Climate Controls

If we treated global warming as a technical problem instead of a moral outrage, we could cool the world.

By Gregory Benford

Although we are getting better and better at it, forecasting the weather is still remarkably tricky. Far easier to predict the *political* climate, especially when it comes to the issue of global warming. To wit: In December, negotiators from around the world will meet in Kyoto to work out an international treaty to deal with what most (though not all) scientists believe is a 0.5-degree-centigrade increase in temperatures over the past century, and the promise of more to come.

All major participants, including the U.S. representatives, will argue that the *only* way to address global warming is to reduce significantly levels of carbon dioxide and other greenhouse gases that are plausibly (though not definitively) linked to the rise in temperatures. Although a group of small island nations will suggest a 20 percent reduction in greenhouse gases, members of the European Union will most likely carry the day with a plan to cut emissions of carbon dioxide, methane, and nitrous oxide by at least 15 percent over the next decade.

The Clinton administration may object to those specific targets, but it will enthusiastically support the consensus that the only way to counter global warming is by reducing emissions. Indeed, the president announced in August that "we owe it to our children" to sign a treaty reducing consumption of greenhouse gases, a position echoed by Interior Secretary Bruce Babbitt, who has called dissenters "un-American," and chief economic adviser Janet Yellen, who has called cost-benefit analyses of cutting greenhouse gases "futile."

Such thinking is perfectly in keeping with the universal environmentalist position, which is best understood as a starkly Puritan ethic: "Abstain, sinner!" "The only way to slow climate change is to use less fuel," asserts Bill

McKibben in *The End of Nature*, a book that roundly condemns such luxuries as privately owned washing machines and oranges shipped to cold climates. And if a 15 percent reduction in greenhouse gases seems extreme, consider that many ecologists champion far more costly conservation measures as the only solution. Ross Gelbspan's *The Heat Is On* even urges a government takeover of the energy sector and a massive propaganda campaign. In the wake of the Kyoto conference, expect to see calls for a Greenhouse Czar as global warming is brought to broad, persistent public notice.

Such hand wringing is as unimaginative as it is unequivocal. Instead of draconian cutbacks in greenhouse-gas emissions, there may very well be fairly simple ways--even easy ones--to fix our dilemma. But the discussion of global warming never makes this clear; it seems designed to preclude any hint that we might remedy the situation except through great sacrifice, discomfort, and cost. Indeed, it seemingly assumes a direct relationship between the level of sacrifice, discomfort, and cost demanded by any proposed solution and its scientific efficacy. Solutions based on suppressing fuel use will cost us dearly, in terms of both dollars spent and standard of living. Economists differ over the price tag, with a rough analysis yielding an estimate of about $250 billion a year to reduce carbon dioxide emissions alone by 15 percent worldwide. (This number is easily debatable within a factor of two.) To this price we must add the cost of reducing other greenhouse gases, a cost felt not merely in our pocketbooks but also in the goods, services, and innovations whose production would be halted or forgone.

But for a number of reasons that I will discuss below, now is precisely the time to take seriously the concept of "geoengineering," of consciously altering atmospheric chemistry and conditions, of *mitigating* the effects of greenhouse gases rather than simply calling for their reduction or outright prohibition. While such a notion may seem outlandish at first blush, it merely acknowledges explicitly what everyone already understands: that human activity has an impact on the planet.

Forty years ago, the noted atmospheric scientist Roger Revelle declared that "human beings are now carrying out a large scale geophysical experiment" by pumping billions of tons of carbon dioxide into the air. The question before us should not simply be how best to stop the experiment--and, by extension, the prosperity and progress allowed by cheap, abundant energy.

Rather, the question should be how best to *design* that experiment, so that we maximize benefits and minimize costs. As the citizens of the advanced nations become convinced that global warming is an immediate threat worthy of response, they will legitimately ask for solutions that demand the least sacrifice.

Politics and Parasols

A little-noticed 1992 National Academy of Sciences panel report spoke directly to this issue. The report clarified the science behind global warming and then ventured far from the ruling environmental orthodoxy: Could we *accept* that greenhouse gases will rise and find ways to compensate for them? Instead of cutting gases, could we intervene to mitigate or offset the warming they may cause?

