Earth's Future: Taming the Climate
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Michael McElroy, PhD, Harvard University
Earth's Changing Climate: Past, Present and Future

Introduction by G. Michael Purdy

G. Michael Purdy: Now it's my privilege to introduce our first keynote speaker, Michael McElroy of Harvard University. To anyone familiar with climate science Professor McElroy needs no introduction. He was the founding chair of the Department of Earth and Environmental Sciences at Harvard, as well as its first director of the Interdisciplinary Center for the Environment. He's a world leader in the study of the effects of human activity on the integrity of the global environment. He is uniquely well qualified to open our symposium for us this morning. His keynote presentation is entitled "Earth's Changing Climate: Past, Present and Future." Ladies and gentlemen, Professor Michael McElroy.

Changes in Atmospheric Carbon Dioxide

Michael McElroy: I have to say this is a formidable task. Mike Purdy asked me to speak to this group and to provide in thirty minutes or so a complete summary of what we know about climate, past, present, and future, and not to leave out any of the significant contributions made by many in this audience.

Let me tell you a little bit about what I'm hoping to do in the next thirty minutes or so. I want to first of all talk about what we understand about the changing composition of the atmosphere, so I'll talk about the information we have on changes in carbon dioxide, the most important of the greenhouse gases. I'll show you and talk about the changes that we see in methane, which is the second most important. And I'll show you nitrous oxide, another important change that's taking place. And then I'm going to switch attention and look at the climate record itself, what changes are taking place, what is our understanding of those changes, and I'll make some comments which will be perhaps mildly critical about the interpretation placed on our level of certainty about what is causing the obvious recent climate changes that have taken place. And then finally I'd like to offer some personal comments on where I see the sensitivities of the climate system to really lie, what are the changes that we really have to watch very carefully if we're going to chart a wise course to address this problem.
So if I can figure out how to use this technology let me begin with this slide, which summarizes the changes in carbon dioxide observed over the past thousand years. And the wonderful record that we have from ice cores has played a critical role, it seems to me, in giving us this historical sense of the changes that are taking place, back as far as 450,000 years before present. But over the last thousand years, you see the changes in CO₂ that occurred most recently, beginning in about 1700–1750 A.D., CO₂ begins to rise and it begins to rise extremely rapidly. Now today we're up at 370 parts per million and surely going to go much higher in the near future.

The changes in CO₂ over the past 450,000 years, also very interesting from the Vostok record, and what you see here is that during the colder periods of the planet's history carbon-dioxide levels were down around 190 parts per million, and during the warmer periods they were up about 270, 280, 290 parts per million, so over the past 450,000 years, as best we can tell, we're in new territory. The CO₂ levels are now higher than they've been at any time over this period of almost half a million years.

Now this is an interesting story also. There's a very interesting paper by Bill Ruderman (formerly at Columbia) recently, which suggests that the human influence occurred much earlier than people basically currently think. In other words, the human influence doesn't simply date from the industrial revolution, but it goes back to the beginning of agriculture. And it's not only the impact of deforestation associated with clearance of land for agricultural purposes, but also, I think even more important perhaps, the use of trees as a feed stock for metal smelting in this early period. Now the beginning of modern agriculture dates from about 11,000 years before present, and this chart is showing that the CO₂ level as it comes out of the last ice age begins to rise at about 8,000 years BP. Now coincident with that rise is a drop in the value of del ¹³C. So the carbon in the atmosphere is becoming lighter at this period, and the simple interpretation of this is that that increase in CO₂ is caused in significant measure by release of biospheric carbon, isotopically light biospheric carbon.

**Atmospheric Methane and Nitrous Oxide**

Switching attention now to methane, the concentration of methane has also risen extremely rapidly over the past 250 years. You see it's relatively flat from 1,000 years A.D. to about again 1750, at a value of about 600, 700 ppb in this case. Where now up at 1800 ppb, and with an uncertain future in terms of what's going to happen to methane in the next few years. The summary of the changes in methane that have occurred since 1983, this has been much interpreted, as an indication that maybe the rise in methane is over. You can see that the growth rate has slowed down in the '90s, and the growth rate is specifically indicated in the bottom part of this figure.
Now we have a paper in press at the moment, James Huang, a former student is the primary author of this paper, which has interpreted these data and shows that you can actually do a pretty good job of interpreting the trend in methane over this period, the slowdown attributable largely to the fact that the production of methane from cattle in particular is asymptotic. The number of cattle in the world, believe it or not, is sort of slacking off, the growth rate in the number of cattle is slowing down. And so also is production of rice, or at least the land devoted to rice, which is the second significant source of methane. However, the bad news is that this is not likely to continue because the source that is not kicking in is the source associated with the growth in the natural gas industry, and so I don't think that one can take for granted that methane has reached an asymptote and is going to stay flat. More likely it's going to resume its upward trend, with the possibility that that may be even more rapid for reasons that I'll come back to in a little while.

