# The Winners of the Blue Planet Prize
# 1996

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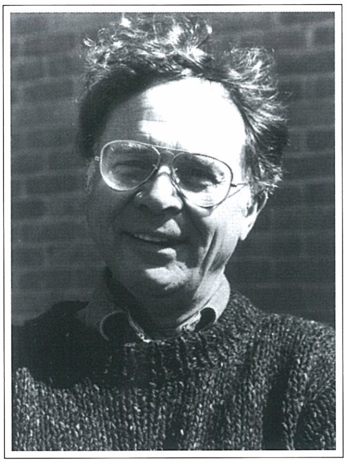
# Blue Planet Prize

## Dr. Wallace S. Broecker (U.S.A.)

Newberry Professor of Geology at Columbia University, Lamont-Doherty Earth Observatory



## The M.S. Swaminathan Research Foundation (MSSRF) (Established in India)

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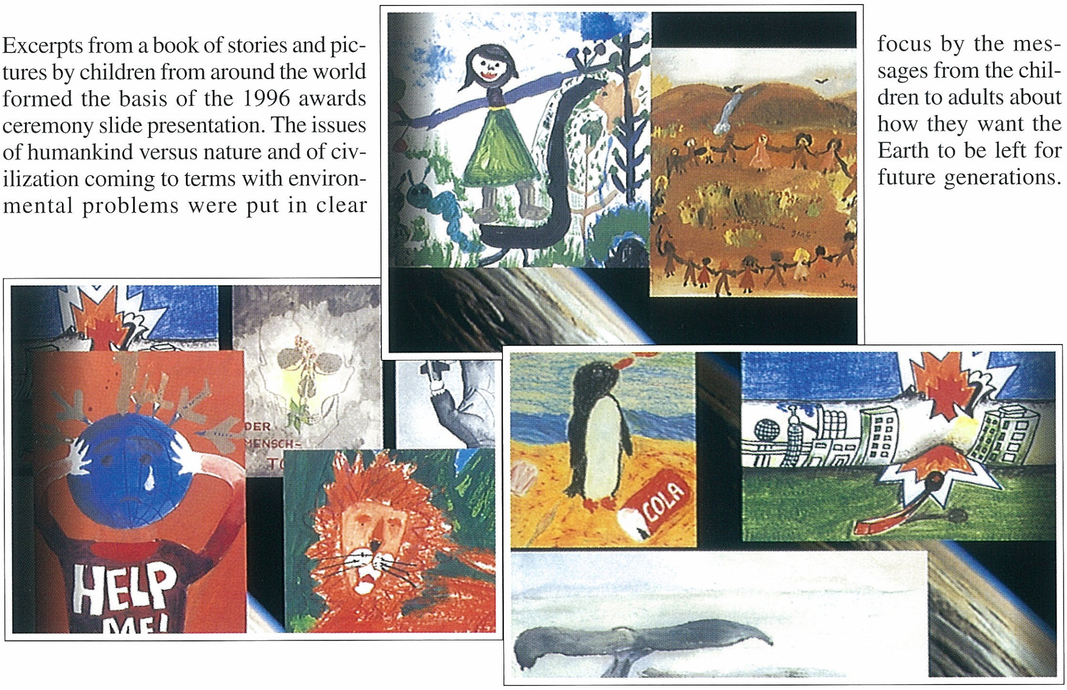
Excerpts from a book of stories and pictures by children from around the world formed the basis of the 1996 awards ceremony slide presentation. The issues of humankind versus nature and of civilization coming to terms with environmental problems were put in clear focus by the messages from the children to adults about how they want the Earth to be left for future generations.



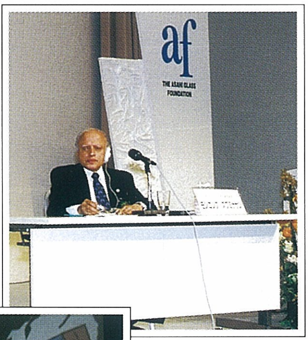
Professor Kenichi Fukui, Nobel laureate and a councillor of the Asahi Glass Foundation, gets the party started with a toast.

His Highness Prince Akishino and Her Highness Princess Kiko congratulate the laureates.

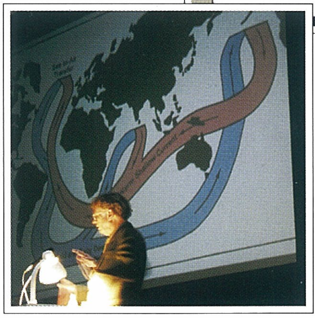
The awards ceremony is opened by Jiro Furumoto, chairman of the Asahi Glass Foundation.

Prior to the awards ceremony, the award recipients are interviewed by members of the press. From right to left: Dr. Swaminathan; Dr. Broecker; Jiro Furumoto; and Osamu Shiragami.

Dr. Swaminathan participates in a follow-up discussion after delivering his lecture on sustainable development.



Walter F. Mondale (left), ambassador of the United States of America to Japan, and Kuldip Sahdev, ambassador of India to Japan, address the audience at the awards ceremony.



During his lectures, Dr. Broecker explains his theory of the ocean's circulation system.

