Global Change and Energy: A Path Forward

Left: This rendering of data from JPL's Atmospheric Infrared Sounder (AIRS) shows local carbon dioxide levels in July 2003 at an altitude of eight kilometers. Lower than average concentrations are shown in blue and higher than average concentrations are shown in red.

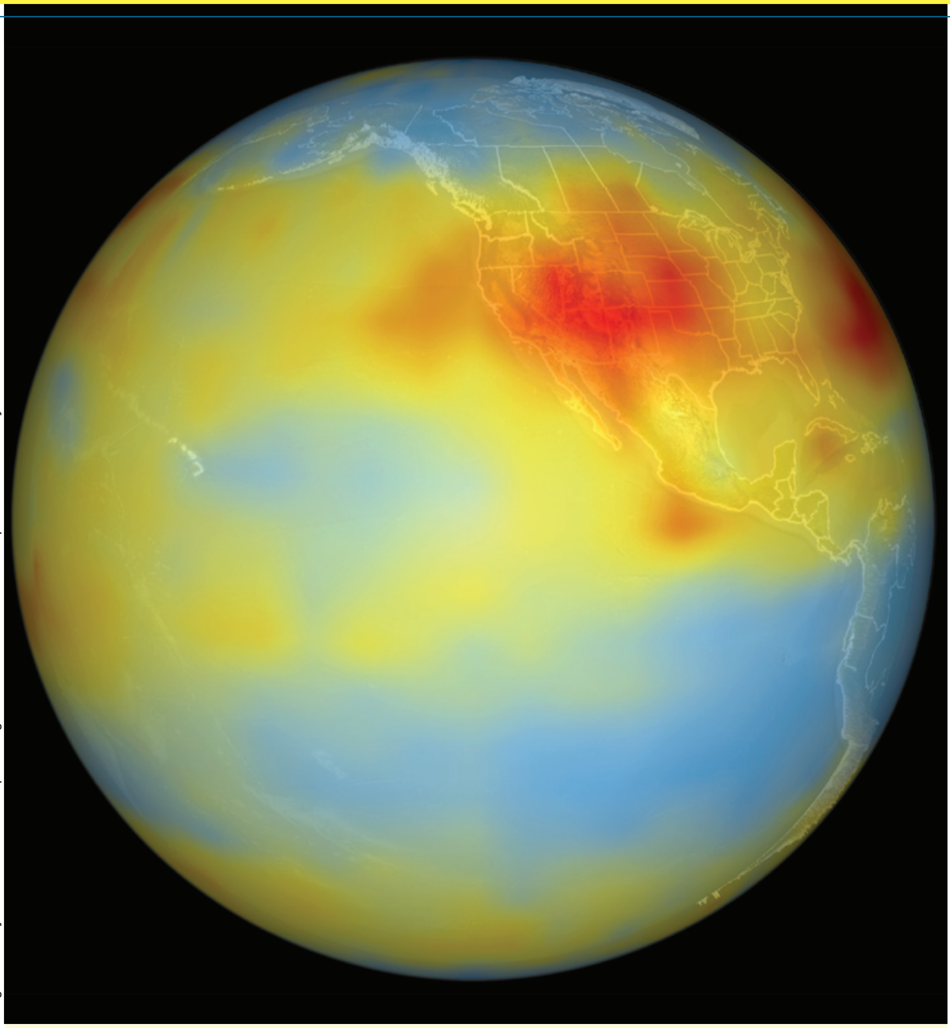


Image courtesy of NASA/Goddard Space Flight Center and NASA/Jet Propulsion Laboratory Scientific Visualization Studio

Can we keep the lights on in New York without inundating Bangladesh? JPL's chief technologist offers some thoughts.

The greenhouse effect is good for you. Without it, Earth's temperature would be like the moon's—they're the same distance from the sun. But it's a bit like aspirin—one aspirin is good, but 20 may kill you. Earth's atmosphere contains a few hundred parts per million of carbon dioxide, and just a whiff of methane—both powerful greenhouse gases. We know what their levels have been over the last 650,000 years or so, by analyzing ice cores from Antarctica and Greenland. These values have increased dramatically in the last couple hundred years, with the CO_2 increase traceable to fossil-fuel burning. The heat-trapping properties of these gases are well understood and their increasing concentration is altering the balance between the solar radiation coming in and the thermal radiation going out. The only way our planet can respond to this imbalance is by raising its temperature, so that it can radiate the excess heat more effectively.

The estimated radiative imbalance is somewhere between one-half and two watts per square meter. We can visualize a one-watt-per-square-meter imbalance by imagining dividing Earth's entire surface—land and sea—into squares 10 meters on edge, and lighting a 100-watt bulb inside each one, as Jim Hansen of the Goddard Institute for Space Studies has noted. The heat from those 100-watt bulbs is warming our planet.

But the effect is not immediate. Consider a large, well-insulated boiler. A relatively small flame may be all that's needed to keep the water hot. If we wrap another two-inch

By Paul E. Dimotakis

insulation blanket around the boiler, the rate of temperature rise will be the flame's heat output divided by the boiler's heat capacity. With a little flame and a lot of water, this rise will be slow but sure, until a new equilibrium is restored. For Earth, this lag is some 30 to 40 years—longer if we wait for the temperature to rise everywhere. Thus the present radiative imbalance will increase Earth's temperature further, even if we were to quit emitting CO_2 today.

