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PHAETON'S REINS

The human hand in climate change

Kerry Emanuel

Two strands of environmental philosophy run through the course of human history. The first holds that the natural state of the universe is one of infinite stability, with an unchanging earth anchoring the predictable revolutions of the sun, moon, and stars. Every scientific revolution that challenged this notion, from Copernicus' heliocentricity to Hubble's expanding universe, from Wegener's continental drift to Heisenberg's uncertainty and Lorenz's macroscopic chaos, met with fierce resistance from religious, political, and even scientific hegemonies.

The second strand also sees the natural state of the universe as a stable one but holds that it has become destabilized through human actions. The great floods are usually portrayed in religious traditions as attempts by a god or gods to cleanse the earth of human corruption. Deviations from cosmic predictability, such as meteors and comets, were more often viewed as omens than as natural phenomena. In Greek mythology, the scorching heat of Africa and the burnt skin of its inhabitants were attributed to Phaeton, an offspring of the sun god Helios, who, having lost a wager to his son, was obliged to allow him to drive the sun chariot across the sky. In this primal environmental catastrophe, Phaeton lost control and fried the earth, killing himself in the process.

These two fundamental ideas have permeated many cultures through much of history. They strongly influence views of climate change to the present day.

LAVIVE HERNÁNDEZ

The myth of natural stability

In 1837, Louis Agassiz provoked public outcry and scholarly ridicule when he proposed that many puzzles of the geologic record, such as peculiar scratch marks on rocks, and boulders far removed from their bedrock sources, could be explained by the advance and retreat of huge sheets of ice. This event marked the beginning of a remarkable endeavor, today known as paleoclimatology, which uses physical and chemical evidence from the geological record to deduce changes in the earth's climate over time. This undertaking has produced among the most profound yet least celebrated scientific advances of our era. We now have exquisitely detailed knowledge of how climate has varied over the last few million years and, with progressively less detail and more uncertainty, how it has changed going back in time to the age of the oldest rocks on our 4.5-billion-year-old planet.

For those who take comfort in stability, there is little consolation in this record. Within the past three million years or so, our climate has swung between mild states, similar to today's and lasting from ten to 20 thousand years, and periods of 100,000 years or so in which giant ice sheets, in some places several miles thick, covered northern continents. Even more unsettling than the existence of these cycles is the suddenness with which the climate can apparently change, especially as it recovers from glacial eras.

Over longer intervals of time, the climate has changed even more radically. During the early part of the Eocene era, around 50 million years ago, the earth was free of ice, and giant trees grew on islands near the North Pole, where the annual mean temperature was about 60°F, far warmer than today's mean of about 30. There is also some evidence that the earth was almost entirely covered with ice at various times around 500 million years ago; in between, the planet was exceptionally hot.

What explains these changes? For climate scientists, the ice cores in Greenland and Antarctica provide the most intriguing clues. As the ice formed, it trapped bubbles of atmosphere, whose chemical composition—including, for example, its carbon dioxide and methane content—can now be analyzed. Moreover, it turns out that the ratio of the masses of two isotopes of oxygen locked up in the molecules of ice is a good indicator of the air temperature when the ice was formed. And to figure out when the ice was formed, one can count the layers that mark the seasonal cycle of snowfall and melting.

Relying on such analyses of ice cores and sediment cores from the deep ocean, climate scientists have learned something remarkable: the ice-age cycles of the past three million years are probably caused by periodic oscillations of the earth's orbit that affect primarily the orientation of the earth's axis. These oscillations do not much affect the *amount* of sunlight that reaches the earth, but they do change the *distribution* of sunlight with latitude. This distribution matters because land and water absorb and reflect sunlight differently, and the distributions of land and water—continents and oceans—are quite different in the northern and southern hemispheres. Ice ages occur when, as a result of orbital variations, the arctic regions intercept relatively little summer sunlight so that ice and snow do not melt as much.

The timing of the ice ages, then, is the combined result of the earth's orbit and its basic geology. But this combination does not explain either the slow pace of the earth's descent into the cold phases of the cycle or the abrupt recovery to interglacial warmth evident in the ice-core records. More disturbing is the evidence that these large climate swings—from glacial to interglacial and back—are caused by relatively small changes in the distribution of sunlight with latitude. Thus, on the time scale of ice ages, climate seems exquisitely sensitive to small perturbations in the distribution of sunlight.

And yet for all this sensitivity, the earth never suffered either of the climate catastrophes of fire or ice. In the fire scenario, the most effective greenhouse gas—water vapor—accumulates in the atmosphere as the earth warms. The warmer the atmosphere, the more water vapor can accumulate; as more water vapor accumulates, more heat gets trapped, and the warming spirals upward. This uncontrolled feedback is called the runaway greenhouse effect, and it continues until the oceans have all evaporated, by which time the planet is unbearably hot. One has only to look as far as Venus to see the end result. Any oceans that may have existed on that planet evaporated eons ago, yielding a super greenhouse inferno and an average surface temperature of around 900°F.

Death by ice can result from another runaway feedback. As snow and ice accumulate progressively equatorward, they reflect an increasing amount of sunlight back to space, further cooling the planet until it freezes into a "snowball earth." It used to be supposed that once the planet reached such a frozen state, with almost all sunlight reflected back to space, it could never recover; more recently it has been theorized that without liquid oceans to absorb the carbon dioxide continuously emitted by volcanoes, that gas would accumulate in the atmosphere until its greenhouse effect was finally strong enough to start melting the ice.

It would not take much change in the amount of sunlight reaching the earth to cause one of these catastrophes. And solar physics informs us that the sun was about 25 percent dimmer early in the earth's history, which should have led to an ice-covered planet, a circumstance not supported by geological evidence.

So what saved the earth from fire and ice?

Life itself may be part of the answer to the riddle of the faint young sun. Our atmosphere is thought to have originated in gases emitted from volcanoes, but the composition of volcanic gases bears little resemblance to air as we know it today. It is thought that the early atmosphere consisted mostly of water vapor, carbon dioxide, sulfur dioxide, chlorine, and nitrogen. There is little evidence that there was much oxygen—until the advent of life. The first life forms helped produce oxygen through photosynthesis and transformed the atmosphere into something like today's, consisting mostly of nitrogen and oxygen with trace amounts of water vapor, carbon dioxide, methane, and other gases. Carbon-dioxide content probably decreased slowly with time owing to chemical weathering, possibly aided by biological processes. As the composition changed, the net greenhouse effect weakened, compensating for the slow but inexorable brightening of the sun.

Thus early life dramatically changed the planet. We humans are only the most recent species to do so.

The compensation between increasing solar power and decreasing greenhouse effect may not have been an accident. In the 1960s, James Lovelock proposed that life actually exerts a stabilizing influence on climate by producing feedbacks favorable to itself. He called his idea the Gaia hypothesis, named after the Greek earth goddess. But even according to this view, life is only preserved in the broadest sense: individual species, such as those that transformed the early atmosphere, altered the environment at their peril.

Greenhouse physics

As this sketch of the planet's early climatic history shows, the greenhouse effect plays a critical role in the earth's climate, and no sensible discussion of

climate could proceed without grasping its nature. (A cautionary note: the greenhouse metaphor itself is flawed. Whereas actual greenhouses work by preventing convection currents from carrying away heat absorbed from sunlight, the atmosphere prevents heat from *radiating* away from the surface.)

The greenhouse effect has to do with radiation, which in this context refers to energy carried by electromagnetic waves, which include such phenomena as visible light, radio waves, and infrared radiation. All matter with a temperature above absolute zero emits radiation. The hotter the substance, the more radiation it emits and the shorter the average wavelength of the radiation emitted. A fairly narrow range of wavelengths constitute visible light. The average surface temperature of the sun is about 10,000°F, and the sun emits much of its radiation as visible light, with an average wavelength of about half a micron. (A micron is one millionth of a meter; there are 25,400 microns in an inch.) The earth’s atmosphere emits as though its average temperature were around 0°F, at an average wavelength of about 15 microns. Our eyes cannot detect this infrared radiation. It is important to recognize that the same object can both emit and absorb radiation: when an object emits radiation it loses energy, and this has the effect of cooling it; absorption, on the other hand, heats an object.

Most solids and liquids absorb much of the radiation they intercept, and they also emit radiation rather easily. Air is another matter. It is composed almost entirely of oxygen and nitrogen, each in the form of two identical atoms bonded together in a single molecule. Such molecules barely interact with radiation: they allow free passage to both solar radiation moving downward to the earth and infrared radiation moving upward from the earth’s surface. If that is all there were to the atmosphere, it would be a simple matter to calculate the average temperature of the earth’s surface: it would have to be just warm enough to emit enough infrared radiation to balance the shortwave radiation it absorbed from the sun. (Were it too cool, it would emit less radiation than it absorbed and would heat up; conversely, were it too warm it would cool.) Accounting for the amount of sunlight reflected back to space by the planet, this works out to be about 0°F, far cooler than the observed mean surface temperature of about 60°F.

Fortunately for us, our atmosphere contains trace amounts of other substances that do interact strongly with radiation. Foremost among these is water, H_2O, consisting of two atoms of hydrogen bonded to a single atom of oxygen. Because of its more complex geometry, it absorbs and emits radiation far more efficiently than molecular nitrogen and oxygen. In the atmosphere, water exists both in its gas phase (water vapor) and its condensed phase (liquid water and ice) as clouds and precipitation. Water vapor and clouds absorb sunlight and infrared radiation, and clouds also reflect sunlight back to space. The amount of water vapor in a sample of air varies greatly from place to place and time to time, but in no event exceeds about two percent of the mass of the sample. Besides water, there are other gases that interact strongly with radiation; these include CO_2, or carbon dioxide (presently about 380 tons for each million tons of air), and CH_4, or methane (around 1.7 tons for each million tons of air).

Collectively, the greenhouse gases are nearly transparent to sunlight, allowing the short-wavelength radiation to pass virtually unimpeded to the surface, where much of it is absorbed. (But clouds both absorb and reflect sunlight.) On the other hand, these same gases absorb much of the long-wavelength, infrared radiation that passes through them. To compensate for the heating this absorption causes, the greenhouse gases must also emit radiation, and each layer of the atmosphere thus emits infrared radiation upward and downward.

As a result, the surface of the earth receives radiation from the atmosphere as well as the sun. It is a remarkable fact that, averaged over the planet, the surface receives more radiation from the atmosphere than directly from the sun! To balance this extra input of radiation—the radiation emitted by atmospheric greenhouse gases and clouds—the earth’s surface must warm up and thereby emit more radiation itself. This is the essence of the greenhouse effect.