I might also comment that in the analysis that we've been doing on methane, there is beginning to be a case to argue that the concentrations of OH, the primary sink from methane, may be overestimated in current models. In other words, the lifetime of methane may be a little longer than the literature currently suggests. What's the implication of that? Well the implication of that is that if the lifetime of methane is longer than the greenhouse gas, forcing potential of methane will go up, so methane may become a more important radiate of forcing of the climate system than we currently believe.

The variations in methane over the past ice age are also very intriguing over the past 110,000 years. And what's particularly intriguing here, the methane date is indicated in the lower of these various panels. The upper panel is an indication of the temperature as recorded by Delo and team. You'll notice over this generally cold period from 110,000 years to roughly 10,000 years is that the methane concentrations don't stay constant. It doesn't simply go down to a low value and stay there; it flickers, and the climate system itself flickers. And these numbers, these interstadial numbers, indicate some of those very significant flickers. And you can also see that some of the increases in methane, which are generally coincident with the onset of a warming event, are extremely rapid in time. In fact, if you look at the one at about 85,000 years BP, that increase in methane is on a rate basis comparable to the increase that we've seen over the past 250 years; it's a very rapid rate of increase. And the flickering of the climate system I'll come back to in a little while. In particular I want to offer some comments on perhaps some new thoughts on how the climate system in these longer timescales is really controlled.

Carbon dioxide is produced by fossil-fuel burning, by deforestation. Methane is produced by cattle, by rice-paddy fields in terms of anthropogenic effects, natural wetlands also making a contribution. Nitrous oxide is the third important greenhouse gas, and this is a really intriguing problem because the rise in nitrous
oxide is also pretty dramatic in recent years, and nitrous oxide is not produced significantly by burning fossil fuel.

The primary source of nitrous oxide is microbial oxidation or reduction of nitrogen compounds. And so the putative contributions here come from agriculture, from chemical fertilizer applied in agricultural systems, and most importantly, in my opinion, from the disposal of human and animal waste. So that increase is basically tied to the fact that our world population is increasing and that we also have an increasing population of ruminants. Nitrous oxide is not only important as a greenhouse gas, it also plays a very critical role in controlling stratospheric ozone.

Fossil Fuels and Atmospheric CO₂

Now a few words about our understanding of CO₂. One of the really critical recent developments in this field of trying to understand what is responsible for the trends that you observe in CO₂ comes from Ralph Keeling, the son of Dave Keeling. And where Dave Keeling spent his life making very precise measurements of CO₂, giving us this incredibly valuable record that goes back to 1958, his son Ralph picked up the same challenge and he said, "Well, if my father can measure CO₂, I'll measure oxygen. And with the combination of oxygen and CO₂, you actually have a very important additional lever on understanding what's going on."

This chart is intended to illustrate how that works. If you imagine starting at some time at point A, and then you release over some period, the analysis that I did here was for a three-year period in the early 1990s, you release a certain amount of CO₂ by burning fossil fuel. Well, you can immediate calculate that that amount of fossil fuel will provide a source of CO₂ that is estimable, and it will also consume some oxygen. So you can estimate that CO₂ level will go up by a predictable amount, and the oxygen will go down. Now the ocean plays an important role in taking up CO₂, but since oxygen is not particularly soluble, ocean uptake doesn't have any significant effect on O₂. So the role of the ocean is to move you back in a sort of horizontal direction. And suppose the actual observation point three years later from point A is point D, you have to get to point D, and the only way you can get there is by following the appropriate ratio of oxygen to CO₂ associated with the biosphere. So this is a really neat technique, and Ralph Keeling's incredible achievement was to make oxygen measurements which were so precise that you could actually apply this methodology.

Now this is a summary of oxygen and CO₂ measurements for the period of the 1990s, and what you see over this decade of the ‘90s is that, okay, CO₂ levels went up, oxygen levels went down. And if you follow this simple analysis that I'm suggesting, you have to invoke not only an uptake of CO₂ by the ocean, but also a net sink of CO₂ by the biosphere. So the global biosphere is currently, at least over the period of the ‘90s, represents a net sink for atmospheric CO₂.
This is a paper by David Keeling and associates, which is a very interesting paper analyzing all of the CO₂ measurements back to 1958. And what he did in this upper chart was to say okay, how can I fit the . . . his assumption was that primary contribution to the increase in CO₂ was fossil-fuel use. Then he said, "Let's now estimate what fraction of the CO₂ that you add to the atmosphere stays in the atmosphere, the rest presumably going into the ocean." So the airborne fraction, as it's called, is 56 percent in this particular calculation that gives you the fit to his data that you see in the upper chart, which is pretty remarkable. So the upper chart is fitting the observations with an assumption that 56 percent of all fossil-fuel use CO₂ release remains in the atmosphere. And David also goes on to essentially try to analyze anomalies over the period of the '80s which I won't particularly talk about.

