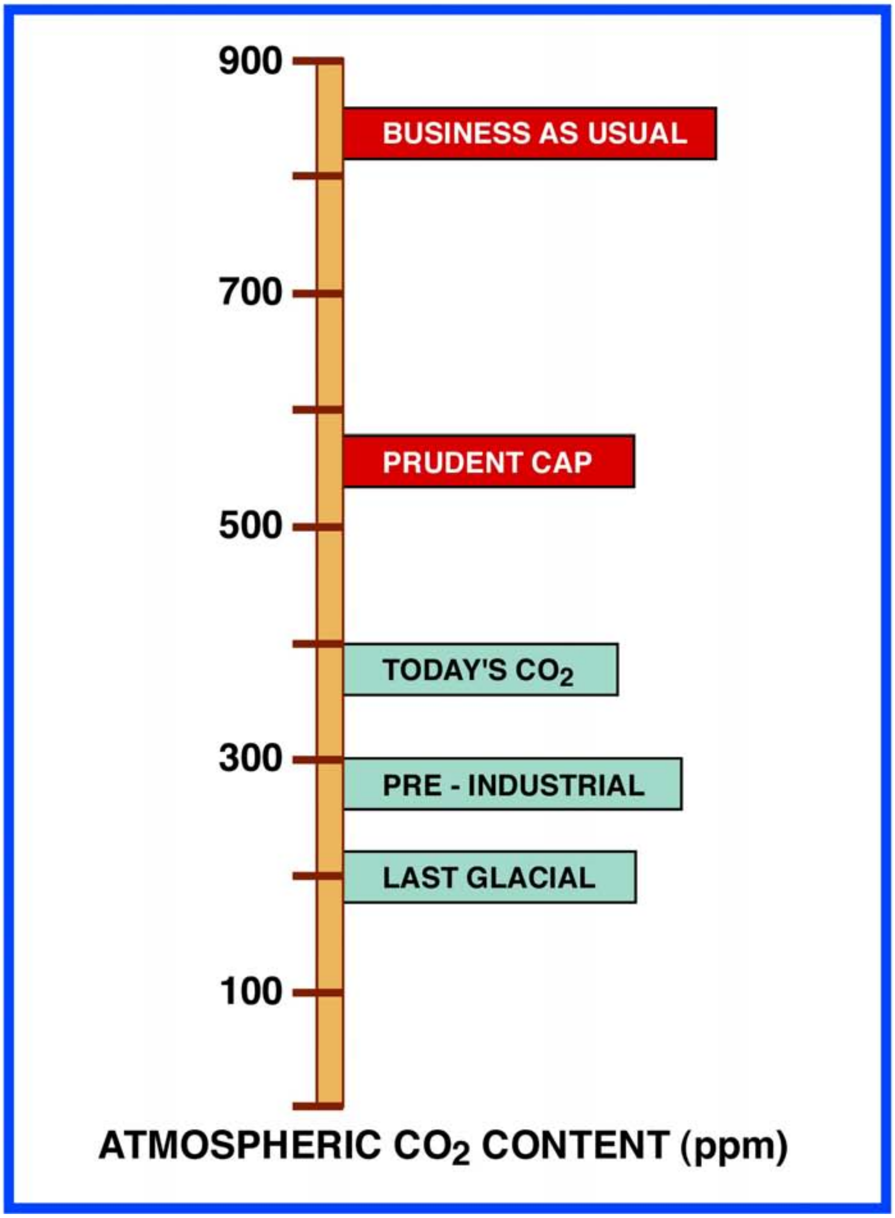
A Business Executive's Guide to Global Warming

Wally Broecker



Author's credentials

Wally Broecker is the Newberry Professor of Geochemistry at Columbia University. Over the last 50 years he has conducted research on the geochemical cycles of the element carbon and on the record of climate contained in polar ice and ocean sediments. He has authored over 400 journal articles and 7 books. He is, perhaps, best known for his discovery of the role played by the ocean in triggering the abrupt climate changes which punctuated glacial time. Broecker is a member of the National Academy of Science and recipient of the National Medal of Science.

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Global warming is an issue which will dominate the environmental agenda for much of this century. As a responsible business leader, it is important that you be fully informed with regard to both the consequences and the opportunities associated with the ongoing increase in atmospheric carbon dioxide. Superimposed on all the other changes this century brings will be a shift in climate conditions which will have impacts on everything we do. To date, many principals of business and government have to a large extent ignored this problem. Fortunately, with the advent of the Kyoto Accords an awakening is taking place. However, even if these Accords were strictly adhered to, only a tiny step toward a solution will have been taken. As yet no long-term road map for carbon management has been put into place.

Two scenarios bracket the course which global warming will follow. The "business-as-usual" scenario threatens a buildup of the atmosphere's carbon dioxide (CO_2) to triple the pre-industrial level. The "prudent cap" scenario involves a concerted effort to halt the increase before the pre-industrial level is doubled.

In the sections which follow I attempt to lay out key aspects of this problem in a manner which I hope will be clear as well as informative.

The Business-as-Usual Scenario

For each inhabitant of our planet, roughly 3 tons of CO_2 is currently produced annually by the burning of coal, petroleum and natural gas. About half of this CO_2 remains airborne leading to a 1.8 part per million (ppm) yearly rise in the atmosphere's CO_2 content. The other half of the CO_2 is taken up by the ocean and by the terrestrial biosphere. As of 2005, the atmosphere's CO_2 content (380 ppm) had, as a result of burning fossil fuels, risen 100 ppm above its pre-industrial level (i.e., 280 ppm).

While projections of future fossil fuel use are fraught with uncertainty, one aspect is clear. Even though our reserves of petroleum and perhaps also of natural gas are limited, those of coal could supply the world's energy needs for a couple of centuries. As coal can be converted to gasoline, our transportation fleet is not threatened by the demise of petroleum reserves. Thus, until cheaper options emerge, fossil fuels are likely to dominate our energy supply.

The key questions related to predicting future atmospheric CO_2 contents are: 1) how will energy use increase during the course of this century, and 2) what fraction of this energy will come from fossil fuels? Up until 15 years ago, energy use in the world's developed nations (currently ~1.5 billion people) was far greater than that in developing nations (currently ~5 billion people). But this situation is rapidly changing. Led by China, energy use in the developing nations is rapidly increasing. This increase will surely eclipse any reductions made by the countries which signed onto the Kyoto Accords. Indeed it is quite possible that worldwide energy use will double and perhaps even triple by the year 2050.

In order to get an idea of what the worst case scenario might be, let's assume that by 2050 per capita energy use will triple and that 85 percent of the energy will be derived by burning fossil fuels. We will also take into account that population is expected to increase from 6.5 to about 9.5 billion. If so, then the rate of CO_2 rise would increase from its current value of 1.8 ppm per year to 7.5 ppm per year. To get a feeling for the magnitude of the CO_2 increase, let's assume that between now and 2050, the average rate of CO_2 rise will increase linearly from 1.8 to 7.5 ppm per year. If so, as of 2050, the atmosphere's CO_2 content will be 540 ppm (i.e., nearly double the pre-industrial value). If after 2050 emissions were to remain constant at the 7.5 ppm per year rate, then by the year 2070 the atmosphere's CO_2 content would reach 790 ppm and, by the year 2090, it would reach 940 ppm.

The weak link in this scenario is the projection that by 2050 per capita energy use will have tripled. It is based on the assumption that by that time the industrial boom now raging in China and beginning in India will have spread throughout the traditionally poor nations of the world. While perhaps on the optimistic side, this scenario certainly lies well within the realm of possibility. It requires only a 1.6 percent per year rise in global energy use.