If air were not in motion, the observed concentration of greenhouse gases and clouds would succeed in raising the average temperature of the earth’s surface to around 85°F, much warmer than observed. In reality, hot air from near the surface rises upward and is continually replaced by cold air moving down from aloft; these convection currents lower the surface temperature to an average of 60°F while warming the upper reaches of the atmosphere. So the emission of radiation by greenhouse gases keeps the earth’s surface warmer than it would otherwise be; at the same time, the movement of air dampens the warming effect and keeps the surface temperature bearable.

Why the climate problem is difficult

This basic climate physics is entirely uncontroversial among scientists. And if one could change the concentration of a single greenhouse gas while holding the rest of the system (except its temperature) fixed, it would be simple to calculate the corresponding change in surface temperature. For example, doubling the concentration of CO_2 would raise the average surface temperature by about 1.4°F, enough to detect but probably not enough to cause serious problems. Almost all the controversy arises from the fact that in reality, changing any single greenhouse gas will indirectly cause other components of the system to change as well, thus yielding additional changes. These knock-on effects are known as feedbacks, and the most important and uncertain of these involves water.

A fundamental difference exists between water and most other greenhouse gases. Whereas a molecule of carbon dioxide or methane might remain in the atmosphere for hundreds of years, water is constantly recycled between the atmosphere, land surface, and oceans, so that a particular molecule of water resides in the atmosphere for, on average, about two weeks. On climate time scales, which are much longer than two weeks, atmospheric water is very nearly in equilibrium with the surface, which means that as much water enters the atmosphere by evaporating from the surface as is lost to the surface by rain and snow. One cannot simply tally up the sources and sinks and figure out which wins; a more involved argument is needed.

To make matters worse, water vapor and clouds are far and away the most important greenhouse substances in the atmosphere, and clouds also affect climate not only by sending infrared radiation back to earth and warming it up but by reflecting sunlight back into space, thus cooling the planet. Water is carried upward from its source at the surface by convection currents, which themselves are a byproduct of the greenhouse effect, which tends to warm the air near the surface. Simple physics as well as detailed calculations using computer models of clouds show that the amount of water vapor in the atmosphere is sensitive to the details of the physics by which tiny cloud droplets and ice crystals combine into larger raindrops and snowflakes, and how these in turn fall and partially re-evaporate on their way to the surface. The devil in these details seems to carry much authority with climate.

This complexity is limited, however, because the amount of water in the atmosphere is subject to a fundamental and important constraint. The concentration of water vapor in any sample of air has a strict upper limit that depends on its temperature and pressure: in particular, this limit rises very rapidly with temperature. The ratio of the actual amount of water vapor in a sample to this limiting amount is the familiar quantity called *relative humidity*. Calculations with a large variety of computer models and observations of the atmosphere all show that as climate changes, relative humidity remains approximately constant. This means that as atmospheric temperature increases, the actual amount of water vapor increases as well. But water vapor is a greenhouse gas. So increasing temperature increases water vapor, which leads to further increases in temperature. This positive feedback in the climate system is the main reason why the global mean surface temperature is expected to increase somewhat more than the 1.4°F that doubling CO_2 would produce in the absence of feedbacks. (At very high temperatures, the water vapor feedback can run away, leading to the catastrophe of a very hot planet, as mentioned before.)

The amount and distribution of water vapor in the atmosphere is also important in determining the distribution of clouds, which play a complex role in climate. On the one hand, they reflect about 22 percent of the incoming solar radiation back to space, thereby cooling the planet. On the other hand, they absorb solar radiation and both absorb and emit infrared radiation, thus contributing to greenhouse warming. Different global climate models produce wildly different estimates of how clouds might change with changing climate, thus constituting the largest source of uncertainty in climate-change projections.

A further complication in this already complex picture comes from anthropogenic aerosols—small solid or liquid particles suspended in the atmosphere. Industrial activity and biomass burning have contributed to large increases in the aerosol content of the atmosphere, and this is thought also to have had a large effect on climate.

The main culprits are the sulfate aerosols, which are created through atmospheric chemical reactions involving sulfur dioxide, another gas produced by the combustion of fossil fuels. These tiny particles reflect incoming sunlight and, to a lesser degree, absorb infrared radiation. Perhaps more importantly, they also serve as condensation nuclei for clouds. When a cloud forms, water vapor does not form water droplets or ice crystals spontaneously but instead condenses onto pre-existing aerosol particles. The number and size of these particles determines whether the water condenses into a few large droplets or many small ones, and this in turn strongly affects the amount of sunlight that clouds reflect and the amount of radiation they absorb.

It is thought that the increased reflection of sunlight to space—both directly by the aerosols themselves and through their effect on increasing the reflectivity of clouds—outweighs any increase in their greenhouse effect, thus cooling the planet. Unlike the greenhouse gases, however, sulfate aerosols only remain in the atmosphere a few weeks before they are washed out by rain and snow. Their abundance is proportional to their rate of production—as soon as production decreases, sulfate aerosols follow suit. Since the early 1980s, improved technology and ever more stringent regulations have diminished sulfate aerosol pollution in the developed countries, aided by the collapse of the USSR and the subsequent reduction of industrial output there. On the other hand, sources of sulfate aerosols have been steadily increasing in Asia and the developing countries, so it is unclear how the net global aerosol content has been changing over the past 25 years.

Important uncertainties enter the picture, then, with water (especially clouds) and airborne particulates. But the uncertainties actually go much deeper: indeed, to understand long-term climate change, it is essential to appreciate that detailed forecasts cannot, *even in principle*, be made beyond a few weeks. That is because the climate system, at least on short time scales, is *chaotic.*

The essential property of chaotic systems is that small differences tend to magnify rapidly. Think of two autumn leaves that have fallen next to each other in a turbulent brook. Imagine following them as

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they move downstream on their way to the sea: at first, they stay close to each other, but the eddies in the stream gradually separate them. At some point, one of the leaves may get temporarily trapped in a whirlpool behind a rock while the other continues downstream. It is not hard to imagine that one of the leaves arrives at the mouth of the river days or weeks ahead of the other. It is also not hard to imagine that a mad scientist, having equipped our brook with all kinds of fancy instruments for measuring the flow of water and devised a computer program for predicting where the leaves would go, would find it almost impossible to predict where the leaf would be even an hour after it started its journey.

Let's go back to the two leaves just after they have fallen in the brook, and say that at this point they are ten inches apart. Suppose that after 30 minutes they are ten feet apart, and this distance increases with time. Now suppose that it were possible to rewind to the beginning but this time start the leaves only five inches apart. It would not be surprising if it took longer—say an hour—before they are once again 10 feet apart. Keep rewinding the experiment, each time decreasing the initial distance between the leaves. You might suppose that the time it takes to get 10 feet apart keeps increasing indefinitely. But for many physical systems (probably including brooks), this turns out not to be the case. As you keep decreasing the initial separation, the increases in the amount of time it takes for the leaves to be separated by 10 feet get successively smaller, so much so that there is a definite limit : no matter how close the leaves are when they hit the water, it will not take longer than, say, six hours for them to be ten feet apart.

The same principle applies if, instead of having two leaves, we have a single leaf and a computer model of the leaf and the stream that carries it. Even if the computer model is perfect and we start off with a perfect representation of the state of the brook, any error—even an infinitesimal one—in the timing or position of the leaf when it begins its journey will lead to the forecast being off by at least ten feet after six hours, and greater distances at longer times. Prediction beyond a certain time is impossible.

Not all chaotic systems have this property of limited predictability, but our atmosphere and oceans, alas, almost certainly do. As a result, it is thought that the upper limit of the predictability of weather is around two weeks. (That we are not very close to this limit is a measure of the imperfection of our models and our measurements.)

While the day-to-day variations of the weather are perhaps the most familiar examples of environmental chaos, variations at longer time scales can also behave chaotically. El Niño is thought to be chaotic in nature, making it difficult to predict more than a few months in advance. Other chaotic phenomena involving the oceans have even longer time scales, but beyond a few years it becomes increasingly difficult for scientists to tell the difference between chaotic natural variations and what climate scientists called "forced" variability. But this difference is important for understanding the human role in producing climate change.

On top of the natural, chaotic "free" variability of weather and climate are changes brought about by changing "forcing," which is usually considered to involve factors that are not themselves affected by climate. The most familiar of these is the march of the seasons, brought about by the tilt of the earth's axis, which itself is independent of climate. The effects of this particular forcing are not hard to separate from the background climate chaos: we can confidently predict that January will be colder than July in, say, New York. Other examples of natural climate forcing include variations in solar output, and volcanic eruptions, which inject aerosols into the stratosphere and thereby cool the climate.

Some of this natural climate forcing is chaotic in nature, but some of it is predictable on long time scales. For example, barring some catastrophic collision with a comet or asteroid, variations of the earth's orbit are predictable many millions of years into the future. On the other hand, volcanic activity is unpredictable. In any event, the actual climate we experience reflects a combination of free (unforced), chaotic variability, and changes brought about by external forcing, some of which, like volcanic eruptions, are themselves chaotic. And part of this forced climate variability is brought about by us human beings.

Determining humanity's influence

An important and difficult issue in detecting anthropogenic climate change is telling the difference between natural climate variations—both free and forced—and those that are forced by our own activities.

One way to tell the difference is to make use of the fact that the increase in greenhouse gases and sulfate aerosols dates back only to the industrial revolution of the 19th century: before that, the human influence is probably small. If we can estimate how climate changed before this time, we will have some idea of how the system varies naturally. Unfortunately, detailed measurements of climate did not themselves really begin in earnest until the 19th century; but there are "proxies" for quantities like temperature, recorded in, for example, tree rings, ocean and lake plankton, pollen, and corals.

Plotting the global mean temperature derived from actual measurements and from proxies going back a thousand years or more reveals that the recent upturn in global temperature is truly unprecedented: the graph of temperature with time shows a characteristic hockey-stick shape, with the business end of the stick representing the upswing of the last 50 years or so. But the proxies are imperfect and associated with large margins of error, so any hockey-stick trends of the past may be masked, though the recent upturn stands above even a liberal estimate of such errors.

