## Editor's Note

Wallace (Wally) S. Broecker is Newberry Professor of Earth and Environmental Sciences at Lamont-Doherty Earth Observatory of Columbia University, New York. He received his PhD (1958) from Columbia University. He is a fellow of numerous renowned scientific societies with many commendations for his significant and pioneering contributions to Earth and Environmental Sciences. He was elected to the American Academy of Arts and Sciences in 1976 and the US National Academy of Sciences in 1979. He has received many awards and medals, only some of which are mentioned here: Maurice Ewing Medal (1979) and Roger Revelle Medal (1995) of American Geophysical Union, Arthur Day Medal (1984) and Don Easterbrook Distinguished Scientist Award (2000) of the Geological Society of America, Urey Medal of the European Geophysical Union (1986), Goldschmidt Award of the Geochemical Society (1986), Alexander Agassiz Medal of the US National Academy of Sciences (1986), Wollaston Medal of the Geological Society of London (1990), US National Medal of Science (1996), Blue Planet Prize of Tokyo Asahi Glass Foundation (1996), Arthur Day Prize and Lectureship of US National Academy of Sciences (2002).

Wally is a world's leading interpreter of the Earth's operation as a biological, chemical and physical system. His research interests include paleoclimatology, ocean chemistry, isotope geochemistry, geochronology and environmental science. He is probably best known for his recognition of a "great conveyor belt" of ocean circulations that plays a critical role in earth's climate (The Great Ocean Conveyor, Oceanography, 1991, 4: 79—89). He says "the climate system is an angry beast, and we are poking it", "evidence points to brief, but dramatic 'flickers' in global temperatures as the Earth system switches from one of its modes to another", and "modest increases in global temperatures due to 'greenhouse warming' could result in similar dramatic changes". Indeed, he is a leading voice warning of the potential danger of increased greenhouse gasses in earth's atmosphere. Wally has pioneered a number of approaches to studying the earth's climate, including the use of carbon and other isotopes to date marine sediments. He has examined ocean circulation patterns over time, studied gas exchanges between the ocean and the atmosphere, and traced carbon as it cycles through the earth's chemical, physical and biological systems. He has published hundreds of research papers and about 10 books. He is also an excellent educator, whose many students are world leaders in the broad field of earth and environmental sciences.

I am not an environmental scientist, but my deep interest in the subject arose from the penetrative influence of Wally's research students and postdocs with whom I shared office spaces and laboratory facility during my post-doctoral period (1992—1993) at Lamont. Perhaps, I heard "global warming", "climate change", "ice caps", "ice cores", "ocean circulation" etc. much more often than "ocean ridge basalts" most of the days. The fact that today's children in my hometown in Northwest China do not seem to have the same luxury as we did to make big snowmen and skate across rivers convinced me that global warming has been happening. But exactly what may have caused it, and to what extent human activities may have contributed to it through releasing greenhouse gasses remain debatable. One thing that is not debatable, however, is that we will face severe consequences if global warming continues and when ice caps all melt. Also, I always feel encouraged by and proud of the unprecedented growth in economy and personal wealth in China, but added cars into the busier streets each day consume more fossil fuels and release more greenhouse gasses. The latter has immediate effects of air pollutions on our living environments, but how to evaluate its contribution to global warming by the most populous nation with potentially most motor vehicles in the next decade or two? Wally has his ideas and his equation. I am very happy that Wally is delighted to contribute this article to *Chinese Science Bulletin*.

(Yaoling Niu, Executive Editor, Department of Earth Sciences, Durham University, UK)

*Chinese Science Bulletin* 2006 Vol. 51 No. 9 1018—1029

DOI: 10.1007/s11434-006-1017-4

# Global warming: Take action or wait?

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Received January 19, 2006; accepted March 1, 2006

**Abstract** A serious split in opinion exists with regard to how to deal with the ongoing buildup of $CO_2$ in our atmosphere. One group contends that, until the warming has more clearly expressed itself, we should put off costly actions. The other group contends that, even if we were to take immediate action, the buildup of $CO_2$ is likely to reach an unacceptable level. Hence action must not be delayed. I stand with the second group. My opinion has been molded by the failure of model simulations to yield the impacts anywhere near as large as those attributable to orbital cycles, to ocean reorganizations, or to solar irradiance. These impacts are well documented in the paleoclimate record. This suggests to me that the models lack important feedbacks and amplifiers present in the real world. Hence they are more likely to underestimate the impacts of $CO_2$ than overestimate them as the critics contend. The world's energy consumption will continue to rise. Because it is so cheap and so abundant, coal will dominate as a supplier. It is also my opinion that $CO_2$ capture and burial will have to play a key role in the struggle to bring the $CO_2$ rise to a halt. Fortunately, it appears that capture and burial are technically and economically feasible. The big question is whether the world can come together and make this happen before $CO_2$ has reached an unacceptable level.

**Keywords: global warming, $CO_2$ sequestration, paleoclimate.**

Of all the changes wrought by human activity, the buildup in our atmosphere of the greenhouse gases, carbon dioxide, methane and nitrous oxide, has generated the most contentious debate. Environmentalists warn that in the absence of firm action, over the next century the warming caused by the ongoing buildup of these gases will have adverse impacts on our planet's agricultural productivity, on its fresh water supply and on its wildlife. Further, the melting of the polar ice caps will cause sea level to rise, leading to the destruction of valuable coastal property. They point to an ongoing melt back of mountain glaciers, to the decrease in Arctic sea-ice extent and to a progressive softening of frozen tundra as evidence that the impacts of this warming are already underway. They warn that in order to avoid much larger future impacts we must stem the buildup of $CO_2$ produced by the burning of coal, oil, and natural gas.

While almost all scientists expert in the subject agree that global warming will bring about a host of undesirable changes, a large segment of the public remains unconvinced. This sentiment is reflected by a reticence on the part of governments in the United States, Australia, and China to join with Europe and Japan in agreements to cut back on $CO_2$ emissions. The economic consequences of such actions are considered to be too large when weighed against what they consider to be rather uncertain long-term consequences of business-as-usual fossil fuel use.

