Environmental Review

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Effects of Global Warming

Introduction:

Everybody talks about the weather, but nobody does anything about it. Now the joke is on us, we have changed the weather. The scientific consensus is that the Earth's surface is getting warmer. The discussion has now shifted from whether global warming is real, to what will be the consequences. There will likely be an increase in some kinds of extreme weather events: a day over 90 degrees in Seattle is quite rare, but it will probably happen more often in the future.

As the human population of the world doubles in the next fifty years, as more people move onto coastlines and floodplains, human communities will be more susceptible to storms and floods. Global warming is expected to cause changes in the distribution of wild plants and animals on a continent-wide scale, indeed such changes are already being reported. Climate has changed rapidly in the past, but the natural world is now so dominated and fragmented by humans that in many places its ability to adapt to climate change is compromised.

A recent report to the President and Congress describes our present understanding of what to expect from global warming[1]. We spoke with David Easterling, one of many contributors to the report as well as a coauthor of a summary in *Science*, about his work on climate change[2].

CONTENTS:

ER: Dr. Easterling, where did you get your training?

DE: I received my Ph.D. from the University of North Carolina at Chapel Hill in 1987, then I took a position at Indiana University in Bloomington on the faculty in the Climate Meteorology program. I taught there for three years and then was recruited by Tom Karl to the National Climatic Data Center to be a research scientist.

ER: What is the National Climatic Data Center?

DE: The NCDC is one of the world's largest depositories of climate data. We collect all kinds of climate data from all around the world; satellite data; ocean data, especially sea surface temperature data; radar data; a lot of data from climate stations; and we have an archive that's many terabytes now. When we receive the data, let's say from the National Weather Service, we quality control it and put it in the archives. And because we have this huge archive of weather data, in addition to servicing customers, we do a lot of research on the observed record, looking at things like climate variability and climate change, which is my specialty.

We're under the National Environmental Satellite Data Information Service, which puts the satellites up and runs them. We're not a part of the National Weather Service, but we are part of NOAA. *[Editor's note: the National Climate Data Center's Website at www.ncdc.noaa.gov is well worth a visit.]*

ER: What can we expect from global warming?

DE: If there is a warming of the climate, then you would expect to see an increase of what we call extreme events. For example, if the average global temperature warms up, then you would expect to see fewer days that go below freezing, and more warm days in the summertime.

We had a workshop to bring together climatologists to look at the observed record (which is what I do), modelers, and people who are using the climate information to see how climate change is going to affect society or biological systems. The *Science* paper came out of that workshop which was in 1998 at the Aspen Global Change Institute.

ER: You work only on the observed record?

DE: That's right. I have done some work looking at modeling results and trying to produce climate scenarios. One of the things that I've recently worked on quite a bit is the U.S. National Assessment of the Potential Consequences of Climate Variability and Change in the U.S., which is a report to Congress and the President that has just been released. In the assessment we used modeling simulations to produce scenarios of climate for the 21st century so they can look at how it might impact various systems, agriculture, for example, or forestry, or human health. But most of my work has been on the observed record, trying to look at what has happened over the past hundred or so years of the instrumental record.

ER: Modelers complain that the observed record has no theoretical basis. I like the idea of putting the two types together and letting them talk and improve our understanding of the observed world.

DE: That was the intent of the *Science* piece, to look at the extremes, to see what the observed record has, and to see how that matches up with what we might expect in the future, both from theory and also from what the models would suggest might happen based on simulations of the 21st century.

ER: When did global warming start?

DE: Well, since 1900 we've had a warming of about six-tenths of one degree Celsius over the 20th century, which doesn't sound like very much, but when you start looking at temperatures from different times in the past, for such a relatively short time it is a pretty big change, but not a huge change. The big concern is not so much that we might be seeing a climate change, because we know that it's been warmer in the past and it's been colder in the past and it will change in the future, the real issue for me is, is it warming much faster that we would expect due to natural variability? And also is that climate change going to be so fast that it's going to have profound impacts on agriculture, society, institutions and natural systems that might not be able to keep up as the climate changes?

So we've had warming of about 0.6 degrees Celsius and the way the temperatures are taken in most of the climate stations is you get two temperatures per day: one is the warmest temperature from the previous twenty-four hours and the other one is how cold it got. Typically the maximum temperature is going to occur around mid afternoon, and the minimum temperature is going to occur around dawn; we call those daytime and nighttime temperatures.

And we found that much of that 0.6 degree warming is associated with a rise in the minimum temperatures. In other words, it's not getting as cold at night as it has in the past. Also, if you look at where it's occurring across the globe, the areas that have experienced the greatest rate of warming are the higher latitudes, particularly in the high latitudes of the Northern Hemisphere.

ER: Like Russia or the far north of Canada?

DE: Russia, Canada. Right.

One of the big issues right now is in attribution studies. We know that we've had an increase in greenhouse gases over the past 250 years. We know that with that increase in carbon dioxide and methane that we would expect to see some warming. The physics are pretty well known: if we increase atmospheric carbon dioxide, we know we're going to get some rate of warming, just how much we're not sure. But one of the big issues right now is, is the warming we've seen over the 20th century attributable to greenhouse gas increases and if so, how much?

One of the approaches in these attribution studies is to look at patterns of warming that you see in the climate models. You start a climate model with present-day carbon dioxide in the atmosphere, then you gradually increase it; and once you reach a certain point, let's say a doubling of carbon dioxide, you look at the spatial warming patterns, where it's warming over the Earth's surface and in the different layers of the atmosphere. You can compare that with historical climate data and see whether or not you can find similar patterns in the observed record. If we get a warming of two or three degrees Celsius over the 21st century, some areas are going to warm much more than others.