Prudent-Cap Scenario

The goal of most environmentalists is to bring to a halt the rise in atmospheric CO_2 content. The elements of such an effort include conservation, alternate sources of energy and purposeful capture and storage of CO_2. As the removal of excess CO_2 by natural processes occurs at a snail's pace, it is essential that we bring net CO_2 emissions to a near halt. Our reliance on fossil-fuel-based energy systems which vent CO_2 directly into the atmosphere makes this an enormous task which, no matter how we do it, will require many decades of intense effort. I find it difficult to believe that no matter how hard we try, we will be unable to cap the rise at less than 560 ppm. Although serious consequences will still ensue, the consequences of an increase of 180 ppm (i.e., 380 to 560) will not be nearly so large as those due to an increase of, let's say, 460 ppm (i.e., 380 to 840).

Assuming that, during the next 25 years, the required technologies are developed, the payment schemes are put into place, and the necessary international agreements are negotiated, serious implementation could begin as early as 2030. As about 50 years would be required to fully implement the scheme, it would be 2080 before the increase in the atmosphere's CO_2 content could be brought to a halt.

Predictions Based on Computer Simulations

All estimates of the impact of excess CO_2 are based on massive computer-based simulations carried out in what we scientists refer to as "general circulation models." These models incorporate all aspects of the atmosphere's operation including its interactions with the ocean and land surfaces. To the extent possible, the models are governed by the laws of physics.

These models are in place at many institutes across the world. At each, an array of simulations has been conducted. In every one of these simulations the planet warms when CO_2 is added to the model's atmosphere. Further, in all of the models, the extent of warming is amplified by a companion increase in the atmosphere's water vapor content. The reason is that the vapor pressure of water rises by 7 percent for each degree the surface ocean warms. Hence the amount of water vapor in the atmosphere increases. Water vapor is a potent greenhouse gas. Depending on the model, excess water vapor amplifies the CO_2-induced warming by a factor of 2 to 3. Hence, the 2°C warming created by tripled CO_2 alone (i.e., 3x280 or 840 ppm) is amplified to 4 to 6°C.

All models predict that the rise in temperature over the continents will be somewhat larger than that over the ocean. All models predict that the Arctic region will undergo the greatest extent of warming.

Impacts

The consequences of a business-as-usual CO_2 increase will be severe. Wild life will take an especially large hit. Agriculture will surely be impacted. Glaciers will melt. Sea level will rise. The tropics will become hotter and wetter; the deserts hotter and drier. Unfortunately, the models are much less reliable with regard to the details of what will happen in a specific area. Further, it is not likely that this situation will soon improve. Hence, we will have to make decisions concerning future action without an exact knowledge of what we are protecting ourselves against. With this in mind, let us consider some of the most important concerns.

Arctic climate: Models suggest that the warming in the Arctic will be significantly greater than that for the Earth as a whole. Indeed, dramatic and historically unprecedented changes are already taking place. Based on satellite observations, the inventory of Arctic sea ice has decreased by about 30 percent during the last 25 years.

The permafrost in the coastal regions is thawing. Extended warm seasons have permitted pest infestations which damage large swaths of Alaska's forests. If, as models suggest, these trends continue, by the year 2030 the Arctic will be largely free of summer sea ice and the ecology of the land surrounding the Arctic will be totally disrupted. Polar bears will not be able to roam the sea ice in search of food. Caribou will not be able to migrate over softening permafrost. The Inuits who inhabit the coastal plains will have to completely change their way of life. Of course, on the other side of the coin, Arctic shipping routes will open. So, a warmer Arctic, while decimating wildlife and threatening indigenous peoples, will offer a benefit to industry. But, do we have the right to create so much damage just to make a marginal economic gain?

Sea level: Sea level is already rising. As the planet warms, the rate of rise will surely accelerate. Roughly 30 percent of this rise is currently driven by the warming (and hence thermal expansion) of the waters in the upper ocean. The remainder is the result of ice melting. Although not well documented, melting around the perimeter of Greenland's ice cap appears to be the major supplier of this water. Were Greenland's ice cap to melt away, sea level would rise by five meters. While few predict a catastrophic melt, models suggest that a doubling of the atmospheric CO_2 could produce a total meltdown on the time scale of a couple of centuries.

Antarctic's ice cap contains an amount of water which if released to the ocean would raise sea level by 65 or so meters. While no one is predicting that the 90 percent of this ice which lies beneath the frigid Antarctic plateau is likely to melt, there is concern about the other 10 percent which is contained in the West Antarctic ice tongue. The seaward portion of this mass is afloat. The concern is that rising sea level will eventually release the ice from the grasp of the small islands which currently act as stabilizing pins. The sea level rise created by the melting of Greenland's ice cap could well destabilize this southern ice mass. Were this to happen, another five meters of sea level rise could occur.

It goes without saying that rising sea level brings with it the loss of valuable property and will threaten many of the world's major seaports. Of all the impacts on humans, this loss will have the most expensive consequences. In addition, such a rise would drown the world's coral reefs and thereby threaten a major fraction of the ocean's biodiversity.

Mountain glaciers: Since the mid 1800s, the glaciers capping the planet's highest mountains have retreated. The extent of this retreat is consistent with the extent to which the Earth has warmed (as measured using thermometers). Almost half of the ice in the European Alps is gone. At the current rate of retreat, Africa's Mt. Kilimanjaro will be ice free in a decade or so. A tripling of CO_2 would cause snowlines to rise on the order of a kilometer virtually denuding the world of mountain ice. As is the case in the Arctic, the plants and animals adapted to a cold existence would lose their niche.

Extreme events: Hurricanes are spawned in the late summer as waters in the tropics reach their maximum temperature. Global warming will make the ocean even warmer and as a consequence extend the hurricane season. We have already seen how the property loss and human misery resulting from hurricanes has sky-rocketed as the density of coastal development rises.

Models suggest that, as the planet warms, the deserts will become drier. If so, then the fraction of time droughts are experienced in drylands (for example, the western U.S.) will increase. The increase in population in desert areas makes coping with droughts ever more expensive.

Tropical warming: For inhabitants of the tropics, life is already difficult. Most of the planet's poor live there. It is difficult to see how a hotter and wetter climate will be a boon. More likely, it will aggravate the hardships these people typically endure. For example, vector-transmitted diseases like malaria will become an even greater problem.

Water availability: Critical to mankind's habitation of planet Earth is the availability of water for agriculture, industry and personal use. Of the concerns regarding the future, water availability is almost always at the top of the list. Not only are we making ever heavier demands on the fixed supply of this resource but we are contaminating it with salt, pollutants, pathogens and even radioactivity. If, as models suggest, the world's desert regions become drier as the planet warms, the situation will proportionally worsen. Much of our irrigation water comes from aquifers underlying currently dry regions. As little recharge of these aquifers is currently occurring, we are to a large extent mining water put in place during wetter glacial times.

Agriculture: By 2050, there will be between 9 and 10 billion people on Earth. This increase will require a 40 to 50 percent increase in food production. In addition, our growing taste for meat is steadily increasing per capita grain demand. Most agriculturalists believe this increased demand can be met by pumping up crop yield. On the positive side, extra CO_2 acts as a fertilizer and thus enhances plant growth. Extra CO_2 also increases water-use efficiency by plants. On the negative side, models suggest that soil moisture content will likely decrease as the planet warms. Ecologists warn that weeds will profit even more than cash crops, and hydrologists warn that water required for irrigation will outstrip the supply.

The predicted impacts of global warming are unsettling. As stewards of our planet, we have an obligation to prepare to deal with these problems.

A Bumpy Ride?

While model simulations chart a smooth response to the ongoing buildup of atmospheric CO_2, the record kept in sediments and polar ice for the last 100,000 years clearly tells us that our climate system has a habit of taking discontinuous jumps from one of its operational states to another. Each of these jumps was completed in just a few decades. During the transition period associated with these jumps, the climate appears to have flickered. Some of these reorganizations appear to have been triggered by shutdowns of a major unit of the ocean's circulation system: namely, the Atlantic's conveyor (see Figure 4 and companion discussion later in text). This being the case, might the greenhouse warming trigger one or more such reorganizations? Although this question is currently unanswerable, climate models suggest that the dramatic cooling of northern Europe which resulted from past reorganizations had its roots in the formation of sea ice in the northern Atlantic. In its present interglacial state, the climate has been much better behaved. One reason is, perhaps, that sea ice extent is limited by warmth. Hence, as the planet's temperature rises, the likelihood of large European coolings will become ever smaller. However, this does not mean that we are off the hook. The more we learn about our climate system, the more we become aware of its ability to do unexpected things. During the past two decades, we have become aware of the widespread impacts of the El Niño-La Niña cycle. Two century-long severe droughts which devastated the dry regions of western North America during the Medieval Era have only recently been documented. As our understanding of these and other climate anomalies remains primitive, by adding CO_2 to the atmosphere, we are in a sense playing Russian roulette with our climate system!