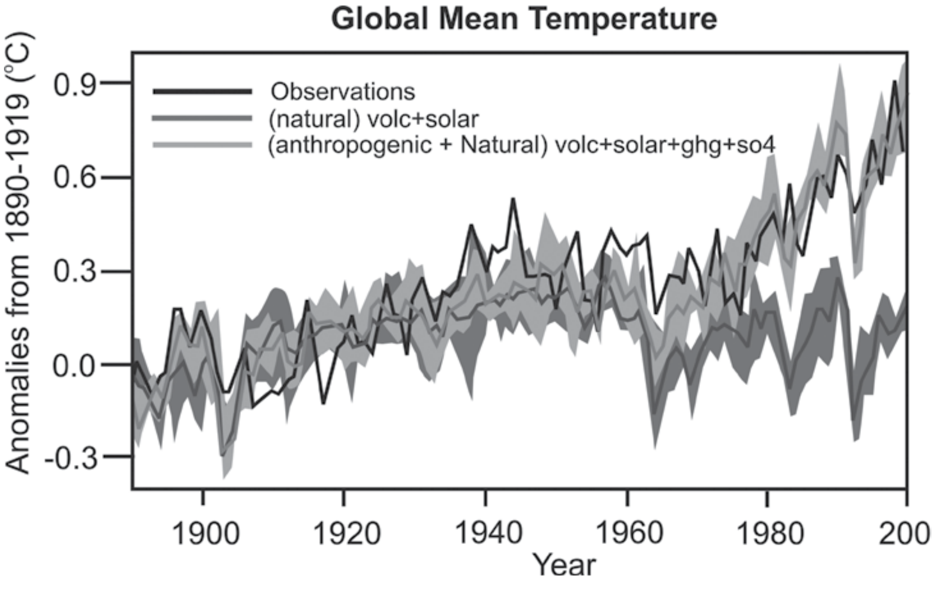
Another way to tell the difference is to simulate the climate of the last 100 years or so with climate models. Computer modeling of global climate is perhaps the most complex endeavor ever undertaken by mankind. A typical climate model consists of millions of lines of computer instructions designed to simulate an enormous range of physical phenomena, including the flow of the atmosphere and oceans, condensation and precipitation of water inside clouds, the transfer of solar and terrestrial radiation through the atmosphere, including its partial absorption and reflection by the surface, by clouds and by the atmosphere itself, the convective transport of heat, water, and atmospheric constituents by turbulent convection currents, and vast numbers of other processes. There are by now a few dozen such models in the world, but they are not entirely independent of one another, often sharing common pieces of computer code and common ancestors.

Although the equations representing the physical and chemical processes in the climate system are well known, they cannot be solved exactly. It is computationally impossible to keep track of every molecule of air and ocean, and to make the task viable, the two fluids must be divided up into manageable chunks. The smaller and more numerous these chunks, the more accurate the result, but with today's computers the smallest we can make these chunks in the atmosphere is around 100 miles in the horizontal and a few hundred yards in the vertical, and a bit smaller in the ocean. The problem here is that many important processes are much smaller than these scales. For example, cumulus clouds in the atmosphere are critical for transferring heat and water upward and downward, but they are typically only a few miles across and so cannot be simulated by the climate models. Instead, their effects must be represented in terms of the quantities like wind and temperature that pertain to the whole computational chunk in question. The representation of these important but unresolved processes is an art form known by the awful term *parameterization*, and it involves numbers, or parameters, that must be tuned to get the parameterizations to work in an optimal way. Because of the need for such artifices, a typical climate model has many tunable parameters, and this is one of many reasons that such models are only approximations to reality. Changing the values of the parameters or the way the various processes are parameterized can change not only the climate simulated by the model, but the sensitivity of the model's climate to, say, greenhouse-gas increases.

How, then, can we go about tuning the parameters of a climate model in such a way as to make it a reasonable facsimile of reality? Here important lessons can be learned from our experience with those close cousins of climate models, weather-prediction models. These are almost as complicated and must also parameterize key physical processes, but because the atmosphere is measured in many places and quite frequently, we can test the model against reality several times per day and keep adjusting its parameters (that is, tuning it) until it performs as well as it can. But with climate, there are precious few tests. One obvious hurdle the model must pass is to be able to replicate the current climate, including key aspects of its variability, such as weather systems and El Niño. It must also be able to simulate the seasons in a reasonable way: the summers must not be too hot or the winters too cold, for example.

Beyond a few simple checks such as these, there are not too many ways to test the model, and projections of future climates must necessarily involve a degree of faith. The amount of uncertainty in such projections can be estimated to some extent by comparing forecasts made by many different models, with their different parameterizations (and, very likely, different sets of coding errors). We operate under the faith that the real climate will fall among the projections made with the various models; in other words, that the truth will lie somewhere between the higher and lower estimates generated by the models.

The figure below shows the results of two sets of computer simulations of the global average surface temperature of the 20th century using a particular climate model. In the first set, denoted by the darker shade of gray, only natural, time-varying forcings are applied; these consist of variable solar output and "dimming" owing to aerosols produced by known volcanic eruptions. The second set (lighter gray) adds in the man-made influences on sulfate aerosols and greenhouse gases. In each set, the model is run four times beginning with slightly different initial states, and the range among the four ensemble members is denoted by the shading in the figure, reflecting the free random variability of the climate produced by this model, while the colored curves show the average of the four ensemble members. The observed global average surface temperature is depicted by the black curve. One observes that the two sets of simulations diverge during the 1970s and have no overlap at all today, and that the observed global temperature also starts to fall outside the envelope of the all-natural simulations in the 1970s. This exercise has been repeated using many different climate models, with the same qualitative result: one cannot simulate the evolution of the climate over last 30 years without including in the simulations mankind's influence on sulfate aerosols and greenhouse gases. This, in a nutshell, is why almost all climate scientists today believe that man's influence on climate has emerged from the background noise of natural variability.



Cymbalta

One of those voices was biologically female and it said,
Put your hand under my mouth,
but don't nuzzle me with your bulldozer the color of Easter.
When a man with rough skin starts undressing himself, he may warble
like a fountain, or brides—
I watched the sides of his mouth quiver in what could only be described as a
gesture of panic.
Was his torso so gilded in birch leaves? Were his nipples excited by fall? I
don't remember
the name of your friend from Montreal,
but I'm sure bugs don't bother him much up there
as they hear the blood pulse through his sweater and tiny scarf.
One does think about bodily delight—
And that makes the tongue burn towards an earlobe,
then the low or soft shoulder beckons,
and I'm back at your starting point, which you were right to call an
interstate
chiseled across our hayfield.

—Stephanie Cleveland

The consequences

Projections based on climate models suggest that the globe will continue to warm another 3 to 7°F over the next century. This is similar to the temperature change one could experience by moving, say, from Boston to Philadelphia. Moreover, the warming of already hot regions—the tropics—is expected to be somewhat less, while the warming of cold regions like the arctic is projected to be more, a signal already discernable in global temperature measurements. Nighttime temperatures are increasing more rapidly than daytime warmth.

Is this really so bad? In all the negative publicity about global warming, it is easy to overlook the benefits: It will take less energy to heat buildings, previously infertile lands of high latitudes will start producing crops, and there will be less suffering from debilitating cold waves. Increased CO_2 might also make crops grow faster. On the down side, there will be more frequent and more intense heat waves, air conditioning costs will rise, and previously fertile areas in the subtropics may become unarable. Sure, there will be winners and losers, but will the world really suffer in the net? Even if the changes we are bringing about are larger than the globe has experienced in the last few thousand years, they still do not amount to the big natural swings between ice ages and interglacial periods, and the earth and indeed human beings survived these.

But there are consequences of warming that we cannot take so lightly. During the peak of the last ice age, sea level was some 400 feet lower than today's, since huge quantities of water were locked up in the great continental ice sheets. As polar regions warm, it is possible that portions of the Greenland and Antarctic ice sheets will melt, increasing sea level. Highly detailed and accurate satellite-based measurements of the thickness of the Greenland ice show that it is actually increasing in the interior but thinning around the margins, and while there are also patterns of increase and decrease in Antarctic ice, it appears to be thinning on the whole. Meltwater from the surface of the Greenland ice sheet is making its way to the bottom of the ice, possibly allowing the ice to flow faster toward the sea. Our understanding of the physics of ice under pressure is poor, and it is thus difficult to predict how the ice will respond to warming. Were the entire Greenland ice cap to melt, sea level would increase by around 22 feet—flooding many coastal regions including much of southern Florida and lower Manhattan.

My own work has shown that hurricanes are responding to warming sea surface temperatures faster than we originally expected, especially in the North Atlantic, where the total power output by tropical cyclones has increased by around 60 percent since the 1970s. The 2005 hurricane season was the most active in the 150 years of records, corresponding to record warmth of the tropical Atlantic. Hurricanes are far and away the worst natural disasters to affect the U.S. in economic terms. Katrina may cost us as much as $200 billion, and it has claimed at least 1,200 lives. Globally, tropical cyclones cause staggering loss of life and misery. Hurricane Mitch of 1998 killed over 10,000 people in Central America, and in 1970 a single storm took the lives of some 300,000 people in Bangladesh. Substantial changes in hurricane activity cannot be written off as mere climate perturbations to which we will easily adjust.

Basic theory and models show another consequential result of a few degrees of warming. The amount of water vapor in the air rises exponentially with temperature: a seven-degree increase in temperature increases water vapor by 25 percent. One might at first suppose that since the amount of water ascending into clouds increases, the amount of rain that falls out of them must increase in proportion. But condensing water vapor heats the atmosphere, and in the grand scheme of things, this must be compensated by radiative heat loss. On the other hand, simple calculations show that the amount of radiative heat loss increases only very slowly with temperature, so that the total heating by condensation must increase slowly as well. Models resolve this conundrum by making it rain harder in places that are already wet and at the same time increasing the intensity, duration, or geographical extent of droughts. Thus, the twin perils of flood and drought actually both increase substantially in a warmer world.

It is particularly sobering to contemplate such outcomes in light of the evidence that smaller, natural climate swings since the end of the last ice age debilitated and in some cases destroyed entire civilizations in such places as Mesopotamia, Central and South America, and the southwestern region of what is today the United States.

In pushing the climate so hard and so fast, we are also conscious of our own collective ignorance of how the climate system works. Perhaps negative-feedback mechanisms that we have not contemplated or have underestimated will kick in, sparing us from debilitating consequences. On the other hand, the same could be said of positive feedbacks, and matters might turn out worse than projected. The ice-core record reveals a climate that reacts in complex and surprising ways to smoothly and slowly changing radiative forcing caused by variations in the earth's orbit. Far from changing smoothly, it remains close to one state for a long time and then suddenly jumps to another state. We do not understand this, and are worried that a sudden climate jump may be part of our future.

Science, politics, and the media

Science proceeds by continually testing and discarding or refining hypotheses, a process greatly aided by the naturally skeptical disposition of scientists. We are, most of us, driven by a passion to understand nature, but that means being dispassionate about pet ideas. Partisanship—whatever its source—is likely to be detected by our colleagues and to yield a loss of credibility, the true stock of the trade. We share a faith—justified by experience—that at the end of the day, there is a truth to be found, and those who cling for emotional reasons to wrong ideas will be judged by history accordingly, whereas those who see it early will be regarded as visionaries.

