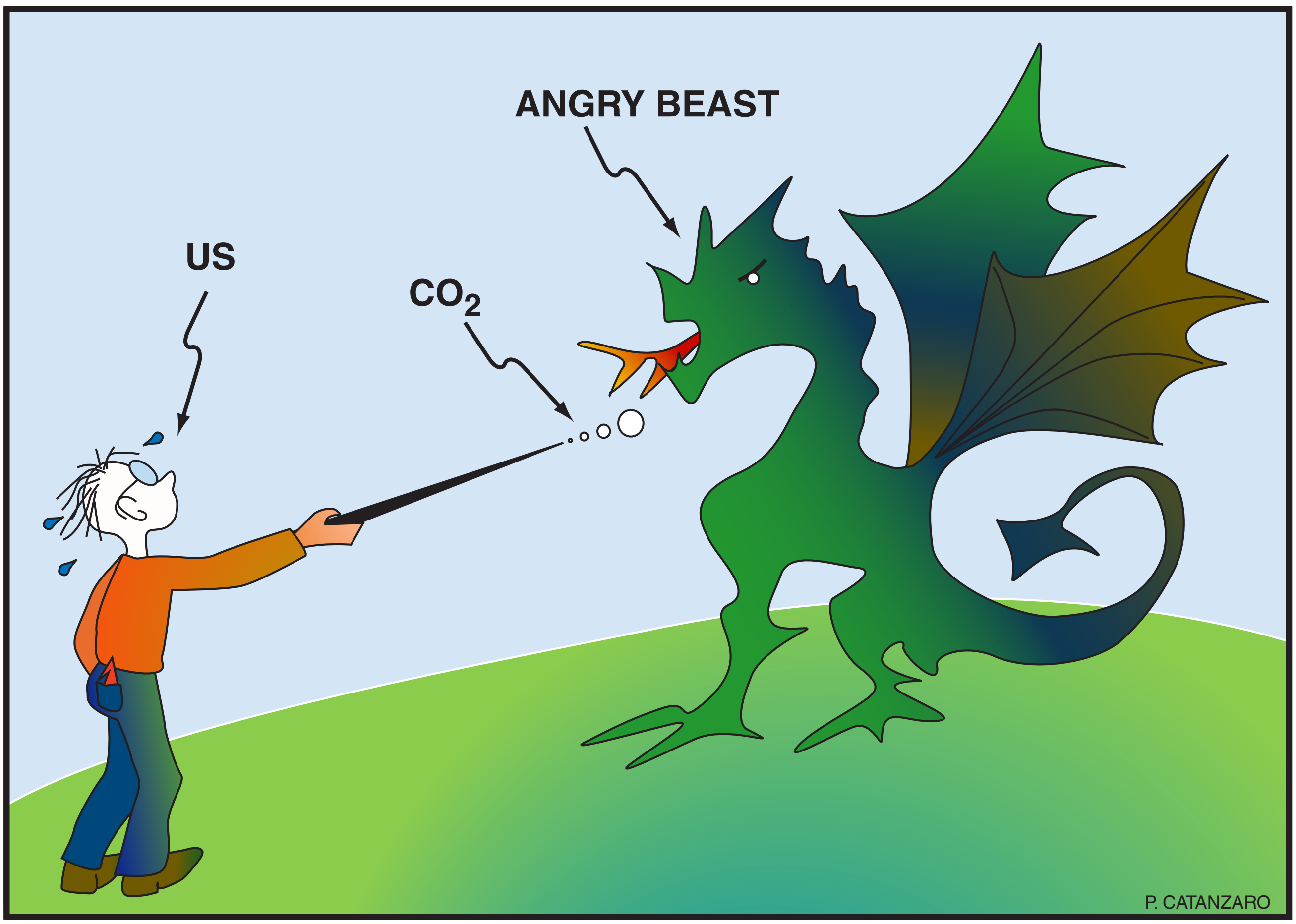
FOSSIL FUEL CO2
AND
THE ANGRY CLIMATE BEAST



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FOSSIL FUEL CO_2 AND THE ANGRY CLIMATE BEAST

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Lecture #1

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. As will be discussed in Lecture #3, 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 could 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 is music to the ears of the Bush administration.

These lectures will focus 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. 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 in the past to be an angry beast. We are poised to give it a nasty poke. Not a good idea!

Production of fossil fuel CO_2

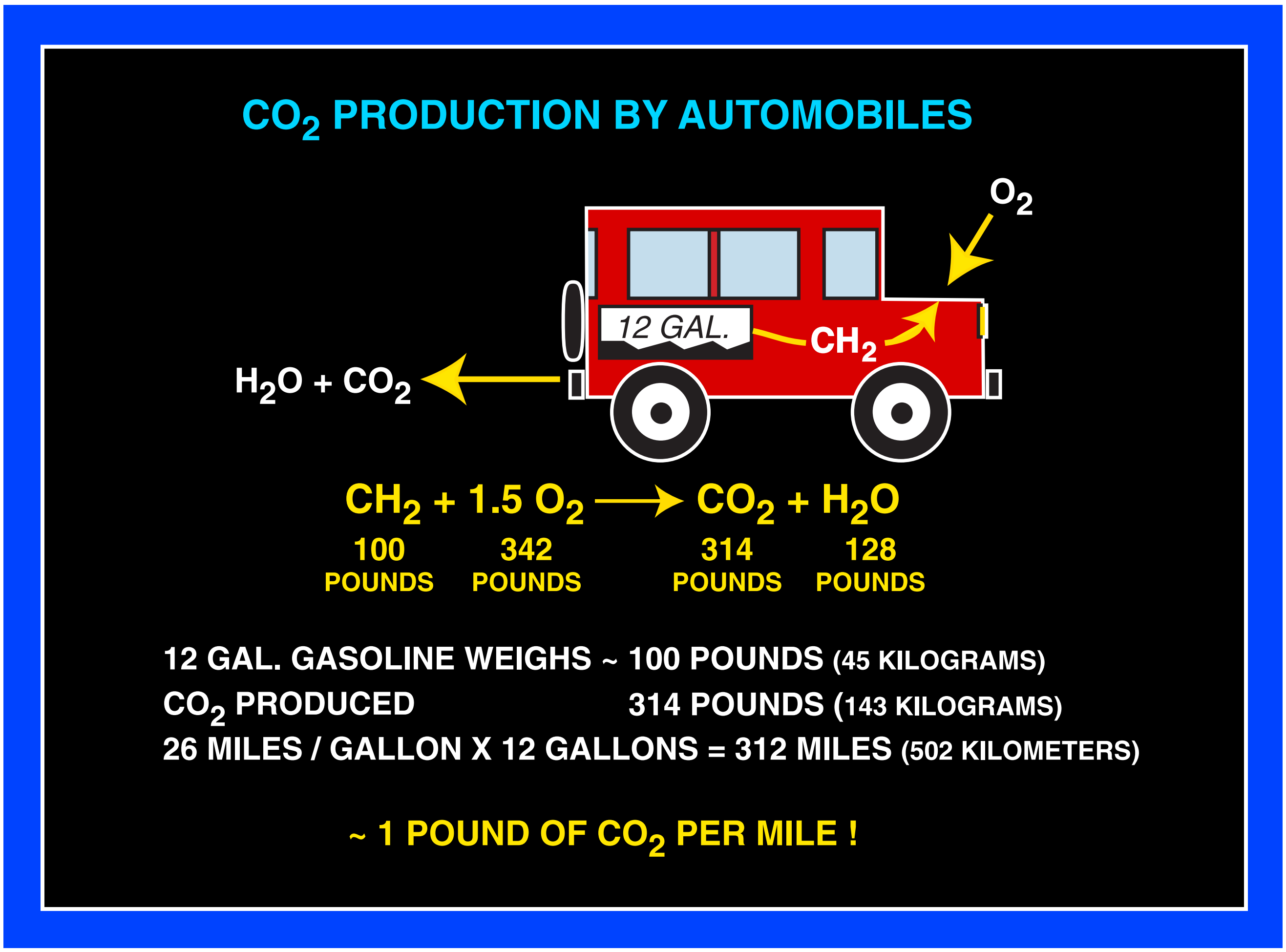
A good way to get a feel for the immense amount of CO_2 produced by the burning of fossil fuels is to consider your automobile. If it s an average sedan about one pound of CO_2 comes out of the tail pipe for each mile you drive. The tank holds 12 gallons of gasoline (weighing close to 100 pounds or 45 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 rates are 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 in 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).

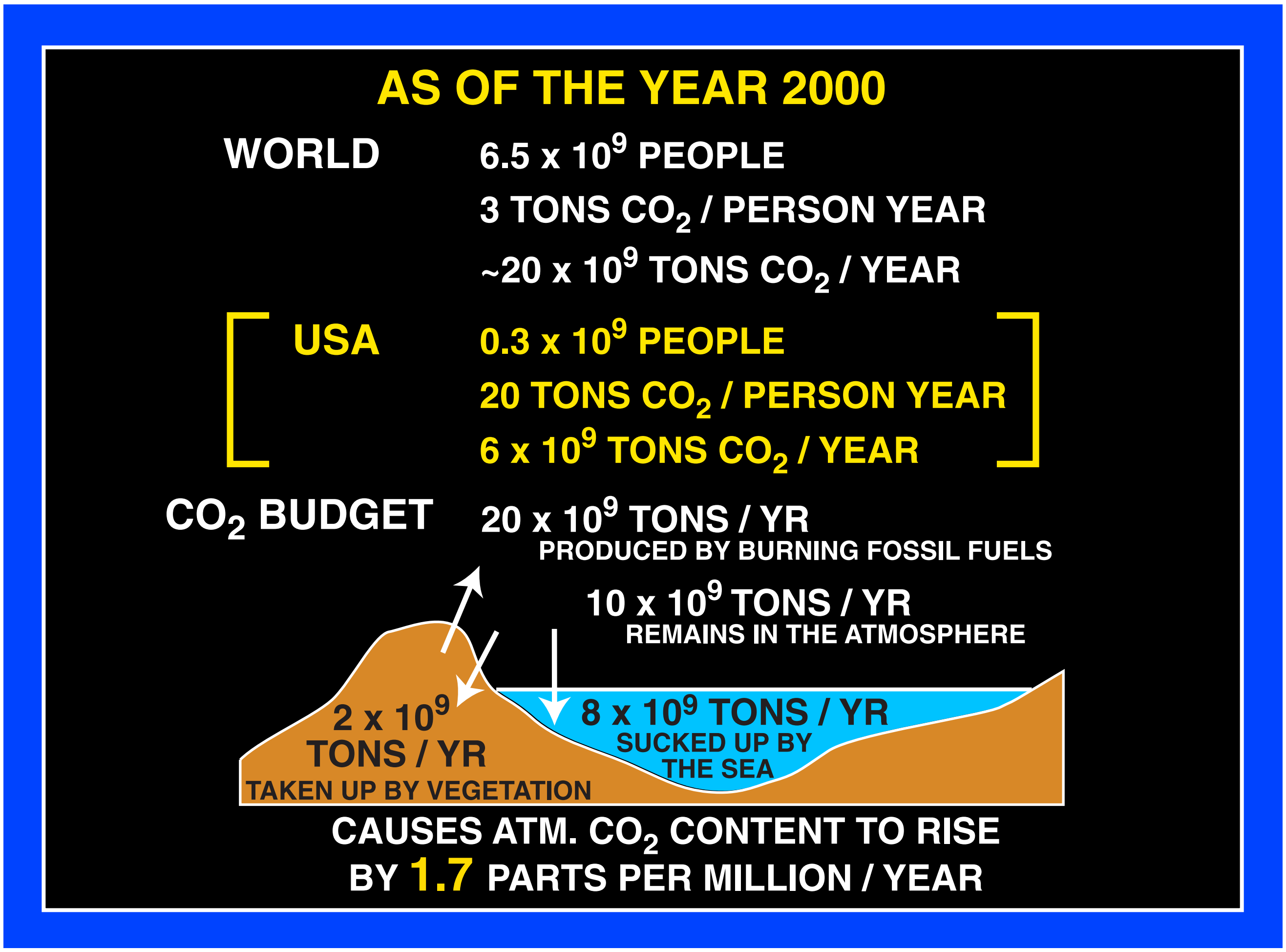
Future fossil fuel use will depend on three things:

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



CO2 PRODUCTION BY AUTOMOBILES
O2
12 GAL.
CH2
H2O + CO2
CH2 + 1.5 O2 ⟶ CO2 + H2O
100 POUNDS
342 POUNDS
314 POUNDS
128 POUNDS
12 GAL. GASOLINE WEIGHS ~ 100 POUNDS (45 KILOGRAMS)
CO2 PRODUCED 314 POUNDS (143 KILOGRAMS)
26 MILES / GALLON X 12 GALLONS = 312 MILES (502 KILOMETERS)
~ 1 POUND OF CO2 PER MILE !

Figure 1



AS OF THE YEAR 2000
WORLD
6.5 x 10^9 PEOPLE
3 TONS CO2 / PERSON YEAR
~20 x 10^9 TONS CO2 / YEAR
USA
0.3 x 10^9 PEOPLE
20 TONS CO2 / PERSON YEAR
6 x 10^9 TONS CO2 / YEAR
CO2 BUDGET
20 x 10^9 TONS / YR
PRODUCED BY BURNING FOSSIL FUELS
10 x 10^9 TONS / YR
REMAINS IN THE ATMOSPHERE
2 x 10^9
TONS / YR
TAKEN UP BY VEGETATION
8 x 10^9 TONS / YR
SUCKED UP BY
THE SEA
CAUSES ATM. CO2 CONTENT TO RISE
BY 1.7 PARTS PER MILLION / YEAR

Figure 2

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

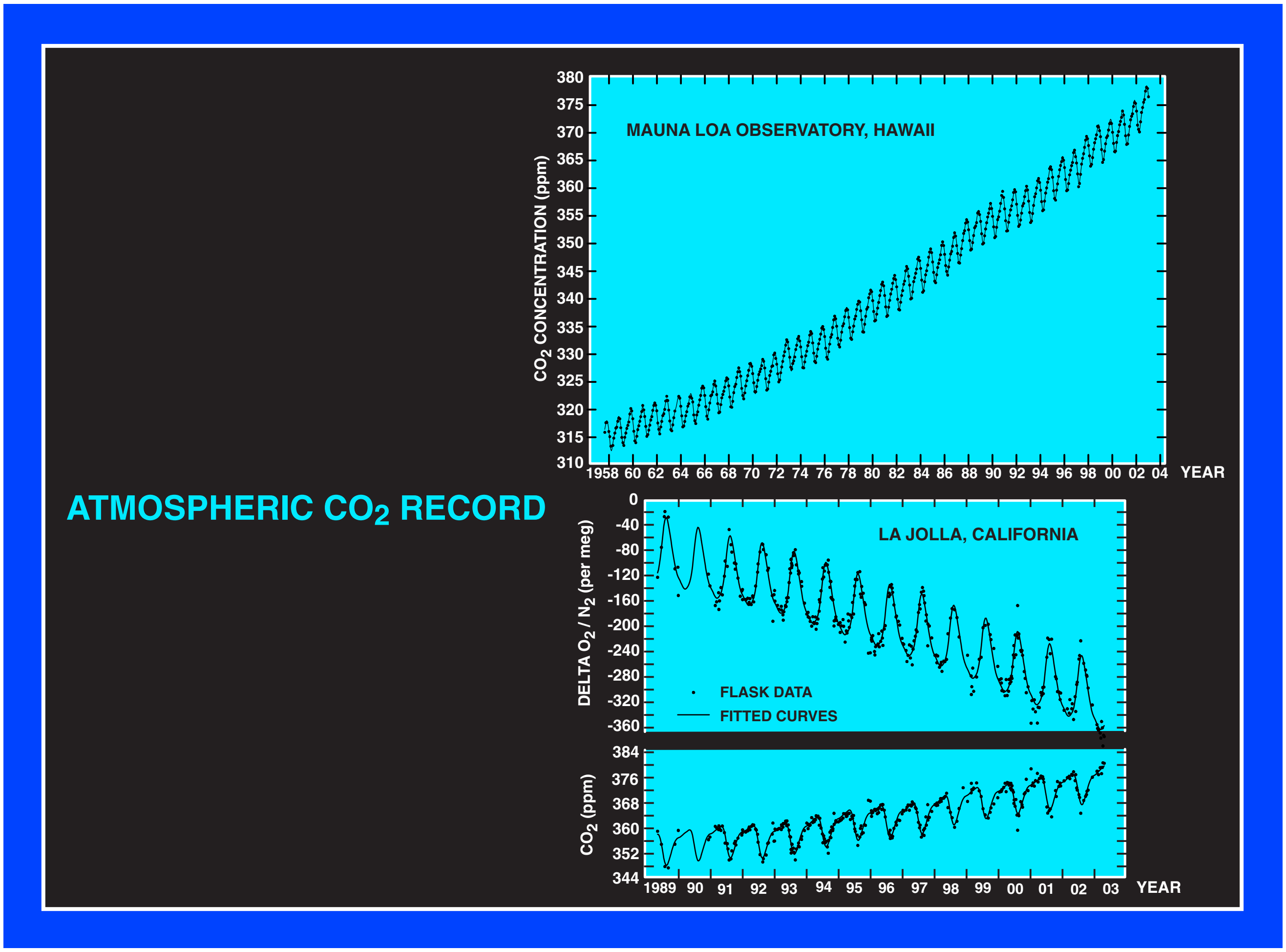
To date only about half of the CO_2 generated by the burning of fossil fuels has remained in the atmosphere. This fraction is determined by comparing the amount by which the atmosphere s CO_2 inventory has increased with the amount of carbon recovered from the Earth in the form of coal, petroleum and 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 part of the 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.

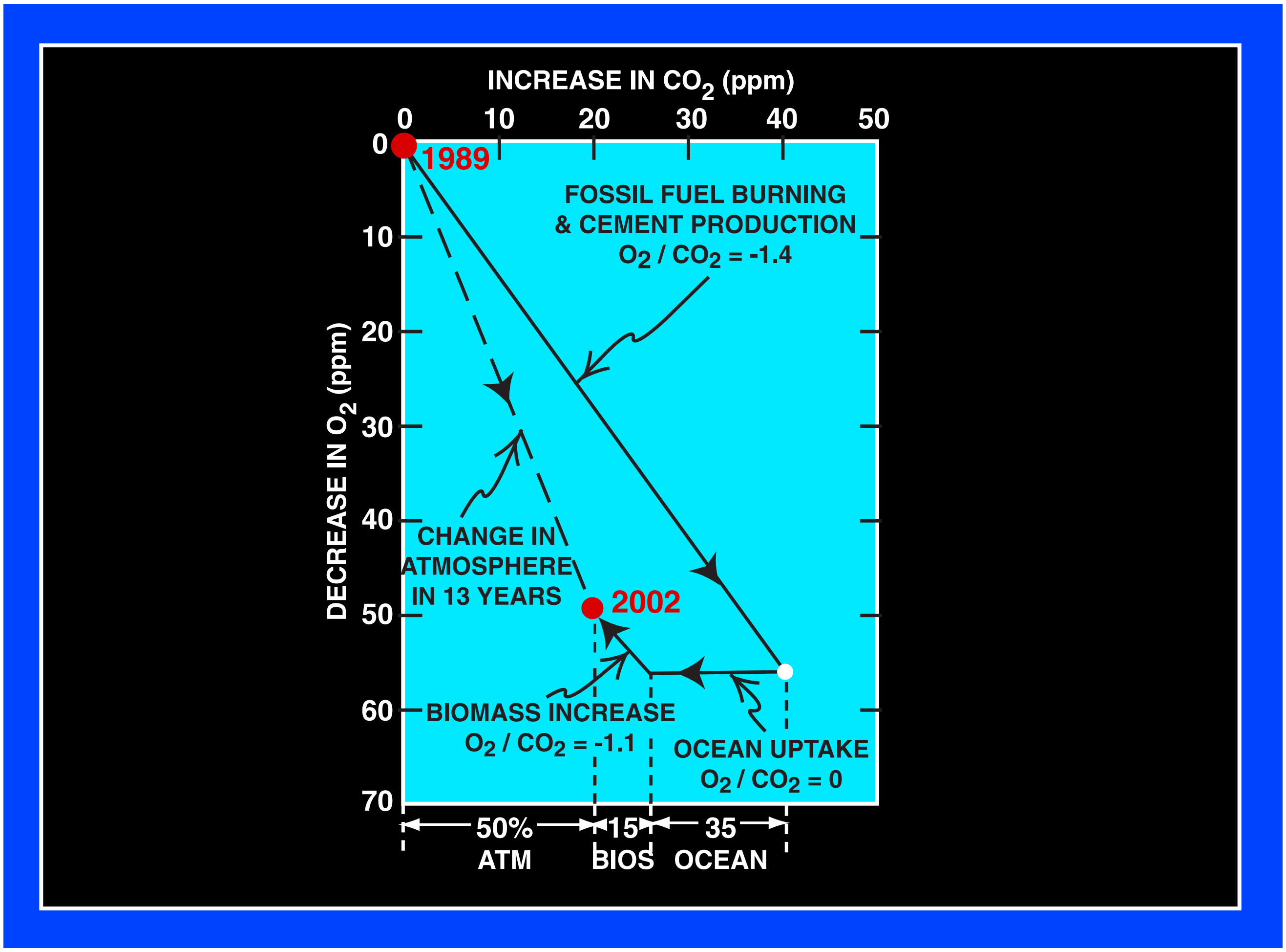
Ralph Keeling, now a scientist at the University of California, while a graduate student, came up with a very clever means of assessing contributions of the ocean and of the terrestrial biosphere to the removal of CO_2 from the atmosphere. Following in the footsteps of his father Charles David Keeling, 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 requires 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



ATMOSPHERIC CO_2 RECORD
MAUNA LOA OBSERVATORY, HAWAII
CO_2 CONCENTRATION (ppm)
380
375
370
365
360
355
350
345
340
335
330
325
320
315
310
1958 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94 96 98 00 02 04
YEAR
LA JOLLA, CALIFORNIA
DELTA O_2 / N_2 (per meg)
0
-40
-80
-120
-160
-200
-240
-280
-320
-360
FLASK DATA
FITTED CURVES
CO_2 (ppm)
384
376
368
360
352
344
1989 90 91 92 93 94 95 96 97 98 99 00 01 02 03
YEAR

Figure 3



INCREASE IN CO_2 (ppm)
0
10
20
30
40
50
0
10
20
30
40
50
60
70
DECREASE IN O_2 (ppm)
1989
2002
FOSSIL FUEL BURNING
& CEMENT PRODUCTION
$O_2 / CO_2 = -1.4$
CHANGE IN
ATMOSPHERE
IN 13 YEARS
BIOMASS INCREASE
$O_2 / CO_2 = -1.1$
OCEAN UPTAKE
$O_2 / CO_2 = 0$
50%
ATM
15
BIOS
35
OCEAN

Figure 4

	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

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) (mostly in the temperate zone). 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 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.

[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 not 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).

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 gain 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 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. If so, by 2050 the CO_2 content of our atmosphere will likely have climbed to more than 500 ppm.