Naysayers

Although almost all scientists view global warming as a serious problem, a few do not. Of these, only MIT's Richard Lindzen has sterling credentials as an expert in atmospheric physics. In an effort to fairly report both sides of the debate, the press has given Lindzen's views an enormous amount of attention. His assessment is that, although the water vapor content of the tropical atmosphere will increase as CO_2 rises, that in air over desert regions will instead decrease. As the dry desert atmosphere acts as the primary escape hatch for outgoing earth light, Lindzen claims that a global-warming will induce a drying of desert atmospheres which will largely null the primary CO_2-induced warming. Although no model simulation supports Lindzen's view, our knowledge of the processes which supply moisture to the desert air column is admittedly limited. Hence his scenario cannot be ruled out. Rather, it can only be declared highly unlikely. It must be kept in mind that Lindzen is an avowed contrarian. Not only is he convinced that increased CO_2 is no threat, he also has stated many times that no proof exists that cigarette smoking causes cancer.

In addition to Lindzen, there are a few scientists from neighboring disciplines who seek recognition by pouring cold water on threats posed by global warming. Of course, their statements are music to the ears of those politicians eager to downplay this problem. Thus, their criticisms feed the frenzy which casts us as "junk" scientists. Oklahoma's Senator Inhofe goes so far as to declare global warming to be the greatest hoax science has ever foisted upon the public. In the paragraphs which follow, I summarize a few claims made by the naysayers.

1) Claim: The warming of the last 30 years has been driven by an increase in the Sun's energy output. Rebuttal: Satellite-based measurements carried out over the last quarter century (a time during which the Earth has steadily warmed) reveal no upward trend in the Sun's irradiance. Rather, they show only a tiny (less than 0.1 percent) cyclic change which correlates with the 11-year sunspot cycle. Keep in mind that, in models, a tripling of CO_2 has an impact equivalent to a three percent increase in solar output.

2) Claim: The warming between 1900 and 1940 was nearly as large as that between 1975 and 2004, yet it has no known man-made cause. Rebuttal: True, this warming was almost certainly natural. What it tells us is that on its own, Earth climate has undergone changes comparable in magnitude to that created to date by greenhouse gases. As the time course of these natural changes has been irregular, we cannot say whether during the last 30 years they have worked to enhance the warming or whether they have worked to retard it. We can say, however, that if the models are correct, then during the next 20 years Earth temperature will surely emerge from the envelope of natural fluctuations.

3) Claim: Climate is no warmer than it has been at several times during the last 12,000 years. Rebuttal: Again true. At the peak of the Medieval Warm Period (800 to 1250), temperatures at high northern latitudes appear to have been comparable to those of

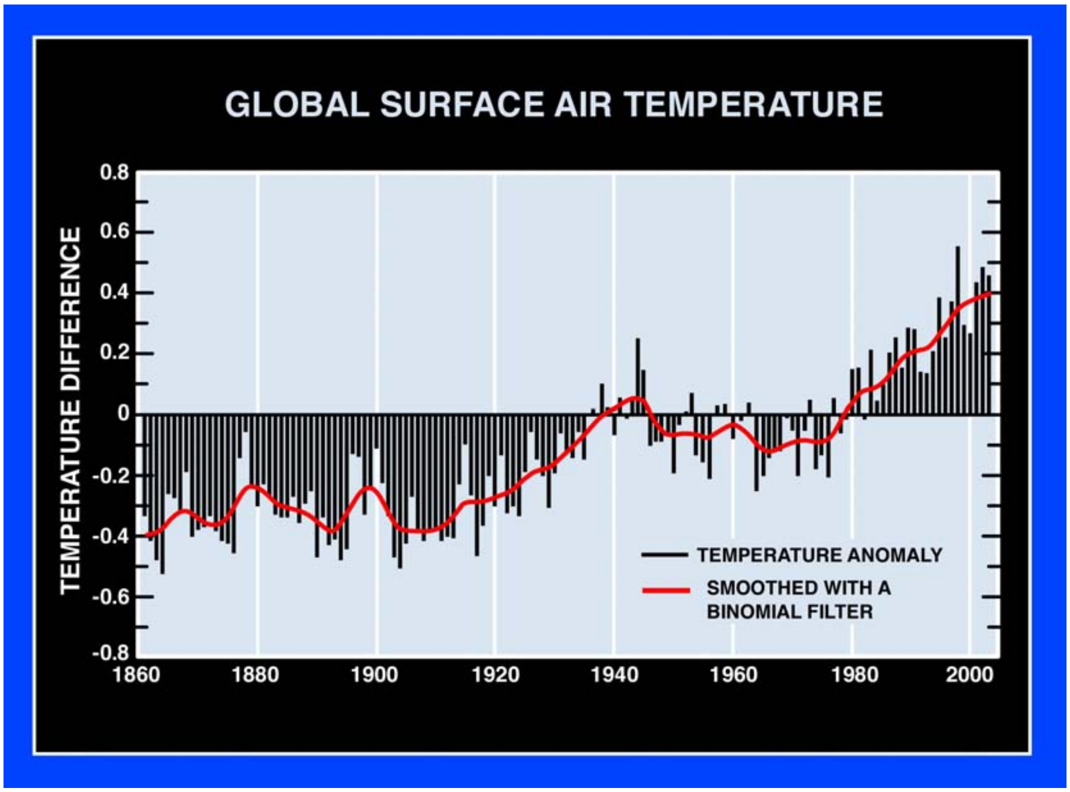

Figure 1. Mean global temperature for the last 145 years based on meteorologic records. Although the post 1975 warming is attributed to excess greenhouse gases, that prior to 1940 likely had a natural origin. The plateau between 1940 and 1975 is thought by some to reflect compensation of the man-induced warming by a natural cooling.

