planet comes directly back to the free-rider effect. It would be difficult to achieve unless the white-painted roofs would pay for themselves through, say, decreased need for air-conditioning.

There are plenty of options in between Mount Pinatubo-style stratospheric sulfur injections and painting roofs white. An oft-mentioned one is creating artificial clouds or brightening those that already exist. Imagine a fleet of satellite-guided ships spraying water into the air to create clouds. The approach doesn't depend on millions of us doing the right thing. It also doesn't inject anything into the stratosphere that could haunt us once it comes down. Water vapor is all you'd get. In short: it might work, emphasis on "might." Brighter clouds could lower average temperatures, and the effects could even be regionally targeted.

A regionally targeted intervention could help avoid some of the problems introduced by global, Mount Pinatubo-style geoengineering. But there could still be plenty of unwanted side effects with enormous implications. The Indian monsoon may be "only" a regional phenomenon, but it's one on which a country of over a billion people depends for its water and food.

As always, it's a matter of trade-offs. Climate change itself will have plenty of unsavory side effects. The question, then, is not whether geoengineering alone could wreak havoc. (It could.) The question is whether climate change plus geoengineering is better or worse than unmitigated climate change.

One thing is clear: what you gain in possible precision in any regional geoengineering method, you lose in leverage. Brightening

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clouds may be cheaper than avoiding carbon dioxide pollution in the first place, but there are limits to what it might accomplish. Mount Pinatubo-style geoengineering has much greater leverage and, thus – for better or worse – overall impact.

All these geoengineering methods have one thing in common: they don't touch the carbon dioxide already up in the air. That makes them potentially cheap. But it also means they avoid tackling the root of the problem.

Opinions differ on the effectiveness of each of these methods. Opinions also differ on whether they should even be labeled "geoengineering." They are methods of geoengineering in the sense that someone would be trying to alter the earth's atmosphere on a grand scale. It's precisely the issue of scale, though, that's open to question.

Most of these approaches run head-on into the free-rider problem. It requires either the coordinated actions of millions to have an impact, or it takes a few to spend so much money that they are unlikely to do so. In other words, these approaches don't share the properties that make Mount Pinatubo-style geoengineering unique. They have a lot less leverage; they are often expensive and slow. In fact, they look much more like reducing carbon emissions in the first place than geoengineering.

The addiction component of Mount Pinatubo-style geoengineering and its vulnerability to interruption may turn out to be its biggest problem yet.

Cue "carbon dioxide removal" (CDR), confusingly also called "direct carbon removal" (DCR). It, in turn, comes under various guises. "Air capture" takes carbon dioxide out of the air and, for example, buries it underground. "Carbon capture and storage" stops carbon dioxide from entering the air in the first place by intercepting it as it is emitted by smokestacks and treating it in a way to prevent it ever escaping into the air. "Ocean fertilization" does just what the name suggests: dumping iron or other nutrients into surface waters make them more fertile for plant life, which naturally takes atmospheric carbon dioxide. "Biochar" is a fancy term for charcoal and may have effects similar to other approaches that remove carbon dioxide from the air and prevent it from escaping back.

You could even put tree growing into that category; trees take carbon out of the atmosphere naturally as they grow. In fact, there's often little that humans need to do other than get out of the way. Nature takes care of reforestation in many situations, as long as there's no interference.

Of course, we aren't saying that the world shouldn't consider any of these approaches. For example, the world should grow more trees, almost regardless of their climate impact. The same may go for painting roofs white to lower air-conditioning costs. But that doesn't mean we should lump these methodologies together with Mount Pinatubo-style geoengineering. All are important. None is in the same category as shooting tiny reflective particles into the stratosphere directly.

ADDICTED TO SPEED

Everyone's very first cup of coffee tastes unpleasantly bitter, no matter how much sugar and milk you add. The second cup in your life may be a bit more pleasurable. By the 20th, you may think you are still not addicted and that you could easily skip the 21st and 22nd. But by the 100th cup, stopping is no longer an option.

Mimicking Mount Pinatubo to cool down the planet would follow a similar pattern. The first attempts at deploying geoengineering might well fail. By the 20th, we might be ready to take a break. By the 23rd we'll have discovered a more refined technology, and sooner or later it will be impossible to stop.

Startup woes come with the territory. It's the addiction component that's a worrisome aspect of Mount Pinatubo-style geoengineering. In 1991, Mount Pinatubo cancelled out 0.5°C of warming. Two years later, after most of the sulfur dioxide from Mount Pinatubo had washed out of the atmosphere, temperatures jumped back by the same 0.5°C and resumed growth where it left off.

To date, temperatures have risen by 0.8°C since pre-industrial times. If we wanted to erase that difference using geoengineering and then suddenly had to stop, temperatures would jump back up by 0.8°C. By 2100, this potential jump-back could be on the order of 3° to 5°C, if we haven't severely restricted emissions long before then.

Scientists don't know what would happen with a jump of 0.8°C. They are pretty sure, though, that jumping 3° to 5°C would create serious problems. Slow warming of this magnitude would be bad enough. A sudden jump from abruptly ending geoengineering would create all sorts of additional issues. Moving major agricultural areas from Kansas to Canada would be disruptive, but doing it over a century would at least be possible. Having to do it within a year or a decade is hard to imagine. At the very least, it would be exponentially more costly. Thus the addiction component of Mount Pinatubo-style geoengineering and its vulnerability to interruption may turn out to be its biggest problem yet.

