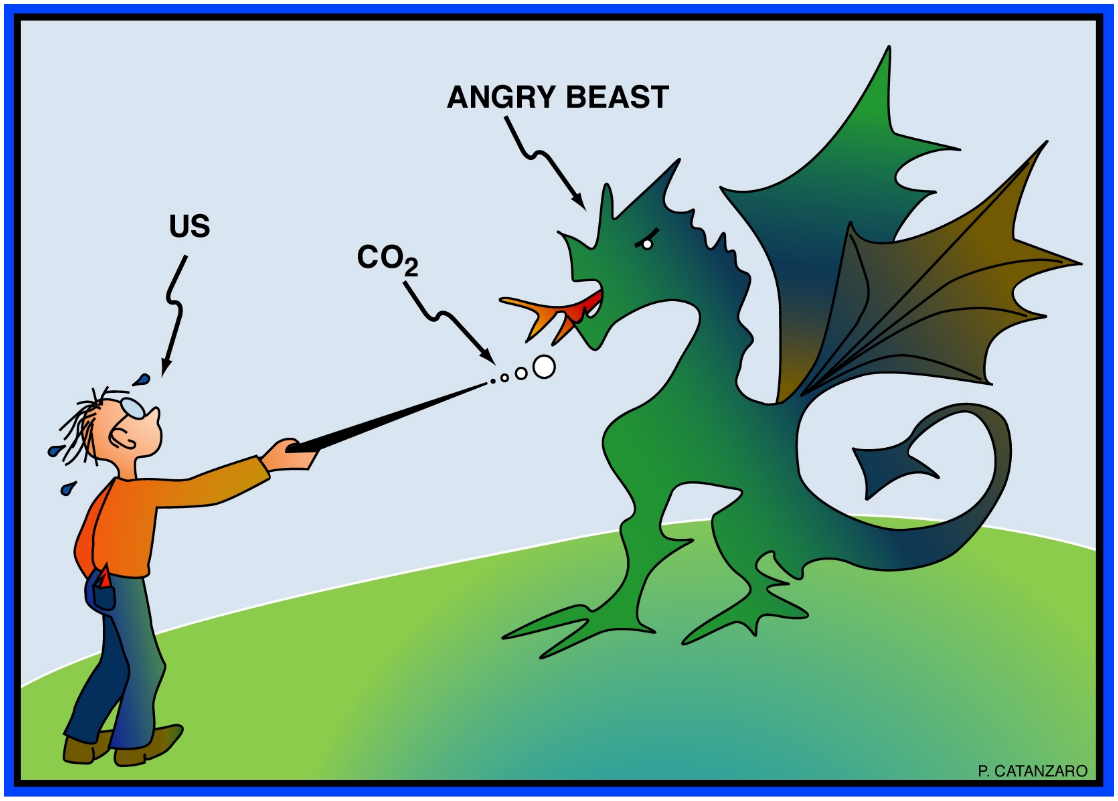
FOSSIL FUEL CO_2
AND
THE ANGRY CLIMATE BEAST



W.S. BROECKER

ELDIGIO PRESS
2003

Preface

This book was written during the summer of 2003 as the text to accompany a series of three 70-minute lectures I was to give in the new Frontiers of Science course, to be required for all Columbia freshmen. It starts with discussion of the fate and climatic consequences of the CO_2 produced by burning fossil fuels and goes on to make the case that we are likely on a path toward tripled atmospheric CO_2 content. Opponents to action designed to stem this buildup refuse to accept predictions of impacts based on computer simulations and choose to attribute the current warming to natural causes. I put aside this issue and focus on the lessons offered to us by past climate changes.

In the middle sections of the book, I make a case that variations in solar irradiance, seasonality changes related to orbital cycles and reorganizations in ocean circulation have driven large changes in climate. Yet, when these forcings are introduced into climate models used to predict the impacts of extra CO_2, none produce impacts anywhere near as large as those observed in the climate record. The failure to reproduce these changes tells us that important amplifiers and teleconnections must be missing in these simulations. The bottom line is that, as our climate has proven itself to be an angry beast, it would be highly imprudent to poke it with tripled CO_2.

The last section of the book presents a plea that we pull out all the stops and create a means by which the flow of CO_2 into the atmosphere might be brought to a halt. In my estimation, only one sure route currently exists by which this might be accomplished. It involves the capture, liquefaction and storage of CO_2. As only about one third of the CO_2 is currently generated in large power plants, as part of this backstop, direct extraction from the atmosphere would have to be implemented. I say 'pull out all the stops' because stemming the buildup of CO_2 in the atmosphere will require at least 60 years, 20 or more to develop the required technologies, payment schemes and international agreements, and 40 or more to implement them worldwide.

My hope is that this book will find use in educating politicians and policy makers.

I am grateful to Patty Catanzaro who created the figures for the book (and for the power point presentation to the class) and to Joan Totton who shepherded the manuscript through its many iterations. Without the encouragement of Jeff Sachs who heads Columbia's Earth Institute, I doubt whether this project would have gotten off the ground.

Table of Contents

Page

Production of fossil fuel CO_2 3

Fate of fossil fuel CO_2 6

Climatic impacts of fossil fuel CO_2 13

Is the planet getting warmer? 21

Natural recorders of temperature 23

The Medieval Warm Period 28

Extending the record back in time 32

Are the 1500-year cycles driven by the Sun? 35

The angry beast 40

Abrupt changes: the evidence 53

The Dansgaard-Oeschger events 60

The trigger for abrupt climate change: shutdowns of the ocean's conveyor circulation 62

The great Agassiz Flood triggers conveyor shutdown 69

Heinrich's ice armadas as triggers for conveyor shutdown 72

Geographic distribution of climate impacts 76

Implications to CO_2 warming 80

What should we do? 83

The hydrogen economy 89

CO_2 sequestration 93

CO_2 storage 93

CO_2 capture from power plants 98

Extraction of CO_2 from the atmosphere 98

Time constraints 105

Summary 108

FOSSIL FUEL CO_2 AND THE ANGRY CLIMATE BEAST

Wallace S. Broecker

Eighty-five percent of the world's energy is produced by burning coal, petroleum and natural gas. The carbon in this "fossil" fuel combines with oxygen from the atmosphere to form carbon dioxide gas (i.e., CO_2). As the result, since the onset of the Industrial Revolution, the CO_2 content of the atmosphere has risen from 280 to 370 parts per million. If the world continues along its business-as-usual pathway, a century from now CO_2 could reach triple its pre-industrial content (i.e., 840 parts per million). Environmentalists consider the climate change which would likely accompany such a rise to be totally unacceptable. While the obvious solution is to turn to other sources of energy (i.e, solar, wind, nuclear, hydro, vegetation…), currently these alternatives cannot compete with regard to price and/or capacity. Further, even though global petroleum reserves will run short during the next 50 years, tar sands, oil shales, and coal could be 'refined' to take its place as sources of liquid fuels. Hence, until some 'miracle' breakthrough occurs, fossil fuels will continue to dominate our energy supply during the 21st century.

To date, we have no proven way out of this dilemma. Energy consumption has been key to prosperity. Currently the average per capita CO_2 production for the 6.5 billion inhabitants of our planet is three tons of CO_2 per year. As population rises and as the planet's poor achieve a better standard of living, global energy use will surely rise. Although we will become more efficient in our use of energy, this by itself is not a solution. Rather, if, for example, we were to attempt to prevent the atmosphere's CO_2 content from rising above 500 parts per million, emissions would have to be reduced to near zero during the latter half of this century. Storing carbon in trees and soil humus, while laudable, is also not the answer. The maximum capacity for such storage is only a small fraction of the amount of fossil-fuel carbon we are likely to burn. This being the case, a backstop strategy must be created so that if fossil fuels continue to dominate our energy supply and if the planet warms at the rate predicted by computer simulations, we have a means to bail ourselves out. Only one plausible safety net is currently on the table. It involves the capture and 'permanent' storage of CO_2 emitted by stationary power plants and also storage of CO_2 removed from the atmosphere. The development of such a backstop involves not only the creation of complex new technologies but also evaluations of environmental side effects, a workable plan for payments and global political agreements. Hence it is a task that will require two or more decades to accomplish. We must add to these two or more decades the four or more decades which would be required to implement CO_2 sequestration worldwide. Hence not only are we in a race against time but we start well behind the curve.

Concern regarding the environmental impacts of excess atmospheric CO_2 is based on computer simulations. Although predictions based on these simulations are subject to large uncertainties, the majority of scientists accept them as a useful guide to what a world with tripled CO_2 would be like. However, a small, but highly vocal, minority of scientists rejects these simulations claiming that they greatly exaggerate the magnitude of the impacts. This dissent is music to the ears of the Bush administration.

This book focuses on an alternate way to look at this problem. The record of past climate changes sends us a startling message. During the last 12,000 years over which our civilization developed, climate has been relatively stable, but during the preceding 100,000 years, it was a very bad actor undergoing abrupt reorganizations which resulted in large globe-wide impacts. The record of past climate found in polar ice; in marine sediments; in stalagmites; and in deposits created by mountain glaciers, is convincing in this regard. However, while we have some hot clues as to what may have triggered these reorganizations, no one has been able to figure out why the climate system reacted so violently to them. When the same models used to predict the consequences of excess CO_2

are applied, they produce temperature responses far smaller than those documented in the geologic record. This leads many of us to urge prudence. Our climate system has surely proven itself to be an angry beast. We are poised to give it a nasty poke. Not a good idea!

Production of fossil fuel CO_2

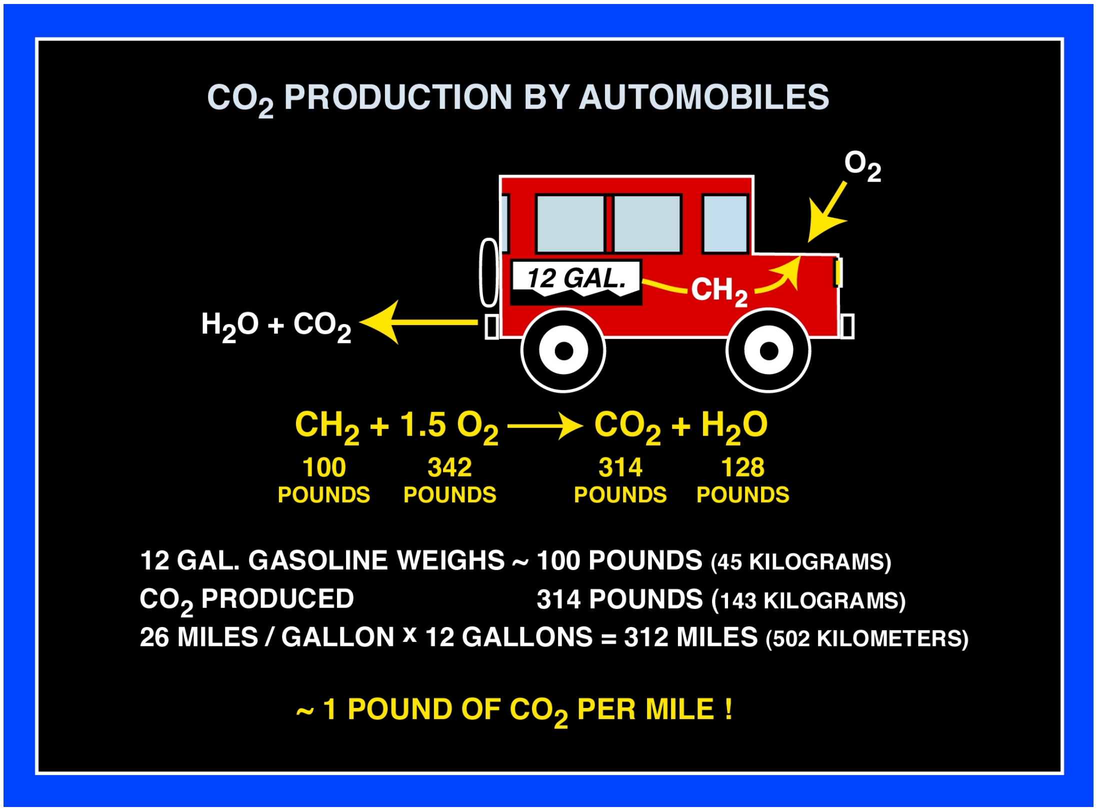
A good way to get a feel for the immense amount of CO_2 produced by the burning of fossil fuels is to consider your automobile. If it's an average sedan about one pound of CO_2 comes out of the tail pipe for each mile you drive. The tank holds 12 gallons of gasoline (weighing close to 100 pounds or 45 kilograms). The combustion of this amount of gasoline produces 314 pounds (or 143 kilograms) of CO_2 (see Figure 1). Even if there were some way to capture it (which there is not), you'd have to find a place to dump it before your next trip to the gas station.

With this in mind, it is not difficult to comprehend that as an average American your share of fossil fuel burning adds up to the release of a staggering 22 tons of CO_2 during the course of a single year. Taken together, your 290 million fellow U.S. residents produce the grand total of about 6 billion tons of CO_2 each year (see Figure 2).

Fortunately, our neighbors in other developed countries use energy more sparingly and consequently their per capita CO_2 generation rate is about 60 percent of our own. In developing countries a large fraction of the people remain too poor to afford fossil fuel energy. However, as is the case for China and India, this situation is changing very rapidly. Taken together, the aggregate production of CO_2 by the world's inhabitants now averages three tons per year (see Figure 2).

Future fossil fuel use will depend on three things:

1) global population
1) per capita energy use
1) the fraction of this energy derived from fossil fuels.



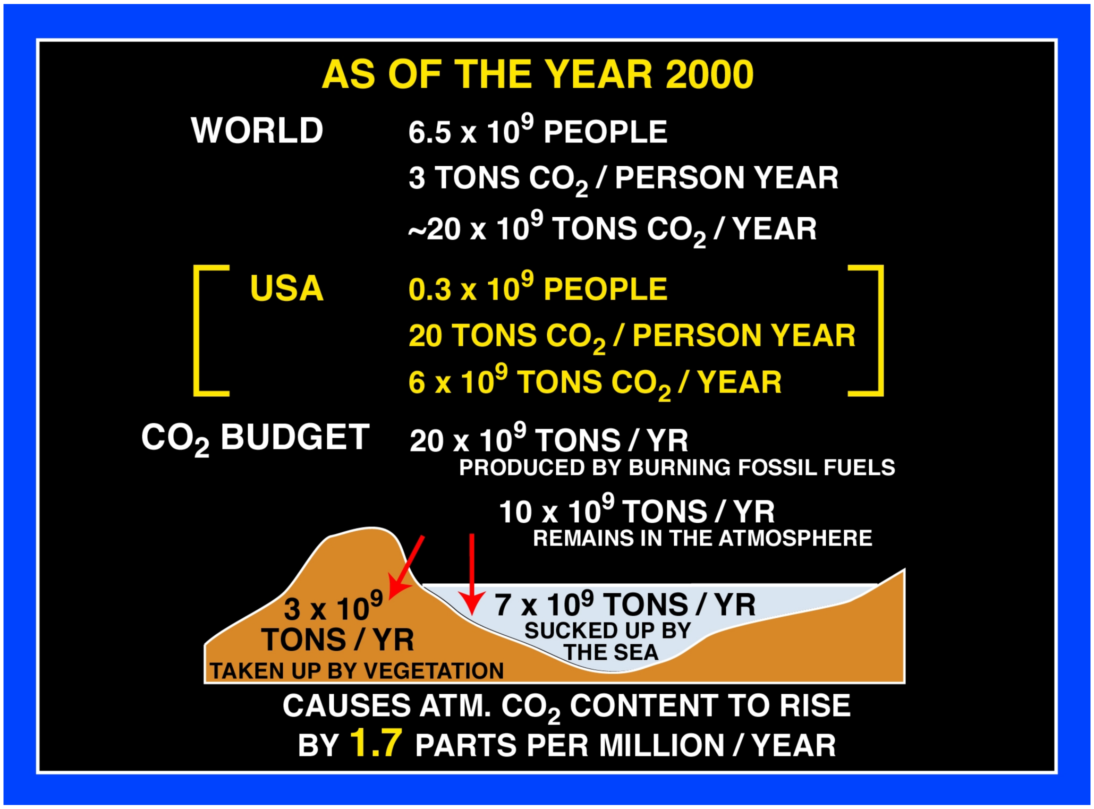
CO_2 PRODUCTION BY AUTOMOBILES

$$\underset{\text{100 POUNDS}}{CH_2} + \underset{\text{342 POUNDS}}{1.5\,O_2} \longrightarrow \underset{\text{314 POUNDS}}{CO_2} + \underset{\text{128 POUNDS}}{H_2O}$$

12 GAL. GASOLINE WEIGHS ~ 100 POUNDS (45 KILOGRAMS)
CO_2 PRODUCED 314 POUNDS (143 KILOGRAMS)
26 MILES / GALLON x 12 GALLONS = 312 MILES (502 KILOMETERS)

~ 1 POUND OF CO_2 PER MILE !

Figure 1. The gas tank in the average automobile holds about 12 gallons of gasoline weighing about 100 pounds. When this gasoline is burned in O_2, a bit over 300 pounds of CO_2 is produced. Assuming the car gets 26 miles to the gallon of gasoline consumed, then one pound of CO_2 is released to the atmosphere for every mile it is driven!



AS OF THE YEAR 2000

WORLD
6.5×10^9 PEOPLE
3 TONS CO_2 / PERSON YEAR
~20×10^9 TONS CO_2 / YEAR

USA
0.3×10^9 PEOPLE
20 TONS CO_2 / PERSON YEAR
6×10^9 TONS CO_2 / YEAR

CO_2 BUDGET
20×10^9 TONS / YR
PRODUCED BY BURNING FOSSIL FUELS

10×10^9 TONS / YR
REMAINS IN THE ATMOSPHERE

3×10^9 TONS / YR
TAKEN UP BY VEGETATION

7×10^9 TONS / YR
SUCKED UP BY THE SEA

CAUSES ATM. CO_2 CONTENT TO RISE
BY 1.7 PARTS PER MILLION / YEAR

Figure 2. Currently, about 20 billion tons of CO_2 is produced each year by fossil fuel burning. This corresponds to about three tons per earth inhabitant. Of course, as in the U.S. per capita fossil fuel use is nearly 7 times the world average, so also is our per capita CO_2 production. While we account for only 5 percent of the world's population, we are responsible for 30 percent of the CO_2 emissions.

Fortunately, only about half of the CO_2 we produce remains in the atmosphere. About 35 percent is sucked up by the ocean where it combines with $CO_3^{=}$ ions to form HCO_3 ions. The remaining 15 percent is being incorporated into wood and humus. The current rate of increase in the atmosphere's CO_2 content is about 0.5 percent per year which corresponds to 1.7 parts per million per year.

At least for the next 50 years 1) and 3) can be predicted reasonably well. Global population is expected to rise to between 9 and 10 billion by the year 2050 and fossil fuels will very likely remain the world's dominant source of energy. However, 2) has a large uncertainty for it depends on how rapidly the world's impoverished people reach the main stream of the world economy. If, as we all hope, during the next 50 years poverty is largely eliminated, per capita energy use will surely rise for the increase in energy use by the world's 'have nots' will greatly eclipse any savings achieved by the 'haves.' For example, in 50 years if the average global per capita energy use were to rise to one half that in the USA (i.e., 10 tons of CO_2 per person per year), if population were 10 billion and if fossil fuel share of energy production were to remain at 85 percent, the amount of CO_2 produced each year would rise by a factor of

$$\frac{10}{3}\times\frac{10}{6.5} \quad \text{or} \sim 5$$

Of course this assumes that by that time the dire poverty suffered by so many humans will be largely eliminated.

Fate of fossil fuel CO_2

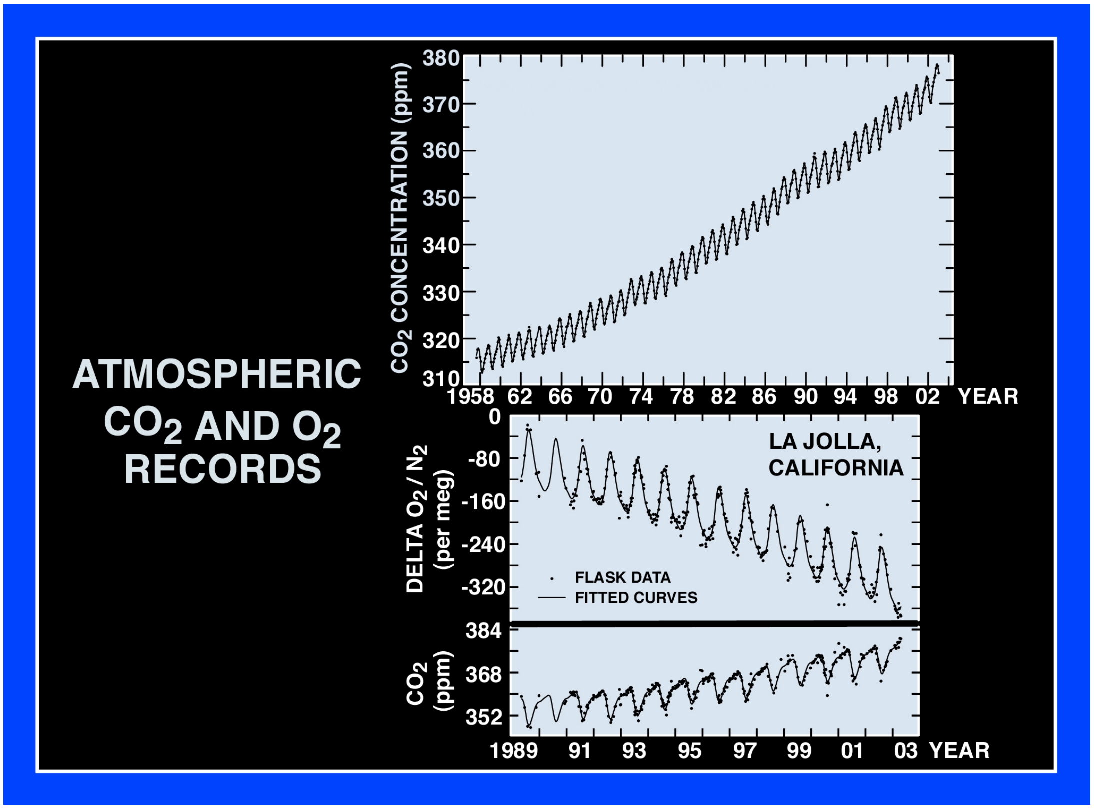
To date only about half of the CO_2 generated by the burning of fossil fuels has remained in the atmosphere. This fraction is determined by comparing the amount by which the atmosphere's CO_2 inventory has increased with the amount of carbon recovered from the Earth in the form of coal, petroleum and natural gas. Only two other carbon reservoirs of importance exist into which the other half of the combustion CO_2 might have gone, i.e., the ocean and the terrestrial biosphere (see Figure 2). The ocean takes up significant amounts of CO_2 because its dissolved salt contains carbonate ions. These ions are able to react with CO_2 molecules to form bicarbonate ions ($CO_2 + CO_3^{=} + H_2O \rightarrow 2HCO_3^{-}$). Therefore the ocean has been able to absorb some of the atmosphere's extra CO_2. Prior to the Industrial Revolution, the ocean and atmosphere had achieved a happy balance; just as many CO_2 molecules left the sea for residence in the atmosphere as left the atmosphere for residence in the sea. However, with the advent of fossil fuel burning the balance was upset. More CO_2 now enters the sea than escapes. These extra CO_2 molecules are retained in solution by reaction with the sea's carbonate ions.

The situation in the terrestrial biosphere is more complicated. Because of extensive deforestation, it might be expected that this global reservoir has been dwindling rather than growing. However, there is reason to believe that loss by deforestation has been more than offset by the fact that our remaining forests appear to be packing away carbon atoms at a greater rate than they did prior to the Industrial Revolution. A plausible explanation is the enhanced availability of two of the basic ingredients for plant growth (i.e., CO_2 and fixed nitrogen). As the result of fossil fuel burning, the atmosphere now has more CO_2 than before. Forests receive extra fixed nitrogen as the result of evaporation of ammonia added as fertilizer to farmlands and as the result of production of nitrogen oxides (NO, N_2O) in automobile engines. This airborne fixed nitrogen is subsequently incorporated into raindrops and by this route some of it gets deposited in forests.

It must be pointed out that even though the vast majority of the Earth's nitrogen resides in the atmosphere as N_2, this huge reservoir is unavailable for use by higher plants. Only a few species of microorganisms which live symbiotically on the roots of certain plants have enzymes capable of breaking the strong N_2 bond. Plants such as clover feed these microbes with root exudates and in return receive fixed nitrogen.

Ralph Keeling, now a scientist at the University of California, while a graduate student, came up with a very clever means of assessing contributions of the ocean and of the terrestrial biosphere to the removal of CO_2 from the atmosphere. Following in the footsteps of his father Charles David Keeling, who has kept track of the atmosphere's rising CO_2 content since 1958, Ralph took on the very difficult task of measuring the rate of depletion of O_2 from the atmosphere. This is far more difficult because there is so much more O_2 (210,000 ppm) than CO_2 (370 ppm) in the atmosphere. Since 1990 Ralph has accurately monitored the decline of O_2. Taken together, the rise in CO_2 and the drop in O_2 allow the fate of fossil fuel CO_2 to be partitioned among the atmosphere, ocean and terrestrial biosphere (see Figure 3).

To see how this is done requires an understanding of the graph shown in Figure 4. On the vertical axis is plotted the atmosphere's O_2 content and on the horizontal axis its CO_2 content. Instead of plotting the actual amounts, only the changes in the amounts are shown. Thus, the red dot in the upper left-hand corner corresponds to the starting point of the measurement series (i.e., January 1, 1989). The second red dot shows the changes which had occurred as of January 1, 2003. During this 13-year period, the atmosphere's O_2 dropped by about 49 parts per million and its CO_2 content rose about 20 parts per million. Based on the amounts of coal, petroleum and natural gas burned during this period the changes expected if the atmosphere were a closed reservoir (i.e., it did not communicate with the ocean or with the terrestrial biosphere) can be estimated. The O_2 drop would have been 56 parts per million and the CO_2 rise would have been 40 parts per million. The white dot shows this composition. The ratio of 56 ppm to 40 ppm (i.e., ~1.4) reflects the mix of fuels (see Figure 5). To burn coal, lignite… requires on the average 1.17 molecules of oxygen per atom of carbon; to burn petroleum 1.44 molecules of O_2 per carbon atom, and to burn natural gas 1.95 molecules of O_2 per carbon atom. It turns out that over this 13-year period the CO_2 rise was only about half of that expected and the O_2 drop only about seven eights of that expected. Two routes are available to get from the white dot to the red dot. One is horizontal and to the left representing uptake of CO_2 by the ocean. The other is diagonal representing enhanced photosynthesis ($CO_2 + H_2O \rightarrow O_2 + CH_2O$) (up and to the left) and deforestation ($O_2 + CH_2O \rightarrow CO_2 + H_2O$) (down and to the right). As the red point clearly lies above the white one, extra forest growth must have more than compensated for deforestation. The result is that 50 percent of the CO_2 produced during this 13-year period remained in the air and 35 percent went into the



ATMOSPHERIC CO_2 AND O_2 RECORDS

Figure 3. Records of the buildup of the atmosphere's CO_2 content and the drawdown of its O_2 content. The Mauna Loa record was initiated by father, Charles David Keeling, in 1958. The La Jolla record was initiated by son, Ralph Keeling, in 1989. The seasonal fluctuations in these records reflect the alternation between the dominance of photosynthesis during summer months and respiration during winter months.

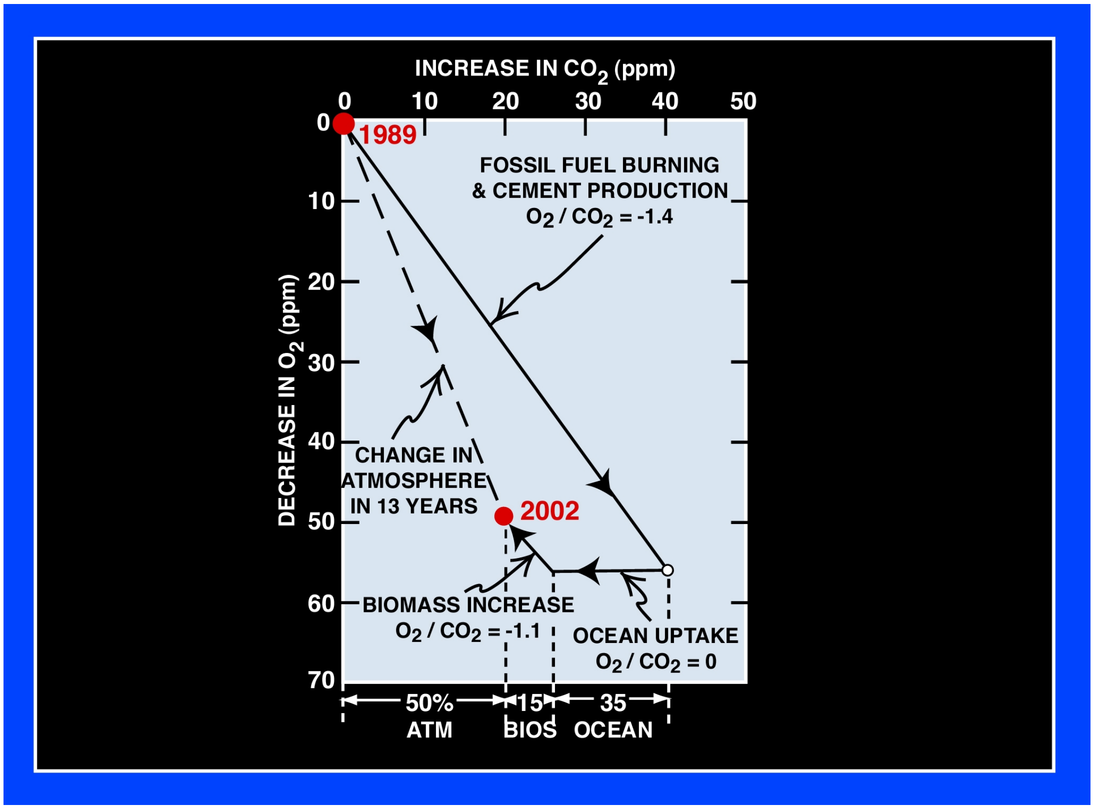
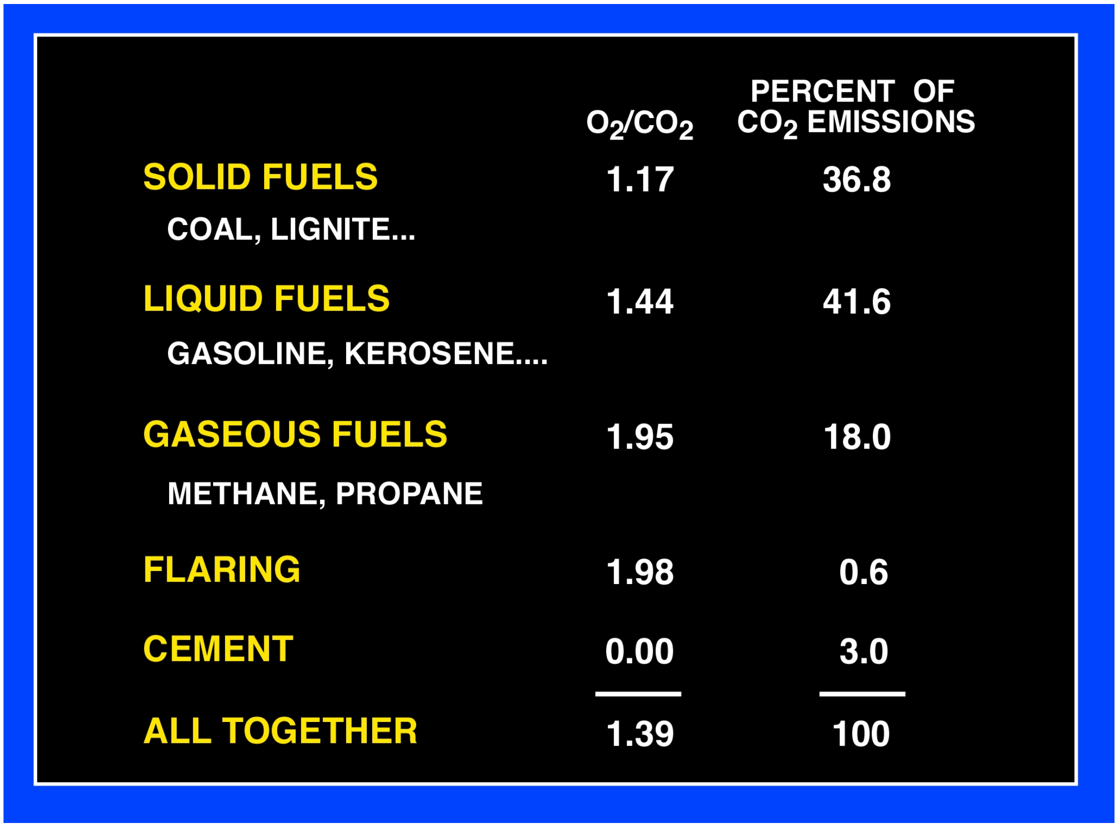


Figure 4. The red dots show the observed change in the contents of CO_2 and O_2 in the atmosphere from 1989 to 2002. During this 13-year period, the atmosphere's CO_2 content increased by 19 parts per million and its O_2 content decreased by 49 parts per million. Had there been no interaction with ocean or with the terrestrial biosphere, based on the amount of fossil fuel burned, the atmosphere should have increased by 40 parts per million in CO_2 and decreased by 56 parts per million in O_2 (see white dot). In order to explain the difference between the expected and observed changes, about 35 percent of the CO_2 emitted must have been taken up by the ocean and about 15 percent by the terrestrial biosphere.



	O_2/CO_2	PERCENT OF CO_2 EMISSIONS
SOLID FUELS COAL, LIGNITE...	1.17	36.8
LIQUID FUELS GASOLINE, KEROSENE....	1.44	41.6
GASEOUS FUELS METHANE, PROPANE	1.95	18.0
FLARING	1.98	0.6
CEMENT	0.00	3.0
ALL TOGETHER	1.39	100

Figure 5. The ratio of O_2 molecules required to combust the carbon contained in various fossil fuels is summarized. The fuel-to-fuel differences in this ratio reflect the hydrogen content of the fuel. For example, as methane has 4 hydrogen atoms per carbon atom, the ratio is 2, i.e., $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$. As gasoline has close to 2 hydrogen atoms per carbon atom, the ratio is close to 1.5, i.e., $CH_2 + 1.5O_2 \rightarrow CO_2 + H_2O$. Cement manufacture is a special case. $CaCO_3$ is decomposed in a kiln to produce the CaO used in concrete, i.e., $CaCO_3 \rightarrow CaO + CO_2$. Taken together, the ensemble of fuels burning and cement production lead to the destruction of close to 1.4 O_2 molecules for each CO_2 molecule released to the atmosphere.

ocean. The remaining 15 percent represents the difference between enhanced biomass storage on the one hand and deforestation on the other.[1]

How will the partitioning of excess CO_2 among these three reservoirs evolve as ever more fossil fuels are burned? The fraction taken up by the ocean will slowly wane. One reason is that the ocean's carbonate ion inventory is being consumed through reaction with excess CO_2. This will reduce the ocean's capacity for additional CO_2 uptake. The other reason is that as the Earth warms, the contrast in density between the warm upper waters and the cold deep waters of the ocean will increase. This will lead to a reduction in the already slow rate of mixing between these two realms. In fact, the ongoing decline in ocean O_2 suggests that a decrease in the rate of vertical mixing is already underway.

The situation for the terrestrial biosphere is less clear. While plant fertilization by excess atmospheric CO_2 and by extra fixed nitrogen should continue to foster increased storage of carbon in trees and in soil humus, a second factor will work in the opposite direction. The amount of humus in soils depends not only on how much new humus is created by decaying plant matter but also on how long the humus survives destruction. The survival time depends on soil temperature. The warmer the soil, the more rapidly the humus is 'eaten' by soil organisms. So, as the globe warms, the lifetime of organic compounds which make up humus is likely to shorten and thereby tend to reduce the total inventory of carbon in soils. Unfortunately, we know too little about these competing influences to say with any confidence which will have the upper hand.