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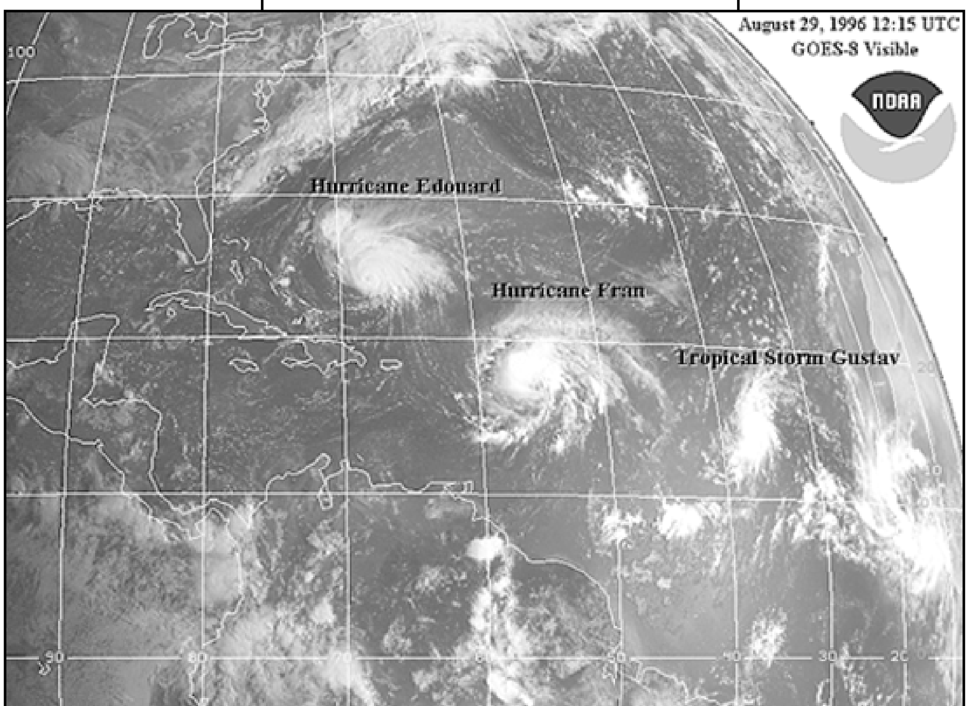
ER: How trustworthy are the climate models?

DE: The biggest issue is how well the models actually reproduce the climate record. If a model can't reproduce the historical climate, then we can't have too much faith in a future pattern we might get out of it. Models a decade ago really were not very good, but the models are now much better at reproducing the state of the climate of the 20th century. They don't do it perfectly by any means, but they're getting better, so we're beginning to place more confidence in future results that they might be producing.

For example, a lot of the models now, not all of them by any means, but a lot of models are projecting that we should see more El Niños, a more El Niño-like state in the future if we have increases in atmospheric carbon dioxide. Then the question is, are we beginning to see that pattern in the observed record? And the answer seems to be yes, we're beginning to see that evidence evolve in the observed record as well. If you look at El Niño behavior since the late 1970s, El Niños have been much more active. We've had two large El Niños since the late 1970s, one in the early 1980s, and the most recent one a couple years ago. El Niños seem to be becoming more powerful, stronger. So there's consistency between what we might expect to see in the future based on the climate models and what we've seen in the last twenty-five years.

Secondly, getting back to the global temperature time series where we saw 0.6 degree warming over the 20th century. That's not a consistent warming. There was a fairly strong warming from about 1910 through the early 1940s; then we had a period of a little bit of cooling; and then starting in the mid-1970s we've had fairly rapid warming. So if you look at the historical record, in particular the most recent warming, that's beginning to be consistent with the model simulations for that period.



This satellite image shows hurricanes Edouard, Fran, and Gustav in the Atlantic Ocean (August 1996).

ER: What does your work on extreme weather focus on?

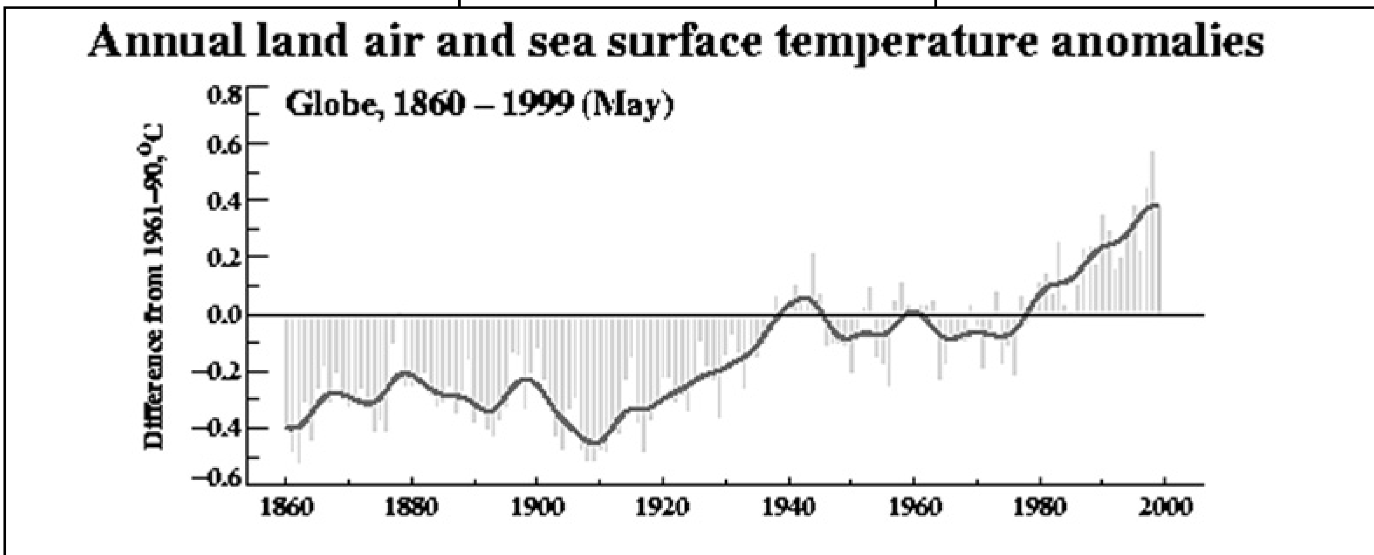
DE: Right now we've just been focusing pretty much on extreme temperatures; for example, fewer days below freezing, changes in the length of the frost-free season. In the U.S. we're seeing a trend to an earlier date of the last spring freeze and a corresponding lengthening of the frost-free season. There's actually been a bit more work done on extremes in rainfall in the areas where we've got good data. But one of the issues with the observed record is that that for large parts of the world we simply don't have very good data. For most of Africa and many parts of South America we simply don't have a lot of good data to do this sort of analysis looking at changes in number of days below freezing or changes in daily rainfall amounts.

But the areas where we do have good data, the former Soviet Union, China, Australia, U.S., Canada, we're seeing a trend towards more heavy rainfall events.

ER: Why does global warming translate into more rain?