Climate modification is time-honored, though not clearly a winner. Cloud seeding in the United States during the 1940s and '50s met some success but ended in a blizzard of lawsuits from those who claimed their local rainfall had been diverted by neighboring areas. (Though such assertions had little scientific proof, courts felt otherwise.) During the Cold War, both sides studied a menu of climatic dirty tricks, including schemes to kill the opponent's crops.

These programs foundered on a fundamental fact: Before *modifying* a climate, one must first grasp it. At the level of understanding available in the 1960s, only spectacular interventions would have left discernible signatures. Climate variability was so little fathomed that weather prediction was pointless beyond roughly a week.

But in progress little noticed by the public, systematic weather prediction has advanced more than tenfold in its assured time range. By watching the sun, atmosphere, ocean, land, and clouds using satellites, advanced aircraft, ships, and a tight grid of land-based observations, we have diminished the uncertainties about long-range weather. We are still just talking about the weather, but the talk is of higher quality. Earlier this year, for instance, the National Oceanic and Atmospheric Agency predicted a coming wet winter six months in advance, based on temperature measurements of tropical waters, presaging a new *El Niño* ocean current. Whether that prediction is right or wrong--the coming months will decide--we are entering a new era in forecasting. With the latest systems, backed by heavy computer modeling, we will shrink uncertainties, identify subtle feedback loops, sniff out regional pollution patterns, discern the spread of deserts and the withering of forests.

Sensitive global measures of disturbance will shed further light on polar and glacial contractions, ozone levels, volcanic dust, levels of the oceans. There is even a technique available for cheaply gauging global reflectivity by measuring "earthshine"--the faint glow of our reflected light, seen on the dark portion of a crescent moon. Using a small telescope and makeshift gear, astronomers easily showed that we reflect 30 percent of incoming sunlight back into space--a number that our satellite system got earlier, at a price tag of hundreds of millions of dollars. Such innovation will lessen the costs and confusions of global understanding, a help we will need dearly if and when the greenhouse predicament worsens.

Geoengineering

Some geoengineering systems appear possible to deploy now, and at reasonable cost. They could be turned on and off quickly if we got unintended effects. It would be relatively easy to run small-scale experiments to answer questions about how our current atmosphere behaves when one alters the kind of dust, or aerosols, in it. Nuanced knowledge is crucial; the biosphere is a highly nonlinear system, one that has experienced climatic lurches before (glaciation, droughts) and can go into unstable modes, too.

Indeed, some critics argue that this simple fact precludes our tinkering with the "only Earth we have." Earth's climate might be chaotically unstable, so that a state with only slightly different beginning conditions would evolve to end up markedly different: An engineered early frost this year might mean an ice age the next. But we also know that Earth suffers natural injections of dust and aerosols from volcanoes, driving weather changes. Experiments that affect the planet within this range of natural variability could be allowed with little to no risk.

The simplest way to remove carbon dioxide, the main greenhouse gas, is to grow plants--preferably trees, since they tie up more of the gas in cellulose, meaning it will not return to the air within a season or two. Plants build themselves out of air and water, taking only a tiny fraction of their mass from the soil. Forests, which cover about a third of the land, have shrunk by a third in the last 10,000 years (though they have grown over the last half-century in the United States, mostly due to market forces).

Like the ocean, land plants hold about three times as much carbon as the atmosphere. While oceans take many centuries to exchange this mass with the air, flora take only a few years. As tropical societies clear the rain forest, the temperate nations have actually been growing more trees, slightly offsetting this effect. In the United States, we have lost about a quarter of our forest cover since Columbus, and replanting occurs mostly in the South, where pine trees are a big cash crop for the paper industry. But globally we destroy a forested acre every second. Just staying even with this loss demands a considerable planting program.