The biggest wild card in connection with carbon partitioning among the various reservoirs is deforestation. Were there no deforestation, then Ralph Keeling's diagram would look quite different. The terrestrial biosphere's role in uptake of fossil fuel CO_2

---

[1] The presentation in Figure 4 has been simplified in order to make it more easily understood. For example, a small release of oxygen from the ocean to atmosphere is neither shown nor explained. Also, the use of parts per million units for O_2 is an approximation since Keeling's measurements are of the O_2 to N_2 ratio and not O_2 to total air ratio. However, the graph is constructed to yield Keeling's conclusions regarding the fate of the CO_2 released by our activities (i.e. fossil fuel burning and the manufacture of lime for cement).

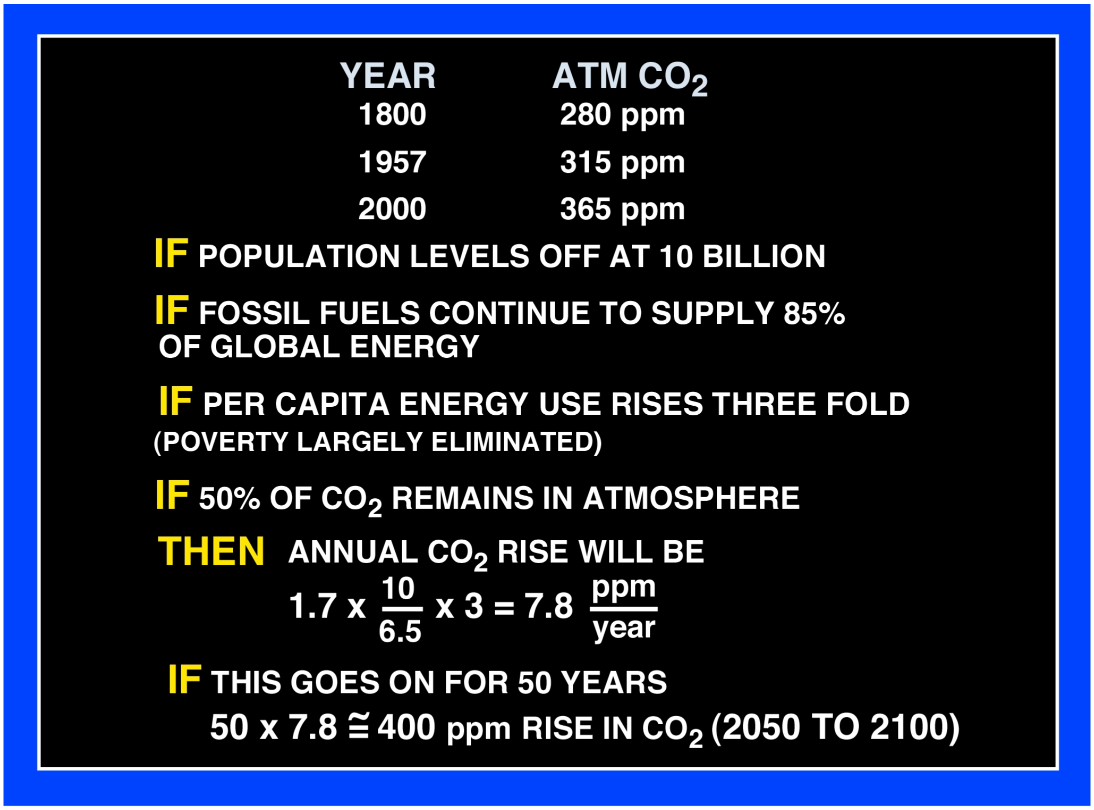
would be more like 30 percent of the total. Thus, as time goes on, a critical element in the carbon budget will relate to forest preservation.

As the situations for both the ocean and the terrestrial biosphere are complex, reliable prediction of future partitioning of the excess CO_2 generated by fossil fuel burning currently lies beyond our reach. However, we do know enough to say the fifty-fifty split between the atmosphere on the one hand and the ocean plus terrestrial biosphere on the other will change only slowly.

We have already estimated that if fossil fuels continued to dominate the energy market and if poverty were to be largely conquered, then over the next 50 years global energy use could rise 5 fold. Currently, the atmosphere CO_2 content is rising at the rate of 1.7 ppm per year. Assuming that the 50-50 split between atmosphere versus ocean plus terrestrial biosphere prevails, then by 2050, the annual CO_2 rise in atmospheric CO_2 content would be more like 8 ppm per year. Were the 8 ppm per year increase to prevail for a half century (say 2050 to 2100 AD), the atmosphere's CO_2 content would increase by another 400 ppm. Hence, one cannot dismiss the likelihood that the atmosphere's CO_2 content will triple by the end of the 21st century (see Figure 6).

Climatic impacts of fossil fuel CO_2

The Earth's mean temperature is not only set by the amount of sunlight reaching the upper atmosphere, but also by the fraction of this sunlight which is reflected back to space and the amount of outgoing earth light which is captured by greenhouse gases and particulates (see Figure 7). Were there no reflection and no greenhouse gases, the Earth temperature would average +5°C. As summarized in Figure 8, the cooling due to reflection is more than offset by the warming due to our greenhouse blanket and hence the Earth's average temperature is 15°C rather than 5°C. Our activities are impacting both the planet's reflectivity and its greenhouse capacity. Extra CO_2, CH_4 and also extra dark particulates capture and then re-radiate outgoing infrared radiation and thereby tend



YEAR	ATM CO_2
1800	280 ppm
1957	315 ppm
2000	365 ppm

IF POPULATION LEVELS OFF AT 10 BILLION

IF FOSSIL FUELS CONTINUE TO SUPPLY 85% OF GLOBAL ENERGY

IF PER CAPITA ENERGY USE RISES THREE FOLD
(POVERTY LARGELY ELIMINATED)

IF 50% OF CO_2 REMAINS IN ATMOSPHERE

THEN ANNUAL CO_2 RISE WILL BE

$$1.7 \times \frac{10}{6.5} \times 3 = 7.8 \ \frac{\text{ppm}}{\text{year}}$$

IF THIS GOES ON FOR 50 YEARS

$50 \times 7.8 \cong 400$ ppm RISE IN CO_2 (2050 TO 2100)

Figure 6. Measurements on air trapped in Antarctic ice tell us that prior to the Industrial Revolution, the atmosphere's CO_2 content was close to 280 parts per million. When Charles David Keeling began his measurements at Mauna Loa, Hawaii, it was 315 parts per million. As of 2004, it had risen to close to 370 parts per million. If, as seems likely, over the next 50 years the annual rate of CO_2 increase rises from 1.7 to 8 parts per million, then in the absence of purposeful intervention, the CO_2 content of the atmosphere could by that time reach more than triple its pre-industrial value (i.e., more than 840 parts per million).

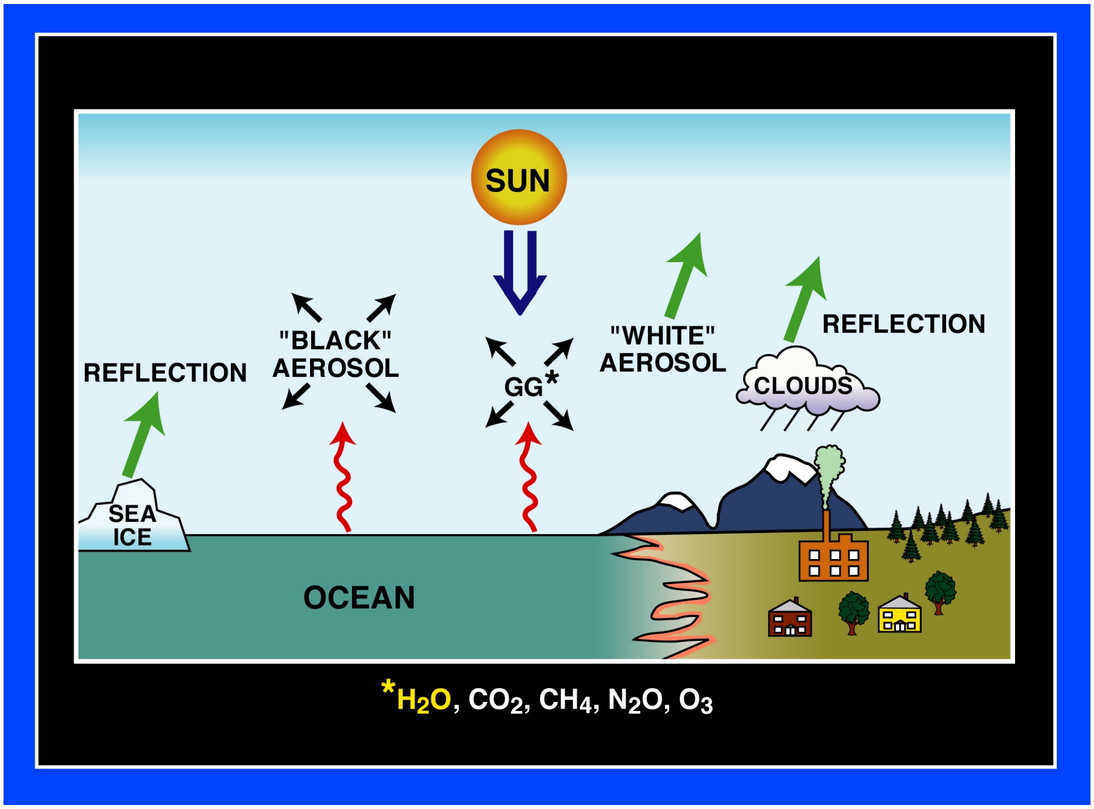


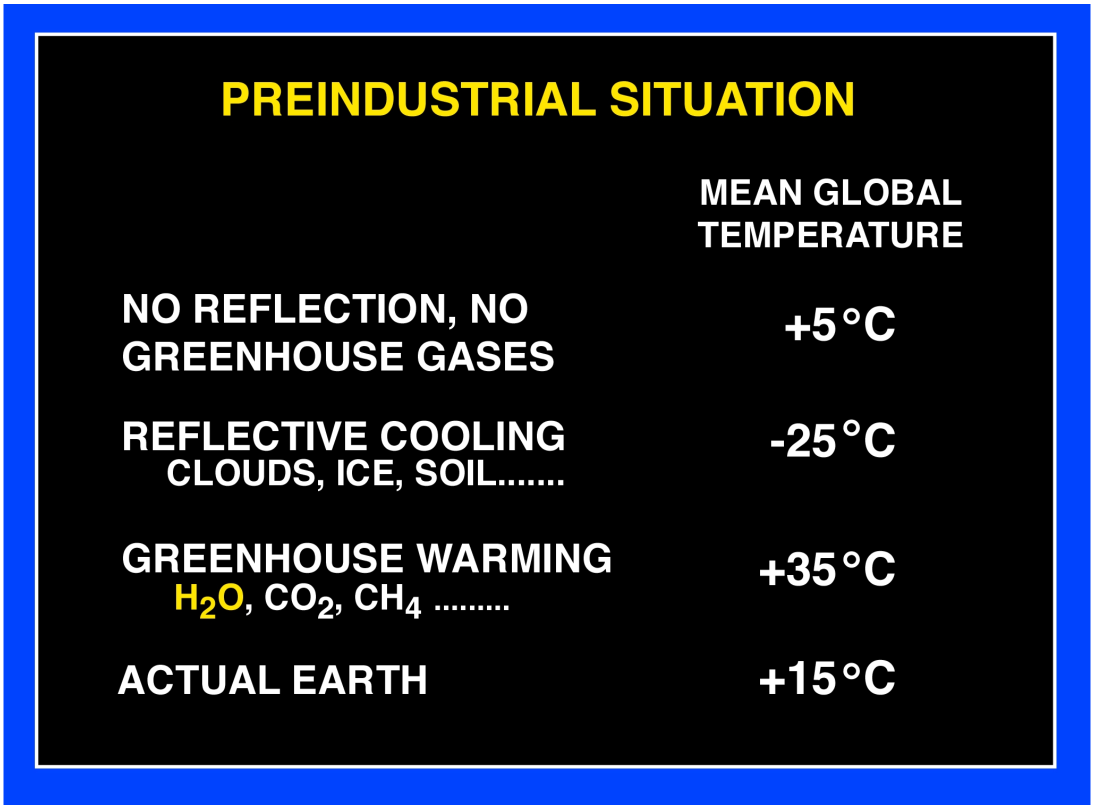
Figure 7. The Earth's temperature is set not only by the amount of sunlight sent our way, but also by the Earth's reflectivity and its greenhouse power. While vegetation and water bodies absorb most of the incoming solar radiation, clouds, ice and snow and bare soil reflect a substantial proportion back to space, thereby cooling the Earth. Compensating for this cooling is the warming by atmospheric gases capable of capturing quanta of outgoing earth light. Although water molecules dominate this capture, carbon dioxide, methane nitrous oxide and ozone are also important. Complicating the situation are atmospheric aerosols for light-colored ones tend to reflect incoming sunlight and dark-colored ones tend to capture outgoing earth light.

to warm the Earth. Extra 'white' aerosols (mainly H_2SO_4 created by the oxidation of the SO_2 released as a byproduct of coal burning) tend to cool the Earth.

Of these atmospheric changes, that of CO_2 poses the greatest concern. The reason is that, unlike particulates and aerosols which remain airborne only days to weeks, and methane which survives oxidation to CO_2 and H_2O for about one decade, the lifetime of CO_2 in the atmosphere is measured in hundreds of years. Further, as we have already seen, CO_2 is a necessary byproduct of our industrial civilization.

Were the water vapor content of the atmosphere to remain unchanged, then a tripling of CO_2 would produce an average warming of close to 2°C. However, when simulated in global models, the warming turns out to be more like 5°C (see Figure 9). The reason is that water vapor serves as an amplifier (i.e., a positive feedback). As the Earth warms, the vapor pressure of water rises allowing the atmosphere to hold more water vapor. Keeping in mind that water vapor is the Earth's dominant greenhouse gas, the more water vapor in the atmosphere, the warmer the Earth.

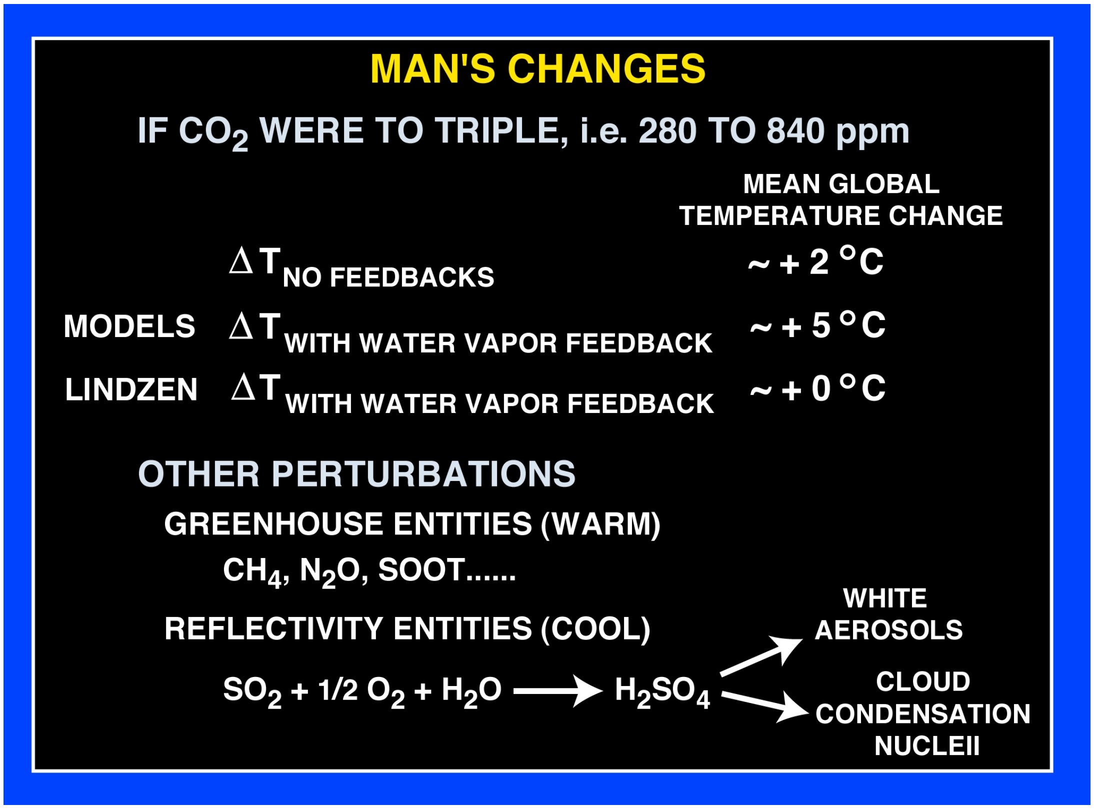
MIT's Richard Lindzen is the guru of a group strongly opposed to any action aimed at stemming the buildup of CO_2 in our atmosphere. Lindzen claims that instead of amplifying the warming, changes in water vapor will largely null it. While agreeing that the water vapor content of the tropical air column will increase as the Earth warms, Lindzen is convinced that the water vapor content of the air over the Earth's desert regions will decrease. Further, because clear skies prevail over deserts, these regions constitute the primary escape hatch for outward-bound infrared light. Hence, Lindzen contends that because water vapor increases everywhere in model simulations, these models must be seriously flawed. He believes instead that over desert regions water vapor will decrease, thereby opening wider the escape hatch for outgoing radiation. As one of the world's premier atmospheric physicists, his claim cannot be disregarded. Thus he gets lots of press. However, to calibrate Professor Lindzen, it must be said that in private conversations, he also denies the reliability of studies which link cancer to cigarette



PREINDUSTRIAL SITUATION

	MEAN GLOBAL TEMPERATURE
NO REFLECTION, NO GREENHOUSE GASES	+5°C
REFLECTIVE COOLING CLOUDS, ICE, SOIL.......	-25°C
GREENHOUSE WARMING H_2O, CO_2, CH_4	+35°C
ACTUAL EARTH	+15°C

Figure 8. Had the Earth neither reflecting surfaces nor earth-light absorbing gases, its mean temperature would be close to 5°C. In reality, the influence of both of these processes turns out to be important. However, the warming by greenhouse gases (+35°C) outweighs the cooling by the reflecting surfaces (-25°C) giving the Earth an average temperature of 15°C.



MAN'S CHANGES

IF CO_2 WERE TO TRIPLE, i.e. 280 TO 840 ppm

		MEAN GLOBAL TEMPERATURE CHANGE
	$\Delta T_{\text{NO FEEDBACKS}}$	~ + 2 °C
MODELS	$\Delta T_{\text{WITH WATER VAPOR FEEDBACK}}$	~ + 5 °C
LINDZEN	$\Delta T_{\text{WITH WATER VAPOR FEEDBACK}}$	~ + 0 °C

OTHER PERTURBATIONS

GREENHOUSE ENTITIES (WARM)

CH_4, N_2O, SOOT......

REFLECTIVITY ENTITIES (COOL)

$SO_2 + 1/2\ O_2 + H_2O \longrightarrow H_2SO_4$

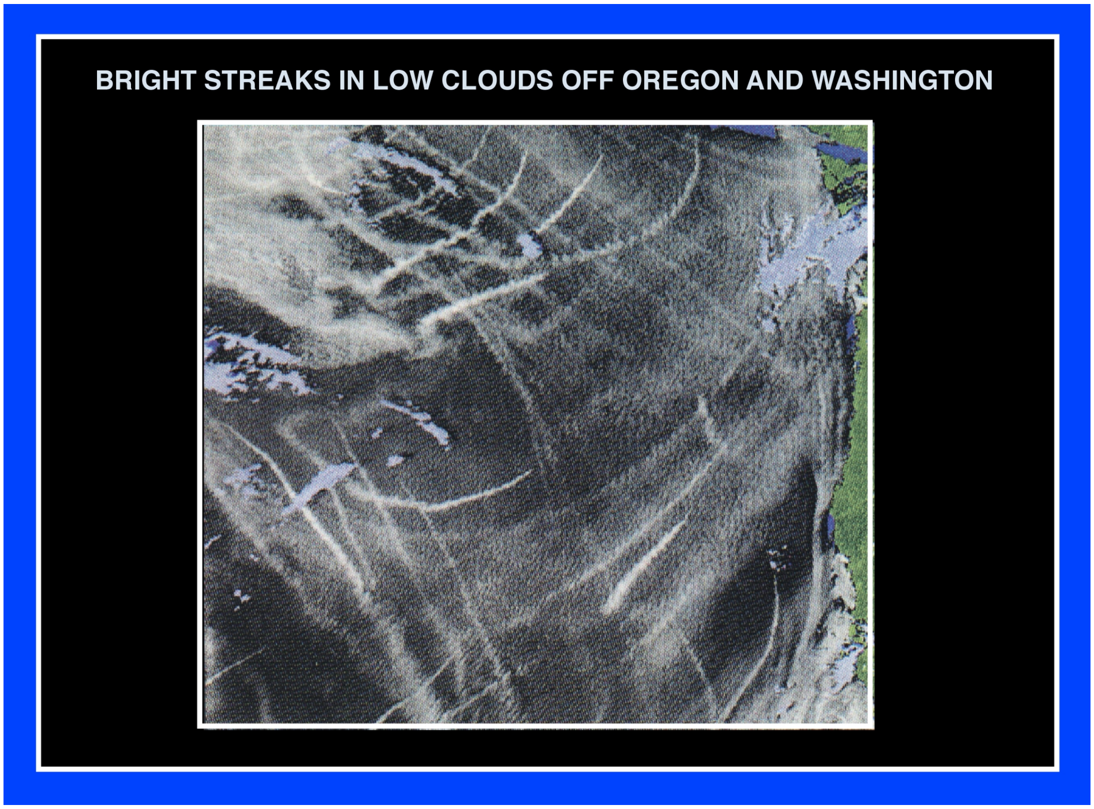
Figure 9. Were there no feedbacks, a tripling of the atmosphere's CO_2 content would warm the Earth by about 2°C. Simulations carried out using powerful computers suggest that because of a feedback from increased atmospheric water vapor, the actual warming will be 2 to 3 times larger. MIT's Richard Lindzen challenges these model results and claims that the water vapor content of the atmosphere over the Earth's desert regions will decrease, thereby creating a feedback in the opposite direction largely nulling the primary 2°C warming. The situation is further complicated by the man-induced increase in atmospheric aerosol loading. Soot released as the result of coal and vegetation burning tends to further warm the Earth. Sulfuric-acid aerosols produced by the oxidation of the sulfur contained in fossil fuels not only tends to cool the Earth but these hydroscopic aerosols also make excellent condensation nuclei which lead to an enhancement of the reflectivity of clouds. The complication is that unlike the greenhouse gases which are spread uniformly throughout the atmosphere, aerosols are extremely patchy showing strong spatial and seasonal gradients. Hence, their impacts cannot be reliably modeled.

smoking. Hence, he is clearly a contrarian who enjoys challenging establishment thinking. While no one pays any attention to his claims regarding lung cancer, his views on climate carry a lot of weight.

Other changes in the cycle of atmospheric water vapor may well take place. Not only do the sulfuric acid aerosols produced in the atmosphere by the oxidation of SO_2 gas reflect away sunlight but they also act as cloud condensation nuclei. Raindrops can only form if they have something to form around (i.e., a condensation nucleus). The more nuclei available in a cloud, the more cloud droplets that will form. However, as there is only so much water vapor available for condensation, the more nuclei, the smaller the drops will be. Drop size has two impacts. First, many smaller droplets are more reflective than fewer larger ones; hence sulfuric acid aerosols can also cool the Earth by increasing cloud reflectivity. Second, smaller droplets fall more slowly and hence are more subject to transport by wind than large droplets. In this way, sulfuric acid aerosols could contribute to a significant redistribution of precipitation on our planet.

A striking example of the impact of extra cloud condensation nuclei is shown in Figure 10. The bright streaks in this aerial photograph of low cloud cover off the west coast of North America are created by smoke rising from passing ships. Where the smoke plume intersects the clouds, more condensation nuclei are available. Hence, the droplets are smaller and the clouds more reflective. Another example is the contrails left behind by high flying jet aircraft. During the week-long shutdown of air travel after the World Trade Tower disaster, the day-night temperature contrast over the U.S. increased by 1°C. This change was the result of the short term absence of contrails produced by jet aircraft, thus increasing the nighttime loss of Earth heat to space (i.e., night-time cooling).

Although the majority of scientists concerned with global warming disagree with Lindzen, they admit that model simulations, no matter how sophisticated, do have serious limitations. While all such simulations yield an amplification of the CO_2 warming by increased water vapor, the magnitude of this amplification differs from model to model.



BRIGHT STREAKS IN LOW CLOUDS OFF OREGON AND WASHINGTON

Figure 10. Bright streaks in the low cloud cover over the ocean off the western U.S. are produced by the smoke rising from the stacks of ships passing beneath. Tiny particles in the smoke serve as cloud condensation nuclei. These extra nuclei allow a larger number of droplets to form. Hence the streaks are more reflective than the ambient clouds.

Further, the agreement among models regarding the magnitude of future climate changes for any given region of the Earth is not nearly as good as that for the global average. For example, while all models predict a melting of a large fraction of the of Arctic’s sea ice and a thawing of the Arctic’s tundra, they give a wide range for the rate at which these reductions will occur. Another example is that while all models predict that warming will bring with it increases in global rainfall rate, they also predict increases in the loss of soil moisture through evaporation. Since moist soils are a prerequisite for agricultural productivity, it matters much whether extra rainfall or extra evaporation is the more important in any given region. Unfortunately, this difference is something that depends on the details of the particular model. Hence, it is not clear whether agricultural productivity in the world’s “breadbaskets” (i.e., the interiors of Europe, Asia, Africa and North America) will increase or decrease as a result of global warming. In the absence of consistent regional scale model predictions, it has proven difficult to get people’s attention. As this situation is unlikely to improve appreciably in the near future, decisions will have to be made in the face of rather large uncertainties.

Is the planet getting warmer?

An enormous effort has gone into analyzing temperature records from meteorological stations scattered across the globe. Although these records become more sparse as one goes back in time, the consensus is that they provide reasonably reliable estimates for the Earth’s mean annual temperature back to about 1880 AD (see Figure 11). The good news, for those who would like to believe predictions based on model simulations, is that during the last 25 years or so the planet’s mean temperature has been increasing. Further, the rate of this warming is broadly consistent with expectations from the models. However, there are two other features of this record which detractors are quick to point out are not consistent with a greenhouse-gas-driven warming. The first occurred early this century when the planet underwent a warming as large as that during the last 25 years. No man-induced change has been proposed to account for this warming.

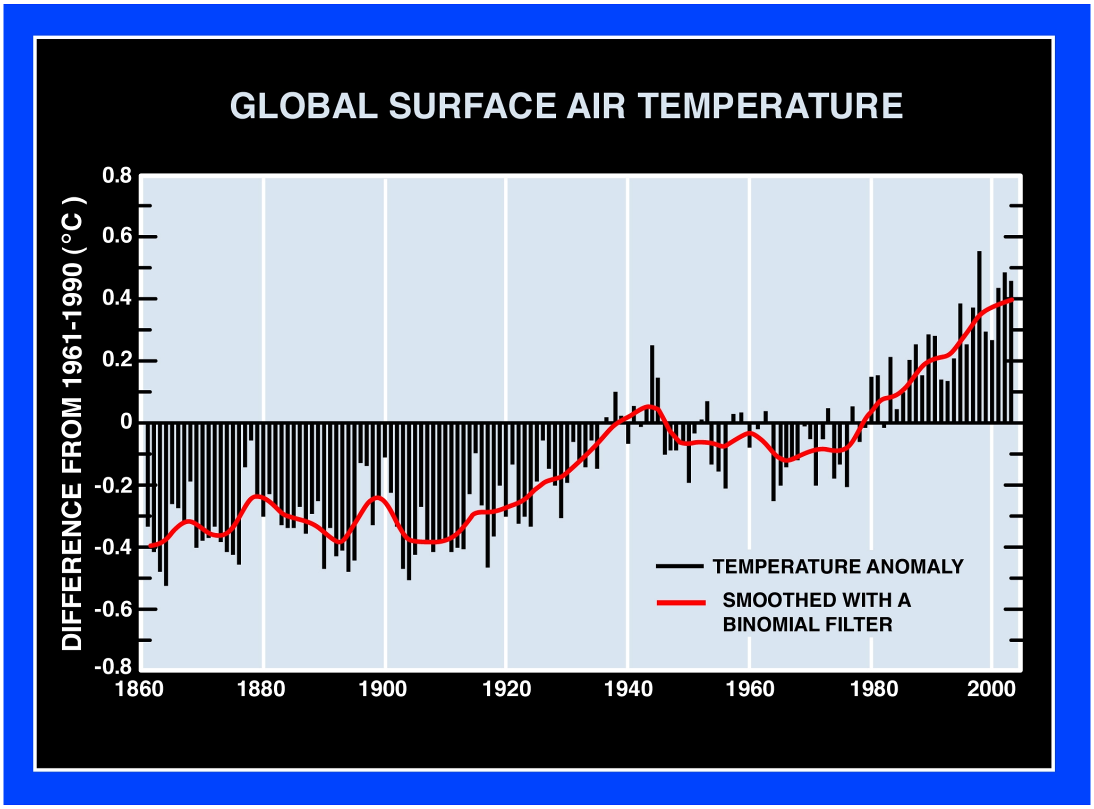


Figure 11. Based on averages of thermometric measurements made at meteorologic stations situated across the planet, an estimate has been made as to how the mean earth surface temperature has evolved over the last 120 years. As can be seen, an increase of about 0.7°C has occurred. This increase came in two steps: one between 1920 and 1940 and the other between 1975 and the present. While the second of these steps could well be in response to excess greenhouse gases, the first occurred during a time period when the rate of increase in the concentrations of these gases was too small to be significant.

Rather, it was very likely natural. The other feature of this record which doesn't fit the greenhouse-gas scenario is the plateau in temperature from 1940 to 1975. Although more modest than that after 1975, increases in CO_2 and other greenhouse gases during this period should have resulted in a measurable warming. Thus it appears that the global mean temperature has, on its own, undergone temporal changes comparable in magnitude to those predicted by simulations of the impact of man-made greenhouse gases. Hence, it is easy for detractors to attribute the entire temperature change since 1880 to natural causes.

Natural recorders of temperature

In order to get a sense of what Earth's climate has been doing on its own we must extend the record back much further in time. A century is simply not long enough. To do this, we must turn to natural recorders of temperature which we in the field of paleoclimate call 'proxies.' This turns out to be an extremely demanding task for the changes we seek to document are very small (i.e., no more than 1°C). Unfortunately, most of the available proxies are simply not up to the task.

One that does meet the challenge is the extent of mountain glaciers. We know for sure that almost everywhere on the planet the tongues of ice streaming down from high mountains were much longer in the mid 1800s than they are today. Consistent with a century of warming, these tongues are slowly melting back. The evidence comes from paired photographs like those in Figure 12 from New Zealand's Alps. Such pairs are available for dozens of glaciers from all parts of the planet. It turns out that these glaciers serve as one of the most sensitive of all natural thermometers. Indeed, so sensitive that they can reflect a change in local air temperature as small as 0.2°C.

While the most visible change in these glaciers has been the retreat of their narrow snouts, the magnitude of the retreat is not simply related to temperature. Hence, it provides only qualitative information: the longer the snout, the colder the temperature. To get the actual magnitude of the temperature change, glaciologists measure the elevation

Figure 12. Matched photographs comparing the extent of the Franz Josef Glacier on the South Island of New Zealand at the time of the Little Ice Age maximum with that in the year 2000. As can be seen, a very large retreat in the ice front occurred during the last 120 years.

of what they refer to as the equilibrium snowline. Everywhere on the Earth the higher you go the colder it gets. Hence mountain tops are often so cold that even in the summer no melting occurs. The equilibrium snowline marks the boundary between the higher elevation portion of the glacier where, averaged over the whole year, accumulation of snow exceeds loss by melting. Below this boundary the opposite is true, melting exceeds accumulation.

It turns out that, as a rule of thumb, two thirds of a mountain glacier's surface lies above the equilibrium snowline and one third below it. This relationship turns out to be a handy one because it allows the equilibrium snowline for the glaciers which existed in the mid-1800s to be reconstructed. Based on geomorphic features created by these glaciers, it is possible to reconstruct their outlines. In the Swiss Alps, this has been done for hundreds of glaciers and the finding is that since 1850 the equilibrium snowline has risen about 100 meters. Based on the atmospheric lapse rate (i.e., the extent of cooling per 100-meter rise in elevation) this corresponds to a 0.6°C warming. After correction is made for the increases in snowfall which has accompanied this warming, the magnitude of the warming (~0.8°C) recorded by the Alpine glaciers agrees quite well with the extent of warming directly measured with thermometers.

In most parts of the world only the glacial extent since the mid-1800s is well documented. However, in the Swiss Alps, paintings and historical accounts document a second maximum in the 1600s (see Figure 13). An even earlier event in the 1300s is recorded by the stumps of trees knocked over by advancing ice. Taken together, these three periods when glaciers achieved a size comparable to that in 1850 are known as the Little Ice Age (see Figure 14).

In Iceland a very long record has been kept of the number of months during each year when sea ice prevented the operation of the fishing fleet. It provides a basis for extending back in time the instrumental record of mean annual air temperature initiated in 1850 (red curve in Figure 13).

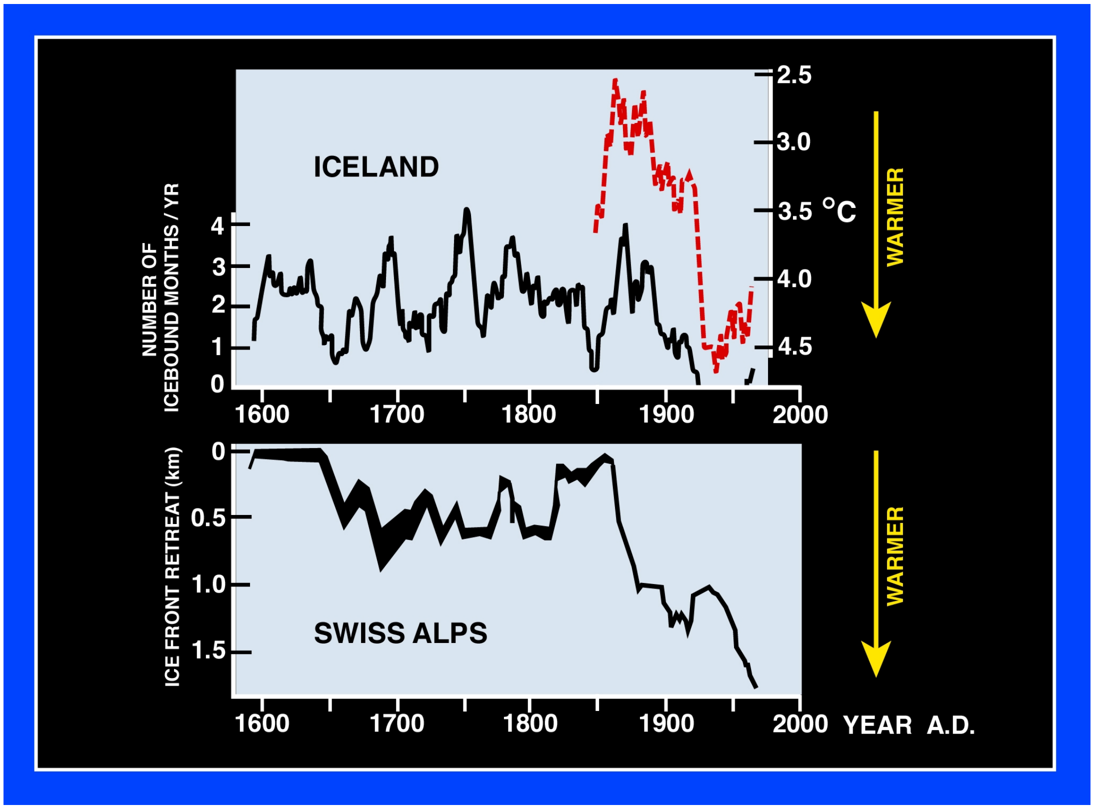


Figure 13. At two places on the planet historic records of climate extend back to the year 1600 AD. In Iceland records were kept of the number of months each year during which sea ice prevented the fishing fleet from leaving port. As can be seen, prior to the pronounced 1°C warming which took place between 1925 and 1930 (see red dashed curve), the fleet was ice-bound from one to three months each year. Since that time, the coast of Iceland has been largely ice-free. In Switzerland, the extent of Grindelwald Glacier has been reconstructed based on paintings and, more recently, on photographs and direct measurements. Two of the three Little Ice Age maxima (one in the first half of the 17th century and the other in the mid 19th century) are well documented. Beginning in about 1860, the front of this glacier began a retreat which continues today.