## 1 $CO_2$ production

The situation is made more complicated by the incredible magnitude of the task. In 2005, worldwide some 25 billion tons of $CO_2$ were produced by burning fossil fuels. If captured and liquefied, this $CO_2$would nearly fill a tank three kilometers on a side and three kilometers deep! Except for the contribution of the $CO_2$ produced as the result of deforestation, fossil fuel burning accounts for the 30 percent increase which has occurred since the beginning of the Industrial Revolution. This cannot be disputed for the increase is only half as large as would be the case if all the $CO_2$ produced by coal, petroleum and natural gas combustion had remained airborne. In several independent ways, it has been documented that much of the other half of this $CO_2$ has been sucked up by the ocean[1]. The small unaccounted-for remainder appears to have gone into increased storage of carbon in vegetation and soils. Models which include the atmosphere, ocean and terrestrial biosphere suggest that this 50-50 split between the atmosphere on one hand and the ocean plus terrestrial biosphere on the other will apply throughout the coming century.

The concentration of $CO_2$ in the atmosphere has already reached 380 parts per million (up 100 ppm from its pre-industrial value of 280 parts per million; see Fig. 1). It is currently rising by nearly two parts per million per year. But, if fossil fuels continue to supply 85 or so percent of the world's energy, as population increases and as the traditionally poor nations industrialize, this rate of increase is expected to double and perhaps even triple.

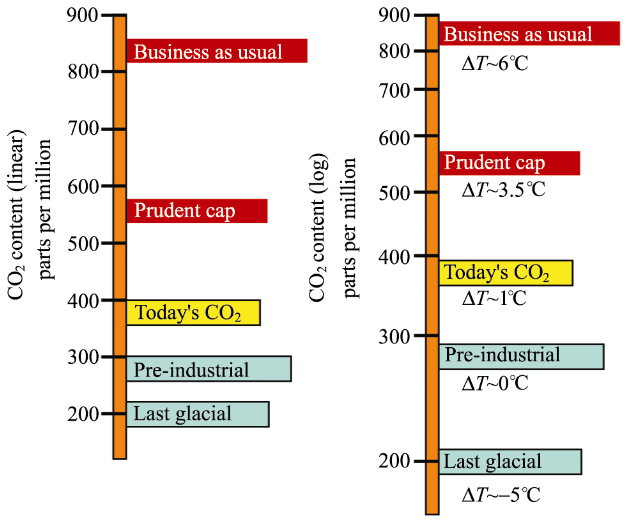



Fig. 1. Atmospheric $CO_2$ contents for past times (blue), for the present (yellow) and for the future (red). The scale on the left is concentration in parts per million. The scale on the right is for the temperature change associated with each of these $CO_2$ levels. The logarithmic spacing of the latter reflects the progressive saturation of $CO_2$ absorption bands as its concentration increases.

In this regard, it must be kept in mind that the rise in $CO_2$ will not be stemmed by a shortage of fossil fuels. Although the reserves of petroleum and natural gas are finite, those of coal are virtually unlimited. Further, as coal can be economically converted into gasoline, there is no danger that fuel for our transportation fleet will fall into short supply. Coal alone can meet all of our energy needs for several centuries to come. Further, it is likely to be many, many years before any other source of energy can compete on a large scale with coal. For example, the prime candidate, solar electricity, currently costs about twenty times that produced in coal-fired plants.

Many environmentalists make the plea that the $CO_2$ content of the atmosphere not be allowed to exceed 450 parts per million. Realists, however, contend that even with great effort, we will not be able to prevent $CO_2$ from reaching a concentration of 560 parts per million (i.e., double the pre-industrial level). Pessimists, who fear that significant action will not be taken, predict that early in the next century the content could reach 840 parts per million (i.e., triple the pre-industrial level).

To see why an attempt to hold the atmosphere's $CO_2$ content below, let's say 560 ppm, poses a very, very difficult challenge, let us consider the limits that would have to be placed on the release of $CO_2$ as the result of fossil-fuel-use consumption. As a rule of thumb, for each four billion tons of carbon burned, the atmosphere's $CO_2$ content rises about one part per million. Hence, were this 560 parts per million limit to be put in place, the maximum allowable carbon burning would be $4 \times (560-380)$ or 720 billion tons. In an ideal world carbon allotments would be divided among the nations of the world in proportion to their respective populations. In this case, the world's traditional industrialized nations would be allocated only about 20 percent of the pie or 144 billion tons (see Fig. 2). As together these nations currently consume about 6 billion tons of carbon per year, if they maintained this pace, they would run through their allotment in only 24 years!

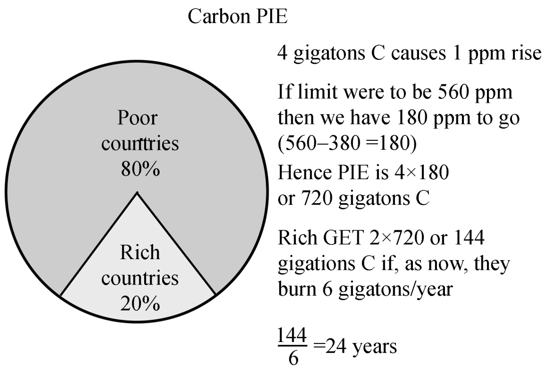



Fig. 2. A division of the carbon "pie" based on population.

The debate about global warming does not center on uncertainties in the projections of the magnitude of the $CO_2$ rise. But rather, it centers on uncertainties in the climatic consequences of this increase. These consequences are based on sophisticated simulations carried out using the world's most powerful computers. While these simulations faithfully incorporate every aspect of the climate system, in those cases where the details of the physics are fuzzy, the designers are forced to resort to empirically determined parameterizations to fill in the gaps. Many of these parameterizations have to do with aspects of the hydrologic cycle (i.e., water vapor, clouds, precipitation, sea ice…).