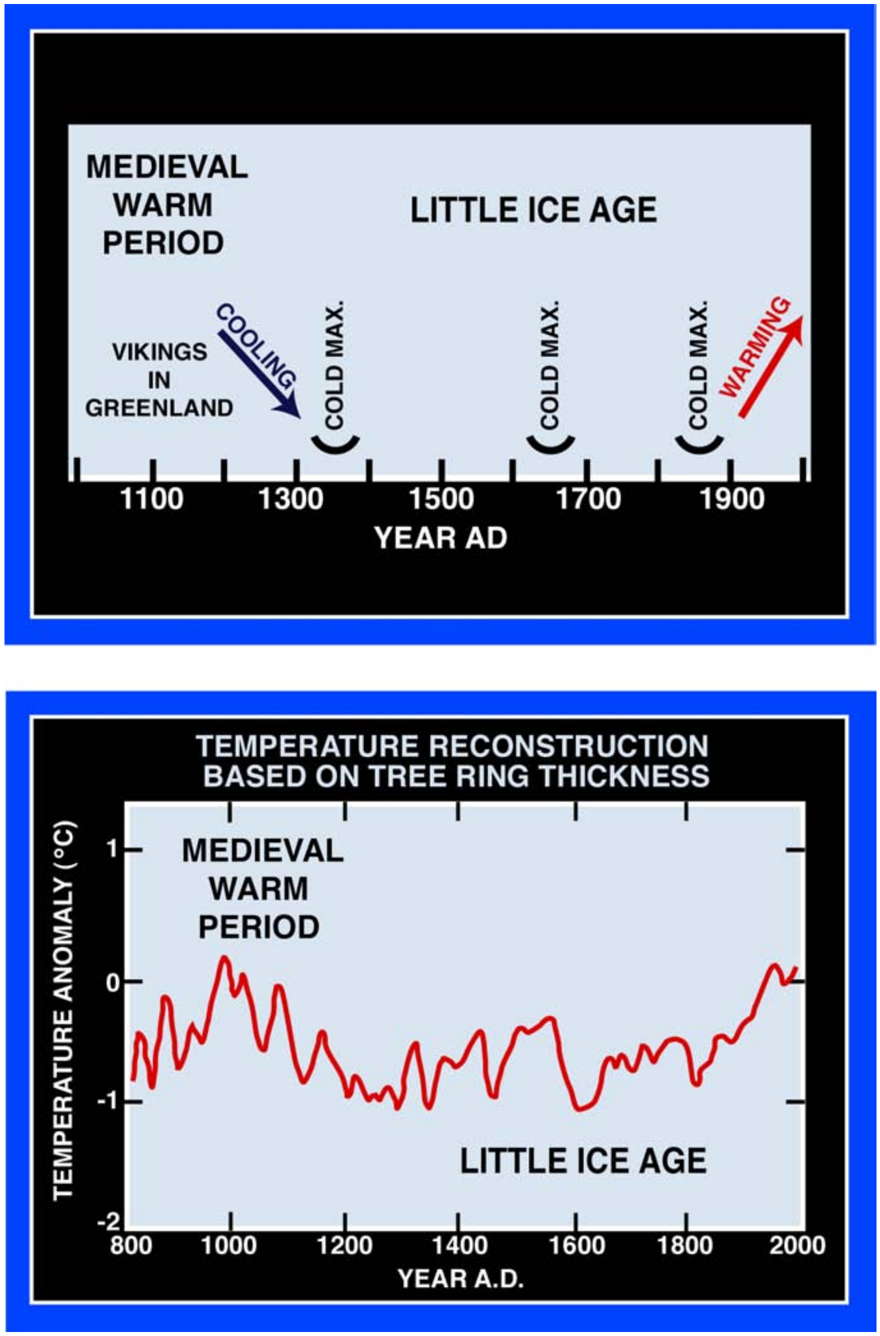

Figure 2. In the upper panel is summarized the state of knowledge as to how temperatures at northern latitudes changed over the last 1000 years. In the lower panel is reproduced a temperature record obtained by averaging ring widths recorded in 1800 trees from areas in the northern hemisphere which experience winter temperatures near the limit for tree survival.

the last decade. Further, radiocarbon dates on wood and peat being swept by summer melt water from beneath shrinking mountain glaciers tell us that at several times during the present interglacial period, these glaciers must have been even smaller than they are now. The point to be made is that our models predict that a business-as-usual CO_2 increase will produce a warming which far outstrips any experienced during the present interglacial (or during previous interglacials). Further, the warming will be so rapid that already stressed wildlife will not be able to adapt.

4) Claim: A substantial part of the warming during the past 30 years has been driven by "dark" aerosols rather than by CO_2. Rebuttal: Man-made aerosols are certainly important players in the Earth's energy budget. But it is not clear whether the "white" aerosols (largely sulphuric acid generated from sulfur dioxide released when coal is burned) or the "black" aerosols (largely carbon black associated with coal and biomass burning) are the more important. As incoming sunlight is reflected by "white" aerosols and outgoing earth light is captured and reradiated by "black" aerosols, their impacts work against each other. The "whites" tend to cool the Earth and the "blacks" tend to warm it. Two points must be kept in mind. First, unlike CO_2, the atmospheric lifetime of aerosols is only days to weeks. Second, as both SO_2 and fine particulates constitute serious health hazards, efforts to reduce them have a high priority. Hence, even if aerosols are currently a significant player in the Earth's energy budget, as time passes, their role compared to that of CO_2 will surely be greatly diminished.

5) Claim: Fossil fuel CO_2 emissions can be easily compensated by changing forestry practice so that more carbon is stored in trees and by changing agricultural practice so that more carbon is stored in soil humus. Rebuttal: Historically the opposite has been happening. Deforestation has exceeded forest re-growth. Agricultural soils have lower organic carbon contents than adjacent native soils. Although during the last decade forest re-growth and inadvertent fertilization with excess atmospheric CO_2 and fixed nitrogen have temporarily reversed this trend, it is not clear whether the increase in

terrestrial biomass will be sustained. In any case, most biogeochemists would agree that at most, over the next 100 years, the excess storage could reach 150 billion tons. Or, on the other hand, the amount of storage may peak and then slowly decline. During this period, if we proceed along the business-as-usual pathway, we will burn more than 1000 billion tons of fossil fuel carbon.

6) Claim: Through purposeful iron fertilization growth of plankton in the ocean could be increased with the consequence that the biologic "pump" which transfers carbon from the upper ocean to the deep ocean would be strengthened. Rebuttal: Indeed, one of the most important discoveries made in the field of marine biology during the past two decades is that plant productivity in regions of the surface ocean rich in plant nutrients is limited by the availability of the element iron. Further, in situ experiments conducted in these areas demonstrate that through the addition of small amounts of iron, plant productivity does undergo a modest increase. But, most biogeochemists agree that the monetary expense and ecologic side effects associated with large-scale iron fertilization would greatly outweigh the modest reductions of atmospheric CO_2 content that could be accomplished in this way.

7) Claim: The Earth's climate system has a built-in tendency to compensate any impetus to change. Rebuttal: The records kept in ice from Greenland, in sediments from the ocean floor, and in stalagmites from caves provide firm evidence that this is definitely not the case. Rather, the climate system appears to have overreacted to the nudges it has received. These nudges have three known origins: tiny changes in the Sun's luminosity, cyclic changes in the Earth's orbital characteristics and reorganizations of the ocean's circulation. Indisputable evidence exists in the records of past climates that the Earth has, in a sense, over-responded to all three. Models suggest that a nudge to our climate system by a tripling of atmospheric CO_2 will be more than an order of magnitude stronger than that from these natural nudges. Hence, it would be prudent for us to establish a cap on the extent of this CO_2 increase.

The Role of the Ocean

I will briefly outline the evidence which points to reorganizations of the ocean's large-scale circulation system as the driver of the most dramatic climate changes experienced by the Earth in the last 100,000 years. The paleoclimatic record contains incontrovertible evidence that during the last glacial period the Earth's climate underwent repeated abrupt jumps from one to another of its distinct modes of operation. Each of these jumps was accomplished in less than four decades. Further, during the several-decade transition period, climate appears to have flickered much as do fluorescent lights when turned on. The intervals between these abrupt reorganizations averaged about 750 years. The same temporal sequence of change recorded in Greenland's ice is repeated in marine sediment from throughout the northern hemisphere and tropics. The locales include the Arabian Sea (off Pakistan), the Santa Barbara Basin (off California) and the Cariaco Basin (off Venezuela). These reorganizations are also beautifully replicated in a stalagmite from a cave in China. Large changes in the dust content of Greenland ice and in the methane content of air bubbles trapped in this ice tell us that storminess in the deserts of Asia (dust) and the extent of tropical wetlands (methane) changed in concert with Greenland's air temperature.

A strong case can be made that these alternate states of operation are tied to discreet patterns of large-scale circulation in the ocean and in particular to the conveyor-like circulation in the Atlantic Ocean. During glacial time, when heat delivered to the northern reaches of the Atlantic by the conveyor's upper limb (i.e., the Gulf Stream) was shut down, winter sea ice expanded far to the south of its present limit thereby shutting down the release of ocean heat to the overlying atmosphere. In the absence of this ocean heat, northern Europe experienced winters akin to those of Siberia. Further, models suggest that the cooling in the north caused the tropical rain belts to shift southward and the monsoons to be weakened.