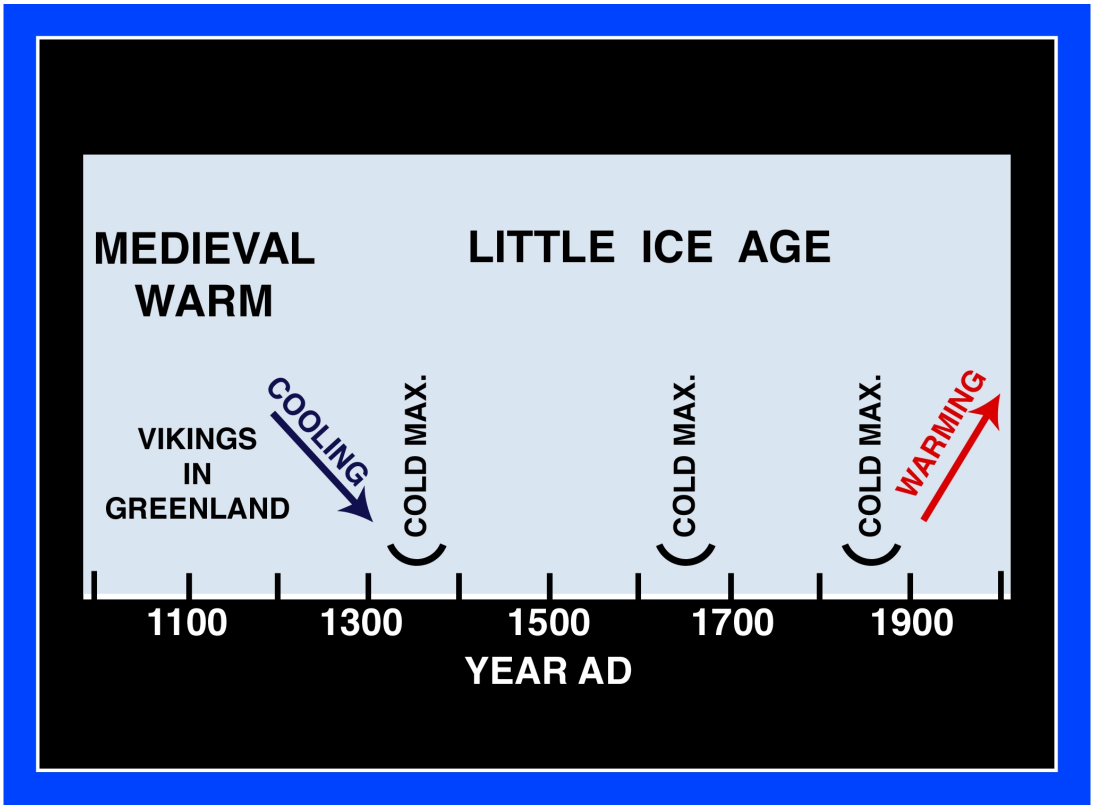


Figure 14. A third Little Ice Age glacial maximum centered in the 14th century has been documented in the Swiss Alps based on radiocarbon ages of stumps of trees knocked over by advancing ice. This early cold maximum marks the transition from the more moderate conditions characterizing what is known as the Medieval Warm period during which the Vikings were able to maintain colonies along the shores of the fjords in southwestern Greenland. These colonies succumbed to starvation early in the 14th century when the growing season appears to have become too short to allow an adequate supply of grain to be grown.

The Medieval Warm Period

We all learned in our childhood that Eric the Red led his band of Vikings to Greenland where they established a colony. It lasted several hundred years and achieved a maximum population of roughly 5000. Initially the Viking's diet was 80 percent mutton supplemented by 20 percent seafood. As time went on, the summers appear to have shortened and ever less grass was available to feed their sheep. In order to compensate, seafood became an ever more important part of the Viking diet reaching as much as 80 percent. This shift in food source is recorded by the ratio of heavy carbon (^{13}C) to light carbon (^{12}C) in Viking bones. In the early 1300s the colony disappeared. Archeologists have uncovered evidence that in desperation the starving colonists were forced to eat their dogs.

The Viking saga has led to the idea that the Little Ice Age was preceded by a warmer time. Less ice existed in the northern Atlantic thus facilitating passage for the Vikings ships. Summers were warmer and longer allowing grass to flourish in the ice-free valleys of southern Greenland. However, as with the snouts of glaciers, this gives us only a qualitative picture of climate. We need a means to quantify this warming. Glaciers would be great but while it is possible to map their perimeters when they were larger than now, it is not possible to do so if the boundaries have been obliterated by a subsequent advance.

One way to do this is through measurements of the thickness of tree rings. At high altitudes (or at high latitudes), tree growth is very sensitive to temperature. This is why mountain tops are often treeless. The winters are too cold. The same is true on the lands surrounding the Arctic. Beyond the northern tree line, the landscape is free of trees. It's too cold for them to survive.

By comparing the records of ring thickness with records of air temperature, it has been shown that for trees growing near their northern limit, the colder the air temperature, the thinner the annual ring. When the ring thicknesses for many, many trees are averaged for any given year, the correlation becomes reasonably good, thus providing a paleotemperature ‘proxy.’

Jon Esper, a young dendrochronologist (i.e., tree-ring scientist), put together ring-thickness records for 1800 temperature-sensitive trees from Siberia, Scandinavia and Canada. As shown in Figure 15, his conclusion from this record is that there was indeed an extended period of warmth a millennium ago. Further, ring thicknesses during this interval were comparable to those for the last decade. This record documents that during the Little Ice Age temperatures were as much as 1°C colder than during the Medieval Warm. This result is, of course, music to the ears of the detractors. They would like to believe that the present warmth is just a repeat of that which occurred 1000 years ago. But wait! The plot will thicken.

Whereas I would like to think that the Medieval Warm Period was global in extent, as our proxies are not up to the task, we don’t know whether or not this is the case. However, as the last of the three Little Ice Age cold maxima (i.e., that at 1850 AD) has been shown to be global, it is my opinion that the Medieval Warm Period will prove to be as well.

In one region, i.e., California’s Sierra Nevada Mountains, the impacts of the Medieval Warm are spectacular. Scott Stine, a professor at the University of California, Hayward, has documented that a profound drought lasting almost 200 years hit that region late in the Medieval Warm Period. At four separate sites, he found dead trees in growth position in places which are currently flooded with water. One set of these trees grew on the bottom of what is now high-Sierra Lake Tenaya. As this lake is 30 meters deep and has overflowed during all but one late spring melt period during the last century, for trees with 180 annual rings to have grown on the lake bed bears witness to an intense drought of long duration. A similar set of stumps appears in the channel of the West Walker River which heads in the high Sierra (see Figure 16). During the 100 or so years these trees grew, the river must have been largely dry. Similarly, woody plants of

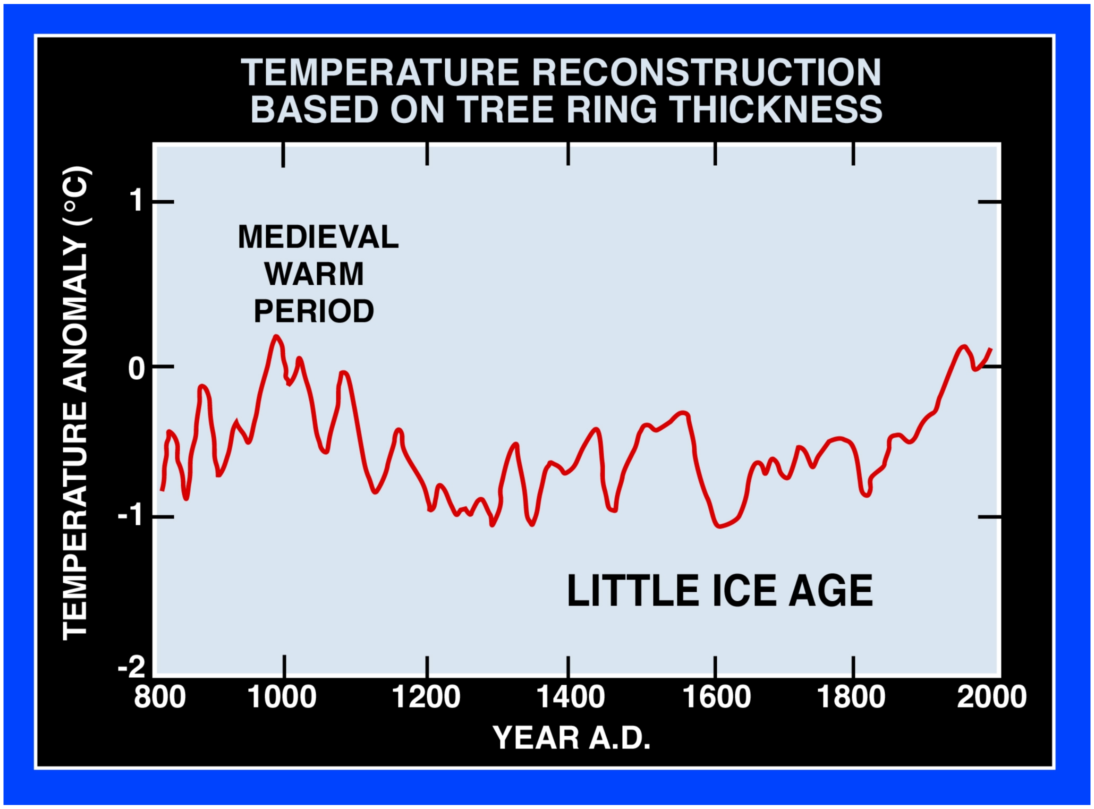


Figure 15. For trees living near their cold limit, the thickness of annual growth rings is influenced mainly by temperature. The temperature record shown in this diagram was constructed by Jon Esper based on a composite of 1800 thickness records from Siberia, Scandinavia, Canada and Alaska and also from north temperate mountains. His reconstruction suggests that temperatures at these locales were as much as 1°C colder than today's at times during the Little Ice Age, and they reached levels comparable to today's at the peak of the Medieval Warm period 1000 years ago.

West Walker River, California (recent photo)
Trees which grew during the Medieval Mega-Drought

Figure 16. One of four locales in California's Sierra Nevada where trees grew in areas now covered by water. In each case, the growth period was up to 180 years and the time of growth was the latter part of the Medieval Warm period. Together, they record a long-term drought more severe than even the short-term ones experienced during historical time.

the same age are found growing from the bottom of Mono Lake which, until diverted into the Los Angeles water supply, was fed by streams draining the adjacent Sierra Nevada. During late Medieval Warm time, the level of this salty desert lake must have been at an all time low. This drought episode suggests that relatively small regional climate changes can have profound impacts on regional water availability, especially in semi-arid zones.

Extending the record back in time

Having documented that during the Medieval Warm thermal maximum, the high northern latitudes were perhaps 1°C warmer than during the Little Ice Age, the question naturally comes to mind as to whether similar swings have characterized the last 12,000 years of warm and fairly stable climate. In this regard, Gerard Bond, a scientist at Columbia's Lamont-Doherty Earth Observatory, made a startling discovery. Bond made his entry into marine geology by studying the distribution in deep-sea sediments of rock fragments carried southward in the northern Atlantic imbedded in the abundant floating ice of glacial time. Upon melting, this ice dropped its debris to the sea floor thereby creating a record of iceberg activity. At one point, Bond decided to extend his study from times of glaciation to the last 12,000 years when ice was relatively scarce. In each sediment sample, he not only noted the abundance and average size of the rock fragments, he also looked for grains which might tell him where the ice had picked up its debris. In particular, he noted that some of the grains had a red hematite stain while others did not. Further, he was struck by a curious cycle in the abundance of these grains. As shown in Figure 17, it swung back and forth from a low of a few percent of the total grains to a high ranging from 15 to 20 percent of the total grains. By obtaining radiocarbon ages (see Sidebar #1) on shell material from various depths in these cores, Bond was able to place a time scale on this record. Note that in this and all the other geological records to be shown, time increases from left to right rather than from right to left as was the case for the historical and tree-ring records. The duration of a single cycle

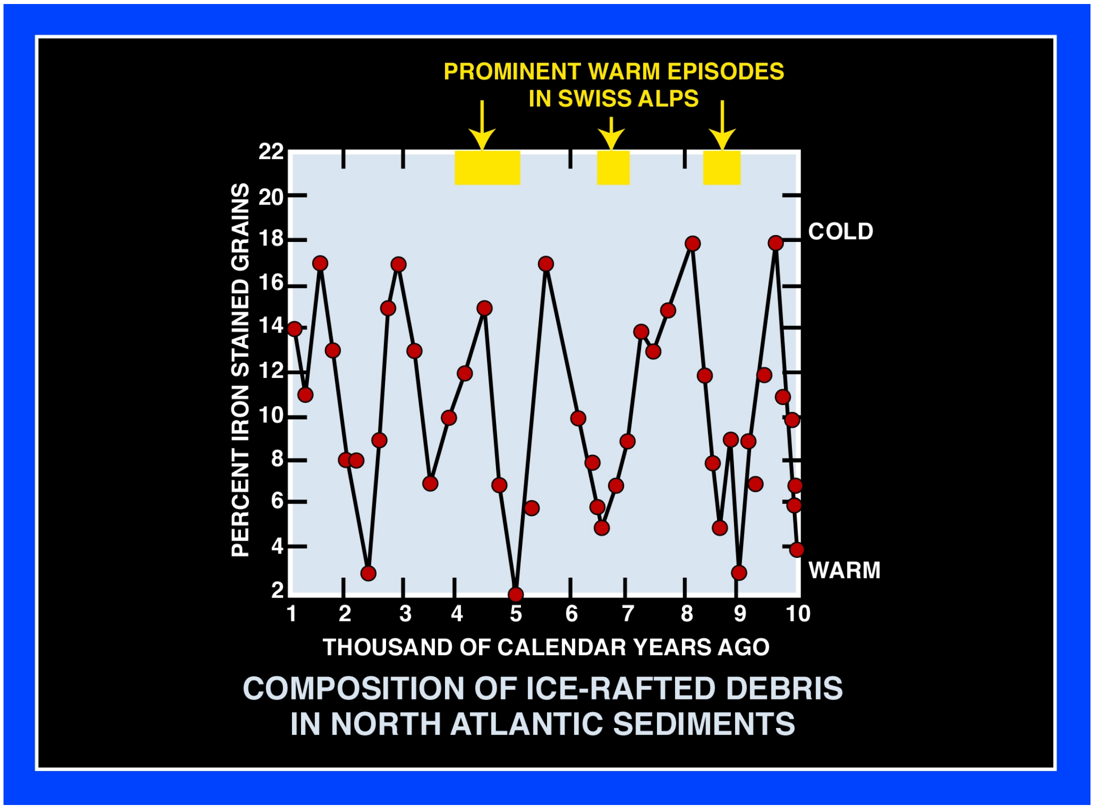
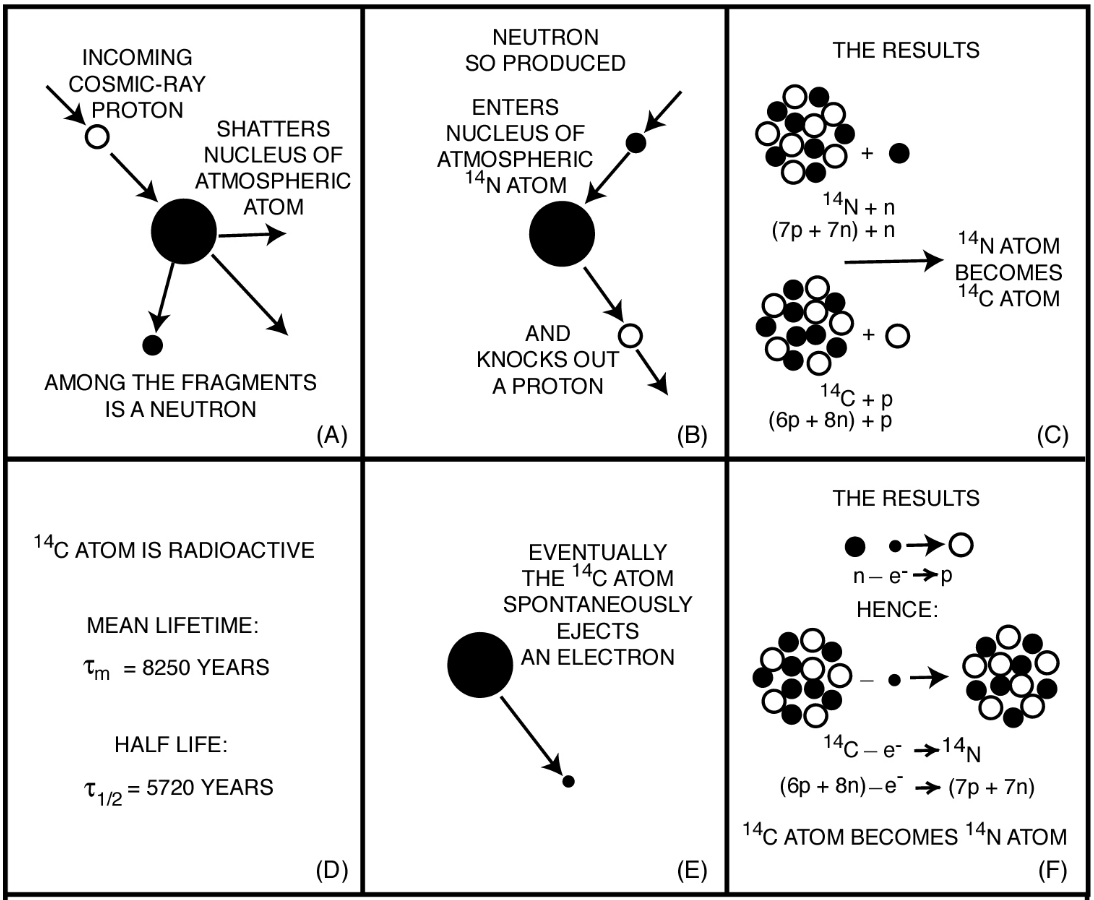


Figure 17. By determining the temporal record of the red-stained ice-rafted grains in deep-sea cores from the northern Atlantic, Gerard Bond has been able to show that the temperature of surface waters in this region has undergone cyclic changes. As the red-stained grains originate mainly in the Arctic, more of the ice in which they are lodged is able to reach the site of Bond's cores during cold times than during warm times. Hence, the swings in the proportion of red grains constitute a crude paleothermometer. The yellow blocks denote the radiocarbon ages obtained on wood and peat swept by summer melt water from beneath glaciers in the Swiss Alps. The trees and peat from which these fragments were derived must have grown during times when the glaciers were even smaller than they now are. Hence, they are expected to correspond to episodes where red grains were rare in Bond's cores.

THE LIFE CYCLE OF RADIOCARBON ATOMS



$$\text{RADIOCARBON AGE} = 8250 \ln \frac{{}^{14}C/C)_{1850}}{{}^{14}C/C_{SAMPLE}} + 100 \text{ YRS}$$

Sidebar #1

averages about 1500 years. Based on the geologic distribution of hematite-coated sandstones and on the composition of grains caught in sediment traps deployed beneath the ice-clogged water which flows southward along Greenland's east coast, Bond convinced himself that the source was ice which formed in the coastal waters of Canada's northern archipelago. He reasons that layers in the sediment rich in red-coated grains correspond to times when the northern reaches of the Atlantic were colder than today, thus allowing the ice bearing these grains to survive melting until it reached the sites of his sediment cores. In other cores Bond was able to show that the most recent of these red-grain rich zones corresponds to the Little Ice Age.

Evidence that Bond's red-grain cycles are indeed related to temperature swings was obtained by radiocarbon dating pieces of wood and peat swept out from under the snouts of glaciers in the Swiss Alps during periods of summer melting. As the forests in which these trees grew and the bogs in which the peat formed are now covered by ice, they represent times when the glaciers were even smaller than they are today. Radiocarbon dating of dozens of these samples reveal that, for the most part, they formed during periods when red grains were rare (i.e., warm times in the northern Atlantic).

Are the 1500-year cycles driven by the Sun?

Bond's great discovery came when he compared his red-grain record with reconstructions of the rates of production of two so-called cosmogenic isotopes, ^{14}C and ^{10}Be, over the last 12,000 years (see Figure 18). The radiocarbon reconstruction is based on measurements of the ^{14}C to C ratio in wood samples whose calendar age has been determined by annual ring counting. The ^{10}Be reconstruction is based on measurements on samples of Greenland ice whose age has also been determined by annual layer counting. These two radioisotopes are produced by the cosmic ray bombardment of our atmosphere (see Sidebar #2). He found a strong similarity between the red-grain and bombardment records. During the warm part of each of his cycles, the rates of production

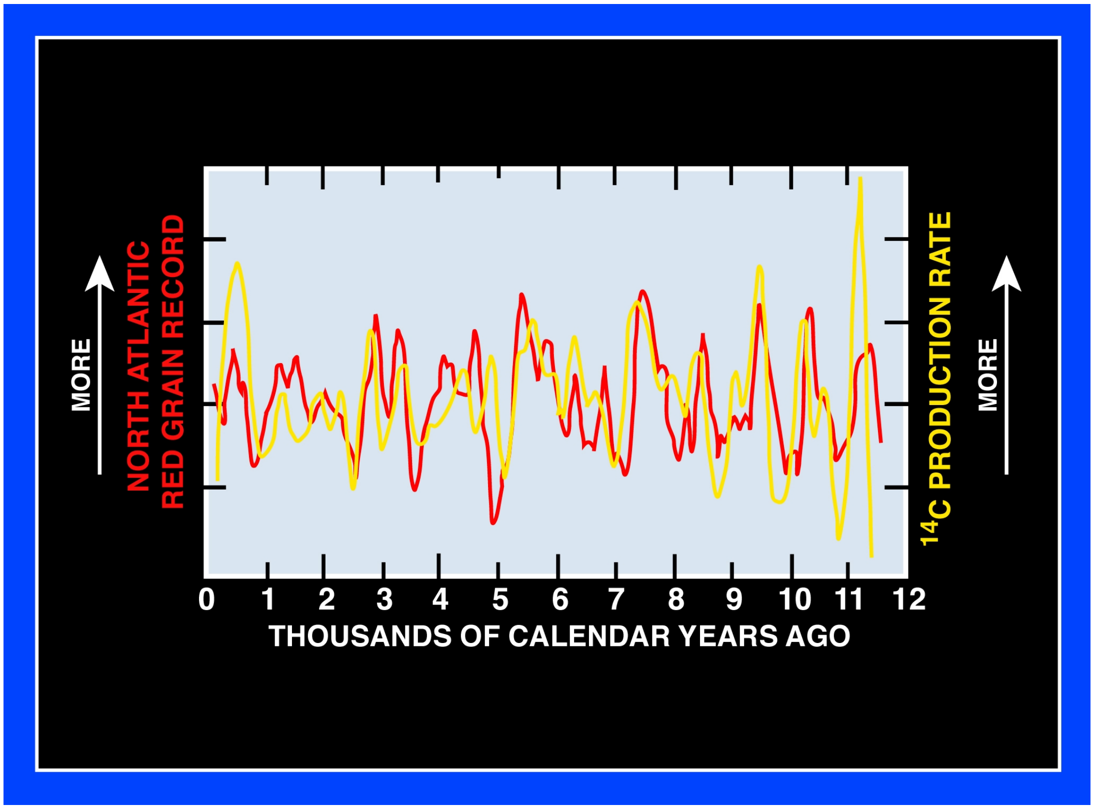
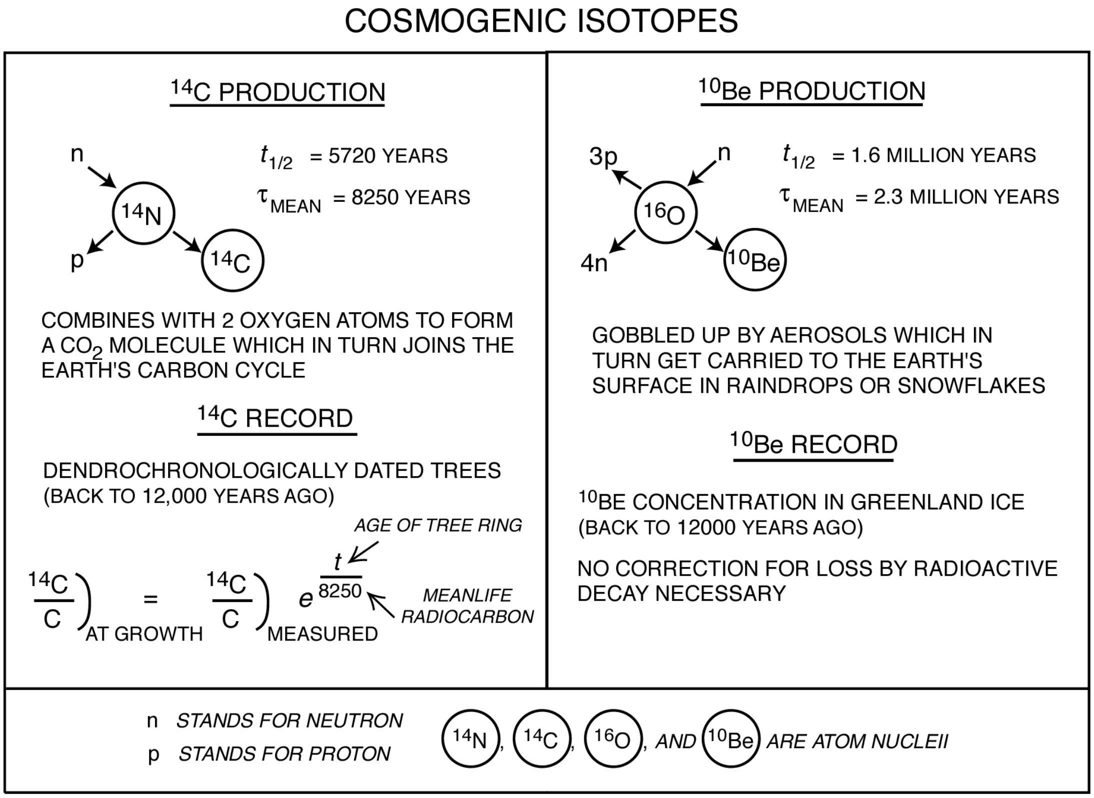


Figure 18. Bond's red-grain oscillations show an amazing similarity to those of the production of ^{14}C atoms in our atmosphere by cosmic-ray bombardment. The production record is based on ^{14}C to C measurements on wood samples whose absolute age has been documented by tree-ring counts. Not shown is the record of ^{10}Be production by cosmic rays based on measurements of this isotope in annually-layered Greenland ice. It matches quite well with the ^{14}C production record. As the flux of cosmic rays into our atmosphere is modulated by the magnetic field associated with ions streaming out from the Sun (i.e., with the solar wind), this match between the red-grain and production records suggests that the fluctuations in surface water temperatures in the northern Atlantic are somehow being paced by the Sun. It is important to note that the Medieval Warm – Little Ice Age oscillation constitutes the most recent of Bond's cycles (and the most recent of the cosmic-ray production cycles as well).


COSMOGENIC ISOTOPES
^{14}C PRODUCTION
n
p
^{14}N
^{14}C
$t_{1/2}$ = 5720 YEARS
τ_{MEAN} = 8250 YEARS
COMBINES WITH 2 OXYGEN ATOMS TO FORM A CO_2 MOLECULE WHICH IN TURN JOINS THE EARTH'S CARBON CYCLE
^{14}C RECORD
DENDROCHRONOLOGICALLY DATED TREES (BACK TO 12,000 YEARS AGO)
AGE OF TREE RING
MEANLIFE RADIOCARBON
$\left.\frac{^{14}C}{C}\right)_{AT\ GROWTH} = \left.\frac{^{14}C}{C}\right)_{MEASURED} e^{\frac{t}{8250}}$
^{10}Be PRODUCTION
3p
n
4n
^{16}O
^{10}Be
$t_{1/2}$ = 1.6 MILLION YEARS
τ_{MEAN} = 2.3 MILLION YEARS
GOBBLED UP BY AEROSOLS WHICH IN TURN GET CARRIED TO THE EARTH'S SURFACE IN RAINDROPS OR SNOWFLAKES
^{10}Be RECORD
^{10}BE CONCENTRATION IN GREENLAND ICE (BACK TO 12000 YEARS AGO)
NO CORRECTION FOR LOSS BY RADIOACTIVE DECAY NECESSARY
n STANDS FOR NEUTRON
p STANDS FOR PROTON
^{14}N, ^{14}C, ^{16}O, AND ^{10}Be ARE ATOM NUCLEII

Sidebar #2.

of these isotopes was lower than average and during the cold parts, they were higher than average. As the production rates of ^{14}C and ^{10}Be in our atmosphere are modulated by the magnetic field generated by ions streaming out from the Sun, this raised the possibility that the cycles in temperature were being driven by the Sun.

The argument runs as follows. As first discovered by Galileo, the Sun's surface is marred by dark spots. These spots come and go following an 11-year cycle (see Figure 19). Electrically charged atoms (i.e., ions) are launched into space from these spots. They generate a magnetic field which acts as a shield against cosmic ray protons headed toward our solar system from the remote regions of the galaxy. The more dark spots, the more ions streaming out from the Sun, the stronger the magnetic shield and hence the fewer ^{14}C and ^{10}Be atoms produced in our atmosphere. Small changes in the production of both ^{10}Be and ^{14}C have been shown to occur on an 11-year time scale (less production during sunspot maxima).

Our interest here is primarily with a 1500-year cycle rather than the better known 11-year sunspot cycle. Key are extended periods when few spots are present. One such period called the Maunder Minimum (see Figure 19) began in 1645 AD, some 35 years after Galileo first documented the existence of spots on the Sun. It lasted for 70 years (until 1715 AD). During this period the increase in the production rates of both ^{14}C and ^{10}Be was even larger than that during the sunspot minima associated with the 11-year cycle. While the Maunder Minimum is the only such sunspot-free period observed using telescopes, based on the records of the production rates of cosmic ray-produced isotopes, similar intervals have occurred many times over the past 12,000 years. More interesting, their spacing is not regular. They appear to have been more frequent during the times of Bond's cold intervals than during his warm intervals. This leads us to believe that the cool periods reflected in Bond's red-grain record were extended periods of low sunspot numbers akin to the Maunder Minimum. Hence, it is the solar irradiance during these spot-free intervals which are probably of importance to climate.

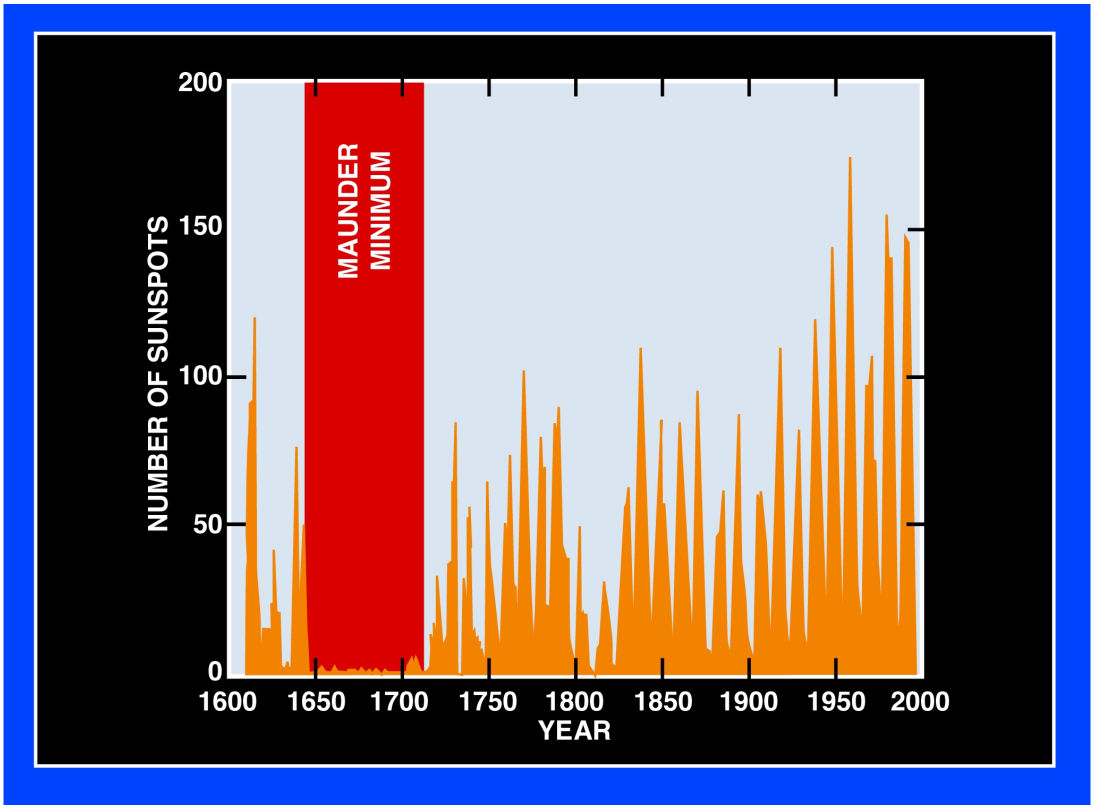


Figure 19. The strength of the solar wind correlates quite well with the number of dark spots on the Sun's surface. Most of the ions constituting this 'wind' appear to be launched from the spots. Hence, the magnetic shielding protecting us from cosmic-ray bombardment is stronger at times of maxima in the 22-year cycle (many spots) than at times of minima in this cycle (few spots). This record extends back to the time of Galileo who first identified sunspots. Between 1645 and 1720 AD, sunspot activity appears to have ceased. This period is referred to as the Maunder Minimum.

Extremely accurate measurements of the Sun's luminosity have been made from satellites for the past two decades. This record now covers two eleven-year sunspot cycles (see Figure 20). The results show that solar irradiance reaching the upper atmosphere is slightly greater (i.e., one part in 1300) during periods of high sunspot number than during those of low. While it is tempting to conclude that the Sun's energy output was even lower during intervals similar to the Maunder Minimum than during the recent sunspot minima documented by satellites, no convincing way of determining whether or not this is the case has been discovered. But no one has proposed that these changes were large enough to rival the impact of tripled CO_2.

Having established the correlations between 1) Earth temperature and cosmic ray bombardment, 2) cosmic ray bombardment and sunspot number, and 3) sunspot number and solar irradiance, a case can be made that changes in solar irradiance have somehow driven significant Earth temperature changes over the last 12,000 years.

Correlation is one thing; causation is another. No one has been able to come up with a convincing explanation as to why these very small changes in the Sun's irradiance should have had any effect on Earth climate. This is only one of a number of indications that Earth's climate system responds strongly to seemingly weak nudges. The change in irradiance from sunspot maxima to sunspot minima recorded by satellites is only one part in 1300. By comparison, model simulations suggest that the climate impact of tripled CO_2 is 20 to 30 times larger than that associated with the 11-year sunspot cycle.