The debate about the interrelationship between our current CO_2 emissions and our changing weather patterns and climate continues, but the geologic record provides examples of cause and effect. About 50 million years ago, India—moving at a speed of almost a foot per year!—was colliding with Asia, thrusting the Himalayas up and grinding over beds of limestone and other carbonate rocks. Carbon dioxide was released, and the resulting temperature rise was enough to melt the Antarctic ice—all of it. This influx of fresh water and the expansion of the warming ocean raised the sea level by some 75 meters above today's levels. Later, as CO_2 was slowly absorbed by the oceans and by vegetation, temperatures dropped. Antarctica froze over again about 30 million years ago and has been frozen since.

Carbon dioxide is a problem because it is virtually indestructible. It's the most oxidized form of carbon. It is no accident that Mars's atmosphere today is carbon dioxide—it's the only molecule that can survive the intense bombardment from the solar wind. Most of Venus's atmosphere is also carbon dioxide. On the other hand, methane, a more powerful greenhouse gas per molecule, is destroyed in about a decade by chemical reactions in our atmosphere.

The discussion about human-caused climate change has been difficult in this country. On the one side, we have the evangelists for the cause, and on the other, people who consider it to be the greatest hoax ever perpetrated. If the two extremes can be persuaded to be quiet, we may have the rational public discourse that the challenge merits. JPL, Caltech, and many other institutions have been contributing data and ideas to the discussion, some of which I will summarize here. I will also describe a path forward. At this point in the debate, one cannot announce that the sky is falling without offering a vision for how to get out from under it.

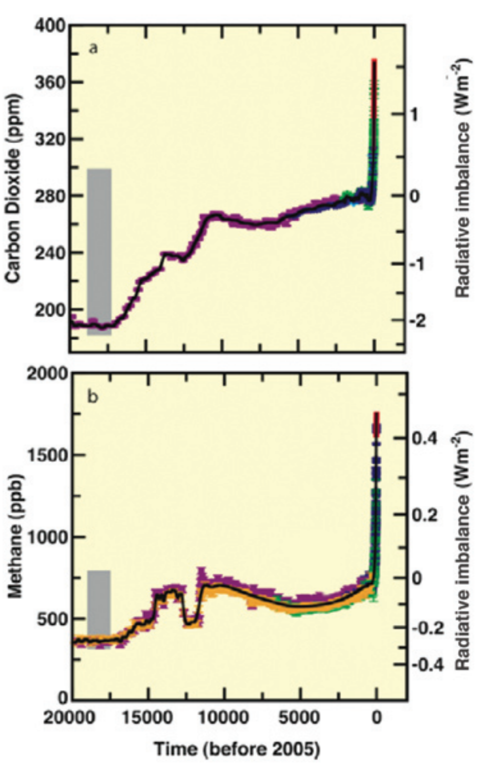
There are three guiding questions that can help our thinking as we look ahead.

QUESTION ONE: WHAT'S THE PROBLEM?

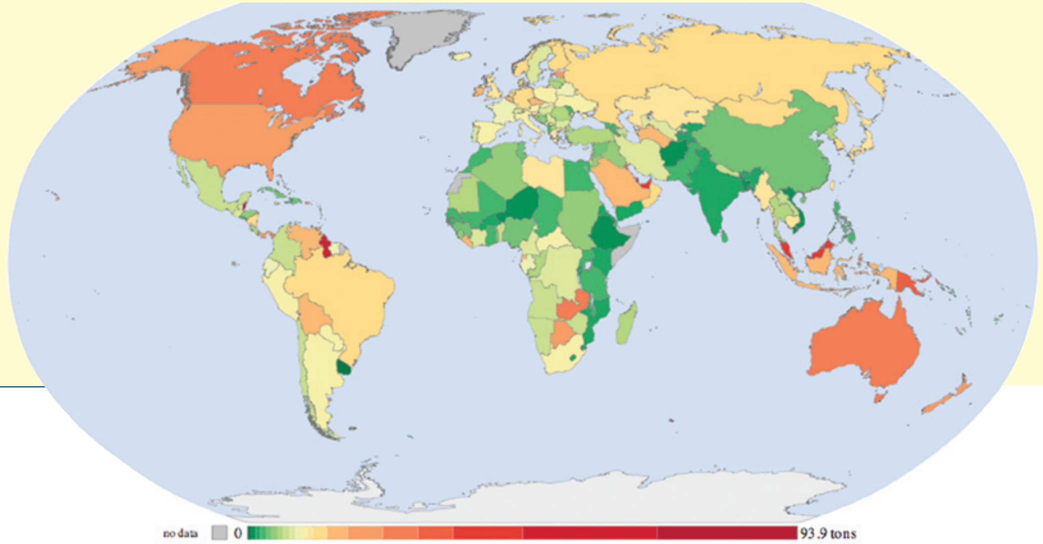
How much CO_2 can our planet's systems safely absorb? There are actually four parts to this question. First, at what rate is CO_2 absorbed by natural long-term repositories, of which there are only a few? Carbonate rocks are laid down in warm, shallow oceans. Rocks on land, particularly peridotites, can also absorb CO_2. Importantly, CO_2 also dissolves in seawater, particularly the cold water of the deep oceans. Second, to what rate must we reduce CO_2 emissions to stay below some acceptable threshold level? Third, what *is* an acceptable threshold level? And finally, what do we mean by *acceptable*?

The first three are global questions, but the fourth is local. Consider the plight of Kiribati, a Pacific archipelago whose highest elevation is only six feet above sea level. They are not going to make it, so Kiribati's president, Anote Tong, asked the world community to help relocate the entire population—about 100,000 people. Next to go may be the Maldives, whose 300,000 or so residents are also looking for a new home, then perhaps the rather more populous Bangladesh.