## 2 Water vapor feedback

Much of the criticism of the climatic projections produced by these simulations stems from what is referred to as "water vapor feedback." By itself, a doubling of the atmosphere's $CO_2$ content would warm the planet by a modest 1.2℃. However, as the planet warms, the vapor pressure of liquid water will correspondingly increase and consequently the atmosphere will be able to hold more water vapor. As do $CO_2$ molecules, $H_2O$ molecules capture outgoing earth light (infrared rays). In all of the numerical models, the increase in atmospheric water vapor associated with a doubling of $CO_2$ amplifies the warming by a factor of 2 to 3[2]. Hence, 1.2℃ becomes 2.4 to 3.6℃. Further, the models yield larger than average warming for the interiors of continents and nearly twice the average warming for the Arctic Ocean and its surrounding lands.

One prominent atmospheric specialist, MIT's Richard Lindzen, vigorously denies that this feedback will occur in the real world[3]. He admits that the water vapor content of tropical air will rise but postulates that the air over the extra tropical desert regions will, instead, become even drier. Because of its low water vapor content and dearth of cloud cover, the atmosphere over the world's deserts acts as the primary "radiator" by which the planet rids itself of the heat supplied by the Sun. Hence, Lindzen envisions that, instead of amplifying the warming produced by extra $CO_2$, the decrease in water vapor in these extra tropical regions will outweigh the increase in the tropics. The net result will be a negative feedback reducing the small warming produced by $CO_2$ itself. Among atmosphere specialists, Lindzen stands pretty much alone in this view and has produced no model simulations to back his intuition. Further, as his detractors point out, Lindzen is well known for his contrarian views. For example, with equal vigor, he denies that cigarette smoking has been proven to cause lung cancer.

## 3 Clouds and aerosols

Another hotly debated aspect of computer simulations is cloudiness. Clouds play a huge role in the Earth's radiation budget for their water droplets intercept both incoming sunlight and outgoing earth light. Small changes in the extent, the location or the elevation of clouds have a significant impact on the model's climate[4]. A further complication stems from the fact that the reflectivity of clouds depends on the mean size of its droplets. Smaller droplets are more reflective than larger ones. The mean size of cloud droplets depends on the availability of so-called cloud condensation nuclei; the more nuclei, the greater number of droplets[5]. The greater the number of droplets, the smaller must be their average size. By generating aerosols, we have increased the number of available nuclei and thereby presumably caused clouds to brighten (see Fig. 3).

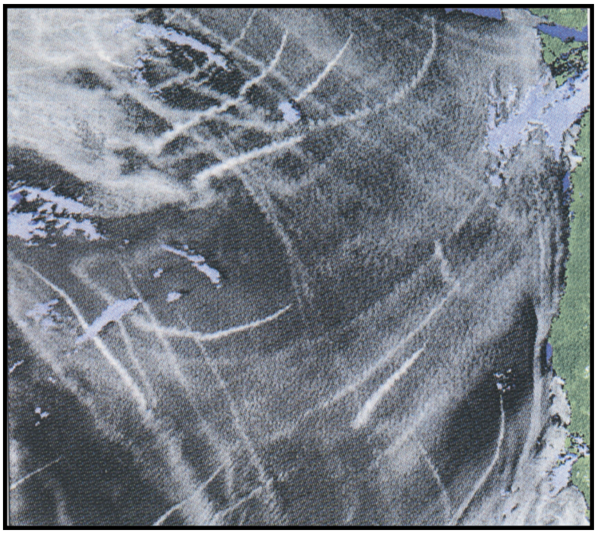


Fig. 3. An air photo taken over an area of low cloud cover off the west coast of the U.S. The bright streaks are produced by cloud condensation nuclei delivered to the clouds with the smoke from the stacks of ships passing beneath.

Second in importance to issues related to water vapor are issues related to aerosols themselves. As do greenhouse gases, aerosols capture and re-radiate outgoing infrared light[6]. Also, as do rain drops, they scatter incoming sunlight. Unlike greenhouse gases, their impacts are not readily modeled. One reason is that rather than being uniformly distributed across the globe, they are patchy and ever shifting. Even more important, while the light-colored sulfuric acid aerosols (i.e., those created by the oxidation of the $SO_2$ gas released during coal burning) primarily reflect incoming sunlight, the dark-colored aerosols (created by both coal and vegetation burning) primarily absorb outgoing earth light. Making the situation even more complex, these aerosols collide with one another and merge to form complex composites. Further, all of these aerosols serve as cloud condensation nuclei. The bottom line is that, while there is no doubt that man's aerosols are altering climate's course, it is not even clear whether the net result is to counter or enhance the warming created by greenhouse gases.

Could it be that the presence of aerosols in the atmosphere will serve on the long term to counter the continuing increase of $CO_2$? Despite the uncertainty with regard to their current impact, it can be stated with some confidence that the importance of aerosols will diminish as time passes. One reason is that aerosols remain airborne for only days to weeks before they are removed by impact with rain drops, tree leaves, etc. By contrast, the $CO_2$ we produce will be removed only on a century time scale. A second reason is that, as aerosols pose a medical hazard, their production in urban environments will certainly be curtailed. So, in the end, $CO_2$ will win out!

## 4 Computer simulations

If one accepts the simulations generated by models, then a doubling of $CO_2$ will certainly result in major climate changes which will impact virtually every human activity and cause a major shift in the habitat available to wildlife. But, as every climate scientist admits, major uncertainties surround these predictions. In order to assess the possible biases created by these parameterizations, a group of scientists in the United Kingdom undertook an elaborate exercise designed to evaluate the sensitivity of the models to the selection of the values adopted for the many required parameters[7]. To this end, they made thousands of model runs for doubled $CO_2$ employing all combinations of the permissible range of values for each of these parameters. This exercise yielded a range of results which were strongly skewed toward warmings greater than that obtained using the usual set of parameters. Further, none of the runs yielded warmings of less than 1.5°C. This exercise suggests that model simulations more likely underestimate the impacts of increased $CO_2$ than overestimate them.

Seemingly, the obvious way to test the reliability of these simulations is to determine whether they correctly reproduce the global temperature record kept by our thermometers. Since the beginning of the Industrial Revolution, the $CO_2$ content of the atmosphere has risen 100 parts per million (from 280 to 380). In addition, increases in methane and other infrared-absorbing gases provide additional greenhouse shielding which nearly matches that by the excess $CO_2$. Hence it is as if $CO_2$ had risen to 450 parts per million. The models predict that such a $CO_2$ increase should have warmed the planet by about 1.5℃. Has it?