The angry beast

During the last 12,000 years climate has have been remarkably quiescent. It is toward the beginning of this interval that modern human civilization was launched. The first steps appear to have taken place in the Middle East where a transition occurred from hunting and gathering to agriculture and animal husbandry. This transition was plausibly triggered by the shift from a glacial to an interglacial climate that followed a long series

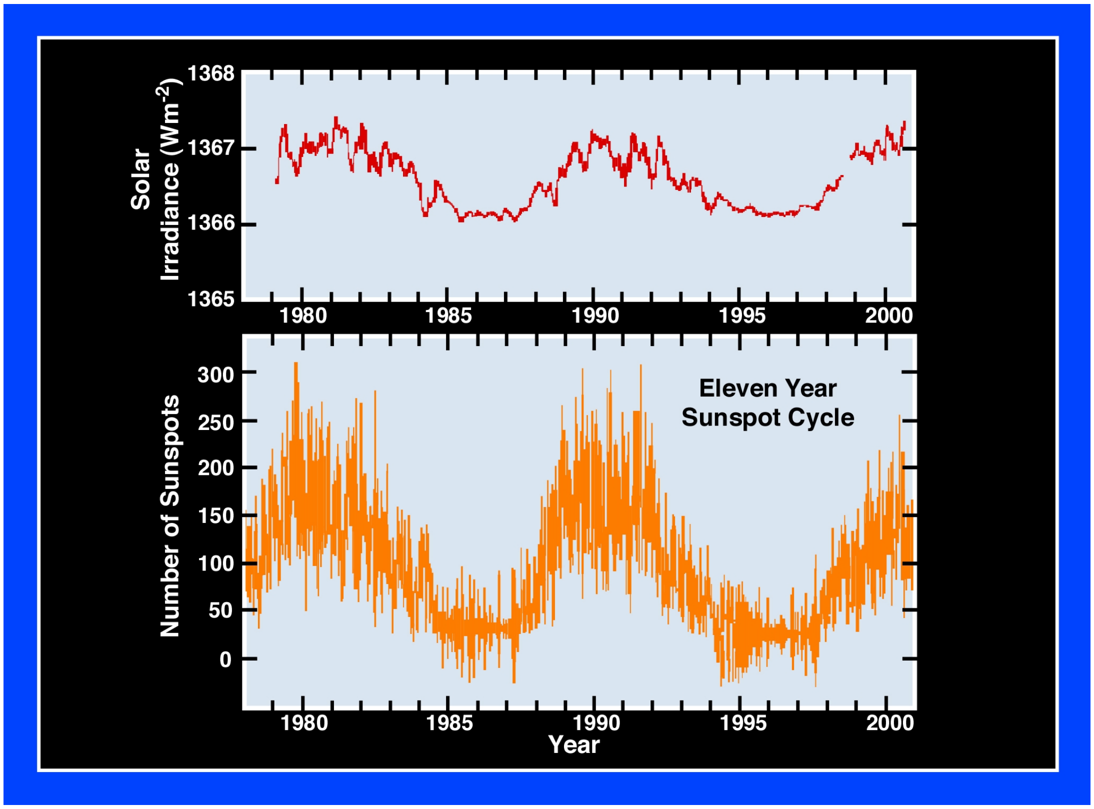


Figure 20. Only since 1979 have measurements of sufficient accuracy been made in order to permit the change in the Sun's irradiance over the course of the 11-year sunspot cycle to be determined. These satellite measurements reveal a tiny (1 part in 1300) decrease in irradiance at times of sunspot minima. This gives rise to the hypothesis that the larger the production rate of ^{14}C and ^{10}Be the smaller the Sun's energy output and hence the colder the Earth. The problem is that the observed irradiance variations appear to be far too small to give rise to the observed temperature changes.

of large and abrupt reorganizations of the climate system which characterized glacial time. But before we delve into these reorganizations, we must place them in context.

About 750,000 years ago for reasons we don't yet understand, Earth's climate system switched to a regime characterized by large asymmetric saw-toothed cycles. Each of these cycles involved a bumpy 100,000-year duration decline from peak warm conditions (interglacial) to peak cold conditions (full glacial). Each of these episodes of glaciation was terminated by an abrupt warming which returned the Earth to full interglacial conditions.

At the peak of each glacial episode, a large ice cap covered nearly all of what is now Canada. As shown in Figure 21, smaller ice caps were also present in the Patagonian Andes and New Zealand's South Island Alps. The difference between the extent of ice cover in the Northern and Southern Hemispheres relates to the asymmetry in availability of high latitude land masses rather than asymmetry in climate between the hemispheres. This is made clear by the north-south similarity in the extent of the glacial lowering of snowlines along the America Cordillera (see Figure 22). In both hemispheres, the equilibrium snowlines descended by close to 940 meters indicating a cooling of bout 6°C. Surface temperatures in the equatorial oceans were 3°C lower then than now. Ten times more soil dust and sea salt were transported through the atmosphere. The atmosphere's CO_2 content was only two thirds that during the time preceding the Industrial Revolution (i.e., 200 parts per million).

We know about these glacial/interglacial cycles because they are beautifully recorded in sediments from the deep sea (see Figure 23) and in ice from Antarctica (see Figure 24). In both the deep-sea records and in Antarctic ice, the key proxy is the ratio of heavy oxygen (^{18}O) to light oxygen (^{16}O). Although these two isotopes of the element oxygen have identical electron clouds and hence undergo the same chemical reactions, the extra weight provided by ^{18}O's two extra neutrons gives rise to a small difference in behavior. For example, water made with ^{18}O has a one percent lower vapor pressure than

Figure 21. Map depicting the extent of ice caps at the time of the last glacial maximum (i.e., 20,000 years ago). The far greater extent of these caps in the Northern Hemisphere reflects the distribution of land masses rather than a greater cooling in the north. Lands poleward of 40°S latitude in Patagonia and New Zealand were thoroughly glaciated.

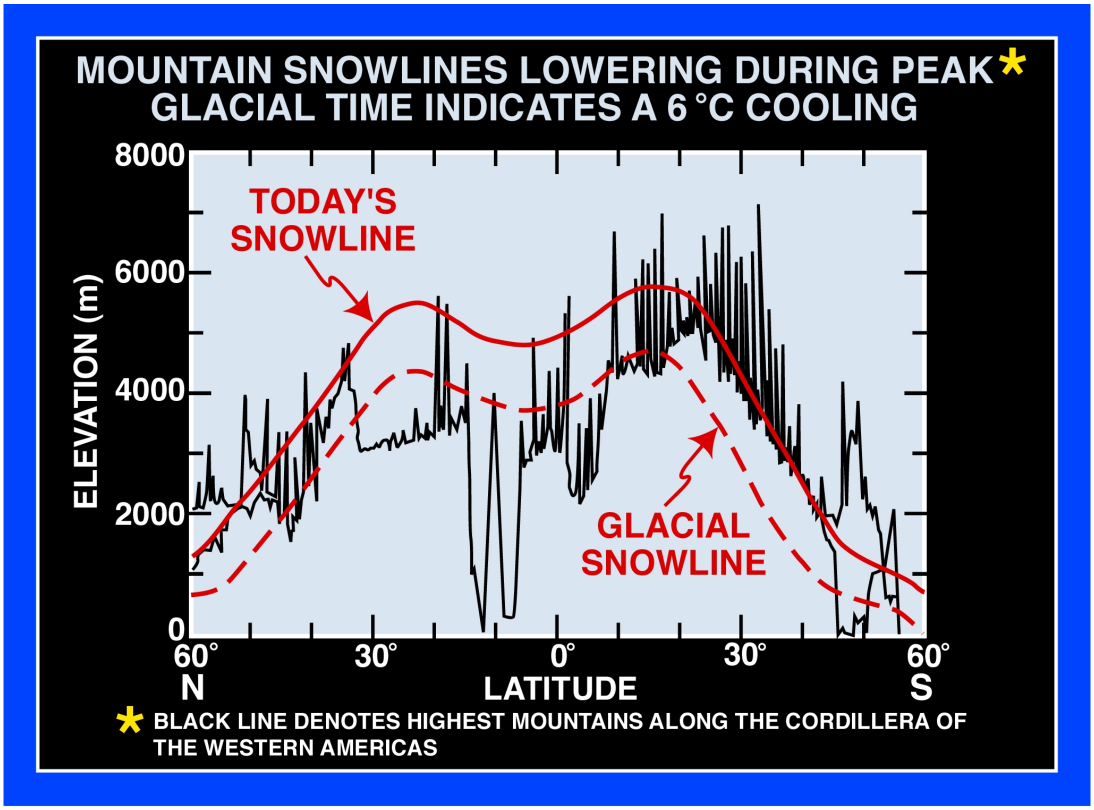


Figure 22. Evidence in support of a Southern Hemisphere glacial cooling comparable in magnitude to that experienced in the Northern Hemisphere comes from the extent to which mountain snowlines were lowered. With the exception of very dry locales such as the Tibetan Plateau, the magnitude of this lowering was close to 940 meters. Based on today's lapse rates, this lowering corresponds to a cooling of about 5°C.

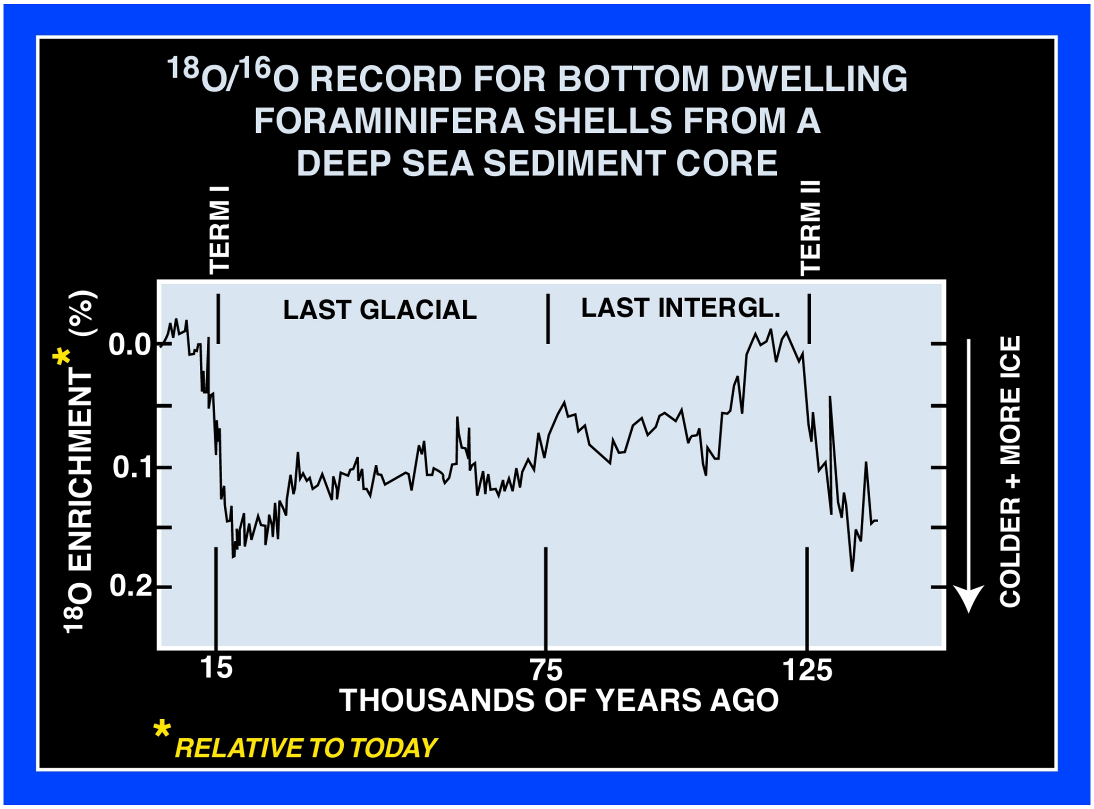


Figure 23. Record from a deep-sea sediment core of the ^{18}O to ^{16}O ratio in the $CaCO_3$ shells of bottom-dwelling micro-organisms (i.e., benthic foraminifera). About half of the 0.175 percent increase in this ratio for shells formed during peak glacial time is attributed to a cooling of waters in the deep sea and about half to the storage of ^{18}O depleted water in the greatly expanded ice sheets. The shape and duration of this most recent major glacial cycle is similar to those of the 6 earlier cycles. For each, a gradual decline from peak interglacial to peak glacial conditions extending over 100 or so thousand years is terminated by an abrupt return to interglacial conditions. As can be seen, the decline appears to have been modulated bumps spaced at intervals of about 20,000 years. Records from deep-sea cores taken throughout the world ocean all share the shape and magnitude of the one shown here.

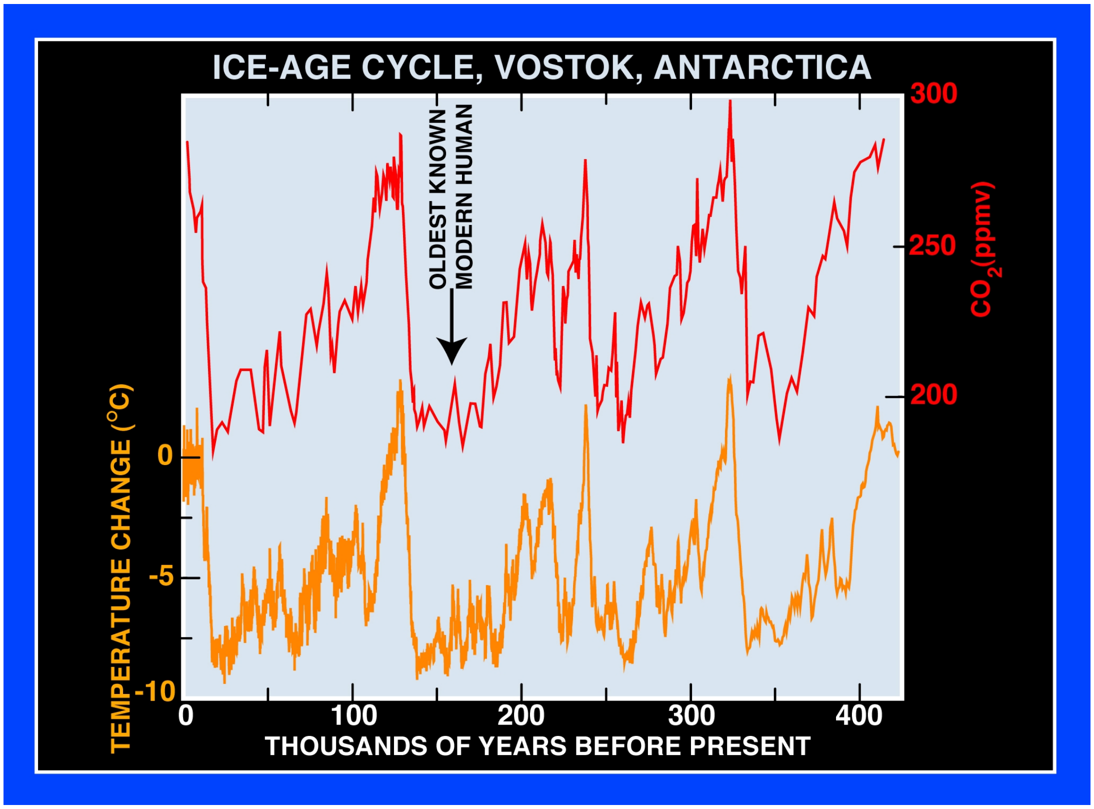
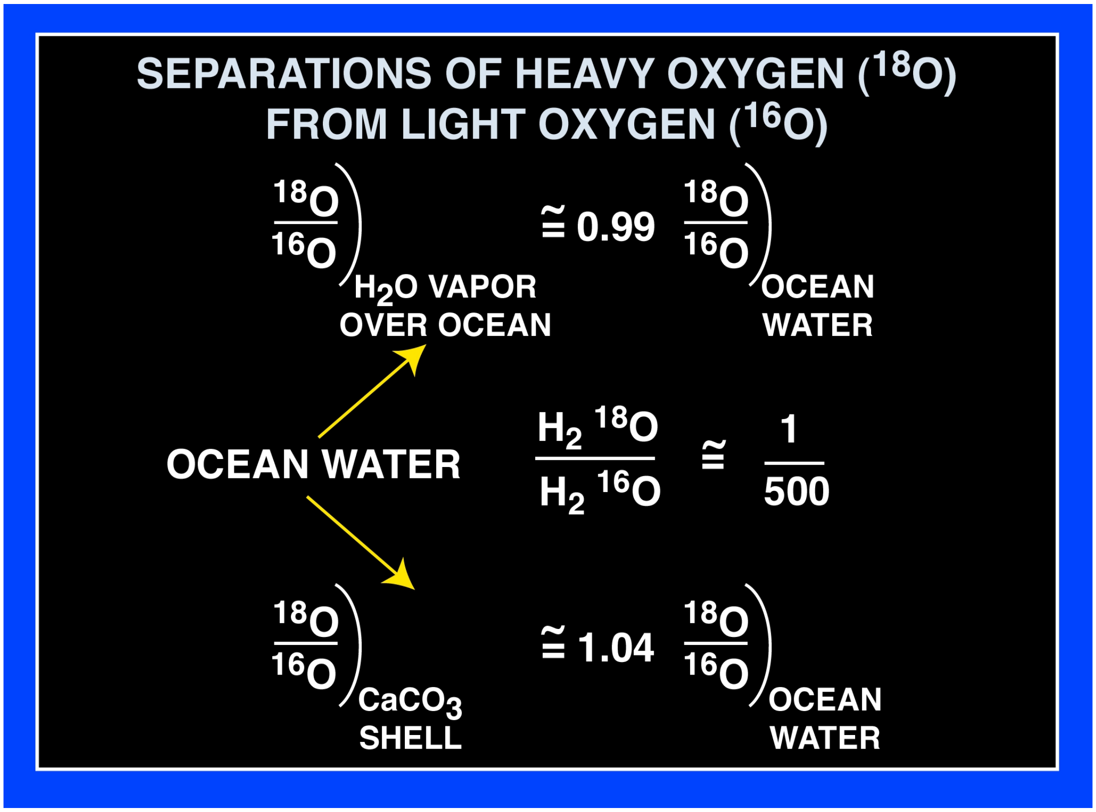


Figure 24. Records of CO_2 content of trapped air and of temperature (based on ^{18}O measurements in the ice itself) from a long ice core raised at the Russian Vostok Station in the interior of the Antarctic ice cap. Four of the seven major glacial cycles are recorded. Each has the shape described in Figure 23 (i.e., a long decline modulated by a 20,000-year cycle and capped by an abrupt return to interglacial conditions). It is of interest that humans with brain capacities equal to our own have existed for at least 160,000 years. However, it was not until last termination (i.e., 12,000 years ago) that our ancestors turned to agriculture and animal husbandry thereby launching our civilization.

water made with ^{16}O (see Figure 25). This difference is the basis for the proxy which allows past temperatures on the Antarctic ice cap to be reconstructed. Because of the difference in vapor pressure, the water evaporating from the surface ocean has a one percent lower ^{18}O to ^{16}O ratio than sea water itself. The air mass containing this water vapor cools as it moves poleward, causing precipitation to occur. Because of the vapor pressure difference, the ^{18}O to ^{16}O ratio in the precipitation is one percent greater than that in the cloud water vapor. So, the first rain to fall has an isotopic composition identical to that for sea water (i.e., the ^{18}O enrichment during condensation cancels the depletion during evaporation). However, the removal of this ^{18}O-enriched rain lowers the ^{18}O to ^{16}O ratio in the remaining cloud water vapor. Hence, the next rain to form will have an ^{18}O to ^{16}O ratio lower than that in sea water (see Figure 26). Each succeeding precipitation event will further decrease the ^{18}O to ^{16}O ratio in the residual water vapor. As air masses reaching the interior of the Antarctic continent contain only a very small fraction of their initial water vapor, their ^{18}O to ^{16}O ratio reaches levels 5 to 6 percent lower than that for sea water. The colder the air mass, the smaller its residual water vapor content and the lower its ^{18}O to ^{16}O ratio. This leads to a close tie between mean annual isotopic composition of high latitude precipitation and mean annual air temperature (see Figure 26). This strong correlation is the basis for the Antarctic ice-core-temperature record shown in Figure 24. The lower ^{18}O to ^{16}O ratios in glacial-age snow compared to modern snow at the same location bear witness to colder glacial temperatures.

A second manifestation of ^{18}O's two extra neutrons is a four percent higher ^{18}O to ^{16}O ratio in the oxygen in the calcium carbonate shells formed by marine foraminifera. In this case, temperature also plays a role. The colder the water temperature, the larger the fractionation (see Figure 27). Hence the ^{18}O to ^{16}O ratios in these shells also provide us with a proxy for sea water paleotemperature.

As is the case for many of our proxies, there are complications related to the fact that they respond to more than one environmental variable. We have already seen that in



SEPARATIONS OF HEAVY OXYGEN (^{18}O) FROM LIGHT OXYGEN (^{16}O)

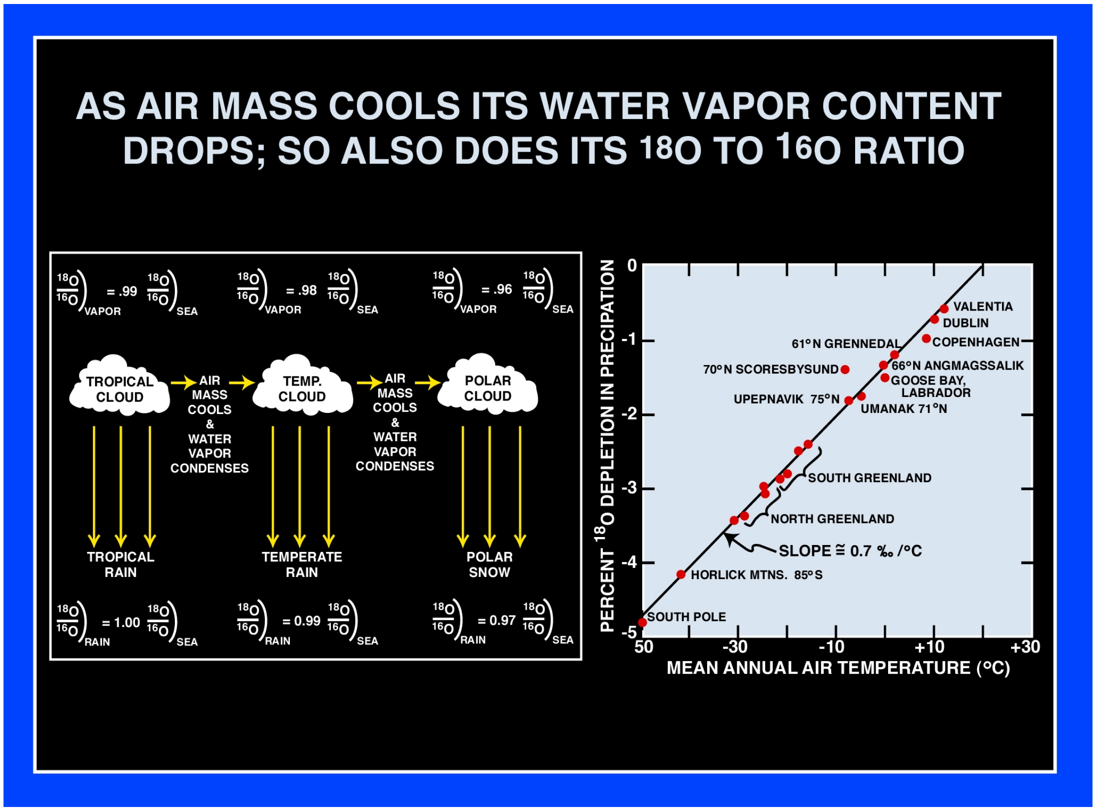
$$\left.\frac{^{18}O}{^{16}O}\right)_{\text{H}_2\text{O VAPOR OVER OCEAN}} \cong 0.99 \left.\frac{^{18}O}{^{16}O}\right)_{\text{OCEAN WATER}}$$

OCEAN WATER

$$\frac{H_2{}^{18}O}{H_2{}^{16}O} \cong \frac{1}{500}$$

$$\left.\frac{^{18}O}{^{16}O}\right)_{\text{CaCO}_3\text{ SHELL}} \cong 1.04 \left.\frac{^{18}O}{^{16}O}\right)_{\text{OCEAN WATER}}$$

Figure 25. Because of the mass difference between ^{18}O (8p, 10n) and ^{16}O (8p, 8n), these isotopes undergo small separations from one another during chemical reactions. Of particular interest to us are the separations which occur during evaporation (and condensation) and during the precipitation of $CaCO_3$. The former separation reflects the 1% lower vapor pressure of $H_2{}^{18}O$ relative to $H_2{}^{16}O$. The latter separation reflects a 4% preference for ^{18}O by calcite over that by the water from which the calcite precipitates.



AS AIR MASS COOLS ITS WATER VAPOR CONTENT DROPS; SO ALSO DOES ITS ^{18}O TO ^{16}O RATIO

Figure 26. The 1 percent difference between the vapor pressures of $H_2{}^{18}O$ and $H_2{}^{16}O$ manifests itself in up to a 5% range in the ^{18}O to ^{16}O ratio in rain and snow. As air masses move from the low latitudes polar-ward, they cool. As they cool, precipitation occurs. The raindrops or snowflakes thus created have a 1 percent higher ^{18}O to ^{16}O ratio than the cloud vapor from which they form. Hence each precipitation event leaves the residual vapor ever more depleted in ^{18}O. Those air masses reaching the very cold polar regions have lost more than 99 percent of their original water vapor and consequently their ^{18}O depletion reaches several percent. As shown by Willie Dansgaard, the isotopic composition of snows at high latitudes nicely correlates with air temperature: the colder the air from which snow forms, the greater the ^{18}O depletion. The greatest depletion is observed in snow which falls on the ultra cold Antarctic polar plateau.

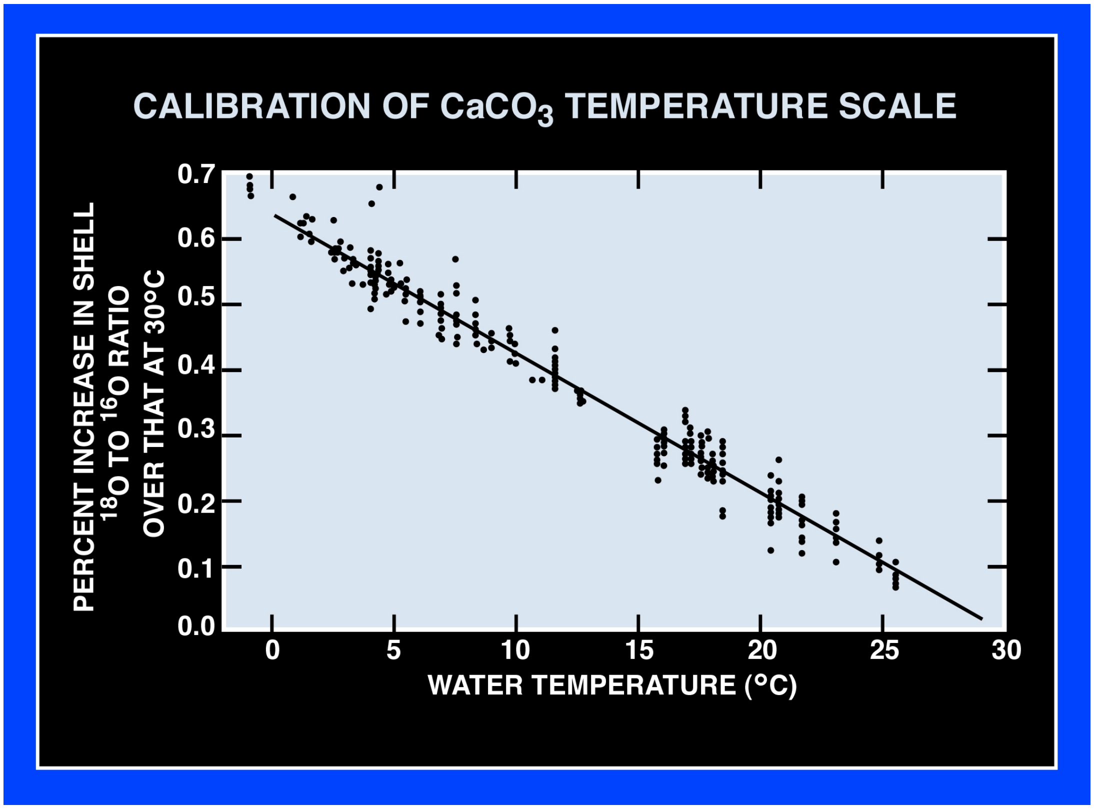


Figure 27. The roughly 4 percent enrichment of ^{18}O relative to ^{16}O in $CaCO_3$ over that in the sea water from which it precipitates is temperature dependent. The enrichment is about 0.7 percent larger for calcite formed in waters near the freezing point of sea water (-1.8°C) than in water from the warmest parts of the ocean (30°C). This dependence gives rise to Harold Urey's paleo temperature method. Shown here are measurements on which this trend with temperature is based.

addition to air temperature, mountain snowline elevations are sensitive to the amount of snow which falls each year. In the case of the ^{18}O to ^{16}O ratio in marine calcium carbonate shells, the major complication is that the isotopic composition of sea water varies with climate. The reason is that the large continental ice sheets which formed during glacial time were depleted in ^{18}O, just as are present-day ice caps. This ‘missing’ ^{18}O was left behind in the ocean. As shown in Figure 23, the shells of bottom-dwelling foraminifera formed during glacial time were enriched in ^{18}O relative to those which form today. For several decades, paleoclimatologists struggled to figure out how much of the glacial ^{18}O increase was the result of colder bottom-waters and how much was the result of larger ice caps. Only recently has this issue been resolved to the satisfaction of most of us. A little more than half of the change was due to ice volume and a little less than half due to colder bottom waters.

It is interesting to note that the oldest fully formed human skull (see Figure 28) found to date has an age of 160,000 years. As shown by the arrow in Figure 24, this person lived during the time of the penultimate glacial period. While endowed with full brain capacity, it was not until 150,000 years later at the onset of the present interglacial climate that humans began to transform the landscape through irrigation and to exert control over hitherto wild animals.

The ice core record of the atmospheric CO_2 content is of particular interest (see Figure 24). The low CO_2 in the atmosphere during glacial times could logically be called upon to explain part of the planet’s cooling. However, when compared to the recent CO_2 rise, there is a disconnect. The mean Earth temperature during peak glacial time averaged 4° to 5°C colder than today’s. The atmosphere’s CO_2 content was 74 percent (200/270) of that for pre-industrial time. Prior to the Industrial Revolution, the Earth’s temperature was about 1°C cooler than now. At that time, the CO_2 content of the atmosphere was 76 percent (280/370) what it is now. Further, models suggest that at most, only about half of the temperature change during the past century can be attributed to CO_2. Hence, lower

ADULT MALE SKULL 160,000 YRS OLD

Figure 28. Despite the fact that the human brain had reached its present size as early as 160,000 years ago, it was not until about 12,000 years ago that civilization was launched.

atmospheric CO_2 was likely only a relatively small contributor to the cold global temperatures of glacial time.

Superimposed on each of the 100,000-year duration declines toward peak glacial cold is a distinct 22,000-year cycle which appears to be driven by changes in the strength of the temperature contrast between the seasons. As shown in Figure 29, the imprint of the 22,000-year cycle is particularly strong in the record of atmospheric methane concentrations.[2] These cycles are caused by the precession of the Earth's rotation axis. When, as now, Northern Hemisphere summers occurred as the Earth rounded the far end of its elliptical orbit and winters occurred as it rounded the near end, the contrast in solar insolation between the summer and winter seasons was somewhat smaller than average. In the Southern Hemisphere, the opposite is now the case and the seasonal insolation contrast is currently somewhat larger than average (see Figure 30). However, 11,000 years ago Northern Hemisphere summers occurred when the Earth was closest to the Sun. Summers in the Northern Hemisphere then were warmer than they are now (see Figure 31). Somehow the Earth's climate has responded to these cyclic changes in seasonal contrast. However, when introduced into models, just as was the case for the very small changes in solar irradiance, no measurable impacts on climate are produced. So once again the geological record seems to be telling us that our climate system has been extremely responsive to small nudges.

Abrupt changes: the evidence

For many years, it was believed that major climate changes were paced by cycles in the Earth's orbital characteristics. In terms of the few centuries since the beginning of the Industrial Revolution, these changes occur so slowly that they can have no bearing on

---

[2] The most important source of atmospheric methane is swamps and wetlands. The invasion of O_2 into sediments is greatly impeded when sediment pores are filled with water. In the absence of an adequate O_2 supply, sediments become anaerobic and methanogenesis replaces respiration. In today's atmosphere, methane molecules survive oxidation for only one decade. Because of this rapid turnover, the record of atmospheric methane content kept in ice cores provides a measure of the rate of production of this gas and hence of the extent of wetlands.

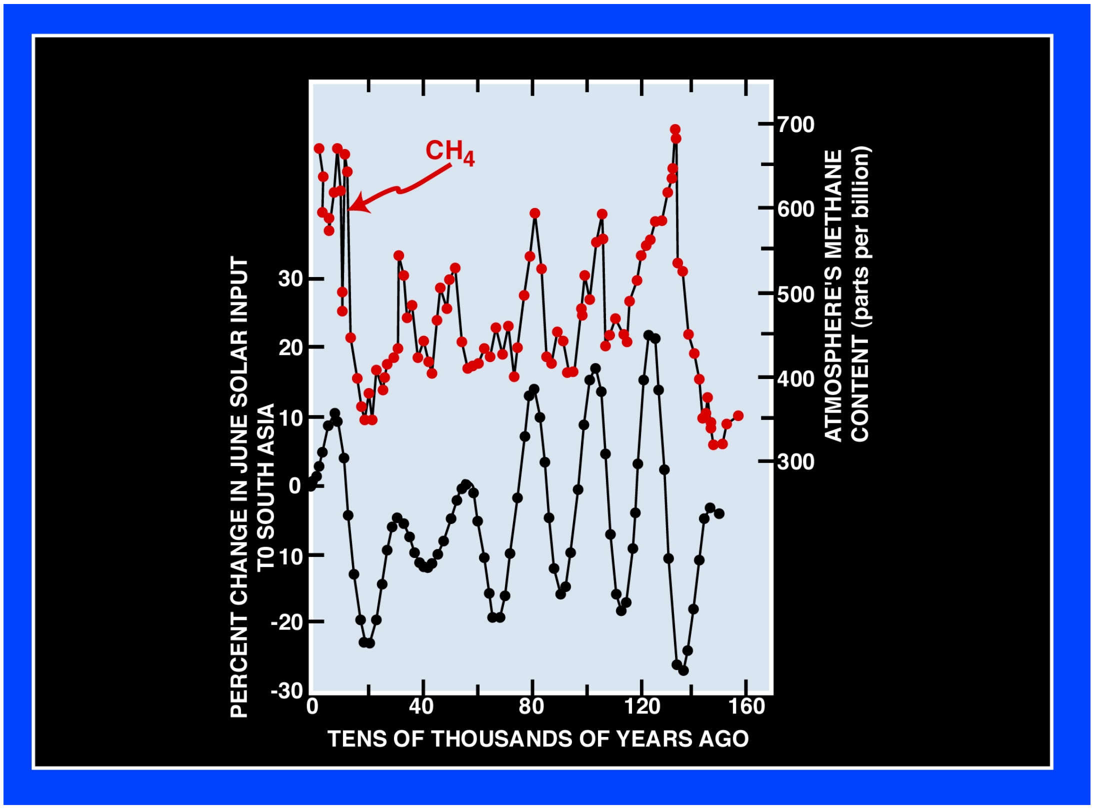


Figure 29. While expressed in the ^{18}O records for benthic foraminifera and in the CO_2 and temperature records for Antarctic ice, the pacing by the Earth's 22,000-year precession cycle shows up most strongly in the methane record from Antarctic ice. As methane is produced largely in swamps and bogs, the amount in the atmosphere at any given time reflects the warmness and wetness of the Earth's lands. As can be seen, the highs in methane content correspond to Northern Hemisphere summer insolation maxima. This likely reflects both the dependence of the intensity of the monsoon rains on the summer heating of the Tibetan Plateau and the extent of snow and ice cover in boreal regions.