One could argue for a cost-benefit analysis. If the price of climate change, such as from sea-level rise, for example, is the loss of less than 1 percent of the world's Gross Domestic Product, perhaps that's acceptable if avoiding it is more costly. However, the costs are not spread uniformly—it may be an all-or-nothing proposition for the losers. Bangladesh's GDP is much less than



The left-hand scale shows the atmospheric concentrations of carbon dioxide (top) and methane (bottom) frozen into the ice and snow of Antarctica and Greenland over the last 20,000 years. The gray bars span the range of values recorded over the last 650,000 years. The right-hand scale shows the estimated radiative imbalance, or atmospheric heating, attributable to that gas at that concentration. Adapted from figure TS.2 of *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.*



Per capita carbon-dioxide emissions in the year 2000, based on the World Resource Institute's Climate Analysis Indicators Tool 4.0 database. This includes estimates of the effects of deforestation and agriculture as well as the burning of fossil fuels. Map created by Vinnie Burgoo, Wikimedia. Image from http://commons.wikimedia.org/wiki/Image:GHG_per_capita_2000.svg

1 percent of the world's GDP. Is it okay to tell the Bangladeshis, "Sorry, you're out?" I doubt very much they'd see it that way. Incidentally, California may not be far behind Bangladesh—but not due to sea-level rise, as we'll see. California is more than 3 percent of the world's GDP and a little nearer and dearer to our hearts.

Atmospheric CO_2 is accumulating at a rate of two parts per million per year, a rate that is itself increasing. However, there's considerable uncertainty about what the acceptable rate is—from 40 percent of our current emission rate, down to 0.1 percent. (The first number comes from noting that the atmospheric accumulation can be accounted for by assuming that about 57 percent of what's emitted hangs around in the air. The second number reflects the fact that the mixing time between the surface and deep oceans is some 1,000 to 2,000 years.) Even though policy makers are used to dealing with uncertainty, this one is too large to plan around, especially if we also say we won't see the effect for 30 to 40 years. We need to try and quantify the uncertainty in our forecasts, which requires modeling Earth's climate a lot better than we do now. When we give policy makers a projection, we need to also tell them what its uncertainty is and why we think so, a little like hurricane-track projections. As scientists, we have not done all we should to help the people charged with making decisions.

QUESTION TWO: HOW CAN WE FIX THE PROBLEM?

Continuing to burn fossil fuels unabated will eventually exceed any conceivable acceptable levels. Some scientists believe the present CO_2 level of 380–385 parts per million is already too high. We should also understand that it doesn't make any difference who emits the CO_2—China, Russia, the U.S., India, Europe—so international agreements will likely be required. How can we implement, monitor, and enforce them? Fortunately, we have examples to guide us.

In 1987, the Montreal Protocol banned ozone-depleting chemicals. The chemical industry was initially dead set against it—selling chlorofluorocarbons was good for business. Things were going nowhere until a bright engineer realized that an agreement would make every refrigerant then in use around the world illegal—plus the present patents were expiring—and who would produce their replacements? Well, the selfsame chemical industry, of course!

A closer analog may be the Comprehensive Nuclear Test Ban of 1996, designed to slow the proliferation of atomic weapons. The signatories rely on a remarkable system of networked land, sea, air, and space sensors, and are convinced that no nuclear explosion can be set off undetected. That's one key. The network is open—the sensors' calibrations and the data produced are accessible to all. If the network indicates a breach, there are agreed-upon procedures for on-site inspections. That's the other key—in case of doubt, you are entitled to see for yourself with your own Geiger counters, or whatnot. Trust, but verify.

So we have three ingredients. The agreement must be to the advantage of the signatories, there must be a way to monitor compliance, and there must be a mechanism for dealing with possible acts of noncompliance. Trillions of dollars would be at stake over an emissions treaty, and—I know this will come as a complete surprise—people cheat for less.

Creating the monitoring system will be a challenge, but it can probably be done. It's the political dimensions—making it advantageous to all—that's the hard part. China recently surpassed the United States in total CO_2 emissions. But China has four times our population. So negotiation is tricky. We cannot sternly say, "No Chinese person can emit more than a quarter of what every American does." The premier of India recently pledged *never* to exceed the per capita emissions of the advanced world. That's a safe bet, as India now emits a 30th of the United States, per person. Some developing nations argue that most accumulated CO_2 emissions are not their fault and that our emissions have led to our prosperity. Therefore, we should let them emit until they reach our per-person emissions, or even our *accumulated* per-person amounts, and *then* we can sit down to agree what to do.

QUESTION THREE: WHAT DO WE NEED FOR A SOLUTION?

Agreements are not solutions. As George Olah of USC said at a JPL seminar, imagine a treaty to ban cancer. Who's against banning cancer? Every nation will sign. Of course, nothing would happen because we don't know how to do it, at least not yet.

The global energy problem is almost unfathomably large, as Nate Lewis [BS, MS '77, the Argyros Professor and professor of chemistry] explained in *E&S* 2007, Number 2. Worldwide fossil-fuel energy consumption is 13 terawatts, or 13 trillion watts, on average, and increasing. Each of the two reactors at the San Onofre nuclear power plant near San Diego produces about a gigawatt, or one billion watts. Thirteen terawatts is 13,000 San Onofre reactors.

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Replacing just the world's electricity supply, which is four to five terawatts, in 30 years means bringing something like one such reactor on line every three days. Going electric for transportation, heating, and other energy uses—the whole shebang—requires one such reactor *per day* for 30 years. There isn't that much capital and there isn't that much uranium in the world (with the present nuclear-reactor technology), and, those two small issues aside, we don't know how to do that.