At the end of the last section, we 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 21^{st} 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 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 is 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

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

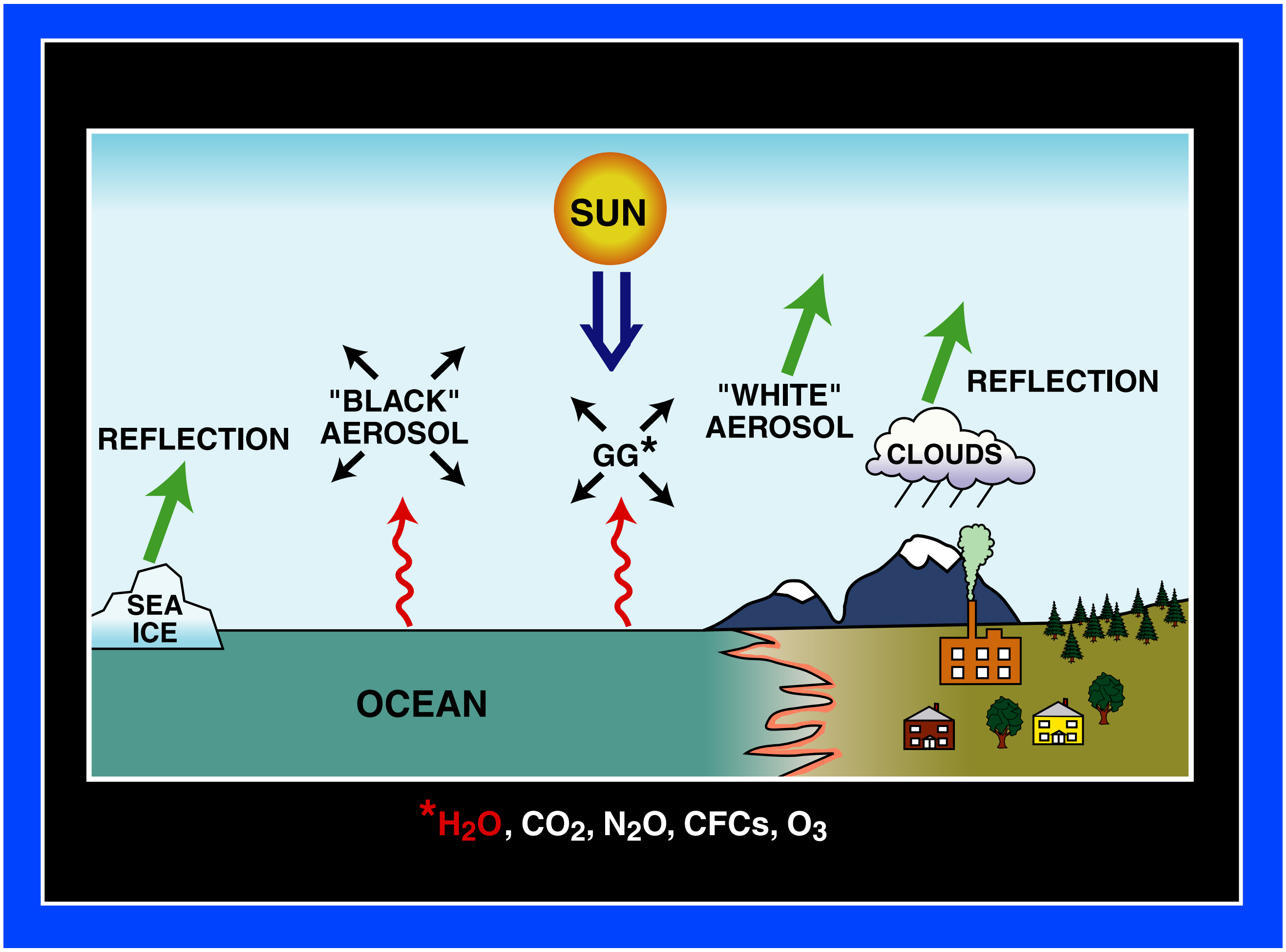

SUN
"BLACK"
AEROSOL
GG*
"WHITE"
AEROSOL
REFLECTION
REFLECTION
CLOUDS
SEA
ICE
OCEAN
*H_2O, CO_2, N_2O, CFCs, O_3

Figure 7

PREINDUSTRIAL SITUATION

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

Figure 8

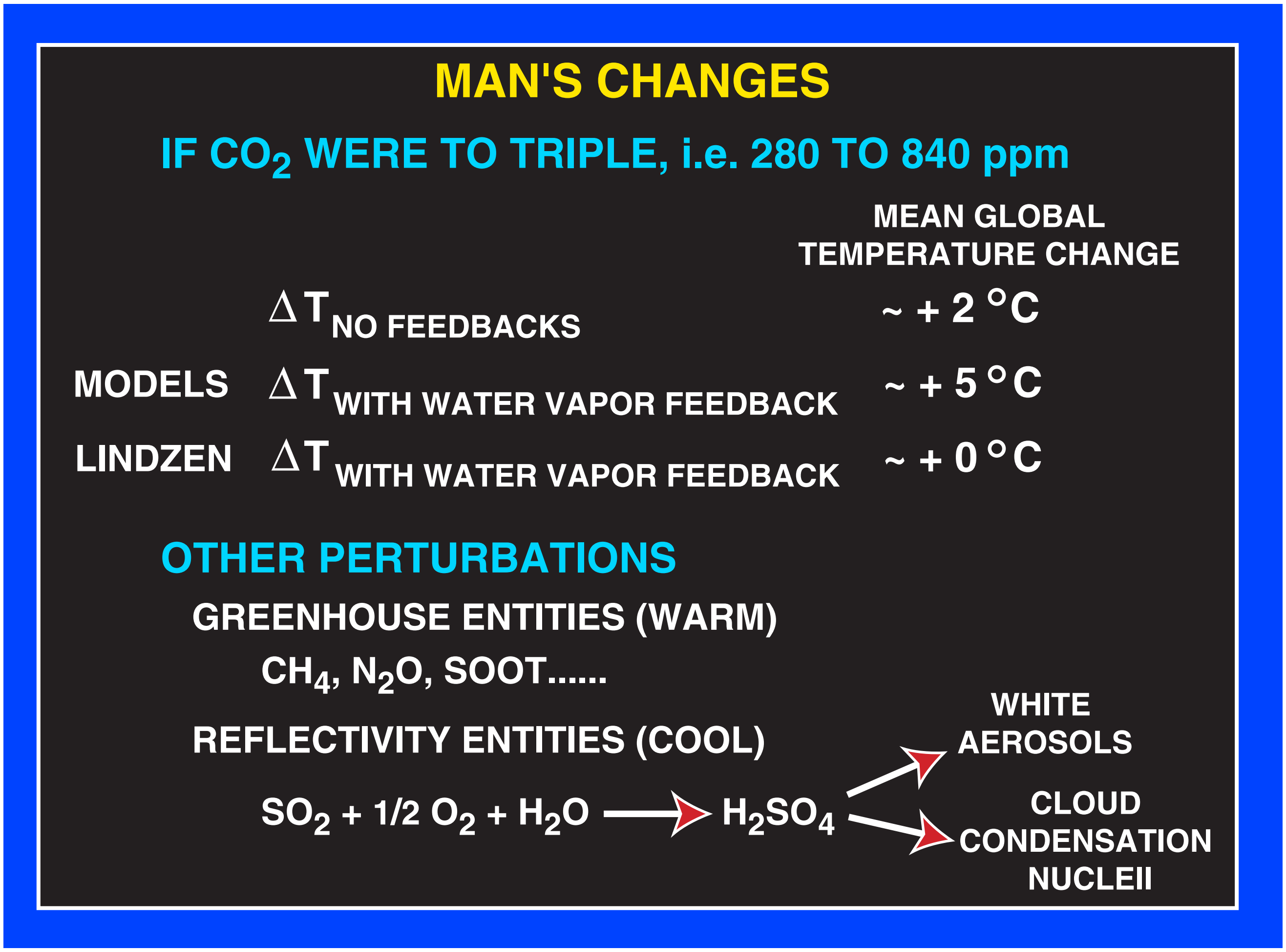

MAN'S CHANGES
IF CO_2 WERE TO TRIPLE, i.e. 280 TO 840 ppm
MEAN GLOBAL TEMPERATURE CHANGE
$\Delta T_{NO\ FEEDBACKS}$ ~ + 2 °C
MODELS $\Delta T_{WITH\ WATER\ VAPOR\ FEEDBACK}$ ~ + 5 °C
LINDZEN $\Delta T_{WITH\ WATER\ VAPOR\ FEEDBACK}$ ~ + 0 °C
OTHER PERTURBATIONS
GREENHOUSE ENTITIES (WARM)
CH_4, N_2O, SOOT......
REFLECTIVITY ENTITIES (COOL)
$SO_2 + 1/2\ O_2 + H_2O \rightarrow H_2SO_4$
WHITE AEROSOLS
CLOUD CONDENSATION NUCLEII

Figure 9

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 for 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 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 large 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 incresing the nighttime loss of Earth heat to space (i.e., night-time cooling).

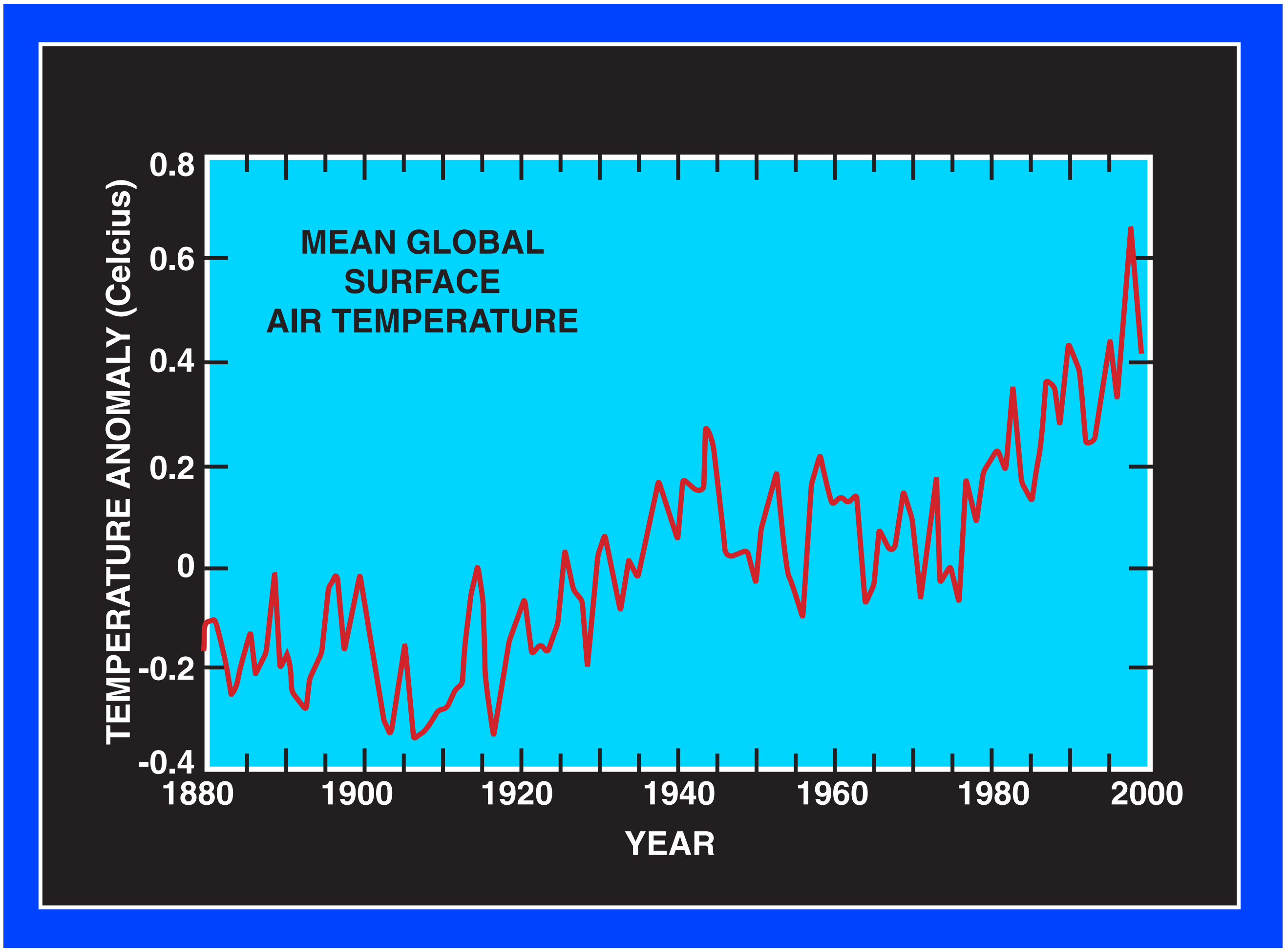
Although the majority of scientists concerned with global warming disagree with Lindzen, they admit that model simulations, no matter how sophisticated, do have serious limitations. While all such simulations yield an amplification of the CO_2 warming by increased water vapor, the magnitude of this amplification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

Figure 10

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, societies are stuck with making decisions 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. 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



TEMPERATURE ANOMALY (Celcius)
0.8
0.6
0.4
0.2
0
-0.2
-0.4
MEAN GLOBAL
SURFACE
AIR TEMPERATURE
1880
1900
1920
1940
1960
1980
2000
YEAR

Figure 11

period should have resulted in a measurable warming. Thus the global mean climate, on its own, has been undergoing 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 (see Sidebar #1). 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 of what they refer to as the equilibrium snowline. Everywhere on the Earth the higher you

WHAT DO OUR PROXIES RECORD?

PROXY	TEMP.	PRECIP.	ICE VOLUME
EQUIL. SNOWLINE ELEV.	X	(X)	
TREE RING THICKNESS	X	X	
^{18}O TO ^{16}O IN ICE	X		
^{18}O TO ^{16}O IN SHELL $CaCO_3$	X		X
^{18}O TO ^{16}O IN CAVE $CaCO_3$	X	X	
Mg TO Ca IN SHELL $CaCO_3$	X		

Sidebar #1

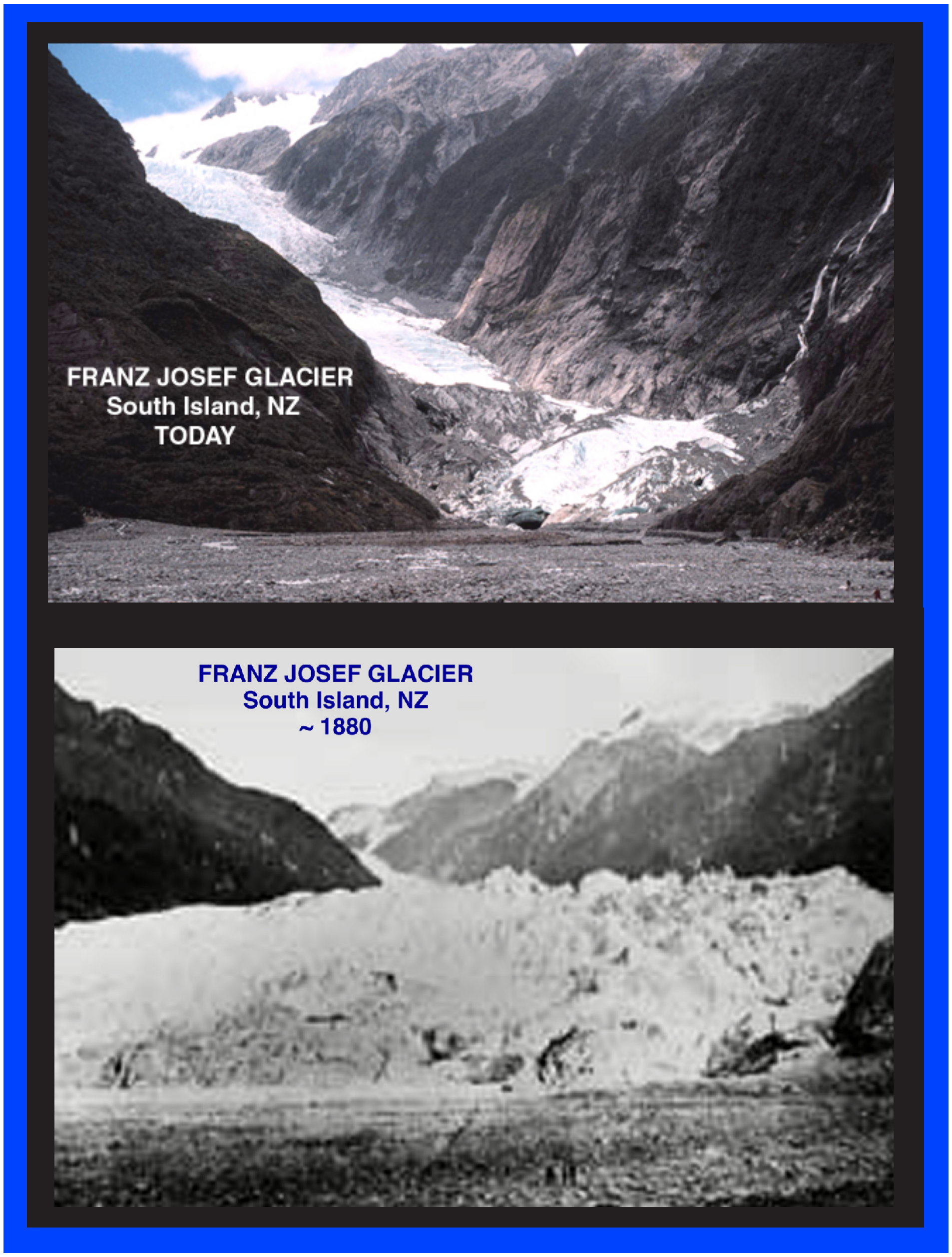

FRANZ JOSEF GLACIER
South Island, NZ
TODAY
FRANZ JOSEF GLACIER
South Island, NZ
~ 1880

Figure 12

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 maximum in glacial extent of 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

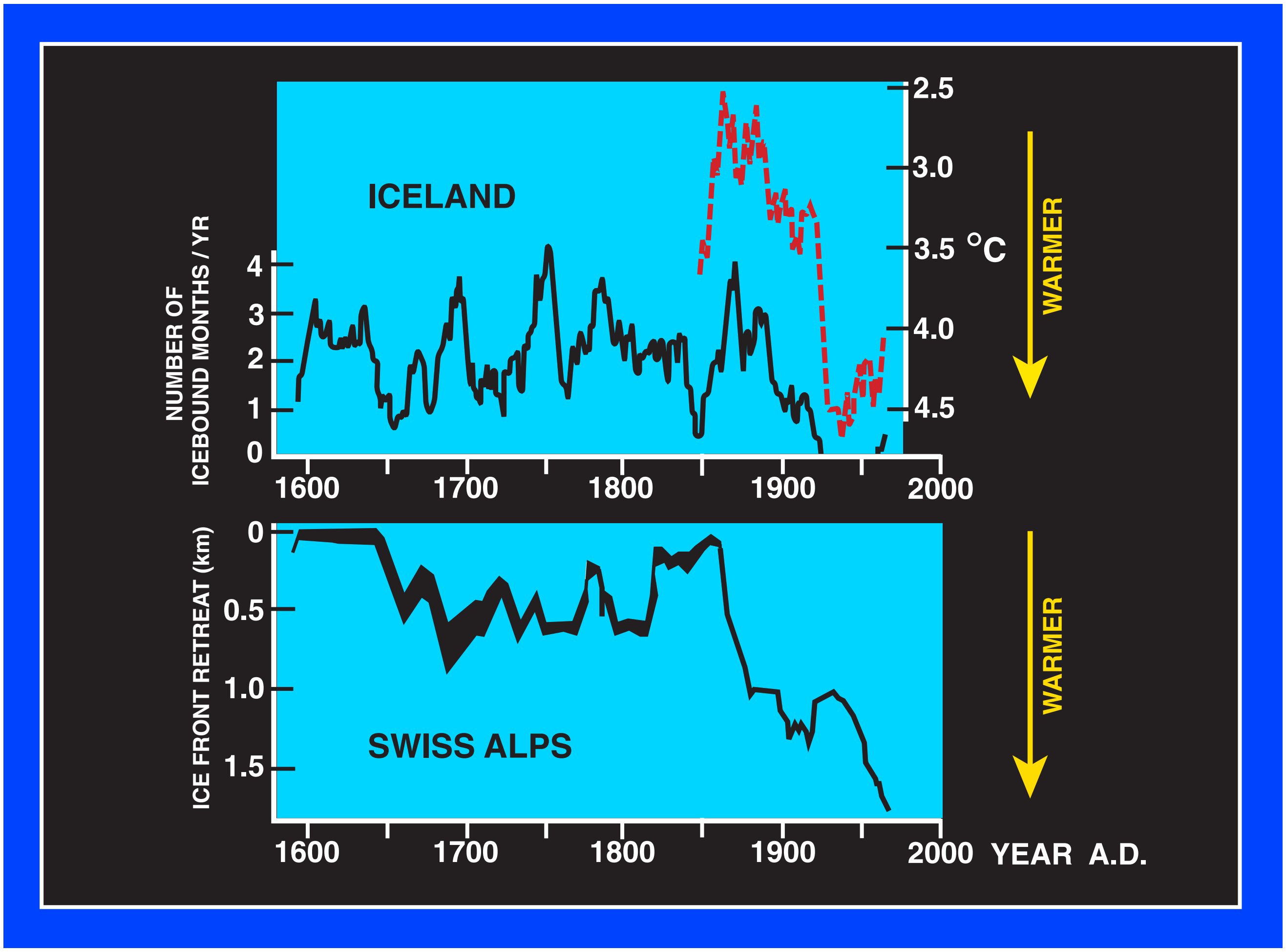
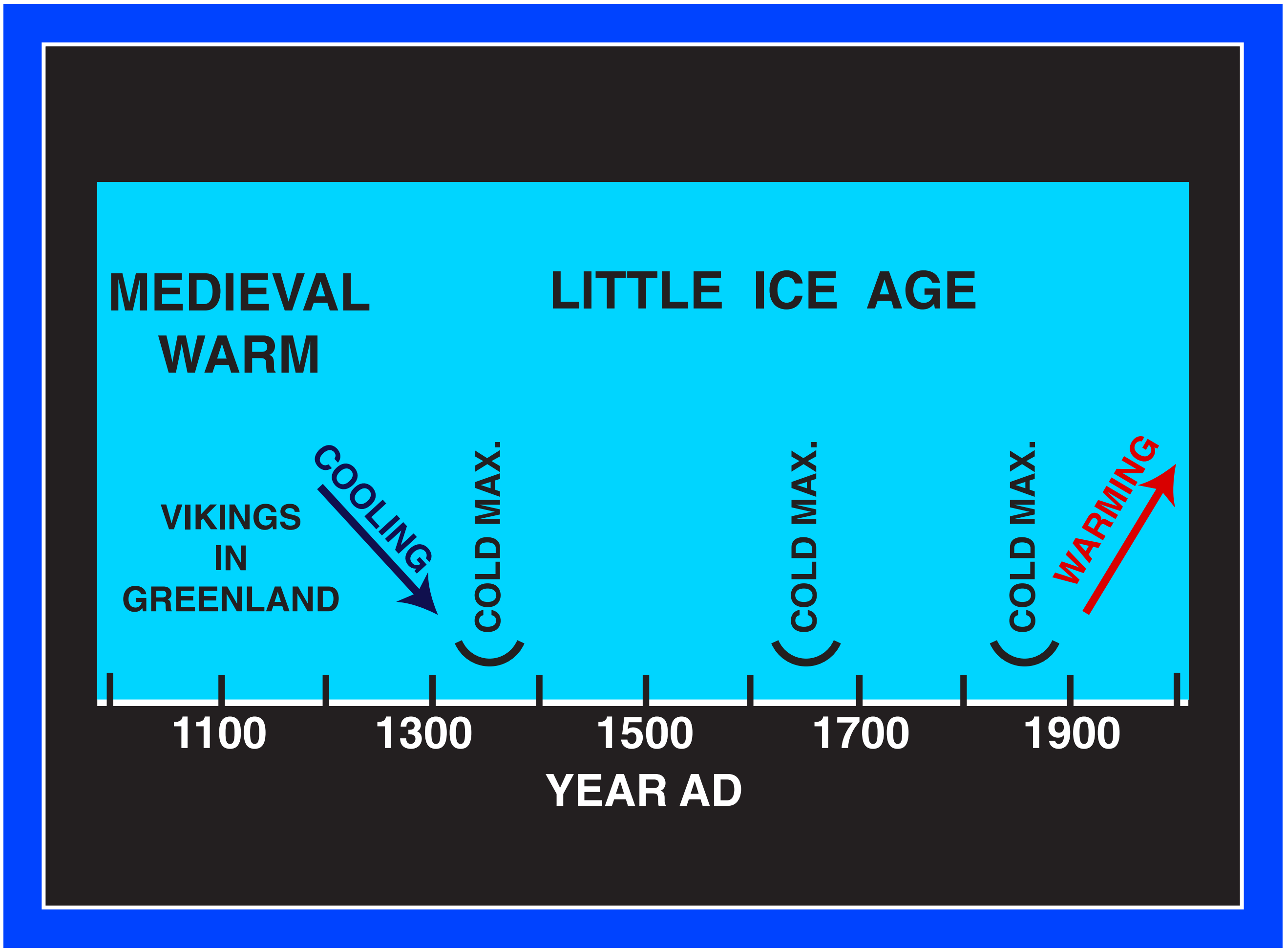

ICELAND
NUMBER OF
ICEBOUND MONTHS / YR
0
1
2
3
4
2.5
3.0
3.5 °C
4.0
4.5
WARMER
1600
1700
1800
1900
2000
ICE FRONT RETREAT (km)
0
0.5
1.0
1.5
SWISS ALPS
WARMER
1600
1700
1800
1900
2000 YEAR A.D.

Figure 13



MEDIEVAL
WARM
LITTLE ICE AGE
VIKINGS
IN
GREENLAND
COOLING
COLD MAX.
COLD MAX.
COLD MAX.
WARMING
1100
1300
1500
1700
1900
YEAR AD

Figure 14

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).

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 altitude (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, temperatures during this interval were comparable to those for the last decade. This record also 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

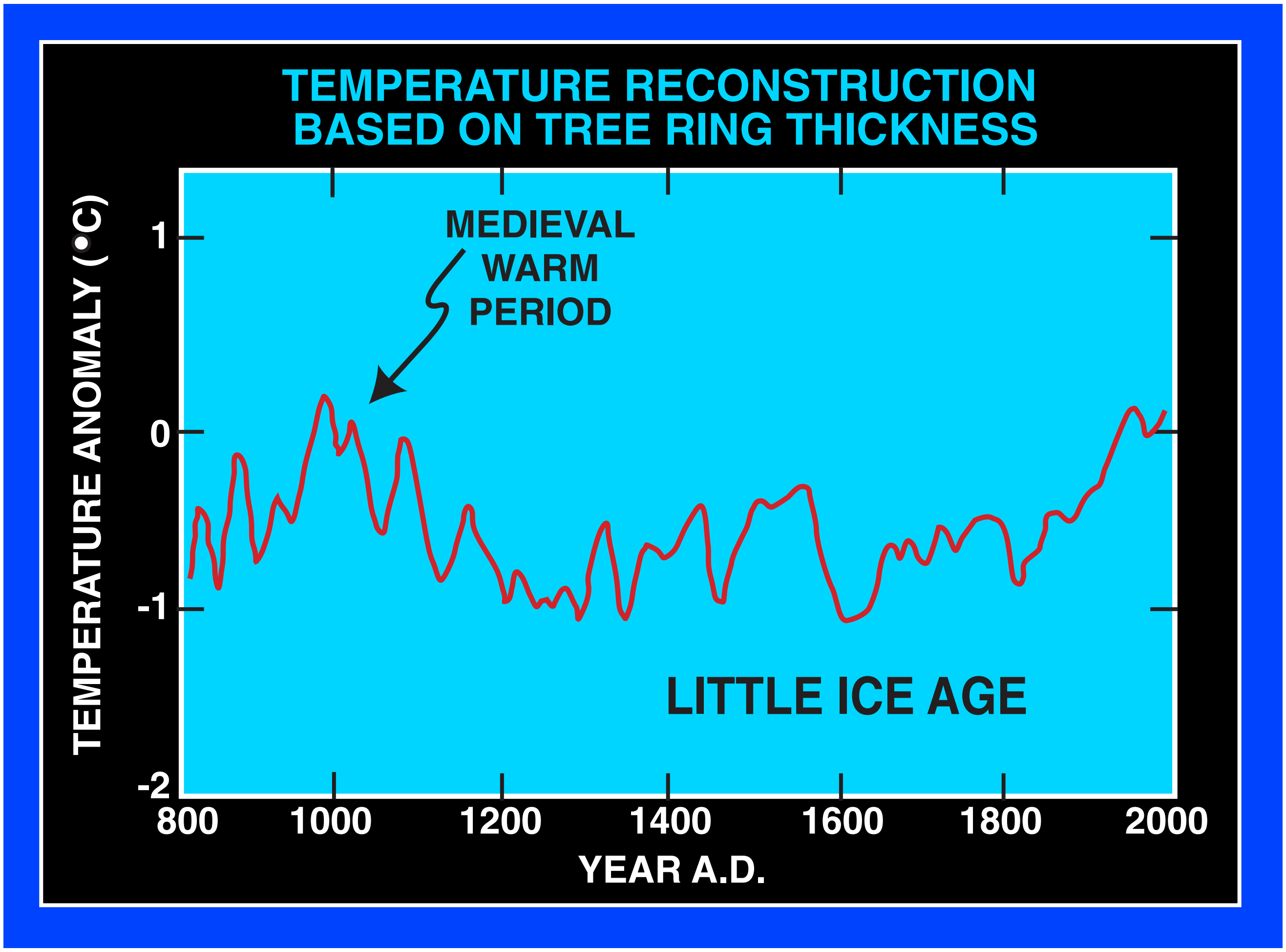

TEMPERATURE RECONSTRUCTION
BASED ON TREE RING THICKNESS
MEDIEVAL
WARM
PERIOD
LITTLE ICE AGE
TEMPERATURE ANOMALY (•C)
1
0
-1
-2
800
1000
1200
1400
1600
1800
2000
YEAR A.D.