DE: If the atmosphere is warmer, it can hold more moisture because warmer air can hold more water vapor than cooler air. So with atmospheric warming you would expect to see an increase in water vapor content of the atmosphere, which we are seeing in the observed record; the models are consistent with that as well. When you get more water vapor in the air, you get heavier rainfall events. This ties together with the observed record because we are seeing warming, we are seeing increases in water vapor, and the models find a similar pattern, an increase in rain.

In the observed record the total annual amount of rainfall over the U.S. is increasing. It's increasing at the higher latitudes, which is interesting because we're also seeing the bigger increases in temperature in the higher latitudes. Much of that increase in annual rainfall is due to heavy rainfall events. We're seeing a warming, an increase in water vapor, and an increase in total annual rainfall, which is due mainly to an increase in the heavy rainfall events.



Average surface temperatures were cooler than the reference period (1960 to 1980) and have been warmer since.

ER: These are what you refer to as extreme events?

DE: Right. We shy away from that language a little bit because a heavy rainfall event in some parts of the world may not really be all that much. What we're really looking at is in a statistical sense the tail of the distribution. So it may be that you're seeing more half-inch rainfall events in some desert areas, but then in some wetter areas it may be two or three-inch rainfall events. But we're seeing the increase out in that tail of the distribution, whatever that heavy event might be for that location.

If you think about it fairly simply in terms of a Gaussian distribution, a normal distribution, and you take the mean temperature and then you shift the whole distribution upwards, what used to be a fairly rare event, for example, a day over 90 degrees in Chicago may have been fairly rare back under the climate of the 20th century but if you were to warm the average up by five degrees and not change the variance, then an unusual event becomes much more common.

It's the same idea with rainfall. If you're increasing the rainfall amount, and not increasing the number of days that it rains, then you have to be getting more rainfall in the heavier events.

Why it's happening is likely due to the fact that we're seeing more water vapor and we're seeing warmer temperatures, which leads to more water vapor in the atmosphere. We have also seen an increase in cloud cover over the U.S. and other parts of the world, Australia, the former Soviet Union.

ER: Does that relate to more particulates in the air and more cloud seeding?

DE: Yes. The cloud seeding due to the pollutants, that's certainly part of it. We have increases in greenhouse gases, which tend to warm the climate, but we also have increases in sulfate aerosols due to pollution, burning coal for instance. Sulfate aerosols act to cool the climate somewhat because they reflect solar radiation back out to space, and also they contribute to cloud formation, which also tends to reflect solar radiation.

ER: So clouds don't act as a blanket or greenhouse gas in themselves?

DE: Well, they do at night in the sense that they tend to keep the temperatures up at night, but during the day then they are going to have the opposite effect. Widespread cloud cover will reflect back enough solar radiation to keep temperatures a little bit cooler.

ER: What about droughts?

DE: When you think of climate change, most people think of the Dust Bowl era, but we are seeing a trend toward more wet spells than drought. This is where the models and the observations diverge a little bit. Many of the model simulations are calling for an increase in rainfall, an increase in temperatures, but also an increase in more drought-like conditions in the mid-continent regions. The way the models are built, a temperature increase is going to produce more evaporation than the increase in precipitation, and as a result you're drying out the soil and leading to drought conditions in, say, the Midwest or in the grain-growing regions in the former Soviet Union.

ER: The modelers predict more droughts in the heartland?

DE: Right. Now, we haven't necessarily seen that in the observed record; right now we're seeing that the increase in rainfall is outweighing the effects of the increase in temperature so far, and so we're not seeing an increase in drought conditions, with some exceptions. The tropics have actually shown a decrease in rainfall; much of that is due to the droughts, for example, in the Sahel region of Africa. So some areas of the world are experiencing an increase in drought conditions; sub-Saharan Africa certainly is one of them.

ER: What about cyclones and hurricanes?

DE: There's no real change there. There is some hint of a change in parts of the world but especially if you look at hurricanes, there's no significant change. There is a lot of variability in those systems. We're actually seeing fewer hurricanes now than we did in the 1940s. We had a period from the 1960s and 70s and into the 80s where we simply did not have many Atlantic hurricanes. We appear to be coming out of that and seeing more storms. But the interesting part of that is even though we're not seeing an increase in the amount of storms, we're seeing much more damage done by the storms due to the fact that more people are building in areas that are hurricane prone.

ER: This is important in less affluent neighborhoods like Bangladesh where millions of people are living on a floodplain a couple of inches above high tide.

DE: Right. So along with warmer temperature and a warmer world, we would also expect to see a rise in sea level. If you take the Bangladesh example, if you raise sea level somewhat and then you have another cyclone hit it, that's going to be even worse because people are already pretty darn close to sea level there as it is. If we raise sea level, we're going to have even more people in peril there. In the early 1970s a cyclone hit there and killed 300,000 people, and then there was one recently that killed on the order of 100,000 people.

ER: Your *Science* article mentioned some paleo weather data.

DE: It is in the sense that it's based on past history. That's some work that Jonathan Overpeck and Connie Woodhouse did at the National Geophysical Data Center in Boulder. It

The areas that have experienced the greatest rate of warming are the higher latitudes, the far north of Canada and Russia.

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was a meta-analysis where they looked at some of their own work and work from other people to reconstruct drought history in the Great Plains region for the last thousand years to get an idea of the long-term variability of droughts there. The question is, is the Dust Bowl era unusual or is it not? It turns out that the Dust Bowl of the 1930s is not that unusual in terms of the paleo-record. Based on their evidence you would expect to see one or two droughts like that a century. So if we were to have another one like that in the next ten or fifteen years, it wouldn't really be that unusual.

ER: The ecology of the Great Plains a thousand years ago was quite a bit different from what's going on there now.

DE: Certainly the land use has changed quite a bit from the Native Americans and the bison, to the nation's bread basket now.

ER: How did they figure out the drought history?

DE: They did a lot of work with tree rings. Every tree ring is a record of that year's growth; tree rings tend to be bigger when conditions are favorable and smaller during droughts. Some of the trees go back many years, and you can not only use living trees but you can also go to dwellings that people built 500 years ago, you can carbon date that wood and look at the tree rings in it to extend your time line back. They have also used pollen analysis where you go to a lake and look at the sediment layers. The kinds of plants contributing to the pollen record tells you something about the conditions on the landscape over time.

ER: What about the societal impacts of climate change?