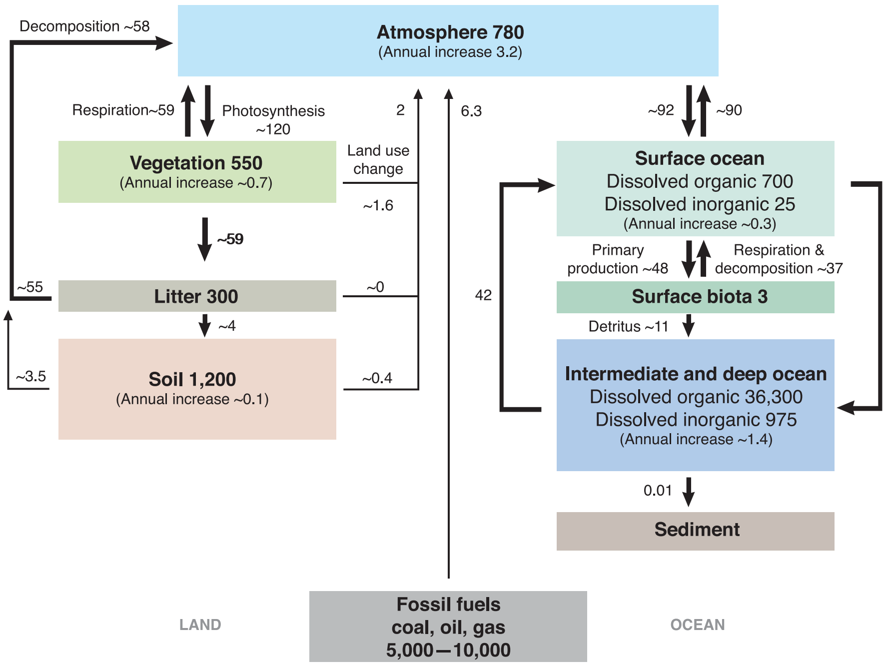
And there's one other difficulty. Time is of the essence. We have a ticking bomb and don't know how much time is on the dial—how long we have before we cross climatic "tipping points" of no return. Yet, transforming our energy infrastructure may have to wait for international agreements. People may not invest at the necessary scale in anticipation that someday, when the world hammers out a global pricing and regulatory system for the new energy economy, they'll have guessed right. Also, a mere 150 people got together to write the Montreal Protocol. There were 13,000 at the United Nations Climate Change Conference in Bali in December 2007. How does one get that many people to agree on *anything*?

TURNING THE BATTLESHIP AROUND

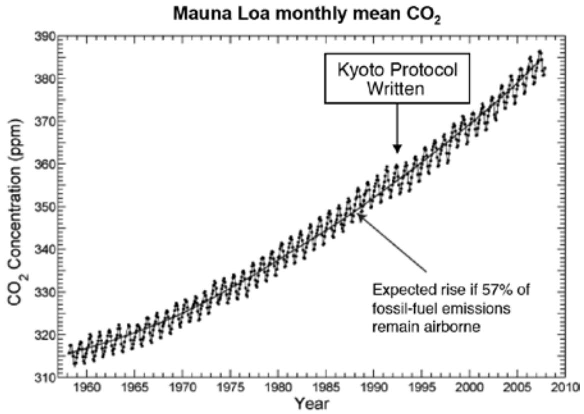
We don't know what a safe CO_2 level is and we can't turn a battleship around on a dime. If the world went cold turkey tomorrow, which will not happen, we'd still see about another 0.6°C, perhaps more, average global temperature rise—the same as the total increase over the last century—because of the time lag. This is why determining safe levels as soon as possible is important, so that we can plan, even as we do the best we can now to gain time. If we've already overshot, our strategy will be very different than if there's still headroom. We can envision ways of slowly replacing the existing CO_2-emitting infrastructure, but nobody has any plausible methods for getting large amounts of CO_2 out of the atmosphere—putting the proverbial genie back in the bottle.

Earth's carbon cycle is a delicate balance, as you can see below left. The oceans emit about 90 gigatons of carbon to the atmosphere per year, with CO_2 coming out of solution in the tropical Pacific, for example, where deep water rises and becomes warm. (Warm, low-pressure water can't hold as much dissolved CO_2 as cold, high-pressure water; another thing to think about as ocean temperatures increase.) At the same time, 92 gigatons per year are absorbed, mostly in the North Atlantic and around Antarctica, giving an estimated net absorption by the oceans of about two gigatons per year. Note that this is the difference of two large numbers, and a relatively small change or uncertainty in either of them will significantly alter that difference. On land, the balance is between photosynthesis that absorbs 120 and decomposition and respiration that put out about 117 gigatons per year. To make matters worse, "land-use change" is an amicable term for "deforestation." Deforestation adds another two gigatons per year at present, for a net absorption on land of about one gigaton per year—again, big numbers whose difference is vulnerable to small changes.