## 5 The instrumental record

In Fig. 4, the trend in mean annual earth surface temperature is shown[8]. Several features jump out. The warming during the last 140 years is only about 1.0℃. Further, about half of this warming took place prior to 1940 (i.e., before there had been an appreciable increase in any of the greenhouse gases). Further, between 1940 and 1975, the temperature remained nearly constant. Only following 1975 has there been a steady increase in temperature which might be attributed to manmade pollutants.

This comparison tells us in no uncertain terms that our activities have yet to produce a global temperature change larger than those which the planet has been undergoing on its own. Clearly, the warming which occurred during the latter half of the 19th century and the

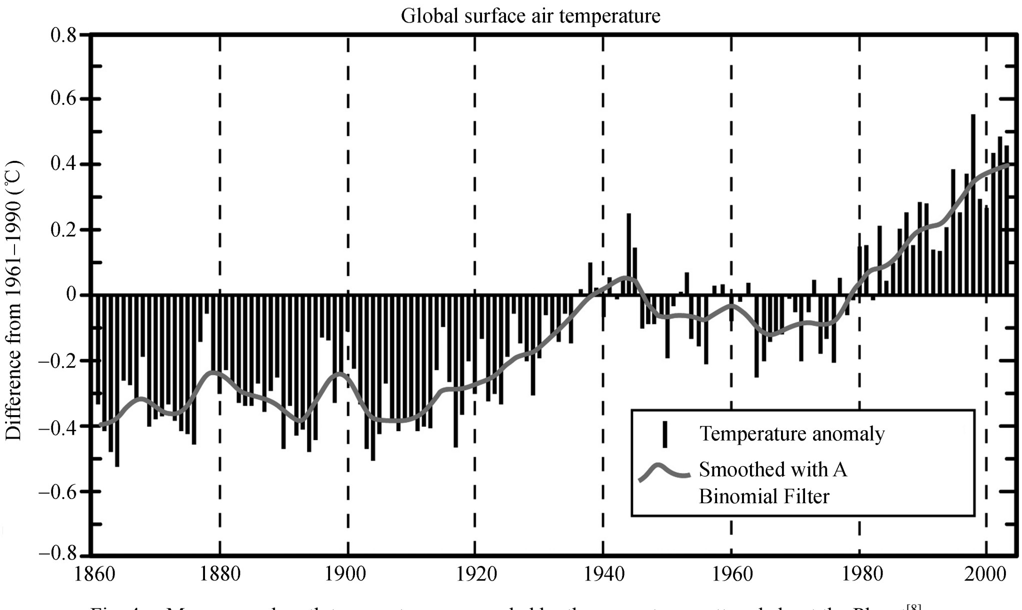



Fig. 4. Mean annual earth temperature as recorded by thermometers scattered about the Planet[8].

first part of the 20th century must be attributed to natural causes. If, indeed, the models have it right, then the pause in warming during the middle of the 20th century suggests a natural cooling during this time interval. By chance, this natural cooling counteracted the man-induced tendency to warm. Only after 1975 did our influence take hold.

Clearly, this is music to critics' ears. Aha, they can say, perhaps the entire warning is natural. Lindzen has it right. A water vapor deficit in desert air has largely nulled the impact of $CO_2$ and other greenhouse gases.

The proponents of action would counter by crying wait! Clearly the man-made warming has yet to push Earth's temperature out of the range of natural "noise." As we have no way to determine how the Earth's temperature would have changed in the absence of the Industrial Revolution, this test is not a valid one. Further, because the atmosphere can warm no faster than the upper ocean, there is a significant lag in response. Finally, the reflection of sunlight by light-colored aerosols and by the aerosol-brightened clouds may be counteracting a sizable portion of the warming by greenhouse gases.

So, in a sense, it is a standoff. Those who refuse to accept the predictions made by computer simulations can use the temperature record as an excuse for inaction. Let us wait until there is clear evidence that greenhouse gases have produced a significant warming before we take expensive action. Those who accept the models as our most reliable guide to the future would counter that unless we create a plan as to how we might curtail the $CO_2$ buildup and unless we begin to implement this plan, we have no chance to prevent $CO_2$ from climbing well above 560 parts per million. For in order to stem the $CO_2$ rise, we will have to make a complete revision in our entire energy infrastructure.

## 6 The paleoclimate record

Fortunately, there is another source of information which in my estimation tips the balance strongly toward the side of those who demand that action be initiated. It is the paleoclimate record stored in ice, in sediments and in stalagmites. In order to correlate the messages preserved in these diverse archives, students of past climates have developed precise methods for absolute dating. Only in this way has it been possible to correlate records preserved in different regions of the planet. The task is akin to that facing historians who depend on calendars to relate events which took place in different countries. In addition to time clocks, these archives must contain proxies which record temperature, or rain fall, or glacial extent, or atmospheric $CO_2$. An amazing array of both clocks and proxies have been developed over the last 50 years[9]. Taken together, they provide us with a clear picture of how the climate of our planet has evolved over the last half million years. To me, this reconstruction shouts out loud and clear, that rather than being immune to nudges, our climate system greatly over-responds to them. By comparison with the nudges responsible for these large climate changes of the past, those associated with even a doubling of atmospheric $CO_2$ will constitute not just a nudge but rather a sizable push.

Space is not available to adequately explain the manner in which the climate records for the last half million years has been reconstructed. Rather, I will briefly recap three types of climate change the Earth has experienced. Each of the three can be shown to have been in response to a known nudge.

Example 1. During the last half million years four major glaciations have occurred. Each involved the growth of large ice sheets in North America and in Europe. That in North America covered all of what is now Canada and penetrated into the United States as far south as the Ohio River and Staten Island. As a result of this growth of ice cover, sea level stood about 120 meters lower than now. Bubbles of air trapped in Antarctic ice tell us that the $CO_2$ content of the atmosphere dipped to as low as 190 ppm during each episode of glaciation. Based on the models we use to predict the future, this $CO_2$ drop by itself could account for a glacial cooling of several degrees.