DE: That's going to be a tough question for me to sort out, although I did some work on that for the national assessment. Human health effects was a contentious issue with the national assessment. Many people say that what happens with that kind of thing is that people acclimate. They have a bad experience like the Chicago heat wave in the 1990s, but then society adapts to it.

There's no doubt that we'll see a doubling of carbon dioxide over pre-industrial levels sometime in the 21st century, and so we know climate is going to warm. The real issue is how much. I would submit that it's 99 percent certain that there's going to be some amount of warming in the 21st century, but trying to translate that warming into some impact is much more difficult. We took that approach in the national assessment: we are virtually certain it's going to warm; we're pretty sure we're going to see an increase in rainfall.

In terms of impacts on the U.S., we felt pretty certain that at least initially agriculture could handle climate changes, mainly due to the fact that farmers can throw quite a lot of technology at it these days. If you start to see more drought conditions, at least initially you can throw some irrigation at it or you can change to a dry-land crop. If you're growing corn in Illinois and the rainfall decreases, you can change to a corn that is more suited to drier conditions. So agriculture looks like it'll be okay, at least in the U.S. But many parts of the world simply can't throw the technology at it that we can.

Water resources is a big issue. It's an issue now and it could be even a more contentious issue in the future. The Colorado River is over-allocated as it is, and if you diminish the flow then you're going to have a lot of unhappy people. People in California, which is using more than its fair share right now, if they're told they have to cut back, there are going to be political disputes. So water could be a real issue, and that feeds back into agriculture. Many of the model simulations project a decrease for the Great Lakes ranging from one foot to as much as three or four feet. That's certainly going to affect water resources in the Midwest, which then could affect agriculture by reducing the amount of water available for irrigation. Not only will there be more competition, there are going to be issues of quantity and quality. If you decrease the quantity, you're also going to affect the quality of water that's available for drinking water.

Environmental Review

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How much it's going to affect it and where, it's difficult to say because we don't know exactly where and what the climate changes are going to be like, but water will be an issue.

Health is somewhat of an issue, although in the U.S. it will be less of an issue I think than some people would believe. If we have heat waves, we will tend to adjust to them. Local governments will develop a response plan. There are other long-term issues such as how climate change might impact air pollution. It could be that if you have higher temperatures in the summer you end up with more days with high pollution, and that's certainly going to impact people's health.

In the assessment the health group looked at some of the other problems such as water-borne and food-borne diseases, insect vector-born diseases, things like encephalitis. It's difficult to make any broad statements on that, but there is some speculation that you could change patterns of vector-borne diseases, diseases due to mosquitoes for instance, simply by changing the climate. The health impacts were pretty unclear. Part of that is due to the fact that the whole idea of climate change impacts on health is an emerging field. The disease researchers are just getting started with this field.

Literature Cited:

[1] *The National Assessment of the Potential Consequences of Climate Variability and Change* is on the Web at http://sedac.ciesin.org/NationalAssessment

[2] *Climate Extremes: Observations, Modeling, and Impacts.* D.R. Easterling et al. 2000 *Science* 289:2068-2074

Breaking the Link between Fossil Fuels and Carbon Dioxide

Introduction:

The Kyoto Protocol, adopted under the U.N. Framework Convention on Climate Change, commits the developed countries to reduce emissions of greenhouse gases by at least 5 percent by the year 2012. Since agreeing to these targets in 1997, the signatories have met every few months at Conferences of the Parties (COP) to iron out the implementation of the agreement. The recent COP5 meeting ended in disarray with the U.S. balking on carbon management costs and strategies; the next COP is scheduled to take place in the early summer of 2001.

The U.S. alone puts 1.5 billion tons of carbon into the atmosphere every year, and it has agreed to the Kyoto Protocols, as have 186 other countries. While it is becoming clear that the U.S. will not meet its emission targets for 2012, it seems reasonable for us not to undertake such a big job without knowing how much it will cost.

The energy we will use in the future will come from a combination of sources: renewables such as solar and wind and hydropower, fossil fuels, and nuclear reactors. However, all energy sources have costs as well as benefits, and we are finding that even renewables have undesirable environmental effects.

We spoke with David Keith of Carnegie Mellon University about some of the economic and environmental costs of carbon management, one of the main sources of contention at the Conferences of the Parties.

ER: Professor Keith, what is your training?

DK: I was trained as a physicist at Massachusetts Institute of Technology. I've formally been at Carnegie Mellon University for only one and a half years, but have been adjunct faculty here the last eight years. About a year and a half ago I switched full-time to policy-focused work.

ER: In spite of candidate Bush's log rolling on global warming, or perhaps because of it, why have all the Kyoto follow up meetings ended in stalemate?

DK: First I would like to give you an answer that tries to set a long-term perspective. The climate problem is not new. We have known the science that says that the increase of carbon dioxide in the atmosphere is primarily due to burning fossil fuels. We have known for a long time that if we keep burning fossil fuels we will see substantial increases in atmospheric carbon dioxide. We are very confident that if we continue burning fossil fuels for the next century or so, we'll see a doubling or tripling of carbon dioxide. And it is highly probable that the climatic effects of that increase will be substantial.

That basic story has been well known for a long, long time. Indeed, almost everything I just said was quite well articulated in a report called Restoring the Quality of Our Environment that was presented in 1965 to the Johnson Administration. At that time they already had an accurate record of carbon dioxide in the atmosphere, although only a few years of it, and they had quantitative models that gave answers not radically different from the answers that quantitative models give today. They had knowledge of the total budget of fossil fuel combustion and they could start to tie the problem together, so this is not at all new.

Several systematic efforts to look at this, notably in 1977 by the National Academy and then more in the early 80s, came to conclusions that basically don't differ dramatically from today's. Regarding what would be the effect of President-elect Bush's view of this problem, my answer actually is, not much. Global warming is a problem that we'll solve on a time scale of decades to centuries, and I don't think that the immediacy of U.S. politics drives the answer one way or the other very much.

One of the most profound things that's happened in the last half decade or so on this problem is that a group of large industrial concerns and countries that have big interests in the fossil enterprise have changed their stance substantially. That may be more important than exactly what happened at Kyoto, or what happened in Bonn a month ago.

Five or eight years ago a number of the large upstream companies (Shell, BP, Exxon, etc.) and some of the large companies that produce equipment that uses fossil energy, like the car companies, paid a fair amount of money to lobbying firms in Washington D.C. to discredit any claims that there was a scientifically verifiable problem. Now, most of those companies, with some exceptions, have pulled out of that effort and have publicly declared that the climate problem is real and that action will be needed.