Now here's a summary of what this means. And what I'm going to do here, and I think Wally may particularly appreciate this, what I'm going to do is to define the airborne fraction here as the net input to the atmosphere excluding the ocean. So if there's a biospheric sink I'm going to subtract it from the fossil-fuel source. When you do that for the period 1991 to 1994, which I did in my book, I got an airborne fraction of 58 percent, compared again with Keeling's value of 56 percent. I said, "Wow, this is really pretty incredible." If you then interpret this a little bit further, you realize that this biospheric uptake is a complicated problem. It's not simply that the biosphere is taking up CO₂, it's that deforestation in the tropics is releasing CO₂ which is being offset to some extent by the uptake of CO₂ at midlatitudes of the northern hemisphere. How do we know that? We know that by analyzing the interhemispheric gradient of CO₂. And the uptake at midlatitudes is not small; it's about one and a half gigatons per year out of a total fossil-fuel source currently of about six gigatons per year. So what actually was happening in the early 1990s, there's no question about this in my mind, is that the relatively large biospheric uptake at midlatitudes stayed more or less where it was, but the tropical deforestation turned off, whereas over the whole Keeling period my interpretation would be that biospheric uptake which was still significant was more or less offset by a comparable source in the tropics. And over the entire period of the 1990s, this is consistent with the result that you get from this analysis that I've just outlined.

**Circulation and Climate Change**

Now let me switch attention and talk about the climate change issue, and I'm going to make a few points which I hope you'll find persuasive. This is the IPCC summary of the measurements for the northern hemisphere, the southern hemisphere, and for the globe, surface-temperature changes. And as you can see the characteristics of the observations that you saw on the previous chart is that the global average temperature from 1850 to 1910 didn't do very much. From 1910 to about 1940 it increased. From 1940 to about 1970 it decreased a little bit. And from 1970 or '75 to present it's been on a rapid upward climb.
Now if you analyze where this temperature change is taking place, as summarized in this particular chart, one of the things that's interesting is that that cooling that occurred over the 1940s to 1975 period you see as largely reflected in the North Atlantic. It's generally a cooling that's most pronounced in the North Atlantic, and you see the very rapid warming over the downwind side of the North Atlantic over the period 1976 to 2000. The North Atlantic oscillation is a fascinating phenomenon, which I think is intimately involved with the changes that we are currently seeing, and perhaps also will be involved with many of the paleo changes that took place.

North Atlantic oscillation, as I'll summarize in the next chart, in very simple terms, at least my simple terms, it reflects the pressure gradient between Greenland and Bermuda; it reflects the pressure difference between the Bermuda high and the Greenland low, which essentially is controlling the speed of the winds that are blowing from the southwest to the northwest across the Atlantic and bringing warm water up into the Arctic and bringing warm air into western Europe. The positive side of this North Atlantic oscillation corresponds to a high-pressure gradient and strong winds. That's been characteristic of the recent past, and you can see. And over this period from about 1970 to present, I think you can make a case that a significant part of that temperature rise is associated with this phenomenon, an intensification of this circulation anomaly controlled by the Greenland and Bermuda pressure gradient. This is from Ahren's book simply showing you for winter conditions the low pressure system over Greenland and the high pressure somewhat to the west of Bermuda, which I think is ultimately controlling this North Atlantic oscillation.

I want to also say the north Atlantic oscillation is not disconnected from the other parts of the polar region, and it's associated not only with strong westerly flow in the Atlantic segment but also with a general intensification of the trade winds. And in particular there's a very recent paper by Ruth Curry and associates that records an increase in the salinity of the tropical and subtropical Atlantic Ocean over the past thirty, forty, fifty years, particularly over the past decade, with a compensating decrease in salinity of the higher latitude Atlantic Ocean. Well I think that may be related to exactly the same phenomenon, that basically the intensification of the trades is in fact providing a larger transfer of vapor from the tropical Atlantic into the Pacific, as well as increased precipitation at high latitudes with the stronger westerlies bringing vapor and freshening up the higher latitude ocean regime.

This is a very interesting chart here because it shows that over the recent period, this is showing you the increase in the heat content of the world ocean and the northern hemispheric ocean and southern hemispheric ocean. So what you see is that the world ocean over the past decade—this period of the past couple of decades, this period of rapid warming—is storing a very significant additional amount of heat. And so you see the indications of this storage in this very interesting paper by Levitas et al.
Issues of concern again related to the recent warming, this is the thinning of the Arctic sea ice. So you see that the extent of the sea ice has been decreasing over this extended period, as has apparently the thickness of the sea ice as well, the presence of multiyear ice has sort of slowed down, the buildup of multiyear ice has slowed down.

So what I want to do here is to emphasize areas of potential sensitivity in the climate system. So this area of the North Atlantic, in particular the influence of the North Atlantic oscillation, basically the influence of the Greenland-Bermuda pressure gradient, which is presumably associated also with the polar distribution of highs and lows around the polar regime in the north, the interesting question is the extent to which that North Atlantic oscillation is currently being influenced by human activity, and that's a question, I don't have an answer. But it is clear to me that you can rapidly change the climate if you adjust that oscillation—the record shows it. I think you can make a very strong case that if you do change the North Atlantic oscillation, you can potentially change the salinity budget of the subtropical Pacific Ocean by changing the amount of vapor that you're sending over with the trade winds. And if you do that, I would presume relatively easily you can change the characteristics of the circulation in the thermocline region in the tropical Pacific, which in turn means that you have the potential to globalize the impact that you invoke in the North Atlantic.