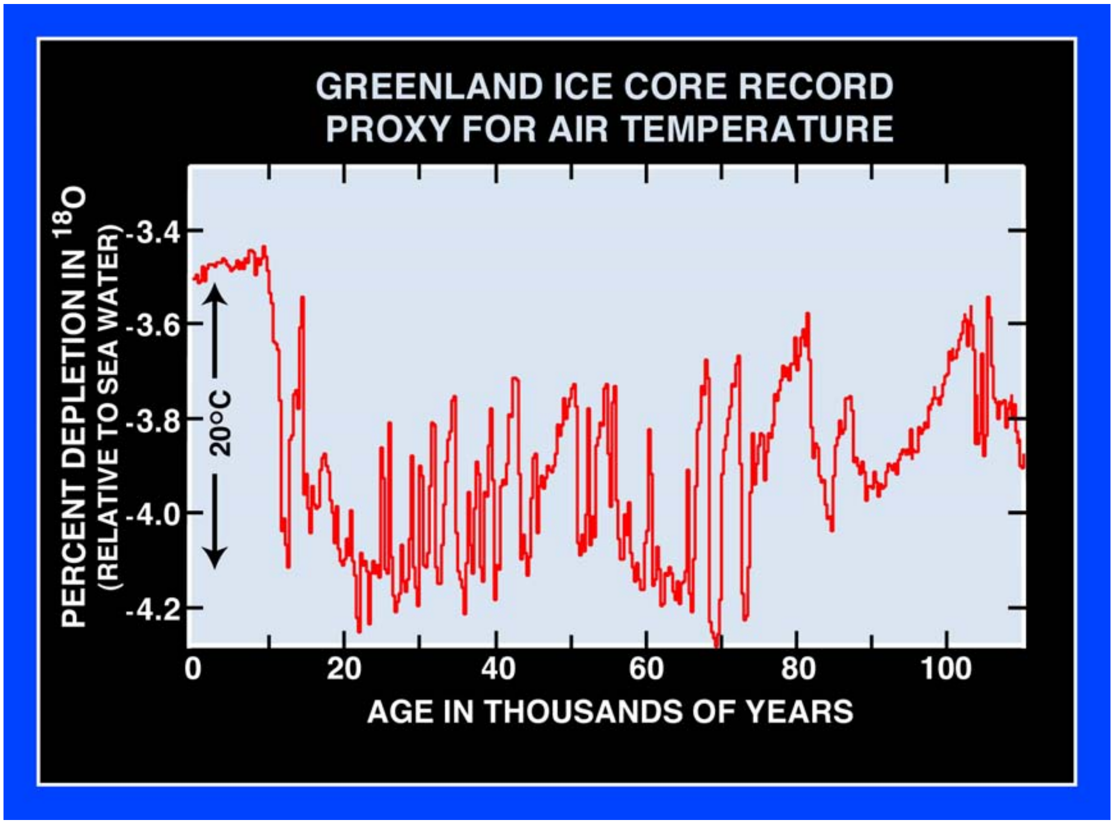

Figure 3. A temperature reconstruction for the last 110,000 years based on isotopic measurements made on ice from a 3 km-long core drilled at the Summit Greenland site.

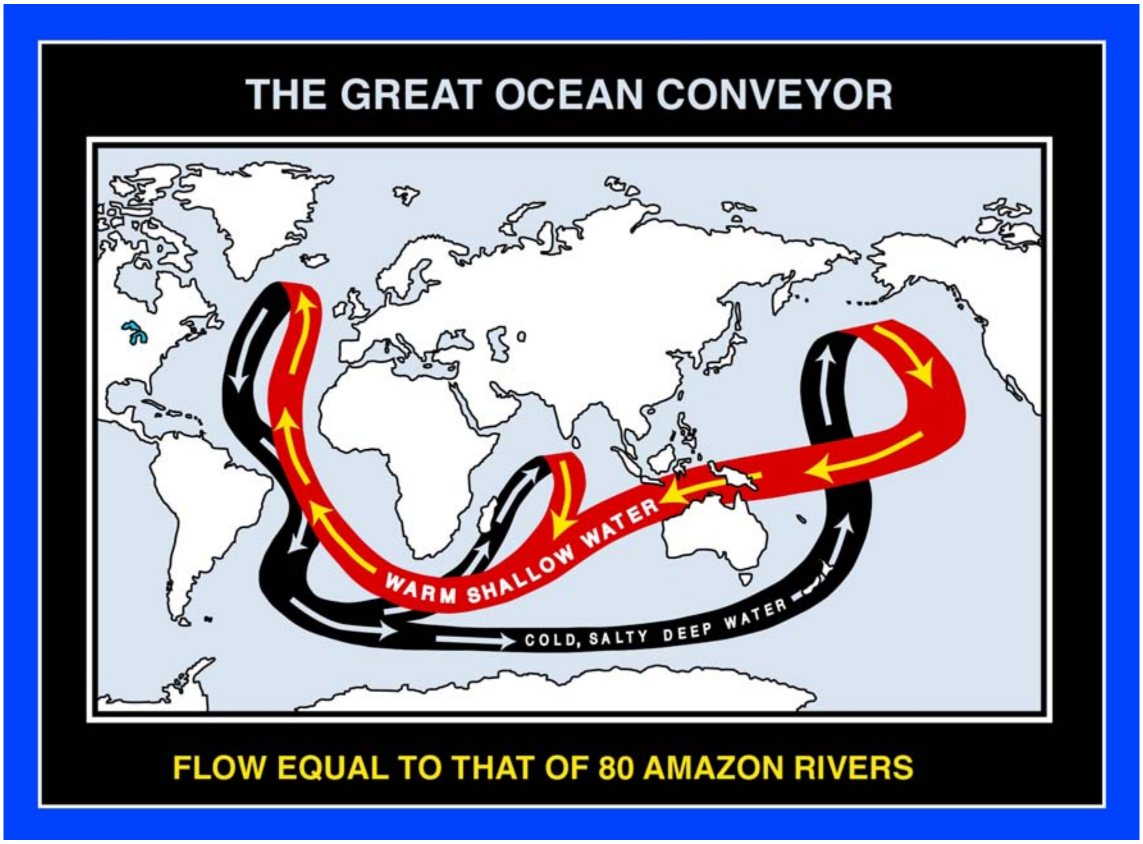

Figure 4. Diagrammatic representation of the first order circulation pattern in the world ocean. In the Atlantic, the pattern can be thought of as a conveyor whose upper limb carries warm upper water northward and whose lower limb carries cold deep water southward.

Several of the shutdowns of conveyor circulation can be tied to the melting of massive armadas of icebergs discharged into the northern Atlantic. Each of these armadas is thought to have been generated by a catastrophic collapse of that portion of Canada's glacial ice sheet centered over Hudson Bay. Two other conveyor shutdowns appear to have been caused by catastrophic floods of fresh water released from a lake which formed in front of the Canadian ice sheet during its meltdown. These releases were triggered as the result of breaches in the ice front which constituted the northern shoreline of the lake.

Now I must hasten to add that, as there are no longer either large ice sheets poised to disintegrate or large lakes held in place by ice, a repeat of the catastrophes which punctuated glacial time is not likely. However, the dramatic events that we now know occurred during glacial time reveal an attribute of the Earth system which we had never even dreamed of. Our climate system is indeed capable of jumping from one mode of operation to another.

Droughts

Despite the fact that climate has been relatively well behaved during the present interglacial period, some scary episodes have occurred. I will mention only one of these. During the so-called Medieval Warm Period (~800 to 1250 A.D.), western North America experienced two century-long droughts much more severe than even the worst of the short-duration droughts (i.e., ~5 years) experienced during historic time. We know this because in six different locations tree stumps still rooted beneath the surface of lakes, bogs or rivers have been discovered. The time of growth of these trees has been documented by radiocarbon dating and the duration of their lives by counting the growth rings. Had "normal" conditions interrupted these droughts for even a few years, the consequent rise in water level would have killed these trees.

A Road Map for Carbon Management

I maintain that by 2070 or so we must bring to a halt the buildup of CO_2 in the atmosphere. This will require an immense change in the way we produce energy. In this section, I consider the options available to us.