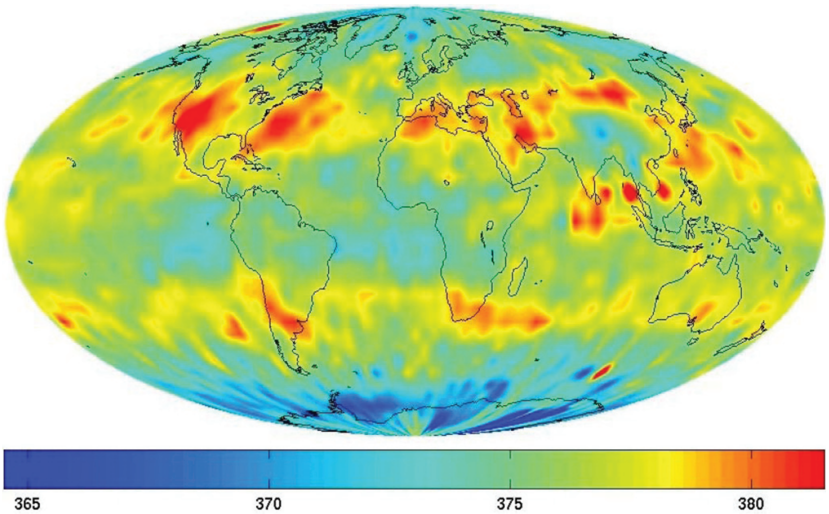
Burning fossil fuels adds 6.3 gigatons per year. There are 5,000 to 10,000 gigatons' worth left in the ground—even at the lower figure, more than enough to do us in. So

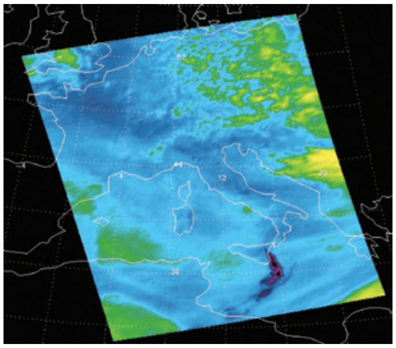


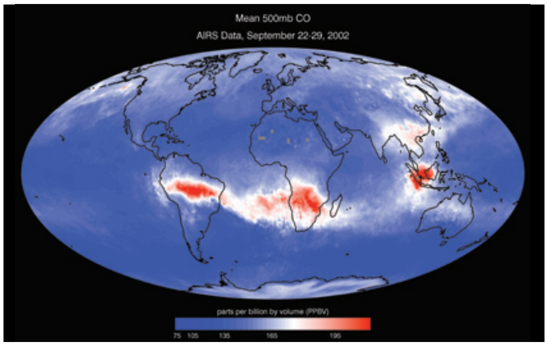
A top-level view of our planet's carbon cycle, using data from the 1990s. All numbers are in gigatons, or billions of tons, of carbon per year. Since the IPCC 2007 report was released, its most pessimistic predictions have been exceeded. Emissions from deforestation and burning fossil fuels have now risen to almost 10 gigatons per year.

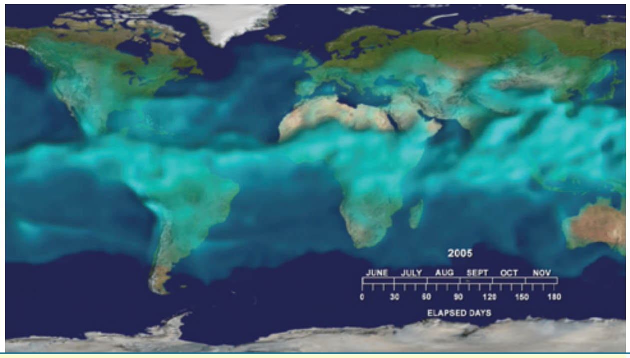


While a postdoc in geochemistry at Caltech (1953–56), Charles Keeling invented an instrument to measure CO_2 levels in air samples. In 1958, as a scientist at the Scripps Institution of Oceanography, he began measuring CO_2 levels at an altitude of eight kilometers on the slopes of Mauna Loa, Hawaii. The curve's sawtooth shape represents the planet "breathing"—plants in the northern hemisphere, where most of the land lies, draw extra carbon out of the air in the spring when they leaf out, only to release it in the fall. Keeling died in 2005, but the Mauna Loa program lives on, providing our longest continuous set of atmospheric CO_2 data. JPL's AIRS instrument takes data at the same altitude as the Mauna Loa site, allowing independent verification of the satellite readings.









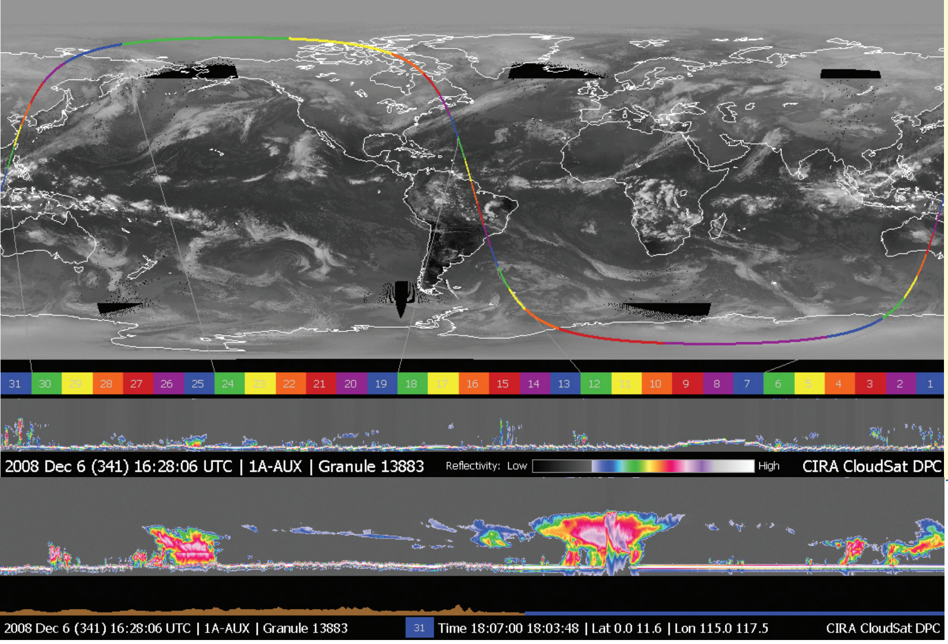
don't count on running out of oil and coal to solve the problem.