**Learning from the El Niño Phenomenon**

The El Niño phenomenon, then, becomes one of considerable interest. And Mark Cane, who's in the audience, and Steve Zebiak and others have made very, very important contributions to our understanding of this particular phenomenon.

It is clear that if you can change the distribution of warm water across the surface of the tropical Pacific by this interesting interaction between the trade winds and the ocean circulation that you get a global impact associated with that, you change the global climate. It's not particularly surprising because what you really have done by distributing the warm water and capping off the cold is you really have changed the average temperature of the tropics quite significantly during an El Niño as compared to the opposite phase the La Niña. And particularly in the winter hemisphere you see dramatic associated impacts on climate, hot, dry, wet, and so on.

This is a set of papers that I find very, very intriguing, and Mark was involved with this as well, but this is an attempt to reconstruct the characteristics of the going back to 1880. I haven't seen a detailed statistical analysis here, but my sense is that—and this is consistent with some of Dan Schreib's work—my sense is that it's been warm more recently than it's been cold, that the El Niño has been a more common phenomenon over the recent, since about 1975, than it was earlier, and Kevin Trenberth has drawn a similar conclusion from a statistical
analysis of data such as this. And of course the two biggest El Niños are in the last twenty years.

Just to make this point about the salinity distribution in the current world's ocean, you see in the subtropical Atlantic, that big red patch is the high salinity region, the salinity has increased in that region over the past thirty, forty years according to Ruth Curry's very interesting paper, and it has decreased in the high latitudes. Now look at that sort of patch of blue that goes off the coast of the Panama Isthmus. That's low-salinity water and that wedge goes out and I think the conventional interpretation is that's associated with precipitation originating in the Atlantic, and is an important part of the circulation that maintains the salinity gradient between the Atlantic and Pacific, and that ultimately controls the conveyor belt that Wally has so creatively discussed in many of his papers.

**Good and Bad News**

Good news, bad news. The bad news is that there's certainly indications that the recent climate, the last twenty years or so and particularly the last ten years, has been pretty unusual. It's been getting warmer and, you know, people can make the connections between what fraction of the nine warmest years in the record occurred in the '90s, statements like that. But the good news is that there's no particular trend in some of the weather phenomena that really has a big impact on our lives, at least in this part of the world. The upper chart is a summary of all U.S. hurricanes going back to 1900, and the black lines indicate the major hurricanes. And the bottom one is a summary of all hurricanes, all major storms. And I don't see any particular indication that we're heading for a disaster associated with the warming that's taken place. Now that doesn't mean that the disaster is not around the corner. Hurricanes, I think as most people know, there are several factors that influence the probability of getting hurricanes in the Atlantic. One is temperature, so it's getting warm, you've got a better chance of triggering the conditions for a hurricane. But the other is the strength of the trade winds, and if you have strong trade winds, you tend to carry the top off the hurricane, it doesn't really get going, the vector system doesn't really grow. So it's quite possible that we've had the warmer conditions to generate hurricanes in the '90s but the stronger-than-usual trade winds associated with North Atlantic oscillation maybe has moderated that, and is that likely to continue in the future? Who knows, but it's certainly something that one to be concerned about.

Same comment about tornadoes. Again devastating weather phenomena in the middle part of the United States, but no significant indication that they're increasing in frequency or intensity.

**Radiative Forcing and Climate Change**

Now I want to talk a little bit about radiative forcing, what's ultimately driving the climate system. And here I'm going to be, I'm afraid, a little critical of some of the conclusions reached by IPCC. This is the IPCC summary of what we know about
radiative forcing. What does radiative forcing mean? For those of you who don't live with this thing every day, this is basically the fact that . . . let's take CO₂. As you increase the CO₂ content of the atmosphere the atmosphere will begin to radiate infrared radiation to space from a higher level, so it will radiate energy to space less than it did before. But if it's absorbing the same amount of sunlight. That means that the Earth's system is gaining energy. And this is a measure of the amount of energy that it's gaining, and radiative forcing is a measure of the net absorption of heat from the Earth's sun system. And so you see on the left-hand side the greenhouse gases: CO₂, methane, nitrous oxide, halocarbons. A little bit more than half of the greenhouse gas forcing is coming from CO₂. Given the caveat I mentioned earlier, maybe that methane contribution is going to go up.

Tropic area ozone, when the IPCC One did its analysis, what they did was to try to compare the model calculations of temperature trend over the past 150 years with what was actually observed, so they're basically testing if our understanding of greenhouse forcing is consistent with the observations. What did they find? They found that they were overestimating the observed change in temperature, and they expressed some concern. In other words, models were predicting a larger temperature change than was actually observed. Now after that IPCC One analysis people started thinking well what else could be going on? And they came up with the idea that sulfate aerosols, sulfur released by burning coal, could provide offsetting cooling, and so the new generation of models were exercised including sulfate cooling. And as you'll see they get very good agreement with the global average temperature by tuning the amount of sulfate cooling that takes place. What that do not show you, however, is that had they done that analysis separately for the two hemispheres, in my opinion, they would've found that they would not have gotten any good agreement for the southern hemisphere because sulfate will not be important in that hemisphere. The lifetime of sulfur in the atmosphere is just days to weeks, and they probably would not have gotten as good a result for the northern hemisphere either. So one must be very cautious about drawing conclusions about understanding, unless you are really critical about the underlying assumptions.