Conservation: There is no question that we can squeeze more use out of the energy we currently produce. Hybrid automobiles, more efficient lighting, better insulated buildings, use of power-plant waste heat come to mind. Indeed much of the reduction in fossil fuel use mandated by the Kyoto Accords will be achieved in this way. However, while a goal of curtailing the buildup of CO_2 can certainly not be achieved by conservation alone, successes in this area will make it easier and cheaper to achieve this objective.

Alternate sources: Many environmentalists entertain the hope that other sources of energy will, during the course of this century, replace fossil fuels. Let us examine the list of candidates.

Hydrogen: The so-called hydrogen economy has received much press. The idea is that hydrogen gas (H_2) will replace gasoline as the propellant for our transportation fleet. Gone would be the dependence on Arab oil. Gone would be the noxious fumes. Gone would be CO_2 emissions. But wait! Two huge problems stand in the way. First, as there are no hydrogen wells, this gas must be manufactured by breaking loose the hydrogen atoms bound into water molecules. This breakup requires energy. One way to do this is by electrolyzing water. Another is by steaming coal. As the second route is currently an order of magnitude cheaper than the first, there is little question as to which route would be initially adopted. But, when coal is steamed, carbon monoxide (CO) gas is created along with the hydrogen gas. The carbon monoxide would be converted to carbon dioxide (CO_2). So, the hydrogen economy, at least initially, would be based on fossil fuel energy. There still would be CO_2 to contend with!

The second problem involves the storage of sufficient amounts of hydrogen on vehicles. Hydrogen gas can be liquefied only if it is cooled to near absolute zero. To accomplish this cooling and to maintain this ultra-low temperature in the storage containers would prove to be prohibitively expensive. Were, instead, the hydrogen to be stored as a gas, the tank would have to be either prohibitively bulky or the pressure in the tank dangerously high. To date, no satisfactory solution to this storage problem has been found.

A more feasible option would be to use hydrogen to make gasoline. This would be done by combining the hydrogen gas with carbon derived from CO_2 molecules captured from the atmosphere. Such a scheme would be CO_2 neutral.

Solar: The most likely long-term replacement for fossil fuel energy is energy from the Sun. Solar panels capable of producing electricity, while already in use, are currently far too expensive to compete in the core energy market. Further, as electricity cannot be stored, some means would have to be developed to bridge periods of darkness. One way would be to use solar energy to decompose water. The hydrogen obtained in this way could be either used in fuel cells to generate electricity or be combined with carbon derived from atmospheric CO_2 to produce gasoline. The great hope is that the ultra abundant energy from the Sun can be harnessed at a competitive price. While the technology is steadily moving toward this goal, it is unlikely that it will be achieved in time to meet a 2070 deadline. But, hopefully, solar energy will become a major player late in this century.

Wind: Europe's giant wind turbines are generating electricity at a price competitive with that produced in coal-fired plants. But I doubt that wind power will replace more than 10 percent of the energy currently produced by fossil fuel burning. In order to supply all the energy required to maintain the average American's lifestyle, a rotor intercepting about 90 square meters of wind moving at a speed of 5 meters per second is required. Hence, to meet America's energy supply would require 300 million such rotors. Were, in 2050, the planet's 9.5 billion people to achieve an average energy use equal to 25 percent of that currently consumed by average Americans and were this energy to come entirely from wind, then some 2.4 billion such rotors would be needed. At this scale, the wind turbines would sap 10 to 20 percent of the energy carried by the world's ground level winds. So, while windy countries like Denmark, will likely generate a fair fraction of their electrical power from wind turbines, this is an impractical solution for most countries.

Nuclear: In principle, nuclear reactors could supply the world's energy. However, two serious drawbacks make this unwise. One is the storage of the radioisotopes created as a by-product of fission. In the USA, all this material currently remains at the sites of the reactors in which it was produced. Hence, it constitutes a target for terrorists. Even if a long-term storage facility could be agreed upon, local communities will resist the transport of fission products from the reactor site to the storage site. The second and more serious concern also has to do with terrorism. The problem is that the reserves of ^{235}U which currently fuels all power reactors are, like those of petroleum, extremely limited. Hence it will be necessary to go to breeder reactors. In these devices the two extra neutrons released as the result of each fission event are used to convert the highly abundant, but not fissionable, ^{238}U and ^{232}Th into plutonium atoms which are fissionable. In this way, each precious ^{235}U atom could replace itself. And, of course, each plutonium atom which was subsequently fissioned could also replace itself. Hence the term breeder. The reserves of ^{238}U and ^{232}Th are large enough that, in this way, the world could be fueled for many centuries. But were a major fraction of our energy to be obtained in this way, it would involve handling tons and tons of plutonium. Were even one kilo of this plutonium to fall into the hands of terrorists, they would have the capability of destroying any one of the world's largest cities. As nuclear terrorism is our worst nightmare, it seems to me that going to a nuclear-powered world would be very dangerous. While technically advanced countries like France can pull it off, it is unthinkable to me that every nation on the planet can in the next 50 years become a France. Thus, like power from the wind, power from the atom is unlikely to supply more than 10 percent of the global energy market. To be honest, I must admit there are many (including the present occupants of the White House) who do not agree with this assessment.

Biomass: Ethanol produced from sugar beets or corn currently fuels automobiles. But, at least in the case of ethanol made in the USA, the energy required to plant, fertilize, harvest and process the corn is comparable to that obtained by burning the ethanol. Hence, at least following current practice, the use of ethanol has not reduced our use of fossil energy.

Putting this drawback aside, let us consider the likelihood that biomass could become a major piece of the energy pie. The limit would surely be placed by the availability of arable land. As of the early 1960s, virtually all of the world's naturally arable land had been put to use for food production. Since then, a modest 15 percent increase has been accomplished by irrigation of lands previously too dry for farming. Currently 40 percent of the world's grain is grown on irrigated lands.

The reason that farmers have been able to keep up with the explosion of population is that, through the use of fertilizer, genetically altered plants and pest control, they have been able to greatly increase the amount of food produced on each hectare of arable land. Even so, malnutrition has not been eliminated.

An important consideration in this regard is that the per capita usage of external energy by people in developed nations is approximately 50 times greater than that created by the food he or she eats. Even though a greater fraction of plant matter can be used for energy production than for food consumption, this difference will not offset the factor of 50. Also, it must be kept in mind that population is expected to increase from 6.5 to about 9.5 billion. Further, one hopes that the plight of the hungry will be reduced. Hence, at least half again as much food will have to be produced. Clearly, land for energy production will become available only with further increases in agriculture yield which eclipse food needs. Because of this limitation, I cannot see the likelihood that energy derived from biomass will capture more than 10 percent of the market.

Hydropower: The era of building large hydro-electric facilities is coming to an end. China's Three Gorges Dam will likely be the last mega project. Silting of the catchment basins behind dams limits their life expectancy. Few of the existing hydro facilities will remain operative in 2070. Most of the obvious sites for hydro expansion have already been developed. Further, in developed countries, there is increasing pressure to tear down existing dams. The reason is that their catchment basins flood some of the world's most beautiful terrain. Thus, no large expansion of the hydro-electric contribution to world energy supply (now 5 percent) is to be expected.

Other: Energy from geothermal and tidal sources, although frequently mentioned, will surely not be major contributors. Of course, Iceland will continue to develop its geothermal potential. Tidal stations may be built at a few especially favorable places (such as the Bay of Fundy). However, when viewed on a global scale, these facilities will remain small potatoes.

Summary: Only two alternate sources, solar and nuclear, have the capacity to supply major chunks of the world's energy. Solar is our hope for the future. Nuclear, while a viable possibility, has serious drawbacks which will likely impede its widespread use.

CO_2 Capture and Storage

I find it difficult to believe that by 2070 or so alternate sources of energy will have totally replaced energy derived from fossil fuel combustion. No matter how hard we try, there will very likely be a substantial shortfall. This being the case, we need an on-the-shelf backstop which could be implemented to fill the gap. Fortunately such a backstop exists. It involves capture and storage of the CO_2 produced by the combustion of fossil fuels.