Each of these four cycles had the same basic shape; a 100 thousand-year-duration decline in temperature and increase in ice extent culminated in a warming which suddenly terminated the glaciation and returned the Earth to its interglacial condition. For the last 10000 years, i.e., the time during which our civilization developed, the Earth has been in such an interglacial state (see Fig. 5).

Superimposed on the episodes of climate decline are prominent 20000-year cycles (see Fig. 5). The existence of these cycles tips us off as to what drives glaciations for their timing beautifully matches that of changes in the distribution among the seasons of the heat received from the Sun. These cycles which involve increases and decreases in the contrast between winter and summer insolation, are the result of the precession of the Earth's spin axis in combination with its elliptical orbit. In addition to the pacing by the 20000-year precession cycles, evidence for an orbital influence on climate comes from the timing of the terminations which brought to an abrupt end each of the 100000-year climate cycles. Each of these terminations occurred at a time of maximal contrast between summer and winter. The match between orbital changes and earth climate is so convincing that it is now universally accepted that glacial cycles were paced by changes in seasonal contrast. The important point for this paper is that when these seasonality changes are introduced into the same models used to predict the impact of rising greenhouse gases, the models barely respond. This tells us that there must be interactions taking place in the real world (but not in the models) which greatly amplify the impact of nudges associated with changes in the distribution of solar heat among the seasons.

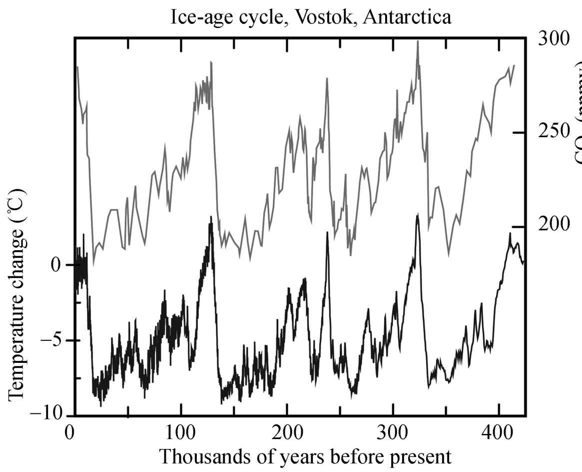



Fig. 5. Records of atmospheric $CO_2$ content and Antarctic air temperature as recorded in the Vostok ice core[10].

Example 2. Paleoclimatologists were puzzled to note that while the changes in air temperature and in atmospheric $CO_2$ content recorded in ice from long borings in the Antarctic ice cap (see Fig. 5) nicely conform to expectation based on cycles in the Earth's orbit, the record from Greenland ice is quite different. It was, as shown in Fig. 6, dominated by abrupt jumps spaced at millennial intervals. During the last glacial cycle, about twenty of these back and forth jumps occurred[11]. They appear not only in the temperature record, but also in those of the dust content[12] of the ice and of the methane content[13] of air trapped in bubbles in the ice. Because Greenland's ice has prominent annual layers, it is possible to show that each of these transitions occurred with great rapidity, i.e., they were completed in a few decades. The mean annual temperature change associated with these jumps has been rigorously documented to be on the order of 10°C[14].

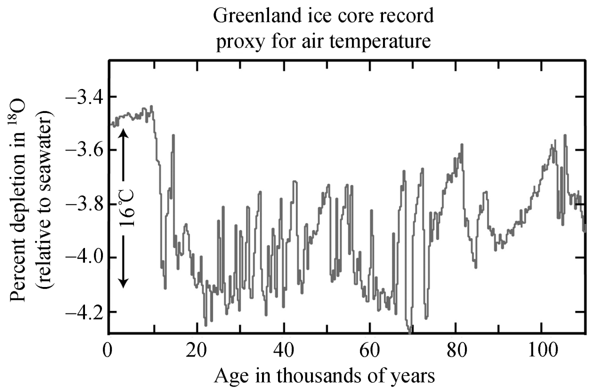
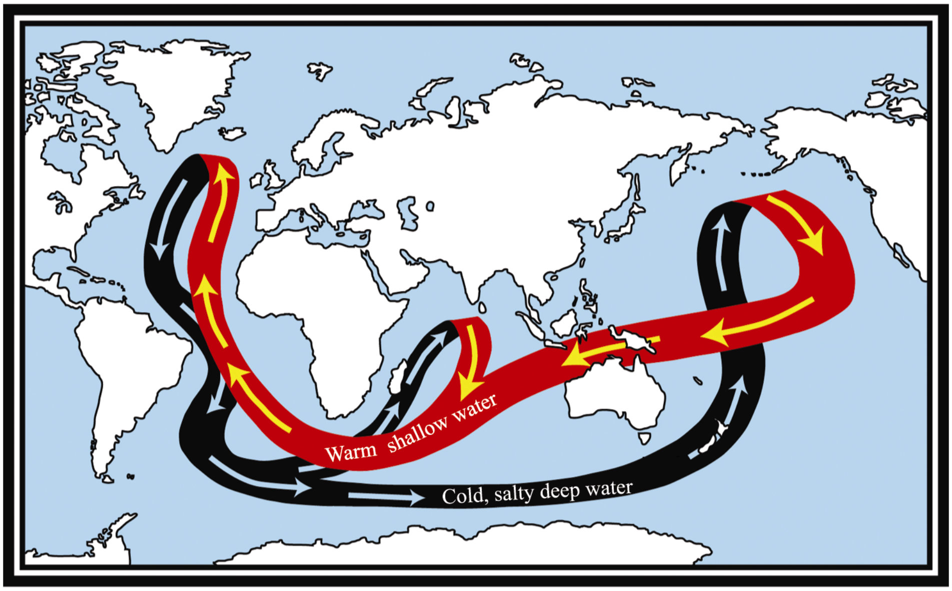



Fig. 6. The record of air temperature kept in the Summit, Greenland ice cores[11].