Now here's the most recent IPCC analysis with all forcing, and if you look at the bottom chart—but notice this is only global average temperature—if you look at the bottom chart, it looks extremely convincing. I mean it looks like they're picking up a lot of the wiggles and so on from a combination of greenhouse-gas forcing, warming, added to which is sulfate cooling, and some black carbon, and some solar variability, many of those factors extremely uncertain, particularly with the aerosol contribution. And voila, at the bottom it looks good. But my strong suggestion is that if you look at this comparison for the northern hemisphere and southern hemisphere separately you might find that things didn't look that good.

Now how do you do these analyses? Well, it's a very tough problem, I don't want to belittle the incredibly important contributions of many people to this climate
modeling exercise. If you are going to describe the climate system, you need to be able to describe the circulation of the atmosphere; you need to be able to describe how it interacts with the ocean and vice versa; you need to be able to describe how sea ice is changing; you need to be able to describe release of energy even associated with cracks in the ice, which can be very significant in winter; you need to be able to describe the changes in the biosphere. It's an incredibly complicated problem. And so the general circulation groups who tried to tackle this problem, they tried to start off in 1850, and then the question is, Can I validate my model by showing that it gives a good record of the changes in temperature observed from 1850? And if it does, then I have some confidence in its ability to predict forward into the future.

Now there's a number of problems with that in my opinion. And the model can be shown to give good agreement with what's been observed as we just saw on that previous chart. The problem with it is that you start off assuming that the climate system is in some steady state. In other words, you ignore the natural variability of the climate system on scales like centuries, like the Little Ice Age in the medieval optimum. And even this chart from IPCC shows that things have not been constant up to 1850. So if you are not capturing in the model the natural centennial scaled variability, and you're now trying to do a test over a 150-year period, beware. I mean that's not necessarily going to give you convincing and conclusive results. And again, scientific honesty in my opinion dictates the appropriate level of caveat on the conclusions drawn from that, which are missing to some extent from the IPCC.

The Last 10,000 Years of Climate Change

Changes in climate over the past 10,000 years. This is a paper that I used extensively in my book a few years ago, which I find extremely interesting. This is a record of changes in a snowfield in Norway, bottom coming out of the Younger Dryas period you see warming coming out of the Younger Dryas, then you see this event of cooling, which Richard Donnelly talks about very nicely in his beautiful book. This is an indication of a final degorging of ice, perhaps through the Hudson Bay route. I think this may be the indication of that cooling event. The timing is probably wrong, but I would guess the timing here has to do with uncertainties in dating of the various events here. Then the snowfield disappeared completely, and then beginning about 5,000 years ago it begins to grow back, and you see these ripples.

The data are represented by the continuous line here. This is the author's interpretation of what the temperature was doing over this long period. You see the warming coming out of the Younger Dryas period, followed by the cooling of this most recent ice degorging event, 8,000 years or so ago, then the warming up the thermal 5,000–6,000 years ago, and then a slow cooling. And what I did on this chart is just for the heck of it I thought I would fit this using the solar insulation at that latitude for the summer sort of a classic Milankovitch kind of
story. And so that dotted line is exactly that. Now I don't pretend that the
temperature in Norway is controlled by summer insulation necessarily, but at
least gives your eye a very good guide to understand that these ripples that are
on that line represent climatic variations that are not insignificant. I mean they
may not be as big as the flickers that you see during the Ice Age or associated
with the Younger Dryas, but they are in human terms significant. The medieval
optimum period, Little Ice Age, these are ripples that we need to understand, and
if we don't understand them and we don't model them I would raise questions
about the absolute validity of the tests that we apply to our understanding of
what's happened in the past 150 years.

Changes in climate over the recent past, the Quelccaya ice core and the
beautiful work by Lonnie Thompson and his colleagues is very intriguing because
the accumulation of snow in that ice field is strongly correlated with the El Niño
phenomenon, with the tropical ocean. And what you see here going back over a
1,500-year period or so is that there are extended periods of higher-than-normal
precipitation and lower-than-normal precipitation. And I would say that the
indications here are that you do have significant centennial-scale variability in the
tropical climate system, and I think also presumably in the global system
associated with that. You might also say that one of the very intriguing results
here is that, as many of you know, this core was drilled in 1974–5 or so. These
guys went back to Quelccaya to get the last twenty years record and they found
out they couldn't get it because between 1972 and 1990 it had rained and the
surface ice had melted and percolated through the core and the core was gone
essentially as a useful scientific tool. So there's no doubt that tropical climate in
the high Andes in the subtropics, at least at Quelccaya, was anomalous over a
1,500-year period for the last decade.