## Profile

# Dr. Wallace S. Broecker

Newberry Professor of Geology at Columbia University, Lamont-Doherty Earth Observatory

**Education and Academic and Professional Activities**

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| 1953 | Received B.A. from Columbia College of Columbia University |
| 1958 | Earned doctorate degree from Columbia University |
| 1959 | Became assistant professor at Columbia University |
| 1961 | Became associate professor at Columbia University |
| 1964 | Became full professor at Columbia University |
| 1977 | Named the Newberry Professor of Geology, Columbia University |
| 1979 | Elected to the National Academy of Sciences (U.S.A.); Elected chairman of the Geochemical Society (U.S.A.) |
| | Maurice W. Ewing Medal of the American Geophysical Union |
| 1986 | Alexander Agassiz Medal of the National Academy of Sciences; |
| | Urey Medal of the European Geophysical Union; |
| | U.M. Goldschmidt Award, Geochemical Society |
| 1987 | Vetlesen Prize, G. Unger Vetlesen Foundation |
| 1990 | Wollaston Medal of the Geological Society of London |
| 1995 | Roger Revelle Medal of the American Geophysical Union |
| 1996 | National Medal of Science |

Through his systematic analysis of measurements of carbon and its isotopes, Dr. Broecker has contributed to the understanding of chemical cycles in the oceans. In the 1980s, he elucidated the importance of the "great conveyor belt," a global ocean current that envelops the Earth, extending from the North Atlantic and circulating through the Indian and Pacific oceans. Often called Broecker's Conveyor Belt, the importance of this phenomenon to the Earth's climate was first recognized by Dr. Broecker. In addition, he clarified how the surface waters and the deep waters of the ocean circulate in a millennia-duration cycle.

Dr. Broecker also pioneered chemical and isotopic methods to determine the rate of gas exchange between the atmosphere and the ocean, permitting the rate of fossil fuel $CO_2$ uptake to be calculated. Among the first to recognize the significance of the global carbon cycle, Dr. Broecker devised a method of analyzing samples of ocean water by using radiocarbon measurements, allowing the rate of mixing of fossil fuel $CO_2$ into the body of the ocean to be analyzed.

In his capacities as teacher and pioneering researcher, Dr. Broecker has offered his ideas and guidance to hundreds of scientists around the world. Describing humankind's emission of greenhouse gases as "playing Russian roulette with the climate," he was among the first to sound the alarm on global warming.

## Essay

# Our Burden of Responsibility

### Dr. Wallace S. Broecker

**April 1997**

Our Blue Planet is entering what promises to be its most critical century. So far, our planet has been largely in the grip of natural forces which have governed for 4.5 billion years. Ready or not, management of the planet is falling into our own hands and, unfortunately, we are more prone to be plunderers than stewards. Further, we have yet to stem the alarming population increases which threaten to outstrip the planet's capacity for food production.

Were our galaxy endowed with Eternal Observers, their attention would certainly be focused on our beautiful Blue Planet. Having witnessed newly emerged intelligent beings take the reins on other planets, these Observers would debate whether or not we could pull off this critical transition with only minimal damage. Or, like so many others in the galactic past, would we botch the job. Would scores of species vanish? Would radioactive contamination threaten those which survived? Would the lands be scarred, the oceans polluted, and the smoothly running geochemical cycles upset? Past observations by the Observers revealed that only in rare cases were the inhabitants able to put aside their tribalism; control their burgeoning numbers; and establish a harmonious relationship with fellow organisms. Our hypothetical Observers would note that this poor success record was directly attributable to rapidly accelerating population growth. In order to keep pace with the exponential increase in their numbers, attention would have been riveted on satisfying their immediately needs. Long-term planning would fall victim to expedience, dogma, and greed.

It appears that our Blue Planet is proving no exception to this dire scenario. We have achieved the ability to eliminate other mammals with whom we once competed for survival. We've learned to annihilate our enemies with nuclear bombs; despoil our forests; harness our most awesome rivers; and squander the planet's once vast reserves of fuel, minerals, and water. As a consequence of these ravages, our atmosphere is being loaded with greenhouse gases and our soils with poisons. Even though aware of the lasting damage our activities can cause our planet, as push comes to shove, we allow more immediate problems to divert our attention. Unfortunately, the long-term solutions prove to be in direct conflict with short-term needs.

I consider population growth to be by far the most important issue confronting us. Whether the threat is compromised climate due to excess atmospheric $CO_2$ or a global social order severely strained by hunger and overcrowding, the situation escalates exponentially with the number of people on the planet. At present, the "good life" requires enormous energy consumption. Nearly all this energy is currently derived from fossil fuels. Roughly half of the $CO_2$ we generate over the next century by burning these fuels will remain in the atmosphere. Since numerous uncertainties still plague our climate models, we cannot adequately predict the consequences of adding this $CO_2$ to the atmosphere. While I am expert only in the area of climatology, my layman's knowledge of the problems created by hunger and overcrowding tells me that their consequences could easily dwarf even those created by climate change.

I usually consider myself a bubbling optimist, but when it comes to assessing our Blue Planet's future, pessimism sets in. Much like doctors opting to treat serious illnesses with Band-Aids and sugar pills, we are proposing solutions which fail to address the root cause of the problem. It is futile to point fingers of blame for we all share responsibility for painting ourselves into a very small corner. Attaining and preserving human dignity should be foremost in the minds of all people and, ironically, it is this same exemplary objective which inhibits the ability to stem population growth, energy use, and the exploitation of natural habitats. Indeed, it propels us toward even more growth in every sector.

While the burden of guilt must be shared by all, in some areas charges can be leveled at extreme offenders. The United States, for example, uses far more energy than necessary. We acknowledge this, but our political leaders are afraid to implement the sizable energy tax required to bring the usage under control. The Vatican hierarchy doggedly maintains its archaic position on birth control. Japan looks aside while its companies buy wood and hence destroy forests around the world. China allows military hardware to be exported to warring nations. And there is the fear that profiteering Russians engage in the sale of plutonium to terrorist organizations.

A perfect example of our Band-Aid and sugar pill approach is the 1991 Rio Accord on $CO_2$ emissions. Even if implemented and rigorously adhered to, it constitutes only a 20% solution. Without this agreement, the $CO_2$ content of the atmosphere would reach perhaps 700 ppm by the year 2100. With it, the rise would be held to about 560 ppm (i.e., 20% lower). While this reduction would ease the threat to climate, it would by no stretch of the imagination solve the problem. Further, were the Clinton administration to propose adherence to the Rio plan, Congress would surely balk. And if it were implemented, the American people would likely express their heated discontent at the ballot box.