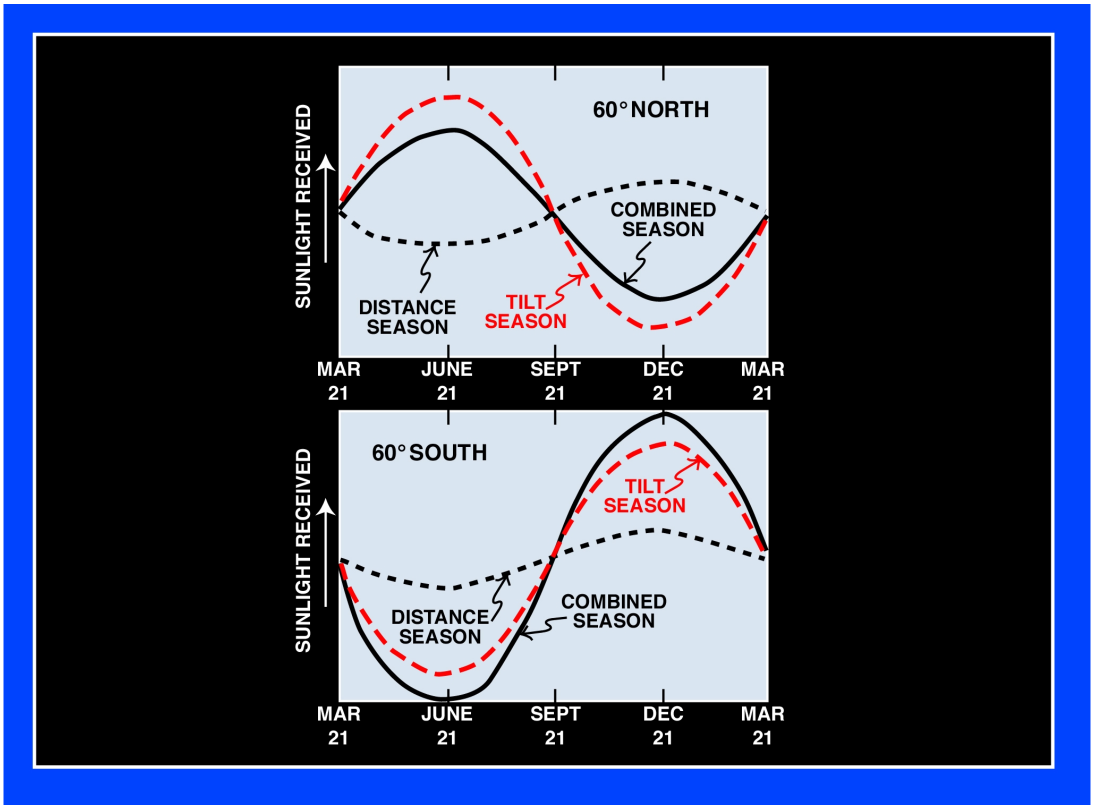


Figure 30. A diagramatic view of phasing between the seasonal cycles associated with the Earth's tilt and with its distance from the Sun. Currently, these cycles oppose one another in the Northern Hemisphere and reinforce one another in the Southern Hemisphere. One half precession cycle in the past (i.e., 11,000 years ago), the opposite was the case: the Northern Hemisphere had a larger than average seasonality and the Southern Hemisphere a smaller than average seasonality.

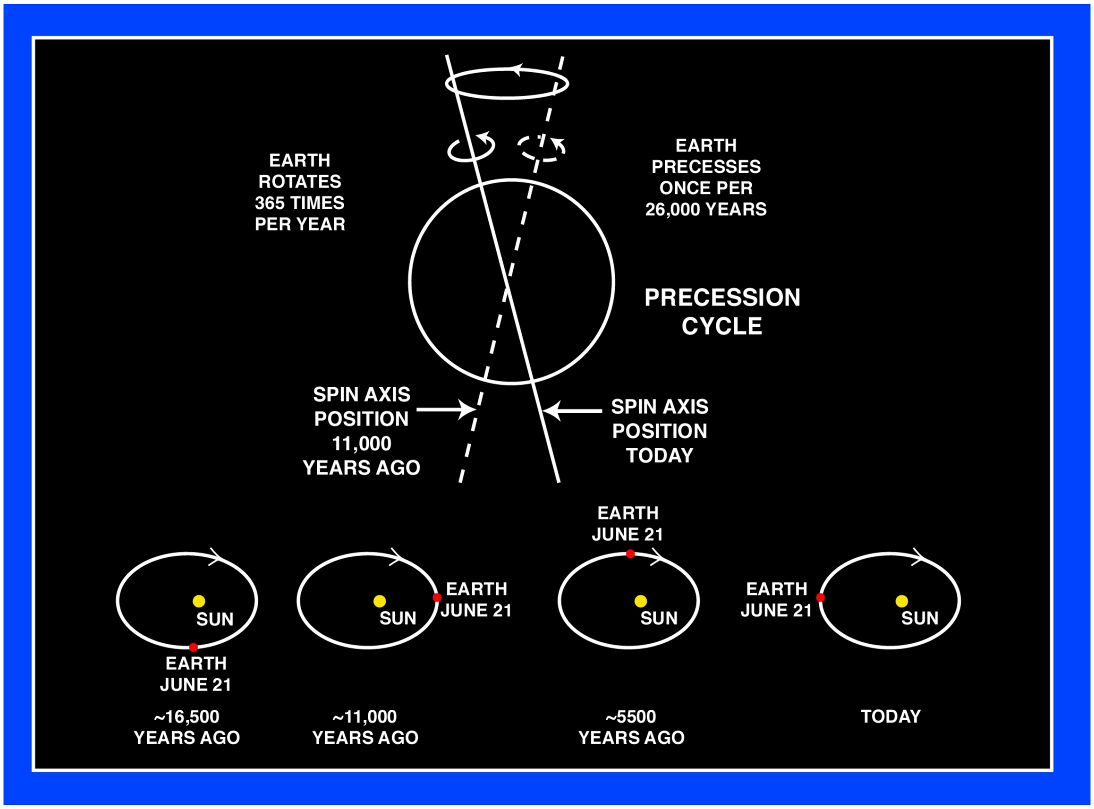


Figure 31. The Earth's equatorial bulge is tilted by 23° with respect to the plane defining the orbits of the objects in the solar system; hence, as does a spinning top, the Earth precesses. Were the Earth's orbit circular, its precession would have no impact on seasonality. However, the orbit is slightly elliptical. The Sun resides at one of the ellipse's two foci. Because of this, the Earth – Sun distance changes during the course of the year. The further the Earth is from the Sun, the less radiation it receives. Because it precesses, there is a cycle in the position in the orbit on June 21 (the date when the Northern Hemisphere points most directly toward the Sun). This gives rise to a 22,000-year cycle in distance sesonality.

The Earth's rotation axis completes a precession cycle once every 26,000 years. However, as the Earth's orbit also precesses, the time between situations where the Earth is closest to the Sun on June 21st averages 22,000 years.

the warming since the late 1800s. It was not until the long borings in the Greenland ice cap were made that it became clear that cycles in seasonal contrast were not the only source of climate irregularity. What stunned the paleoclimate community was that unlike the records from open ocean sediments and from Antarctic ice, those from Greenland ice were dominated by large and abrupt changes (see Figure 32). Only during the most recent 12,000 years did conditions stabilize. During the previous 100,000 years, climate as recorded in Greenland rarely stood still. Rather, it periodically underwent large jumps. When it wasn't jumping, it was drifting.

One might ask why these changes don't show up in the marine sediment record. In fact, they do, but only in places where the sediment accumulates at a very high rate (10 to 100 centimeters per 1000 years). Until the record in Greenland was obtained, scientists had focused their attention on studies of sediments from the open ocean where accumulation rates rarely exceeded a few centimeters per 1000 years. In their search for food, worms churn these sediments to depths of 6 to 10 centimeters and in so doing they destroy any record of millennial duration climate changes.

This, however, cannot be the explanation for the absence of millennial changes in the Antarctic ice record. While lacking the annual layers so valuable in dating Greenland ice, nevertheless the record is undisturbed and should certainly preserve millennial-duration events seen in Greenland. A closer look at these records reveals that millennial-duration events are present but unlike Greenland, they are dwarfed by the longer-term cyclic changes in climate.

By counting the annual layers preserved in Greenland ice, it was shown that the climate jumps were accomplished in just a few decades! Electrical conductivity measurements made by scratching a pair of electrodes along a freshly cut ice surface (see Figure 33) reveal that during these transitions climate appears to have flickered much as do fluorescent lights when first turned on. The air temperature changes associated with these jumps were a whopping 10°C. In addition, the infall rates of both soil dust and of

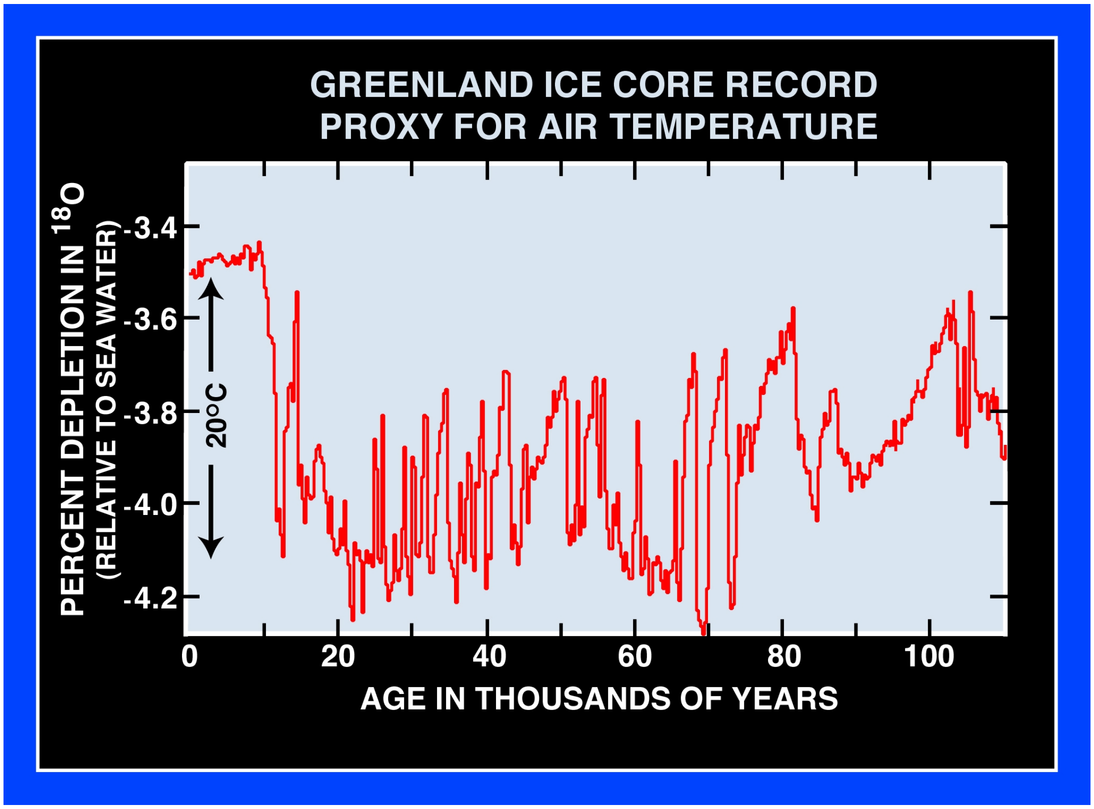


Figure 32. Unlike the record in Antarctic ice which is dominated by stately 100,000- and 22,000-year cycles, that in Greenland ice is dominated by large and abrupt millennial-duration fluctuations known as Dansgaard-Oeschger events. Another difference between these records is that while ice as old as 900,000 years has now been recovered in Antarctica, despite repeated attempts the Greenland records all terminate during the last interglacial period giving rise to the hypothesis that Greenland's ice cap largely melted during this episode of interglacial warmth. The temperature scale shown on this diagram is based on a deconvolution of downhole temperature measurements rather than on the ^{18}O measurements which suggest only half as large a temperature change. The reason appears to be that during glacial time winter snowfall was largely absent, strongly biasing the ^{18}O toward the less negative summer values.

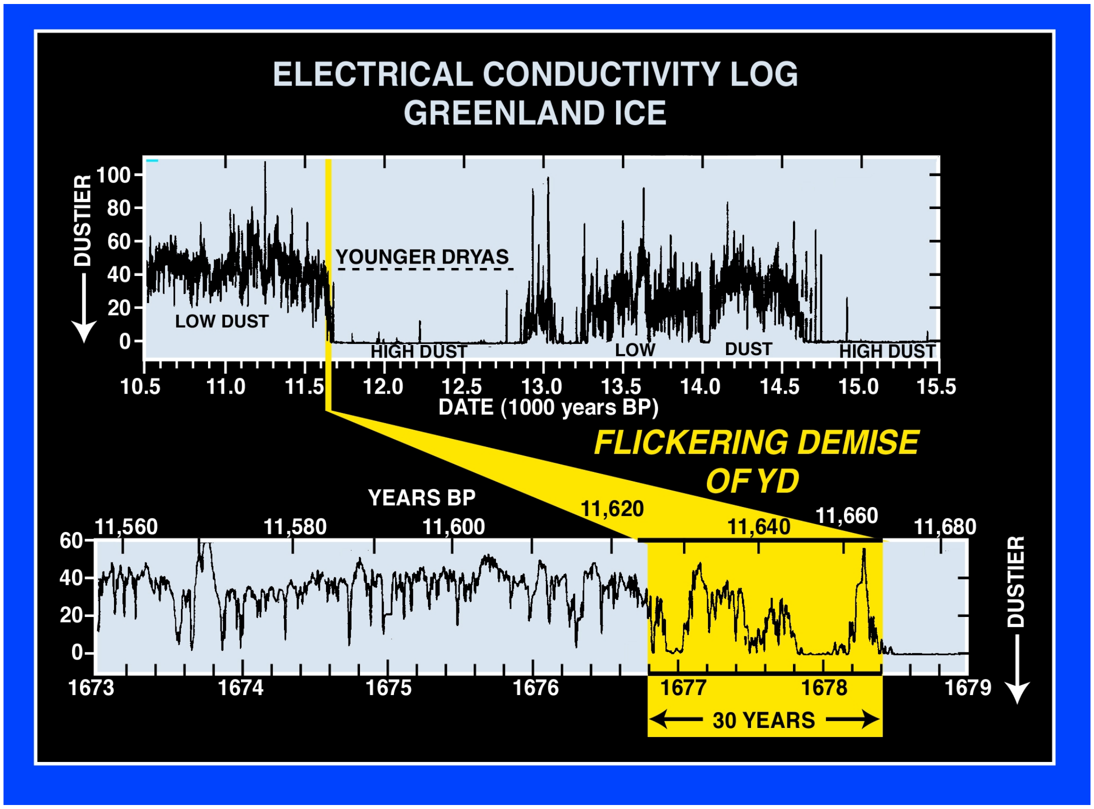


Figure 33. Electrical conductivity logs obtained by dragging a pair of electrodes down a clean ice surface, provide by far the most detailed records of events in Greenland. In particular, they yield a detailed picture of what transpired during the abrupt warming which terminated the Younger Dryas (and also during the initiation of each of the D-O cold event). As can be seen, the transition was not a smooth one. During the three-decade transition period, the climate appears to have flickered back and forth between its cold and warm states. During cold times, the $CaCO_3$ in the dust reaching the ice cap was able to completely neutralize the incoming acids and thereby squelch the electrical conductivity generated by the acid's protons. During warm times, the $CaCO_3$ supply was insufficient and protons from the acids accumulated in the ice and are able to move through it in response to an electrical potential.

sea salt onto the Greenland ice cap jumped back and forth by factors of three and accompanying each temperature jump was an abrupt shift in the atmosphere's methane content. During glacial time the dominant source of methane was swamps in the tropics, and that of soil dust reaching Greenland was deserts in Asia. Thus from the Greenland ice core record alone it could be shown that the jumps in climate impacted a large portion of the planet. The periods of intense cold in Greenland corresponded to periods of less extensive methane-producing tropical wetlands and to periods of more frequent intense dust storms in the Asian deserts.

In the discussion of the factors influencing Earth temperature, dust and sea salt were not mentioned. While currently minor players, during peak glacial time the dust and sea salt burdens of the atmosphere were perhaps ten times larger than today's. At that time they must have contributed to the cooling of the planet. As can be seen in Figure 34, especially when blown out over the ocean, dust increases the reflectivity of the planet. As sea salt aerosols serve as cloud condensation nuclei, they may well have enhanced the Earth's reflectivity during cold times.

The Dansgaard-Oeschger events

Punctuating much of the ice core record of the last period of glaciation in Greenland are a series of Dansgaard-Oeschger (D-O) events which in many ways resemble the YD. The climate in Greenland appears to have jumped back and forth between a state of extreme cold and a state of moderate cold. During the intervals of extreme cold, the rain of soil dust and sea salt onto the ice cap was three times higher than during the intervening intervals of moderate cold. The methane content of the air trapped in the ice also underwent sympathetic jumps. The shifts from ultra cold to moderate cold were extremely sharp, occurring in just a few decades.

Stefan Rahmstorf of the Potsdam, Germany modeling group pointed out an interesting coincidence. Aware of Gerard Bond's finding that the 1500-year cycle in the proportion of red-coated grains continued largely unchanged back through the entire

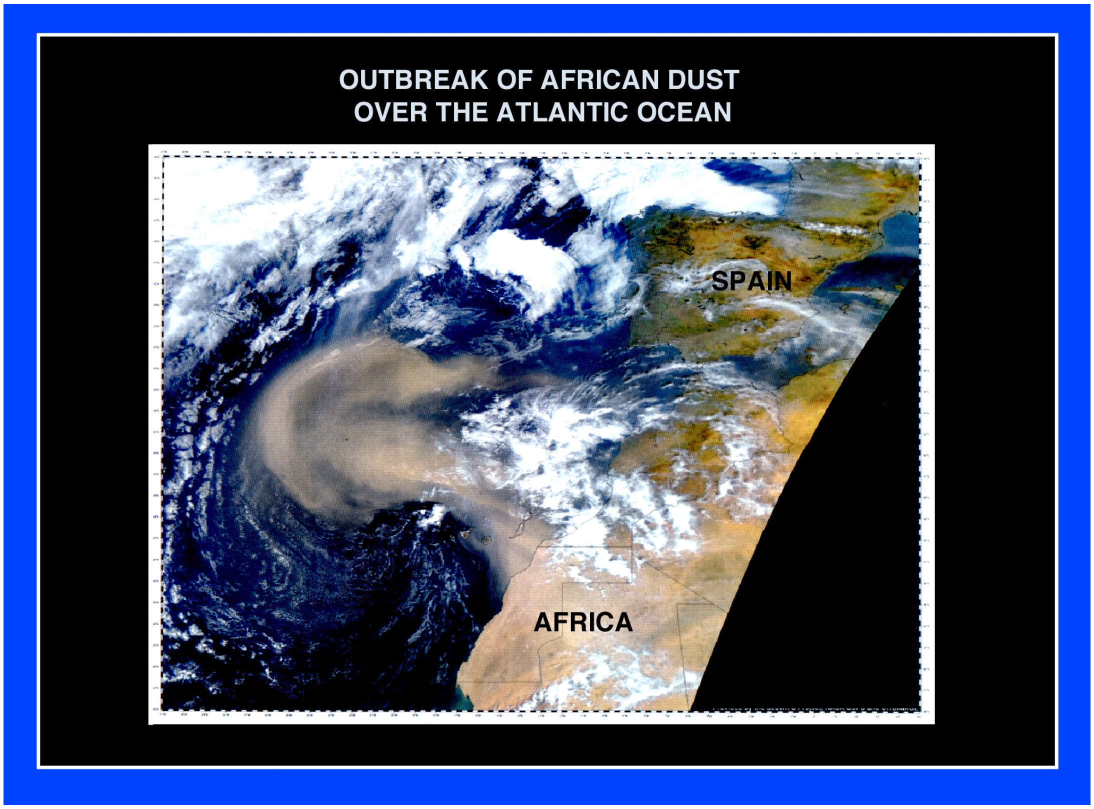


Figure 34. Today dust plumes such as that shown here make only a small contribution to the Earth's reflectivity. But these plumes were likely to have a far greater impact during times of peak cold when an order of magnitude more dust was being transported through the atmosphere. As shown here, dust makes its biggest impact on the planet's albedo when blown out over the non-reflective ocean.

glacial period (see Figure 35), Rahmstorf noted that the abrupt warmings (including that which brought the YD to an end) fell uncannily close to time marks spaced at 1470 years (i.e, the mean duration of Bond's red-grain cycles). Following Bond's proposal, that the 1500-year cycle observed in North Atlantic deep-sea sediments is paced by the Sun, Rahmstorf proposed that so also were the Dansgaard-Oeschger events (see Figure 36). As 'hits' occurred at only half of the time marks, Rahmstorf was forced to conclude that only during certain time intervals was the climate system poised to respond to a solar nudge. If Rahmstorf's idea proves to be correct, then in its glacial condition, the Earth's climate system appears to have been far, far more responsive to small nudges than it has been during the last 12,000 years. As we don't yet even understand how the tiny changes in solar irradiance caused temperature to swing back and forth by 1°C during the present interglacial, explaining the much larger jumps of glacial time will prove to be a very tough nut to crack.

The trigger for abrupt climate change: shutdowns of the ocean's conveyor circulation

Although our understanding of how the climate system accomplishes its jumps from one mode of operation to another is far from complete, the scenarios which receive the most attention are those which involve the ocean's large-scale circulation system. The deep sea is filled with cold water. The reason is that as sea water cools, it becomes ever more dense. Thus, for the same reason that oil floats on water, warm water floats on cold water. This situation is, however, hardly static, for the water in the deep sea is being steadily heated by the downward mixing of the overlying warm water and also by the upward diffusion of heat through the sea floor. As the deep waters warm, they become less dense allowing surface waters of higher density to sink to the abyss and underride the deep water column. In today's ocean, this renewal process goes on at a rate such that the waters in the deep sea are replaced about once each 800 years. In other words, the amount of new deep water sinking to the abyss in 800 years is enough to fill the deep sea.

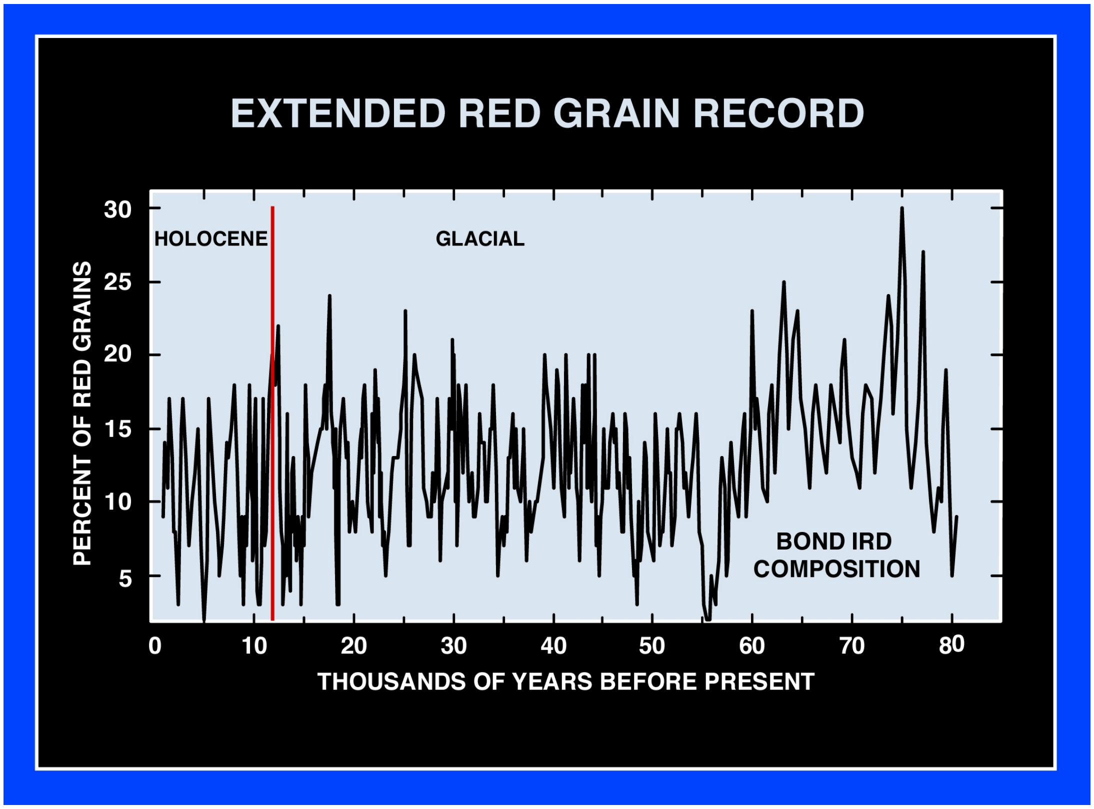


Figure 35. When Gerard Bond extended his red-grain record back beyond the Holocene (i.e., the present interglacial) into the last glacial period, he was amazed to find that the quasi 1500-year swing back and forth between times when iron-stained grains constituted more than 15 percent of the ice-rafted grains and times when they constituted less than 10 percent continued despite the much larger flux of ice-rafting material during glacial time. As shown in Figure 36, this observation gave rise to the suggestion by Stefan Rahmstorf that small changes in solar output paced the very large climate changes associated with the D-O events.

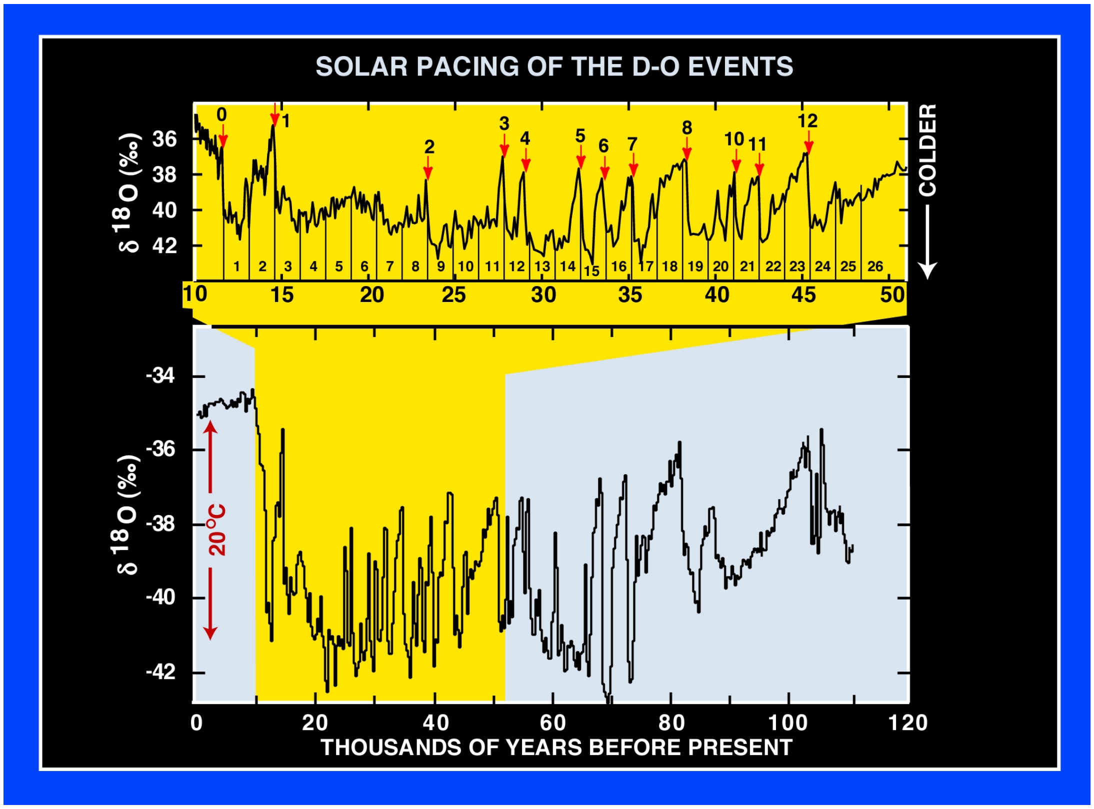


Figure 36. Stefan Rahmstorf pointed out an intriguing coincidence between the timing of the abrupt warmings which mark the onset of each D-O event (and also the end of the Younger Dryas). Starting with the end of the YD, he made 26 time marks spaced at intervals of 1470 years (i.e., the average durations of Bond's red-grain cycles). He noted that each of the 12 abrupt warmings which occurred during this 35,000-year interval fell close to one of these time marks. Based on this coincidence, he postulated that the small variations in solar irradiance were somehow capable of triggering jumps from one climate system state to another. In order to explain why only about half of the solar pulses succeeded in initiating a jump, he postulated that this is only possible when the system is close to its limit of stability.

This situation is made more complicated (but more interesting) by variations in dissolved salt. On average, each liter of sea water contains 35 grams of dissolved salts (mainly sodium chloride). However, the sea's salt is not uniformly distributed. Of interest to us is the fact that the greater its salt content, the more dense the water is. Polar surface waters turn out to be somewhat less salty than tropical surface waters and surface waters in the Atlantic Ocean are saltier than their counterparts in the Pacific Ocean. So important is salt to the densification of sea water that new deep water forms only in those high latitude (i.e., cold) regions where the salt content is the highest. In today's ocean, two such places exist: one in the northern Atlantic and the other along the margin of the Antarctic continent. The deep Pacific and Indian Oceans are currently filled with a 50-50 mixture of waters produced in these two source regions. The deep Atlantic is dominated by water sinking in the northern Atlantic.

Of great importance to the scenario that the trigger for abrupt change resides in the ocean is the fact that although water can be transported as vapor through the atmosphere from one part of the ocean to another, salt moves only through the sea. In those regions of the ocean where the gain of fresh water by precipitation and river runoff exceeds the loss by evaporation, the salt content is diluted. For the ocean to be at steady state, this ongoing dilution must be balanced by a continuing replacement of these fresher waters by saltier counterparts from elsewhere in the ocean. In other words, water vapor transport through the atmosphere must be compensated by the transport of salt within the sea.

Of primary interest is the Atlantic Ocean's conveyor-like circulation (see Figure 37). Surface waters made more salty by evaporation flow northward to the vicinity of Iceland where they are cooled by the frigid winter winds coming off Canada and Greenland. Already salty, these waters are cooled to the point where they become sufficiently dense to sink to the abyss. Once at depth, they move southward through the deep Atlantic and eventually pass eastward around the tip of Africa where they join the

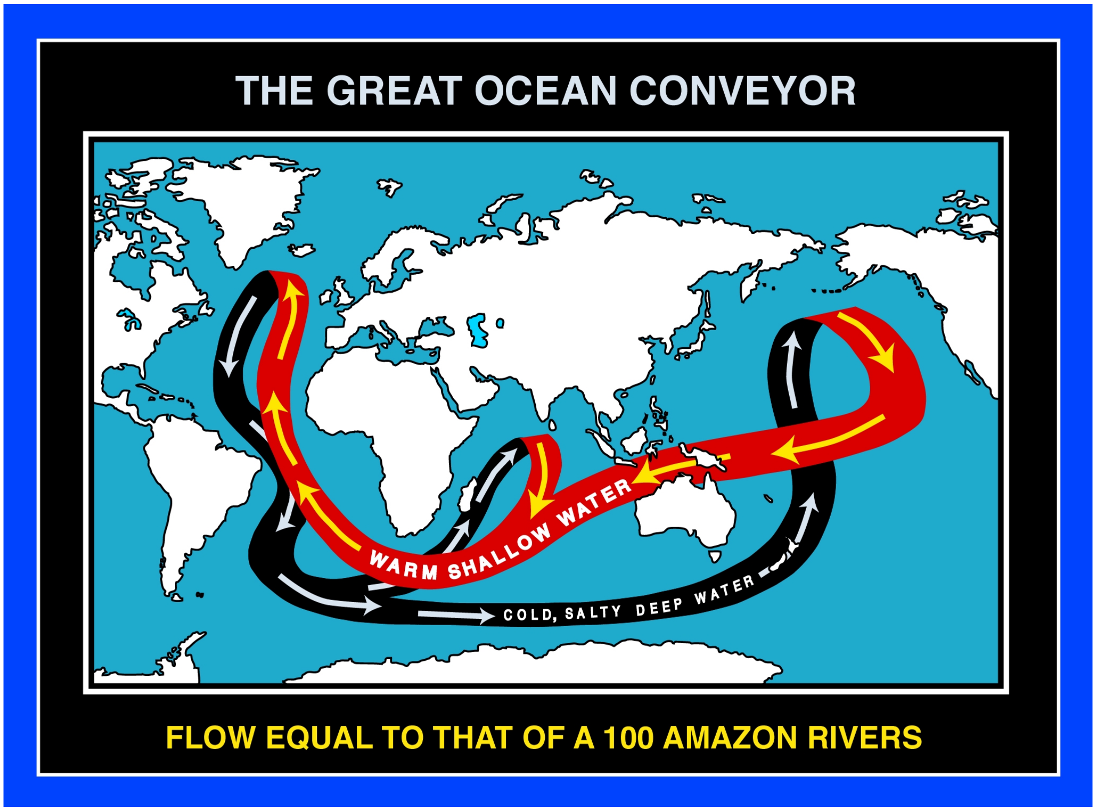


Figure 37. The ocean's largest scale circulation unit, the Great Conveyor, is driven by the production of deep water in the northern Atlantic. Cooling in the vicinity of Iceland by the winter winds flowing off frigid northern Canada, densifies the already extra salty Atlantic surface waters to the point where they sink to the abyss. These newly formed deep waters flow to the south until they reach the tip of Africa at which point, they turn left and join the strong circum Antarctic current. This current is also fed by a roughly equal amount of new deep water which sinks along the margins of Antarctica. Portions of this mixture 'ventilate' the deep Indian and Pacific Oceans where they eventually upwell to the surface and begin the return trip. The amount of water carried by the Atlantic's Conveyor (15 million cubic meters per second) is equal to the flow of 100 Amazon Rivers. It also matches all the world's rainfall!

rapidly circulating circum-Antarctic current. Here they blend with deep waters formed along the margin of the Antarctic continent. A portion of this blend peels off and floods the deep Indian Ocean. Another portion peels off and floods the deep Pacific Ocean. As the waters of the lower limb of the Atlantic's conveyor are a bit more salty than those with which they blend, they carry with them the excess salt left behind in the Atlantic as the result of the transport of water vapor from the Atlantic Ocean to the Pacific Ocean.

One might ask why there is a net transport of water vapor from the Atlantic to the Pacific. The reason has to do with the position of the great mountain belts and the direction of the planetary winds (see Figure 38). At temperate latitudes west winds dominate. After passing across the Pacific Ocean they encounter the so-called American Cordillera, a chain of high mountains which extends from Alaska all the way to Patagonia. As it passes up and over this topographic barrier, the air is cooled. The cooling causes water vapor to condense. The resulting precipitation falls on the western slopes of the cordillera and is carried by rivers back to the Pacific. As no similar topographic barrier exists in Eur-Asia or Africa, water vapor picked up over the Atlantic Ocean by the westerlies is not recaptured to the same extent as that picked up over the Pacific.

In the tropics, the trade winds flow from east to west compensating for the west to east transport of air in temperate latitudes. Although the trade winds also encounter the American Cordillera, the result is not the same as for the westerlies. The reason is that in Panama and other parts of Central America the mountains are not very high, allowing vapor evaporated from the Atlantic to escape and fall as rain in the Pacific.