I wanted to use this mostly to raise a speculative—I don't think it's that
speculative—suggestion. My sense is that if you look at the recovery of the Earth
from the last ice age, and if you look at the lowest chart here . . . what I find
intriguing here is the indication that the recovery from the last ice age first shows
up in Antarctica and then on a delayed basis, maybe 3, 4, 5,000 years later you
begin to see the effect in Greenland. And this is a fairly characteristic thing it
seems to me of many of the climatic fluctuations that are recorded in the ice
cores and in the deep-sea records. So what can be going on here? The rapid
warming that precedes the Younger Dryas is indicated in the GRIP's core, and
there's a cooling that precedes the warming, cooling in Antarctica that seems to
precede the warming seen in Greenland.

Wally's sort of view of the general circulation difference between glacial and
interglacial time is illustrated schematically here, the idea being that today we
have deep water forming largely in the North Atlantic and a small intrusion of very
cold, relatively fresh water from Antarctica, but in glacial times maybe the system
reversed, and you had the Antarctic source playing a much larger role than the
source in the high-latitude northern region. So the question is, What might be
changing the role of the southern part of this conveyer belt? How can you modulate the supply of cold water, deep water in the southern region?

I think that focusing attention on sea ice in the southern hemisphere is a very important thing to do. You'll notice here that Antarctic sea ice is very extensive in the local winter season, and it could be extremely variable. And my suggestion is that a very important control on the climate system, particularly in the longer timescales, may be exercised by the changes in insulation, I suggest, in September at a latitude of about 40 degrees south. Why do I pick that? I pick that because it gives a very good fit to the total climate record, as a matter of fact, but on a physical basis the idea is that that's the region where the export of heat from the atmosphere has the potential to beat back the spring advance of the sea ice. And once you do that you've liberated an enormous heat source. The ocean is warm compared to the atmosphere in winter, so you have this big heat source, and I think that's a plausible explanation for what you see in Greenland. And the associated changes in circulation are going to have a major impact, I think, on how the recovery from the glacial condition might occur. That's not to say that the conventional Milankovitch operation mechanism in the northern hemisphere is not also operating.

Here's a comparison of . . . conventional forcing of the climate system is to use June insulation at 60 degrees north, and actually it doesn't give a very good fit to the Greenland data because it would suggest that the warming in Greenland should've occurred at about 25 K BP. However, the September insulation at 40 degrees south gives a very good fit to what you observe in Greenland, and I think that the climate change coming out of the Ice Age and throughout the Ice Age is in fact a combination of the two.

Now I need to wrap up very soon, but you may have noticed that the climate system was extremely variable between 30 and 60 thousand years BP. That's when you had all those interstadials and methane flickers. Notice that over that 30 to 60 K period, there's more variability in insulation at 40 degrees south than there is in the north. This is the competition between the processional effect and the up and down nodding of the rotation axis, playing a differential role at different latitudes.

This actually was just to illustrate. The shaded area to the right is showing this 8.2-kiloyear event that I mentioned earlier, this flicker that may be associated with the last degorging of ice from North America.

**Modeling the Future Climate**

Now a few words about the future. Given all of the uncertainty, it's a pretty daring thing to predict the future. But I don't think that the criticism that I've tried to advance here of the certainty with which we can do a direct attribution of changes in twenty years to a particular cause takes away from the concern about what may happen in the future. And our best effort to understand what might
happen in the future is going to come from those same models that I'm actually being a little bit critical of. Now this is a chart that I took from the Hadley Center, I don't know that it was ever actually published, but with their permission I included it in my book. What it shows, in their case . . . this is using one of the IPCC profiles for future growth in CO₂, a relatively moderate one, they're talking about quite significant changes in global average temperature and differences as you would expect between ocean temperature and land temperature. The next chart is the temperature map that they produced for 2040–2050, so if you think about Columbia being founded 250 years, it's sort of like the next 250 years. But it's actually less than 250 years because this particular chart is actually for 2040–2050, so it's of real practical interest to people alive today. Now what does it show? Well it shows, as most models do, that you have very significant warming, particularly at high latitudes in winter. And there are good reasons why that should be the case. That's where the trapping of heat in winter is going to have the biggest impact. There's no sunlight, you trap the heat, it's going to keep summer warming in place for a longer period of time, and so you've got a warmer high-latitude regime.

But the more interesting thing for me, and the reason I included this chart, was that it shows a very significant warming, like 6 degrees, in the Brazilian rainforest region. In fact this model predicts that the rainforest in Brazil will disappear in twenty, thirty years. And why is that? Well, the next chart gives you the clue.