When first faced with this option, the reaction is often that it will allow profligate consumption to continue. My response is that exorbitant lifestyle and global warming are separate issues. Were we to merge them by erecting barriers to energy use in order to crimp excessive lifestyle, we would likely lose on both fronts. Greed would trump environmental concern. Rather, we must deal with these issues separately. Quelling CO_2 emissions is by itself an enormous challenge. We cannot afford to put aside options which might hold the key to success.

Briefly, the idea is as follows: CO_2 would be captured at its source in electrical power facilities. But, since roughly 60 percent of energy production occurs in small units (automobiles, homes, small factories…), capture of CO_2 from the atmosphere would have to play a large role in this strategy. Once captured, the CO_2 would be converted to a liquid form (by compression to 14 atmospheres). It would then be transported in pipelines (akin to those used for petroleum or natural gas) to the disposal site. Initially, storage would likely be mainly in saline aquifers which underlie the interiors of continents at depths of 1 to 3 kilometers. As these were filled, a transition to mineralization would likely take place. The CO_2 molecules would be bound to magnesium oxide derived from rock rich in the mineral olivine (magnesium silicate). The magnesium carbonate ($MgCO_3$) created in this way is a highly stable mineral. It would be dumped back in the holes created by excavating the olivine.

Capture: If capture of CO_2 from the atmosphere is to be an essential part of our backstop, the question arises as to whether it can be accomplished at an affordable cost. Klaus Lackner, currently a professor at Columbia University, was the first to make the case that indeed capture is not only possible but surprisingly simple. He showed this by comparing the size of facilities required to harness wind energy with the size of those required to capture CO_2 from the same air stream. The startling conclusion is that in order to capture the amount of CO_2 produced were the energy generated by burning fossil fuels, only one percent of the amount of air required to produce the same amount of energy via wind turbines would have to be intercepted. Stated in another way, the size of the facilities necessary to create energy using wind-driven turbines would be one hundred times larger than those required to capture an amount of CO_2 equal to that emitted were the energy instead to have come from fossil fuels. A critic would likely counter that the technology for wind turbines has evolved over hundreds of years and has reached a high level of sophistication while that for CO_2 removal has yet to be even tried. The rebuttal would be that CO_2 capture does not involve rocket science; rather it is based on straight-forward chemical engineering.

Indeed, a small company launched in February 2004 had by October 2004 constructed a smoothly operating prototype CO_2 extraction system. While the details remain proprietary, the CO_2 contained in the passing wind stream is absorbed in liquid sodium hydroxide. Having largely completed the first phase of their effort to develop an extraction unit which could later be mass produced, the company's team has turned its attention to a mechanism to release the CO_2 captured in the sodium hydroxide. Their goal is to have a fully operative prototype ready for display by early 2006. If they succeed, with the expenditure of only a few million dollars, they will have taken a major step in the solution of a trillion dollar problem.

Klaus Lackner estimates that to capture and store the CO_2 produced by burning gasoline, for example, would initially add about 80 cents (US) to the cost of a gallon. He is confident, however, that this cost could be reduced to between 25 to 35 cents per gallon. This would constitute a 15 percent increase in the current cost of gasoline in the U.S. and a substantially smaller percentage of the cost of petrol in Europe.

Because of the much higher concentration of CO_2 (~10 percent by volume) in the stack gases produced in coal-fired electrical power plants, CO_2 capture would seemingly be simpler and hence less expensive than retrieval from the atmosphere. However, the very large capital cost associated with retrofitting existing power plants would largely offset this advantage. Rather, the thinking is that, during the next 50 years, there will be a large expansion of electrical power facilities. China will lead the way. Also during the period, most of the world's existing electrical power facilities will have to be replaced. The idea is that the new plants would steam coal to generate hydrogen gas. In this way, the CO_2 released would not be mixed with ten times its volume of air as it is in a traditional coal-fired power plant, but, rather, the CO_2 would be mixed with a nearly equal volume of hydrogen gas making the separation far simpler. Further, these new plants would be designed in such a way that retrofitting for CO_2 capture could be done for a modest cost.

Storage: A wide range of sites for the storage of liquid CO_2 have been proposed. A number of these are currently being investigated. Each has its own set of advantages and disadvantages.

Deep aquifers: Statoil, a Norwegian energy company, is already piping CO_2 separated from natural gas into an aquifer beneath the North Sea. In this way it avoids Norway's CO_2 emission tax. As aquifers suitable for CO_2 disposal exist in many places, they constitute the prime target for disposal. Of course aquifers containing potable water would be avoided. Rather, those containing water too salty for irrigation would be chosen. It has been estimated that these aquifers could hold a quantity of CO_2 equal to that to be produced worldwide in the next 15 years. But not all countries have access to such aquifers. Further, in earthquake-prone countries like Japan pumping CO_2 into subsurface reservoirs would be dangerous.

Deep ocean: Most of the CO_2 we produce will ultimately end up in the deep sea. But it will take hundreds of years for it to get there. We could short circuit this slow, natural delivery by pumping liquid CO_2 directly into the deep sea. Below a depth of 3500 meters liquid CO_2 is more dense than sea water. Further, under the near freezing temperatures and high pressures which characterize this realm, the CO_2 molecules would react with water molecules to form a solid ($6H_2O + 1CO_2$) which is even more dense than liquid CO_2. Hence this solid would sink and pile up on the sea floor. With time, this so-

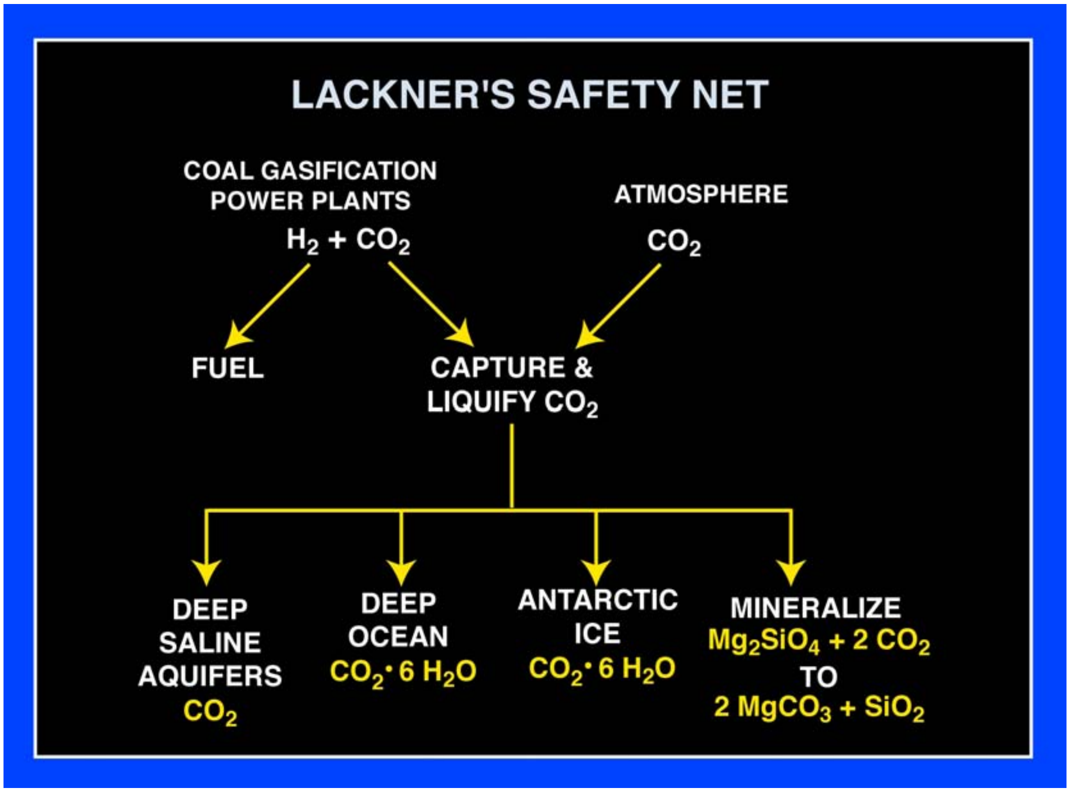

Figure 5. Klaus Lackner has the vision that the CO_2 produced by fossil fuel burning be captured and stored. In the case of large electrical power facilities, the CO_2 would be captured on site. However, such facilities currently account for only about one third of the CO_2 produced. The other two thirds of the CO_2 comes from small units (automobiles, airplanes, home-heating units…) for which CO_2 capture at its source is impractical. Lackner proposes that it be recaptured from the atmosphere. In either case, the captured CO_2 would be liquefied (at 14 atmosphere's pressure) and piped to a storage site. Four storage possibilities exist): 1) as liquid CO_2 in the pores of deep continental aquifers, 2) in the deep sea initially as a solid CO_2 clathrate, 3) in lakes beneath the Antarctic ice cap as CO_2 clathrates and 4) as the mineral, $MgCO_3$, using MgO dissolved olivine-bearing rocks.

called CO_2 "clathrate" would dissolve into the passing bottom water and the CO_2 would be neutralized by reaction with this carbonate and borate contained in the sea water. While in many ways an ideal solution, environmentalists will surely exert strong opposition to this use of the global commons for this purpose.