No, I am afraid that our ever more democratic world is incapable of exerting the strict discipline necessary if we are to move with sufficient speed to quell the dangerous spiral of growth. Further, even if a benevolent global planning authority were created, its chances of survival would be slim indeed.

What will happen? Likely we will keep our heads in the sand hoping that the transition will be accomplished with only minor damage and pain. Surely there is a fair possibility that such a scenario will come to pass. But we indulge in a dangerous game. In the United States we call it Russian Roulette. It could go very wrong.

What would it take to reduce the extent of my pessimism? The answer is, a series of incredible actions by powerful people. For example, what if the Pope were to announce that he had received a clear directive from on high that immediate measures be put into place designed to reduce the global birthrate. Or, were Albert Gore to become President of the United States and declare that his administration would enact very tough policies directed toward remedying the dire environmental problems outlined in his book, *Earth in the Balance*. Or were Microsoft's Bill Gates to allocate 95% of his enormous income to help educate

Africa's poor? Or were a future prime minister of Japan to announce that henceforth his country would pay developing countries more to save their trees than they would receive by selling them.

Put simply, as we are being forced to take the reins of our planet's future, we have only ourselves to turn to. The Blue Planet's message to us is unequivocal: we are forcing it to the brink and we must now take the helm, accepting the sacrifices required to insure its future.

**Lecture**

# Will Our Ride into the Greenhouse Future Be a Smooth One?

## Dr. Wallace S. Broecker

(As submitted to *GSA TODAY*)
Revised February 1997

## Abstract

The climate record kept in ice and in sediment reveals that since the invention of agriculture some 8,000 years ago, climate has remained remarkably stable. By contrast, during the preceding 100,000 years, climate underwent frequent, very large and often extremely abrupt shifts. Furthermore, these shifts occurred in lock step across the globe. They seem to be telling us that the Earth's climate system has several distinct and quite different modes of operation and that it can jump from one of these modes to another in a matter of a decade or two. So far, we know of only one element of the climate system which has multiple modes of operation, namely, the oceans' thermohaline circulation. Numerous model simulations reveal that this circulation is quite sensitive to the fresh water budget in the high latitude regions where deep waters form. Perhaps the mode shifts revealed in the climate record were initiated in the sea.

This discovery complicates predictions of the consequences of the ongoing buildup of greenhouse gases in the atmosphere. If the major climate changes of glacial time came as the result of mode shifts, can we be certain that the warming will proceed smoothly? Or is it possible that 100 or so years from now, when our ancestors struggle to feed the 15 or so billion Earth inhabitants, that climate will jump to another of its states. It is difficult to comprehend the misery which would follow on the heels of such an event!

The debate regarding the eventual consequences of the ongoing buildup of greenhouse gases in the atmosphere concerns the magnitude of the coming changes. Most atmospheric scientists agree that the warming during the coming century will be sufficiently large to pose serious difficulties. But, because to date the warming has been smaller than predicted by most general circulation models, a vocal minority pooh-pooh this supposed threat. On the other hand, little debate has occurred regarding the shape of the path climate will follow as $CO_2$ and other infrared-absorbing gases build up in our atmosphere. Whether large or small, nearly everyone assumes that the warming will be a smooth climb with climate keeping pace with the ever increasing strength of the greenhouse blanket. But will it? Certainly the Earth's climate system has proven beyond any doubt that it is capable of undergoing abrupt jumps from one state of operation to another. Can we be sure that it won't respond to our push by lurching into another of its operational modes?

**Figure 1** Oxygen isotope ratio record in ice from a three-kilometer-long core taken by the European GRIP group at the Summit site in central Greenland (Dansgaard et al., 1993). This ratio is related to air temperature; the greater the depletion in the heavy isotope the colder the temperature. Based on the measurements of temperature in the bore hole, it has been possible to demonstrate that the mean air temperature in Greenland must have been 16 °C colder during glacial time than during the present interglacial (Cuffey et al., 1995). The time scale was obtained by counting annual couplets in the ice (Meese et al., 1994). Note that only during the last 10,000 years has Greenland's air temperature remained nearly constant. By contrast during the last ice age and during the latter portion of the last interglacial, large and rapid shifts occurred. Greenland's air temperatures never paused at a single value for more than 1,000 years.
The electrical conductivity of Greenland ice is set by the amount of acid present. Measurements made on the GISP ice core (a duplication of the GRIP core 40 kilometers away) reveals that during the very cold intervals the electrical conductivity fell to near zero values (Taylor et al., 1993). The reason is that the rain of $CaCO_3$ contained in the wind-blown dust exceeded the amount required to neutralize the acid fallout. Because electrical conductivity can be measured continuously by scratching the ice with a pair of sharp electrodes, a very detailed record was obtained. As shown here, this record reveals that the transitions between climate states were extremely abrupt, being completed in a few decades. Furthermore during this brief transition period, the input of dust (and presumably also global climate) flickered on the time scale of just a few years.
The rapidly accumulating (1 $m/10^3$ years) sediments in the Santa Barbara basin record each of the so-called Dansgaard-Oeschger events seen in the Greenland ice core record. Behl and Kennett (1996) established this based on the alternation between sections with and without annual laminations. The laminated sections represent times when the pore waters in the sediment were anaerobic, preventing burrowing by bottom dwelling worms. The absence of laminations in the intervening sections reflects times when the pore waters were oxygenated, allowing burrowers to thoroughly stir the sediment. The alternations match almost perfectly the alternations in Greenland air temperature. During very cold intervals, such as the Younger Dryas, waters rich in $O_2$ must have descended into the North Pacific's thermocline. As today's surface waters of the northern Pacific are too low in salt content to permit direct ventilation of deeper portions of the thermocline, these alternations suggest major changes in the salinity distribution in this region of our planet.