This is the diagnostics in the model of precipitation. And what it implies to me is you'll notice that Brazil becomes extremely dry, and so it becomes very dry, and that means it gets very hot because you don't have evaporative cooling taking place, and you don't have that nice forest system maintaining a reasonably benign temperature. And what I think this says, and there's no discussion that I can see in the Hadley Center Web page of what they think it means, so this is just my off-the-cuff interpretation of what it is. It looks to me as though their model is actually predicting a significant change in the characteristics of the tropical Pacific Ocean, and is predicting what you might describe as a sort of a permanent El Niño kind of condition, the thermocline perhaps going deeper, because you've got a larger warm water pool in that region. And so as a consequence you get the predicted El Niño effect, you get droughts in Indonesia, and you shift the precipitation pattern closer to the central Pacific, and you get droughts in northeast Brazil, which are problems of today for places like Fortaleza or Ceará. And if this were the case, there were a real indication of what could happen in the future, this is a big deal. I mean it's a big deal for a lot of poor people who will have great trouble in adjusting to this particular problem. So I'm a skeptic about our level of confidence, but the analogy I would use is that I'd buy fire insurance for my house, and I don't buy fire insurance with the hope that the house will burn down, I buy fire insurance with the hope that it will not burn down. And same thing with this climate system: the weight of the evidence is that this is a big deal problem, and we have to take it very seriously. But at the same time I think we in the scientific community have an absolute obligation to be
scrupulously honest in how we state our confidence and our understanding. And in this high-visibility world where a word here becomes a newspaper headline, there's a great danger that we're not sensitive enough to how these things can go. But certainly official or semiofficial reviews such as IPCC has to be super cautious, and I think on the whole IPCC does a very, very good job, so my criticisms are really not that serious perhaps in the larger sense.

Preparing for the Future

Let me wrap up with a few summary charts.

Is human activity largely responsible for the recent rise in greenhouse gases? Not a question, there's no question about it. So you cannot play around with crazy interpretations of what's responsible for the rise in CO₂ or methane or nitrous oxide of CFCs. We know what they are, and they're all associated with different forms of human activity, fossil fuels, animals, people, those are the primary forcing functions.

Now can you conclude based on the global average-temperature trends over the last thirty years or so that anthropogenic forcing is necessary the primary cause? No, I don't think you can absolutely draw that conclusion for all the reasons I said, natural variability we don't understand, we've got to work harder to understand. But I think it's still likely that human activity is a big deal for the reasons that I've tried to state.

Uncertainty is a two-edged sword, so whenever we talk about potentially modest changes in the future, if you a person that wants not to take it seriously, just remember that uncertainty goes the other way, too. And there's surely a tendency, a bias, in models to give you a slow secular change whereas the complicated physics that gives you the rapid change is probably not going to be easily resolved by the model unless it has some clue as to the underlying cause. I mean the models are not going to get the El Niño phenomenon unless they explicitly work to get it. So I think that the problem could be worse rather than better.

Now number four here. I think in terms of really getting ready for the future and keeping an eye on things we should be particularly sensitive [to], not just to the global average-temperature trend but specifically to where we think there are opportunities for rapid change. And I'm sure there are more, but I've sort of highlighted three here, one of which I haven't actually talked about it. One is this NAO; the other is the behavior of the tropical Pacific—is there any change in the average position of the tropical thermocline? If it's going down, that's a warning sign; if it's going up, that might be good news for those who wish to argue that the climate system is going to warm up more slowly. The stratosphere I want to mention is a very interesting one because some of the biggest changes that have occurred in the climate in the past, periods where the polar regions didn't cool off,
are probably in my opinion the result of intense releases of methane converted to water vapor in the stratosphere, the water vapor in the cold polar regions forming relatively dense polar stratospheric clouds, providing the world's greatest greenhouse. And today a significant fraction of the water vapor that is produced, that you see in the stratosphere, actually comes from oxidation of methane, and it is further controlled by the climate system underneath. The water vapor that gets into the stratosphere is drawn in by waves breaking in the stratosphere. We need to keep an eye on that because upper-level water vapor is the critical part of the water greenhouse effect, not the lower-level water vapor. So there's the potential for rapid change there that we need to be watching. And finally, feedback we haven't really worried about too much, we need to be careful about. For example, there's no doubt that the record suggests that we're seeing significant warming in the polar region. Well, if you have warming in the Arctic region what is that going to do to CO₂? I suspect Steve Wofsy may say a little bit about that, but the indication is that you're beginning to see where carbon is going into the biosphere at midlatitudes, at higher latitudes with winter warming CO₂ is being released from the tundra, but in particular here's an incredible place where you might get a heck of a lot of methane, not just from methane captured but just simply from bacterial activity associated with the water logging and the oxygen deprivation in those very, very rich organic soils. There's as much carbon in the tundra region as there is in the entire tropical rainforest environment, so that's a source that we need to keep an eye on. And so you can imagine other feedbacks here, with warming you get more methane release, you get more CO₂ release and then the problem is fairly clear.