WALK BEFORE YOU RUN, RESEARCH BEFORE YOU DEPLOY

Fortunately, we aren't yet close to anyone seriously proposing to *deploy* geoengineering at scale. Even David Keith, a physicist who wrote *A Case for Climate Engineering*, says that he wouldn't vote for geoengineering deployment now. We are, however, way past the time when serious people are rejecting the idea of proposing *research* on geoengineering.

Asilomar 2.0 was chock-full of scientists and engineers who are actively looking into the "how" of geoengineering; hence their desire for guidelines for moving forward with their research. Plenty of options are already on the lab table. Researchers want to know how far they can go in testing and refining their methods in the real world.

One real hurdle to performing research with the entire planet as your test subject is discerning when the proverbial signal rises above the noise.

The bigger the experiment, the easier it would be to detect the effects. But the lines between research and deployment would quickly get blurry. Even studying the full effects of Mount Pinatubo has proven difficult for precisely this signal-versus-noise issue. Putting 20 million tons of sulfur dioxide into the atmosphere constituted a major disruption; little else could have contributed to global cooling of 0.5°C in the subsequent year. Similarly, reasonable atmospheric mechanisms could explain how adding carbon dioxide and then dimming the lights a bit by means of geoengineering would means less average rainfall around the globe. That alone would explain a higher likelihood for droughts. But despite general advances in being able to attribute single extreme weather events to climate change, linking any one particular flood or drought to single geoengineering interventions would be fraught with difficulties.

CASUALTIES, SCHMASUALTIES

Public opinion does not react well to policy mistakes and unintended consequences. And geoengineering is nothing if not fraught with the potential for error. But not all errors are created equal. There's a big difference between errors of omission and commission: driving by the scene of a car crash is bad, but not as bad as causing the crash in the first place.

It's one thing to study the effects of Mount Pinatubo. The harm had already been done. No one could have prevented the eruption. And it has turned out to be the best-studied major volcanic eruption ever. Let's use that for all it's worth. (Not studying it to its fullest may be an error of omission all by itself.)

All seven billion of us – especially the one billion high-emitters – are committing sins of commission every single day.

It's similarly easy to model Mount Pinatubo-style interventions on a computer. It's cheap; it's low-impact. It may divert attention from pursuits aimed at limiting carbon dioxide emissions, but that's about the worst that can happen. Little harm is done by a graduate student spending extra time on a Saturday in the lab running one more simulation.

It would be very different for scientists to go out and intentionally experiment with the atmosphere. Now we are in the realm of commission, a complicated realm, indeed.

It may not be sensible to link a failed harvest to a small experiment halfway around the world that barely produced enough data to identify the signal from all other climatic noise. But that might not matter. The burden of proof in the court of public opinion would be on those running the experiment.

Let's just take a quick step back to try to put it all into perspective. The greenhouse effect has been a fact of science since the 1800s. The term "global warming" has been around since 1975. The basic science has been settled for decades. We have no excuse to believe that using our atmosphere as a sewer for carbon emissions isn't uneconomic, unethical or worse. All seven billion of us – especially the one billion high-emitters – are committing sins of commission every single day. The effects of our collective actions may end in catastrophe. No individual is guilty of causing climate change, but collectively we all are.

Now contrast that with a group of scientists committed to finding a way out of the global warming mess. They understand the science. They understand that the free-rider effect discourages society from acting in time. They understand that the siren call of the free-driver effect is pushing us toward an all-too-alluring quick fix. They are working on trying to understand if and how that fix could work, and how it could be made safe enough to consider using.

We are not trying to excuse any and all scientific (mis)conduct. Science has plenty of misfits, mercenaries and ill-intentioned missionaries. Not all budding geoengineers should be considered heroes. But at the very least they shouldn't all be branded villains until proven otherwise. Scientists themselves are asking for guidance, as the Asilomar 2.0 meeting and similar efforts make clear. They know they can't go this one alone, even if they wanted to. And most don't want to.

AN ALMOST PRACTICAL PROPOSAL

One of the more sensible proposals for what to do next comes from geoengineering proponent David Keith. It starts with the M word, as in "moratorium." Scientists themselves need to acknowledge there's a clear danger for the science to run ahead of the public conversation. The only way to stop that is a self-imposed moratorium. Keith, together with Ted Parson, a UCLA law professor, proposes to guide research on geoengineering by three simple steps:

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• Accept that there must be limits.

• Declare flat-out a moratorium on all research above a certain scale.

• Set a clear and very low threshold below which research may proceed.

In a sense, these three steps just formalize the natural progression of research: start small; experiment; evaluate; tackle the next challenge. By declaring such a moratorium, their thinking goes, the smaller experiments would become more acceptable. Of course, everything depends on where that line is drawn. It must be very low, indeed; zero is a good starting point.

In all of this, we need to remember that humans are already spewing massive amounts of pollutants into the atmosphere, including the very substances that some geoengineers propose to use to help cool the planet. Research that has a fraction of the impact of any one jet engine is one thing. Research large enough to have detectable impact beyond the narrow confines of the experiment should be a clear nonstarter. In any case, the goal must be a much better understanding of the full set of benefits and costs – and especially the costs of geoengineering.

The fact that Mount Pinatubo-style geoengineering invites a free-driver problem means that sooner or later it will be hard to maintain any such self-imposed moratorium. As long as there are only a dozen or so geoengineers on the planet, all of whom know and respect one another and all of whom agree on the importance of not letting the science get ahead of the public, the moratorium should be manageable. But it's not hard to imagine some scientist somewhere wanting to leave a mark and go it alone.

There's a larger question at work here, too. Moratorium to what end? Eventually, we may need to have a conversation about lifting the moratorium. What comes then? How do we decide to lift the moratorium? Who will decide?