EYES IN THE SKY

JPL and other NASA centers are providing global data to climate modelers. I'll just briefly mention a few JPL instruments and missions here. The Atmospheric Infrared Sounder (AIRS), which flies on NASA's Aqua spacecraft as part of the Earth Observing System (EOS), is racing around Earth at about seven kilometers per second. AIRS gives CO_2 measurements that agree with ground-based measurements to within one part per million. This phenomenal accuracy is a great tribute to the AIRS team's scientists and engineers—it would be a challenge to match it in your laboratory. AIRS also measures temperature, carbon monoxide, ozone, water vapor, methane, sulfur dioxide, and dust.

AIRS measures CO_2 in the mid troposphere, about halfway up the atmospheric pressure scale. The red regions in the map at top left show excess concentrations of CO_2. The southern hemisphere is interesting because there are only two main regional anthropogenic sources of CO_2 there. One is in South Africa, which is very rich in coal. They burn a lot of it and convert part of it to liquid fuels. When an oil embargo was imposed on them during the apartheid years, they followed Germany's World War II example and built coal-to-liquid conversion plants. Unfortunately, turning coal into a liquid fuel takes about as much energy per gallon as

Above is a small sampling of some of the things AIRS sees, thanks to spectroscopic and other techniques invented and implemented by Moustafa Chahine, the AIRS lead scientist, and the AIRS team.
Top: Carbon dioxide levels in excess of 380 parts per million are seen in red in this data from July, 2003.
Middle, left: The sulfur dioxide plume (blue) of an erupting Mt. Etna on October 26, 2002.
Middle, right: Carbon monoxide levels on September 29, 2002, show slash-and-burn agricultural regions.
Bottom: A frame from a 3-D, time-lapse movie tracking the distribution of water vapor in the atmosphere.



Left: Radar data from a single CloudSat orbit. Each colored segment along the track in the upper image represents about three minutes. The bottom image shows Segment 31's overflight of Vietnam in more detail. The brown and blue bar across the very bottom shows altimetry data, with blue being ocean.
Below: The CloudSat spacecraft.

you get from burning the liquid, so you emit double the CO_2 of just burning oil. China is planning similar coal-to-liquid plants.

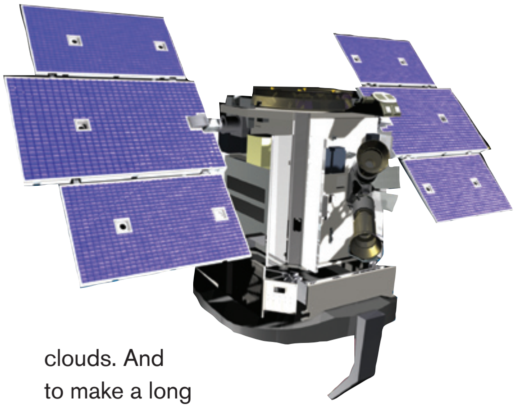
The other source is power plants in southeastern Australia, but you don't see a plume there because it's blown across the Pacific below the altitude where it's detectable by AIRS. The CO_2 then gets kicked up by the Andes in South America, where AIRS picks it up. The same thing may be happening over California. We get China's emissions, which are carried east and kicked up by the continental divide. CO_2 is a global problem—it's all one swimming pool, and there's no filter.

JPL's Orbiting Carbon Observatory (OCO), slated to launch in February 2009, will tell us about CO_2 near ground level. Every second, it will measure CO_2 levels to accuracies of one to two parts per million over a square 100 kilometers on edge, or roughly the distance from Santa Monica to San Bernardino. OCO—which I'm sure you chemists have noted is the structural formula for carbon dioxide, a linear molecule—will cover the entire state of California with six overflights that repeat every 16 days. OCO, in concert with AIRS and other instruments, will revolutionize our understanding of carbon dioxide's regional sources and sinks as well as its patterns of global transport.

JPL instruments also track other things important to climate. MLS, the Microwave Limb Sounder, flies on the Aura spacecraft, which is also part of EOS. MLS measures sea-surface temperatures to an accuracy of 1–2°C. It also continuously measures, to within a few percent, the amount of water vapor in a column from the planet's surface up to the edge of space. The condensation of rising water vapor from the warm ocean releases a lot of heat—the fuel of hurricanes. After Katrina hit, *New York Times* columnist Thomas Friedman asked in Caltech's Ramo Auditorium, did *we* do this? Scientists can't answer that question, but models do link hurricane intensity with sea-surface temperature. If you warm the ocean, you'd better run for cover during hurricane season. Columbus left Spain on August 3, 1492, and arrived in the Bahamas on October 12. You'd be ill-advised to try that today. The safe-crossing period for sailors starts ever later, pushed now to late November, perhaps early December, because with warmer tropical sea-surface temperatures the annual hurricane season lasts so much longer.

Sea-level rise is a valuable global thermometer. Josh Willis at JPL and collaborators at the Scripps Institution of Oceanography compared altimetry data from JPL's Jason-1 oceanographic satellite, built in collaboration with France, with temperature readings from about 3,000 floats bobbing up and down around the world's oceans. Temperature data show that the water's thermal expansion is contributing about 1.3 millimeters per year, but the total rise observed from space is about 3.4 millimeters per year. The difference is fresh meltwater from continental ice packs. Melting sea ice doesn't raise ocean height, as Archimedes explained some time ago. But if you melt ice on land, the runoff does.