Final comment and I'm going to wrap up. I want to come back to repeat what I tried to say about our understanding of the CO₂ cycle. I believe that there are three factors that are critically important in determining the current and future fate of CO₂. One is the amount of fossil fuel we release. The second is the continuing capacity of the northern midlatitude biosphere to suck up carbon. And the third is what we're doing with deforestation in the tropics, in Indonesia and in Brazil. The deforestation averaged in the tropics is accounting for something like 20 or 25 percent of the . . . it's a contribution equivalent to 25 percent, maybe as much as 25 percent, of the fossil-fuel source globally. The biospheric uptake is about the same magnitude, but varying year to year, which is what you see reflected in these oxygen-CO₂ trends. The easiest thing we could do to slow down the rate of change of CO₂ would be to provide incentives to discourage deforestation of the tropics. You can pick up one and a half or two gigatons a year, and I think you can do that in a fashion that would be of great benefit to biodiversity, and of great benefit to maintaining the integrity of the tropical ecosystem, and in principle a great benefit to the poorer people who live in that region, if not to the small privileged number that may be profiting from burning the forest.

Thank you very much. I'd be happy to take your questions.

**Question 1: Criticizing Climate Modeling**
G. Michael Purdy: Thank you very much Professor McElroy. We've got just a few minutes for a couple of questions. If you'd step up to the microphone, sir. Thank you. If you could identify yourself, please.

Man: Gavin Schmidt. I'm actually a climate modeler, and I was a little bit disturbed that you kind of accused climate modelers as being a little scientifically dishonest, which I think is a quite strong statement. I mean we work very hard on trying to incorporate natural variability, we work very hard on trying to identify the amount of forcings from the different aerosols and greenhouse gases, and we're very aware that, you know, 1850 was not a magic starting date. We're very aware that many of the important forcings are extremely spatially heterogeneous and difficult to assess, even going back before 1979. So we try quite hard to look at the metrics that allow us to distinguish the amount of forced versus intrinsic variability. Now the global mean temperature seems to be a good metric to look at for distinguishing that, because the amount of intrinsic variability in that is quite small. And so it's not dishonest to show that the global mean temperature responds to the global mean forcings.

Michael McElroy: First of all, if I gave the sense that I was accusing my colleagues of being dishonest, let me make it clear that that was not what I was trying to say. I didn't say it very well. What I was trying to say is that how you present and interpret results, particularly when you get this thing pulled into an executive summary at the front and then it gets into the newspapers and the policymakers and so on, there's a real problem there. And I sympathize with those who have to sort of run herd over that particular translation process. But let me repeat my specific criticism, which I don't think is contradicted by what you said. If the people who did that latest IPCC report focused up-front on this global average-temperature trend, and surely you will agree that the uncertainty in sulfate effect is so large that I can . . . that's a knob I can twiddle, big time. If you twiddle that knob to get a good agreement with the global average temperature, which is very interesting, had you also presented the northern hemisphere and southern hemisphere separately, which was presented in the later IPCC report, it would not have looked as good.

Man: If you look at the source publications for the summaries all of these things are discussed, you know, there's maps and maps and maps and maps. You know, they have to summarize, and so you know, they just show one.

Question 2: Aerosols and Solar Radiation

G. Michael Purdy: Go ahead, Wally. We'll repeat your question.

Michael McElroy: The comment from Wally Broecker was that there's significant indication of something that is inhibiting the transfer of solar radiation to the surface, both northern hemisphere and southern hemisphere, presumably related to fine aerosols. And my comment was that I think that the aerosol issue is the
big atmospheric chemistry challenge right now, to understand it. It's a very complicated problem. There's an interesting paper by Jim Hanson and his colleagues, I don't know if Jim is here, which attempted to take the existing database around the world on transmission of solar radiation and with some spectral resolution, admittedly a limited database, to try to resolve the relative importance of absorptive aerosols and scattering aerosols, black carbon sulfate, to make it simple. And the conclusion, if I remember correctly from that paper, was that they're more or less offsetting today, positive forcing and negative forcing about the same, but both are significantly large, and I think there's a real need to understand the whole aerosol problem, including the raised fine dust that clearly plays a role in the northern hemisphere with dust transfer from the Asian region all the way across to the western U.S., so presumably in the southern hemisphere you have comparable sources that can not be ignored.

G. Michael Purdy: Okay one just very quick question, because we're 15 minutes over right now.

**Question 3: Prioritizing Efforts to Manage CO₂**

**Man:** I'm Lewis Gilbert. You showed that it's unquestionable that the human impact upon the CO₂ increase—everybody agrees on that. You also demonstrated that there is debate about the relative role between human and natural functions and temperature. I'm curious from the perspective of making policy and from managing the carbon cycle why the question of the human versus natural impact on temperature is an important problem versus a problem of managing the larger carbon system?

**Michael McElroy:** I'm not sure I really understand.

**Man:** From the perspective of managing the carbon cycle, wouldn't our placing effort on managing the large human signal be the place to prioritize our effort as opposed to separating and natural signals in temperature?

**Michael McElroy:** I agree, I think that's true. I think that focusing initial attention on how to reduce the demonstrable radiative forcing is the right way to go. And I think—I mean I know Jim Hanson may disagree with this—I think it's tough to do things that are really going to significantly affect methane. What do you want to do? Order that all Indians kill a cow every day? I mean I don't think it's easy, or that Chinese people stop eating rice? But CO₂, deforestation, conservation, some of the creative ideas that Klaus and Wally and people here have been talking about in terms of the carbon sequestration are all very, very interesting strategies to use.