This discovery triggered a search for equivalents in records from elsewhere on the planet. In rapid succession evidence turned up at widely spaced north temperate and tropical locales. But at Southern Hemisphere locales, if present, they were muted and shifted in time. While from the beginning it was postulated that these shifts were triggered by reorganizations of the large scale conveyor-like circulation in the Atlantic Ocean (see Fig. 7), nearly twenty years passed before an explanation for their abruptness and widespread geographic distribution was found. The key turned out to be a huge amplification resulting from large changes in the extent of sea ice cover in the northern Atlantic[16]. These changes occurred in response to a turning on and off of the Atlantic's conveyor-like circulation. In its on mode, the conveyor's northward flowing upper limb flooded the Norwegian Sea with water warmed during its passage through the tropics. This warmth prevented ice from forming. But, when the conveyor shut down, this delivery of tropical heat no longer occurred, allowing winter sea ice to cover the northern Atlantic as far south as Great Britain. This ice would not only have blocked the transfer of ocean heat to the atmosphere, but also it would have reflected away much of the incoming sunlight. As a result, winters in Europe would have rivaled those which now plague Siberia.

But it was the search for the connection to the tropics which posed the greatest challenge. Climate records from caves in China and from sediments from the Arabian Sea clearly indicate that the monsoons were

The great ocean conveyor




Flow equal to that of a 100 Amazon rivers

Fig. 7. Idealized cartoon depicting the ocean's global conveyor system[15].

greatly weakened during periods when sea ice covered the northern Atlantic. Further, the record contained in sediments from the Cariaco Basin just off the Caribbean coast of South America and that in stalagmites from a cave in southeastern Brazil revealed that during times when sea ice covered the northern Atlantic, the belt of tropical rainfall was shifted southward. Models endowed with northern Atlantic sea ice were able to account for both the weakening of the monsoons and for the southward shift of the tropical rain belt[16]. The latter reflected the southward shift of the thermal equator resulting from the severe northern cooling. The former was caused by the lengthened presence of snow cover in the north temperate region which delayed the summer warming of Asia and thereby weakened the monsoons[17].

This second example not only reveals one of nature's hidden amplifiers, but also makes it clear that interactions between the ocean and atmosphere give rise to what might be termed as discrete quantum states of climate. The Earth system is capable of abrupt jumps between these states. These jumps have profound impacts on not only the distribution of temperature and precipitation, but also on the contents of carbon dioxide and methane in the atmosphere.

Example 3. By comparison with the last glacial period, climate during the present interglacial has been remarkably well behaved. Only once (8200 years ago) did the Atlantic's conveyor circulation shut down[18]. But rather than remaining off for many centuries, only a few decades elapsed before it popped back into action. Of interest in connection with our quest to evaluate the predictions made by computer-generated simulations is a series of small cycles in temperature[19] well recorded at high northern latitudes. Each full cycle involved a temperature swing of about 1℃ and lasted about 1500 years. The Medieval Warm (800 to 1350 AD) - Little Ice (1350 to 1850) pair was the most recent of this series. Interest in these cycles stems from the fact that their timing closely matches that for cycles in the production rate in our atmosphere of two radioisotopes, carbon fourteen and beryllium ten[19]. These changes in production rate reflect the modulation of the inflow of energetic galactic cosmic rays into our atmosphere. This modulation is the result of variations in the strength of the magnetic field created by ions which stream out from our Sun's dark spots (i.e., the so-called solar wind). The more dark spots, the more ions shot forth and the stronger the magnetic shield they create. Satellite-based observations show that during the course of the last two full 11-year sunspot cycles, the Sun's luminosity has undergone tiny changes (see Fig. 8). Its output was one part in 1300 greater at the times of the last two sun-spot maxima than at times of the intervening sun-spot minima[20]. Even though our visual observations of sunspots date back only to 1604 when they were discovered by Galileo, the proxy record provided by radioisotopes allows it to be extended back through the entire Holocene (i.e., the present interglacial). The mystery is that no way has been found for changes in luminescence on the order of one part in a thousand to generate the observed one degree temperature fluctuations. According to the models, luminescence changes of this magnitude are capable of producing swings in temperature of no more than one tenth of one degree[21]. So, once again, we have evidence that our Earth's climate system has hidden amplifiers which allow it to greatly over respond to very small nudges.

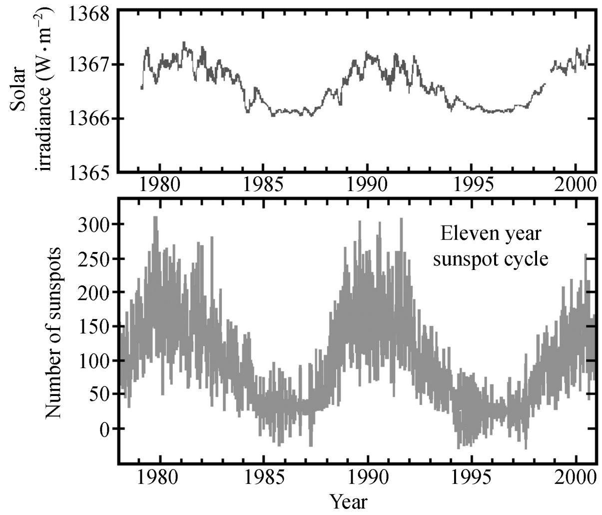



Fig. 8. Solar irradiance as measured from satellites for the last two 11-year duration sunspot cycles[20].

The failure of models to produce the impacts on climate resulting from the seasonality changes produced by cyclic changes in the Earth's orbit or from tiny changes in the output of radiation from the Sun suggests that these models might also underestimate the long-term impact of $CO_2$ and other greenhouse gases. Further, large and abrupt changes triggered by reorganizations of ocean circulation warn us that the ride into the greenhouse future may be punctuated with large bumps. My read of the paleo record leads me to believe that climate is akin to an angry beast which responds violently when poked. Hence, I am convinced that we should do everything we can to minimize the greenhouse poke.