The result is that there is a net transport of water vapor from the Atlantic Ocean to the Pacific Ocean. The magnitude of this net loss of water from the Atlantic is such that if not compensated by salt export, over a period of one thousand years the salt content of the Atlantic would rise by about one gram per liter. Of course, export of salt from the Atlantic does occur, balancing the loss of water vapor. As already stated, today this export is primarily via the lower limb of the Great Ocean Conveyor.

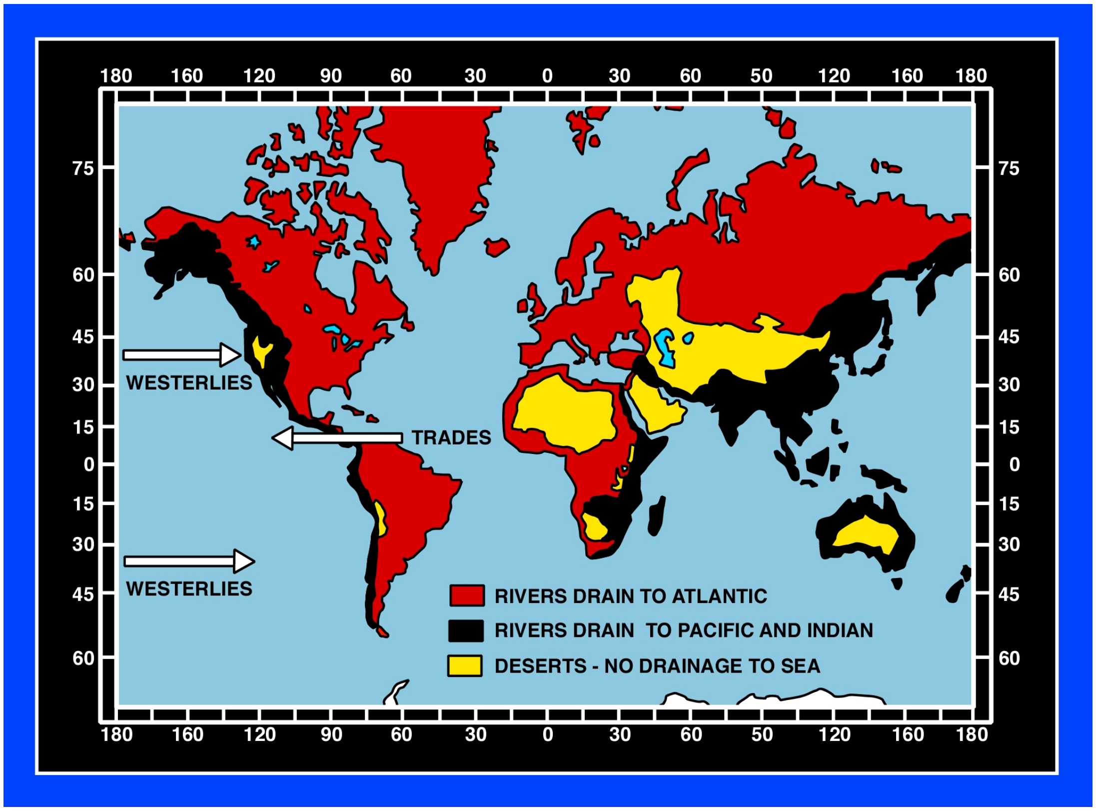


Figure 38. The Atlantic's waters are maintained at a slightly higher salt content than waters elsewhere in the ocean by the transport of water vapor through the atmosphere. Water evaporating from the Atlantic is transported by the westerlies across Eurasia and Africa to the Pacific and Indian Oceans. Similarly, the easterlies (i.e., trade winds) carry water vapor across Panama. Because of the configurations of the world's mountain ranges, these exports of water vapor are not matched by imports. The high mountains of the American cordillera sap the westerlies entering the Americas of this vapor burden and channel the resulting rain water back into the Pacific. Similarly, the equatorial mountains in Africa block the return flow of the moisture via the easterlies. In order to maintain a steady state in the ocean's salt distribution, today the buildup of salt in the Atlantic resulting from vapor export is balanced by an export of salt via the Conveyor's lower limb.

If for some reason the balance between the export of water vapor and the export of salt were to be disrupted, then in order to compensate, the ocean's circulation system would be forced to reorganize. Indeed, as we shall see, a number of such disruptions appear to have occurred during the last glacial period.

The great Agassiz Flood triggers conveyor shutdown

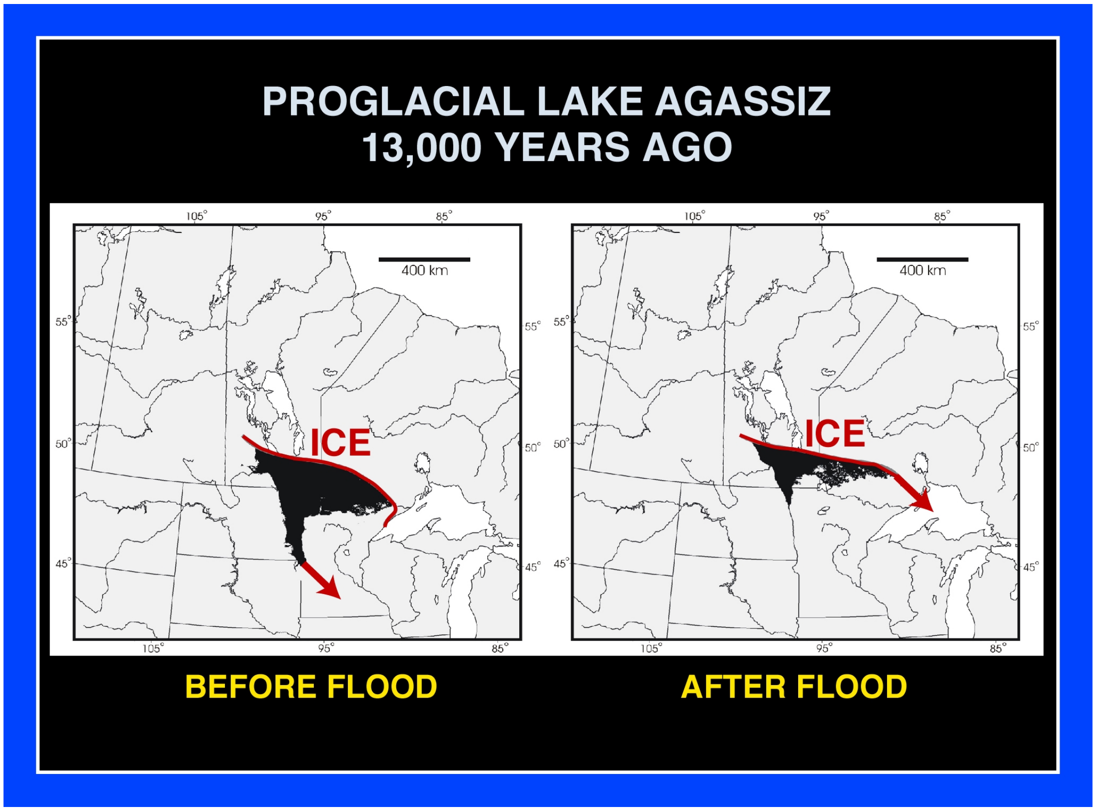
The transition from the cold and chaotic climate of glacial time to the warm and stable climate of the last 12,000 years was punctuated by a millennium-duration cold relapse which was given the name Younger Dryas (YD) by Scandinavian paleobotanists. They chose this name because sediments formed at low elevation during YD time contain the remains of a flower (the Dryas, see Figure 39) which today flourishes only high in the mountains. Its presence at low elevation heralded the return of colder conditions.

A reasonably strong case can be made that the YD was triggered by a shutdown of the Great Ocean Conveyor which had snapped back into action 15,000 years ago at the close of glacial time. Further, a prime suspect responsible for triggering of this shutdown has been identified. At the time of the sudden onset of the YD, 10,000 cubic kilometers of water stored in a lake, which had formed in front of the retreating North American ice sheet, was suddenly released. Now extinct, Lake Agassiz (see Figure 40) occupied a depression produced by the weight of the two kilometer-thick ice cap.

The margin of the retreating ice sheet formed the northern and eastern shorelines of this lake. Prior to the YD, the lake spilled to the south over a rock lip into the Mississippi River drainage. Then one day, the lake broke through the ice which formed its eastern shoreline and deluged through the Great Lakes region and St. Lawrence River valley into the northern Atlantic where it diluted the surface water salt content and thereby shut down the conveyor.

The immediate impact was a shutdown of the vast amount of heat carried to the northern Atlantic by the upper limb of the Atlantic's conveyor. Although this provides a seemingly straight forward explanation for the pronounced YD cooling of Greenland and

Figure 39. The name Younger Dryas given to the 1200-year-duration cold snap which punctuated the transition to the present interglacial was assigned in recognition of the first evidence for its existence. During the 19th century, Scandinavian paleo-botanists found the remains of the Dryas flower in sediments formed at low elevation in Norwegian fjords. As today this flower grows only in high mountain locales, they realized that climate must have been far colder at the time when these sediments formed.



PROGLACIAL LAKE AGASSIZ
13,000 YEARS AGO

BEFORE FLOOD

AFTER FLOOD

Figure 40. As the great Laurentide ice sheet retreated at the close of glacial time, a large water body, now referred to as Lake Agassiz, formed adjacent to the ice front. It occupied a moat created by the weight of the two kilometer-thick mass of ice. Initially, the melt water entering this lake spilled over a rock lip at its southern end and joined the Mississippi River drainage into the Gulf of Mexico. Then one day a breach created by the retreat of the ice which formed the lake's eastern shoreline occurred. Through this breach, some 10,000 cubic kilometers of water catastrophically escaped passing through what is now the Great Lakes, and onward through the St. Lawrence lowlands into the northern Atlantic. The resulting dilution of the salt is thought to have brought the Conveyor to a halt and thereby initiating the Younger Dryas cold snap.

Scandinavia, paleoclimate records from ocean sediments, peat bogs and mountain moraines in far-flung places reveal that the YD had impacts far beyond what would be expected from the reduction in the supply of ocean heat to the northern Atlantic region (Figure 41). With one exception, in all of these places the change recreated conditions similar to those which characterized glacial time. An example is the accumulation of $CaCO_3$ dust on the Greenland ice cap (see Figure 42). About 15,000 years ago the deposition $CaCO_3$-bearing dust came to a precipitous halt, heralding the demise of the frequent intense Asian wind storms of glacial time. Then just as suddenly 13,000 years ago at the onset of the YD, the dust storms resumed. It was not until the abrupt end of the YD that the dust rain was once again shut down. It has not resumed. Another example is the YD expansion of the mountain glaciers of New Zealand's South Island (see Figure 43). The one exception is Antarctica where records from ice cores show that the YD was a time of rapid warming. This finding was music to the ears of the proponents of the ocean trigger hypothesis. The reason is that if the supply of dense water to the deep sea is cut off at one place, it must soon be compensated by a supply from another place. We suspect that this alternate source was the margin of the Antarctic continent. A greater rate of deep water production in this region would supply extra ocean warmth and hence explain why, during the YD, climate shift on the Antarctic continent was opposite to that for the rest of the world.

What is not understood is how a reorganization in ocean circulation could impact the climate of the entire planet. Even harder to understand is how it could do so on the time scale of just a few decades. Yet it happened. The take home message is that the Earth's climate system is not only highly responsive, but it also has built-in teleconnections which allow messages to be sent rapidly across the entire globe.

Heinrich's ice armadas as triggers for conveyor shutdown

In 1988, a young German scientist, Harmut Heinrich, reported that a study of a deep-sea core in the eastern North Atlantic Ocean revealed six layers made up ex-

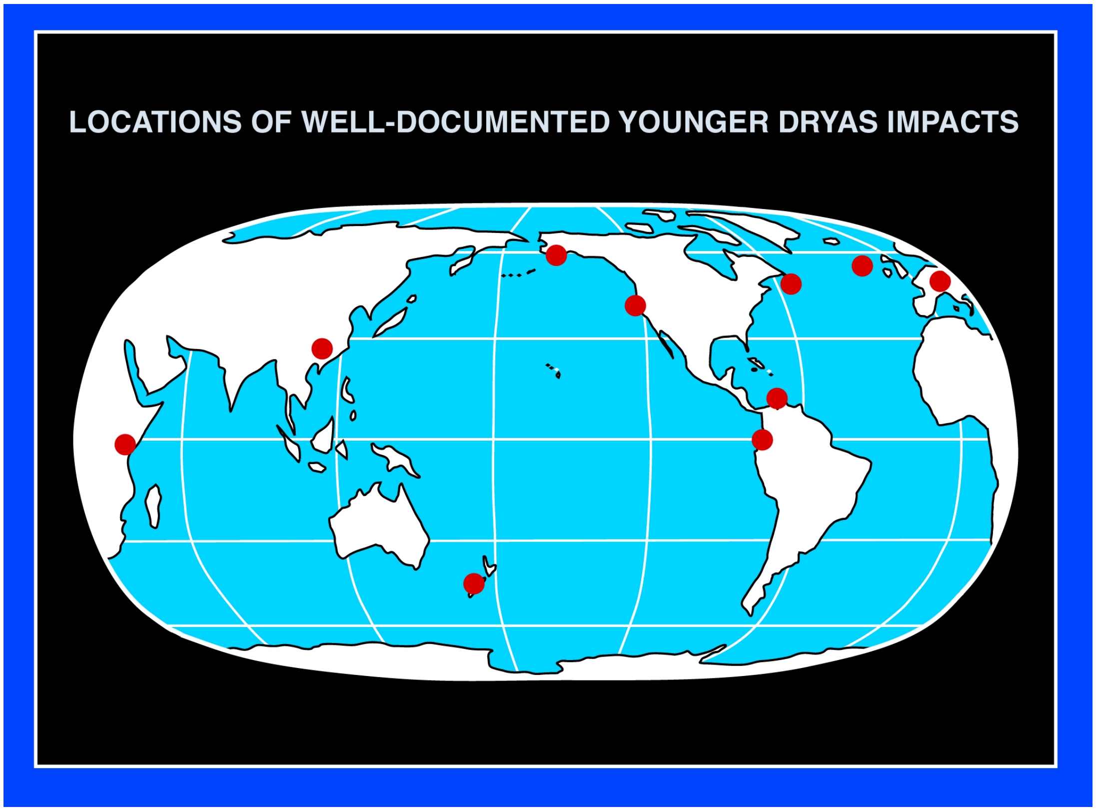


Figure 41. The original idea that the impacts of the Younger Dryas were restricted to regions which directly benefited from the heat released to the atmosphere over the northern Atlantic had to be abandoned when evidence for a synchronous return to glacial conditions was documented at places far removed. These include the Cariaco Basin off Venezuela, the high equatorial Andes, the Santa Barbara Basin, Alaskan peat bogs, Hulu Cave in China, and the closed basin lakes in east Africa. While an advance of mountain glaciers on the South Island of New Zealand has also been documented, the radiocarbon dates hold open the possibility that its onset predated that of the Younger Dryas by several hundred years. In any case, the YD impacts equally strong as those in the northern Atlantic basin occurred across much of the planet.

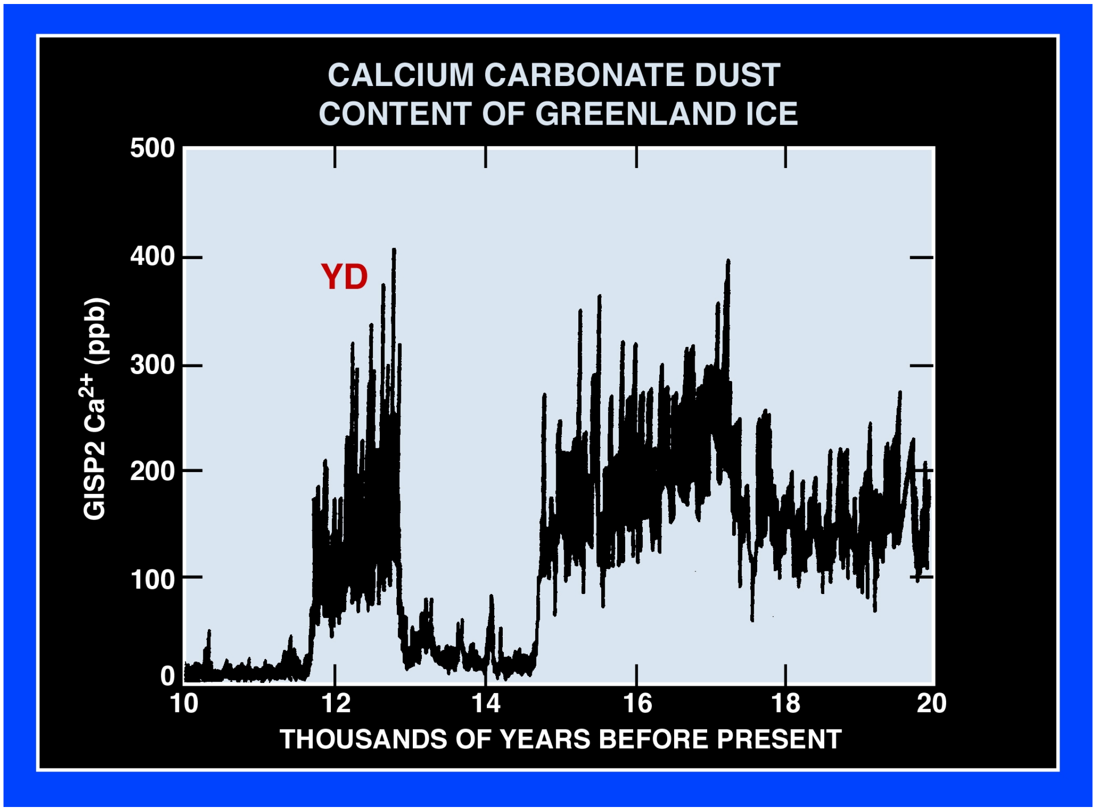


Figure 42. Not only did Greenland's air temperature plummet to near glacial levels during the Younger Dryas but also the deposition of dust jumped back to its high glacial level. Using isotopic fingerprints, Pierre Biscaye has documented that this dust originated in Asia's deserts. Hence, the suggestion is that the frequent intense storms which plagued glacial time returned with a vengeance! The likely driver of these storms was the intensified latitudinal temperature gradient created by the expansion of sea ice and land snow cover in the northern part of the planet.

Figure 43. A beautifully formed arcuate moraine bulldozed into place by an advance of Franz Josef Glacier down the steep west side of New Zealand's Alps. Although broadly synchronous with the Northern Hemisphere's Younger Dryas, the radiocarbon dates on a large number of wood samples span from 500 years before to 300 years after the onset of the YD in the north. Whether this reflects pre-aging of the wood in up-valley avalanche deposits or an earlier Southern Hemisphere onset remains uncertain.

clusively of debris dropped from melting icebergs. Punctuating the record for the last period of glaciation, these layers were spaced at intervals of about 8 thousand years. Heinrich envisioned that this debris was dropped as huge armadas of icebergs launched from eastern Canada melted. Subsequent studies verified Heinrich's discovery by showing that these layers formed a swath extending from Canada's Hudson Bay all the way across the Atlantic to the British Isles (see Figure 44). Apparently during the 8000-year periods separating these layers, the ice over Hudson Bay steadily thickened until earth heat diffusing up from beneath caused its base to melt. This lubrication triggered a massive surge of ice out into the Atlantic Ocean. Heinrich's (H) ice armadas gradually melted as they drifted across the Atlantic with the prevailing currents. The dilution of salt created by this melt water appears to have squelched the production of deep water in the northern Atlantic. Again, for reasons not yet understood, the consequences of these shutdowns were felt across much of the globe. Southern France experienced its coldest temperatures. The monsoon rainfall in China was greatly reduced. The dry lands of eastern Brazil and of central Florida were deluged with precipitation. In other words, enraged by the impact of these armadas, the angry climate beast struck back.

Geographic distribution of climate impacts

We have already seen that, with one exception, the YD cold snap appears to have caused a relapse toward glacial-like conditions everywhere on the globe. The exception is the Antarctic continent where the climate warmed. Although the number of sites where D-O and H impacts have been identified is much smaller than for the YD, enough is known to say that the pattern and/or intensity of the impacts of D-O events differed from that of the H events (see Figure 45).

H impacts are not seen in the Greenland records of air temperature, nor in those of soil dust and sea salt, nor in that of methane. In contrast, D-O events are not seen in the records from eastern Brazil or central Florida (see Figure 46). In these two places, the times of H events stand out as episodes of intense rainfall. In records from the ocean

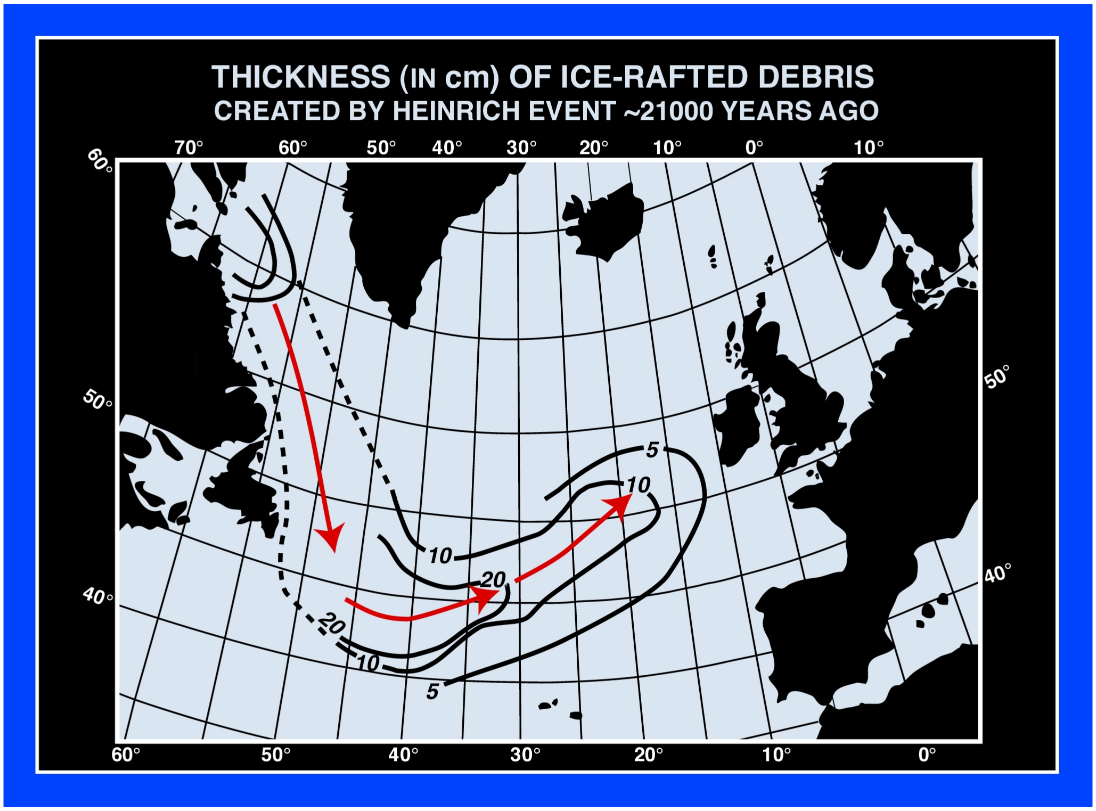


Figure 44. Six times during the course of the last glacial period large armadas of glacial ice spewed forth from Canada into the northern Atlantic. As the icebergs drifted eastward across the Atlantic, they melted and dropped their loads of mineral debris to the sea floor. The layers produced in this way have been identified and dated in many sediment cores. The fact that the layers thin to the east is consistent with a Canadian source. Isotopic fingerprinting of the debris suggests that four of the six armadas issued forth from Hudson Straits. Although a number of scenarios have been proposed which might account for these outbursts, the favored one is Doug MacAyeal's binge-purge hypothesis. His idea is that as the ice cap thickens over Hudson Bay, its base is heated from below by earth heat. Eventually the base of the ice melts lubricating the bed allowing the ice to slide through Hudson Straits out to sea.

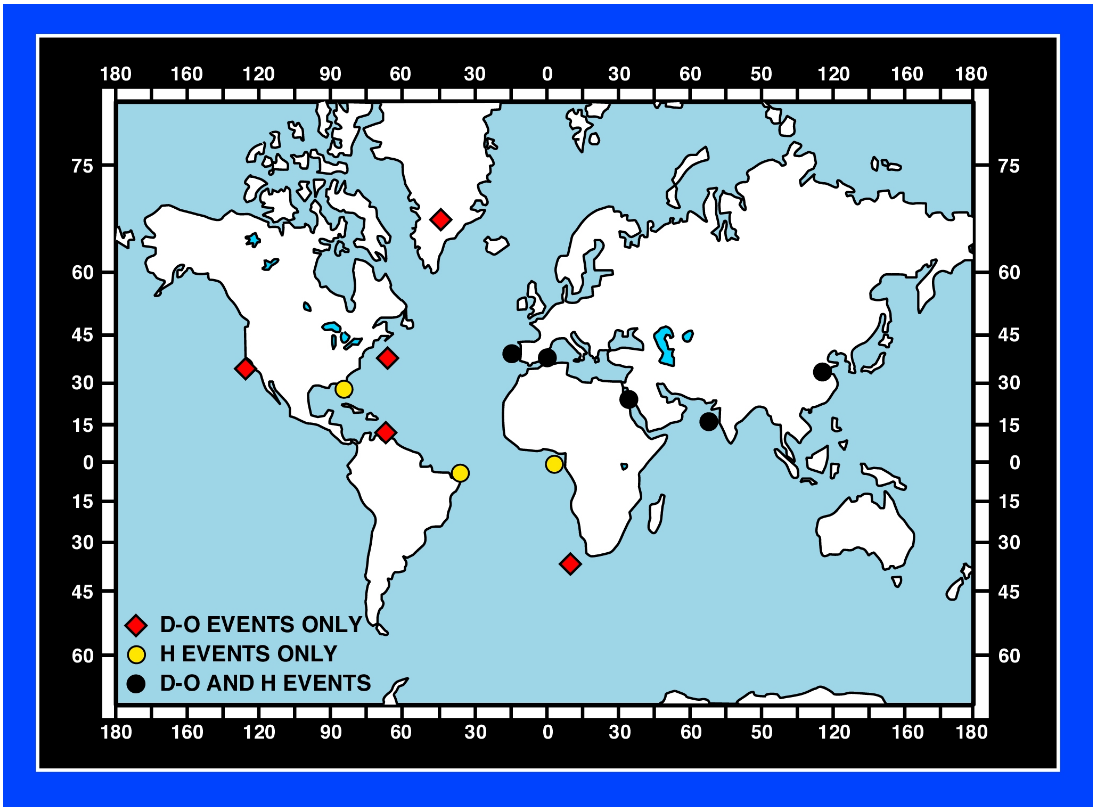


Figure 45. As are those of the Younger Dryas (YD) cold snap, the climatic impacts of the Heinrich (H) events and Dansgaard-Oeschger (D-O) events are widespread. Often both are distinguishable in the same record. Puzzling, however, is that in some records only the D-O impacts are seen and in others only H impacts. Examples of these three types of record are shown in Figure 46. It is interesting to note that YD impacts appear to be present in all the records.

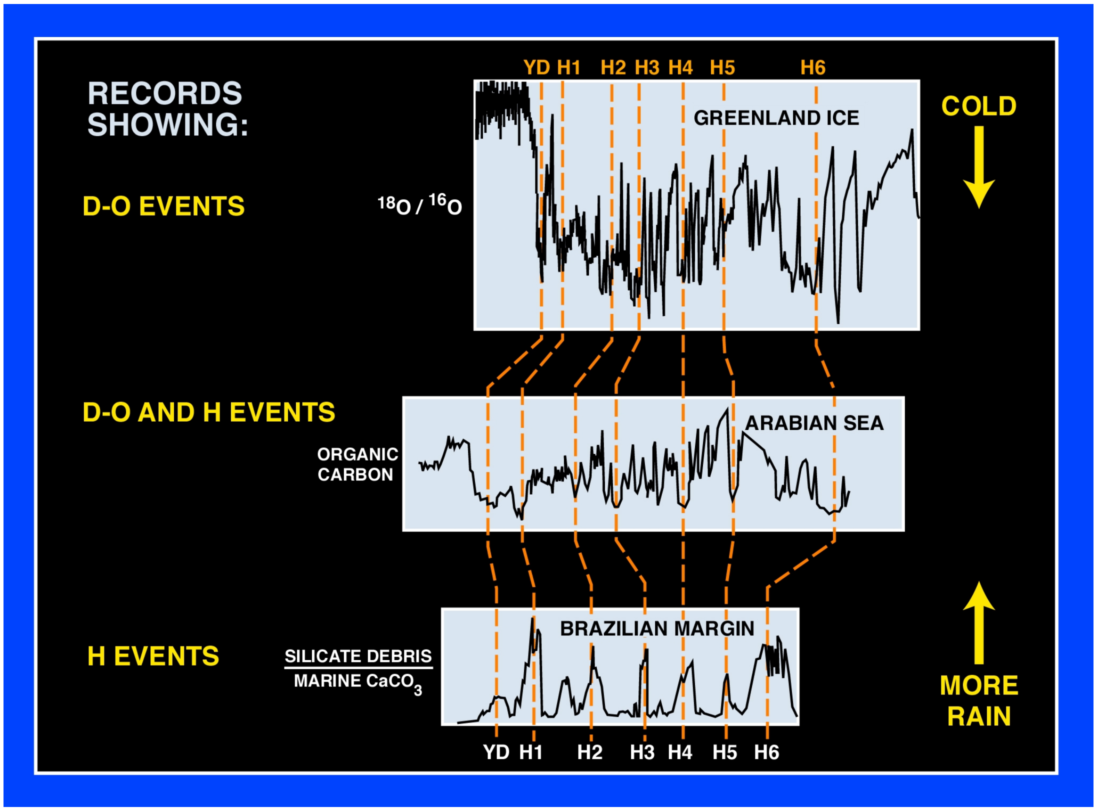


Figure 46. An example of a record dominated by D-O impacts (top), a record showing both D-O and H impacts (middle) and a record showing only H impacts (bottom). By comparing northern Atlantic deep-sea sediment records which depict D-O impacts and contain H debris layers, Gerard Bond has been able to place the times of the H events in the ice core ^{18}O record.

off the Iberian Peninsula and from southern China, both D-O and H impacts are seen. But in both places, the H impacts are stronger than the D-O impacts. For the Iberian Peninsula the times of coldest temperature correspond to H events. Both D-O and H events are prominently displayed in the record for a stalagmite from Hulu Cave in China. As is the case for Greenland ice, annual layers can be readily identified (see Figure 47). In addition, the calcite which makes up the stalagmite can be very precisely dated by measuring the ratio of ^{230}Th to ^{234}U.[3] The strength of the monsoon rains is recorded by the ratio of ^{18}O to ^{16}O in the calcite. Clearly, these geographic patterns hold clues crucial to deciphering the mysteries surrounding the abrupt climate changes which punctuated glacial time.

Implications to CO_2 warming

While the record for glacial time sends us a very clear message that our climate system can be likened to an angry beast, it also raises many questions. For example, does the absence of climate jumps during the last 12,000 years mean that the system misbehaves only during cold and icy times? If so, then one might conclude that by warming the Earth with man-made greenhouse gases, we could fortify this stability. But the last interglacial sends us a message that we shouldn't bank on this. It was also a period of climate stability. But it came to an abrupt end. Hence, as happened in previous warm and stable periods of interglaciation, the current one is destined to come to an end whether by natural causes or by a nudge from fossil fuel CO_2. In the absence of floods from large amounts of fresh water released from ice-dammed lakes or put in place by the melting of huge armadas of icebergs, is there an alternate way to trigger an abrupt change? Perhaps. Computer simulations suggest that on a warmer planet, it would rain

---

[3] ^{234}U is radioactive and decays to produce ^{230}Th. Because the element uranium is water soluble whereas the element thorium is water insoluble, cave waters are highly depleted in thorium relative to the uranium. Hence, cave deposits are much like hourglasses. When they form, all the sand (^{234}U) is in the upper half of the glass. With time, the lower half gradually fills with sand (^{230}Th). The ratio of ^{230}Th to ^{234}U constitutes a very precise clock (see Sidebar #3).

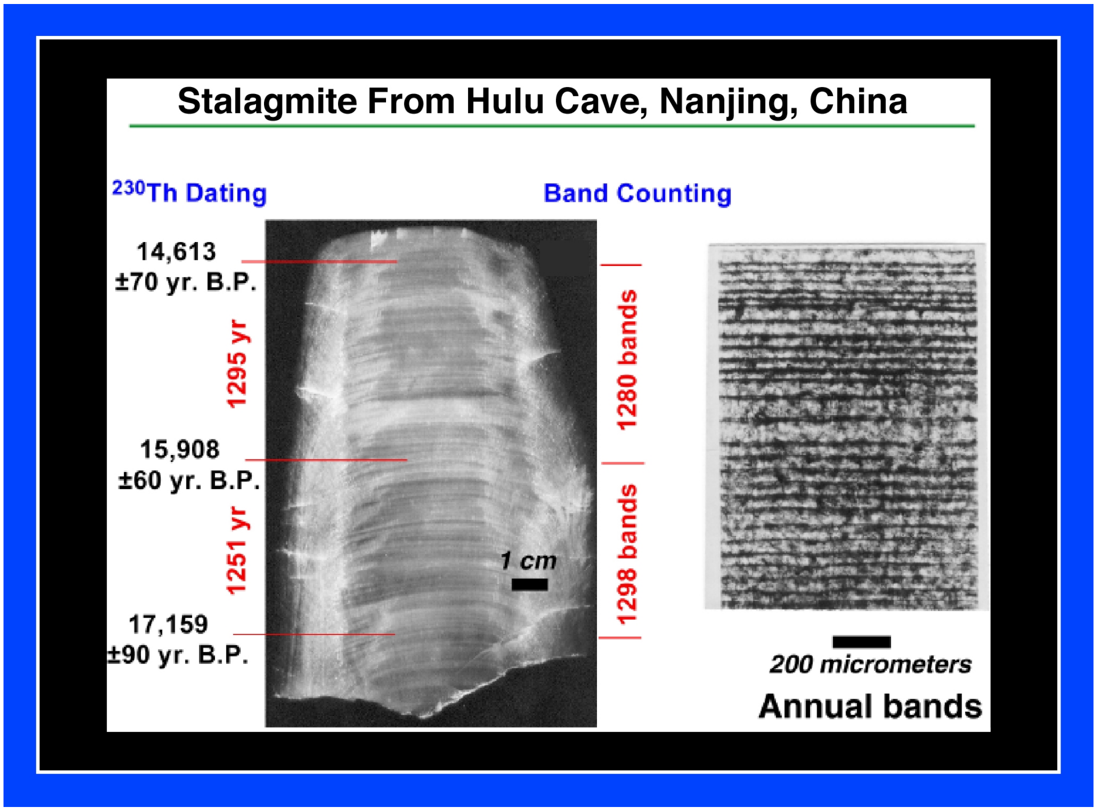
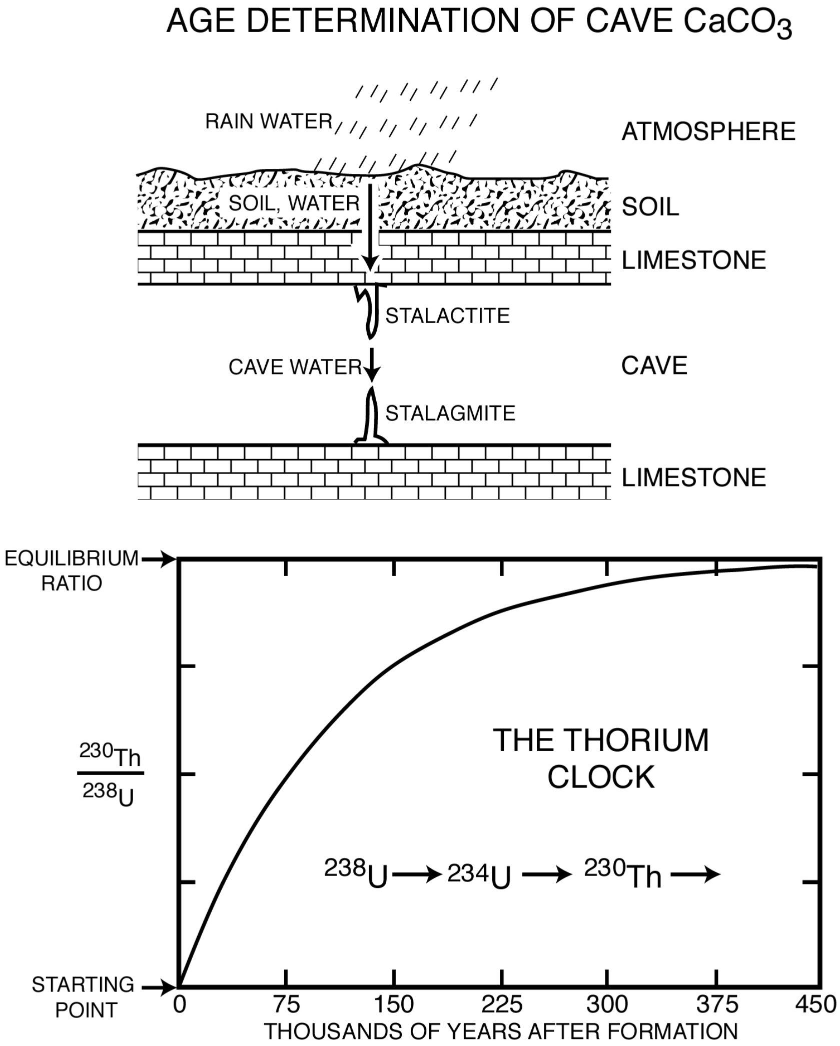


Figure 47. A major breakthrough came when it was shown that cave deposits could be precisely dated by using the isotopic ratio of ^{230}Th to ^{238}U and that the ^{18}O record in the cave calcite appears to be related to the strength of the monsoons. This discovery will allow records from many localities on the continents to be added to those from marine sediments and glacial ice. As an added bonus, the calcite in stalagmites is often annually layered. As a test of the reliability of ^{230}Th dating and of the reliability of annual layering, Larry Edwards compared age differences obtained by both methods on a stalagmite from Hulu Cave in China. As can be seen, the two independent estimates agree to within the ^{230}Th measurement error (i.e., to better than ± 100 years).