Figure 15

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 the same age are found growing from the bottom of Mono Lake which, until the streams feeding it were 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 Earth was 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. 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


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

Figure 16

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 #2) 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 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 long enough to reach the sites of his sediment cores before melting. In other cores Bond was able to show that the most recent of these red-grain rich zones correspond to the Little Ice Age.

Evidence that Bond s red-grain cycles were 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,

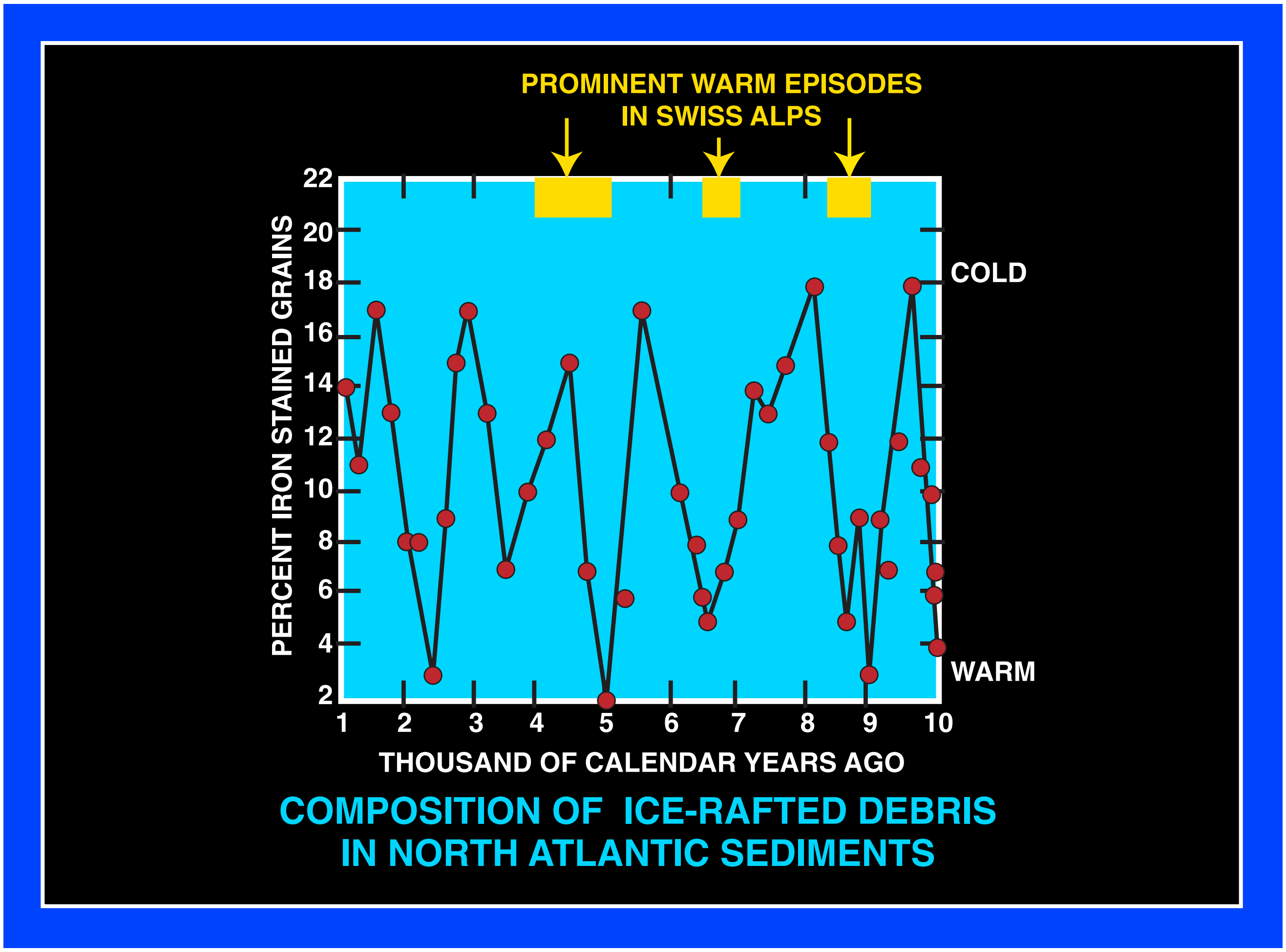
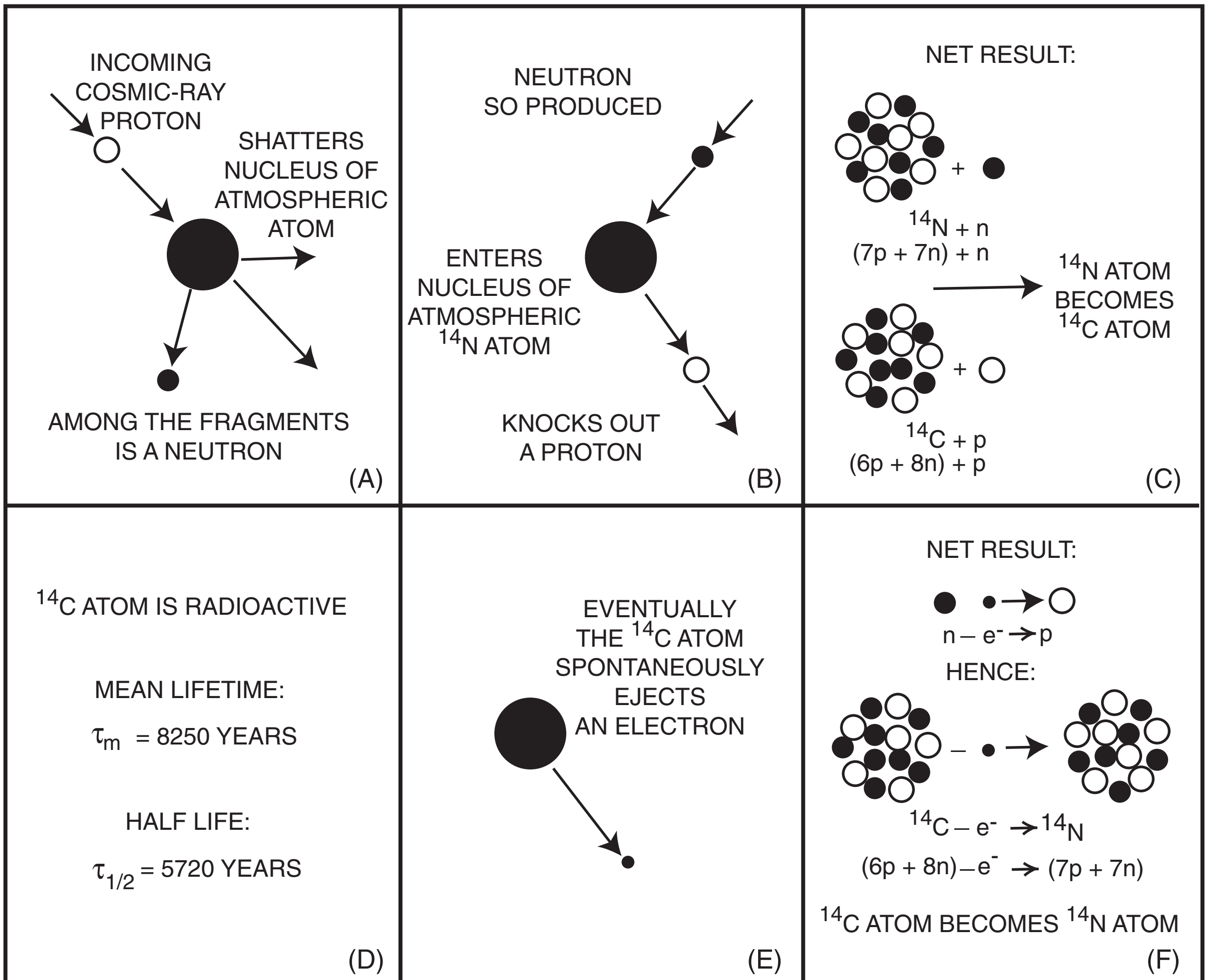

PROMINENT WARM EPISODES
IN SWISS ALPS
PERCENT IRON STAINED GRAINS
22
20
18
16
14
12
10
8
6
4
2
COLD
WARM
1
2
3
4
5
6
7
8
9
10
THOUSAND OF CALENDAR YEARS AGO
COMPOSITION OF ICE-RAFTED DEBRIS
IN NORTH ATLANTIC SEDIMENTS

Figure 17

THE LIFE CYCLE OF RADIOCARBON ATOMS



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

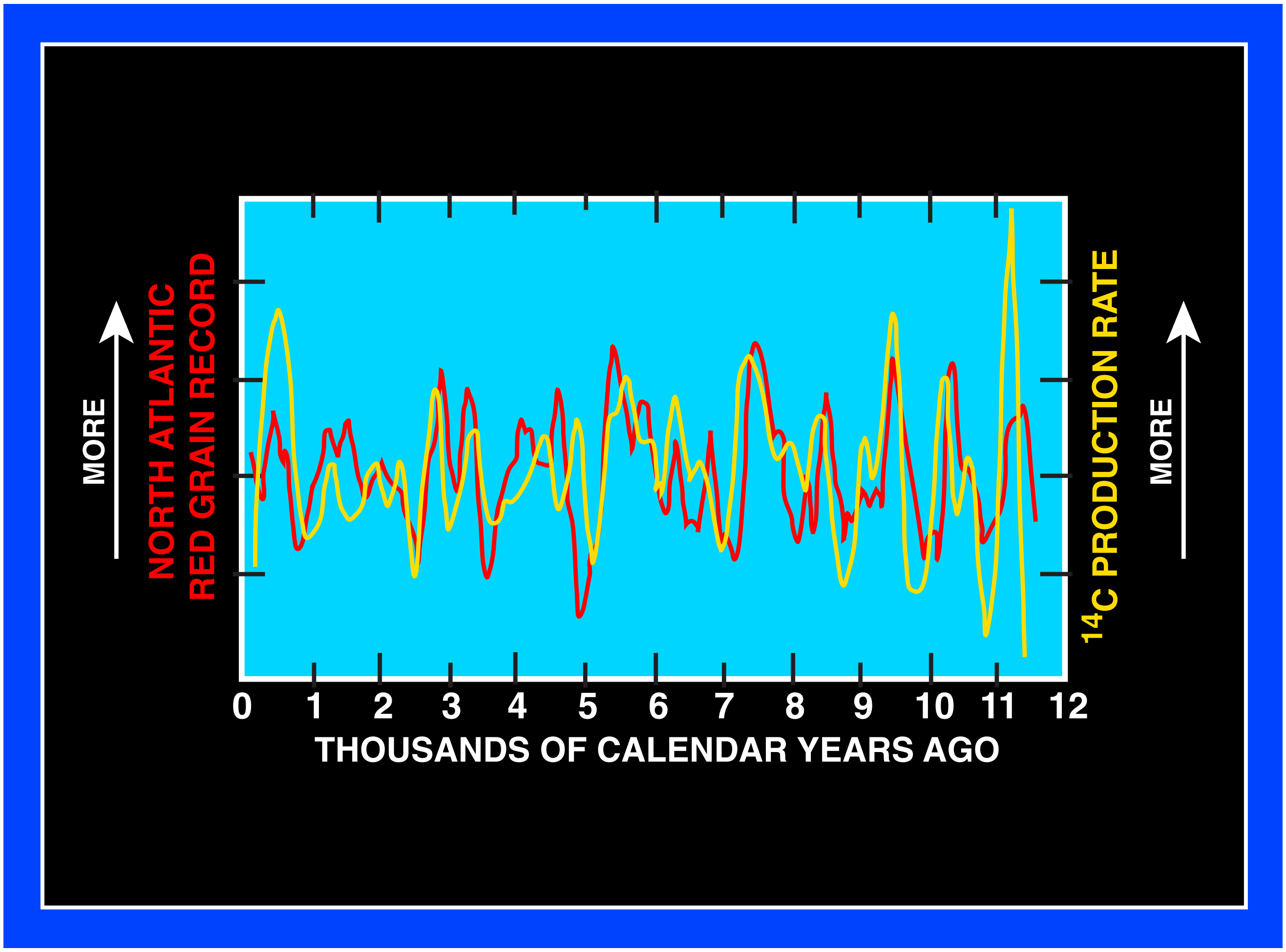
Sidebar #2

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 #3). 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 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

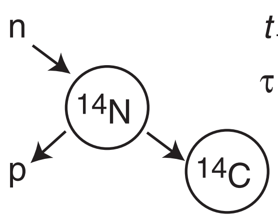


MORE
NORTH ATLANTIC
RED GRAIN RECORD
^{14}C PRODUCTION RATE
MORE
0
1
2
3
4
5
6
7
8
9
10
11
12
THOUSANDS OF CALENDAR YEARS AGO

Figure 18

COSMOGENIC ISOTOPES

^{14}C PRODUCTION



$t_{1/2}$ = 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

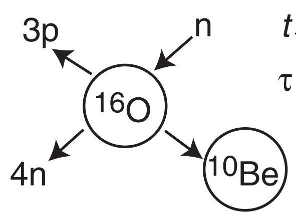
DENDROCHRONOLOGICALLY DATED TREES (BACK TO 12,000 YEARS AGO)

$$\left.\frac{^{14}C}{C}\right)_{\text{AT GROWTH}} = \left.\frac{^{14}C}{C}\right)_{\text{MEASURED}} e^{\frac{t}{8250}}$$

AGE OF TREE RING (t)

MEANLIFE RADIOCARBON (8250)

^{10}Be PRODUCTION



$t_{1/2}$ = 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)

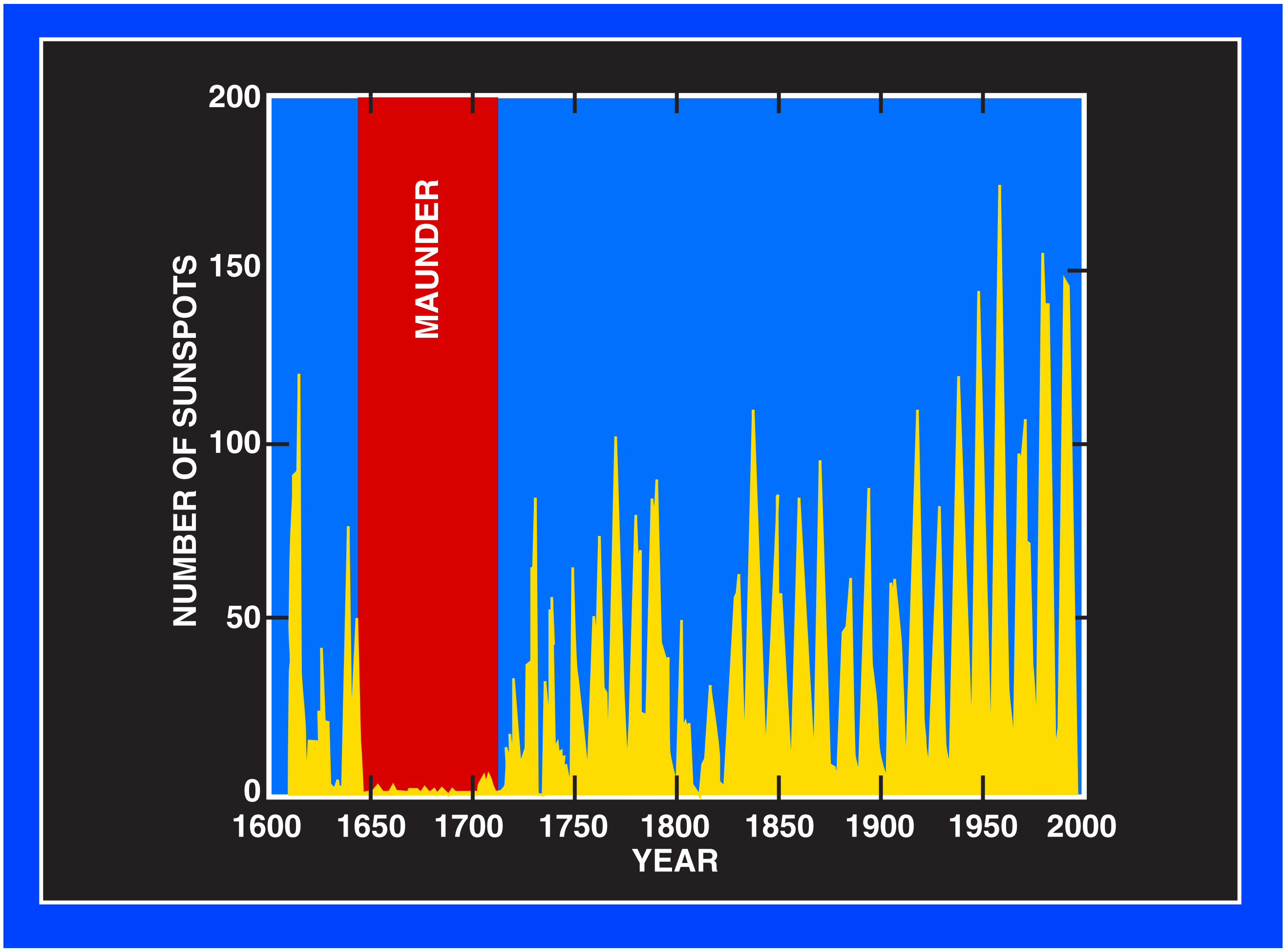
NO CORRECTION FOR LOSS BY RADIOACTIVE DECAY NECESSARY

n *STANDS FOR NEUTRON*

p *STANDS FOR PROTON*

(^{14}N), (^{14}C), (^{16}O), *AND* (^{10}Be) *ARE ATOM NUCLEII*

Sidebar #3



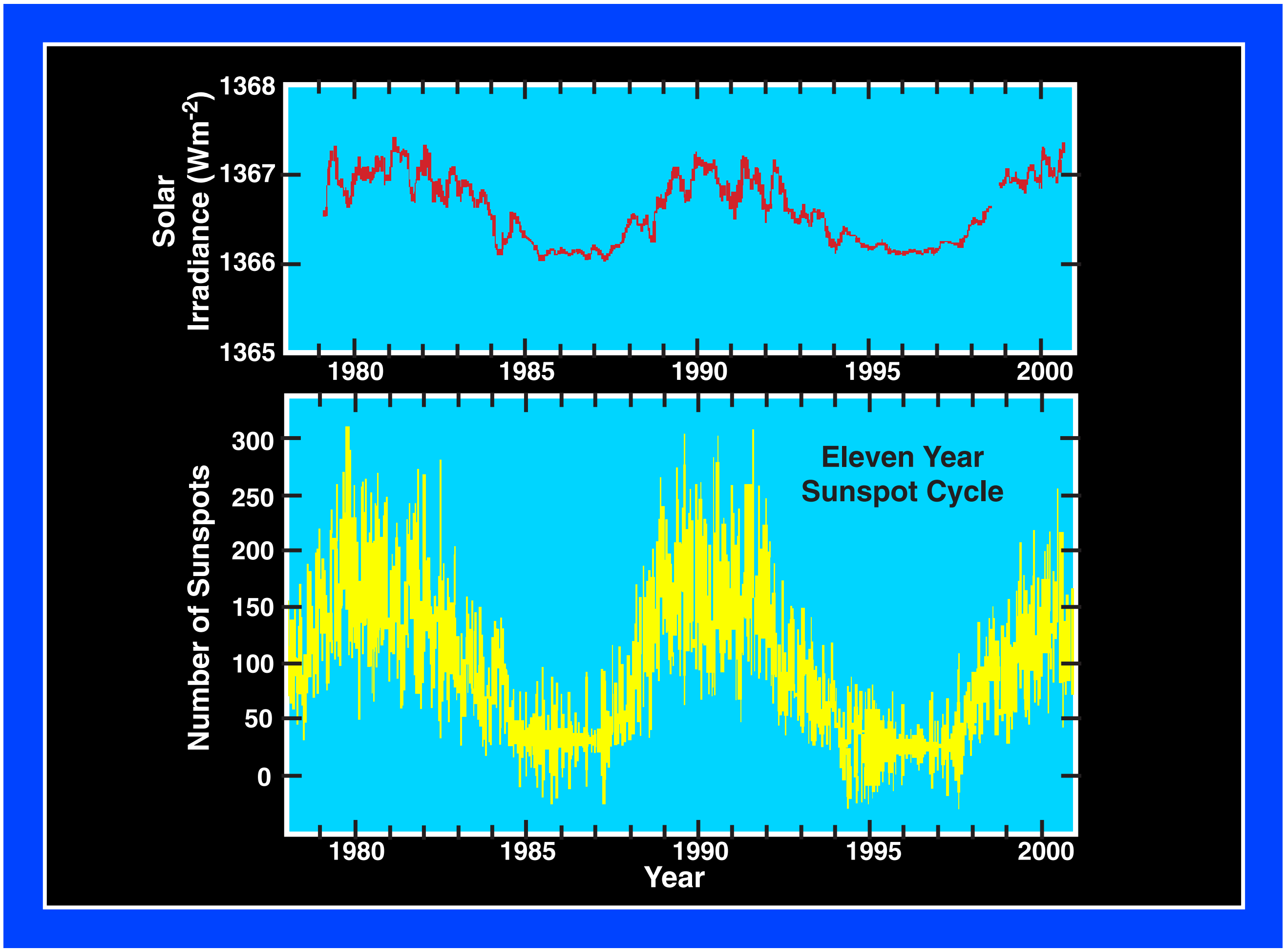
200
150
100
50
0
NUMBER OF SUNSPOTS
MAUNDER
1600
1650
1700
1750
1800
1850
1900
1950
2000
YEAR

Figure 19

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 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 were 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.

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



Solar Irradiance (Wm-2)
1368
1367
1366
1365
1980
1985
1990
1995
2000
Number of Sunspots
300
250
200
150
100
50
0
Eleven Year Sunspot Cycle
Year

Figure 20

whether 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 driven significant Earth temperature changes over the last 12,000 years.

Correlations are 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.

Lecture #2

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 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). At the time of each full glacial 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 southern Andes and New Zealand s South Island. 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. Surface temperatures in the equatorial oceans were 3°C lower 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). Each of these episodes of glaciation was terminated by an abrupt warming which returned the Earth to full interglacial conditions.

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, a water molecule made with ^{18}O has a one percent lower vapor pressure than 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.