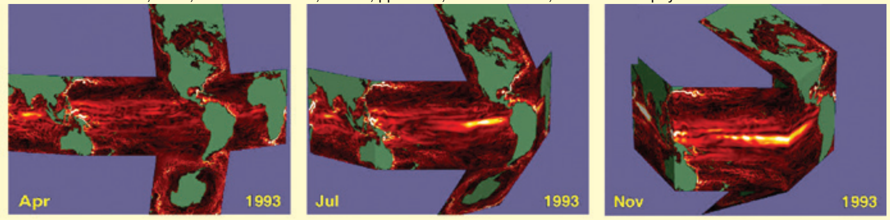
And finally, JPL's CloudSat, launched in April 2006, takes, for the first time, radar slices of clouds that allow us to determine the distribution of water and ice within them all the way down to the ground. Of all the things a climate model must do correctly, it's



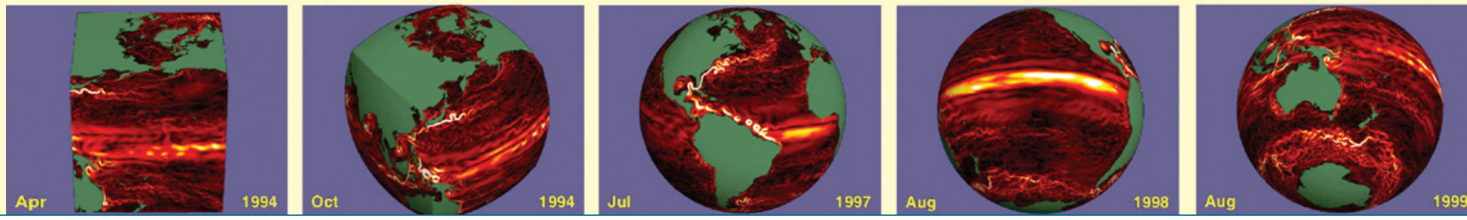
clouds. And to make a long story short, the present models do not agree with cloud observations.

Oceans are important. If the atmosphere is weather, the oceans are climate. Ichiro Fukumori and others at JPL, along with sci-

From D. Menemenlis, et al., *EOS Transactions*, Vol. 86, pp 89-96, 2005. © 2005, American Geophysical Union.



This JPL/MIT/Scripps model of how water circulates in the global ocean has a resolution of one-sixth of a degree. For ease of computation, Earth is computed on a set of flat surfaces—the faces of a cube, which morphs into a sphere.



entists at MIT and the Scripps Institution of Oceanography, have made great progress with a global oceanic circulation model. In such a model, you don't want to use spherical coordinates—even though that's what we teach our students—because there is a nasty singularity at each pole, where meridians converge. This model solves the equations on the surface of a cube and maps the cube onto Earth's surface, avoiding the polar singularities. The colors in the pictures above are ocean-current speeds at 15 meters' depth. You can see the Gulf Stream, the Japan Current, many other features, and a lot of activity around Antarctica. There, the currents are constrained to go through the Drake Passage, the shallow, narrow strait between Argentina and Antarctica, causing the waters of the upper ocean to mix with the deep ocean. Much of the planet's upper-lower ocean mixing occurs there.

Meanwhile, a JPL-UCLA collaboration took several global-climate models that calculate conditions at widely spaced grid points, incorporated a finer grid covering central and southern California, and ran the models to see what detailed predictions each one makes about our region. The forecasted temperatures all go up, but there's quite a spread. Worse, the precipitation predictions are all over the place—not very useful if we want to know what's going to happen to California's water supply. Despite this, all the models predict that we're going to lose the snowpack in the Sierra Nevada. Much of California's water is stored there so, if true, the loss will be serious.

A PATH FORWARD

Countries like the U.S.—the largest energy user, both per capita and as a nation—can decrease energy use without much difference in our quality of life, if changes are gradual. As Nate Lewis said, the cheapest and cleanest power plant is one you don't have to build. (Amory Lovins once called these watts "negawatts.") With a sustained reduction in U.S. energy use of only 2 percent per year, or so, we may not even have to replace every older, less-efficient power plant as it reaches the end of its design life. This is eminently doable—Californians use only *one-half* as much electricity as the average American, in terms of kilowatt-hours per person per year, thanks in part to the work of Arthur Rosenfeld, an inspired physicist at Berkeley, and the support he was able to muster. This led to California setting efficiency standards for new buildings, as well as for appliances such as refrigerators, after the 1973–74 energy crisis. In 1972, Californians used about as many kilowatt-hours per person per year as the rest of the country. Our consumption has held steady at 1972 levels ever since, while the rest of the nation's has gone up. California's standard of living has not suffered as a consequence.

Next, we need to try carbon sequestration. However, if CO_2 is placed deep underground, it can leak. A leak rate of, say, 1 percent per year may sound pretty good. It isn't. At that rate, your first year's CO_2 will be back in the atmosphere in 100 years. Even so, we have to try to sequester, even if it doesn't work perfectly, because it will buy time. Carbon sequestration in the deep ocean is a possibility, as is reforestation, which we know works while forests are growing. Of course, before we consider planting new trees, we should stop cutting down the forests we already have.