So there is dispute about how much action, when, who should take it, who pays, whether Kyoto makes sense, whether Kyoto is acceptable unless the Chinese sign on, a whole laundry list of concerns, many of which are completely reasonable and valid, but that is different from the situation we had a decade ago where many of those groups took the attitude that they would fight to stop any action and fight to discredit the idea that there was a problem.

In Europe as compared to America, there is widespread acceptance that action will be needed and that it will have real costs. My guess is that that acceptance will spread to the U.S. on the scale of about a decade, and that there will be climate policy with teeth; that is, policy that actually starts to cost real money and push us all into making changes in technology and behavior. That will start on the scale of a decade or so quite independent of what happens to the framework convention process.

It is technically possible to use fossil fuels without emitting carbon dioxide to the atmosphere...

ER: Perhaps an EPA-like entity?

DK: I'm not sure we need any new entities. We just need political will to act, and I think that that will have to come from the top at the level of national politics, but I think it will happen. There are various independent entities we might need. For example, if we're going to have carbon management in a way where we can trade permits and have money changing hands on financial instruments that allow us to control carbon, we may need some new entities perhaps analogous to the Federal Reserve System that are not tightly coupled to politics, that allow some long-term decisions to be made about, say, the number of these permits available. That's in the future.

ER: What were the issues that caused the Bonn meeting to disband in disarray?

DK: One of the key issues is that if we allow all of the flexibility mechanisms; that is, various forms of international trade in carbon credits, trade between the developed countries or trade between the developed countries and the poorer countries, if all those mechanisms are allowed the way the U.S. wanted them, then formal compliance with the Kyoto Protocol could be achieved at costs that are not large. That was the position that the U.S. wanted to take, and some other countries did too. The central sticking point was between that view and one that says we actually need to start action in the industrial countries soon, to put economic pressure on the relevant industries to accelerate the production of innovations that will in the long run buy down the cost of deep cuts in carbon dioxide emissions.

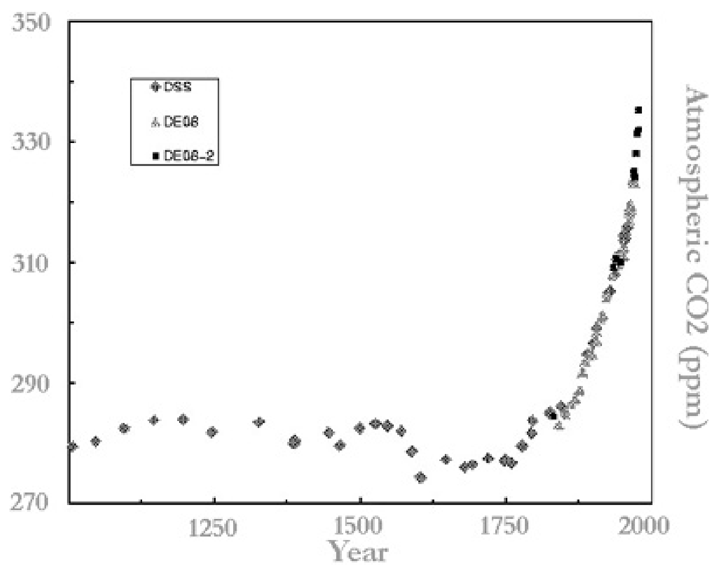
Perhaps it needs to be said that the Kyoto Protocol, which is a protocol under the Framework Convention, which is ratified and in force, says that we have to stabilize emissions at a level sufficient to avoid broad environmental damage.

ER: I'm surprised that they didn't pick a number out of the air.

DK: That would have been impossible because there is no fixed number for a level that causes no damage. But what is important is that they did say stabilization of atmospheric carbon dioxide, and the world has, for what it's worth, agreed to that. Stabilization means that over the millennial time scale carbon emissions go to zero. And so the Kyoto agreements, which agreed to a certain formula among the developed countries of binding cuts to emissions by the year 2010 — the first so-called commitment period - that protocol does not by any means stabilize carbon dioxide concentration, and so it's in a sense a small step along the way.

Those of us who are thinking about the next hundred years of this problem and realize the need to stabilize concentrations at a level which is acceptable — and we all have different views about what acceptable is — know that we will have to make large cuts in emissions compared to business as usual, cuts on the order of a factor of two or more by about 2050.

If we want to achieve stabilization under 500 parts per million, approximate double pre-industrial carbon dioxide, we will need to cut emissions roughly by a factor of two by the year 2050. That is a major reorganization of our industrial systems. Those of us who buy an argument about technological change say that the sooner we start something happening that is not just talk and not just research, but actions that put an effective price on carbon by a tax or other mechanism, the sooner we do that the sooner we will begin buying down the long-run cost of control. I say that because our experience of many previous environmental legislation or environmental control technologies is that over the long run we can bring down the cost of control substantially, but we can't expect it to happen all at once. You need decades for innovations to propagate through these capital-intensive, slow-turnover industries like the electric utility sector.



Air samples from Antarctic ice cores show the atmospheric CO_2 concentration for the last 1,000 years.

ER: It took over a hundred years to build these systems up.

DK: The time scale does matter. The time scale for the big waves of transformation of the major energy transforming systems like the ones that transform fossil fuels into electricity, and the major distribution networks like the electric and gas distribution network, that time scale is of the order of fifty years, not centuries.

Indeed, the buildup of the U.S. electric sector, most of it happened over thirty to forty years, and we will have to make a transformation of about that speed, about the speed we have made before. What would not work is if we try to do that in ten or twenty years, and if we want to do it at a reasonably low cost, we need to start some actions now.

So the core breakdown at Kyoto was between a strong green position that was most exemplified by the European green movement that says that the treaty had to ensure that there be meaningful cuts in industrial countries, and that meant U.S. emissions, and that they would not accept the interpretation of the treaty that allowed it to be formally abided by the process of trading by using all these flexibility mechanisms.

ER: In other words, they wanted us to tackle some of the hard problems before we take the easy options off the table.

DK: More or less, that's right. I guess there are two reasons for that. One is a moralistic reason that says that the world is greatly over-consuming and that we need to take action to stop over-consumption and that anything else is just talk. So there's a moralistic attitude, which I actually partly subscribe to, but then there's also this induced technological change argument that I've just been talking about, that we need to buy down the long-run costs.

ER: What about the linkage between fossil fuels and carbon emissions?