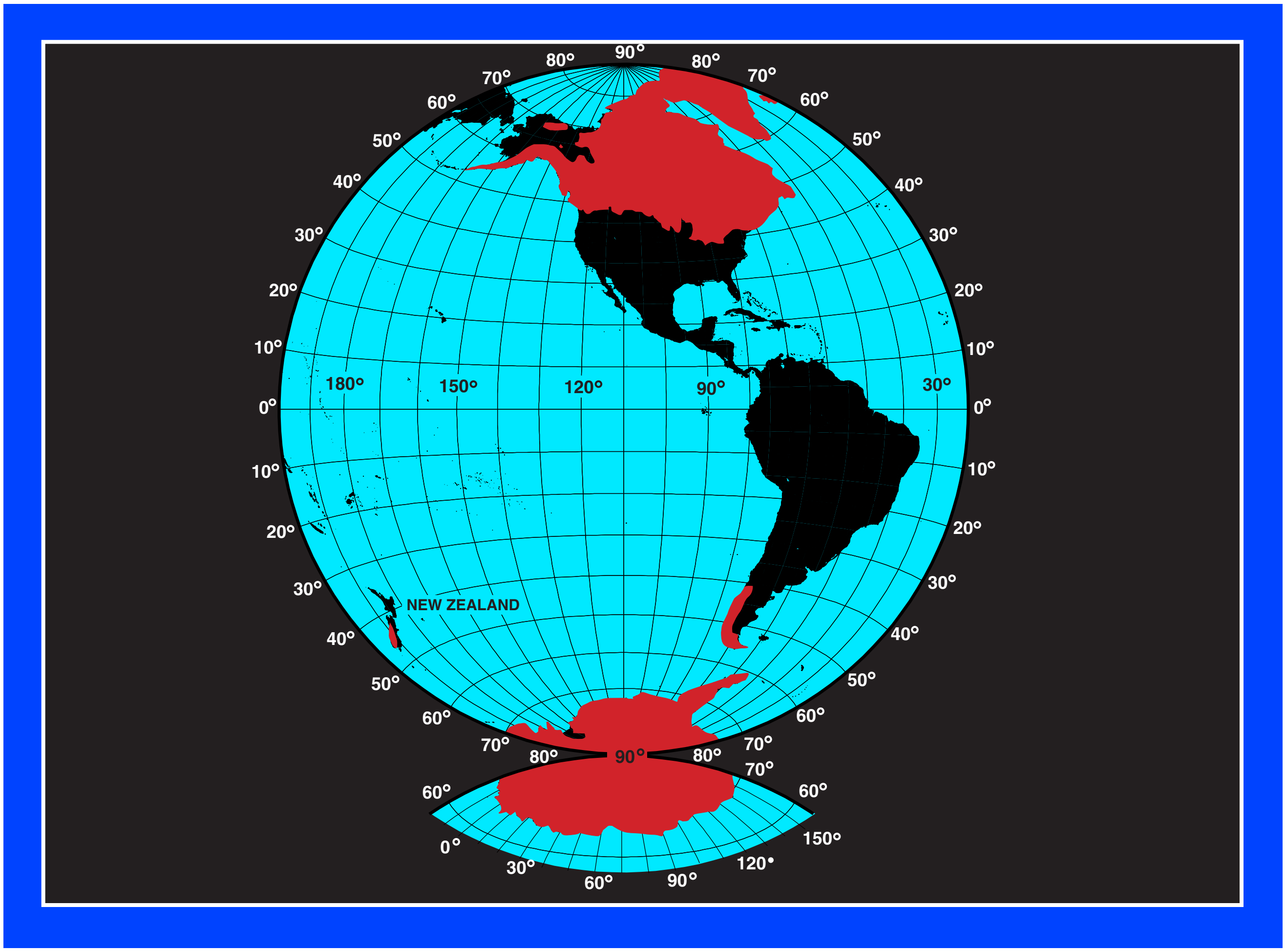
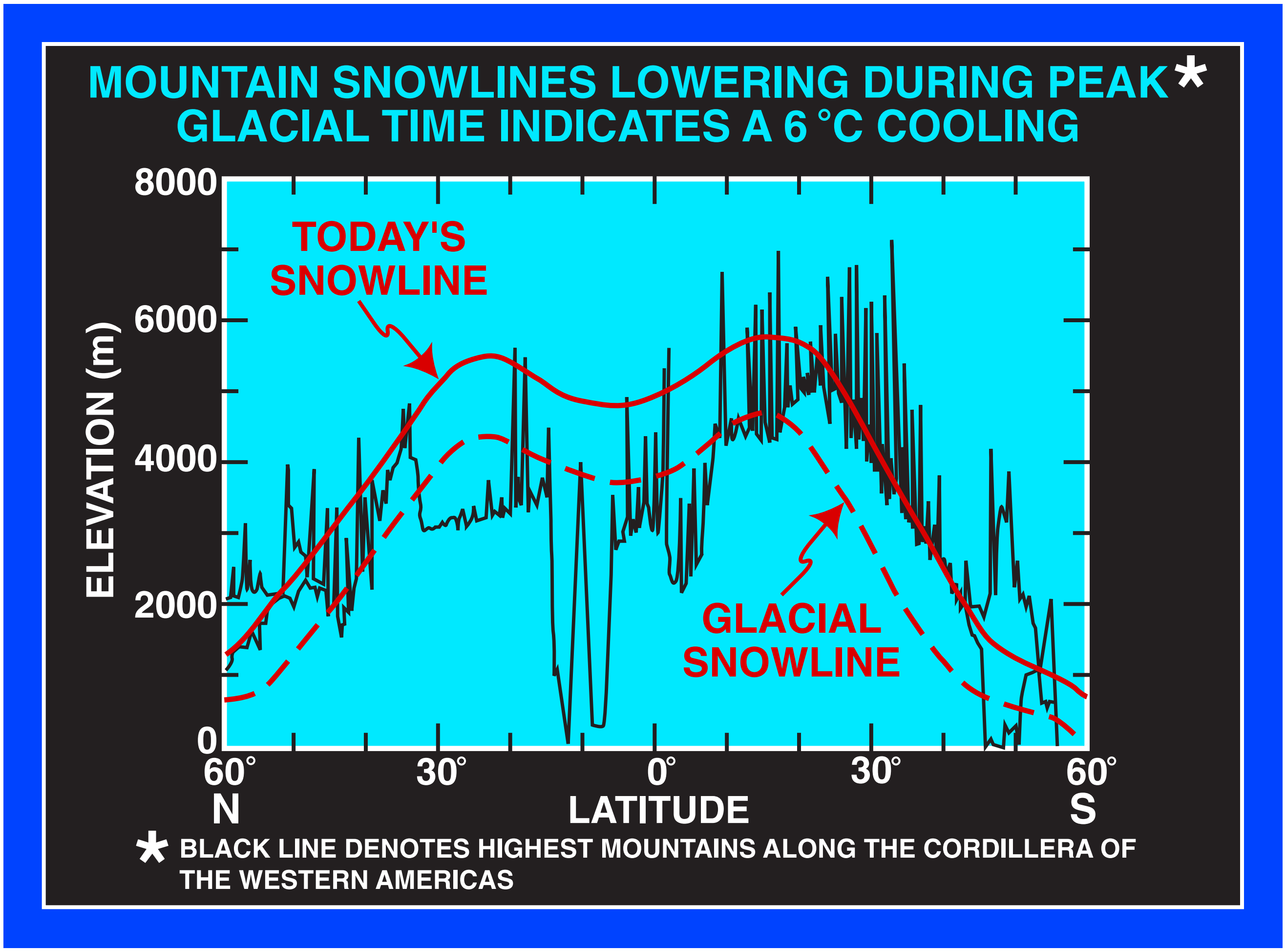
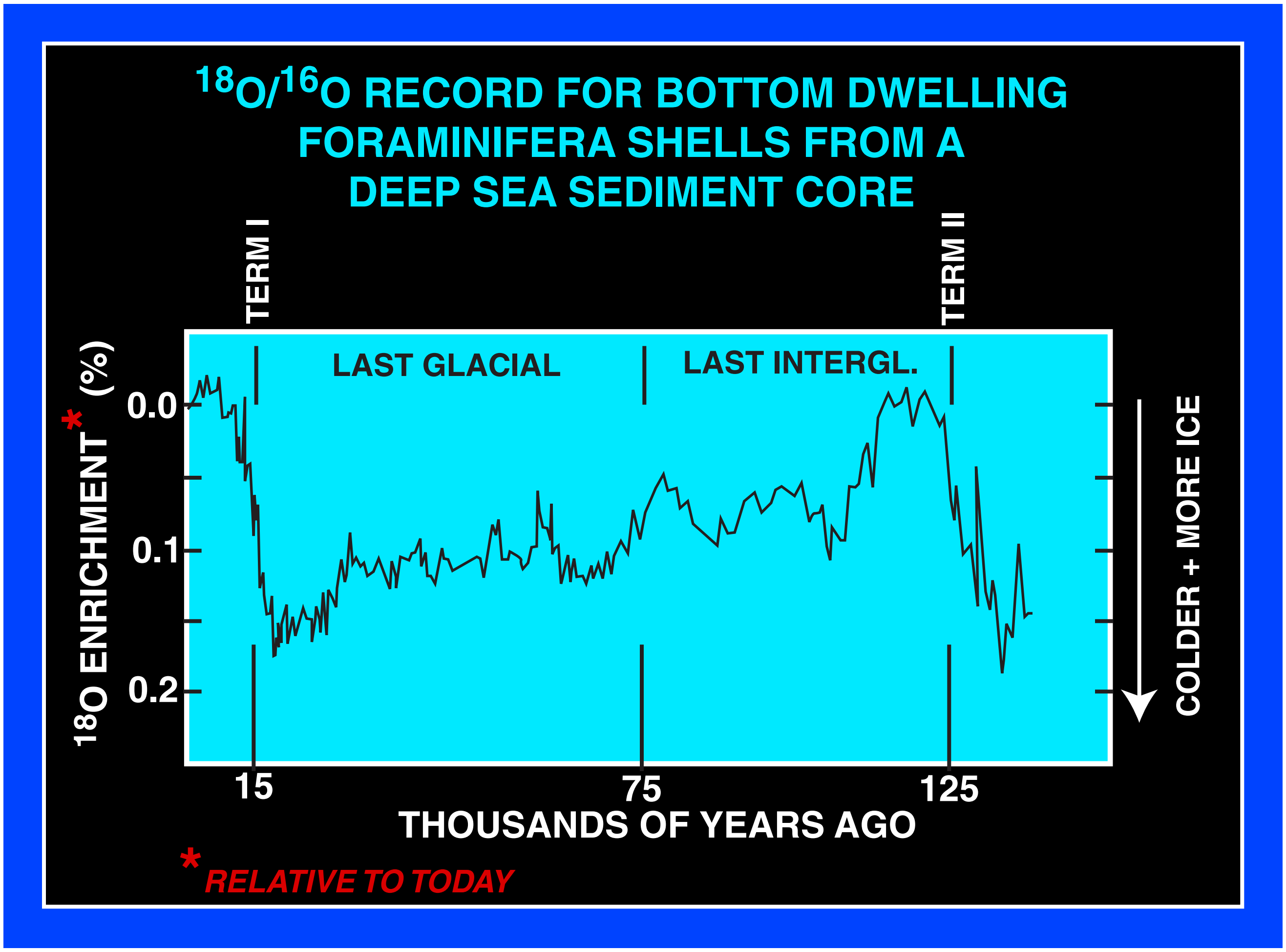


Figure 21



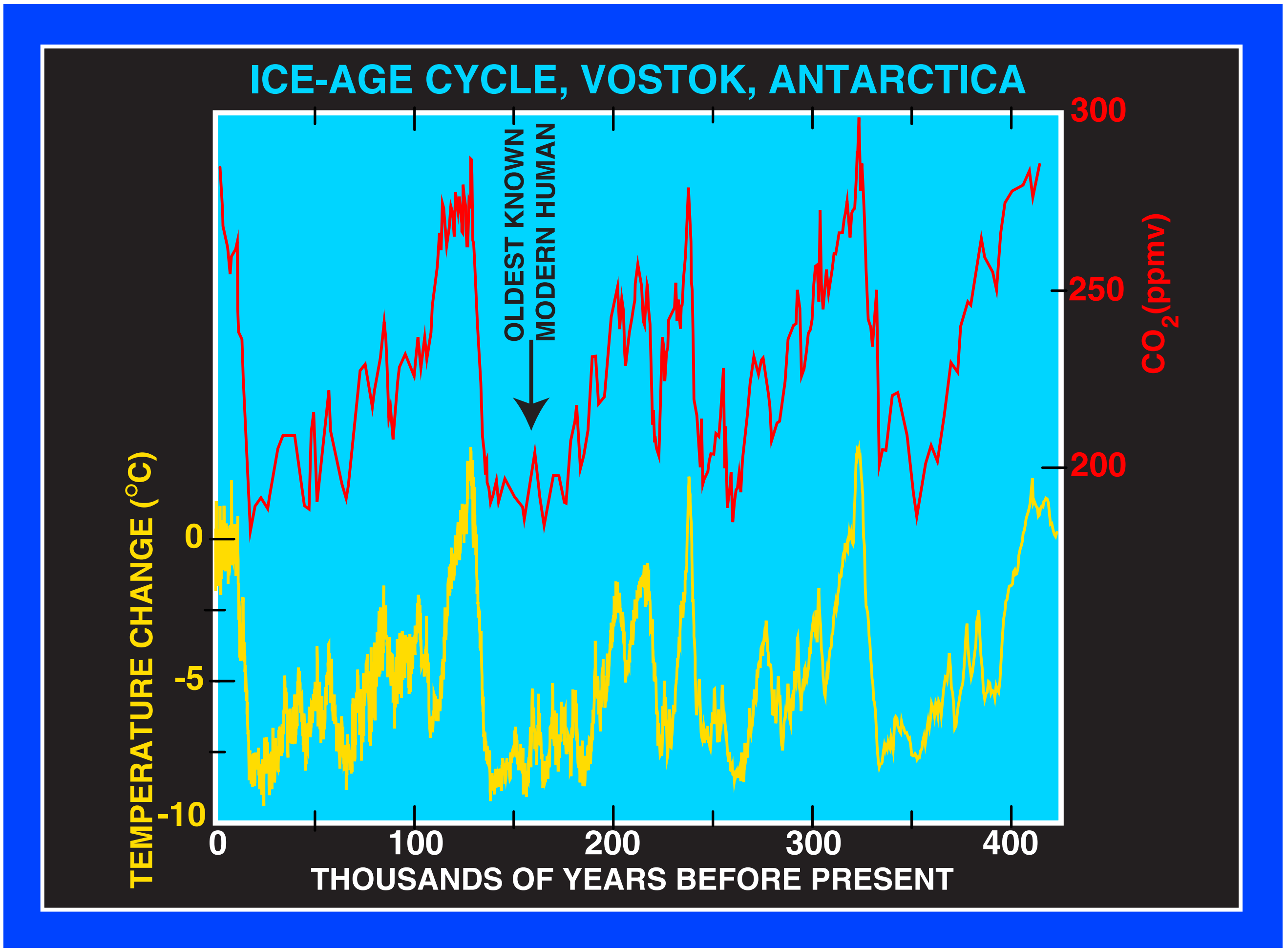
MOUNTAIN SNOWLINES LOWERING DURING PEAK*
GLACIAL TIME INDICATES A 6 °C COOLING
8000
6000
4000
2000
0
ELEVATION (m)
TODAY'S
SNOWLINE
GLACIAL
SNOWLINE
60°
N
30°
0°
30°
60°
S
LATITUDE
* BLACK LINE DENOTES HIGHEST MOUNTAINS ALONG THE CORDILLERA OF THE WESTERN AMERICAS

Figure 22



18O/16O RECORD FOR BOTTOM DWELLING
FORAMINIFERA SHELLS FROM A
DEEP SEA SEDIMENT CORE
TERM I
TERM II
LAST GLACIAL
LAST INTERGL.
18O ENRICHMENT* (%)
0.0
0.1
0.2
15
75
125
THOUSANDS OF YEARS AGO
COLDER + MORE ICE
*RELATIVE TO TODAY

Figure 23

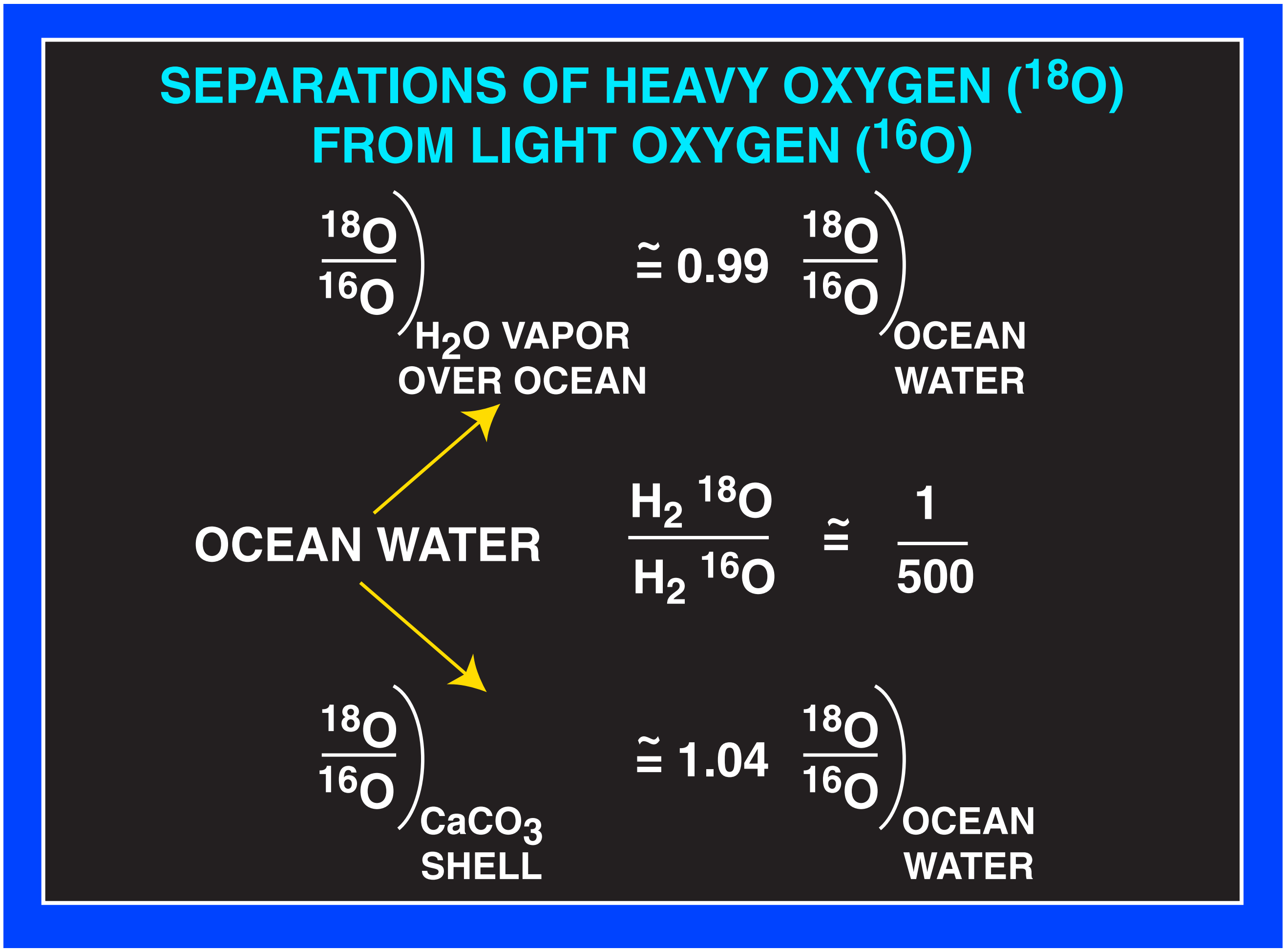


ICE-AGE CYCLE, VOSTOK, ANTARCTICA
OLDEST KNOWN
MODERN HUMAN
TEMPERATURE CHANGE (°C)
0
-5
-10
300
250
200
CO2 (ppmv)
0
100
200
300
400
THOUSANDS OF YEARS BEFORE PRESENT

Figure 24

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. As the air mass containing this water vapor is cooled as it moves poleward, precipitation occurs. 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 paleotemperatuere.



SEPARATIONS OF HEAVY OXYGEN (18O)
FROM LIGHT OXYGEN (16O)
18O/16O H2O VAPOR OVER OCEAN ≅ 0.99 18O/16O OCEAN WATER
OCEAN WATER
H2 18O / H2 16O ≅ 1/500
18O/16O CaCO3 SHELL ≅ 1.04 18O/16O OCEAN WATER

Figure 25

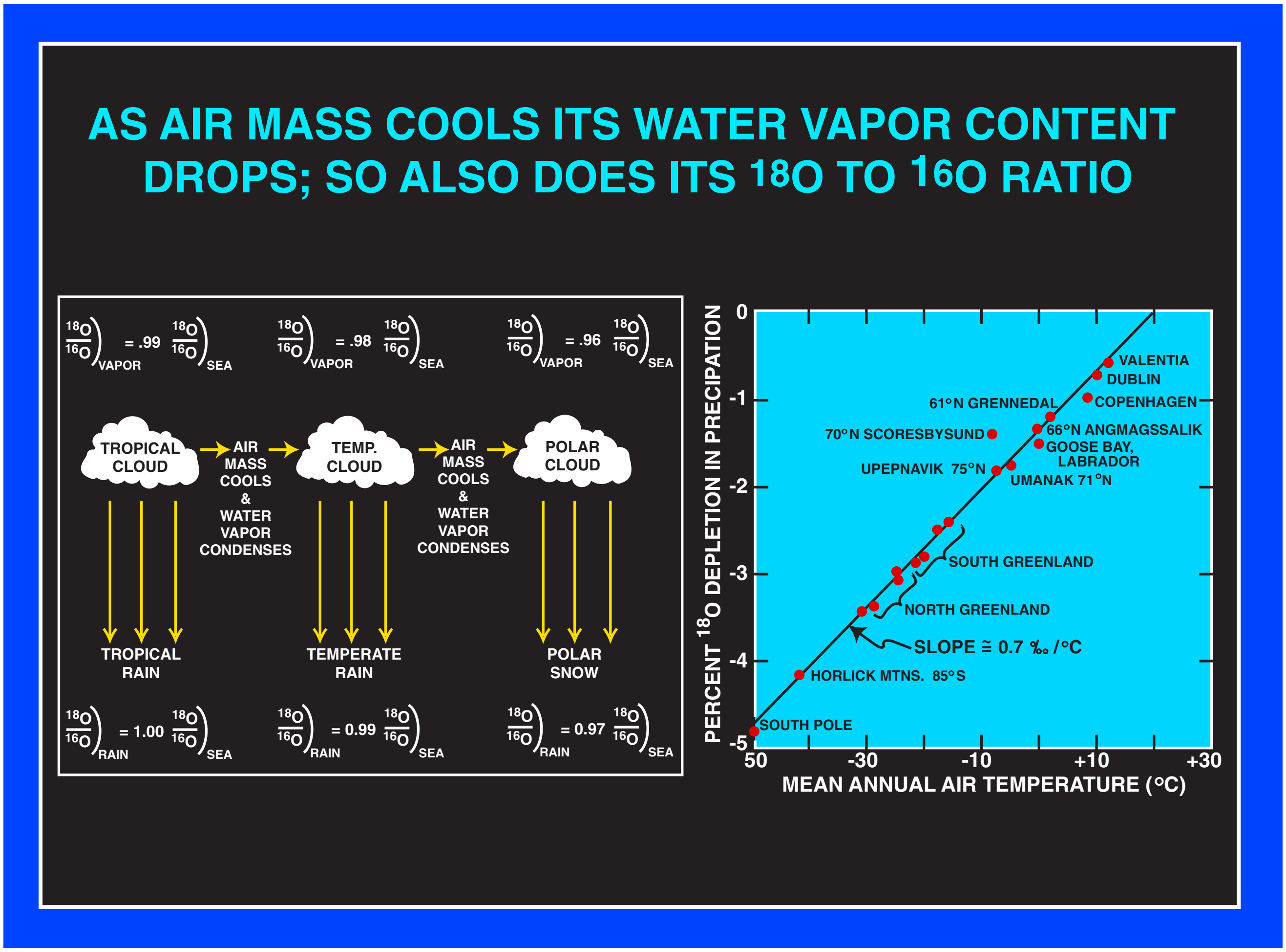
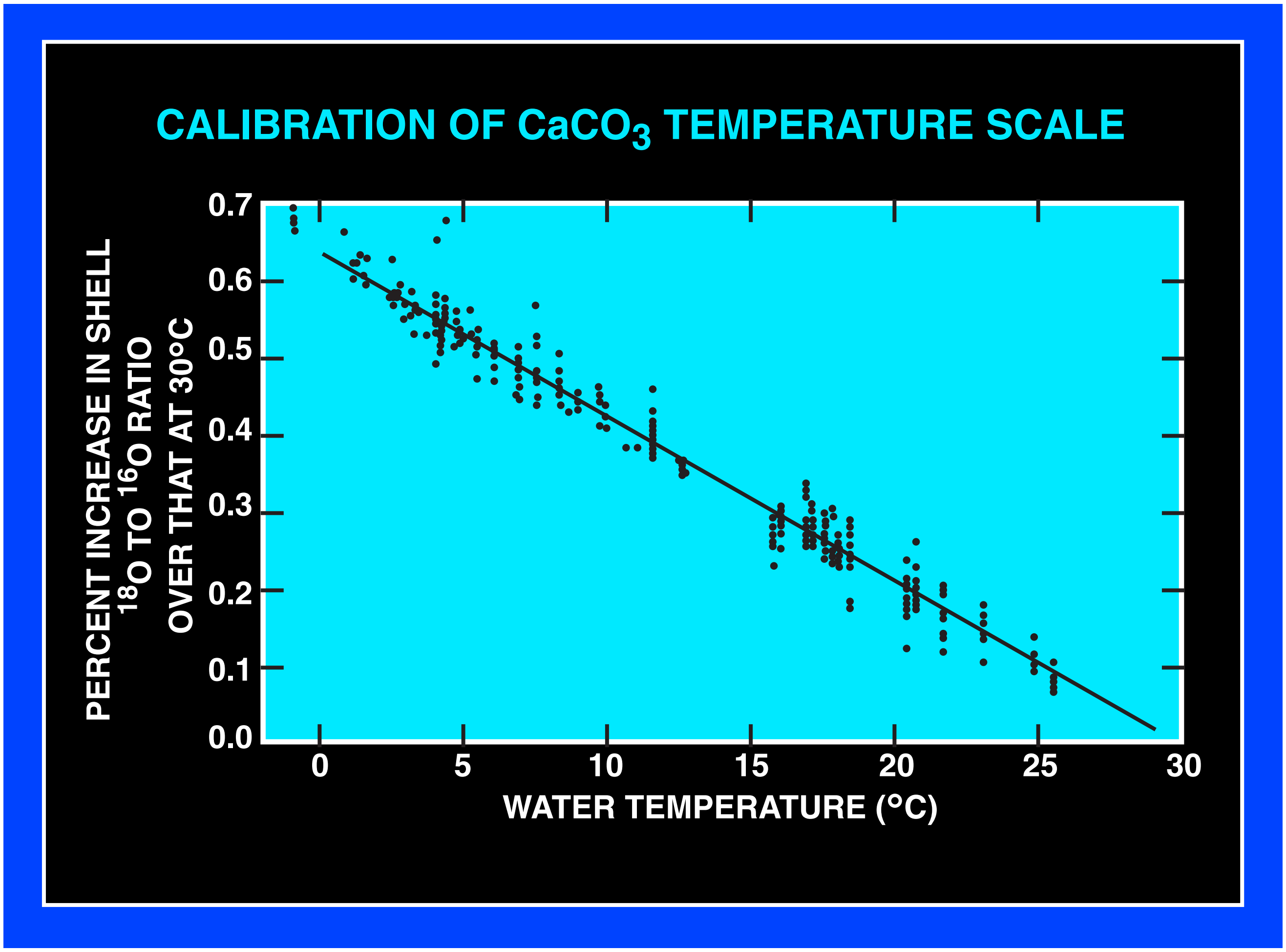