## 7 Coming conveyor shutdown?

Much attention has gone into claims that global warming will lead to a shutdown of the Atlantic's conveyor circulation with the consequence that Europe will be hit with another ice age. In my estimation, we can now say that these claims are greatly exaggerated. True, model simulations do suggest that greenhouse-induced excess rain onto and river runoff into the Arctic and northern Atlantic could dilute the salt content of surface waters to the point where deep water could no longer be produced thereby bringing the conveyor to a halt. But, rather than an abrupt switch from on to off, akin to those thought to have brought about the dramatic climate changes of glacial time, the models suggest a gradual slowdown spread over an entire century[22]. Further, to produce a large enough input of extra fresh water, the models call on a 4 to 6°C warming of the planet; something that would require a tripling of the pre-industrial $CO_2$ level. Were the planet to warm to this extent, there would be no chance that the conveyor shutdown would allow sea ice forming in the northern Atlantic. It would be too warm. In the absence of the large amplification induced by ice cover, such a shutdown would lose much of its punch. Instead of initiating another European ice age, it would likely only partly offset the greenhouse warming in this part of the world.

If a future shutdown is predicted to occur gradually, how could it be that those of glacial time (and also that which occurred 8200 years ago) happened suddenly? The answer is that several of these shutdowns have been documented to have been triggered by catastrophic additions of fresh water to the northern Atlantic. One such mode of addition was through the melting of huge armadas of icebergs launched into the northern Atlantic as the result of a collapse of the ice dome centered over Hudson Bay[23]. Another was gigantic floods associated with the sudden escape of fresh water impounded in lakes in front of the retreating Canadian ice sheet[24]. Today, only the Greenland ice cap holds an amount of "poised" fresh water capable of triggering a sudden conveyor shutdown. However, none of the models of Greenland's response to global warming suggest a sudden massive collapse into the sea. Rather, just as the amount of high latitude precipitation will slowly increase, so also will the rate of melting of Greenland's ice.

## 8 Water related crisis

If the above assessment is correct, can we assume that no large bumps lie along the greenhouse warming road? Perhaps, but as for the last half-million years the Earth has not experienced climates significantly warmer than today's, we are about to enter unknown territory. If surprises are in store for us, my guess would be that they will involve redistribution of rainfall (i.e., droughts and floods). Climate models suggest that as the world warms, the tropics will receive ever more rainfall and the world's desert regions will receive ever less. While we lack warm analogues, we do have a well-documented cold analogue. During glacial time closed basin lakes in the deserts of western North America, the Middle East, northwestern China and Australia were several times larger than now. While evidence from the tropics is sparse, it has been shown that Lake Victoria was dry during late glacial time[25] and that the other lakes in the Africa's rift valleys were considerably smaller than they are today. Thus, it appears that when the Earth was colder the tropics got less rainfall and the desert regions got more. Thus, the paleo record adds credence to the prediction by models.

But one might ask whether these changes in moisture delivery will be gradual or is there a chance that they will come upon us suddenly? Although no firm answer can be given to this question, regional droughts during the present interglacial offer some important clues.

The most dramatic of these droughts are two which hit the dry lands of western North America during the Medieval Warm interval, (i.e., the time when Eric the Red and his band of Vikings colonized Greenland). These western North America droughts are dramatically recorded by the trunks of dead trees which project above the water level in present day lakes, rivers and swamps in the mountains along the western border of the desert. Counts of annual rings reveal that some of these trees survived for 150 years. Radiocarbon dates place them in two time intervals, 1050 to 1200 and 1300 to 1375 AD[26]. Of particular interest are the tree trunks projecting through the surface of Lake Tenaya in the high country near Yosemite Valley. These trees are rooted 13 meters below the bed rock sill which serves as the lake's outlet. Over the last 130 years only once did this lake fail to overflow in response to the input of snow melt. Yet for two century-long intervals during the time of the Medieval Warm, it was never once filled to capacity. Instead, the reduced inflow must have been lost entirely by evaporation. We can state this with confidence for, had the lake risen to its sill level and overflowed, it would surely have killed the trees.

Fossil tree trunks from a number of other localities tell similar stories (for one of these see Fig. 9). Clearly,


Fig. 9. Stumps of trees which grew in the bed of the West Walker River during the first of the Medieval droughts (courtesy of Scott Stine, California State University, Hayward).

western dry lands experienced two century-duration droughts more intense than any of the three to eight-year-duration droughts which have occurred during the last 100 years. This comes as a surprise for, as far as we can tell, climate during the Medieval Warm was not significantly warmer than today's.

But, this leaves open the question as to whether these droughts began and ended suddenly. At present, it can only be said that the two medieval droughts were separated by a time when closed-basin Owens Lake and Mono Lake which occupy the desert just east of the steep front of California's Sierra Nevada mountain range both achieved high stands[27]. Research is currently underway to determine what dendro-correlated tree-ring thicknesses have to say about the onset and demises of these mega-droughts.

## 9 Summary

Although reasonably strong, the case I make is far from air tight. So, a dissenter might plead that action be delayed until the Earth's temperature has clearly emerged from the envelope of natural variability. I might agree if there existed a well designed road map spelling out the means and time schedule for stemming the buildup of $CO_2$ in our atmosphere. However, as we are in a race against time, we cannot afford to wait. At least two decades will be required to develop the means by which the $CO_2$ rise can be brought to a halt and at least four more to fully implement it. However, not only is there no such plan, but there is not even a consensus as to what are to be its key elements. Further, there are indications that, even if we started now, we would not be able to prevent $CO_2$ from reaching well above double its pre-industrial concentration.

## 10 What must we do?

During the 30 years which have slipped by since the Earth's temperature began its steady rise, relatively little has been accomplished toward halting the buildup of $CO_2$. True, the Kyoto Accord has been activated. But it constitutes only a baby step toward the ultimate goal. Even if those countries who did sign meet their commitments, because of increased fossil fuel use in the developing world, each year the $CO_2$ content of the atmosphere will rise a bit faster than it did during the previous year. True, wind power has come into its own, but even if it meets the most optimistic of projections, it will produce no more than ten percent of world's energy. True, nuclear energy is making a comeback but, in a world preoccupied with terrorism, few believe that it will become the energy work horse which will replace fossil fuels. Solar electricity, many people's dream solution, will remain just that, until its price is driven down by an order of magnitude.