Sidebar #3. Age determinations of cave deposits based on the 75,000-year half-life isotope, ^{230}Th, are possible because of a major difference between the chemical reactivities of the elements uranium and thorium. The former is quite soluble and is leached from the overlying soils and incorporated into the cave calcite. The latter is immobile and remains behind in the soil. Thus, when formed, cave calcites are nearly devoid of ^{230}Th. With time ^{230}Th 'grows' back toward radioactive equilibrium with its parent uranium. Not shown here is ^{234}U, a daughter product of ^{238}U with a half-life of about 250,000 years. Because ^{234}U is 'loosened' from its mineral site in the soil by the recoil associated with its birth, it often is found in excess over ^{238}U in cave calcites. While making the math somewhat more complicated, the ^{234}U excess does not have any adverse impacts on ^{230}Th dating.

more and the extra precipitation reaching the northern Atlantic and its surrounding lands, would eventually cause a shutdown of conveyor circulation. But, even if this were to happen, would the consequences be as awesome as they were during glacial time? These are not questions we will soon be able to answer. So, it's as if we are blindfolded and walking toward a cliff. Unfortunately, we have only a vague idea how far away the cliff might be and we can't even be sure that it actually exists.

What should we do?

Even among those who have serious concerns about the possible consequences of global warming, there is no unanimity of opinion with regard to what should be done to stem the ongoing buildup of CO_2 (see Figure 48). To many, the Kyoto Accord was to be a healthy first step toward such a solution. The thrust of this international agreement is that the industrial nations would by 2015 cut their CO_2 emissions back to their 1990 levels. It was envisioned that this would be accomplished by a combination of more efficient use of energy and the substitution of non-fossil fuel energy sources (i.e., wind, nuclear, biomass…). As an inducement to nations reluctant to sign on, the accord was amended to give credit for carbon storage as biomass (more trees, more soil organics). Even with this amendment, the United States, Australia and Russia refused to sign on.

Although the Kyoto Accord constitutes a significant step toward limiting CO_2 emissions, it has some serious drawbacks. Clearly, the problem can't be solved by a series of Kyoto-like steps. For example, if conservation were the main thrust of these steps, this would mean moving toward zero energy use. Clearly, if all the Earth's inhabitants are to achieve an acceptable life style, energy use will have to substantially increase. If substitution of non-fossil fuel sources were to be the main thrust, it would very likely require a shift to nuclear power. In a world where terrorism has become a major political instrument, this would surely be a dangerous path.

Storage of carbon as biomass is appealing. However, when the space available for new forests and capacity of soils to store humus are quantified, it turns out that the

SO WHAT SHOULD WE DO ABOUT
FOSSIL FUEL CO_2?

IT SURELY CONSTITUTES A BIG NUDGE!

PLENTY OF COAL, OIL, NATURAL GAS

WOULD TAKE AT LEAST 60 YEARS
TO STOP CO_2 BUILDUP

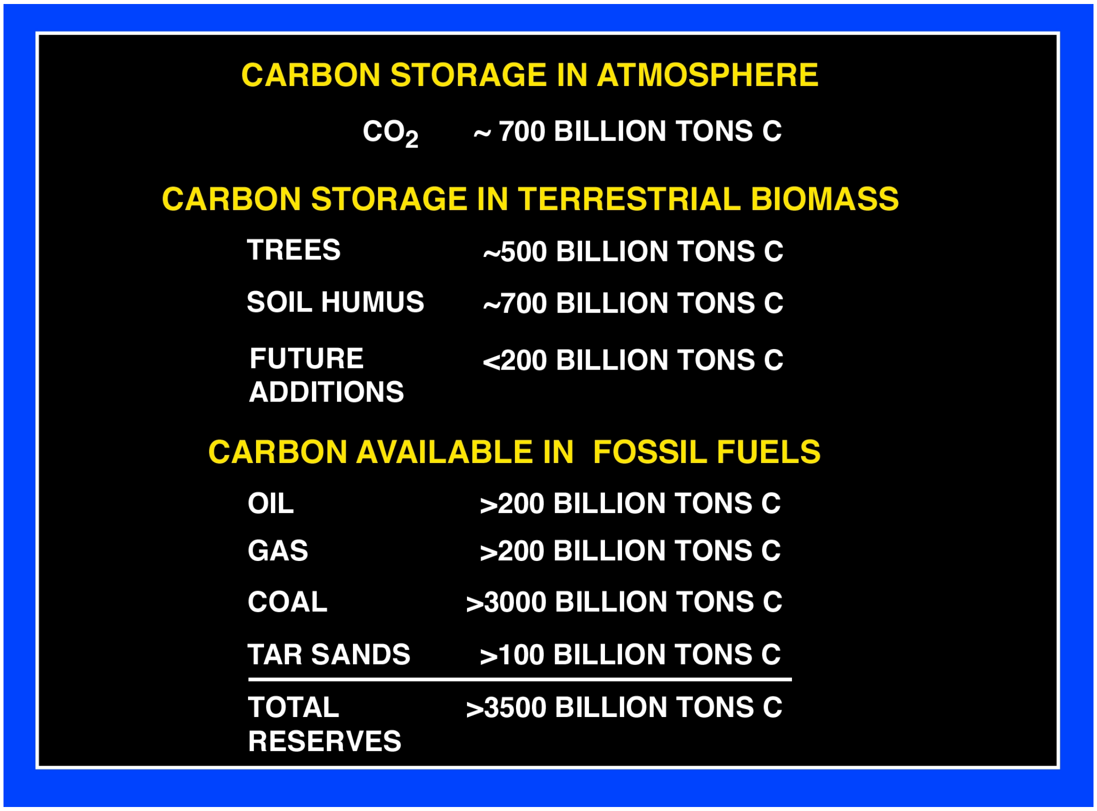
WE MUST HAVE A SAFETY NET!!

Figure 48. As fossil fuels are plentiful and cheap, the temptation will be to stick with them as the world's primary energy source. If we continue along this path for the entire century, we will surely give the climate system a large nudge. Hopefully, our political leaders will eventually wake up to the potential dangers associated with the ongoing CO_2 buildup and move toward stemming it. To do so will require many decades. Hence while we wait, a safety net should be created and readied for implementation.

optimistic upper limit for such storage is about 200 billion tons of carbon (see Figure 49). Business-as-usual projections suggest that if fossil fuels continue to dominate the energy market, we are likely to consume 1000 to 2000 billion tons of fossil carbon over the next 100 or so years (see Figure 50). Hence, storage in biomass is destined to play a minor role.

Taken together, two of the three components of the Kyoto Accord, i.e., energy conservation and biomass storage, are capable of only a modest reduction in the rate of buildup of CO_2 in our atmosphere. In order to prevent the CO_2 content of the atmosphere from reaching levels deemed undesirable, by the latter half of this century it will be necessary to entirely eliminate CO_2 emissions. This leaves only two options. Either we need to come up with an acceptable, safe and affordable alternate to fossil fuel energy or we must capture and store the CO_2 produced by fossil fuel burning.

Forty or so years ago, nuclear power appeared to be the panacea for energy production. This euphoria came to an end with Jane Fonda's performance in the movie "China Syndrome" which alerted the public to the dangers associated with nuclear reactors. Then three weeks after the opening of this film, the Three Mile Island disaster occurred. Finally, these fears were solidified by the explosion of Russia's Chernobyl reactor. The emergence of terror as an international weapon has added yet another dimension to the problem. Most sobering is the possibility that plutonium produced as a byproduct of power generation would be converted to nuclear weapons by terrorist groups or rogue nations. The situation is made even more complicated by the fact that like crude oil, fissionable ^{235}U is a limited resource. Only one uranium atom in 138 is fissionable ^{235}U (see Figure 51). The rest are non-fissionable ^{238}U atoms. If nuclear power is to become the mainstay of our energy supply, then a new type of facility called the breeder reactor will have to be substituted for conventional nuclear reactors. In a breeder, a fraction of the neutrons released during fission are used to convert either non-fissionable ^{238}U or ^{232}Th to fissionable form. Hence such a reactor breeds at least as



CARBON STORAGE IN ATMOSPHERE

CO_2	~ 700 BILLION TONS C

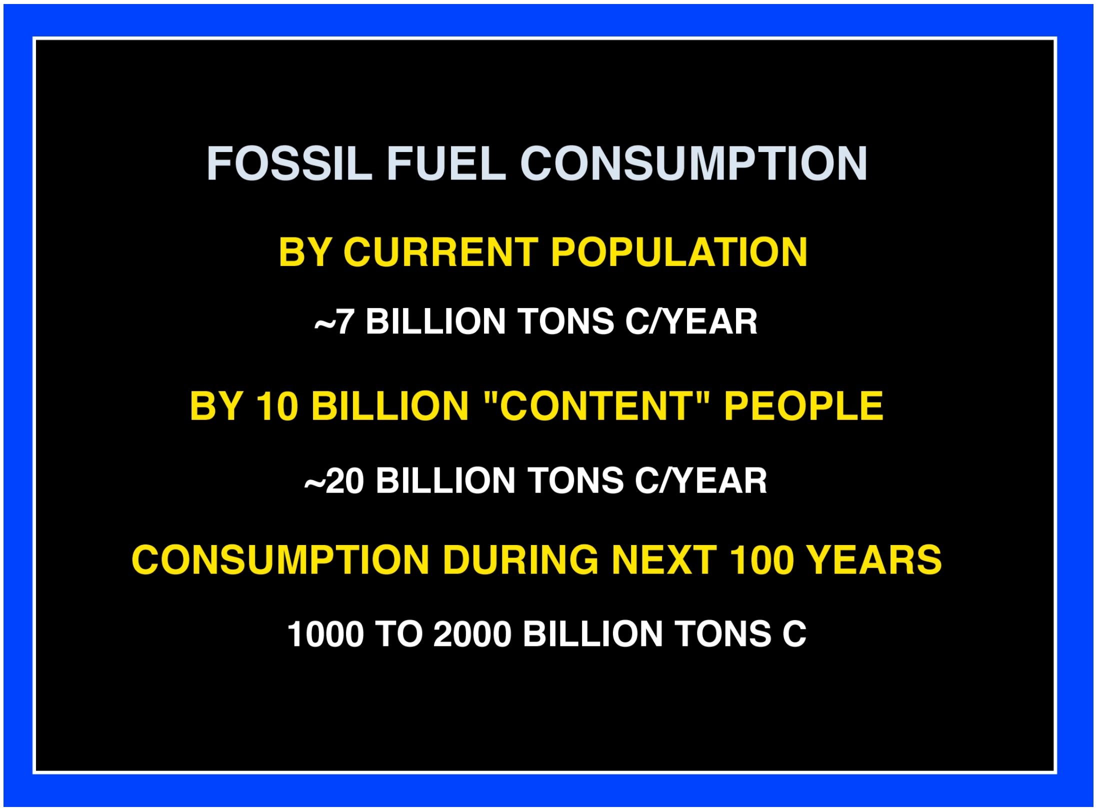
CARBON STORAGE IN TERRESTRIAL BIOMASS

TREES	~500 BILLION TONS C
SOIL HUMUS	~700 BILLION TONS C
FUTURE ADDITIONS	<200 BILLION TONS C

CARBON AVAILABLE IN FOSSIL FUELS

OIL	>200 BILLION TONS C
GAS	>200 BILLION TONS C
COAL	>3000 BILLION TONS C
TAR SANDS	>100 BILLION TONS C
TOTAL RESERVES	>3500 BILLION TONS C

Figure 49. One oft stated option for stemming the buildup of CO_2 in the atmosphere is to plant more trees and to engineer the buildup of humus in soil. However, a serious look at this option reveals that no matter how hard we try, it is unlikely that it could lead to storage of more than 200 billion tons of carbon. And indeed, depending on how deforestation in the tropics proceeds, it is possible that there will instead be a net decrease in the amount of terrestrial carbon. In any case, by comparison, the amount of fossil fuel carbon available for burning is staggering.



FOSSIL FUEL CONSUMPTION

BY CURRENT POPULATION

~7 BILLION TONS C/YEAR

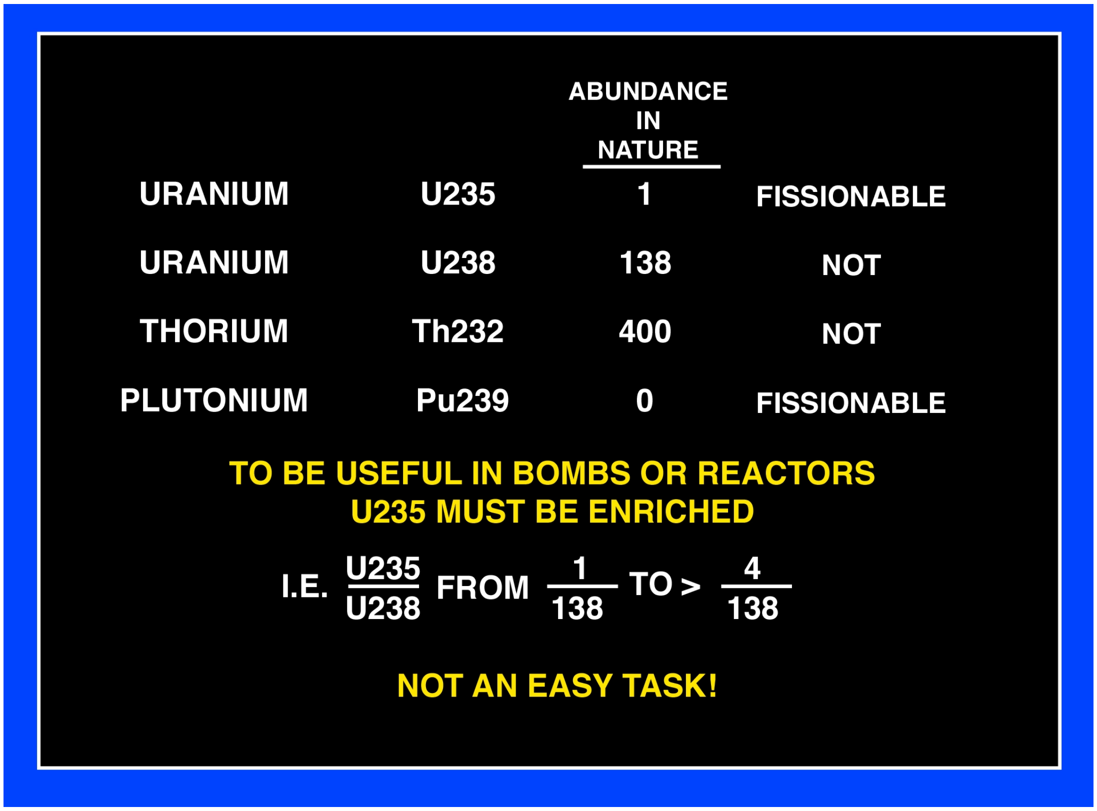
BY 10 BILLION "CONTENT" PEOPLE

~20 BILLION TONS C/YEAR

CONSUMPTION DURING NEXT 100 YEARS

1000 TO 2000 BILLION TONS C

Figure 50. As already discussed, if all the world's developing nations were to match the strides being achieved in China and India, it is well within the realm of possibility that the rate of fossil fuel consumption will rise from its current value of 7 billion tons of carbon per year to 20 billion tons of carbon per year. If so, then continued dependence on fossil fuels over the next century will result in the burning of 1000 to 2000 billion tons of carbon.



		ABUNDANCE IN NATURE	
URANIUM	U235	1	FISSIONABLE
URANIUM	U238	138	NOT
THORIUM	Th232	400	NOT
PLUTONIUM	Pu239	0	FISSIONABLE

TO BE USEFUL IN BOMBS OR REACTORS
U235 MUST BE ENRICHED

$$\text{I.E. } \frac{\text{U235}}{\text{U238}} \text{ FROM } \frac{1}{138} \text{ TO} > \frac{4}{138}$$

NOT AN EASY TASK!

Figure 51. Of the three naturally occurring long-lived isotopes of the elements uranium and thorium, only one, ^{235}U, fissions when struck by a neutron. Further, the concentration of ^{235}U in natural uranium is too dilute to be used either in bombs or in reactors. During World War II, the extremely difficult and expensive task of separating ^{235}U and ^{238}U was undertaken. Success in this enterprise opened two doors. The obvious one was to make an atomic bomb. But more important, the ^{235}U-enriched uranium could be used in reactors designed to 'breed' fissionable plutonium (an element not present in nature).

much nuclear fuel as it consumes (see Figure 52). As the supply of ^{238}U and ^{232}Th is 500 times larger than that of ^{235}U , such reactors could power the world for many centuries. However, the plutonium produced in breeder reactors could equally well be used to make atomic bombs. Finally, no breeder reactor for conventional electrical power generation has yet been brought on line.

Renewable energy sources certainly have allure. Solar panels, windmills, hydroelectric dams, geothermal heat, and biomass burning are viable substitutes for fossil fuels. However, each has serious limitations which make unlikely its adoption as the primary successor to fossil fuels. Electricity produced from solar cells remains far too expensive. Further, as electricity cannot be stored, solar power would have to be coupled with some means to take over during night hours and periods of heavy cloud cover. Windmills are currently economically competitive. However, were they to dominate the global energy market, they would sap 10 percent or so of the energy from the planetary wind system and thereby likely create major climate changes as well. And, of course, there would have to be tens of millions of windmills. Ugh! Hydroelectric power is severely limited by the availability of suitable sites. Further, environmentalists are strongly opposed to additional construction of large dams and are even seeking to remove some of those already built. More worrisome is the fact that the reservoirs behind great dams like Aswan in Egypt, Tarbela in Pakistan and Three Gorges in China will eventually fill with silt rendering them inoperative. Despite extensive efforts, use of geothermal heat remains extremely limited. Biomass burning is a tantalizing option. Corn is already being used to produce an ethanol replacement for gasoline. Unfortunately there is not enough arable land available to both grow crops for human food as well as for industrial energy.

The hydrogen economy

More and more we encounter references to the so-called hydrogen economy. The idea behind all of this hype is that hydrogen could become a substitute for fossil fuels. It

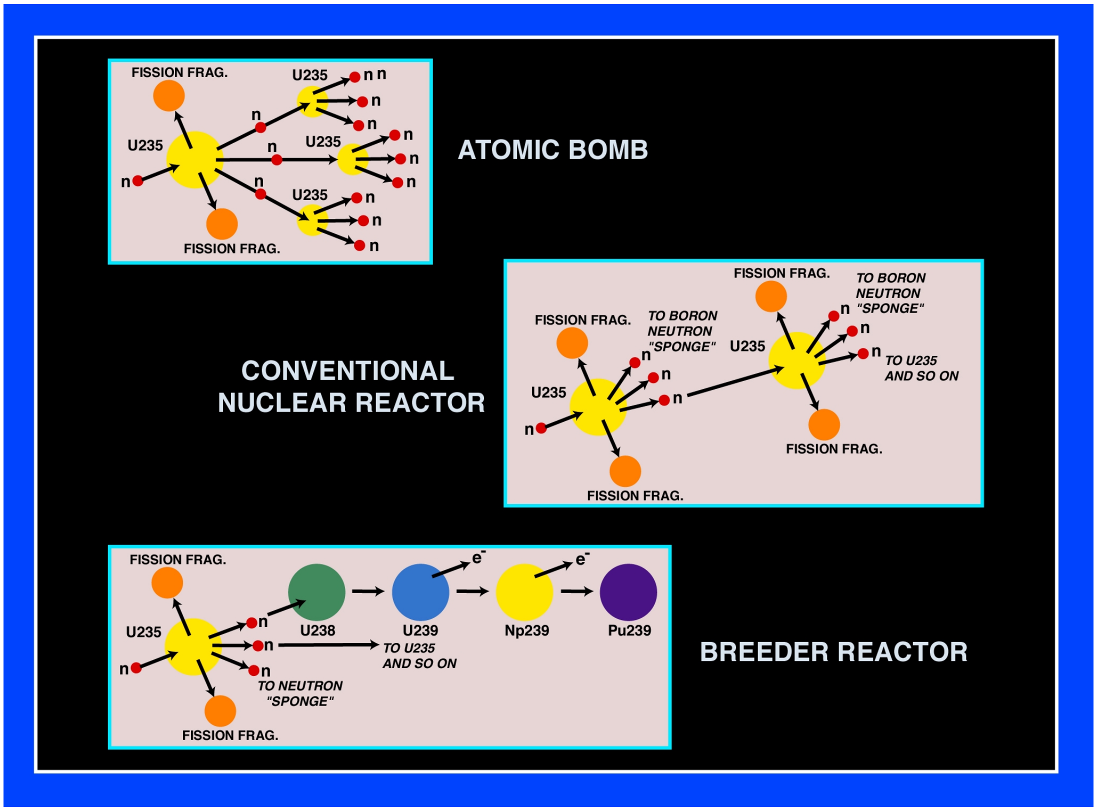
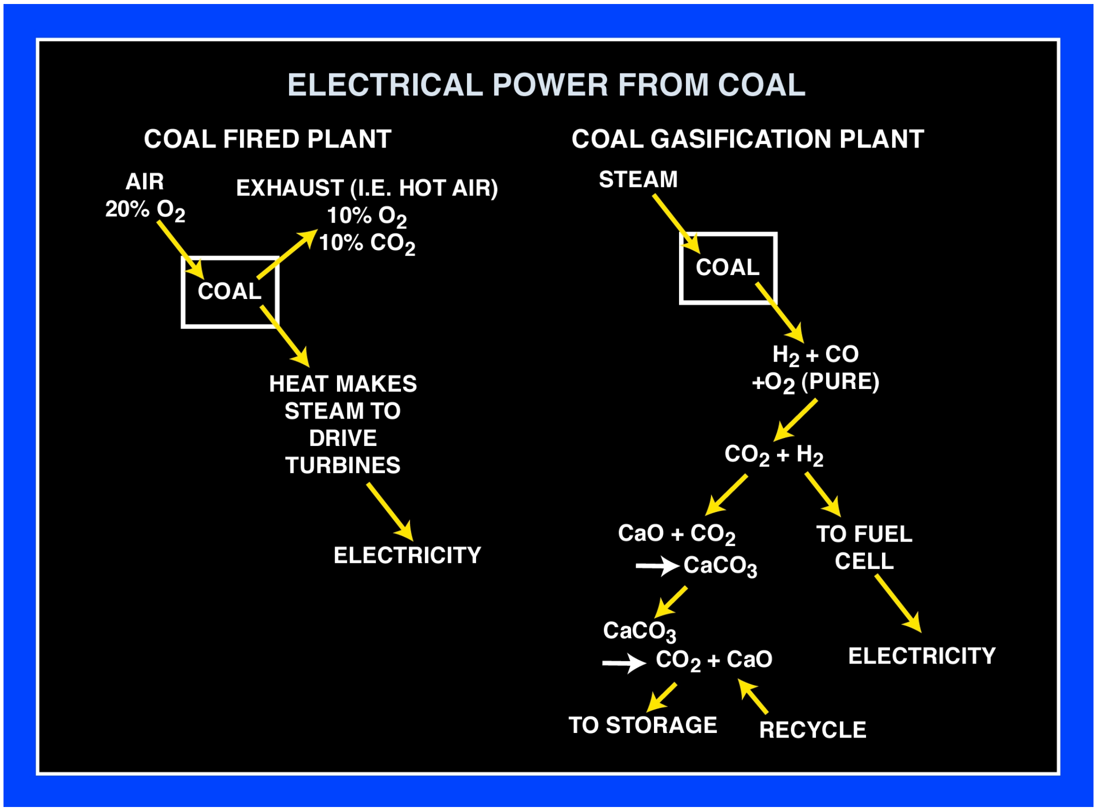


Figure 52. There are three quite different ways in which ^{235}U fission can be used. Each depends on the fate of the roughly three neutrons released when fission occurs. In an atomic bomb, ideally all three neutrons go into fissioning other ^{235}U nuclei. In conventional nuclear power stations, only one goes into fission; the other two are absorbed into the nuclei of boron atoms contained in the reactor's control rods. In a breeder reactor, one neutron perpetrates the fission chain; one is sponged up into the control rods and one goes into a ^{238}U nucleus converting it to the short-lived radioactive ^{239}U. This isotope shoots out an electron thereby converting itself to a short-lived isotope of the element neptunium. This isotope promptly shoots out an electron, thereby converting itself to a long-lived radioisotope of the element plutonium. As ^{239}Pu is fissionable, this type of reactor creates as much nuclear fuel as it consumes.

would be used in fuel cells to produce electricity and to power automobiles. Because water is its ultimate product (i.e., $2H_2 + O_2 \rightarrow 2H_2O$), the hydrogen economy would be largely non-polluting. Sounds great but a second look reveals some flies in the hydrogen ointment. First of all, no hydrogen wells exist for the natural abundance of this gas is extraordinarily low. Rather, hydrogen must be manufactured. One way to do this is to electrolyze water ($2H_2O \rightarrow 2H_2 + O_2$) which requires large energy inputs. Another is to treat coal in steam ($C + H_2O \rightarrow CO + H_2$) and to then oxidize the CO to CO_2 ($2CO + O_2 \rightarrow CO_2$). Were a cheap and unlimited source of energy available, then clearly electrolysis would be preferred. But as such a source remains a pipe dream, if hydrogen is to fuel the world, it will very likely be produced by steaming coal. The reason is that at current prices, H_2 derived by steaming coal is 10 times cheaper than that produced by the electrolysis of water. So what would be gained by the shift to a hydrogen economy? Just as in conventional coal-fired electrical power plants, in a coal-gasification plant (i.e., one that produces H_2) the coal would be converted to CO_2 (see Figure 53). But there is an advantage. The capture of CO_2 from a coal gasification plant can be done much more economically than from conventional coal-fired power plants. Further, if the hydrogen were used in a fuel cell, a greater fraction of the coal's chemical energy could be converted to electrical energy, thus raising the efficiency.

Those intrigued by the hydrogen economy dream of automobiles fueled by hydrogen rather than gasoline. Were this possible, then CO_2 production by the transportation fleet would be eliminated. Instead, the CO_2 would be produced in large coal gasification plants where it could be readily captured. Indeed, General Motors has as one of its goals the hydrogen-powered automobile. The fuel cell which would replace the internal combustion engine is pretty much ready to go. However, a huge and perhaps insurmountable problem remains, namely, how to store the hydrogen onboard the vehicles. At one atmosphere pressure, hydrogen can be liquefied but only at a temperature below -252°C (hence only 20°C above absolute zero temperature). An



ELECTRICAL POWER FROM COAL

COAL FIRED PLANT

AIR
20% O_2

EXHAUST (I.E. HOT AIR)
10% O_2
10% CO_2

COAL

HEAT MAKES
STEAM TO
DRIVE
TURBINES

ELECTRICITY

COAL GASIFICATION PLANT

STEAM

COAL

H_2 + CO
+O_2 (PURE)

$CO_2 + H_2$

CaO + CO_2
$\rightarrow CaCO_3$

TO FUEL
CELL

ELECTRICITY

$CaCO_3$
$\rightarrow CO_2$ + CaO

TO STORAGE

RECYCLE

Figure 53. The chemical energy from coal can be harnessed in two quite different ways. In conventional power plants, coal combines with O_2 to produce CO_2 and H_2O. The heat produced in this way is used to drive turbines which generate electricity. An alternate path is to steam coal and in this way produce CO and H_2. The H_2 is then combined with O_2 in a fuel cell (i.e., a flow through battery). The CO is oxidized to CO_2. Such plants can be more economically upgraded for CO_2 capture than can conventional coal-fired plants. For example, the CO_2 might be reacted with CaO to form $CaCO_3$ (thereby directly separating it from the H_2). The $CaCO_3$ would then be thermally decomposed to CaO and CO_2. The CaO would be recycled. The CO_2 would be liquefied and piped to a storage site.

alternate would be to store the H_2 as a gas at thousands of atmosphere's pressure. No one has come up with an acceptably safe and inexpensive tank that could hold enough H_2 to operate an automobile for weeks at a time.

CO_2 sequestration

In my estimation there is currently only one sure route by which the buildup of CO_2 in the atmosphere can be brought to a halt. As championed by Columbia University's Klaus Lackner, it involves capture and storage of the CO_2 produced as a byproduct of fossil-fuel-based energy production (see Figure 54). The CO_2 generated in electrical power facilities would be captured on site, liquefied (under pressure) and piped to a storage site. But as large power plants currently account for only about one third of the total amount of CO_2 generated, this route alone cannot solve the problem for we must head toward zero CO_2 emissions. However, as outlined below, it may be possible to remove CO_2 from the atmosphere. If so, vehicles could continue to be powered by gasoline.

CO_2 storage

Before discussing how CO_2 would be captured, it makes sense to first consider where it would be stored. A number of proposals have been put forward (see Figure 55).

1) *Deep-sea storage*. Currently only about one sixth of the ocean's capacity for CO_2 uptake is being utilized. The reason is that subsurface waters are replaced only very slowly by waters which have been in contact with the atmosphere. The deeper the water the slower its replacement. As the deeper parts of the ocean will not take up their share of the fossil fuel CO_2 for hundreds of years, the idea is to short-circuit the delivery by pumping liquid CO_2 directly into the deep sea. Although liquid CO_2 is less dense than surface ocean water, it is more compressible. At a depth of 3500 meters, the densities of sea water and liquid CO_2 become equal. Below this depth liquid CO_2 is more dense than sea water. Hence, if injected below a depth of 3500 meters, liquid CO_2 would sink to the sea floor. Further, it would not remain a liquid,

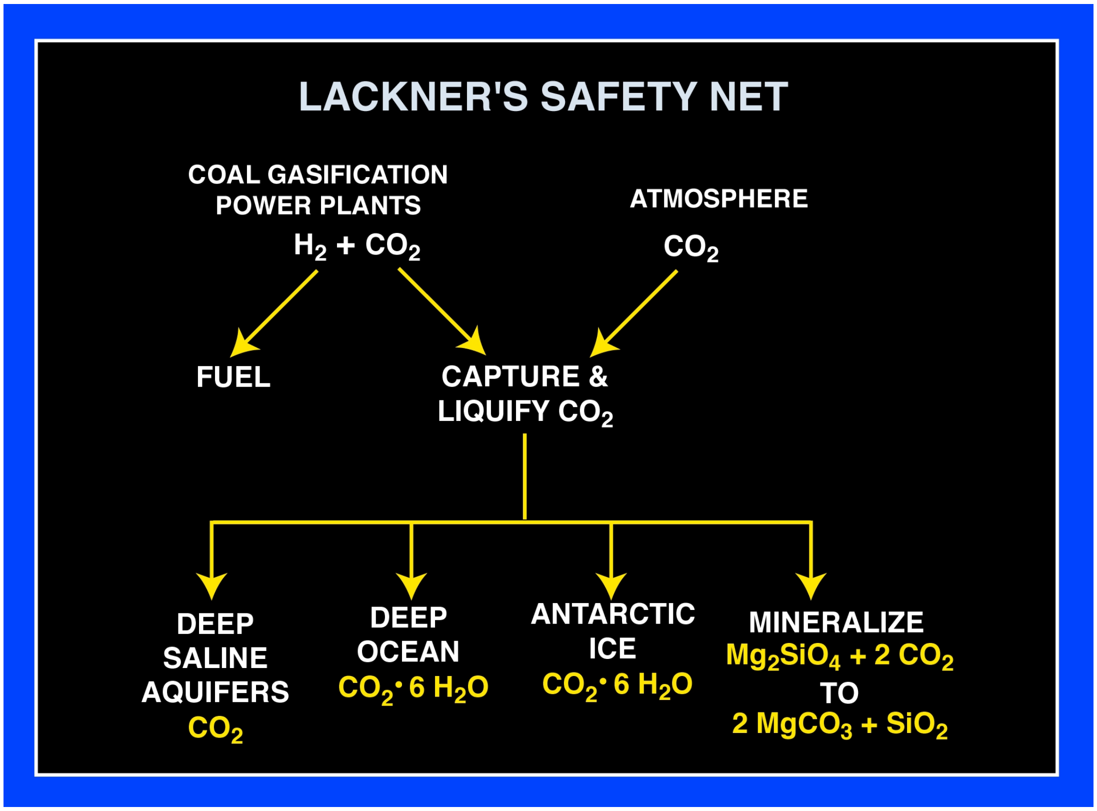


Figure 54. Klaus Lackner has the vision that the CO_2 produced by fossil fuel burning be captured and stored. In the case of large electrical power facilities, the CO_2 would be captured on site (see Figure 54). However, such facilities account for only about one third of the CO_2 produced. The other two thirds of the CO_2 comes from small units (automobiles, airplanes, home-heating units…). As in these cases, it is totally impractical to capture the CO_2 at its source, 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 obtained by dissolving ultrabasic rocks which consists largely of the mineral olivine, i.e, Mg_2SiO_4.