DK: For a long time we have assumed that using fossil fuels necessarily meant that we would emit carbon dioxide to the atmosphere, that the core carbon dioxide-climate problem was that problem. I think we can now say that that is simply wrong. It is technically possible to use fossil fuels without emitting carbon dioxide to the atmosphere, and almost all the component technologies to do that exist in full industrial scale.

The basic technologies involve two parts, separation of the carbon from the combustion process, and sequestration of that carbon away from the atmosphere. Separation involves building, say, a power plant that takes as input coal or natural gas and produces as output an energy carrier like electricity or hydrogen, and also produces various wastes, and also produces a stream of high-pressure carbon dioxide which we can then sequester.

The most obvious way to do the sequestration is to put the carbon dioxide into underground geological formations. Surprisingly, that latter practice is well developed at large scale. The oil industry has a thirty-or-more-year history of moving around tens of millions of tons a year of carbon dioxide in pipelines up to almost a thousand kilometers long. They are injecting the carbon dioxide underground not of course for the purpose of stopping carbon dioxide emissions for climate change, but to enhance oil recovery. But nonetheless people know how to build carbon dioxide pipelines and they knew how to inject carbon dioxide into geologic formations. And at least one place in the world, in Norway, they are now injecting large quantities of carbon dioxide into an underground formation for the purpose of preventing climate change.

ER: So Norway is out in front on carbon management.

DK: Right. All natural gas comes out of the ground with some mixture of carbon dioxide, anywhere from a few percent to essentially 100 percent of carbon dioxide. Commonly in the natural gas business, if you have more than about two percent of carbon dioxide, you have to strip it out. Normally it's vented to the atmosphere, and then they sell the natural gas into the pipeline and finally to the customer.

Stabilizaton of atmospheric carbon dioxide under the Kyoto agreement means that over millenial time scale, carbon emissions go to zero.

And so in one of the largest natural gas fields in Europe, run by the Norwegians, the normal way of doing things would have been to ship the gas to shore, strip the carbon dioxide off, vent it to the air, and send the natural gas to Europe. But because of a Norwegian carbon tax explicitly designed to cut carbon dioxide emissions because of concerns about climate, the Norse gas company instead built on their offshore platform the unit that separates out the carbon dioxide, and they now re-inject about one-third of a million tons of carbon per year into a porous sandstone formation underneath the ocean floor.

ER: How long is that expected to stay in the ground?

DK: That's a key question. It seems certain that the answer is 10,000 years or longer; that is, long enough so that it isn't an issue for the climate problem. But the question of long-term disposal is central to whether or not any of this technology for using fossil fuels without emitting carbon dioxide makes sense or not. If we go forward to do this on a large scale, we will have to develop a systematic procedure that has room for public input, to decide what sorts of reservoirs are safe and to decide how long the carbon dioxide should stay sequestered.

ER: What about the cost of burying it?

DK: There is a whole range of concerns about these technologies. We do know how to capture carbon dioxide from power plants. We do it already commercially for the purpose of producing carbon dioxide for carbonating beverages, and there is reason to believe that we could buy power plants that would come online, say, ten years from now that could produce electricity with little or no carbon dioxide emissions and capture the carbon for subsequent sequestration at an electric price that would be between one and two or three cents per kilowatt hour higher than the current prices, which are around three. This is at the most a factor of two higher prices at the power plant, but that translates to much less than a factor of two higher prices to the consumer.

Price is a big deal. The conventional assessments assume that the only technologies that would allow us to

Environmental Review

Volume Eight Number Three
March 2001

make electricity without emitting carbon dioxide are technologies that cost much more. Wind is an exception, wind does not cost much more but there are some other issues with wind.

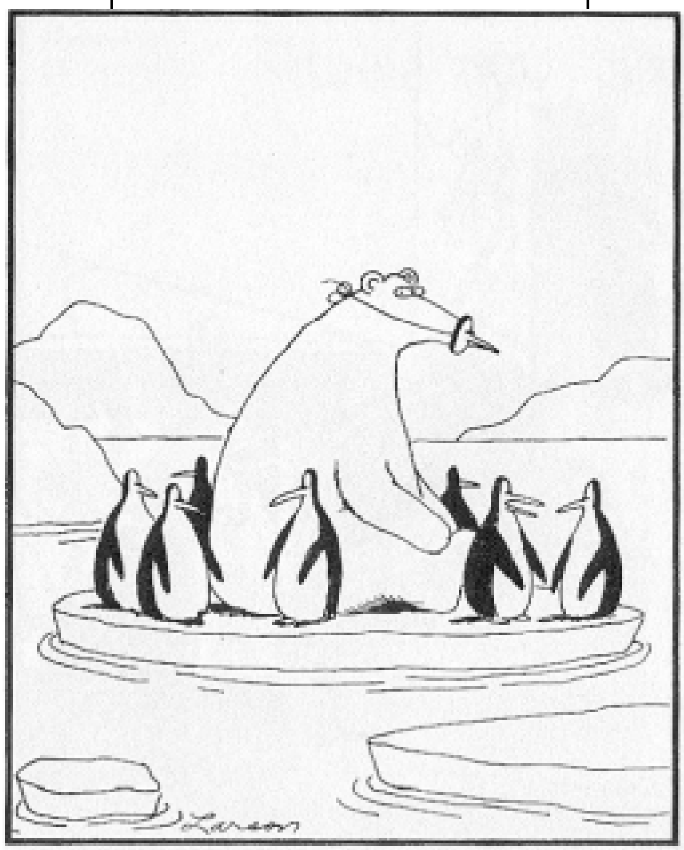
ER: If we followed this path, what would be the effects on the U.S. economy?

DK: The current assumptions are that to stabilize atmospheric carbon dioxide concentrations at levels of 450 to 500 parts per million would require a marginal price on carbon, perhaps through a tax, that was as high as $1,000 per ton carbon. What does that mean? Well, the U.S. emits about 1.5 billion tons of carbon per year right now. So if you put a tax of $100 a ton on it, it would be a total tax revenue of about $150 billion a year. It doesn't mean that would be that much actually removed from the economy because it could be recycling, but that gives you a sense of what a $1,000 a ton tax would be.

Part of the reason that developed countries have been unwilling to agree to a binding target is the fear that these costs will be as high as that. There's of course a tight coupling between people's willingness to agree to binding targets and assumptions of what the price is. I would argue that if we believe the price was $30 a ton carbon, just to pick a number out of the air, that we wouldn't be having this conversation, that most countries would just agree to do it.