## A Message from Greenland

A clear demonstration that the climate system can jump from one state to another comes from a record kept in Greenland ice (see Fig. 1). European and American teams have drilled through the entire thickness of the Greenland ice cap. The most recent and best documented of these records is a pair of three-kilometer-long ice cores from right on the summit of Greenland. These cores provide not only a record of climate in Greenland but also implications regarding climate in other places on the globe that extend back 110,000 years before the present. As precise counting of individual couplets of winter and summer snow extends back to at least 45,000 years, little question exists regarding the chronology of this ice core (Meese et al., 1994).

The isotopic composition of this ice is related to the air temperature over Greenland. For the last 10,000 years, Greenland has enjoyed, at least compared to the previous 100,000 years, a very stable climate. There was one cold blip 8,000 years ago; but other than that its climate has remained pretty much unchanged. But prior to 10,000 years ago, the climate leaped back and forth between states of intermediate cold and extreme cold. The median temperature at this site during the ice age has now been well established through thermal profiles in the ice itself to have been on the average 16 °C colder than during the last 10,000 years (Cuffey et al., 1995).

Further, during the last five years, evidence from a variety of investigations has clearly demonstrated that these changes were not confined to Greenland; rather, they were global! Before reviewing the evidence for these far-reaching impacts, let us consider the rapidity of these changes. This is best done by focusing on the last warming, i.e., that which ushered in the present interglacial. Shown in Fig. 1 are blow-ups of measurements of the electrical con-

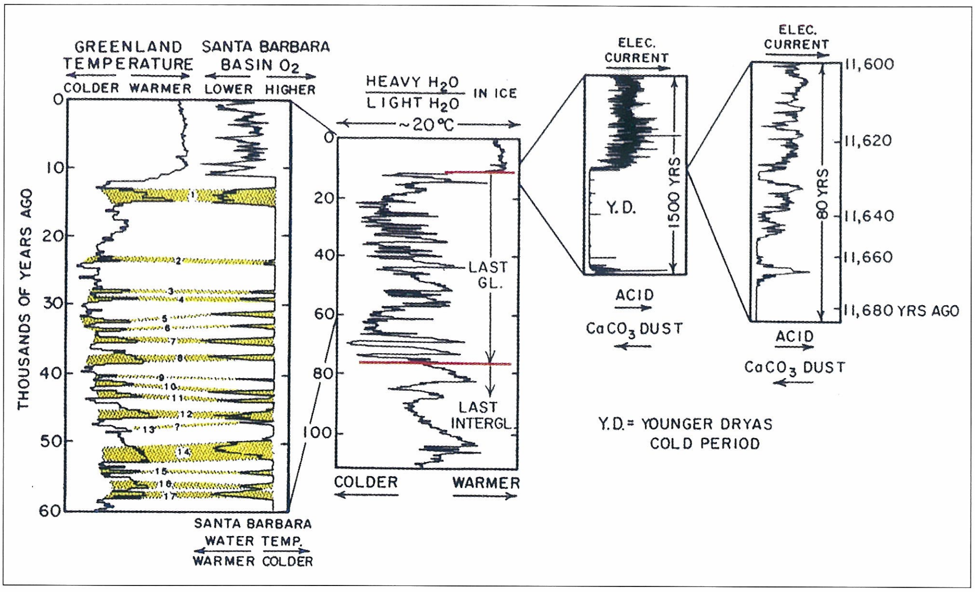

**Figure 1**

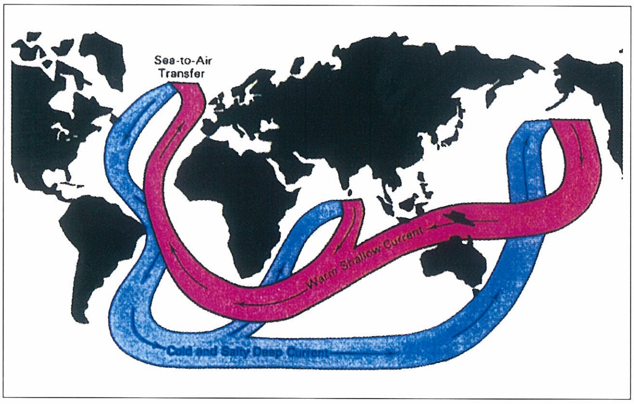

**Figure 2** The great ocean conveyor carries warm water to the region around Iceland where cooling by cold Canadian air masses densifies the water, allowing it to sink to the bottom forming a southward-moving water mass. The flux of water (20 million cubic meters per second) matches that of 100 Amazon rivers and is equal to the flux of global rainfall. So immense is the heat released to the atmosphere that it maintains northern Europe 5°C to 10°C warmer than it would be were the conveyor to shut down.

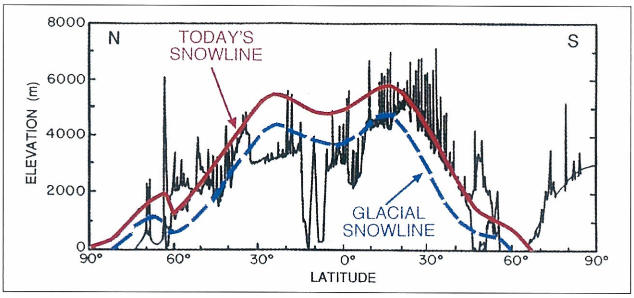

**Figure 3** The highest mountains at all latitudes along the cordillera of the Americas are currently capped by glaciers. At elevations above the 0°C isotherm, more snow accumulates than melts (or evaporates). The solid line shows how the elevation marking the lower boundary of net accumulation varies with latitude. Reconstructions based on geomorphic evidence (see dashed line) show that during times of peak glacial cooling the snowline on these mountains descended almost one kilometer. Combined with oxygen isotope composition of glacial age ice recovered by Thompson et al. (1995) from 6 km elevation on the tropical Andean mountain, Huascarán, this lowering suggests not only colder, but also drier conditions in the tropics during glacial time.