AS AIR MASS COOLS ITS WATER VAPOR CONTENT DROPS; SO ALSO DOES ITS 18O TO 16O RATIO
TROPICAL CLOUD
AIR MASS COOLS & WATER VAPOR CONDENSES
TEMP. CLOUD
AIR MASS COOLS & WATER VAPOR CONDENSES
POLAR CLOUD
TROPICAL RAIN
TEMPERATE RAIN
POLAR SNOW
VAPOR
SEA
RAIN
= .99
= .98
= .96
= 1.00
= 0.99
= 0.97
PERCENT 18O DEPLETION IN PRECIPATION
MEAN ANNUAL AIR TEMPERATURE (°C)
VALENTIA
DUBLIN
COPENHAGEN
61°N GRENNEDAL
70°N SCORESBYSUND
66°N ANGMAGSSALIK
GOOSE BAY, LABRADOR
UPEPNAVIK 75°N
UMANAK 71°N
SOUTH GREENLAND
NORTH GREENLAND
SLOPE ≅ 0.7 ‰ /°C
HORLICK MTNS. 85°S
SOUTH POLE

Figure 26



CALIBRATION OF CaCO3 TEMPERATURE SCALE
PERCENT INCREASE IN SHELL
18O TO 16O RATIO
OVER THAT AT 30°C
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
5
10
15
20
25
30
WATER TEMPERATURE (°C)

Figure 27

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 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, 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

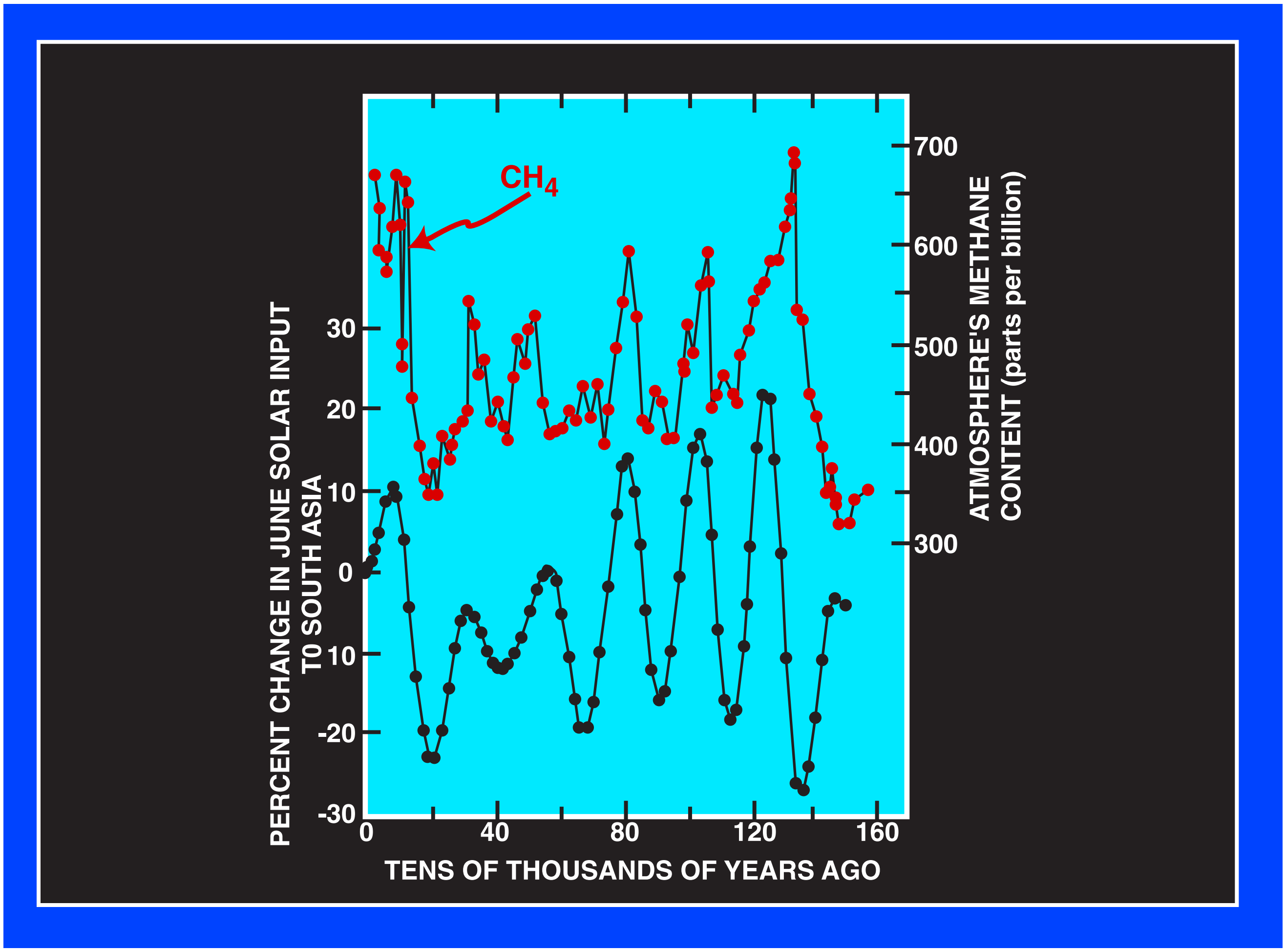
Modern look. This skull of an adult male from Ethiopia is about 160,000 years old, but it already looks like a modern human's.

Figure 28

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 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 orbital parameter changes in seasonal contrast. However, when introduced into models, just as was the case

[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.



CH4
PERCENT CHANGE IN JUNE SOLAR INPUT
T0 SOUTH ASIA
30
20
10
0
10
-20
-30
0
40
80
120
160
TENS OF THOUSANDS OF YEARS AGO
700
600
500
400
300
ATMOSPHERE'S METHANE
CONTENT (parts per billion)

Figure 29

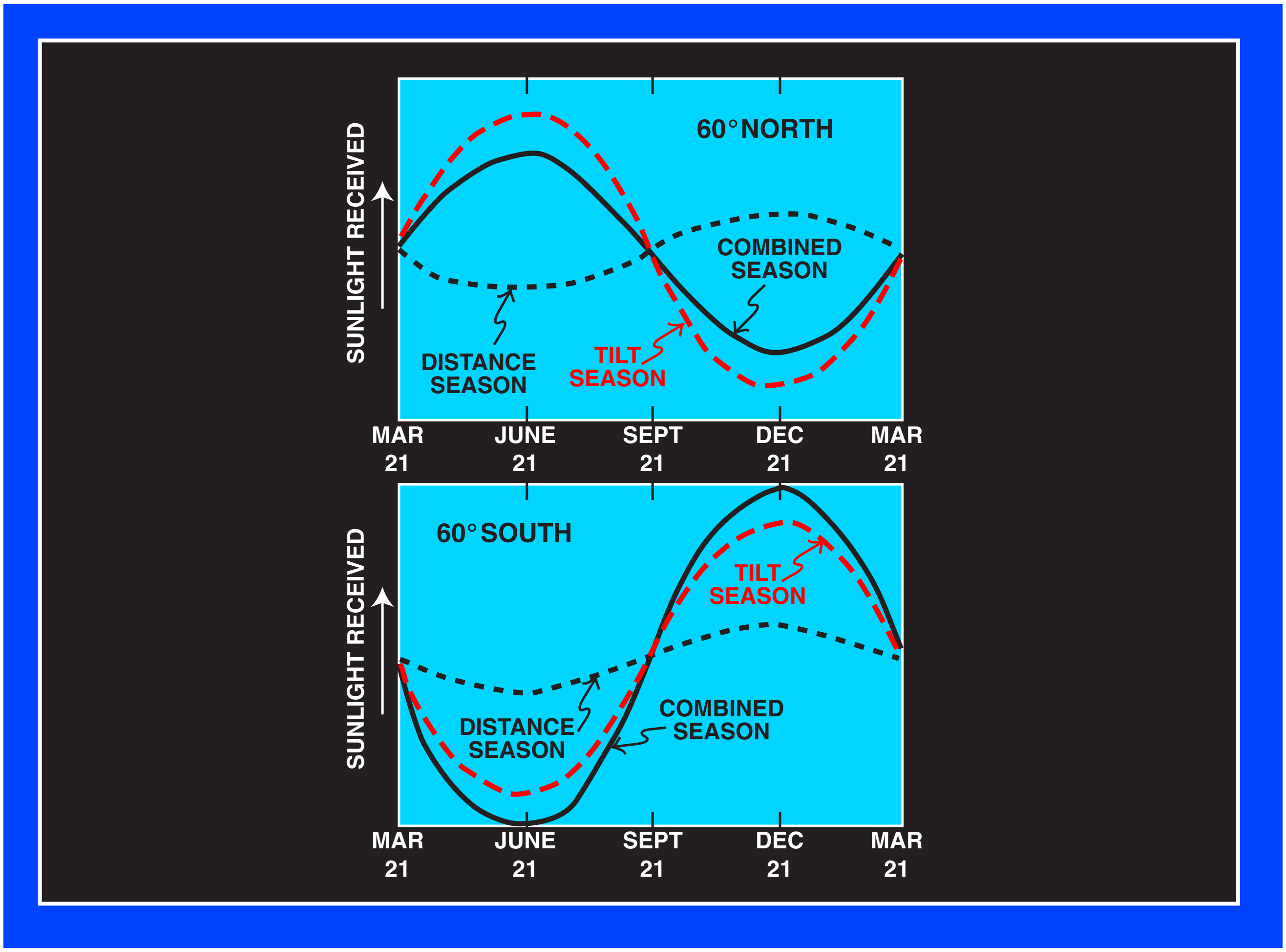
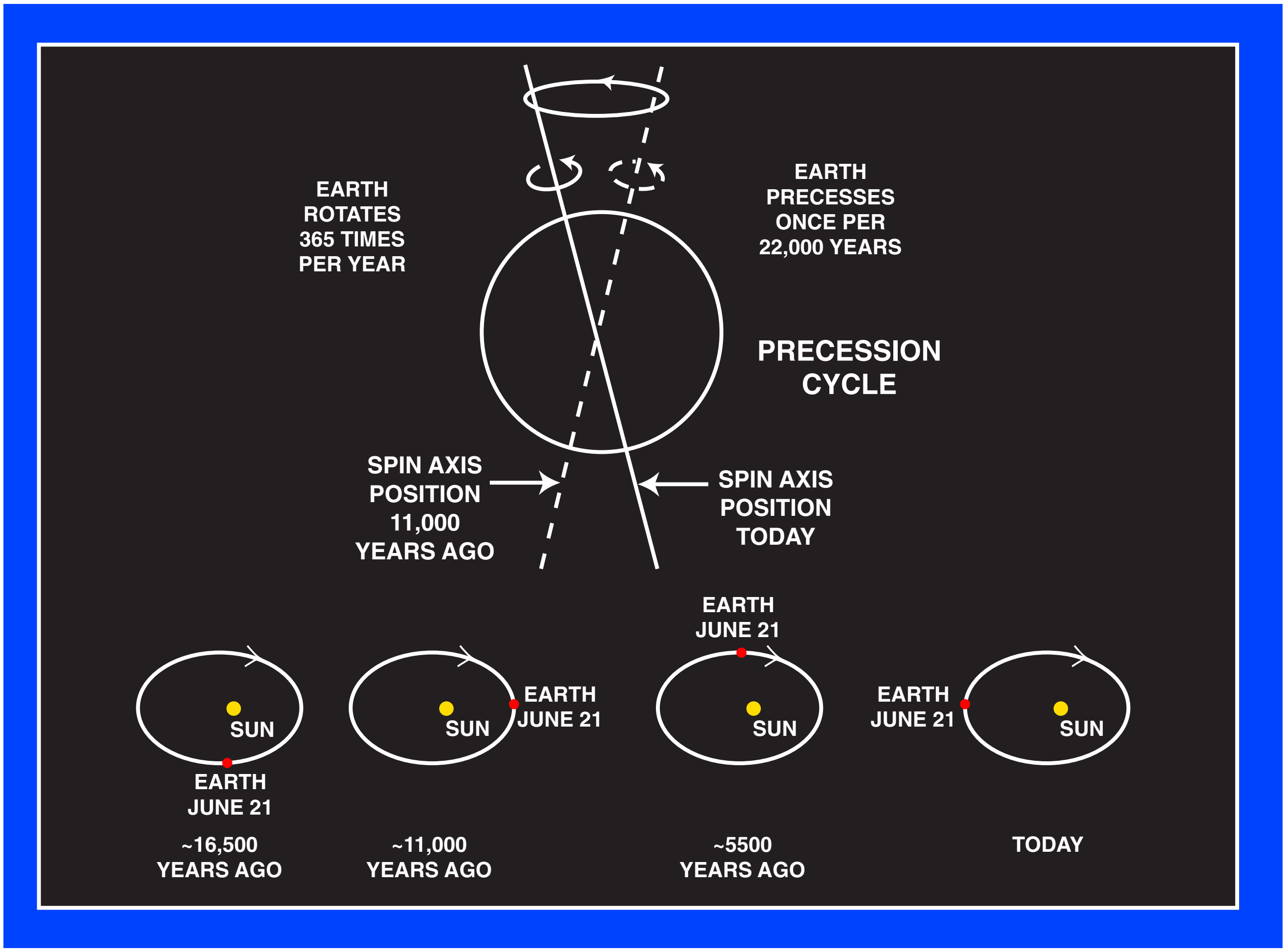

60° NORTH
SUNLIGHT RECEIVED
COMBINED SEASON
DISTANCE SEASON
TILT SEASON
MAR 21
JUNE 21
SEPT 21
DEC 21
MAR 21
60° SOUTH
SUNLIGHT RECEIVED
TILT SEASON
COMBINED SEASON
DISTANCE SEASON
MAR 21
JUNE 21
SEPT 21
DEC 21
MAR 21

Figure 30



EARTH
ROTATES
365 TIMES
PER YEAR
EARTH
PRECESSES
ONCE PER
22,000 YEARS
PRECESSION
CYCLE
SPIN AXIS
POSITION
11,000
YEARS AGO
SPIN AXIS
POSITION
TODAY
EARTH
JUNE 21
SUN
EARTH
JUNE 21
SUN
EARTH
JUNE 21
SUN
EARTH
JUNE 21
SUN
~16,500
YEARS AGO
~11,000
YEARS AGO
~5500
YEARS AGO
TODAY

Figure 31

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 appears to have 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 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 observed in ocean sediment and in Antarctic ice, those for Greenland 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 Greenland ice,

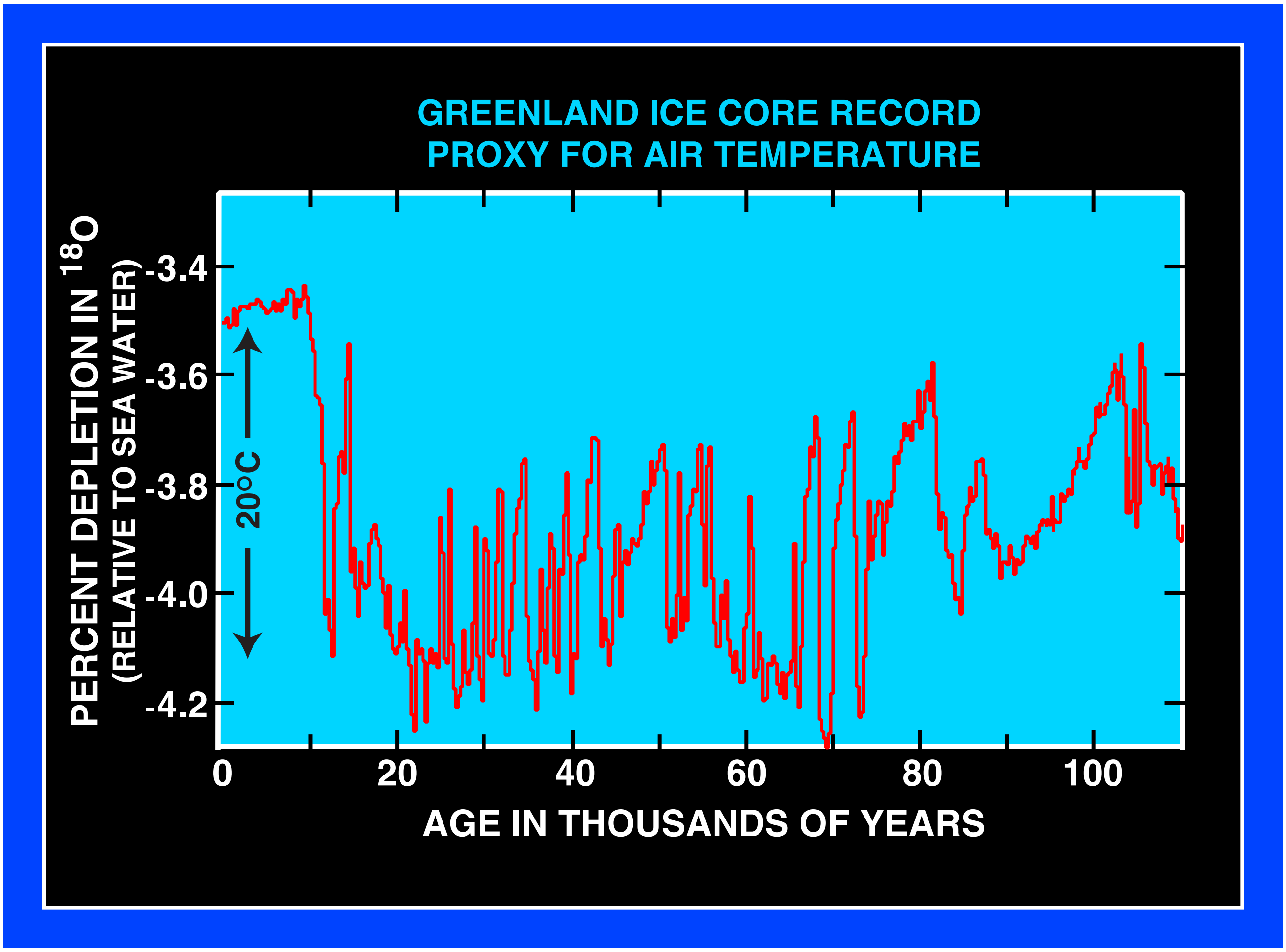
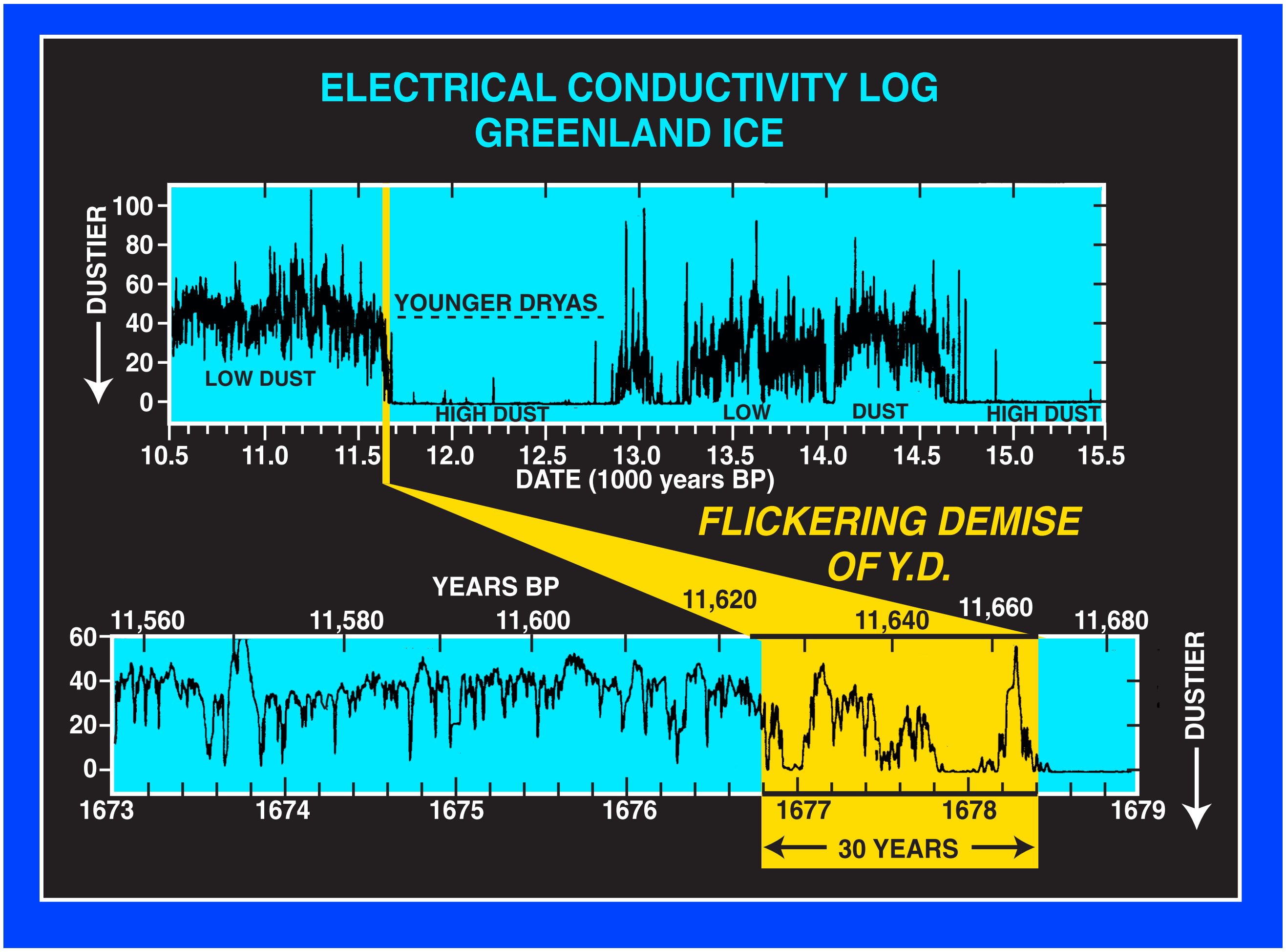

GREENLAND ICE CORE RECORD
PROXY FOR AIR TEMPERATURE
PERCENT DEPLETION IN 18O
(RELATIVE TO SEA WATER)
-3.4
-3.6
-3.8
-4.0
-4.2
20°C
0
20
40
60
80
100
AGE IN THOUSANDS OF YEARS

Figure 32

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 6° to 10°C. In addition, the infall rates of both soil dust and of 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 atmospheric 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 was 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 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



ELECTRICAL CONDUCTIVITY LOG
GREENLAND ICE
DUSTIER
100
80
60
40
20
0
YOUNGER DRYAS
LOW DUST
HIGH DUST
LOW
DUST
HIGH DUST
10.5
11.0
11.5
12.0
12.5
13.0
13.5
14.0
14.5
15.0
15.5
DATE (1000 years BP)
FLICKERING DEMISE
OF Y.D.
YEARS BP
11,560
11,580
11,600
11,620
11,640
11,660
11,680
60
40
20
0
1673
1674
1675
1676
1677
1678
1679
30 YEARS
DUSTIER