I am convinced that, no matter how hard we push energy conservation and renewable energy, fossil fuel burning will continue to rise. The much ballyhooed hydrogen economy is certainly no panacea, for the energy required for hydrogen manufacture is ten times smaller when it is created by steaming coal than when it is created by electrolyzing water. Just as electricity generated using solar rays will not be competitive until the price comes down, similarly the use of hydrogen generated using nuclear electricity awaits more favorable economics.

There are those who will say don't worry, human ingenuity will bail us out by creating some combination of nuclear power safe from terrorists, solar electricity competitive with that from coal and perhaps even fusion power. But what if this doesn't happen? Shouldn't we have a proven backup plan? Fortunately there is a feasible backup strategy which would allow us to derive our energy from fossil fuels without increasing the atmosphere's $CO_2$ content. In other words, we can have our cake and eat it.

The idea is to capture $CO_2$ and bury it. One approach would be to capture the $CO_2$ from electrical power plant exhausts. But, as two thirds of the energy we currently use is produced in small units (automobiles, homes, factories, airplanes…), this alone will not be adequate. In addition, $CO_2$ would have to be recaptured from the atmosphere[28].

Could these $CO_2$-capture strategies be carried out at a reasonable cost? The answer is yes. In the case of plants deriving energy from coal, it would be more economical if the coal were steamed to produce hydrogen which could then be used to generate electricity in fuel cells. The reason is that the infrastructure required to separate hydrogen gas from the carbon monoxide produced during the steaming would be far cheaper than that required to scrub $CO_2$ from the flue gas emitted by traditional coal-fired electrical power stations.

Although the idea of recapturing $CO_2$ from the atmosphere, at first thought, might appear to be an impossible challenge, it turns out to be quite feasible. To see why this is the case, let us contrast the amount of kinetic energy carried by a given wind stream with the amount of $CO_2$ it carries. This might sound like the comparing of apples and oranges, but actually, it's not. The amount of $CO_2$ carried by the air stream can be thought of in terms of the amount of fossil fuel which would have to be burned in order to create it.

Thought of this way, we're comparing energy with energy. The comparison shows that $CO_2$ wins out over kinetic energy by more than a factor of 100. Further, $CO_2$ can be absorbed into a basic solution and then released in pure form allowing the absorbent to be recycled.

So, if wind turbines can compete with coal-fired electrical power plants, then it should be possible to economically recapture $CO_2$ from the atmosphere (see Fig. 10). Indeed, a small company in Tucson, Arizona has, for two years, been hard at work creating the prototype of such a capture device. It is their hope that it will be ready for field testing early in 2007. They estimate that the cost of capture will be on the order of 15 percent that of the energy derived from its generation. In other words, were the cost of capture passed along to the consumer, the price of a gallon of gasoline or of a kilowatt-hour of electricity would increase by a factor of about 1.15.

Lackner $CO_2$ extractor

Fig. 10. Artist's conception of a device for capturing $CO_2$ from the atmosphere.

Of course, once captured, whether it be from a power plant or directly from the atmosphere, the $CO_2$ must be put into storage. Several options have been suggested, each with its own cost, its own capacity and its own environmental consequences. In each, the first stop would be to convert the captured $CO_2$ to liquid form. At room temperature this involves pressurizing the $CO_2$ gas to 14 atmospheres. In liquid form, it could be transported to the storage site through the same kind of pipe lines used to transport petroleum. Among the disposal options are burial in salty aquifers (found at one or two kilometers depth in sedimentary terrains), in lakes beneath the Antarctic ice cap, in the abyssal ocean and in porous zones which separate successive basalt flows. Another somewhat more expensive option would be to mine, grind and dissolve silicate rock rich in the element magnesium. The magnesium recovered in this way would be reacted with the $CO_2$ to form the highly stable magnesium carbonate mineral, periclase[28].

A few pilot projects are already underway. The Norwegian company, Statoil, is separating at the well head the $CO_2$ contained in natural gas from beneath the North Sea[28]. The $CO_2$ is liquefied and pumped back down into an aquifer overlying the natural gas-bearing stratum. British Petroleum is planning to use the pipe lines constructed to deliver North Sea petroleum, to export liquid $CO_2$ derived from coal burning for storage in the now depleted reservoir.

As might be suspected, Green Peace vigorously opposes moves to even test marine disposal. Even stronger opposition would likely arise if disposal beneath the Antarctic ice cap were to be seriously proposed. Storage in either basalt or saline aquifers (or in periclase) has the advantage that it does not involve use of the global commons. Rather, these disposal sites are, for the most part, subject to the jurisdiction of single nations.

While there is no doubt in my mind that $CO_2$ capture and storage hold the key to any plan designed to stem the rise in atmospheric $CO_2$ content, an enormous amount of effort will be required before this strategy can be implemented on a wide scale. Coal gasification plants equipped with devices for $CO_2$ capture must be built and tested; so also will units for air capture. Storage evaluations will have to be conducted to insure that leakage back to the atmosphere is minimal, and that no chance for violent release exists.

In addition, a method must be worked out by which payments by the energy user are smoothly transferred to the companies which capture and bury $CO_2$. Finally, fossil fuel $CO_2$-emission allocations among the world's nations will have to be agreed upon and a means created to monitor and enforce compliance once they are in place. It doesn't take much imagination to see that of the three tasks, the last will be by far the most difficult. How will $CO_2$ production in the past be ranked against future production? What fraction of the disposal costs should be borne by the economically developed countries? How can countries that balk at signing on be brought into the fold?

## 11 Conclusions

It is my firm belief that the answer to the question raised in the title of this paper is that action on global warming cannot delayed. The Earth's climate system has demonstrated its ability to overreact to small nudges. We are poised to give it a sizable push. Prudence demands that we create the wherewithal to cap the rise in $CO_2$ at a value not exceeding double the pre-industrial concentration. While we must do everything possible to conserve energy and to employ renewable energy, these actions alone will not be enough. The availability of cheap coal and the desire by developing countries for more energy virtually guarantees that, despite our best efforts, $CO_2$ production will continue to rise. If we are to succeed in capping the rise, we will need to supplement conservation and renewables with $CO_2$ capture and burial.

**Acknowledgements** Thanks go to Jeff Severinghaus and Huan-Hui Li for their careful reading of this paper and to the Columbia Earth Institute for funding.

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