The evolution of the scientific debate about anthropogenic climate change illustrates both the value of skepticism and the pitfalls of partisanship. Although the notion that fossil-fuel combustion might increase CO_2 and alter climate originated in the 19th century, general awareness of the issue dates to a National Academy of Sciences report in 1979 that warned that doubling CO_2 content might lead to a three-to-eight-degree increase in global average temperature. Then, in 1988, James Hansen, the director of NASA's Goddard Institute for Space Studies, set off a firestorm of controversy by testifying before Congress that he was virtually certain that a global-warming signal had emerged from the background climate variability. At that time, less was known about natural climate variability before the beginning of systematic instrumental records in the nineteenth century, and only a handful of global climate simulations had been performed. Most scientists were deeply skeptical of Hansen's claims; I certainly was. It is important to interpret the word "skeptical" literally here: it was not that we were sure of the opposite, merely that we thought the jury was out.

At roughly this time, radical environmental groups and a handful of scientists influenced by them leapt into the fray with rather obvious ulterior motives. This jump-started the politicization of the issue, and conservative groups, financed by auto makers and big oil, responded with counterattacks. This also marked the onset of an interesting and disturbing phenomenon that continues to this day. A very small number of climate scientists adopted dogmatic positions and in so doing lost credibility among the vast majority who remained committed to an unbiased search for answers. On the left, an argument emerged urging fellow scientists to deliberately exaggerate their findings so as to galvanize an apathetic public, an idea that, fortunately, failed in the scientific arena but which took root in Hollywood, culminating in the 2004 release of *The Day After Tomorrow*. On the right, the search began for negative feedbacks that would counter increasing greenhouse gases: imaginative ideas emerged, but they have largely failed the acid test of comparison to observations. But as the dogmatists grew increasingly alienated from the scientific mainstream, they were embraced by political groups and journalists, who thrust them into the limelight. This produced a gross distortion in the public perception of the scientific debate. Ever eager for the drama of competing dogmas, the media largely ignored mainstream scientists whose hesitations did not make good copy. As the global-warming signal continues to emerge, this soap opera is kept alive by a dwindling number of deniers constantly tapped for interviews by journalists who pretend to look for balance.

While the American public has been misinformed by a media obsessed with sensational debate, climate scientists developed a way forward that helps them to compare notes and test one another's ideas and also creates a valuable communication channel. Called the Intergovernmental Panel on Climate Change, or IPCC, it produces a detailed summary of the state of the science every four years, with the next one due out in February 2007. Although far from perfect, the IPCC involves serious climate scientists from many countries and has largely withstood political attack and influence.

The IPCC reports are fairly candid about what we collectively know and where the uncertainties probably lie. In the first category are findings that are not in dispute, not even by *les refusards*:

- Concentrations of the greenhouse gases carbon dioxide, methane, ozone, and nitrous oxide are increasing owing to fossil-fuel consumption and biomass burning. Carbon dioxide has increased from its pre-industrial level of about 280 parts per million (ppmv) to about 380 ppmv today, an increase of about 35 percent. From ice-core records, it is evident that present levels of CO_2 exceed those experienced by the planet at any time over at least the past 650,000 years.
- Concentrations of certain anthropogenic aerosols have also increased owing to industrial activity.
- The earth's average surface temperature has increased by about 1.2°F in the past century, with most of the increase occurring from about 1920 to 1950, and again beginning around 1975. The year 2005 was the warmest in the instrumental record.
- Sea level has risen by about 2.7 inches over the past 40 years; of this, a little over an inch occurred during the past decade.
- The annual mean geographical extent of arctic sea ice has decreased by 15 to 20 percent since satellite measurements of this began in 1978.

In the second category are findings that most climate scientists agree with but are disputed by some:

- The global mean temperature is now greater than at any time in at least the past 500 to 1,000 years
- Most of the global mean temperature variability is caused by four factors: variability of solar output, major volcanic eruptions, and anthropogenic sulfate aerosols and greenhouse gases

- The dramatic rise in global mean temperature in the past 30 years is owing primarily to increasing greenhouse-gas concentrations and a leveling off or slight decline in sulfate aerosols.
- Unless measures are taken to reduce greenhouse-gas production, global mean temperature will continue to increase, about 2.5 to 9°F over the next century, depending on uncertainties and how much greenhouse gas is produced.
- As a result of the thermal expansion of sea water and the melting of polar ice caps, sea level will increase six to 16 inches over the next century, though the increase could be larger if large continental ice sheets become unstable.
- Rainfall will continue to become concentrated in increasingly heavy but less frequent events.
- The incidence, intensity, and duration of both floods and drought will increase.
- The intensity of hurricanes will continue to increase, though their frequency may dwindle.

All these projections depend, of course, on how much greenhouse gas is added to the atmosphere over the next century, and even if we could be certain about the changes, estimating their net effect on humanity is an enormously complex undertaking, pitting uncertain estimates of costs and benefits against the costs of curtailing greenhouse-gas emissions. But we are by no means certain about what kind of changes are in store, and we must be wary of climate surprises. Even if we believed that the projected climate changes would be mostly beneficial, we might be inclined to make sacrifices as an insurance policy against potentially harmful surprises.

Youth Is Not Absolution for Treachery; It Is a Morning Star of Some Kind

If you keep punching at a man's head
it will mix his mind. So fast.
So pretty.
I want my brain to be the jangled thud
my body makes when it bangs against the ground.
I want you to say my name,
knock a broken branch against its tree
and that song will be a page
in a book you love to hold in your hand
because it is a birdcall that proves
you are privy to a superhuman scale.
I believe God is healing my soul right now
by killing my body. Slowly.
The opposite is true for your body, illuminated
by a light fired from another world,
seeing what other men have only thought.
Infinite are the fast mercies,
infinite the pretty occlusions.

—Travis Nichols

The politics of global climate change

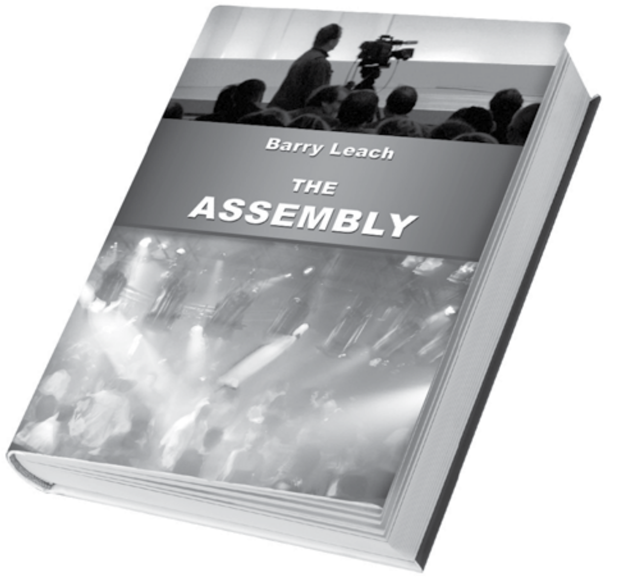
Especially in the United States, the political debate about global climate change became polarized along the conservative–liberal axis some decades ago. Although we take this for granted now, it is not entirely obvious why the chips fell the way they did. One can easily imagine conservatives embracing the notion of climate change in support of actions they might like to see anyway. Conservatives have usually been strong supporters of nuclear power, and few can be happy about our current dependence on foreign oil. The United States is renowned for its technological innovation and should be at an advantage in making money from any global sea change in energy-producing technology: consider the prospect of selling new means of powering vehicles and electrical generation to China's rapidly expanding economy. But none of this has happened.

Paradoxes abound on the political left as well. A meaningful reduction in greenhouse-gas emissions will require a shift in the means of producing energy, as well as conservation measures. But such alternatives as nuclear and wind power are viewed with deep ambivalence by the left. Senator Kennedy, by most measures our most liberal senator, is strongly opposed to a project to develop wind energy near his home in Hyannis, and environmentalists have only just begun to rethink their visceral opposition to nuclear power. Had it not been for green opposition, the United States today might derive most of its electricity from nuclear power, as does France; thus the environmentalists must accept a large measure of responsibility for today's most critical environmental problem.

There are other obstacles to taking a sensible approach to the climate problem. We have preciously few representatives in Congress with a background or interest in science, and some of them display an active contempt for the subject. As long as we continue to elect scientific illiterates like James Inhofe, who believes global warming to be a hoax, we will lack the ability to engage in intelligent debate. Scientists are most effective when they provide sound, impartial advice, but their reputation for impartiality is severely compromised by the shocking lack of political diversity among American academics, who suffer from the kind of group-think that develops in cloistered cultures. Until this profound and well documented intellectual homogeneity changes, scientists will be suspected of constituting a leftist think tank.

On the bright side, the governments of many countries, including the United States, continue to fund active programs of climate research, and many of the critical uncertainties about climate change are slowly being whittled down. The extremists are being exposed and relegated to the sidelines, and when the media stop amplifying their views, their political counterparts will have nothing left to stand on. When this happens, we can get down to the serious business of tackling the most complex and perhaps the most consequential problem ever confronted by mankind.

Like it or not, we have been handed Phaeton's reins, and we will have to learn how to control climate if we are to avoid his fate. ♦



EVOBASSMAN

Economics must be at the heart of any discussion of how to fight climate change

Nicholas Stern

The scientific case on climate change now seems overwhelming: we face an enormous problem and tremendous costs for inaction. The latest science also gives us insight into the magnitude of damage we are risking if we continue to emit greenhouse gases on a business-as-usual basis. If we carry on emitting on this basis, temperature increases by 2035 could well take us outside of human experience, and the costs for disruption to economic and social activity could rise to 20 percent of global GDP. Moreover, to prevent this from happening, stabilization of global emissions would mean cutting annual emissions by at least 25 percent by 2050.

On the brighter side, the cost of stabilization can be limited to around one percent of global GDP a year. But to achieve stabilization at that cost, action over the next few decades is crucial. Like any policy problem, to keep the costs down, it will be necessary to formulate a clear, robust policy framework that uses a mix of instruments (including carbon pricing through trading and taxes, regulation, and technology policy) across sectors and countries in the short and long term. Poorly constructed policy will increase the costs of stabilization.

Action by individual countries is, however, not enough, and it will prove more costly. Climate change is a global problem, and solutions will require coordinated action by rich and poor countries, based on a shared vision of long-term goals and mutually reinforcing approaches at the national, regional, and international level. With a globally shared vision, policy can then reap the benefits of joint action and global markets for the lower carbon technologies that will be necessary. Action need not be anti-business or anti-growth—in fact, failing to act is anti-growth, since it risks the future of growth itself. A transformation of global infrastructure and an investment in energy, transport, buildings, and agriculture offers new opportunities and markets.

But these markets can only be created at scale if an effective global response is realized. Climate change is the biggest market failure the world has ever seen, and strong policy will be necessary to correct it. The UN Framework Convention on Climate Change and the Kyoto Protocol provide a basis for international cooperation, but more ambitious action is required, and economics has to be at the heart of any serious discussion of how to proceed.