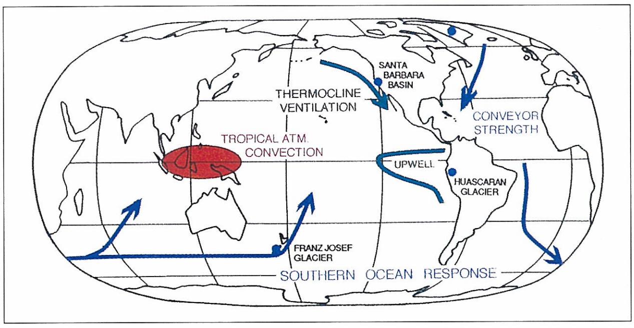

**Figure 4** A possible causal chain leading to the global climate change is as follows. A sizable reduction in the strength of the Atlantic's conveyor had repercussions throughout the ocean. Included were changes in operation of the upper ocean as recorded in the Santa Barbara basin. One impact of these changes may well have been an increase in the strength of upwelling in the east equatorial Pacific. We know from studies of the El Niño periods that changes in upwelling have wide repercussions in the tropical atmosphere. I propose that, somehow, the ocean upwelling change led to a reduction in the rate of delivery by tropical convection of water vapor to the atmosphere. As water vapor is the Earth's dominant greenhouse gas, this reduction would cool the Earth.

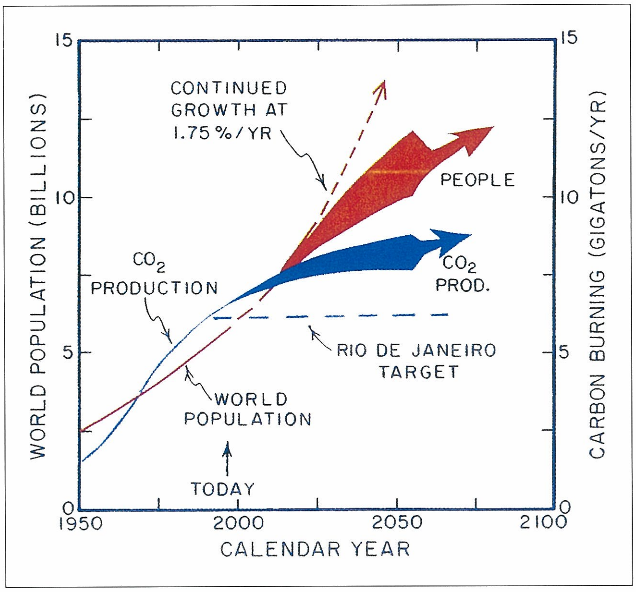

**Figure 5** Population is currently increasing at the rate of 1.75% per year. While this rate is projected to gradually decrease, by the middle of the next century population will reach somewhere between 10 and 15 billion. Despite a desire to hold $CO_2$ production from fossil fuel burning to the 1990 level, the demand for energy is bound to rise as the number of people rises. It will likely reach at least 7.5 gigatons of carbon per year by the mid-21st century.

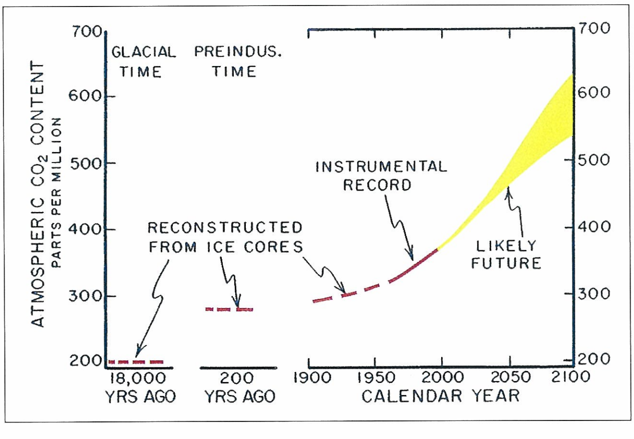

**Figure 6** During the last glacial period, the $CO_2$ content of our atmosphere was only 200 ppm. Upon deglaciation it rose to about 280 ppm and has hovered about this value until the onset of the industrial revolution. Due mainly to fossil fuel burning, it has risen over the last 100 years to its current level of 365 ppm. This rise will continue, reaching double its pre-industrial value by the end of the next century.

ductivity record for one of the Greenland ice cores (Taylor et al., 1993). This property of the ice was measured in great detail by scratching a fresh surface of the ice with a pair of electrodes. This record provides a measure of the ratio of the fallout of acids to that of calcium carbonate-bearing dust. During the Younger Dryas cold event (YD), the rate of $CaCO_3$-bearing dust infall was so high that it totally neutralized the acid. Therefore the electrical conductivity was very low. And then at the onset of the present warm period, the dust input dropped way back, allowing the acids to dominate. As the protons from the acid sustain the electrical conductivity in ice, the conductivity is high. So we see that it was not only Greenland's air temperature which changed but also the dustiness of the air masses reaching Greenland. The isotopic fingerprint of this dust is consistent with an origin in the Gobi Desert (Biscaye et al., in press). If so, Asian climates must also have undergone abrupt changes.