Antarctic lakes: Beneath the Antarctic ice cap there are at least 100 lakes. These lakes were created by geothermal heat diffusing up from beneath the ice cap. Were liquid CO_2 piped down into any one of these lakes, just as in the deep sea, it would combine with water to form a clathrate. The clathrate would sink to the bottom of the lake and accumulate. Despite the loss of its water to clathrate formation, the lake's volume would change, only very slowly. The reason is that the heat given off as a result of the formation of the clathrate would melt ice from the roof of the cavity, replenishing the lost water. The clathrates thus formed would remain trapped beneath the ice cap for many tens of thousands of years. But, as for deep ocean storage, there is bound to be strong opposition to the use of Antarctica for this purpose.

In situ mineralization: At several places on the planet, there exist huge lava fields formed when plumes of material thought to originate at the core-mantle interface erupted at the surface. The Deccan basalts in western India, the Siberian basalts in central Russia and the Columbia River basalts in the western United States are examples. The idea is to make use of the magnesium and calcium oxides which are major ingredients of basalt. Rather than mining, grinding and dissolving the basalts, liquid CO_2 would be injected into the shatter zones which separate individual lava flows. The CO_2 would slowly react with the basalt and dissolve out magnesium and calcium. Once the concentration of these ions became large enough, $MgCO_3$ and $CaCO_3$ would precipitate, filling the space between flows. Of the many questions to be answered is whether the rate of reaction between the liquid CO_2 and rock would be rapid enough to make this method of disposal feasible.

Industrial mineralization: The ultimate means of CO_2 storage will be to mine rock rich in the element magnesium and dissolve it. The magnesium oxide released in this way would be reacted with liquid CO_2 to form $MgCO_3$. In this form, the CO_2 would be stabilized for eternity. The target source of magnesium would be what geologists refer to as ultrabasic rock or its hydrous equivalent (serpentine). As these rocks consist of 90 percent magnesium silicate, they are ideal for this purpose. While mining and grinding can be done cheaply, it is the dissolving that will require energy and hence dominate the cost. Much research will be required to determine whether this route is affordable.

Implementation: The likely course to be followed will be to test and tune the extraction process by capturing CO_2 from the air at the sites of "spent" oil fields. As much as half of the petroleum contained in these reservoirs fails to spontaneously come up the well. Part of this residual can be loosened and transported to the surface by the injection of liquid CO_2. As oil runs short, this practice will become more common. While the amount of CO_2 required by petroleum companies will constitute only a drop in the bucket compared to global CO_2 production, it will provide an opportunity to jumpstart a CO_2 capture and store industry.

One might then envision that, as the next step, environmentally-minded states (like California) or countries (like Norway) would put a surcharge on the purchase of any vehicle which gets less than 30 miles to a gallon of gasoline. The money obtained in this way would be used to capture and bury an amount of CO_2 equal to the excess emitted during the lifetime of the vehicle.

Leveling the Playing Field

If an international agreement is to be reached requiring the capture and storage of CO_2 produced by burning fossil fuels, then China, India, Brazil, Mexico…. will somehow have to be convinced to sign on. As was the case for Kyoto, these nations will point out that the industrial countries have been adding CO_2 to the atmosphere with abandon for a century and it hasn't cost them a dime. They will claim it's now their turn. The ability to capture CO_2 from the atmosphere offers an ace-in-the-hole in this regard. The traditionally rich nations could agree to remove, at their own expense, some portion of the CO_2 they emitted in the past. It is still there. This, of course, would be in addition to the capture of the CO_2 they currently emit. Not only would this allow the playing field to be leveled but it would make it that much easier to prevent the atmosphere's CO_2 content from reaching more than twice its pre-industrial level.

Resetting the Atmosphere's CO_2 Content

Once we have succeeded in capping the rise of the atmosphere's CO_2 content, the question will arise as to what the long-term level should be. For example, if the CO_2 level were capped at twice its pre-industrial level and were to remain there for a century or two, a sizable fraction of the planet's ice caps would melt. The consequent rise in sea level would have immense consequences. Parts of most of the world's cities would have to be diked off or abandoned. Beach property would be lost worldwide. This threat alone would lead to a demand that the world be cooled back down so that the melting could be stemmed. The ability to remove CO_2 from the atmosphere would offer a means to accomplish the cooling.

Countering Excess CO_2

A quite different strategy designed to cool the Earth would be to reflect a portion of the sunlight which would otherwise reach the Earth. One way to do this would be to place an object at that point where the gravitational pull by the Sun exactly balances that by Earth. This object would be programmed to remain positioned exactly on the line connecting Earth and Sun. It would be designed to deflect away a small fraction of the sunlight headed for the Earth. Like Venetian blinds, it could be adjusted to create the desired amount of cooling. Hence, as the atmosphere's CO_2 content changed, its shielding could be correspondingly adjusted. It goes without saying that the cost of putting such a device in place would be many, many trillions of dollars.

Another way in which a cooling could be accomplished would be to inject SO_2 gas into the stratosphere. Once there, it would react with ozone to form tiny droplets of sulfuric acid. These droplets would scatter (and hence reflect) sunlight. Unlike aerosols in the lower atmosphere which survive removal for only a few days, those created in the stratosphere would remain aloft for the better part of a year and hence would have to be replaced on that time scale. Unlike the multi-trillion-dollar reflector which must be viewed as a very long-range solution, the sulfuric-acid aerosol strategy should be viewed as an emergency means for supplying quick relief from a CO_2 warming that got out of hand.

Summary

Important points to be kept in mind are as follows:

1) Our best science tells us that CO_2 will warm the planet creating highly significant global impacts. Regardless of how effectively we act, we will experience the consequences of this warming. However, if we choose to move to the prudent-cap pathway rather than continuing along the business-as-usual pathway, we can certainly minimize these impacts.

2) Our goal should be to stabilize the atmosphere's CO_2 content by the year 2070. Although maximizing the efficiency with which energy is used is extremely important, it cannot be the sole answer. Rather, some combination of non-fossil fuel energy sources and CO_2 capture and burial will be necessary.

3) I find it difficult to believe that non-fossil fuel energy sources will be able to do the entire job; hence CO_2 capture and burial will have to be an important part of the mix. Fortunately, the technology for capture and burial lies well within our grasp and is clearly affordable.

4) To be on the safe side, we should also create an insurance policy against a bad CO_2 "trip." To date, the best prospect is SO_2 delivery to the stratosphere. However, its

potential impact on stratospheric ozone must be carefully researched. Other options should be explored.

5) For the very long time scale (i.e., beyond 2100), thought should be given to putting in place a reflector at the point where the Sun's gravitational pull balances that by the Earth.

6) The task before us is immense and time is short. Hence, we must soon map out a program for carbon management and begin its implementation. If we continue at the pace that has typified the last 30 years, by default, we will remain on the business-as-usual pathway. A sense of urgency must be injected into the process. Thus, it is important that knowledgeable business leaders step up to the plate!