Consider where the greenhouse gases come from: mostly from energy use that is *central to economic activity*. Electricity and heat generation, transport, industry, and other energy is 61 percent of the story. Land use accounts for a large percentage, too: deforestation is 18 percent and agriculture also is another 14 percent. Furthermore, with economic growth, countries become larger sources of greenhouse gases. Thus, the big emitters now are the United States and Western Europe; China is also quite big. Going forward, the increases for China and India are expected to be substantial. My rough rule of thumb is that rich countries are responsible for 79 percent of the cumulative energy emissions over the last 50 years or so; in a decade or so the emissions from the developing countries will overtake those from rich countries; and in 20 to 25 years, the current developing countries will likely be responsible for 70 percent. (The importance of this is that the developing countries currently don't have targets under the Kyoto agreement, and there will be a major challenge in bringing them into the whole story of emissions.)

What follows from these economic fundamentals?

Global collective action. You can't conjure collective action out of the air, especially when interests partially conflict. All the players need to understand the implications for them, their growth, their mortality rates, and the survival of species and natural flora and fauna in their country. In addition, policy has to take into account equity and fairness in the burdens of adjustment. The rich countries are primarily responsible for where we are now. But the poor countries are going to be major contributors to future emissions, so even if the rich world takes on responsibility for absolute cuts in emissions of 60 percent to 80 percent by 2050, developing countries must take significant action too. Moreover, the costs of taking action are not evenly distributed across sectors or around the world. So developing countries should not be required to bear the full costs of this action alone. But they will not have to. Carbon markets in rich countries are already beginning to deliver flows of finance to support low-carbon strategies of economic development, including through the Kyoto's Clean Development Mechanism (which permits countries to achieve emissions reductions by investing in projects in developing countries that reduce emissions and that would not have otherwise happened). A transformation of these flows is now required to support action on the scale required.

The existing literature on the economics of climate change is very useful, but its focus—on the environmental *effects* of economic growth—is a bit narrow in helping us understand the international collective-action problems that we will face. In particular, we have to look at what economists call the "endogeneity of growth": the fact that the rate of growth not only shapes environment, but that changed environment also shapes subsequent economic growth. If you disrupt the monsoon in North India, or the advance of the Sahara is accelerated in Africa, that will have a fairly profound effect on the rate of growth in those countries. Projections of the likely effects of climate change on crop yields in Africa look worrying for 20, 30, 40 years ahead—reductions of upwards of ten percent. If you get crop reductions of that magnitude in sub-Saharan Africa, you will have very serious problems. So climate change is likely to increase the case for overseas development aid as an element of collective action.

There will be large economic impacts in rich countries, too. The scorching summer of 2003 could well be normal in 30 to 50 years, and cool by the last quarter of the century. This change is bound to affect opportunities for growth.

Technology. Given the scale of the climate problem, effective reductions in greenhouse-gas concentrations will require action across a broad area. We need to think about halting deforestation (which is a big part of the story), carbon-free electricity generation, transportation adjustments, building construction, and energy efficiency. The relevant technologies vary across these different problems.

Carbon-free electricity, for example, is perfectly possible; it comes with a cost, but it's perfectly possible. Basically, we have a problem when we take carbon from underground and let it into the air. So you can do one of two things. One is to leave it underground—that means renewables or nuclear, bio fuels and so on. The other is to take it out by using fossil fuels, capture carbon from coal or gas or oil in the generation of electricity, and then send the carbon back underground. So carbon-free electricity generation is possible. It's also possible to imagine stopping deforestation; you can do it with the right kinds of incentives and institutions and management. Transport is more difficult. But if you've got carbon-free electricity, you could have your cars, at least in towns, just plugged in overnight, and you could use electricity.

So what is possible and how close that technology is varies depending upon where you look. And it's going to be very important to keep an open mind about those technologies. So picking technological winners in this area is something that one should do with care.

Incentives. We have to be aware of these technological issues in order to think about the right kinds of incentives to put in place. There is a challenge in asking oneself how much of a role government or groups of governments should play in developing technologies. Technologies are ideas; they're public goods. The global atmosphere is a public good, and the technologies to reduce emissions are also public good. So there's a challenge there in determining how far the public sector should play its role. But I think it's fairly clear that most of the action—choosing how to save energy, choosing how to reduce carbon—will be made by the private sector. The big question is how does a government set the right kind of incentives for the private sector.

Now, the private sector is actually quite specific on this point. Its slogan is that the incentive structure should be loud, long, and legal. But "loud, long, and legal" is actually the vulgar phrase for "clear, long, and credible." If you're thinking about investments in the kinds of infrastructure and durables that we're talking about, the incentive structure needs to be clear, long-term, and credible. And putting those kinds of incentive structures together is actually quite difficult. You have to try to bind yourself going forward in a way that governments find it quite difficult to do—a problem the economists have studied right across the board in other areas, including monetary policy, competition, and so on. We have to try to put together those kinds of structures.

Growth. President Bush is concerned with the effect of all this on growth and the way of life in the United States. He's right to be concerned, as are the leaders and people who represent other nations. The challenge for analysts is to try to say systematically what the consequences of different kinds of arrangements and incentives might be for economic growth.

The Indians and Chinese will very understandably put that on the table right at the beginning. Their leaders might be expected to say, "I take it you're not telling us to grow slower and leave our people in poverty for longer?" And you can understand where they're coming from. And some people might add, "And further to that, it's all your fault anyway."

To address these concerns, you've got to be able to understand that if, for example, you want to use carbon capture at the coal power stations that are going to be so important in the generation of electricity in India and China, you have to understand what it's going to cost. It will cost a bit more. How much more? When? What kind of technologies are available? Are they likely to develop and get much more sophisticated and cheaper? And so on. You've got to be able to try at least to give some guidance on those questions: countries need to know if the consequences of some new technology will be destructive for economic growth. And in the case of India and China and the other developing countries, you've got to face up to the question of who pays. I think there is a growing understanding that the consumers in rich countries should have something to pay through the price of electricity for reducing carbon emissions elsewhere, so that those countries can grow without ruining the global climate.

Mechanisms. We also have to think about what kind of mechanisms we're going to bring into those international negotiations. If they're treaties, are they monitored and enforced? If they're market mechanisms, what kind of institutional structures do we need to support them? Market-trading mechanisms for carbon use pieces of paper that say that I have produced less carbon than I would otherwise have produced. In many parts of the world, some might claim that if I want a piece of paper that says I have produced less carbon than I would otherwise have produced, I can easily get one if I pay for it. So you need institutional arrangements to verify the credibility of these kinds of statements and the paper they are printed on.

Verification is complicated. When I was in India just about six weeks ago, there was a guy with a dietary supplement for cows to reduce their flatulence, thus reducing atmospheric methane. I thought that was actually a rather interesting idea. But how detailed do you get in checking his results? If a town decides that it's going to insist on electric cars beginning in 2020, how do you build that kind of action and make it count? You've got to have institutional structures that are going to pick up all these kinds of things. If a country uses a significant tax on carbon emissions, if it does it that way, how are you going to bring that to count as a contribution to tackling the problem? This isn't impossible. None of this is impossible, but all of it requires care and thoughtful attention.

It is very important, then, to think through the institutional and incentive structures. You need to give people information, but you also have to tell good stories and come up with good examples and develop actions and practices that are going to give you support for all these measures. And the institutional challenge is not small. We are already on the way; but we need to move these efforts to a higher plane.

Economics has a great deal to say about all these issues: economists, who think about incentives and about institutions to support those incentives, contribute a great deal more to the world than people who don't know about the interactions between incentives and institutions. But we also need to pay attention to a set of issues that gets much less attention from economists: issues of persuasion, education, and changing preferences. People smoke less in public places, not simply because somebody's told them it's bad for them, or because the price of cigarettes is high; it's not simply information or incentives. It's also because they've learned what it means for other people and then go a step further to think through what responsible behavior means. The same is true for the climate: children who are educated now have learned much more about climate change at school than some of the older among you ever did, and that affects their view of responsible behavior.

John Stuart Mill talked a lot about the role of public discussion in a democracy. Like earlier political philosophers, Mill understood the important role of public discussion in forming our attitudes and preferences. So incentives—and institutions to support the incentives—will be fundamental, as will information and analysis. But we also need the process of public discussion: of exchanging ideas, changing preferences, constructing new norms and ideas of personal and collective responsibility, and building mutual understanding across nations and across generations. ♦

The only practical approach is to pursue technologies that burn coal more clearly

David G. Victor and Danny Cullenward

Almost every facet of modern life—from driving to the grocery store to turning on a light—relies on inexpensive and abundant fossil fuels. When burned for power, these fuels yield emissions of carbon dioxide that accumulate in the atmosphere. They are the leading cause of global warming.

Assuring ample energy services for a growing world economy while protecting the climate will not be simple. The most critical task will be curtailing emissions from coal; it is the most abundant fossil fuel and stands above the others in its carbon effluent. Strong lobbies protect coal in every country where it is used in abundance, and they will block any strategy for protecting the climate that threatens the industry. The only practical approach is to pursue technologies that burn coal much more cleanly.

Such new technologies exist on the drawing board, but governments and regulators are failing to bring designs into practice with deliberate speed. Instead, most of the policy effort to tackle global warming has focused on creating global institutions, such as the Kyoto Protocol, to entice change. Although noble, these global efforts usually fall hostage to the interests of critical countries. After negotiating the Kyoto treaty, for example, the United States refused to sign when it found that it could not easily comply with the provisions. Australia did the same, and Canada is also poised to withdraw. Nor have treaties like Kyoto crafted a viable framework for engaging developing countries; these countries' share of world emissions is rising quickly, yet they are wary of policies that might crimp economic growth.

Breaking the deadlocks that have appeared in the Kyoto process requires, first and foremost, a serious plan by the United States to control its emissions. The United States has a strong historical responsibility for the greenhouse-gas pollution that has accumulated in the atmosphere, but little has been done at the federal level. (A few states are implementing some policies, and they, along with rising political pressure, might help to catalyze a more aggressive federal approach.) It will be difficult, however, for the United States (and other industrial countries) to sustain much effort in cutting emissions unless its economic competitors in China and the other developing countries make some effort as well. Without a strong policy framework to contain emissions throughout the world, levels of greenhouse-gas pollution will reflect only the vagaries in world energy markets. We need a proper strategy for moving away from harmful emissions.

A few years ago, many analysts thought that market forces were already shifting away from coal. They predicted the growth of natural gas, a fuel prized for its cleanliness and flexibility. That vision was good news for the climate because electricity made from natural gas leads to half of the carbon-dioxide emissions of electricity from coal. But natural-gas prices, which tend to track oil prices, have skyrocketed over the past few years, and, unsurprisingly, the vision for the growth of natural has dimmed. Natural-gas plants, which accounted for more than 90 percent of new plants built in the 1990s, are harder to justify in the boardroom. Most analysts now see a surge in the use of coal. One hundred new coal-fired plants are in the planning stages in the United States. Absent an unlikely plunge in gas prices, coal is here to stay.