In the blow-up on the extreme right of Fig. 1, are shown the calendar ages defined by annual layer counting. This allows the duration of the transition interval to be well documented. Clearly, the onset of this warming was abrupt. The initial change took place in only two or three years, but then the climate flickered, the dust came back in spurts before the situation stabilized in the low dust state. The entire transition took place in less than three decades (Taylor et al., 1993).

Ice cores also tell us something about tropical climates. They do so because air bubbles trapped in the ice contain methane, a gas which is currently produced in rice paddies and cow pastures. But, prior to the invention of agriculture, the major source of methane was swamps. Currently, many of these swamps are located in the temperate latitudes of the northern hemisphere. During glacial time when the planet was very cold, all these northern swamps were either covered by ice sheets or frozen into tundra. Hence they could not have been methane producers. So, during the Younger Dryas, most methane must have been produced in the tropics. In concert with the big warming at the end of this last cold event, the methane content of the Earth's atmosphere jumped from slightly below 500 up to about 750 parts per billion. I think that this rise was driven, at least in part, by a wetting of the tropics, i.e., to an increase in the size and number of methane-producing swamps and soils. It's therefore interesting to explore the relationship between the timing of this methane jump and the abrupt warming in Greenland. A former graduate student of mine, Jeffrey Severinghaus, working in the laboratory of Michael Bender at the University of Rhode Island, made a major discovery when he found a means by which in these same air bubbles he could obtain a measure of air temperature change in Greenland. He used these measurements to show that Greenland's warming began no more than a decade or so before the onset of the increase in methane. Somehow, when Greenland suddenly got much warmer, the tropics suddenly got wetter. So the impacts of this mode change extended, from Greenland at least, down into the tropics.

## Climate Change: Global as well as Large and Abrupt

A friend of mine, George Denton of the University of Maine, working with a colleague, Chris Hendy, studied a very interesting moraine left behind by a major advance of New Zealand's Franz Josef Glacier. The expansion of interest extended down the steep valley toward the Tasman Sea and created at its outer limit the Waiho Loop moraine . The rock rubble making up this moraine is underlain by lots of wood. Denton and Hendy (1994) postulate that as the glacier advanced, it moved through a forest, tearing out trees and bulldozing them to its terminus. They obtained 25 radiocarbon measurements on separate pieces of this wood and determined the age of this basal wood deposit to be 11,150 plus or minus about 50 $^{14}$C years. This is very close to the radiocarbon age that's been obtained in the northern hemisphere for the onset of the Younger Dryas cold interval (Hajdas et al., 1995). So, Denton would say that the southern hemisphere knew about this event; the mountain glaciers responded to a substantial lowering of the zero degree isotherm. To achieve this descent required a substantial southern hemisphere cooling.

Quite recently, a spectacular set of results from sediments in a basin just off Santa Barbara, California, verifies that this phenomenon was widespread and strong, not only during the Younger Dryas, but also for the entire series of so-called Dansgaard-Oeschger (i.e., D-O) events. These events, named in honor of two of the heroes of ice core research, punctuated the period between about 65,000 and 25,000 years ago. Previously it had been impossible to duplicate this ice record only in ocean sediments from the northern Atlantic (Bond and Lotti, 1995). The reason is that for the most part they accumulate so slowly that the stirring by worms obliterates millennial duration events. After much begging, Jim Kennett, of the University of California at Santa Barbara, convinced the deep-sea drilling program to spend one day drilling two shallow holes in the Santa Barbara basin. This brief effort produced a gold mine of information. As these sediments accumulated at a rate of about 1 meter per 1,000 years, they have adequate resolution to fully preserve the Dansgaard-Oeschger events. And indeed they did. As shown by Behl and Kennett (1996), during each of the warm phases, the sediment shows annual banding while during each of the cold phases stirring by bottom dwelling organisms homogenized the sediment. This suggests that during the warm phase of each D-O cycle the $O_2$ content of the water filling the Santa Barbara basin was sufficiently low and the rain rate of organic matter sufficiently high that the sediments were anoxic. Thus, burrowing organisms were excluded. By contrast, during each of the cold phases (including the YD), the pore waters in the upper sediments must have been oxygenated. To me this suggests that during the cold phases conditions in the northern Pacific were quite different than now. The low salinity surface waters which currently cap this region and thereby prevent direct ventilation of the main thermocline must have been replaced with saltier water allowing the northern Pacific to operate much as the northern Atlantic does today. And what Behl and Kennett (1996) found is that 16 of the 17 D-O events in Greenland ice core are clearly present in the Santa Barbara record.

So, what does this tell us? To me this supplies an extraordinarily important piece in the puzzle. The ventilation of the North Pacific's thermocline (by this I mean, the sinking of waters from temperate latitudes to intermediate depths) increased greatly during the cold phases of the D-O events (i.e., the intervals during which laminations disappear). So the cold spells in Greenland are matched in the North Pacific Ocean by what must have been a radical change in the style of upper ocean circulation.

To summarize, I've recapped what I consider to be the highlights of evidence for the global extent, large magnitude, and abruptness of these D-O events. Now let's move along to the consideration of what might have triggered these amazing changes.

## Causes: The Oceanic Conveyor Belt

The basic idea came to me in 1984 while I was listening to a lecture given by my longtime friend, Hans Oeschger, at the University of Bern in Switzerland. He pointed out that the Greenland ice core record suggests that the Earth's climate was jumping back and forth from one state of operation to another, staying in one for a millennium or so, and then jumping to the other. I was captivated by Hans' thought and began to ponder what these states might be. It soon dawned on me that they could be related to a change in a major feature of the ocean's thermohaline circulation system which I subsequently termed its conveyor belt. Now that it's famous, people refer to it as Broecker's Conveyor Belt. But it's only fair to say that I have a colleague, Arnold Gordon, who thinks it's his conveyor belt rather than mine. But, it doesn't really matter. We both agree that it's an extremely important feature of the Earth's climate system.