Trees soak up carbon fastest when young. Planting fast-growing species will give a big early effect, but what happens when they mature? Eventually they either die and rot on the ground, returning nutrients to the soil, or we burn them. If this burning replaces oil or coal burning, fine and good. Even felling all the trees still leaves some carbon stored longer as roots and lumber. Buildings can hold lumber out of this cycle for a century or so.

About half the U.S. carbon dioxide emissions could be captured if we grew tree crops on economically marginal croplands and pasture. More forests could enhance biodiversity, wildlife, and water quality (forests are natural filters); make for better recreation; and give us more natural wood products. Even better, one can do the cheapest part first, with land nobody uses now. This would cost about $5 billion a year, and a feel-good campaign would sell easily, with merchants able to proclaim their eco-virtue ("Buy a car, plant a grove of trees").

This would work reasonably well in the short run. But trees take water, and one must be careful not to exhaust the soil, so this is a solution with a clear horizon of about 40 years. Soaking up the world's present carbon dioxide increase solely through trees would take up an Australia-sized land area--that is, a continent. Most such land is in private hands, so the job cannot be done by government fiat. Still, a regional effort could make a perceptible dent in overall carbon dioxide levels.

The Geritol Solution

The oceans comprise the other great sink of greenhouse gases; some researchers estimate that they absorb 40 percent of fossil- fuel emissions. In coastal waters rich in runoff, plankton can swarm densely, a million in a drop of water. They color the sea brown and green where deltas form from big rivers, or cities dump their sewage. Tiny yet hugely important, plankton govern how well the sea harvests the sun's bounty, and so are the foundation of the ocean's food chain. Far offshore, the sea returns to its plankton-starved blue.

The oceans are huge drivers in the environmental equations, because within them the plankton process vast stores of gases. Though cause and effect are not quite clear, we do know that in ice ages, carbon dioxide levels dropped 30 percent.

Could we do this today? Driving carbon dioxide down should lower temperatures, certainly. But how?

The answer may lie not in the tropics but in the polar oceans, where huge reserves of key ingredients for plant growth--nitrates and phosphates--drift unused. The problem is not weak sunlight or bitter cold, but lack of iron. Electrons move readily in its presence, playing a leading role in trapping sunlight.

A radical fix would be to seed these oceans with dissolved iron dust. This may have been the trigger that caused the big carbon dioxide drop in the ice ages: The continents dried, so more dust blew into the oceans, carrying iron and stimulating plankton to absorb carbon dioxide. Mother Nature can be subtle.

Such an idea crosses the momentous boundary between quasi-natural mitigation such as tree planting and self-evidently artificial means. Here is the nub of it, the conceptual chasm. With a boast that may cost his cause dearly, the inventor of the idea, John Martin of the Moss Landing Marine Laboratories in California, said, "Give me half a tanker full of iron, and I'll give you another ice age."

The captured carbon gets tied up in a "standing crop" of plankton. These tiny creatures dwell within a few meters of the surface. To truly bury the gas, they must somehow carry it into the vast bulk of the whole ocean. Some biologists believe that from the plankton the carbon dioxide should slowly dissolve into the lower waters, though we are uncertain of this. Perhaps the carbon dioxide eventually is deposited on the seabed. This last process no one has checked. Somehow, though, a good deal of carbon does end up in the deep ocean sinks.

First proposed by Martin in 1988, the "Geritol solution" of adding iron to the ocean had a rocky history. Many derided it automatically as foolish, arrogant, and politically risky. But in 1996 the idea finally got tested by the U.S. government, and it performed well. Near the Galapagos Islands lies a fairly biologically barren area. Over 28 square miles of blue sea, scientists poured 990 pounds of iron during a week of testing. Immediately the waters bloomed with tiny phytoplankton, which finally covered 200 square miles, suddenly green. Plankton production peaked nine days after the experiment started. One thousand pounds of iron dust stimulated over 2,000 times its own weight in plant growth, far greater than the performance of any fertilizer on land. The plankton soaked up carbon dioxide, reducing its concentration in nearby sea water by 15 percent. It quickly made up this deficiency by drawing carbon dioxide from the air.