Despite the challenges of handling coal responsibly, the potential of research and deployment of advanced technologies to help the United States and the major developing countries find common interest on the climate problem is great. In advanced industrialized countries, the vast majority of coal is burned for electricity in large plants managed by professionals—exactly the setting where such technology is usually best applied. In the United States, for example, coal accounts for more than four fifths of all greenhouse-gas emissions from the electricity sector.

Most of the innovative effort in coal is focused on making plants more efficient. Raising the temperature and pressure of steam to a "supercritical" point can yield improvements in efficiency that, all told, can reduce emissions about 20 to 25 percent. Boosting temperature and pressure still again, to "ultra-supercritical" levels, can deliver another slug of efficiency and lower emissions still further. Encouraging investments in this technology is not difficult: most countries and firms are already searching for gains in efficiency that can cut the cost of fuel; a sizeable fraction of new Chinese plants are supercritical; India is a few steps behind, in part because coal is generally cheaper in that country, but even there the first supercritical unit is expected soon. Across the advanced industrialized world, supercritical is the norm, at least for new plants. A few companies are taking further steps, investing in ultra-supercritical units. Two such plants are going up outside Shanghai, using mainly German technology, evidence that the concept of "technology transfer" is becoming meaningless in the parts of the world economy that are tightly integrated. Markets are spreading the best technologies worldwide where their application makes economic sense. In other countries, technologies to gasify coal—which also promise high efficiency—are also being tested.

But power-plant efficiency alone won't account for the necessary deep cuts in emissions. Already the growth in demand for electricity is outstripping the improvements in power plants such that the need for more plants and fuel is rising ever higher, as are emissions. This is spectacularly true in fast-growing China.

A radical redesign of coal plants will be needed if governments want to limit emissions of carbon dioxide. Here, the future is wide open. One track envisions gasifying the coal and collecting the concentrated wastes. Another would use more familiar technologies and separate carbon dioxide from other gases. All approaches require injecting the pollution underground where it is safe from the atmosphere. This is already done at scale in oil and gas production, where injection is used to pressurize fields and boost output. The consequences of injecting the massive quantities of pollution from power plants, however, are another matter. Regulatory systems are not in place or tested, and public acceptance is unknown.

While these technologies can work, they won't be used widely before they progress on two fronts. First, they must become commercially viable. Despite the huge potential of adopting them, it is striking how little money is being spent on advanced coal technologies. The U.S. government has created some financial incentives to build advanced coal plants, but much of that investment is slated for plants that are not actually designed to sequester CO$_2$. In fact, the uncertainty of American policy gives investors in power plants an incentive to build conventional high-carbon technology, because it is more familiar to regulators and bankers. Worse yet, increased emissions today might actually improve a negotiating position in the future when targets for controlling emissions are ratcheted down from whatever is business as usual. Some private firms, such as BP and Xcel, are putting their own money into carbon-free power—but the totality of the private effort is small compared with the size of the problem. There are good mechanisms in place for encouraging public research and private investment in such technologies; the real shortcoming is in the paucity of the effort.

The second problem is that countries such as China, India, and other key developing nations won't spend the extra money to install carbon-free coal. Yet these countries' share of global coal consumption has soared almost 35 percent over the past ten years.

The inescapable conclusion is that the advanced industrialized countries must create a much larger program to test and apply advanced coal technologies. Electricity from plants with sequestration might eventually cost half more than from plants without the technology. That's not free, but it is affordable and is less than the changes in electric rates that many Americans already experience and accept.

State and federal regulators need to create direct incentives—such as a pool of subsidies—to pay the extra cost until the technology is proven and competitive with conventional alternatives. That subsidy, along with strict limits on emissions, will set a path for cutting the carbon from U.S. electricity without eliminating a future for coal. They must also extend the same incentives to the major developing countries, which have no interest in paying higher rates for electricity because their priorities do not rest on controlling CO$_2$. Yet these countries' involvement now is essential. Averting emissions has a global benefit regardless of where the emissions are controlled. And developing countries are especially unlikely to shoulder more of the burden themselves, in the more distant future, unless they are first familiar with the technologies.

Solving the climate problem will be one of the hardest problems for societies to address—it entails complicated and uncertain choices with real costs today, and benefits in the distant future. Yet the stakes are high and the consequences of indecision severe. Serious action must contend with existing political constituencies and aim at existing resources that are most abundant. The technologies needed to make coal viable will not appear automatically. An active policy effort—pursued worldwide and initially financed by the industrialized world—is essential. ◆

The Kyoto Protocol is an important catalyst, and carbon finance is its most powerful tool

Kirsten Oleson
and Chandra Shekhar Sinha

The earth's climate is the ultimate example of a global commons—a shared resource vital to survival for all the earth's inhabitants. Human actions that degrade it therefore present a set of notoriously difficult environmental problems.

Because the problems are urgent, reducing human greenhouse-gas emissions will require creativity and widespread action. We will need to change the way we do business: how we generate energy, propel our vehicles, and clean up our countless other greenhouse-gas-intensive activities.

But climate change also presents us with an unusual opportunity: since all that ultimately matters is the concentration of greenhouse gases in the whole atmosphere, it doesn't matter where on the globe those emissions occur. So reductions in emissions anywhere are good for people everywhere. Enter the possibility of carbon finance, a key element of the Kyoto Protocol.

The Kyoto Protocol is an important stimulant of change, and carbon finance is its most powerful tool. The Kyoto Protocol sets clear limits on the amount of greenhouse gas a country can emit. However, instead of simply forcing nations to meet inflexible emission targets, carbon finance establishes the necessary market structures to trade the right to emit a unit of greenhouse gas as a commodity: countries can exceed their cap by purchasing permits from other countries, under rules described below.

This "cap-and-trade" system encourages innovative nations to conserve more than is strictly prescribed, since every unit conserved now has value for nations that are slower to adapt. Experts expect that almost half of the emissions reductions mandated under the Kyoto Protocol will be achieved through trading. Already, carbon trading is a multi-billion-dollar business. With the Kyoto Protocol having come into force in February 2005 and the European Commission having put in place an EU-wide trading scheme in January 2005, the market for emission reductions has rapidly expanded, with the sale of emissions reductions from developing countries reaching over $22 billion in the first nine months of 2006.

How far we as a global community want to limit emissions is determined by the cap, but our ability to meet those limits will in large part be determined by the ability to trade under the cap. In the abstract, the core ideas behind carbon finance are as simple as supply and demand, but the mechanistic reality of these increasingly important trading schemes hinges on a few particular details.

On February 16, 2005, the Kyoto Protocol came into force: its purpose is to reduce the amount of greenhouse gas emitted in the course of human economic activity. Developed nations and economies in transition, referred to as "Annex 1" nations, are required to adhere to an annual limit on the total amount of greenhouse-gas emissions. These nations must reduce their emissions to an average of five percent below their 1990 levels by 2012. Developing nations that are signatories to the Kyoto Protocol (Non–Annex 1) do not have a cap, but they must produce an annual emissions inventory.

Annex 1 countries may attain their emissions reductions through three means. First, they may make direct reductions in emissions within their borders. Second, under "Joint Implementation," they may purchase surplus reductions from another Annex 1 nation that reduced its emissions below its set cap. The surplus reductions are then available as tradable emission credits on a market exchange. Finally, under the "Clean Development Mechanism" (CDM), they may purchase reduced emissions from a Non–Annex 1 nation.

The CDM enables us to take advantage of opportunities for low-cost abatement in developing nations (when compared to the cost in richer countries) and gains from trade on both sides. Non–Annex 1 nations, though they are not yet subject to caps on their own emissions, can agree to sell any emissions reductions to an Annex 1 country. These reductions are achieved through substituting high-carbon-emission projects (the baseline) with more environmentally friendly projects. The crucial stipulation in the CDM is that the greener projects would not have been possible without the purchase of the certified emissions credits (proof must be supplied). In other words, if a hydroelectric power plant was already planned before applying for CDM involvement, no emissions reductions would be granted from not building a hypothetical coal power plant. A third-party auditor verifies the emissions reductions. The non–Annex 1 nation then notes its reduction in its annual, audited emissions inventory and the Annex 1 nation augments its Kyoto emissions allotment by the amount of Certified Emission Reductions it purchased.

For these complex trading schemes to work efficiently, the market requires experienced facilitators to broker the trades and rigorously analyze potential emission-reduction strategies. One pioneering international broker is the Carbon Finance Unit at the World Bank. As an organization whose mission is poverty alleviation and sustainable development, the World Bank is committed as a leader in combating climate change. Climate change has the potential to devastate the poorest nations and undermine economic-development gains. Carbon-finance operations in the World Bank have grown from $180 million in the original Prototype Carbon Fund (fully capitalized in 2000) to activities that now involve capital of over $1.9 billion. Nine carbon funds and facilities created by 13 governments and 73 private companies are involved.

World Bank staff identify projects based on their emissions-reductions potential. For example, if a coal-fired power plant is on the books to be built next year, World Bank staff would flag it as a possible project. If the energy could be generated through wind farms instead, less carbon would go into the atmosphere. But a wind farm will undoubtedly be more expensive, and the technology might be unproved in that nation. To alter the business-as-usual baseline, the World Bank brings in financing and technical support, originating from buyers seeking to purchase reduction credits.

Annex 1 nations and companies who expect to exceed their carbon allotments contact the Carbon Finance Unit. Brokered by this unit, the buyer signs an emissions-reduction purchase agreement with the entity that agreed to implement the more environmentally friendly technology. Sometimes this is a nation, but often it is a private partner. This agreement stipulates the conditions: how many tons of carbon emissions are expected to be avoided, how much the buyer will pay, what the monitoring arrangements are, and so forth. In this way, capital from Annex 1 parties is invested in clean-energy technology, sustainable agriculture, and forestry in return for income in the developing nation from sales of greenhouse-gas emissions reductions.

Importantly, by limiting its financial commitment to a quarter of the purchase agreement, the World Bank leverages financing from private investors and banks who otherwise might shy away from carbon-finance projects due to the risk. The primary focus of the World Bank's work in carbon finance in the period between 1997 and 2005 has been to create demand by building confidence in the market. In this period, carbon finance in the World Bank expanded from a prototype engagement in an emerging trade of emission reductions to an increasingly mainstream World Bank activity that directly supports the sustainable-development goals.

The World Bank's carbon funds strive for technological and regional diversity; its project pipeline includes 190 projects with an estimated carbon-asset value of more than 2.2 billion tons carbon equivalent as of August 31, 2006. Fifty-seven projects have active, signed emission-reductions purchase agreements totaling $1.2 billion. The technological diversity includes a major emission-reduction contract with China for HFC-23 destruction, landfill gas recovery in Mexico, energy efficiency, renewable energy development (such as wind, hydro, geothermal, sugar cane and other biomass, and biogas generation), and reforestation. In terms of geographic distribution of the portfolio, East Asia, particularly China, accounts for about three fourths of the total value of the carbon finance, but numerous projects are scattered around Latin America and the Caribbean region, Eastern Europe and Central Asia, as well as Africa.