My idea can be summarized as follows. As shown in Fig. 2, one of the most prominent features of today's ocean circulation is the strong northward movement of upper waters in the Atlantic. When these waters reach the vicinity of Iceland, they are cooled by the cold winter air that streams off Canada and Greenland. These waters, which arrive at 12 to 13°C, are cooled to 2-4°C. As the Atlantic is a particularly salty ocean, this cooling increases the density of the surface waters to the point where they can sink all the way to the bottom. The majority of this water flows southward and much of it rounds Africa joining the Southern Ocean's circumpolar current.

The importance of this current to climate is the enormous amount of heat it carries. The conveyor's flow is equal to that of 100 Amazon Rivers! It's similar in magnitude to all the planet's rainfall. So if you have three pipes, one carrying North Atlantic deep water, one carrying all the rain falling on the Earth, and one carrying 100 Amazon Rivers, the outflow from these pipes would be about the same. The amount of heat carried by the conveyor's northward flowing upper limb and released to the atmosphere is equal to about 25% of the solar energy reaching the surface of the Atlantic north of the Straits of Gibraltar.

I had known about this because my career has had a dual aspect. One part of it involved a study of the ocean's deep circulation using radiocarbon and other tracers. The focus was to try to understand how rapidly fossil fuel $CO_2$ would be absorbed into the ocean. The other involved studies of paleoclimate. I was captivated by the observation that each of the major 100,000-year duration glacial cycles that have hounded us during the last million years came to a catastrophic close. So in 1984, I realized that I could merge these two studies and ask the question, "What would happen if this major current were to be shut off or turned down?" Any such modification would certainly make a major change in the climate of the northern Atlantic region. At my prodding, modelers launched computer simulations of this phenomenon and quickly showed that were the input of warm water to the northern Atlantic to be cut, the mean annual temperature of the lands around the North Atlantic basin would drop by 5° to 10°C. These climate changes would be felt in Newfoundland and Greenland and would penetrate well into northern Europe. However, the models suggested that this cooling would not extend across America to the Santa Barbara basin nor would it extend to the tropics. It certainly would not impact New Zealand.

In addition, ocean modelers followed up on the early work of Henry Stommel (1962) who first demonstrated from a theoretical point of view that the ocean must have several distinct modes of operation. Employing a variety of simulations, they demonstrated that because of the very great sensitivity of deep-water formation to the input of fresh water in polar regions, the ocean could circulate in quite different ways. As rain water contains no salt, its addition lowers the density of surface waters. Further, at high latitudes rainfall and continental runoff exceed evaporation. Because of this, the distribution of places where deep waters can and cannot be generated is sensitive to the pattern of fresh water delivery. So this new class of models verified what Stommel had predicted; indeed their model oceans could make dramatic jumps from one way of operating to another. And in so doing, the amount of heat delivered to the northern Atlantic region greatly changed. But while changes in the conveyor provide a likely explanation for the Greenland ice core record, in no case does any joint ocean-atmosphere model produce the far-field impacts displayed in the paleoclimate record.

### Causes: Is Water Vapor up to the Task?

Now we must turn to a more speculative realm because explaining the global extent of these changes is something that we're a long way from accomplishing. An important piece of information in this regard is the state of the Earth's system during the extreme cold millennia of glacial times. At these times, all of Canada and a major portion of the northeastern and midwestern U.S. was covered by a huge ice sheet. Mountains everywhere on Earth experienced a snowline descent of about one kilometer. Geomorphologists have traversed the globe comparing the elevation of the present-day mountain snowlines with those for the last glaciation (reconstructed from geomorphic features). Figure 3 shows the results of such investigations along the American Cordillera. Everywhere from 40°S to 40°N, snowlines descended about one kilometer! Because of this, the southern Andes and New Zealand's South Island, which now have very small glaciers, had quite large ones.

What this tells us is that somehow the Earth got itself into a much colder condition during glacial periods. To my way of thinking, no one has adequately explained how the Earth could ever have accomplished this. We now have new evidence from glacial-age corals (Guilderson et al., 1994) and from glacial-age ground waters (Stute et al., 1995) that the tropics may have been as much as 5°C colder during glacial times. How could the Earth have changed its climate so much in the absence of any strong external forcing?

When I consider the mountain glacier record together with the isotope record obtained for glacial-age ice from six kilometers' elevation on Andean Huascarán (Thompson et al., 1995), I'm forced to the conclusion that the water vapor content of our atmosphere must have been much lower during glacial time. Hence, either the processes which deliver or those which remove water vapor from our atmosphere must have been different during glacial time. But this reduction is something that no model of the atmosphere has yet to accomplish. In fact, these models are powerless to produce the large global changes that the paleo records prove to have taken place. You might ask why water vapor. The answer is that water vapor is the atmosphere's most powerful greenhouse gas. If you wanted to cool the planet by 5°C and could by magic alter the water vapor content of the atmosphere, a 30% decrease would do the job. In fact, the major debate that rages among atmospheric scientists regarding the magnitude of the coming greenhouse warming hinges on what's referred to as the water vapor feedback. If the water vapor in the atmosphere were to remain exactly the same as it is now, then a doubling of $CO_2$ would heat the planet only about 1.2°C. However, when $CO_2$ is doubled in these models, their atmosphere holds more water vapor, enhancing the warming to 3.5°C ± 1.5°C. A 3.5°C warming would certainly cause major problems for agriculture, especially where conducted in continental interiors. The debate concerns whether the models change the water vapor in the same way that it will change as $CO_2$ rises in the real world.