Projections show that since this process would affect only about 16 percent of the ocean area, a full-bore campaign to dump megatons of iron into the polar oceans probably would suck somewhere between 6 percent and 21 percent of the carbon dioxide from the atmosphere, with most recent estimates settling around 10 percent. Such scary, big-time tinkering is the extreme; the method would have to be tested at far lower levels. Still, this mitigation could dent the greenhouse problem, though not solve it entirely.

Even such partial solutions attract firm opponents. Geoengineering carries the strong scent of hubris. What is best described as eco-virtue reared its head immediately after the 1988 proposal, even before any experiments took place. Following the Puritan model that any deviation from abstinence is itself a further indulgence, many scientists and ecologists saw in Martin's plan an incentive for polluters. "A lot of us have an automatic horror at the thought," commented atmospheric authority Ralph Cicerone of the University of California at Irvine.

Other specialists retaliated. Russell Seitz of Harvard said the Galapagos experimenters were afraid to seem politically incorrect. "If this approach proves to be environmentally benign," Seitz said, "it would appear to be highly economic relative to a Luddite program of declaring war against fire globally."

Large uncertainties remain: How would the iron affect the deeper ecosystems, of which we know little? Will the carbon truly end up on the seabed? Can the polar oceans carry the absorbed carbon away fast enough to not block the process? Would the added plankton stimulate fish and whale numbers in the great Antarctic Ocean? Or would some side effect damage the entire food pyramid? Even if the idea worked, who should run such a program? Additionally, there is some evidence that little of the newly fixed carbon in the Galapagos experiment actually sank.
It seems to have come back into chemical equilibrium with the air. Controversy surrounds this essential point; clearly, here is where more research could tell us much.

This much seems certain (and should allay many fears): If we decide to stop the Geritol solution because of unforeseen side effects, control is easy. The standing crop will die off within a week, providing a quick correction.

Costs, too, are easy to figure. There is nothing very high-tech about dumping iron. Martin estimated that the job would take about half a million tons per year. Depending on what sort of iron proves best at prodding plankton, and implementation methods, the iron costs range between $10 million and $1 billion a year. Throwing in 15 ships steaming across the polar oceans all year long, dumping iron dust in lanes, brings the total to around $10 billion. This would soak up about a third of our global fossil-fuel-generated carbon dioxide emissions each year.

Reflecting on Reflectivity

Not all mitigation efforts need take place on land or sea. In fact, the most intuitive approach may be simply to reflect more sunlight back into space, before it can be emitted in heat radiation and then absorbed by carbon dioxide. People understand the basic concept readily enough: Black T-shirts are warmer in summer than white ones. We already know that simply painting buildings white makes them cooler. We could compensate for the effect of all greenhouse gas emissions since the Industrial Revolution by reflecting less than 1 percent more of the sunlight.

A mere 0.5 percent change in Earth's net reflectivity, or albedo, would solve the greenhouse problem completely. The big problem is the oceans, which comprise about 70 percent of our surface area and absorb more light because they are darker than land.

When it comes to increasing albedo, it would be wise to begin the discussion by introducing positive measures that can be easily understood and are close at hand. Reflecting sunlight is not a deep technical idea, after all. Simply adding sand or glass to ordinary asphalt ("glassphalt") doubles its albedo. This is one mitigation measure everyone could see--a clean, passive way to Do Something.

A 1997 UCLA study showed that Los Angeles is 5 degrees Fahrenheit warmer than the surrounding areas, mostly due to dark roofs and asphalt. Cars and power plants contribute, but only a bit; at high noon, the sun delivers to each square mile the power equivalent of a billion-watt electrical plant.

This urban "heat island" effect is common. But white roofs, concrete-colored pavements, and about $10 billion in new shade trees could cool the city below the countryside, cutting air conditioning costs by 18 percent. Cooler roads lessen tire erosion, too. About 1 percent of the United States is covered by human constructions, mostly paving, suggesting that we may already control enough of the land to get at the job.