Both inside and outside the World Bank there is recognition that carbon finance can be a powerful new tool for financing sustainable development and an important asset to help reduce greenhouse-gas emissions. Successful projects range from the expected renewable-energy development such as wind farms to less obvious capture of methane emissions from landfills or energy-efficiency schemes in water-supply networks. Carbon financing is attainable for many levels of projects—from individual energy generators interested in new technology to municipalities trying to improve solid waste management to nations implementing energy-efficiency policies. The possibilities are promising and expanding. Already, developing nations are successfully participating in the emerging carbon market, achieving both developmental and environmental goals. ◆

For China, the shift to climate-friendly energy depends on international collaboration

Jeffrey Logan, Joanna Lewis, and Michael B. Cummings

According to the latest International Energy Agency forecast, China may become the world's largest emitter of greenhouse gases as early as 2009. While it will be many decades before China surpasses the United States in cumulative emissions, annual emissions from China are clearly rising rapidly, with potentially dangerous global implications.

Scientists in China have declared the urgency of the climate-change problem, and the highest levels of government now acknowledge that it is a serious issue. Zhang Guobao, the vice-chairman of the National Development and Reform Commission (which oversees economic and energy policy), recently remarked, "Because we're a coal-dominant country, we have to take responsibility for lowering greenhouse emissions." However, these sentiments have yet to be reflected in either domestic climate policy or international-level commitments. China has taken a wait-and-see approach in the international climate change negotiations, unwilling to discuss making a commitment to reduce emissions until the developed world demonstrates its own commitment to do so.

But while China waits and sees, it is also constructing hundreds of pulverized-coal-fired power plants that are likely to lock in a trajectory of high greenhouse-gas emissions for 50 years or more. Coal will likely remain the fuel of choice for many decades in China, despite the severe economic, social, and environmental dislocations it creates, making future efforts to stabilize atmospheric concentrations of carbon dioxide significantly more difficult.

In the absence of an explicit national-level climate-change mitigation strategy, China's energy strategy—driven by its economic-development goals—by default becomes its climate policy. The 2003 comprehensive National Energy Strategy Policy calls for maintaining growth in energy use at half the rate of GDP growth—essentially a doubling of energy use between 2000 and 2020 while GDP quadruples. Yet even to maintain this relatively impressive intensity of GDP and energy growth through 2020, the Chinese energy sector is poised to continue its breathtaking expansion.

Although the National Energy Strategy Policy calls for reducing the overall contribution of coal to the energy mix (down to less than 60 percent), overall coal capacity is slated to increase rapidly. Also planned are dramatic expansions of nuclear power, small- and large-scale hydropower, and increased renewable energy utilization (including large growth targets for wind-power and solar-energy technologies). Nuclear capacity is to expand more than four times by 2020, large-scale hydro is to more than double (requiring the building of a dam the size of the Three Gorges Project every two years), and non-hydro renewables are to grow by more than 100 times. However, targets and predictions related to Chinese economic and energy growth are notoriously uncertain, and the feasibility of these projections have been questioned, including the implications of expanding the use of nuclear power and large dams. Also uncertain is China's ability to reduce its reliance on coal, particularly since China's increases in coal capacity in the last two years were the largest ever. In the event that nuclear or renewable energy goals are not met, coal may end up filling the void—leading to an even greater increase in China's greenhouse-gas emissions than currently projected.

The decentralized nature of the institutions and actors of China's energy sector poses additional challenges to effective greenhouse-gas mitigation. Development of China's energy sector is carried out largely at the local and regional level, where central-government mandates are not always reflected in local decisions. Moreover, the central government has little control over the construction of new power plants: regional power shortages have spurred a wave of new plant construction, often completed without central-government approval.

All these factors combined call into question the Chinese central government's ability to move down a different, more climate-friendly path without meaningful international engagement and assistance. It is therefore critically important for the international community to increase bilateral and multilateral collaboration with China to address shared energy and environmental concerns before it commits to half a century of carbon-intensive infrastructure. Five areas are particularly well-suited for further engagement and offer strong opportunities to expand global benefits:

Energy efficiency. Efforts to improve energy efficiency are the most effective and affordable measures China can take to meet development goals while reducing greenhouse-gas emissions. Continuing its tradition of relatively impressive energy-efficiency policies, China recently approved new fuel-economy standards for its rapidly growing passenger-vehicle fleet that are more stringent than those in Australia, Canada, and the United States. Moreover, the government has set an extraordinarily ambitious target of cutting energy intensity by one fifth by 2010.

International partners can help China to build on these important efforts, in particular by promoting the business, financial, and regulatory skills needed for energy-efficiency projects and standards, and to reform policies that impede market-driven projects. Developing incentives for accelerated technology transfer, particularly for the private sector, are also crucial. Many of these efforts are already underway, and Chinese government officials are open to proposals that can help them meet their targets. Foreign partners need to be open and flexible so that their efforts can have maximum impact.

Energy security with climate benefits. China's booming economy has required a huge expansion in imported raw material, especially oil, since 2001. Chinese national oil companies have begun to purchase oil and gas assets around the globe as a way to increase energy security. Some nations view these actions with alarm, since there are potentially destabilizing military, political, and economic implications. From a climate perspective, China's growing interest in coal liquefaction is also alarming because making transportation fuels from coal through chemical transformation sends approximately twice as much CO_2 into the atmosphere as using standard crude oil.

Better integrating China into the processes of managing the global energy system would make it a more helpful partner in managing that system. Increased participation in the IEA, G-8 and other global bodies involved in high-level energy dialogues would provide opportunities for developing shared understandings on topics affecting global energy security. Such dialogues could lead to energy-security-enhancing initiatives with climate benefits, and could lead the way toward climate-focused dialogue between the major energy consumers of the world. But any such endeavours will need to be backed by meaningful actions. China and its international partners could also discuss deeper technical collaboration on vehicle technologies, alternative fuels, and associated policies. However, any partnerships first need to focus on a dramatically improved atmosphere of trust and sincerity.

Advanced coal technologies and carbon sequestration. For the past few years, China has built, on average, one new large power plant each week. Provided that it can overcome technical, financial, regulatory, and social barriers, carbon capture and storage (CCS) may become a critical option for reducing greenhouse-gas emissions from fossil-burning plants throughout the world, but especially in coal-intensive countries such as China. While China is unlikely to invest in CCS systems for coal plants in the next decade or two due to the cost, it is looking to collaborate on advanced coal technology research including coal gasification. China is also keenly interested in enhanced oil-recovery methodologies that could use carbon dioxide in the process. CO_2-enhanced oil recovery can help anchor early investments in CCS infrastructure that might otherwise have to wait for a more comprehensive climate policy.

Once more, international partnerships can help. A new U.K.-led initiative, part of the China–EU partnership on climate change, aims to accelerate experience with CCS by building a demonstration plant in the next decade. And Huaneng, China's largest coal-based power-generation company, is one of 12 energy companies participating in the U.S. FutureGen "clean coal" project, attempting to become the world's first integrated sequestration and hydrogen production research power plant.

China is also collaborating with international partners on coal and CCS technologies through the Asia Pacific Partnership on Clean Development and Climate, known as the AP6. Officially launched in January 2006, the AP6 brings together China, the United States, Australia, India, Japan, and the Republic of Korea in an agreement based on clean energy technology cooperation. Some have criticized the AP6 as an attempt to further weaken the Kyoto Protocol, but limited funding raises doubts about whether there is enough glue to hold the membership together. The AP6 does bring together an important grouping of nations, and therefore has the potential to lay the groundwork for future action.

Finally, China is a member of the Carbon Sequestration Leadership Forum, an international initiative of 22 countries currently collaborating with the International Energy Agency to deliver recommendations to the G-8 in 2008 on how CCS can be enhanced in the near term. The Forum is opening its meetings to new participants but doesn't yet seem to offer much interest for developing countries such as China.

Safe and Secure Nuclear Power. China's leaders have called for a new growth era in nuclear power, motivated in part by a recognition of its over-reliance on coal. Despite almost certain difficulties in reaching its ambitious goals for nuclear power in the coming decades, China is still likely to significantly increase its nuclear fleet. The international community should engage China and other nuclear countries in developing and enforcing an enhanced regime of international waste and proliferation safeguards to ensure that growth is done responsibly. If successful, such an enhanced international regime could help to ensure an acceptable role for nuclear power to contribute to long-term global efforts to address climate change. Until this is addressed, in actions such as the recent agreement between the U.S. and India, proliferation concerns may outweigh potential climate benefits.

Research, development, and demonstration for renewables. Motivated by the economic and environmental benefits that these technology industries provide, China is committed to developing indigenous renewable-energy technology industries and has set aggressive targets. China's national renewable-energy law went into effect in January 2006, offering financial incentives for renewable energy development. Targets that have been announced in conjunction with the renewable-energy law and subsequent government documents include 16 percent of primary energy from renewables by 2020 (includes large hydropower—which would place the current share at about seven percent today), and 20 percent of electricity capacity by 2020, which includes 30 gigawatts of wind power, 20 gigawatts of biomass power, 300 gigawatts of hydropower capacity. Policies to promote many renewable-energy technologies in China also aim to encourage local technology-industry development; China is already producing commercial wind turbines that sell for approximately 30 percent less than similar European and North American technology, and 35 million homes in China get their hot water from solar collectors—more than the rest of the world combined. China also has a burgeoning solar photovoltaic industry.

Nevertheless, non-hydro renewable technologies will make up a relatively small fraction of the energy mix in China over the next few decades. Yet given the challenges facing the widespread deployment of CCS and nuclear power in the near term, the commercialization of renewables by the major energy-consuming countries of the world offers an important opportunity for international collaboration with China. The entry of Chinese manufacturers into these rapidly expanding global markets may drive cost reductions and increase the viability of renewable energy technology utilization worldwide. Assistance with several embryonic Chinese technologies could push these technologies into the marketplace. Combining China's growing manufacturing prowess with the innovation experience of other industrialized countries to enable widespread commercial deployment of solar photovoltaic and utility-scale wind turbines should be a high priority of the international community. Many existing international forums, such as the UNFCCC and the WTO, are being underutilized to discuss key issues surrounding renewable-energy technology transfer, including the role governments can play in facilitating the sharing and protection of intellectual-property rights.