Figure 33

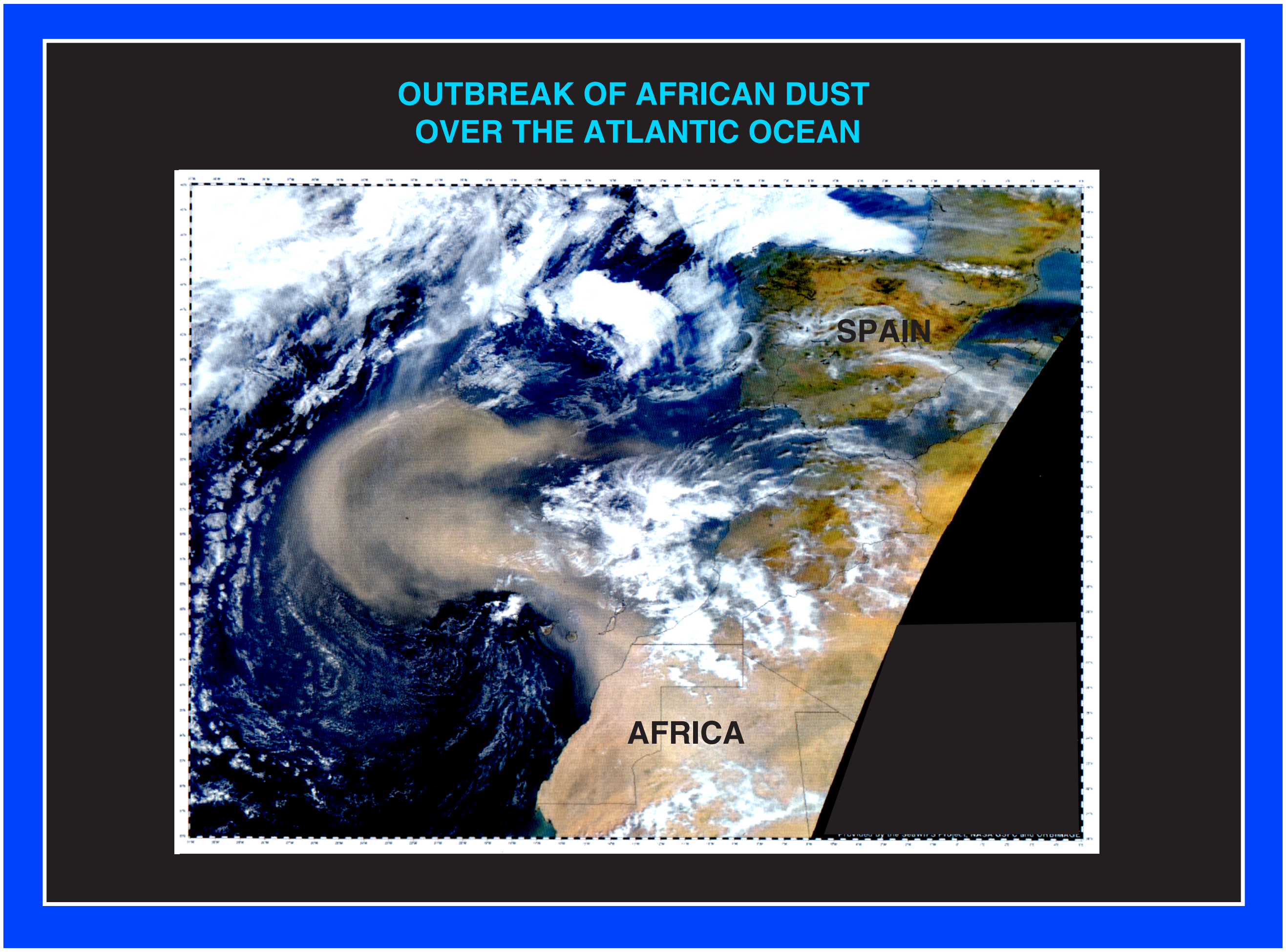

OUTBREAK OF AFRICAN DUST
OVER THE ATLANTIC OCEAN
SPAIN
AFRICA

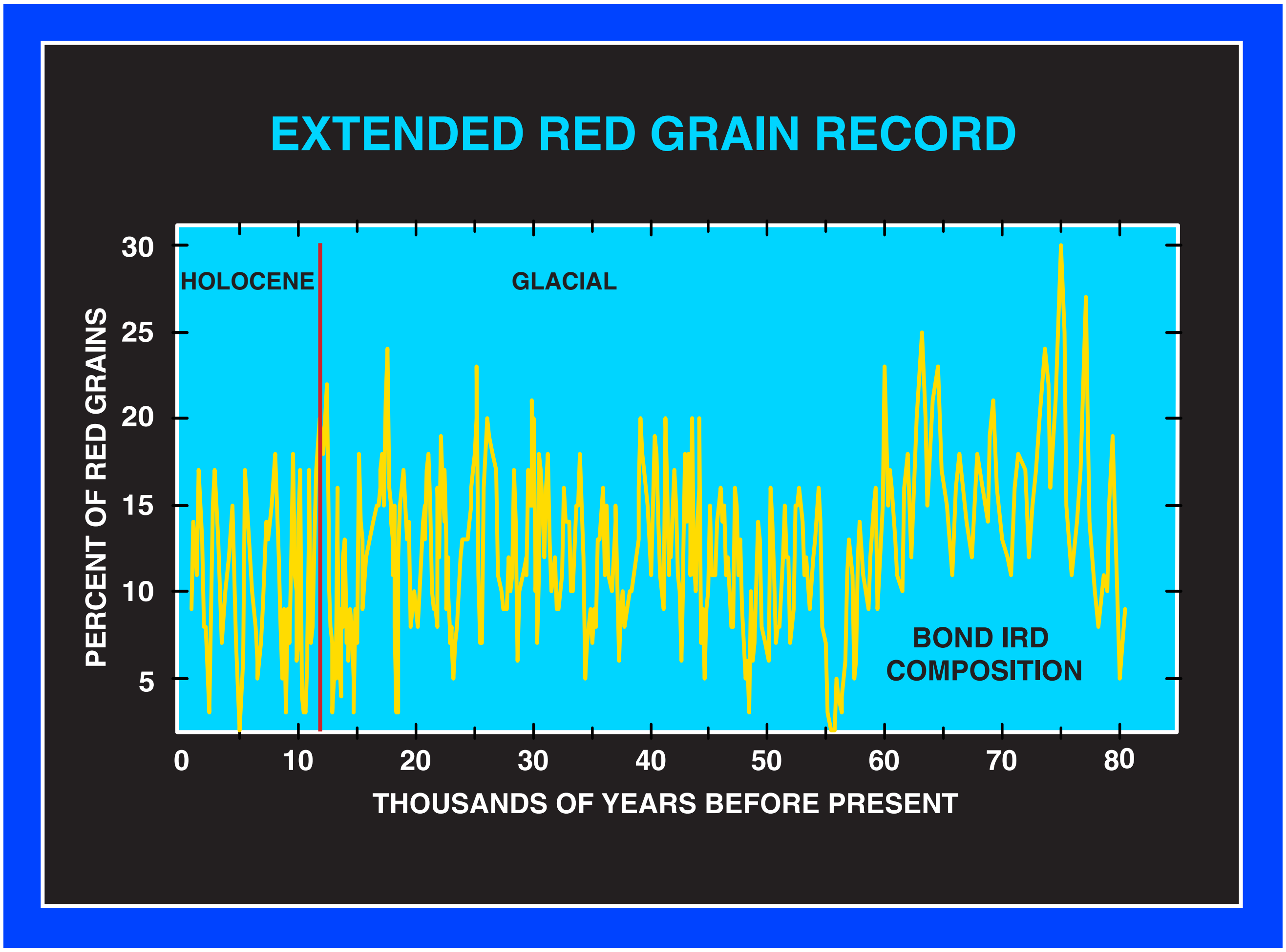
Figure 34

sea salt aerosols serve as cloud condensation nuclei, they may well have enhanced the Earth s reflectivity.

The Dasgaard-Oeschger events

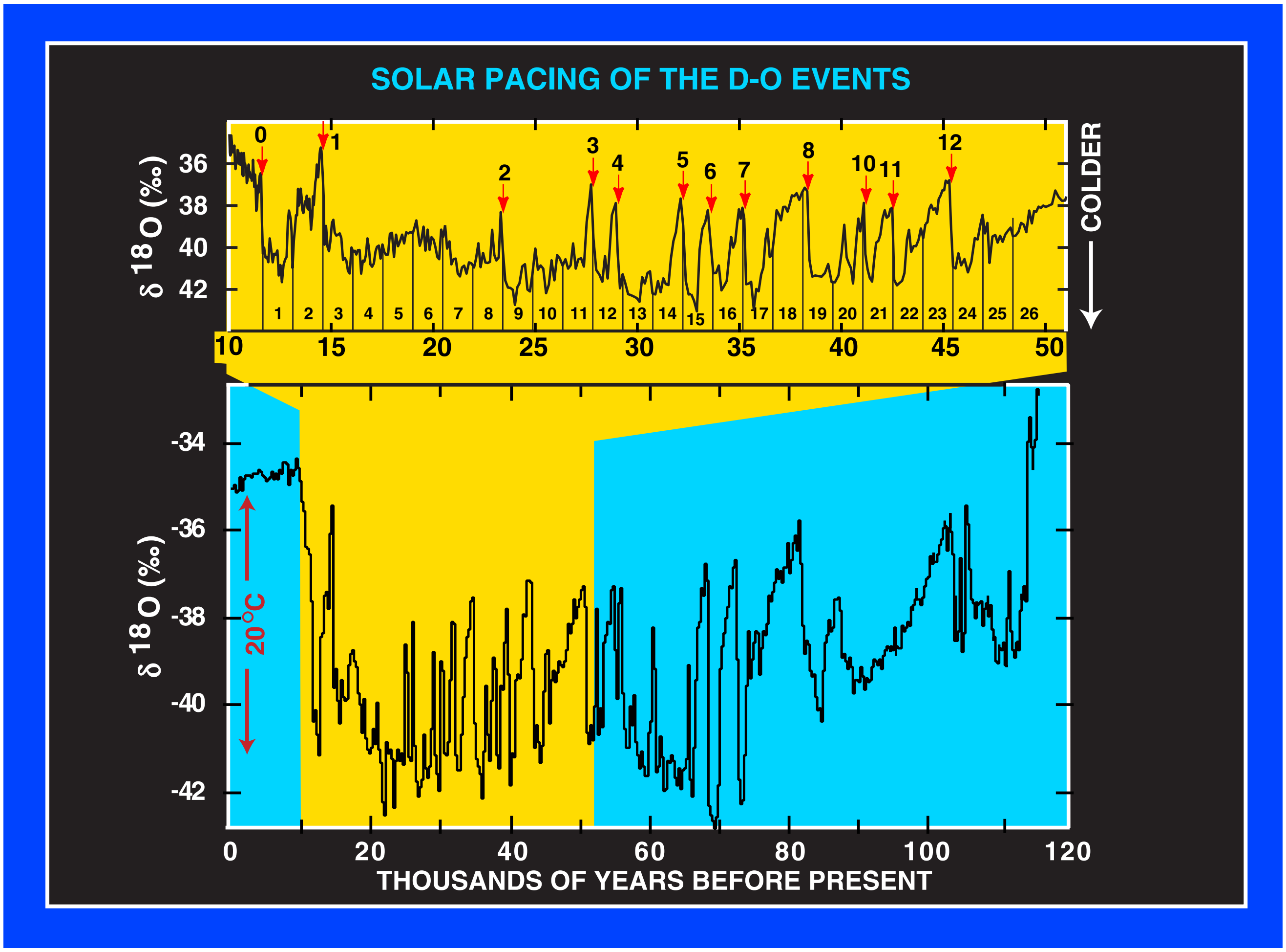
Punctuating much of the ice core record of the last period of glaciation in Greenland are a series of Dansgaard-Oeschger (D-O) events which in many ways resemble the YD. The climate in Greenland appears to have jumped back and forth between a state of extreme cold and a state of moderate cold. During 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 abundance of red-coated grains continued largely unchanged back through the entire 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 had 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 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



EXTENDED RED GRAIN RECORD
HOLOCENE
GLACIAL
BOND IRD COMPOSITION
PERCENT OF RED GRAINS
30
25
20
15
10
5
0
10
20
30
40
50
60
70
80
THOUSANDS OF YEARS BEFORE PRESENT

Figure 35



SOLAR PACING OF THE D-O EVENTS
δ 18 O (‰)
36
38
40
42
0
1
2
3
4
5
6
7
8
10
11
12
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
10 15 20 25 30 35 40 45 50
COLDER
-34
-36
-38
-40
-42
20°C
0 20 40 60 80 100 120
THOUSANDS OF YEARS BEFORE PRESENT

Figure 36

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.

Lecture #3

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.

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 it 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 produced 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 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

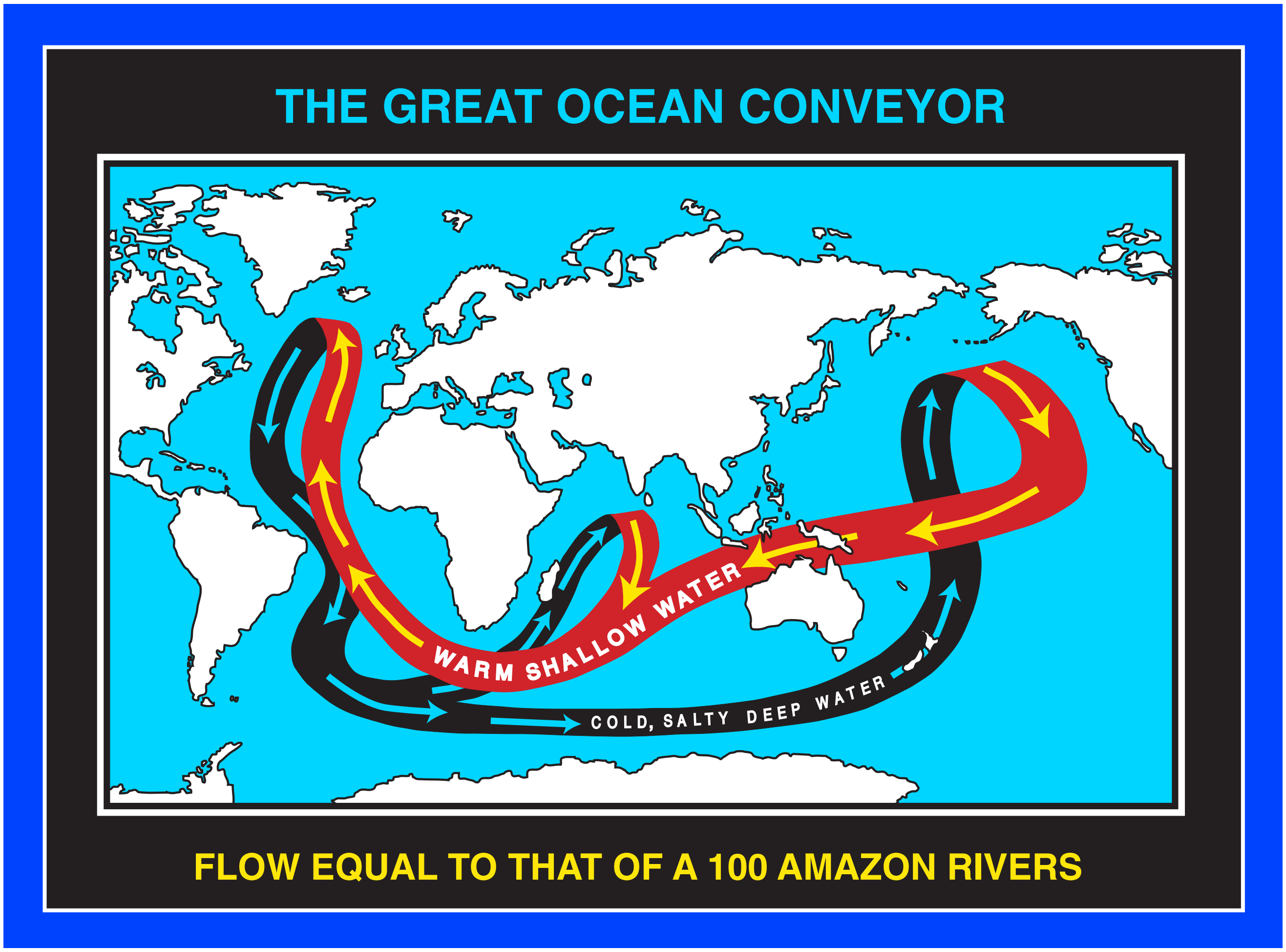

THE GREAT OCEAN CONVEYOR
WARM SHALLOW WATER
COLD, SALTY DEEP WATER
FLOW EQUAL TO THAT OF A 100 AMAZON RIVERS

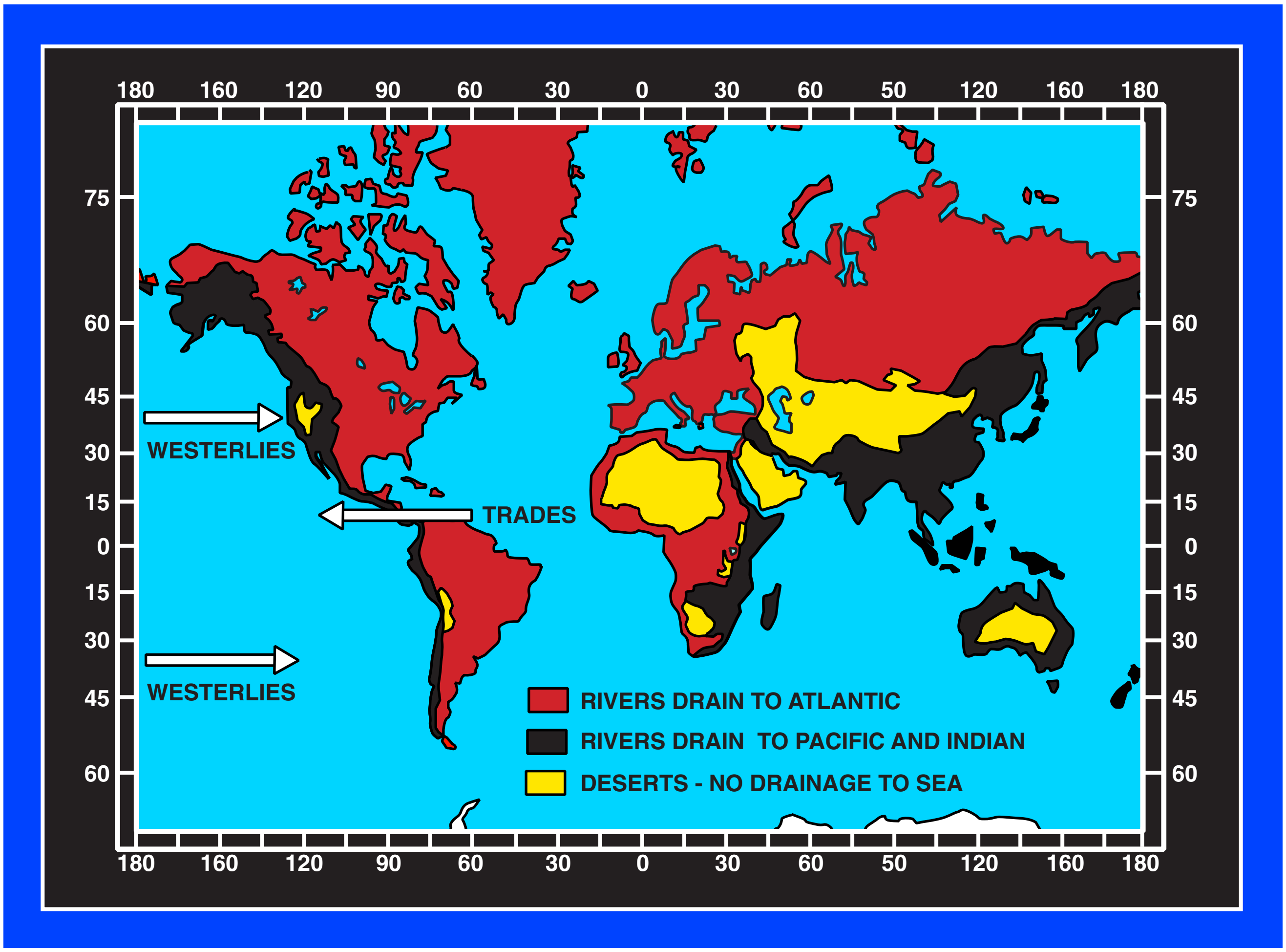
Figure 37

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 extent of 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 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.



180
160
120
90
60
30
0
30
60
50
120
160
180
75
60
45
30
15
0
15
30
45
60
WESTERLIES
TRADES
WESTERLIES
RIVERS DRAIN TO ATLANTIC
RIVERS DRAIN TO PACIFIC AND INDIAN
DESERTS - NO DRAINAGE TO SEA

Figure 38

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 margin 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.

Figure 39

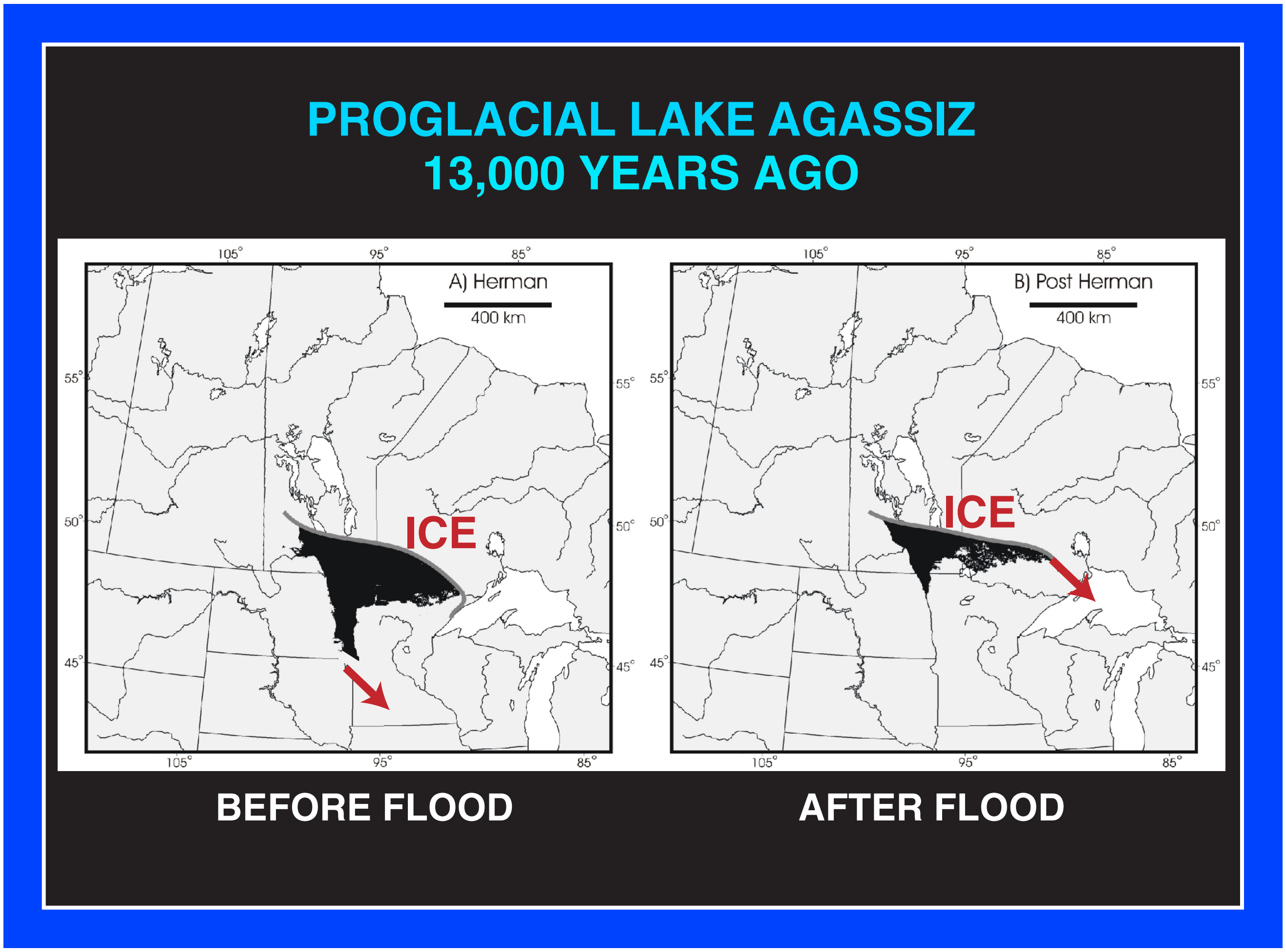

PROGLACIAL LAKE AGASSIZ
13,000 YEARS AGO
A) Herman
400 km
ICE
B) Post Herman
400 km
ICE
BEFORE FLOOD
AFTER FLOOD

Figure 40

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 straight forward explanation for the pronounced YD cooling of Greenland and 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 tended to recreate conditions 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 dropped precipitously, 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

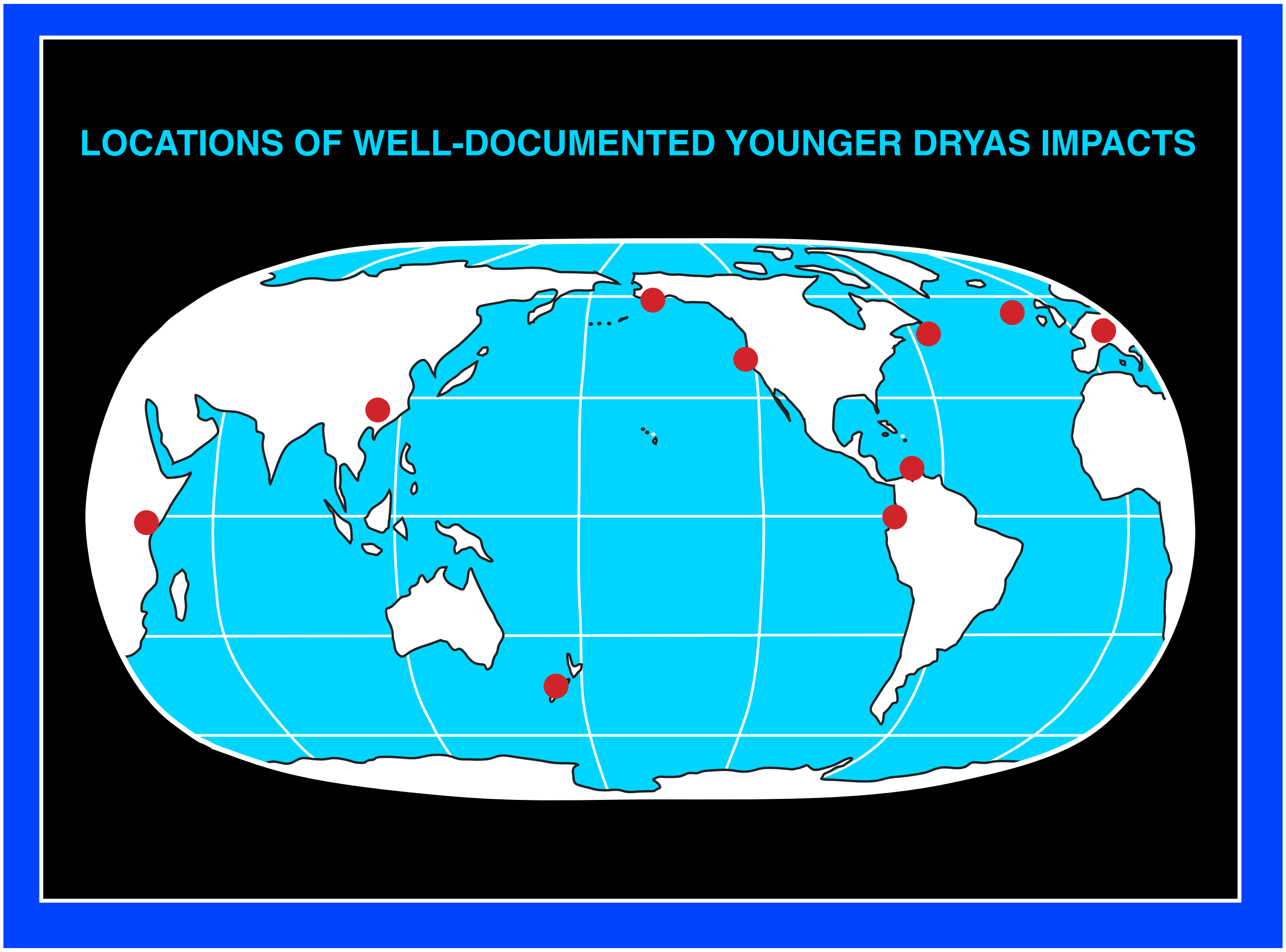


Figure 41

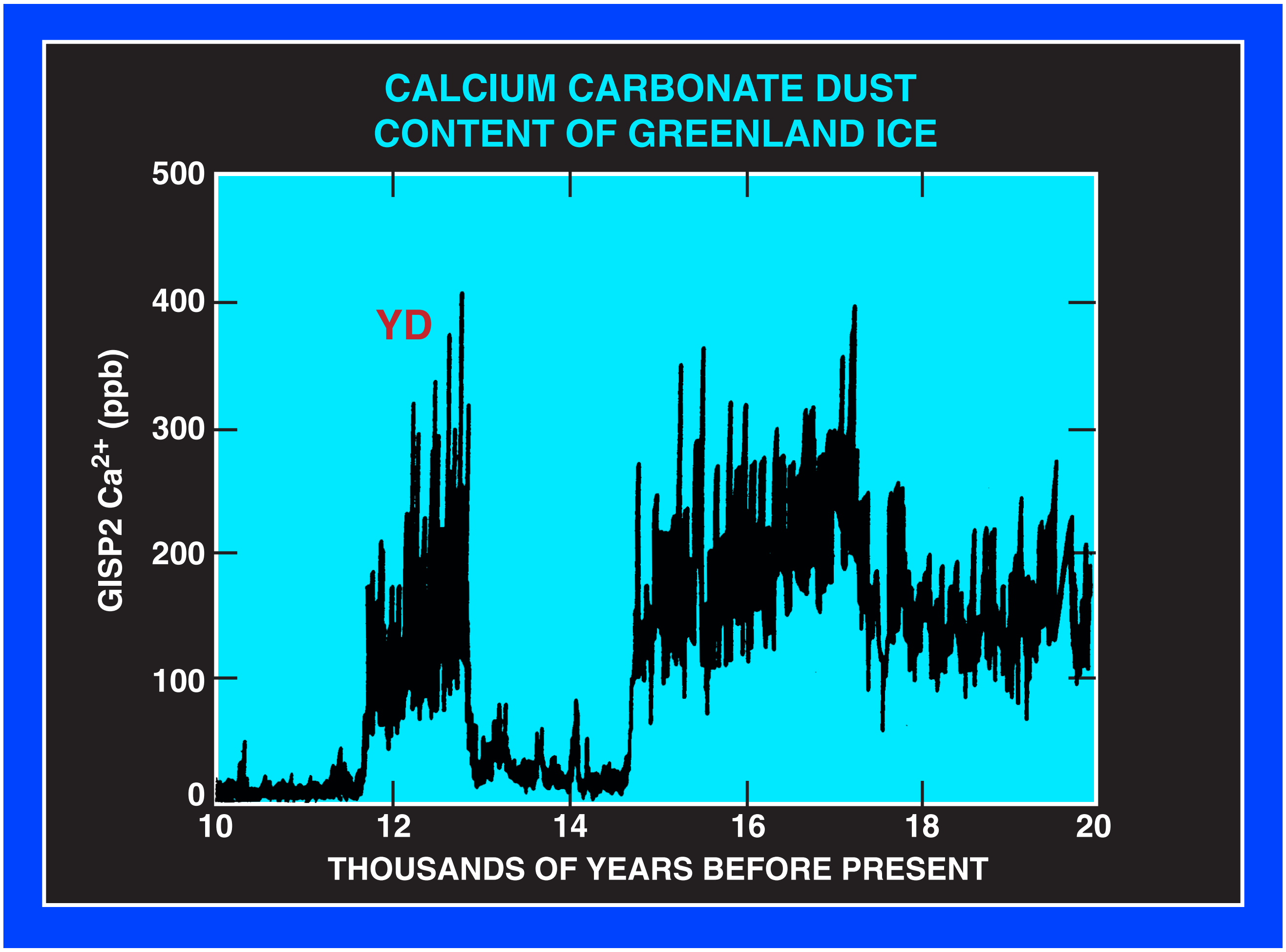

CALCIUM CARBONATE DUST
CONTENT OF GREENLAND ICE
YD
GISP2 Ca2+ (ppb)
500
400
300
200
100
0
10
12
14
16
18
20
THOUSANDS OF YEARS BEFORE PRESENT