From such homegrown solutions, we could make the leap to space. The most environmentally benign proposal for increasing the planet's albedo is very high-tech (and expensive): a massive orbiting white screen, about 2,000 kilometers on a side. Even if such parasols were broken into small pieces, putting them up would cost about $120 billion, a bit steep. We would also have to pay a lot to take them down if they caused some undesirable side effects. (One is certain: a night sky permanently light-polluted, irritating astronomers and moonstruck lovers.)

Using more-innocuous dust to reflect sunlight does not work; it drifts away, driven off by the sun's light pressure. But the upper atmosphere is still a good place to intervene, because much sunlight gets absorbed in the atmosphere on its way to us. Also, measures far above our heads trouble us less.

Other sorts of reflectors at high altitudes are promising. Spreading dust in the stratosphere appears workable because at those heights tiny particles stay aloft for several years. This is why volcanoes spewing dust affect weather strongly. The tiny motes that redden our sundowns reflect more sunlight than they trap infrared.

Even better than dust are microscopic droplets of sulfuric acid, which reflects light more effectively. Sulfate aerosols can also raise the number of droplets that make clouds condense, further increasing overall reflectivity. This could then be a local cooling, easier to monitor than carbon dioxide's global warming. We could perform such small, controllable experiments now. The amount of droplets or dust needed is a hundredth of the amount already blown into the atmosphere by natural processes, so we would not be venturing big dislocations. And we would get some spectacular sunsets in the bargain.

As usual, there are human-centered concerns. The Environmental Protection Agency hammers away at particulate levels, blaming them for lung disorders. Luckily, high-
altitude dust would come down mostly in raindrops, not making us cough. The cheapest way of delivering dust to the stratosphere is to shoot it up, not fly it. Big naval guns fired straight up can put a one-ton shell 20 kilometers high, where it would explode and spread the dust. This costs only a hundredth as much as the space-parasol idea. But booming naval guns that rattle windows for miles around are likely to provoke more than a few Not in My Backyard reactions.

Fortunately, there is a ready alternative to dust in any form: jet fuel. Changing the fuel mixture in a jet engine to burn rich can leave a ribbon of fog behind for up to three months, though as it spreads it becomes invisible to the eye. These motes would also come down mostly in rain, not troubling the brow of the EPA. Fuel costs about 15 percent of airlines' cash operating expenses, and running rich increases costs by only a few percent. For about $10 million, this method would offset the 1990 U.S. greenhouse emissions. Adding this to the cost of an airline ticket would boost prices perhaps 1 percent. An added asset is that quietly running rich on airline fuel will attract little notice, doesn't even change sunsets, and is hard to muster a media-saturated demonstration against.

But there are, as always, side effects. Dust or sulfuric acid would heat the stratosphere, too, with unknown impact. Some scientists suspect the ozone layer could be affected. If a widespread experiment showed this, we could turn off the effect within roughly a year as the dust settled down and got rained out. (Smaller experiments should show this first, of course.)

These ideas envision doing what natural clouds do already as the major players in the total albedo picture. A 4 percent increase in stratocumulus over the oceans would offset global carbon dioxide emission. Land reflects sunlight much better than the wine-dark seas, so putting clouds far out from land, and preferably in the tropics, gets the greatest leverage.

Clouds condense around microscopic nuclei, often the kind of sulfuric acid droplets the geoengineers want to spread in the stratosphere. The oceans make such droplets as sea algae decays, and the natural production rate sets the limit on how many clouds form over the seas. Clouds cover about 31 percent of our globe already, so a 4 percent increase is not going to noticeably ruin anybody's day.

Tinkering with such a mammoth natural process is daunting, but in fact about 400 medium-sized coal-fired power plants give off enough sulfur in a year to do the job for the whole Earth. (This in itself suggests just how much we are already perturbing the planet.) There are problems with using coal: Arguing that *more* air pollution is good for Mother Earth sounds intuitively wrong. Coal plants sit on land, and the clouds would be most effective over the oceans. A savvy international strategy leaps to mind: Subsidize electricity-dependent industry on isolated Pacific islands, and ship them the messiest, sulfur-rich coal. The plants' plumes would stretch far downwind, and the manufactured goods could revitalize the tropical ocean states, paying them for being global good neighbors. The wealthy states would then get their mitigation carried out far from home and far from vexatious neighborhood committees, using labor purchased at low rates. And nobody *has* to take the plants; prices will mediate the demand.