My speculation (see Fig. 4) is that despite the fact that the primary climate impacts of the change in the deep ocean circulation are restricted to the northern Atlantic basin, somehow, as a result, the water vapor budget for the atmosphere must have been altered. Water vapor is supplied to the atmosphere primarily in the tropics by plumes of air which ascend to the upper troposphere along the inter-tropical convergence zone. So if one is to invoke a change in the atmosphere's water vapor inventory, one has got to look to the tropics, and, in particular, to the western tropical Pacific. It is here where convective activity feeds a major portion of water vapor into the air.

If so, the change in the deep circulation must have repercussions throughout the upper ocean. As evidence that this is the case, we have the Santa Barbara basin record, which indicates that, at least in the North Pacific, there must have been a major change in the style of upper ocean ventilation. This is important because the energy budget of the tropical atmosphere is influenced by the upwelling along the equator of cold ocean water. This cold water is fed in from the thermoclines to the North and South Pacific. The now famous El Niño cycle involves a turning on and off of this upwelling. This cycle has a strong impact on today's global climate. So I think that somehow the change in the vigor of upper ocean circulation must have altered the strength of upwelling into the equatorial region and, in turn, the delivery of water vapor into the atmosphere.

This aspect of my argument is particularly speculative, because we don't know how it could happen. But to produce large and abrupt changes in global climate that are symmetrical around the equator, it seems to me that only atmosphere's water vapor is up to the task. If water vapor were the villain, then we must look to the equatorial systems for the key. My guess is that changes in the fresh-water budget of the surface North Atlantic threw the ocean's deep circulation into chaos. If it reformed in another mode of operation, in so doing, it triggered changes in other parts of the ocean and in turn in the delivery of water vapor to the tropical atmosphere. As this source maintains the atmosphere's water vapor inventory all the way out to 35 degrees either side of the equator, the impact would be global. This way of looking at it suggests that we might be able to find in the paleo climatic record a causal chain from northern Atlantic to equatorial Pacific and hence to the atmosphere. But I doubt it. The links likely act so fast that, within the accuracy of even the most precise of our dating tools, all the changes occurred at one time. We have already seen that Greenland air temperature, Asian dust production and global methane production changed together. Some of the impacts may take longer than others to reach a new steady state but all were likely initiated during a time interval of no more than a few decades.

## Our Future

So the question naturally arises as to whether this finding about past climates has any implications for the future. First, in this connection, let's review some things that most of you already know about. Human population is rising at a rate of 1.75% each year. If continued, by the middle of the next century, population would reach the staggering level of 14 billion. Fortunately, most predictions suggest that declining birth rates will ease somewhat this potentially desperate situation. But regardless, we're headed for an excess of 10 billion people (see Fig. 5). At just the time we expect sizable greenhouse warming impacts, we're going to have at least five billion more people to feed than we do now. That is an enormous challenge, even in the absence of a climate change.

The amount of $CO_2$ we produce depends on two things. How many people there are and how much energy they use. Keep in mind that the poorer people on the Earth are going to seek a better standard of living and that's going to require more energy. Almost all of our energy now comes from burning fossil fuels, and hence involves adding $CO_2$ to the atmosphere. The hope at the Rio Conference was that the production rate of $CO_2$ could be held to its 1990 level, but the production rate has already risen well above that level. Some politicians believe that this Rio goal is achievable, but I don't. So I suspect that we are going to generate seven or more gigatons of carbon as $CO_2$ every year. At this rate, the $CO_2$ content of the atmosphere will rise at the rate of about two parts per million (ppm) per year (see Fig. 6).

So the $CO_2$ content of the atmosphere will continue to go up. How far depends on a lot of things. Maybe there will be a miracle and we'll find some alternate energy source which is socially acceptable and economically fundable. But, there's little doubt in my mind that late in the next century, the $CO_2$ content of our atmosphere will reach twice its pre-industrial value of 280 ppm (i.e., 560 ppm). And before we're free from our dependence on fossil fuels, we'll probably drive the $CO_2$ content up to 700 ppm or more.

For this rise in $CO_2$, models yield a range of global warmings. The reason is that they differ in the extents of water vapor feedback. As already stated, were there no such feedback, the warming would only be about 1.2°C and would not produce much difficulty. But if the extent of warming for doubled $CO_2$ were 3, 4, or 5°C, as some models predict, then I think everybody would agree there is going to be big trouble.

What I've injected into this already complicated situation is the realization that in the past climate changes haven't come gradually. Whatever pushed the Earth's climate didn't lead to smooth changes, but rather to jumps from one state of operation to another. So the question naturally arises, what is the probability that through adding $CO_2$ we will cause the climate system to jump to one of its alternate modes of operation? I contend that since we can't yet reproduce any of these jumps in computer simulations, we don't really know how many modes of operations the Earth has, and we certainly don't have any idea what it might take to push the system from one mode to another. We do know, however, that a substantial warming would surely reduce the density of polar surface water and thereby tend to cut off deep ventilation. So we're entering dangerous territory. It seems to me that we're provoking an ornery beast. Our climate system has proven that it can do very strange things. And since we've only recently become aware of this capability, there's nothing concrete that we can say as far as the implications of this capability to the future. But this discovery certainly gives us even more reason to be prudent about what we do. We must prepare for the future by learning more about our wicked climate system and we must create the wherewithal to respond if the $CO_2$-induced climate changes are large or worse yet if they come abruptly, changing agricultural conditions across the entire planet. We have to think all this through. Even if there is only a 1% probability that such a change might occur during the next 100 years, its impact would be sufficiently catastrophic that it warrants a lot of preparation.

In conclusion, my lifetime study of the Earth's climate system has humbled me. I'm convinced that we have greatly underestimated the complexity of this system. The importance of obscure phenomena ranging from those which control the size of raindrops to those which control the amount of water pouring into the deep sea from the shelves of the Antarctic continent make reliable modeling very difficult, if not impossible. If we're going to predict the future, we have to achieve a much greater understanding of these small-scale processes which add together to generate big-scale effects.

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