Figure 42

Younger Dryas Moraine - South Island, New Zealand

Figure 43

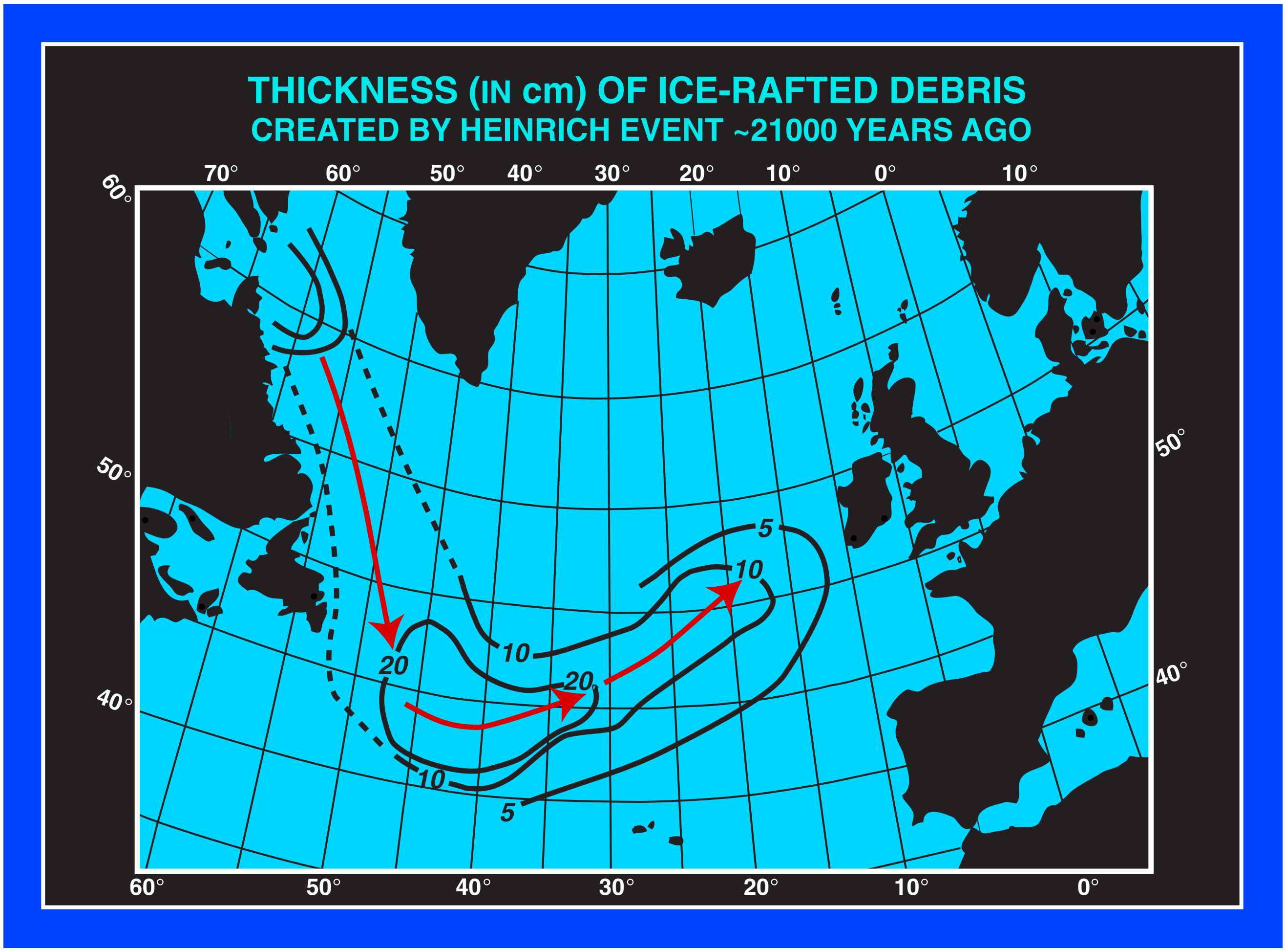
time scale of just a few decades. Yet it happened. The take home message is that the Earth s climate system is not only highly responsive, but it also has built-in teleconnections which allow messages to be sent rapidly across the entire globe.

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 exclusively 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. These Heinrich (H) 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



THICKNESS (IN cm) OF ICE-RAFTED DEBRIS
CREATED BY HEINRICH EVENT ~21000 YEARS AGO
70°
60°
50°
40°
30°
20°
10°
0°
10°
60°
50°
40°
50°
40°
5
10
20
10
20
10
5
60°
50°
40°
30°
20°
10°
0°

Figure 44

was 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).

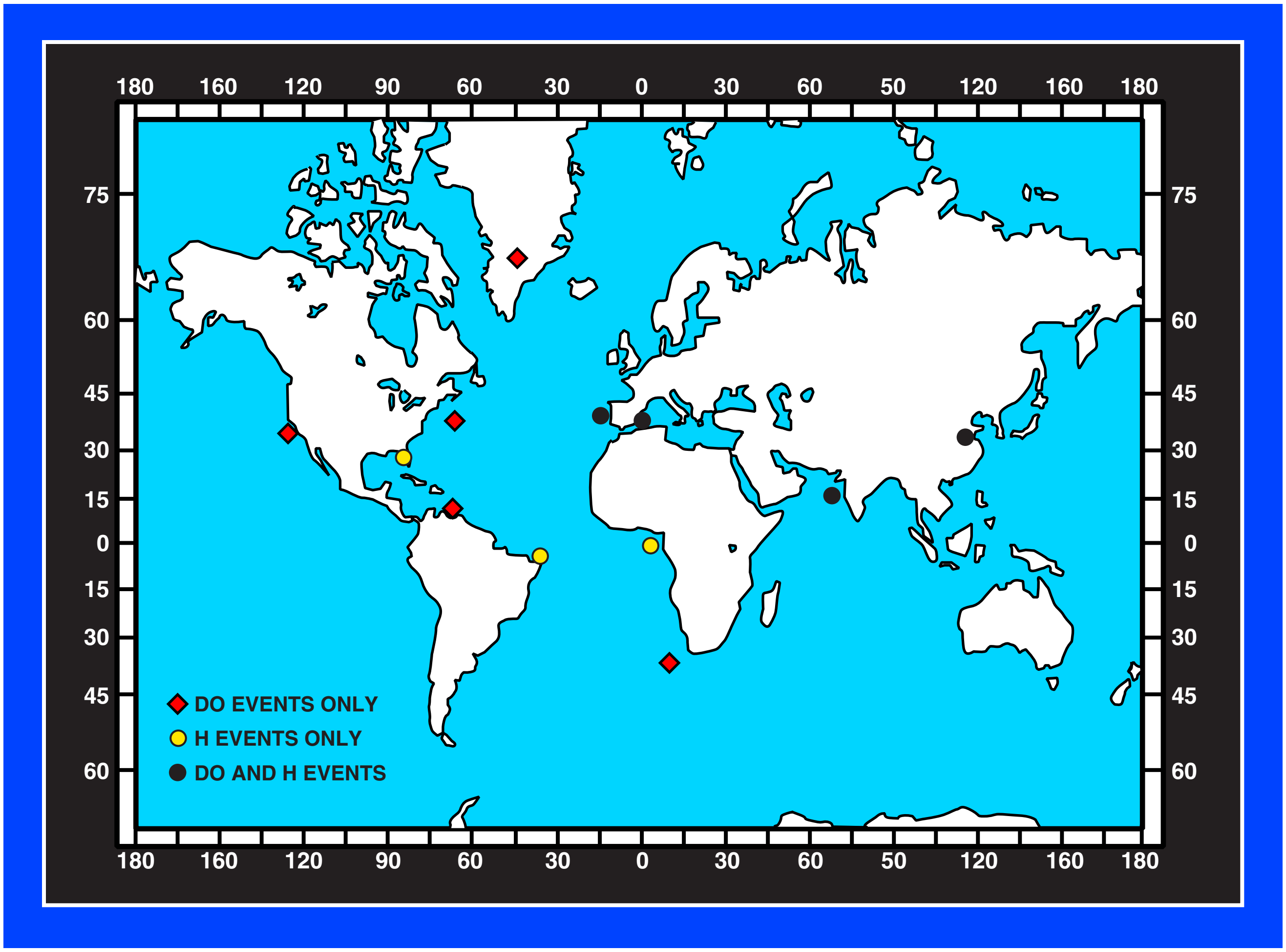
H impacts are not seen in the Greenland records of temperature, nor in those of soil and sea salt, nor in that of methane. In contrast, D-O events are not seen in the records from eastern Brazil or central Florida (see Figure 46). But in these latter two places, the times of H events stand out as episodes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

---

[3] ^{234}U is radioactiive 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 hour glasses. 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 #4).



180
160
120
90
60
30
0
30
60
50
120
160
180
75
60
45
30
15
0
15
30
45
60
DO EVENTS ONLY
H EVENTS ONLY
DO AND H EVENTS

Figure 45

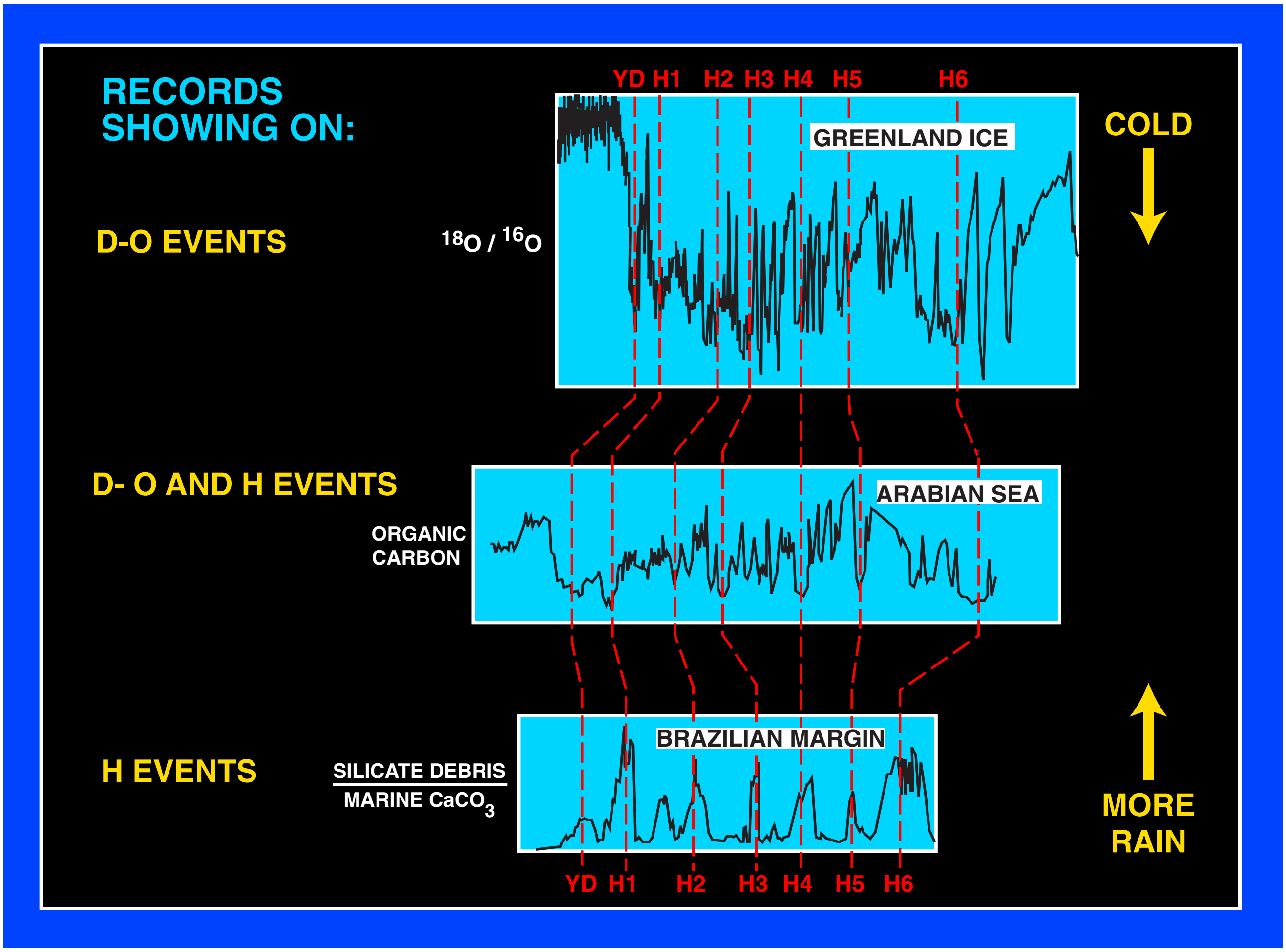
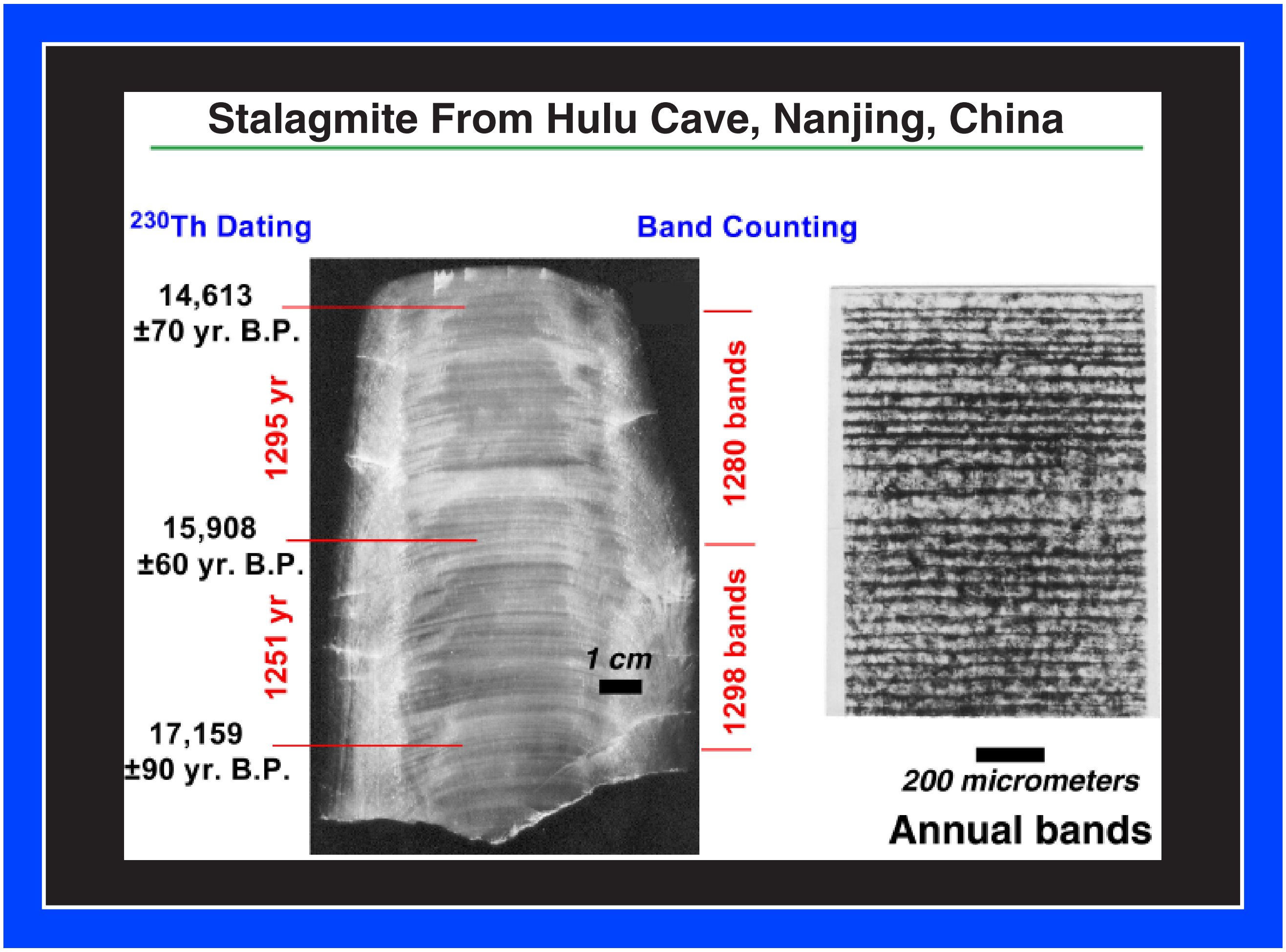

RECORDS
SHOWING ON:
D-O EVENTS
^{18}O / ^{16}O
YD H1 H2 H3 H4 H5 H6
GREENLAND ICE
COLD
D- O AND H EVENTS
ORGANIC
CARBON
ARABIAN SEA
H EVENTS
SILICATE DEBRIS
MARINE $CaCO_3$
BRAZILIAN MARGIN
YD H1 H2 H3 H4 H5 H6
MORE
RAIN

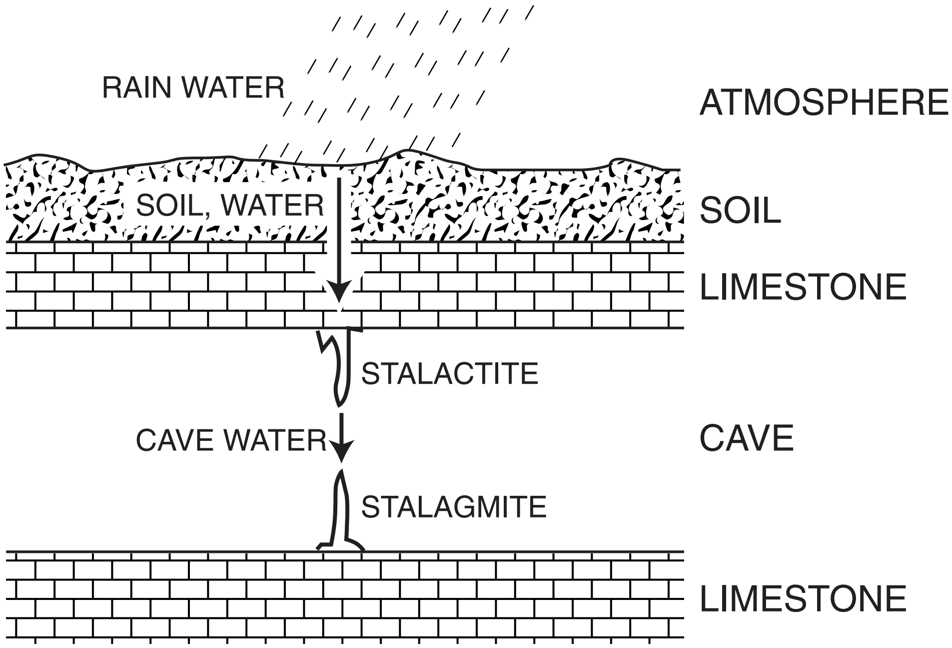
Figure 46

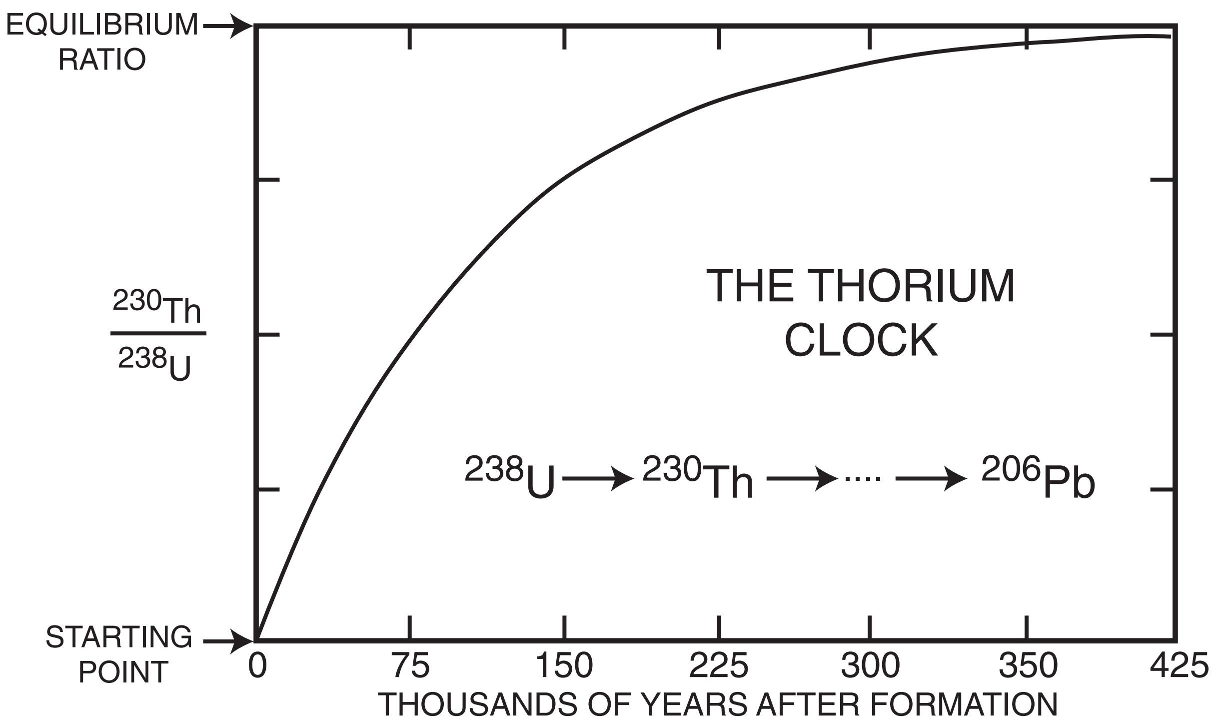


Stalagmite From Hulu Cave, Nanjing, China
230Th Dating
Band Counting
14,613
±70 yr. B.P.
1295 yr
15,908
±60 yr. B.P.
1251 yr
17,159
±90 yr. B.P.
1280 bands
1298 bands
1 cm
200 micrometers
Annual bands

Figure 47

AGE DETERMINATION OF CAVE $CaCO_3$





Sidebar #4

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 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 U.S. 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

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

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 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 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 a major fraction of the CO_2 produced by fossil fuel burning.