If what we are saying is correct about using fossil fuels without emitting carbon dioxide, then it is true that we could reduce the carbon dioxide emissions from, say, all of the electric sector and from other significant parts of the economy at prices that are more like $100 or $200 per ton carbon, and that's the big deal: it radically buys down the cost of climate control.

The Far Side by Gary Larson



"And now Edgar's gone . . . Something's going on around here."

ER: How would that play out? The primary generators of carbon are electric power plants and automobiles.

DK: In the electricity sector it's most understandable, and the reason is that we already have an electric grid and the electric grid more or less doesn't care where the electric power comes from. So if you replace an existing coal facility with a huge wind farm or a facility which burns fossil fuels without emitting carbon dioxide, the electric grids would still function the same way and the consumer doesn't care or know where the electricity came from. So in that sense it's fundamentally easier to introduce these new technologies in the electric sector than, say, in transportation.

If you want to decarbonize the transport sector the obvious thing to do is use a fuel which doesn't contain carbon, and that means hydrogen or electricity, and both of those are extremely problematic, especially for cars and the light trucks that people use as cars in this country. That sector is perhaps the single hardest thing to deal with. But my answer is that you can just leave that for last. In fact transportation accounts for about 30 percent of total U.S. carbon emissions, but only 60 percent of transportation is personal automobiles, which are the hardest thing to deal with. So despite the hype about fuel cells and hydrogen, it is one of the hardest and most expensive places for us to make progress on this topic and I don't think it's a wise place to start.

ER: So personal transportation only represents 20 percent of our total carbon emissions?

DK: Yes, and in Europe the share carried by personal automobiles is less. One cannot overstate how large a change this is in our thinking about the future of fossil fuels. In the 1970s most of us thought that the future of fossil fuels would be short because we would run out. In fact in those days we were told that the reserve to production ratio then was about twenty or thirty years; that is, we should be running out about now. Now, with much higher rates of production of natural gas, the reserves have grown so fast that the reserve to production ratio is eighty years. So in the 1970s we thought the future of fossil fuels would be short because we would run out. I think we can now say that that is simply false on the time scales that matter for the climate problem. There are large fossil resources.

Second, those of us who started to get worried about climate in the last decade or two thought that the future of fossil fuels was short because there was an unbreakable link between using fossil fuels and putting carbon dioxide in the atmosphere. These technologies of industrial carbon management may not be the wise choice, they may not be the choice we're going to take, they may have real environmental problems, but it is now clear that that second proposition is also false: we can use fossil fuels without emitting carbon dioxide to the atmosphere. This changes our thinking about the energy future of our economy and allows us to at least consider using fossil fuels for a century or more into the future and still deal with the climate problem.

ER: How do we decide which way to go?

DK: I think we need a broad discussion that involves the whole citizenry of our democracies about what energy future we want because there are in fact many ways we could deal with the climate problem. So while some people would have you believe that we're heading towards a brick wall and that there's the potential for global disaster if we don't act, I think the reality is not like that at all. I think there are several different routes which likely would work.

ER: What are some of the options?

DK: One route is that we let carbon dioxide go to quite high levels and just adapt. Most of us live in cities and don't care much about nature despite the fact that we like to watch it on TV. We in the developed countries have enough technology to allow us to substantially adapt to quite significant changes in climate. This is not a course I want to follow, but it's a course that could be followed.

Another course is that we could consume less. Again, most academics don't like to talk about that because it's a moralistic issue, but clearly one of the ways to deal with this is that we could cut primary energy consumption dramatically. Lots of other societies seem to be perfectly healthy and don't seem to derive any less happiness than we do at per capita energy consumption that's half or one third ours. There are many countries in Europe we could point to that have those numbers, and it is not simply that we are physically large, it's that we use a lot of energy.

Thirdly, we could do large-scale renewables. It is certainly possible to use wind and biomass especially, which are the renewables which have reasonable prices nowadays, and it's possible to use those at much larger scale than the renewable community has traditionally thought about in order to reduce carbon dioxide emissions. There are real environmental problems with doing that, but it's doable.

It's also possible to use nuclear power at a large scale; and it's possible to use this technology I'm talking about, using fossil fuels without emitting carbon dioxide. I think the solution will be some mixture of all of the above. It's important to realize that there are a number of possibilities, but some real dialog about what future we want is necessary because this is not just a technical choice. There are real implications with respect to people's values: how much you value, say, the land that might be used by a biomass farm, or how much you value risks associated with nuclear energy, or how much you value the damage that might be caused by the continuing extraction of fossil resources, because even if we use fossil fuels without emitting carbon dioxide, we still have to drill for oil and mine coal and there are environmental consequences of doing that. None of these answers is environmentally perfect.

I think one of the hard things that will have to happen over the next decade or so if this debate is engaged is for all sides to realize that there is no perfect answer here. All the large-scale renewables that we currently have on the table at a reasonable price have some serious environmental drawbacks, so it is by no means an easy choice. There are some that are currently too expensive for which the environmental drawbacks are much less. Solar photovoltaics would be great, but currently it costs a factor of ten more than the other ways that we have to generate electricity, and that's after a decade of large-scale research and product manufacture. I think that there's some question about whether we'll be able to bring those prices down soon enough for photovoltaics to have a big impact on stabilizing carbon dioxide emissions over the next fifty years.

All the large-scale renewables that we currently have on the table at a reasonable price have some serious environmental drawbacks, so it is by no means an easy choice.

ER: Isn't solar the electricity source of the future?

DK: Solar photovoltaics may play a central role in the second fifty years of this century, but if we care about stabilizing carbon dioxide emissions, we have to do a lot in the first fifty years, and I think you have to be a true believer in solar panels to believe that they could get cheap enough and to diffuse quickly enough to play a big role on that time scale.

ER: If we keep burning fossil fuels, where is the best place to store the carbon?

DK: That's right, if we wanted to go forward with substantial use of fossil fuels without emission of carbon dioxide, we have to put the carbon dioxide somewhere. There are three kinds of choices: you can put it in geological structures, this is something that we already know something about.

Or we could put it in the ocean, or we could react it with silicate rocks to form carbonates, which is the natural longest time-scale sink for carbon dioxide anyway. This last is the most speculative option, and currently seems to be the most expensive but does offer permanent storage and completely environmentally compatible storage. But oceanic disposal is currently not taken seriously by the environmental community, and I don't think it's likely to be. So while I think there are some arguments you might make for keeping oceanic disposal of carbon dioxide on the table, I don't think it's going to play a role.