A more boring approach, worked out by the National Academy of Sciences panel, envisions a fleet of coal-burning ships which heap sulfur directly into their furnaces. (Maybe some collaboration would work here. Freighters burning sulfur could also spread iron dust, combining the approaches, with some economies.) The ships spew great ribbons of sulfur vapor far out at sea, where nobody can complain, and cloud corridors form obediently behind. It would be best to use these sulfur clouds to augment the edges of existing overcast regions, swelling them and increasing the lifetime of natural clouds. The continuously burning sulfur freighters would follow weather patterns, guided by weather satellite data.

At first these could operate as regional experiments, to work out a good model of how the ocean's cloud system responds. This low-tech method would cost about $2 billion per year, including amortizing the ships.

The biggest political risk here lies with shifts in the weather. The entire campaign would increase the sulfur droplet content in our air by about 25 percent. Probably this would cause no significant trouble, with most of the sulfur raining out into the oceans, which have enormous buffering capacity. Keeping the freighters a week's sailing distance from land would probably save us from scare headlines about sudden acid rains on farmers' heads, since about 30 percent of the sulfur should rain out each day.

Albedo Chic

The NAS panel found that "one of the surprises of this analysis is the relatively low cost" of implementing some significant geoengineering. It might take only a few billion dollars to mitigate the U.S. emission of carbon dioxide. Compared with stopping people in China from burning coal, this is nothing.

We should not take the 1992 panel report, thick with footnotes and layers of qualifiers, to be a road map to a blissful future. The NAS estimates are simple, linear, and made with poorly known parameters. They also ignore many secondary effects. For example, forests promote clouds above them, since the water vapor they exhale condenses quickly. Those lovely cumulus puffs reflect sunlight. So growing trees to sop up carbon dioxide also increases albedo, a positive feedback bonus. But is that the end of the chain? No, because water vapor itself is a greenhouse gas. Thick clouds absorb infrared as well. If forests respire a lot, they can partially trap their own heat. Understanding this, and calculating it in detail, will take a generation of research.

But perhaps the greatest unknown is social: How will the politically aware public react--those who vote, anyway? If geoengineers are painted early and often as Dr. Strangeloves of the air, they will fail. Properly portrayed as allies of science--and true environmentalism--they could become heroes. Not letting the radical greens set the terms of discussion will matter crucially.

A major factor here will be whether mitigation looks like yet another top-down contrivance, another set of orders from the elite. Draconian policing of fuel burning will certainly look that way, a frowning Aunt Bessie elbowing into daily details, calculating your costs of commuting to work and setting your thermostat level. In contrast, mitigation does not have to push a new camel's nose into our tents. Technical solutions can play out far from people's lives, on the sea or high in the air.

Better, widespread acceptance of mitigation strategies could lead to an albedo chic--ostentatious flaunting of white roofs, the Mediterranean look, silvered cars, the return of the ice-cream suit in fashion circles. White could be appropriate after Labor Day again.

More seriously, every little bit would indeed help. This is crucial: Mitigation wears the white hat. It asks simple, clear measures of everyone, before going to larger-scale interventions. Grassroots involvement should be integral from the very beginning. Local efforts should go apace with those at the nation-state level, especially since mitigation intertwines deeply with diplomacy.

Here appearances are even more critical, given the levels of animosity between the big burners (especially the United States) and the tropical world.

Plausible solutions should stay within the NAS panel's sober guidelines. Learning more is the crucial first step, of course. This is not just the usual academic call for more funded research; nobody wants to try global experiments on a wing and a prayer.

Beyond more studies and reports, we must soon begin thinking of controlled experiments. Climate scientists so far have studied passively, much like astronomers. They have a bias toward this mode, especially since the discernible changes we have made in our climate generally have been pernicious. Such mental sets ebb slowly. The reek of hubris also restrains many. But a time for many limited experiments like the iron-dumping one will come. This will be the second great step as we ponder whether to become geoengineers. Constraints must be severe to ensure clear results.