So how *should* we produce the energy we need? Solar-thermal power-generation plants, like the Nevada Solar One facility in Boulder City, provide a good large-scale option. Such plants use computer-controlled mirror arrays to track the sun and focus its light to heat a liquid to nearly 400°C. This fluid is pumped through a heat exchanger to make steam that spins standard steam turbines that make electricity. Estimates indicate that with this technology in its current form, the southwestern United States and northern Mexico could meet the daytime power needs of the U.S., Canada, and Mexico. And we can do better—the Solana Generating Station being built near Gila Bend, Arizona, will be able to produce power for up to six hours after the sun goes down. The plant will have excess sunlight-collecting capacity that will be used to melt salt, which will be stored in giant thermos-like silos and circulated through the heat exchanger after sundown. Solana will crank out a peak of 280 megawatts, a quarter of a San Onofre unit, but will require three square miles of land. Real estate does become an issue at some point.

Nuclear power will play a role. Conventional nuclear plants need enriched uranium, because they run on uranium-235. U-235 is only 0.7 percent of the natural ore, which

Power production without smokestacks. The Nevada Solar One facility, left, has been running since June 2007. The third-largest facility of its kind in the world at the moment, it puts out 64 megawatts—enough to supply over 14,000 households. The Superphénix fast-breeder reactor, right, in Creys-Malville, Isère, France, was decommissioned in 1997.

The California High-Speed Train Project—a "bullet train" system proposed to link San Diego, Los Angeles, San Francisco, and Sacramento got its initial funding when voters approved Proposition 1A last November.

is mostly U-238. But a fast-neutron breeder reactor can use most of the U-238. It can also burn the "spent" fuel now stored as radioactive waste. France built such a plant, the Superphénix, in the 1970s. It was rated at 1.21 gigawatts, a little more than one of the San Onofre units. It used liquid sodium to cool the reactor core, which works fine as long as no sodium leaks into the heat exchanger's water side. You may remember from high-school chemistry that when water and sodium get together, exciting things happen—you get explosive hydrogen gas and lots of heat to ignite it. So even though nothing went wrong, the French decommissioned it. They're now building a new reactor that's safer *and* more efficient—and, ironically, uses CO_2 as its working fluid instead of steam.

Wind is cost-effective and wind farms on land may be able to meet about 10 percent of our power needs. JPL's Timothy Liu, Wenqing Tang, and Xiaosu Xie analyzed eight years of data from JPL's QuikSCAT satellite to estimate the wind power available over the oceans. They concluded that ocean wind farms, strategically located, could harvest up to 500 to 800 watts per square meter. (For comparison, average annual power available from sunlight at midlatitudes is some 250 watts per square meter.) We'd need to run power lines undersea, but we do a lot harder things routinely. However, one can only pump so much wind power into the grid, because wind is intermittent. Too large a fraction of it can make the grid unstable, unless one averages out its contribution through some sort of electrical storage system, which is expensive and difficult today at the required scale.

We could make big strides in transportation. Right now a plug-in hybrid, a converted Prius, can go up to 30 miles—more than the average American round-trip commute—on just the battery, and battery technologies are improving. But we need to start designing lightweight cars so that less energy is needed per mile traveled—as an aeronautics professor, I assure you that the typical payload fraction of today's cars is abysmal. For medium-length trips along transportation corridors, we need to expand rail transit. We'll probably keep jet planes for the long haul. We're not going to invent an electric commercial airplane any time soon.

As we transform our energy systems, we'll need to develop regional and global regulatory and pricing environments—cap-and-trade systems and carbon taxes, for example—that encourage a profitable, phased implementation with the least disruption. One could implement a carbon tax while cutting other taxes, for example, so that there is no net tax increase. However, any change leaves winners and losers, so we need to help losers to also be winners. That's not as difficult as it sounds, as the refrigerant engineer realized—the Montreal Protocol was *good* for the chemical industry.

THE ECONOMIC IMPERATIVE

This past May, former CIA director Jim Woolsey gave a talk at Caltech on energy. He pointed out that in 2003, the U.S. imported about 53 percent of the oil it consumed. Today it's about 60 percent. He said that we're borrowing $1.5 billion per *day* to pay for imported oil. Consumption and prices are now down because of the economy, but both will come back up as the economy recovers. The problem will not go away. It may take 30 to 40 years for Earth's radiative imbalance to catch up with us, but this financial imbalance is unsustainable and will catch up with us a lot sooner.

Conversely, transforming our energy system would provide a major economic stimulus, as the President-elect has noted. Besides creating jobs at home, the U.S. could sell efficient, reduced-carbon technology worldwide. America seems to need to reinvent itself every 20 to 25 years to stay competitive, as Tom Cwik, my friend and JPL's associate chief technologist, has noted. World War II pulled us out of the Great Depression. Then came Sputnik and the space race, followed by the Internet and the information-technology revolution. It's hard to imagine a better business plan for the nation than a significant increase in energy efficiency and a smart reduction in fossil-fuel use. With much of the world continuing to build old-style energy systems, little else would make the U.S. as competitive.

The year 2009 is a triple sesquicentennial. In 1859 Edwin Drake drilled the first commercial oil well, in Titusville, Pennsylvania; John Tyndall discovered that CO_2 absorbs in the infrared and noted the greenhouse-gas consequences; and Charles Darwin published *On the Origin of Species*. It'll be interesting to see how we evolve to solve this problem. e&s

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Dimotakis arrived at Caltech as a freshman in 1964, and has been here ever since, earning his BS (physics, '68), MS (nuclear engineering, '69), and PhD (applied physics, '73) before joining the faculty after a brief stint as a postdoc.

In his spare time, he is an avid sailor.

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