If you talk to people who do geological injection of carbon dioxide in the oil and gas business, they think this is as easy as falling off a log, that we could easily inject large quantities of carbon dioxide and, with technologies that are quite foreseeable with the knowledge we have now, ensure that the carbon dioxide stayed underground for the time scales that matter for the climate problem, which after all are only a couple hundred years or perhaps a thousand years at the most.

But in fact, the experience in enhanced oil recovery in the oil and gas business does not necessarily give us such extraordinary confidence because in many of those businesses they try to recover the carbon dioxide so that they can use it again in the next field. They try not to leave too much of it underground, and they have not done any long-term monitoring of how well carbon dioxide stays in formations and, how well the wells are sealed up because it simply hasn't been an issue for them. Clearly, if we were going to do this in large scale there's a lot of technology and science development that needs to be done to be sure that we understand it.

Separately, there has to be a regulatory foundation built. We have to have some idea of what the goal is, and right now there is none. Is the goal one percent leakage in a thousand years or one percent in ten thousand? Both those numbers seem to me to be plausible, but it makes a big difference which one we choose. If there were a carbon tax tomorrow and as a company I actually wanted to do this, there's nobody in the federal government to whom I could turn who would be able to tell me what the answer was. There are some existing regulations for injecting toxic waste deep underground. This is something we do, and there's a reasonable, well-developed process where non-governmental organizations are actively involved in the process of certifying these sites, but I think that's different from the way that we would treat carbon dioxide.

So there's a lot of work to do, even assuming we decide that we want to go down this road, in developing a policy system that works, that has real public involvement, that has the involvement of environmental non governmental organizations, that has the involvement of the government and the oil business to figure out how to permit and site these facilities.

ER: Is decarbonizing fossil fuels just a matter of stripping the carbon dioxide in the waste gas stream?

DK: Not necessarily. There are a couple of approaches. In a way the most obvious is to take a normal power plant, and just as we now remove sulfur and nitrogen oxides from the waste gas, we can also remove carbon dioxide from the waste gas. That's the thing that we currently do in a few plants in the world when people want the carbon dioxide for some purpose. But that's by no means the only way to do it. It's my guess that will not in the long run be the cheapest way to do it, but in the beginning it may be cheap because we can apply it to existing facilities.

It's also possible to take fossil fuels and reform them to produce a carbon dioxide stream and a hydrogen stream; then you can burn the hydrogen to produce electricity. That method is called precombustion decarbonization.

Thirdly, it's possible to burn the fossil fuel in pure oxygen and then all you have to do is separate out the water and you have a pure carbon dioxide stream.

Those are the three basic methods and right now it's an open race which one wins, but there are policy implications. You might say from the outside of the power plant, unless you're an engineer, who cares what's going on? Well, it actually matters. If you pick precombustion decarbonization, that means you have large-scale production of hydrogen without carbon dioxide emissions inside that plant, so you can then grow a hydrogen economy by starting to sell that hydrogen over the plant fence into pipeline networks or into large transportation vehicles or what have you. Many of us think that there are some reasons to weight the competition a little bit in that direction because of the advantages of getting started on the hydrogen infrastructure, but currently it's an open proposition.

ER: What is a realistic estimate of how high atmospheric CO_2 will go?

...whichever road we take, we'll find the costs are likely less than we thought, that's been our history of previous environmental controls...

DK: The conventional view in climate policy circles is that anything under about a 550 parts per million target, which is roughly equivalent to a doubling, is aggressive and that would be a real win for the environmental community to get us to actually stabilize under 550. My guess is that views on this will steadily shift and that while there is essentially no clean way to monetize what the actual damages are of the climate change that would ensue from a doubling of carbon dioxide, that over the next twenty years as people think more and more about whether that level of interference in the global environmental cycles is acceptable, that we will move towards lower and lower targets. This is just my personal prediction. And in fact while the economic damages for doubling carbon dioxide are likely not large, there are going to be substantial damages to unmanaged ecosystems that many of us care about, high mountain ecosystems and the Arctic are two prominent examples.

I submit that since it seems like there are solutions and prices we can actually pay without breaking our economy, then in fact there will be a steady pressure to lower the target. And as we start to build the technologies that reduce carbon dioxide emissions, whichever road we take, we'll find that the costs are likely less than we thought — that's been our history of previous environmental controls — and that we will in fact be able to do this. That's my optimistic take, and that we'll do it at quite an aggressive target in the long run, whatever the next ten years of Kyoto negotiations has to say.

I think that the fact that carbon dioxide capture was essentially not even on the table a decade ago shows you how poor we are at predicting technological innovation. It's my judgment that if we start to lean hard on reducing carbon dioxide emissions from our industrial societies, that there are in fact quite a number of ways to do it. While it's certainly much harder than earlier problems like reducing sulfur emissions, it's doable and there will be growing public pressure to push harder. But the question is what to stabilize at, and the answer will depend on the costs of stabilizing at different

Table of Contents: *Environmental Review* Volume Six

January - December (2000)

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Environmental Review

Volume Eight Number Three
March 2001

numbers.

I think this is essentially an issue of how we go about managing the planet, which is and will increasingly be a focus of concern for the industrialized world. We will not have a global catastrophe, I believe, if we increased carbon dioxide content by 50 percent or even a factor of two. But the question is, how important is it to us to maintain some ecosystems and some relics of the world that was here before we started to manipulate it? We'll have to grow into deciding that.

ER: How long will it take for us to get a handle on greenhouse gases?

DK: My guess is actually this issue will go away, that eighty years from now the climate problem will be well in hand and won't be a big topic any more. We may instead be more concerned about the large-scale manipulation of the environment by the systematic release of genetically modified organisms. I don't think there is that much danger of accidental release, but we will increasingly see people desiring to manipulate the environment directly by large-scale modification of both human and nonhuman genomes. I would guess that this whole climate concern will gradually fade away.

Editor's note: The U.S. Department of Energy has an excellent Website on fossil fuel technologies at www.fe.doe.gov

NEXT MONTH

ARE PARKS A GOOD CONSERVATION TOOL?
Richard Rice & Aaron Brunner

HOW TO IMPROVE SNAKE RIVER SALMON SURVIVAL
Michelle McClure

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