Most important, perturbations in climate must be local and reversible--and not merely to quiet environmentalist fears. Only controlled experiments, well designed and well analyzed, will be convincing to all sides in this debate. Indeed, the green plume near the Galapagos Islands showed this. Its larger features were best studied by satellite, which picked up the green splotch strongly against the dark blue sea. But the crucial issue of whether the carbon stayed tied up in ocean waters was poorly addressed. Satellites were of no help. Slightly better funding and more scientists in dispersed, small craft could have told us a lot more.

Careful climate modeling must closely parallel every experiment. Few doubt that our climate stands in a class by itself in terms of complexity. Though much is made of how wondrous our minds are, perhaps the most complex entity known is our biosphere, in which we are mere mayflies. Absent a remotely useful theory of complexity in systems, we must proceed cautiously.

While computer studies are notorious for revealing mostly what was sought, confirming the prejudices of their programmers, methods are improving quickly. They can explore the many side avenues of small-scale geoengineering experiments. Invoking computer models as crucial watchdogs in every experiment will calm fears, at least among those who read beyond the headlines.

Who pays, in the end? Political pressure may well compel nations to comply with some target goals. A crucial factor will be what ratio to use in assessing a nation's (or region's) rectitude: net fossil-fuel consumption divided by what? Population? This favors the poor and populous nations. Economic value created with the fuels? The United States would fare reasonably well. Some weighted mean between the two?

To avoid descending into pure power politics and making policy sausage in public, a World Warming Authority could copy our fledgling pollution-voucher methods, bringing some market forces into play. But instead of simply trading the right to burn more--a negative unit--one could use a positive Mitigation Unit as well. Industries amassing them by, say, paying for rich-burning jet fuel could then burn more oil themselves. A market-driven dynamic equilibrium could then minimize costs for a given anti-warming target.

Such approaches might drive the emergence of suites of methods, which regions could choose among to their best advantage. Deserts reflect light well (though their roads are usually dark), so added cloud cover is less effective there overall; the whitewashing of cities could be measured by their average decrease in the heat-island effect; lands with high rainfall may favor forestation. Any such policy calculus should hover over the intricacies of markets, which will move faster and with more ingenuity than any committee. Rigid mandates will inevitably fail.

Still, going from the local to the global is fraught with uncertainty--and sure to inspire much anxiety. We will always be ambivalent stewards of the Earth. And greenhouse gas emissions certainly will not be our last problem, either. We are doing many things to our environment, with our numbers expected to reach 10 billion by 2050. What new threats will emerge? Catastrophes may come at a quickening pace, springing from the many synergistic effects that we must trace through the geophysical labyrinth.

As we begin correcting for our inadvertent insults to Mother Earth, we should realize that it's *forever*. Once we become caretakers, we cannot stop. The large tasks confronting humanity, especially the uplifting of the majority to some semblance of prosperity, must be carried forward in the shadow of our stewardship.

And yet, even among the able nations, those who have the foresight to grasp solutions, an odd reluctance pervades the policy classes. As the atmospheric physicist Ralph Cicerone has noted, "Many who envision environmental problems foresee doom and have little faith in technology, and therefore propose strong limits on industrialization, while most optimists refuse to believe that there is an environmental problem at all."

Having sinned against Mother Nature inadvertently, many are keenly reluctant to intervene knowingly. Sherwood Rowland, a chemist at the University of California at Irvine who predicted, with Mario Molina, the depletion of the ozone layer, declared, "I am unalterably opposed to global mitigation." This added considerable weight to the abstention cause. At root, such people see mankind as the problem; only by behaving humbly, living lightly upon our Earth, can we atone. Here most scientists and theologians agree, at least for now.

The next century will see a protracted battle between the prophets who would intervene and the moralists who see all grand-scale human measures as tainted. Even now, many argue that even to speak of geoengineering encourages the unwashed to more excess, since the masses will think that once again science has a remedy at hand.

Some, though, will say quietly, persistently, *Well, maybe science does....*

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