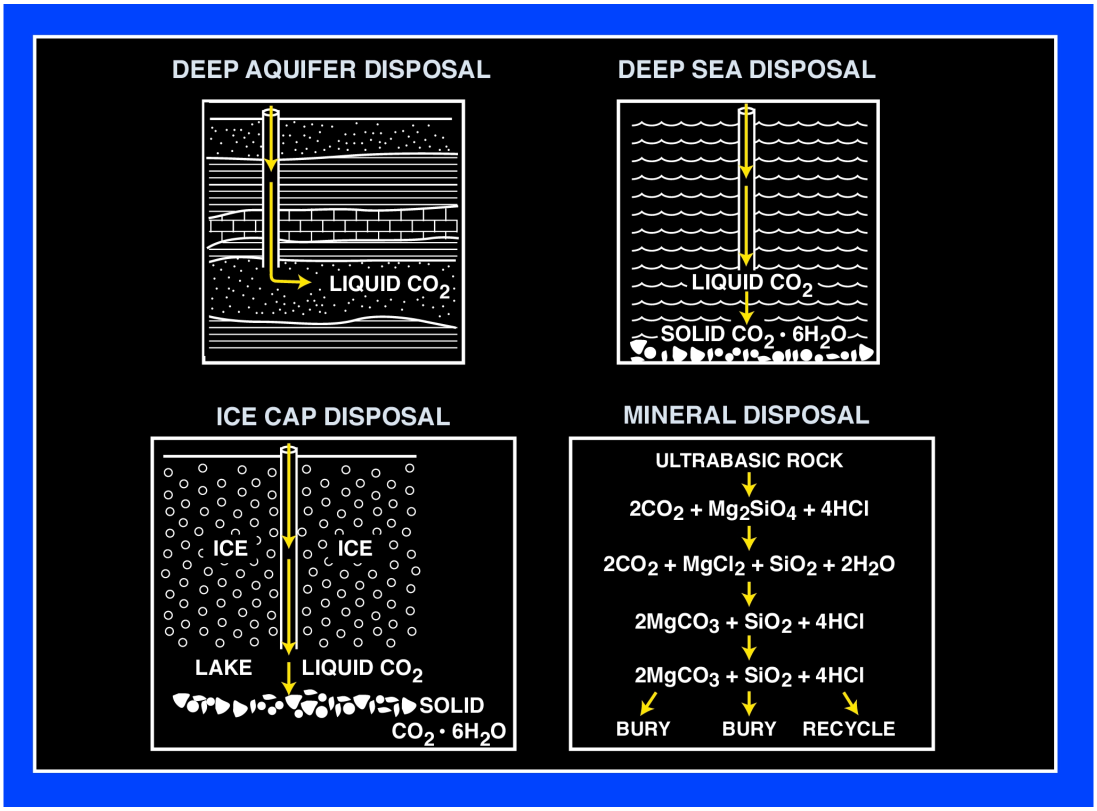


Figure 55. One might ask why disposal in the pores of deep sediments is unlike disposal in the deep sea or in sub-ice lakes. The reason has to do with the difference in temperature. Cold temperatures favor clathrate formation. At the temperatures encountered in aquifers beneath the continents, geothermal heat maintains temperatures well above those at the surface. By contrast, the temperatures in the deep sea and in sub-ice lakes are close to the freezing point of water. In both situations this works out favorably. If clathrates were to form in aquifers, the pores would clog preventing injection. In contrast, as the clathrates formed in the deep and in sub-ice lakes are more dense than water, they sink to the bottom.

for under the cold and high pressure conditions which prevail in the deep sea, the CO_2 would combine with H_2O to form a solid CO_2 x $6H_2O$. Chemists refer to this type of solid as a clathrate. As under these conditions the clathrate is more dense than either liquid CO_2 or sea water, it would pile up on the bottom. Of course, over time, the clathrate would dissolve and the CO_2 would be dispersed throughout the deep sea where it would react with the resident carbonate ions to form bicarbonate ions. In this way, delivery of CO_2 to the deep sea could be greatly accelerated.

2) *Storage in polar ice caps*. Antarctica's ice cap is underlain by hundreds of lakes. They form because Earth heat, diffusing up from beneath, warms and in some places melts the basal ice. The idea would be to pipe liquid CO_2 down through the ice into these lakes. Upon arrival, the CO_2 would react with the lake water and form a clathrate which would sink to the lake bottom. As it would be prohibitively expensive to pipe liquid CO_2 to Antarctica, method of storage would have to be coupled with CO_2 extraction from the air over the ice cap. As the atmosphere mixes extremely rapidly, CO_2 removal could be carried out anywhere on the planet. Just as the air over regions like the New York metropolitan area does not experience a significant buildup in CO_2, neither would the air over Antarctica experience a significant depletion.
3) *Storage in saline aquifers*. The pores in the deep strata of sedimentary basins are invariably filled with very salty waters known as brines. As the brines have been trapped in these reservoirs for millions of years, another option is to pump liquid CO_2 into these salty waters. Unlike the deep ocean and the lakes beneath Antarctica, these brines are too warm for CO_2 clathrates to form. Hence, the CO_2 would remain in liquid form. This is fortunate because were clathrates to form, they would clog the sediment pores and prevent the liquid CO_2 from spreading out into the aquifer. Statoil, a Norwegian energy company, is already doing this. They recover methane-carbon dioxide mixture from a reservoir beneath the North Sea. The CO_2 must be

separated before the methane can be burned. Normally, this separated CO_2 would be released to the atmosphere. But, as Norway has an emission tax of 50 dollars per ton of CO_2, Statoil decided it would be cheaper to liquify the separated CO_2 and pump it back down into a water-filled stratum. This is now being done routinely. A tiny beginning!

4) *Conversion to $MgCO_3$.* With somewhat additional effort, it is possible to permanently immobilize CO_2. This option involves reacting CO_2 with MgO to form a tough and resistant magnesium carbonate mineral. The MgO would be obtained by grinding up and dissolving ultrabasic rock whose dominant mineral is olivine with a chemical formula Mg_2SiO_4. Hence, the reaction would be

$$Mg_2SiO_4 + 2CO_2 \rightarrow 2MgCO_3 + SiO_2$$

Nearly all of the Earth's ultrabasic rock resides in its mantle far below the surface and hence is unavailable to us. However, surface outcrops do exist in many places. So, large electrical power plants and air extraction facilities could be constructed at the sites of these ultrabasic rock outcrops.

None of these storage options is without environmental impacts. Concern has been raised about the possible impacts of deep-sea storage on organisms inhabiting the ocean deeps. Green Peace has already taken a strong stand against this option. In order to implement Antarctic disposal, it would likely be necessary to modify an existing treaty which bans mining on the continent of Antarctica. Further, there would likely be a strong opposition to the construction of large commercial structures required for air-extraction on the pristine polar plateau. Before permitting large quantities of liquid CO_2 to be injected into saline aquifers beneath their homes, people would want to be assured that this activity would not trigger damaging earthquakes or lead to catastrophic releases of CO_2. Finally, even the conversion of CO_2 to $MgCO_3$ is not free of environmental problems. Large quantities of rock would have to be mined. As the volume of the products would exceed that of the rock mined, large mounds of $MgCO_3$ and SiO_2 would have to be made at the sites of this activity. Further, if as is often the case, the ultrabasic rock has been partially altered to serpentine, then the release of asbestos to the atmosphere during the mining operation would be a concern.

Clearly, any solution to the CO_2 problem will have its own set of environmental concerns. This is unavoidable; hence, the goal would be that the environmental damage stemming from the solution be far, far smaller than that from the CO_2 itself.

CO_2 capture from power plants

Although it is possible to capture CO_2 from the stacks of conventional coal-burning power plants, it would require very expensive retrofitting and the process would be cumbersome and expensive. A more economical option would be to move away from electrical power plants which combust coal in atmospheric O_2 (i.e., coal-fired plants). Instead facilities where coal is steamed to produce H_2 and CO_2 would be built (see Figure 53). The hydrogen would be used in fuel cells designed to generate electricity. Facilities of this type go by the name of coal gasification plants. It turns out that retrofitting this type of plant for CO_2 removal is far more economical. So the idea is that as new electrical power plants are built or old ones replaced, it should be with coal gasification units instead of conventional coal-fired units. If this strategy were to be immediately put into place, the eventual implementation of CO_2 capture would be far more easily achieved.

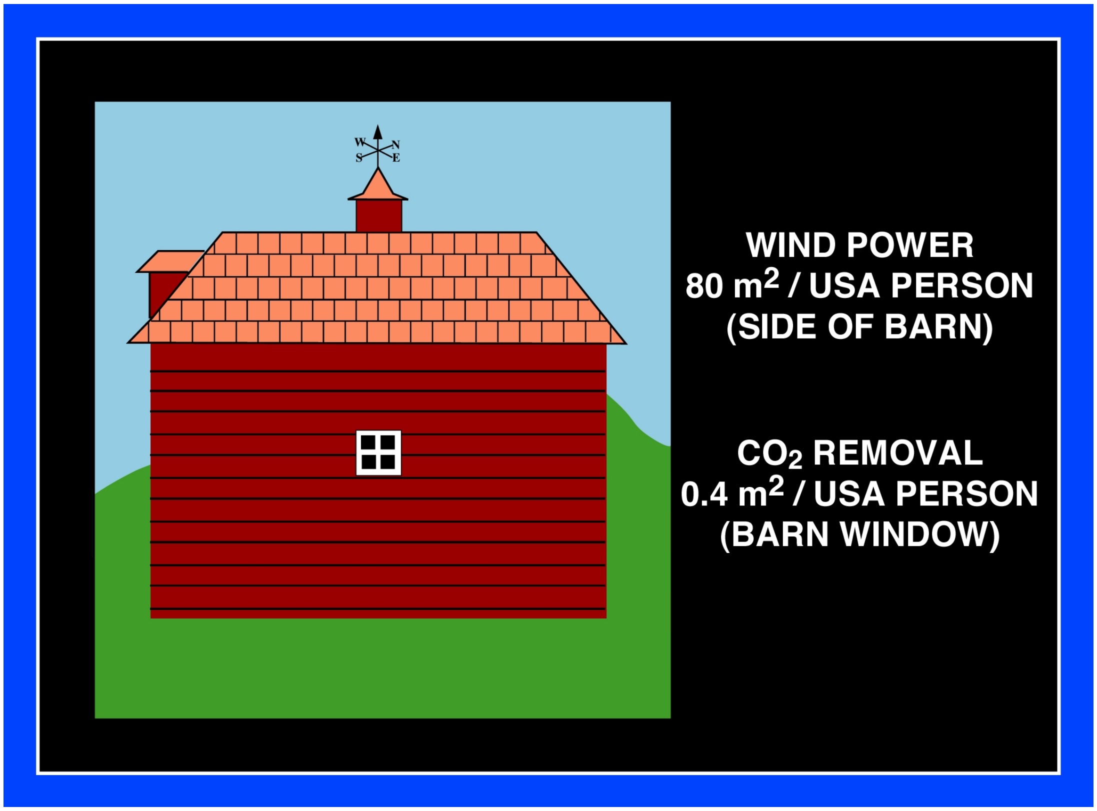
Extraction of CO_2 from the atmosphere

Klaus Lackner, a scientist at Columbia University, stunned the energy world by demonstrating that CO_2 removal from the atmosphere is not only feasible but that it can likely be done at a cost equivalent to a 25 to 50 cent 'tax' on a gallon of gasoline. His case is based on an analogy to wind power. In order to supply the energy utilized by the average USA resident, a rotor sweeping an area of about 80 square meters is required and must be installed at sites characterized by brisk winds. In other words, brisk winds passing through an area the size of the side of a barn would have to be intercepted.

Klaus points out that if, instead, the CO_2 produced by the burning of enough fossil fuel to supply the energy utilized by the average USA resident were to be extracted from the same wind stream, then only 0.4 square meters would have to be intercepted. In other words, the wind area intercepted would be equal to the size of a small window in the side of the barn (see Figure 56). Of course, there is no way that all the CO_2 could be removed from the passing air. But, even if only one half were to be captured, the size of the apparatus would be 100 times smaller than that required to generate an equivalent amount of wind energy.

Extraction of CO_2 from the air has two other advantages. First, China will probably not agree to sequester the CO_2 produced in its electrical power facilities until a means of balancing the international books on CO_2 emissions has been agreed upon. In other words, the world's rich nations would have to compensate for their past massive CO_2 production. A compromise might involve an agreement by the world's industrial nations to remove from the atmosphere some agreed upon amount of CO_2 in payment for their past excesses. A second consideration is that the ability to remove CO_2 from the atmosphere has this long-term advantage: if it is decided that the world was more habitable at some lower CO_2 content than that reached during the next hundred or so years, the means would exist to reestablish this desired level.

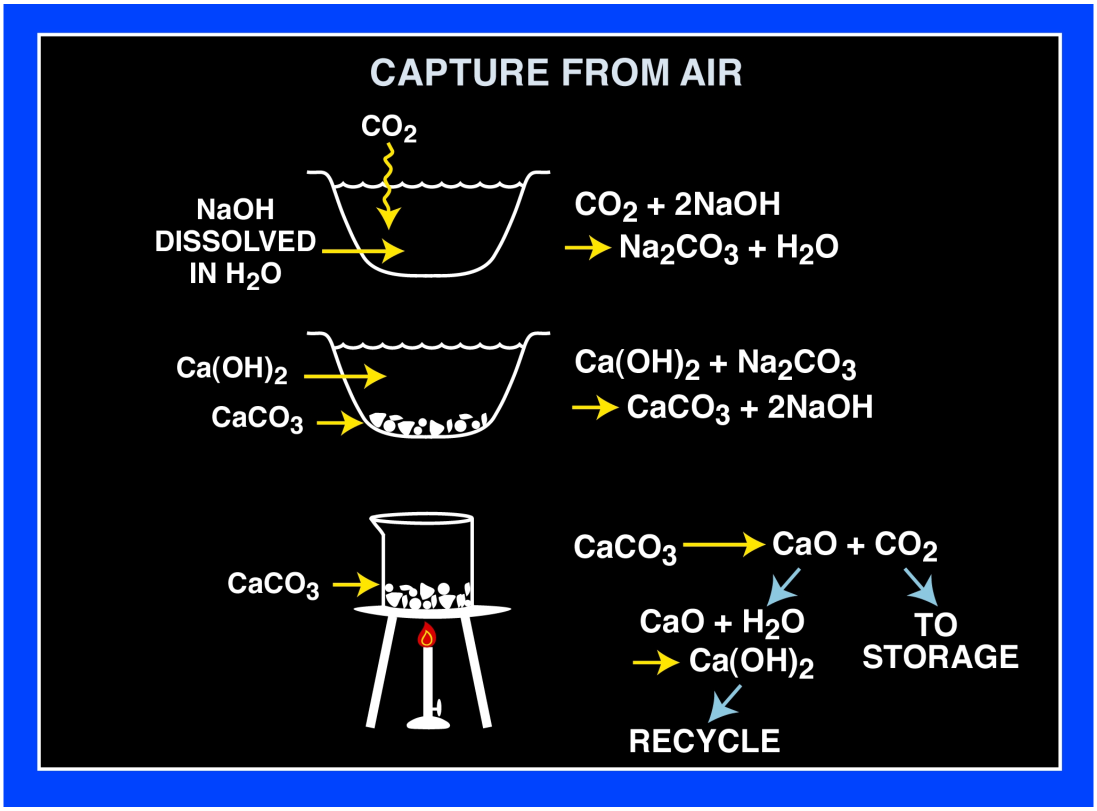
But how can air extraction be accomplished? In concept, it's quite simple (see Figure 57). If a tray containing liquid sodium hydroxide (NaOH) is exposed to air, it will absorb CO_2 ($2NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O$). The next step is to add calcium hydroxide to the sodium hydroxide, and calcium carbonate will promptly precipitate ($Ca(OH)_2 + Na_2CO_3 \rightarrow 2NaOH + CaCO_3$). This precipitate could be separated from the liquid sodium hydroxide and then heated to the point where it decomposed ($CaCO_3 \rightarrow CaO + CO_2$). The CO_2 could then be liquefied for storage. The calcium oxide would



WIND POWER
80 m^2 / USA PERSON
(SIDE OF BARN)

CO_2 REMOVAL
0.4 m^2 / USA PERSON
(BARN WINDOW)

Figure 56. Klaus Lackner surprised the energy world by pointing out that CO_2 extraction has potentially a very large advantage over wind power. His reasoning is as follows. In order to supply the energy required by the average American, wind-driven rotors would have to intercept about 80 square meters of air moving at three meters per second. If, instead, the CO_2 produced by an average American who obtained all his energy by burning fossil fuels were removed from the same air stream, only 0.4 square meters would have to be intercepted. Hence, Lackner proposes that extraction of CO_2 from the atmosphere could well be a viable alternative to battery or hydrogen-powered automobiles.



CAPTURE FROM AIR

$CO_2 + 2NaOH \rightarrow Na_2CO_3 + H_2O$

$Ca(OH)_2 + Na_2CO_3 \rightarrow CaCO_3 + 2NaOH$

$CaCO_3 \longrightarrow CaO + CO_2$

$CaO + H_2O \rightarrow Ca(OH)_2$

Figure 57. CO_2 is readily absorbed in basic solutions such as sodium hydroxide. It can then be recovered by adding calcium oxide or calcium hydroxide to the sodium hydroxide and thereby precipitating calcium carbonate. The calcium carbonate is then separated from the sodium hydroxide and heated in a kiln. At 900°C, the $CaCO_3$ dissociates into calcium oxide and CO_2. The calcium oxide is recycled. The CO_2 is liquefied and piped to the storage site.

then combine with water ($CaO + H_2O \rightarrow Ca(OH)_2$) and hence be readied for reuse.[4] Sounds simple but there are complications. First off, both sodium and calcium hydroxide are exceedingly caustic (in the sense that they readily dissolve the skin off your fingers!). Hence it would be necessary to prevent entrainment of the absorbent by the passing air and also to make sure the apparatus is constructed of materials immune to attack. Second, as calcium carbonate holds onto CO_2 with great tenacity, in order to force it to decompose, it must be heated to 900°C. The heating requires energy. Energy costs money and if produced from fossil fuels also generates additional CO_2.

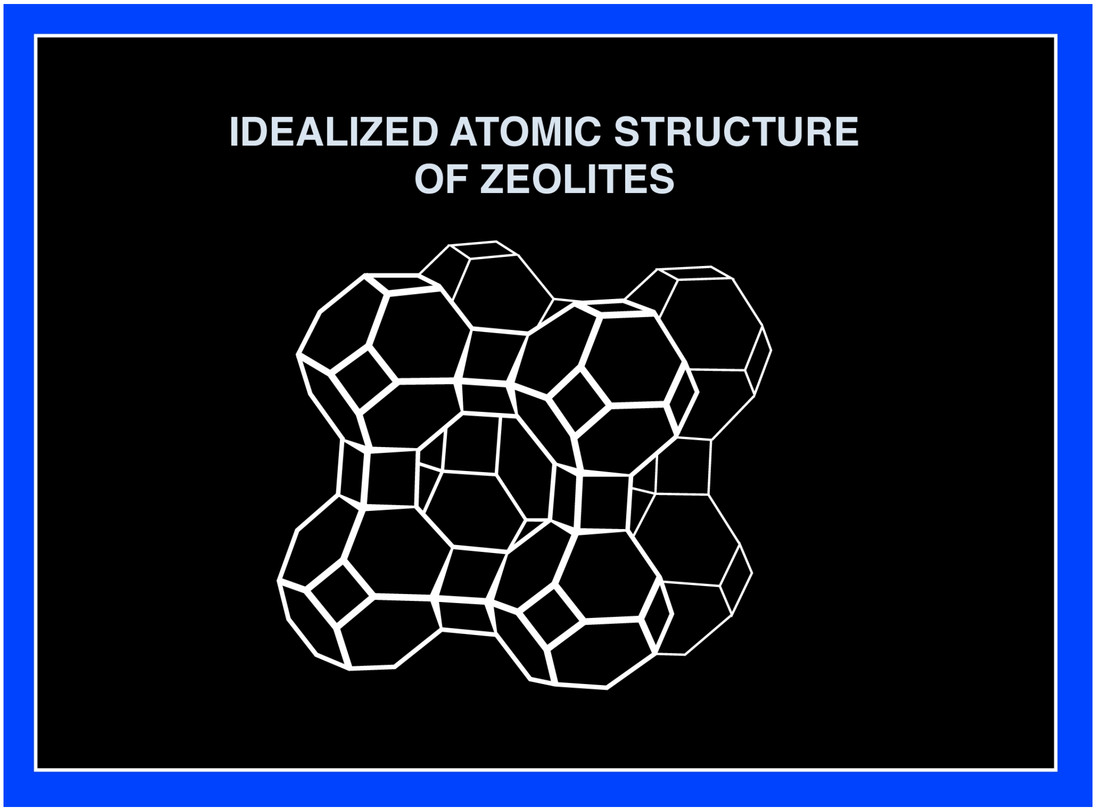
Another option is to create an organic solvent which will combine with CO_2 at 'room' temperature but release it when heated to a modest temperature. This solvent would not only have to be less chemically objectionable than NaOH but it would also have to require less energy input to implement CO_2 recovery than that required to decompose $CaCO_3$. Finally, this solvent would have to have a vapor pressure sufficiently low that its loss through evaporation would be acceptably small. To my knowledge, a solvent with all these properties has yet to be identified.

A third option involves a solid absorber. It would likely be a custom-designed artificial relative of the mineral, zeolite (see Figure 58). The focus is on zeolite because its structure contains an atomic scale cavity ideal for trapping a gas molecule. The idea would be to manufacture a zeolite cousin which would hold onto CO_2 molecules but not H_2O molecules. As the ratio of H_2O to CO_2 in air is very high, only such a zeolite would be able to pick up CO_2 without becoming clogged with water molecules.

Regardless of the CO_2 absorber selected, the required apparatus would be immense. Klaus Lackner envisions huge towers akin to the virtual one placed in New York's Central Park by Stonehaven Film (see Figure 59). If the absorber were zeolite balls, they would perhaps bounce down a series of baffles or slide down a mesh netting.

---

[4] As there are no natural deposits of CaO, it must be obtained by thermally decomposing the $CaCO_3$ which makes up limestone. This is equivalent to the process used to produce cement from limestone.



IDEALIZED ATOMIC STRUCTURE
OF ZEOLITES

Figure 58. Zeolites are a class of naturally occurring silicate minerals. They are of particular interest because a channel exists in their atomic architecture which accommodates gaseous molecules. Because of this, synthetic zeolites are widely used by chemists as catalysts. It is Klaus Lackner's hope that a zeolite capable of absorbing CO_2 but shunning the far more abundant water vapor can be synthesized for use in air extraction.

LACKNER CO_2 EXTRACTOR

Figure 59. Stonehaven, a Canadian film company, superimposed over New York's Central Park a virtual representation of the extraction devise envisioned by Klaus Lackner for CO_2 extraction of CO_2 from the atmosphere. This device would remove the CO_2 generated by 3000 people.

The idea would be to design their descent through the tower so that when they reached its base, they would have picked up an optimum amount of CO_2 from the air stream. The balls would then be transferred to a chamber at the base of the tower. The chamber would be evacuated allowing a cryogenic coil placed within the chamber to pull the CO_2 off the zeolite capturing it to dry ice (solid CO_2). Once freed of their CO_2, the zeolite balls would be sent back to the top of the tower for another pass. The dry ice would be converted to liquid CO_2 and piped to a storage site.

If the absorber were a liquid, it would likely trickle down a porous framework placed in the wind stream. Upon reaching the tower's base, it would be heated and passed down a similar but smaller framework and the CO_2 would be released from the heated solvent. It would be liquefied and piped to the site of storage.

However, as no such apparatus has yet been built, the ultimate design could well be quite different. Whatever it turns out to be, several criteria will have to be met.

1) The framework on which the absorbent is held must present minimal resistance to the flow of the air.
2) As the absorbent must be recycled, its loss during each cycle must be kept small.
3) The amount of heat required to release the CO_2 from the absorbent must be kept to a minimum.

Time constraints

No matter what course were taken to eliminate CO_2 emissions, it would be a huge enterprise. Were all the CO_2 currently created by fossil fuel burning to be liquefied, about one cubic kilometer would be generated every two weeks. The technology required to capture and store CO_2 remains largely on the drawing boards. Only a small fraction of the people on the planet are convinced that such massive action is warranted. The unconvinced would surely argue; why should we pay to capture and store CO_2 when we can release to the atmosphere for free? The Bush Administration is hesitant to take any action, claiming more research is required. It is clear that proponents of action face a major uphill battle.

If the decision were made to create a backstop against an unfavorable greenhouse buildup involving capture and storage of CO_2, how might the schedule look? I see the next 20 years devoted to four tasks (see Figure 60).

1) Developing and testing the apparatus required for CO_2 capture and storage.
2) Working out a scheme for financing CO_2 capture and storage.
3) Making the complex set of political arrangements required to bring on board most of the world's 180 nations.
4) Monitoring the extent of climate change as a means of convincing the world's populace of the necessity to cut off the flow of CO_2 to the atmosphere.

While 20 years sounds like a long time, it very likely is not nearly enough to complete these four tasks. To build and test a new type of power plant takes about 15 years. The Kyoto Accord was 10 years in the making. Almost nothing of consequence has been accomplished during the 30 years which have elapsed since scientists first raised a warning flag. So, if it's to be accomplished, we would have to move quickly into high gear on all four of these fronts.

In order to achieve the participation of dubious governments, it will likely be necessary to agree to hold off decisions regarding the rate of deployment of the sequestration apparatus until late in this 20-year period. This determination will likely be based on the rate at which global warming proceeds. If, as Lindzen predicts, little change occurs, then the technology would likely be shelved. On the other hand, if the extent of warming were to exceed that predicted by the models, then implementation would be pushed forward at the greatest economically permissible rate. Even if the preparation period can be kept as short as 20 years, when account is taken that the minimum time required to replace the existing energy infrastructure is roughly 40 years,

STRAWMAN 20 YEAR PLAN

1) DEVELOP AND TEST TECHNOLOGIES REQUIRED FOR CO_2 CAPTURE AND STORAGE

2) CREATE A WORKABLE PLAN FOR FINANCING CO_2 CAPTURE AND STORAGE

3) NEGOTIATE INTERNATIONAL AGREEMENTS REQUIRED TO BRING 180 NATIONS ON BOARD

4) MONITOR THE EXTENT OF CLIMATE CHANGE

Figure 60. Despite 30 years of concern regarding the possible long-term adverse impacts of excess atmospheric CO_2, no concrete plan has been put in place as to how the discharge of this gas into the atmosphere might be brought to a halt. In my estimation only one surefire route exists. It involves capture and burial of CO_2. However, in order to create this backstop, four aspects will have to be vigorously pursued. 1) The required technologies will have to be developed and tested; 2) a payment scheme will have to be created; 3) an international concord with regard to its implementation will have to be worked out, and 4) the evolution of regional climate will have to be carefully monitored. Each of the first three tasks will require at least 20 years of effort. During this period the world's inhabitants will have to be educated with regard to the wisdom of paying the modest cost which will be required to shut down the flow of fossil fuel CO_2 into the atmosphere.

the zero emission goal could not be achieved earlier than 2065 AD. The task is a huge one. If, for example, the CO_2 produced to support 10 billion people were all to be extracted from the atmosphere, roughly 300,000 Lackner units would be required (see Figures 61, 62). Hence, if we are to beat the clock, we must inject urgency into the preparation process.

Summary

Those who oppose serious action with regard to stemming CO_2 emissions base their case on the lack of solid evidence that climate change caused by this buildup will have serious consequences (see Figure 63). They would like to believe that we will be able to adjust to gradual warming. Some go further and, based on Lindzen's analysis, claim that no significant CO_2-induced warming will occur. Instead, they choose to attribute the warming which has occurred during the last 30 years to natural causes with the Sun being the favorite culprit. The finding that the Earth's temperature is currently no warmer than it was a millennium ago is taken as evidence in support of this conclusion.

Those who push for action base their case on computer simulations which suggest that the climate changes to be brought about by the rise in atmospheric CO_2 content will have highly adverse consequences to the world's remaining wildlife and will likely force major changes in how humans make their livelihood. Admitting that ongoing natural climate changes and the introduction to the atmosphere of man-made particulates complicate the situation, this group attributes the warming of the last 30 years primarily to increases in CO_2 and other greenhouse gases. Some go a step further and warn that a large buildup of CO_2 could trigger a reorganization of the global climate system. Based on the evidence from the records in polar ice and marine sediments, such reorganization would likely occur rapidly (decades) and during the transition period, climate would flicker much as do fluorescent lights when turned on. Their concern is

A HUGE TASK

IF ONE UNIT WERE REQUIRED TO
REMOVE 3000 PEOPLE'S CO_2

THEN FOR
10 BILLION
PEOPLE

300 THOUSAND
EXTRACTORS
WOULD BE
NEEDED

Figure 61. To remove an amount of CO_2 form the atmosphere equal to that produced each year by fossil fuel burning would require several hundred thousand Lackner extractors. As shown here, they would have to be spaced sufficiently far from one another so that airflow through them would not be impeded.

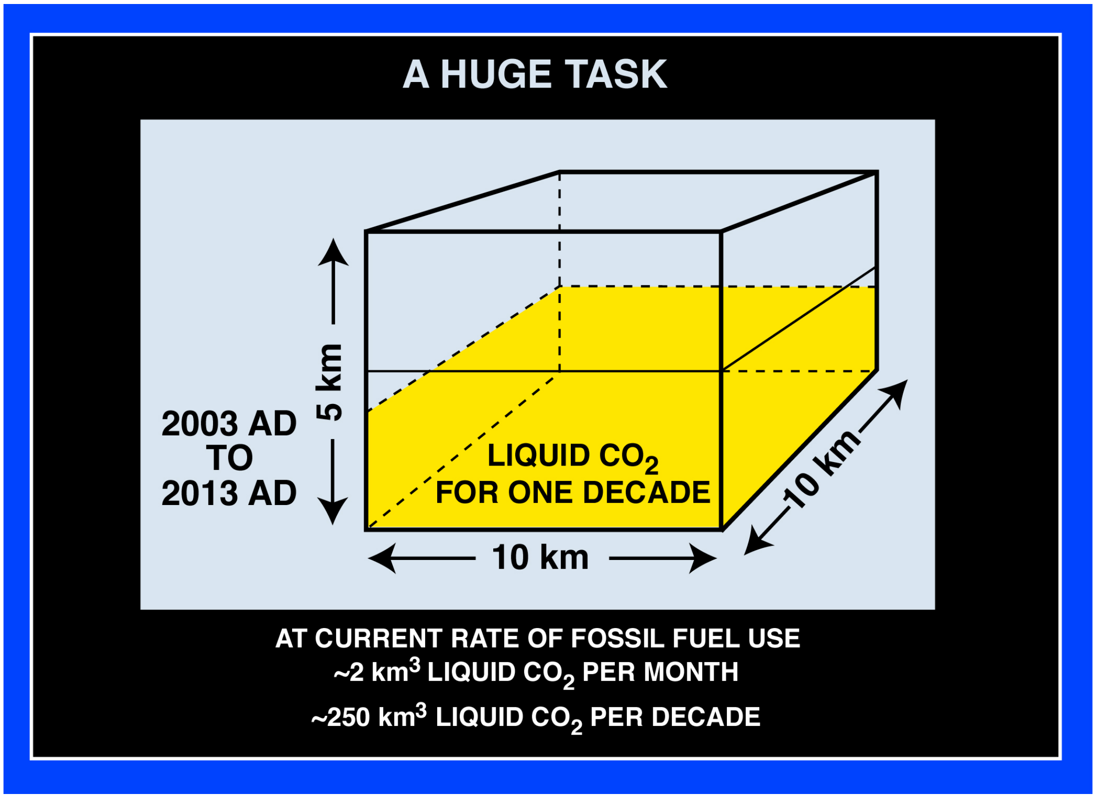
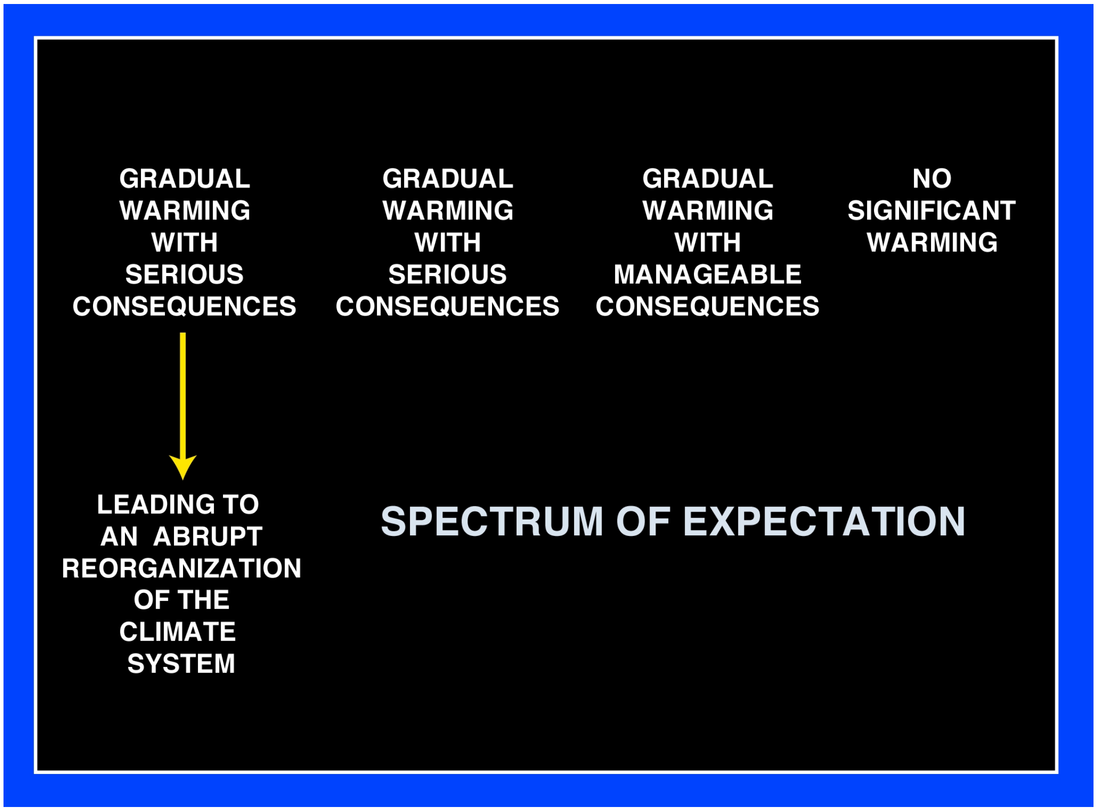


Figure 62. The amount of CO_2 produced each year by fossil fuel burning is enormous. If liquefied, it would in one year fill a tank with a volume of 27 cubic kilometers (i.e., a cube three kilometers on a side). Over a decade the volume of liquid CO_2 produced would fill a tank with an area about one third the size of Manhattan Island to a depth of 2.5 kilometers.



GRADUAL
WARMING
WITH
SERIOUS
CONSEQUENCES

LEADING TO
AN ABRUPT
REORGANIZATION
OF THE
CLIMATE
SYSTEM

GRADUAL
WARMING
WITH
SERIOUS
CONSEQUENCES

GRADUAL
WARMING
WITH
MANAGEABLE
CONSEQUENCES

NO
SIGNIFICANT
WARMING

SPECTRUM OF EXPECTATION

Figure 63. Were citizens in the U.S. asked into which of the four categories shown here they viewed the long-term prognosis for the impacts of rising CO_2, 70 percent would likely vote for one or the other of the right-hand columns. In Europe the vote would be skewed much more toward the two columns on the left. For those of us convinced that action must be taken to shutdown the flow of CO_2 into the atmosphere, the message is clear. We must do a much better job of educating people to the potential dangers associated with doing nothing and also of their responsibility as stewards of our planet.

that by adding large amounts of CO_2 to the atmosphere we are prodding the angry climate beast.

I stand with this latter group. It is my view that, as we have interfered with so many aspects of our planet's operation, we have inadvertently taken on the role as its steward. As such, we must carefully consider the long-term impacts of our activities on not only the welfare of our species but also that of all the other species with whom we share the planet. To me, it would be totally irresponsible not to pull out all the stops in an effort to develop a means to deal with rising CO_2. This task will require at least 20 years, and once completed, will require at least another 40 years to implement. We cannot afford to waste anymore time, for we are already well behind the curve.

The strategy of the Bush Administration to wait until research has produced more firm predictions is in my estimation deeply flawed. For despite the impressive ongoing efforts to depict how our climate system operates, the goal of making reliable predictions is not getting significantly closer. The more we learn, the broader the pallet of complexity. So, the answer will instead come from the Earth itself. During the 20-year preparation period proposed here, we should observe how much the tropics warm; where droughts become more severe; how much of the Arctic's ice melts; how much sea level rises. These observations will allow computer simulations to be correspondingly adjusted and hopefully lead to more reliable predictions.