Providing modern energy services for 1.3 billion people in a climate-friendly manner is a daunting challenge. Fortunately, the Chinese central government is demonstrating increasing awareness of the problems posed by climate change and interest in altering China's current energy-development trajectory. However, the central government's ability to significantly alter this trajectory without meaningful international engagement during the critical time period of the next ten or 20 years is questionable. In particular, U.S. leadership to address energy and climate issues at home and in international forums is essential to expand cooperation with China and other large developing countries. There are ample opportunities to address linked climate-protection, energy-security, and economic-development issues—more opportunities for collaboration available than political willpower currently supports. But change can come quickly, and those prepared to engage will benefit first. ◆

Adapted from "Understanding the Climate Challenge in China," in Climate Change Science and Policy, *edited by Schneider, Rosencranz, and Mastandrea, forthcoming. Original version includes citations.*

The Eden Archives

Whatever I said I was,
was blown youth, delirious smoke in the woods

where the boy had been.
Wet-dark, chameleon's dish, in the sheets

where the mouth had been,
the data into circuitry—her face her eyes "her spittle . . .

Life's own fount to me."
The data out: *let me be your new and improved.*

Where the words had been,
the seventeen-year-old atmosphere squeezed,

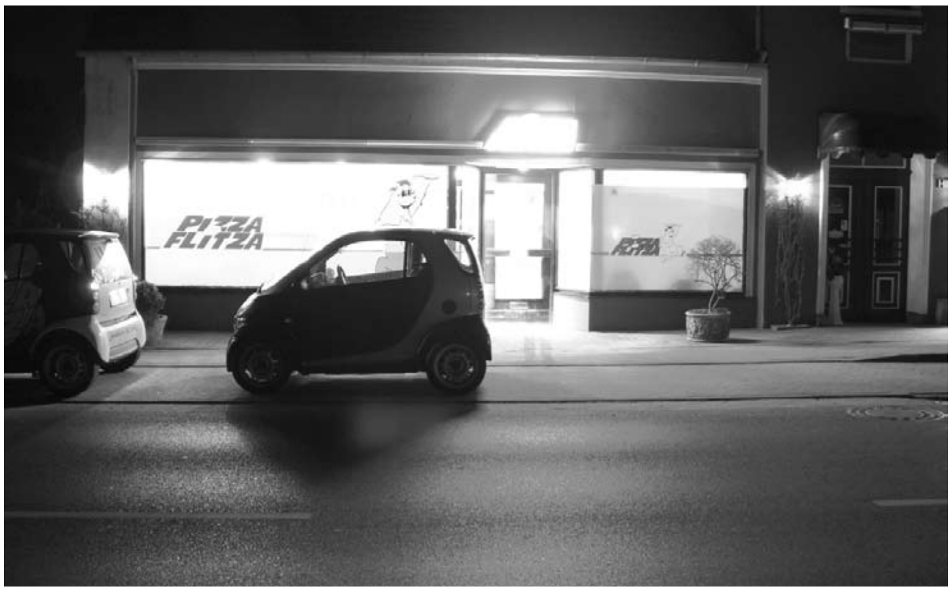
my mouth unhinged northwesterly,
the shine and steam of the carwash became me.

From the soap-scudded interior, I surfaced
and nothing was the matter, people scurried

with vacuums; my loneliness populated!
And it was good. It was *progress* (which I resented).

And I walked up and down upon my own skin.
And I never returned.

—John Isles



MARIUS KALLHARDT

Changing course will require major policy change, and the United States must lead the way

Judy Layzer and William Moomaw

Despite the complexity and unpredictability of the global climate system, there are factors that make some futures far more likely than others. In particular, we know that society's introduction of more heat-trapping gases into the atmosphere will almost certainly lead to a warmer world, higher sea levels, and more intense droughts and storms. Furthermore, because half of each ton of carbon dioxide we emit today will be in the atmosphere a century from now, and because the thermal momentum of the oceans and the melting of glaciers we have already set in motion will continue for 3,000 years even if we stop burning fossil fuels immediately, some damages are inevitable. We also know that concerted efforts to reduce emissions and enhance the ability of terrestrial ecosystems to absorb carbon dioxide can minimize the rise in global temperature, thereby dampening the most severe consequences of global warming. Given the high probability of extremely adverse outcomes and our ability to forestall them, a prudent person would conclude that we should act now. Why, then, is the United States moving so slowly—and how might we change course?

The main reason for our political inertia is that proponents of policies to address global warming have struggled to translate climate-change science into a politically compelling story, while their opponents have effectively shifted attention to the potential costs of addressing the problem. For many years the U.S. environmental community lacked the elements of a narrative that could capture the public imagination: the villains were ordinary Americans, and the most affected victims were small island nations; the relationship between heat-trapping gases and global temperature was complex—mediated by many variables and amplified or dampened by highly uncertain feedbacks; and the crisis, should there be one, appeared to be at least a century away. Opponents countered this already weak narrative with a persuasive alternative storyline. They emphasized the uncertainties in climate-change science, actively supporting a handful of contrarians. As important, they claimed that instituting policies to curb emissions of carbon dioxide and other greenhouse gases would cripple the American economy. For a decade, these arguments—which were widely disseminated thanks to enormous infusions of cash from fossil-fuel-based industries—succeeded in defusing public concern.

Over the last five years, however, scientists have provided a steady stream of research that strengthens the global-warming story and decisively discredits the contrarians. First, a more visible and increasingly certain international scientific consensus about humans' impact on the global climate has rendered absurd claims that scientists are divided. As the IPCC points out, in recent years the cause-effect relationship between human-caused carbon-dioxide emissions and rising global temperature has emerged unmistakably from the statistical noise. Scientists have corrected divergent satellite temperature measurements, quantified most climate-forcing factors, and tested and rebutted the most plausible alternative explanations for the observed temperature rise.

Second, scientists have sought to detect and forecast regional impacts of a changing climate and thereby highlight the extent to which Americans not only are the perpetrators but also will be the victims of global warming. They have generated scenarios that reveal the enormous local costs of regional climate changes; for example, the Northeast will experience severe flooding as the Atlantic Ocean rises; California will suffer severe disruptions in its water supplies as snow packs diminish; and throughout the West, droughts will become longer and more frequent, and wildfires will become more numerous and severe. As for the crisis, research indicates that it draws closer by the day: scientists are already documenting changes in the nesting and mating habits of species around the world and faster-than-expected melting of polar ice caps and glaciers from Greenland to Antarctica and tropical glaciers from the Andes to Kilimanjaro. Moreover, scientists are detecting unanticipated impacts of additional carbon dioxide, such as increases in the ocean's acidity and phytoplankton declines that promise to be disastrous for marine ecosystems.

Less publicized but as important is the likelihood that addressing global warming could be relatively painless. It is true that to maintain concentrations of atmospheric carbon dioxide low enough to keep the global temperature from rising three times the amount it already has (1.2 degrees Fahrenheit)—an increase many scientists believe will destabilize the climate in dangerous ways—we must reduce global emissions by 75 percent or more. But although that figure sounds overwhelming, we can achieve it if the United States and other industrial economies reduce their emissions by three percent per year between now and mid-century. Continuing at this rate until the end of the century will bring our emissions down by nearly 95 percent, and as a result atmospheric carbon-dioxide concentrations will begin to fall back to today's levels.

Technological solutions are necessary but insufficient to reduce emissions by three percent per year; we will need to make lifestyle changes as well. But most of those adjustments will be negligible—and many will yield multiple benefits. For the American who drives 1,000 miles each month—the national average—driving 30 miles less per month for a year constitutes a three-percent reduction for that year. Most drivers could save those miles by occasionally sharing a ride to work or taking public transit. Others could achieve equivalent savings by driving less aggressively. Even better, by replacing an SUV with a fuel-efficient vehicle, a driver can instantaneously cut her emissions in half—the equivalent of an annual three-percent savings for 23 years. Similarly, it is relatively simple to reduce emissions from most existing buildings by 30 percent simply by adding insulation and energy-efficient lighting; we can make even greater reductions by replacing old appliances and installing modern windows and furnaces or ground-source heat pumps.

These changes are unlikely to come about in response to market forces alone; fortunately, however, as decades of experience with environmental regulation demonstrates, putting in place a set of policies that establish consistent and predictable rules can spur both rapid technological innovation and behavior change. As a first step, we should dismantle the web of policies that overwhelmingly favors fossil-fuel production and use and actively discriminates against new technologies and practices that would reduce harmful emissions. We routinely subsidize fossil fuels by allowing mining companies to extract coal by blowing off the tops of mountains and dumping the waste into Appalachian rivers; streamlining permits to develop oil and gas on publicly owned territory in the Rocky Mountain West and offshore Alaska; and using military force to prop up oil-producing regimes around the world. Similarly, policies that protect large, obsolete coal-burning power plants in the United States obstruct efforts to make a transition to newer, more efficient power sources, including renewables and distributed, combined heat and power systems.

The second step is to institute federal, state, and local policies that reverse the disincentives created by the existing policy structure and force users to pay the costs of extracting, transporting, and burning fossil fuels. The most straightforward and effective policy changes would include a carbon tax; an increase in the corporate average fuel economy (CAFE) standards; and a large increase in funding for mass transit, both within cities and along heavy travel routes on the East and West coasts. A less obvious policy change would be to require those who introduce energy-consuming technologies to offset or save one and a half times the amount of new emissions generated. State and local governments can adopt growth-management policies that reflect the environmental costs of sprawling and inefficient development—such as upgrading building codes to ever-tightening Energy Star standards for renovations and new construction; creating incentives to increase urban densities and redevelop inner-city brownfields; downzoning rural areas; and putting areas of critical environmental concern, such as coastal and freshwater wetlands, off limits to development.

In deciding which technologies and behaviors to encourage, we will need to depart from our past practice of treating each remedy in isolation and instead think at a systems level. For example, widespread use of biofuels may reduce emissions from power plants and vehicles, but if their production entails clearing additional land or using more fertilizer, we could negate any benefits by eliminating carbon sinks and producing more heat-trapping nitrous oxide. Similarly, although some commentators have touted nuclear energy as a straightforward solution to global warming, no one has yet developed a credible plan for storing highly radioactive waste or dealing with the very real threats of natural disasters, technological failure, or the use of nuclear technology by terrorists or hostile states. In short, when choosing from the menu of available policy tools, we should give top priority to those that encourage reducing consumption and adopting technologies that minimize rather than shift environmental impacts.

Of course, devising effective policies is much easier than implementing them. Enacting major policy change entails political risk and is likely only if aspiring leaders perceive substantial public concern—and therefore the possibility of political support for their stands. Fortunately, although the public has been slow to react to the threat of global warming, public opinion—like the climate system—is subject to tipping points, and there is abundant evidence that the United States is nearing one. Actions taken at the state and local levels not only attest to widespread public concern but are also triggering positive economic and political feedbacks that strengthen demands for national policies. As the federal government responds and the United States demonstrates the benefits of environmentally friendly technologies and behaviors at home, we will gain the credibility to promote their adoption abroad. ♦