Forty or so years ago, nuclear power appeared to be the panacea for energy production. Jane Fonda s performance in the movie China Syndrome 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

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

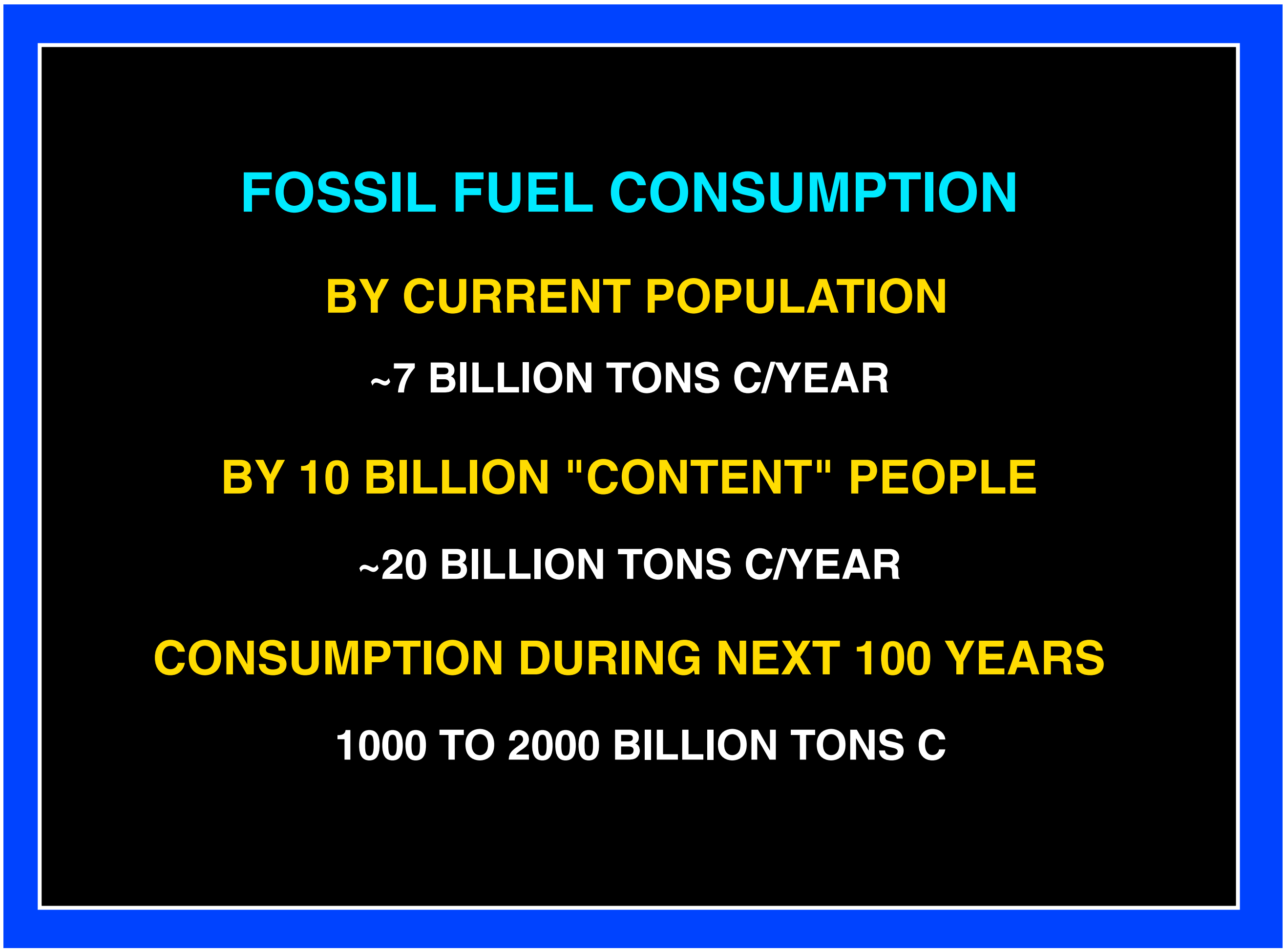

FOSSIL FUEL CONSUMPTION
BY CURRENT POPULATION
~7 BILLION TONS C/YEAR
BY 10 BILLION "CONTENT" PEOPLE
~20 BILLION TONS C/YEAR
CONSUMPTION DURING NEXT 100 YEARS
1000 TO 2000 BILLION TONS C

Figure 50

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 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 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

		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

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

NOT AN EASY TASK!

Figure 51

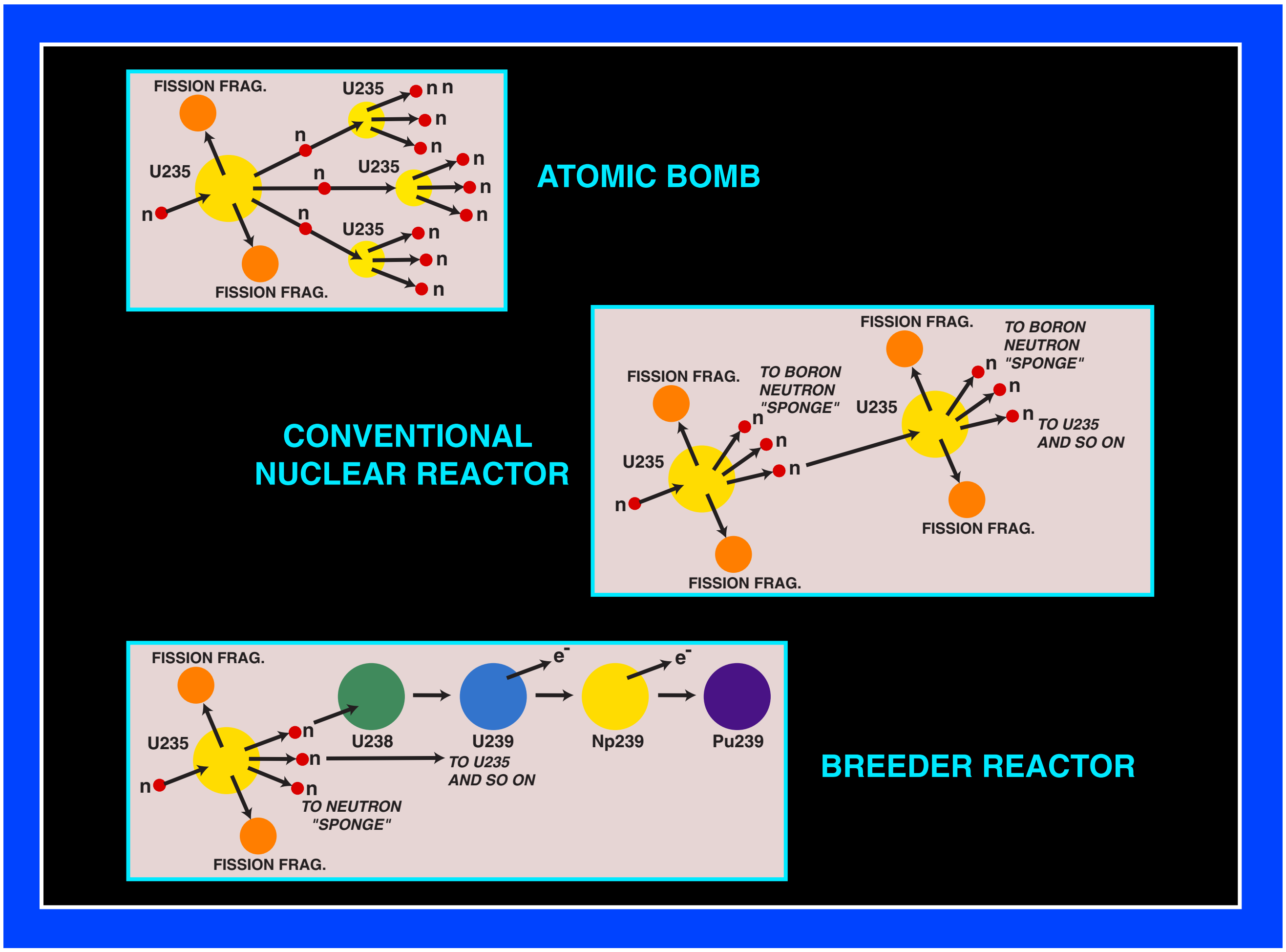

FISSION FRAG.
U235
n
ATOMIC BOMB
CONVENTIONAL
NUCLEAR REACTOR
TO BORON
NEUTRON
"SPONGE"
TO U235
AND SO ON
U238
U239
Np239
Pu239
e-
TO NEUTRON
"SPONGE"
BREEDER REACTOR

Figure 52

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 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 cheaply 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

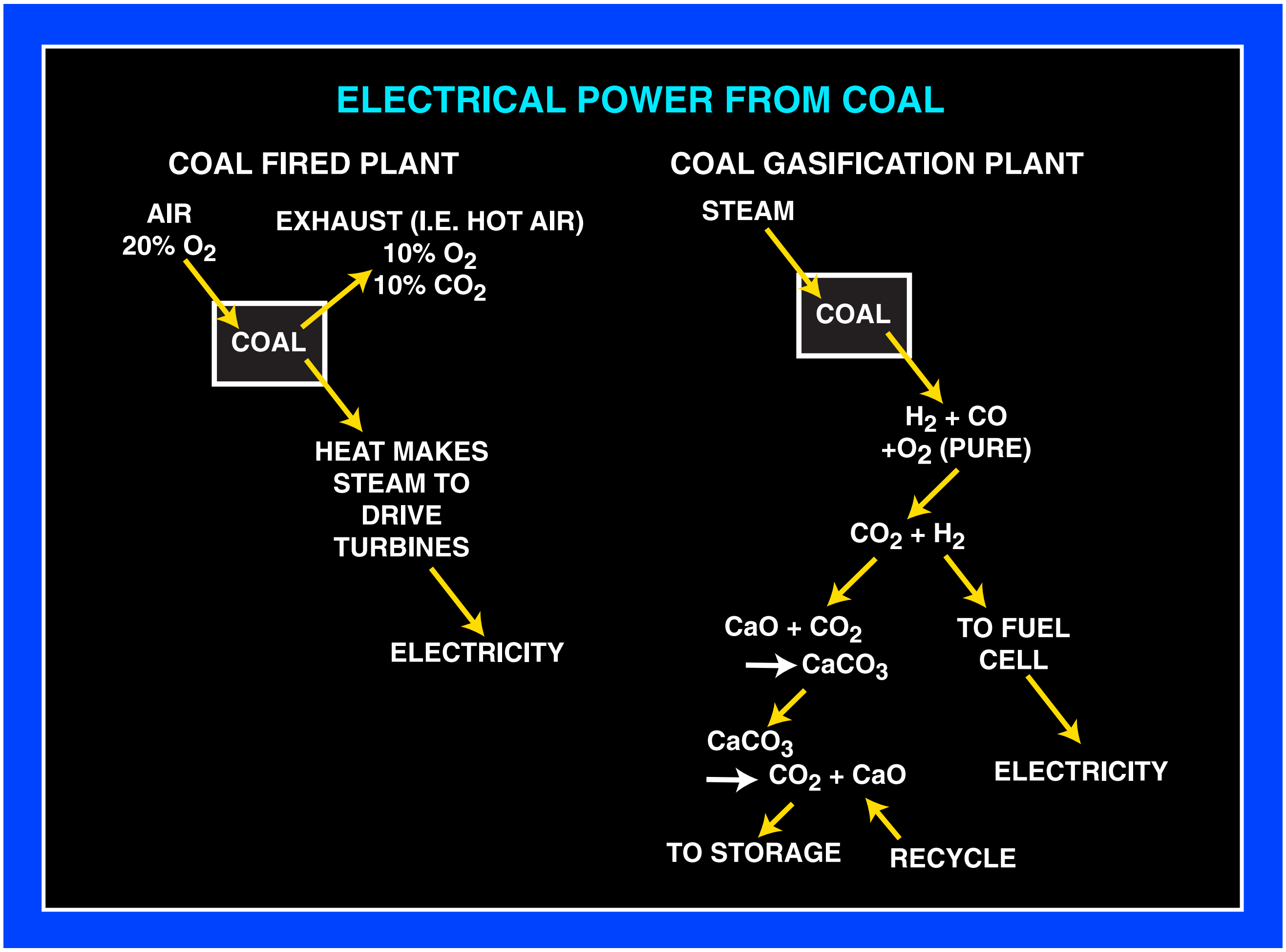

ELECTRICAL POWER FROM COAL
COAL FIRED PLANT
AIR
20% O_2
EXHAUST (I.E. HOT AIR)
10% O_2
10% CO_2
COAL
HEAT MAKES
STEAM TO
DRIVE
TURBINES
ELECTRICITY
COAL GASIFICATION PLANT
STEAM
COAL
H_2 + CO
+O_2 (PURE)
CO_2 + H_2
CaO + CO_2
→ $CaCO_3$
TO FUEL
CELL
$CaCO_3$
→ CO_2 + CaO
ELECTRICITY
TO STORAGE
RECYCLE

Figure 53

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 liquified but only at a temperature below -252°C (hence only 20°C above absolute zero temperature). An 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, liquified (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

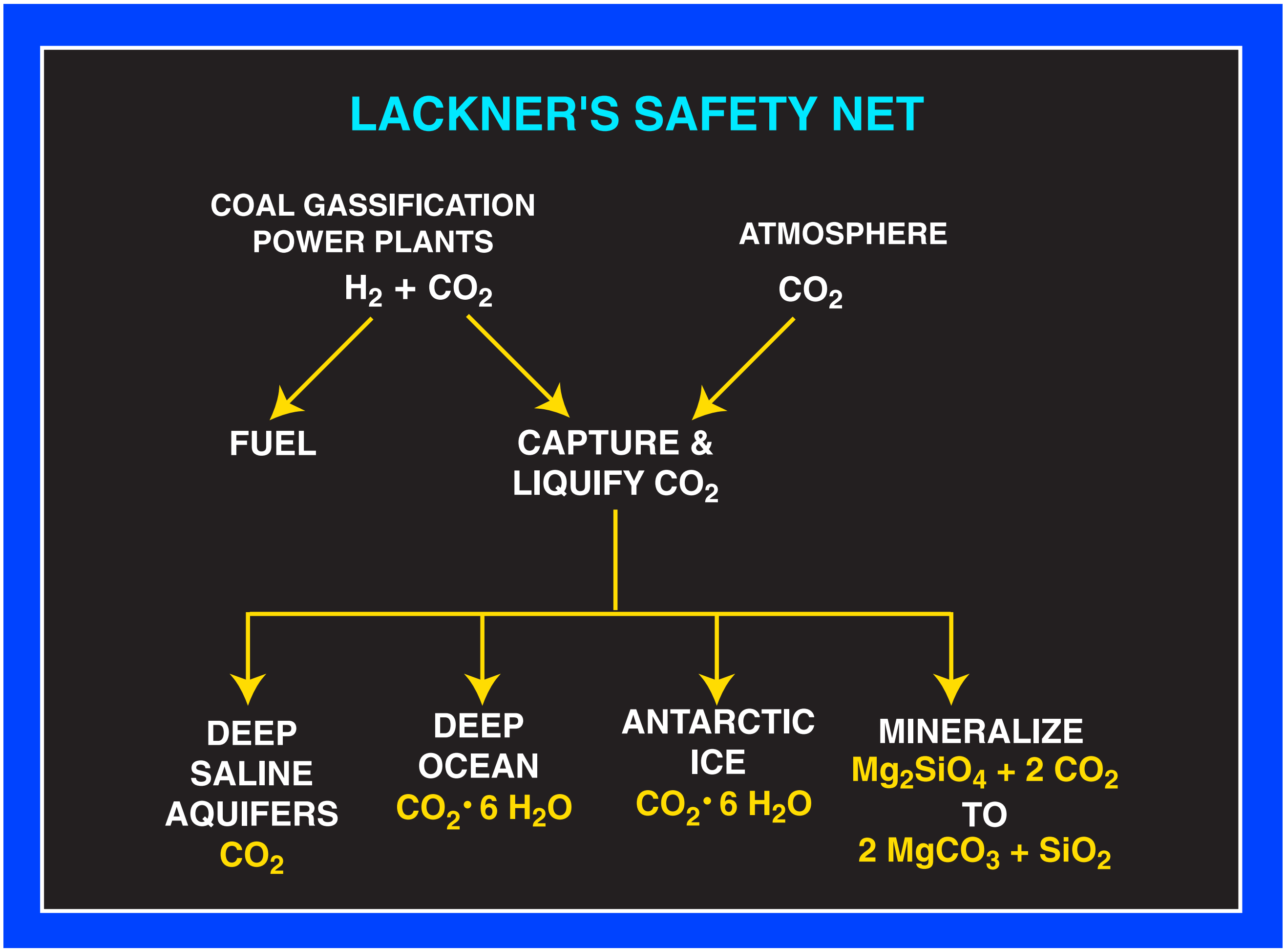

LACKNER'S SAFETY NET
COAL GASSIFICATION
POWER PLANTS
$H_2 + CO_2$
ATMOSPHERE
CO_2
FUEL
CAPTURE &
LIQUIFY CO_2
DEEP
SALINE
AQUIFERS
CO_2
DEEP
OCEAN
$CO_2 \cdot 6\ H_2O$
ANTARCTIC
ICE
$CO_2 \cdot 6\ H_2O$
MINERALIZE
$Mg_2SiO_4 + 2\ CO_2$
TO
$2\ MgCO_3 + SiO_2$

Figure 54

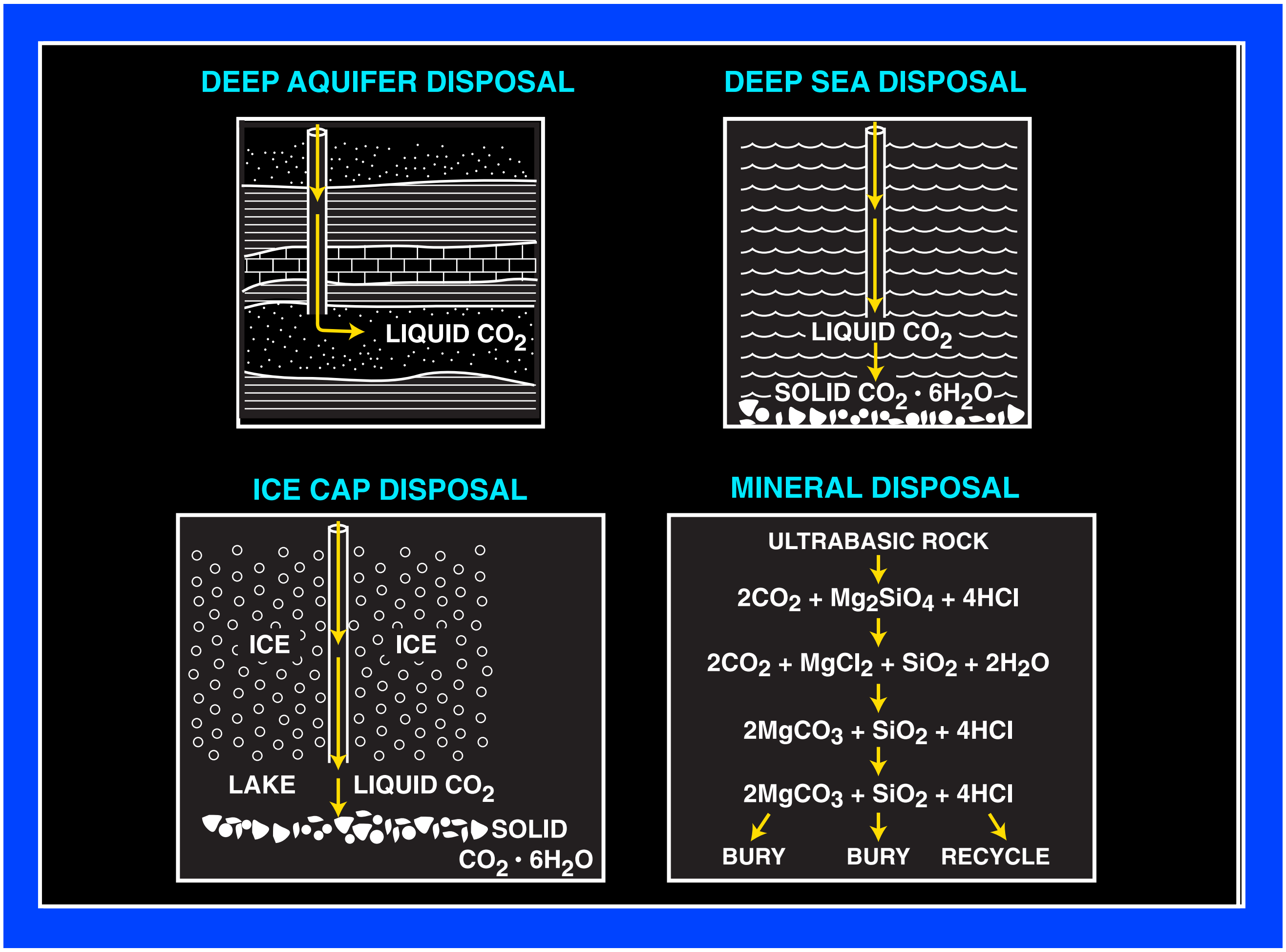

DEEP AQUIFER DISPOSAL
LIQUID CO_2
DEEP SEA DISPOSAL
LIQUID CO_2
SOLID $CO_2 \cdot 6H_2O$
ICE CAP DISPOSAL
ICE
ICE
LAKE
LIQUID CO_2
SOLID $CO_2 \cdot 6H_2O$
MINERAL DISPOSAL
ULTRABASIC ROCK
$2CO_2 + Mg_2SiO_4 + 4HCl$
$2CO_2 + MgCl_2 + SiO_2 + 2H_2O$
$2MgCO_3 + SiO_2 + 4HCl$
$2MgCO_3 + SiO_2 + 4HCl$
BURY
BURY
RECYCLE

Figure 55

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, 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, it 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 be stable. Hence, the CO_2 would remain in liquid or gaseous 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 from a reservoir beneath the North Sea. The 15 percent CO_2 this gas contains 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 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 that pristine polar plateau. Before permitting large quantities of liquid CO_2 to be injected into saline aquifers beneath their homes, for example, 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. As this is unavoidable, 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 easier and their operation is less cumbersome and hence less expensive. 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 would be 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 0.2 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 80 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.

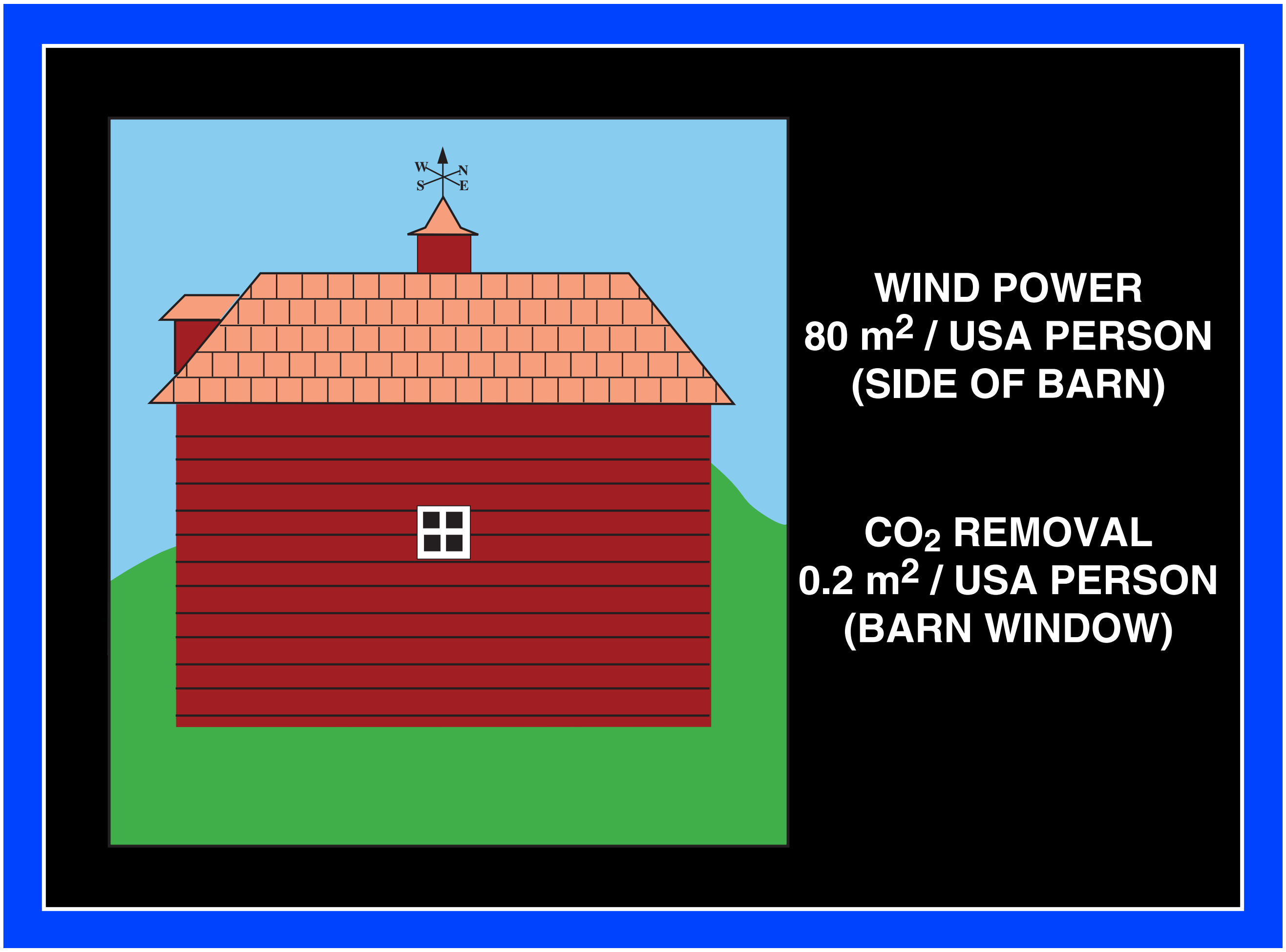

W
N
S
E
WIND POWER
80 m2 / USA PERSON
(SIDE OF BARN)
CO2 REMOVAL
0.2 m2 / USA PERSON
(BARN WINDOW)

Figure 56

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 liquified for storage. The calcium oxide would 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 corrosion. 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

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[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.

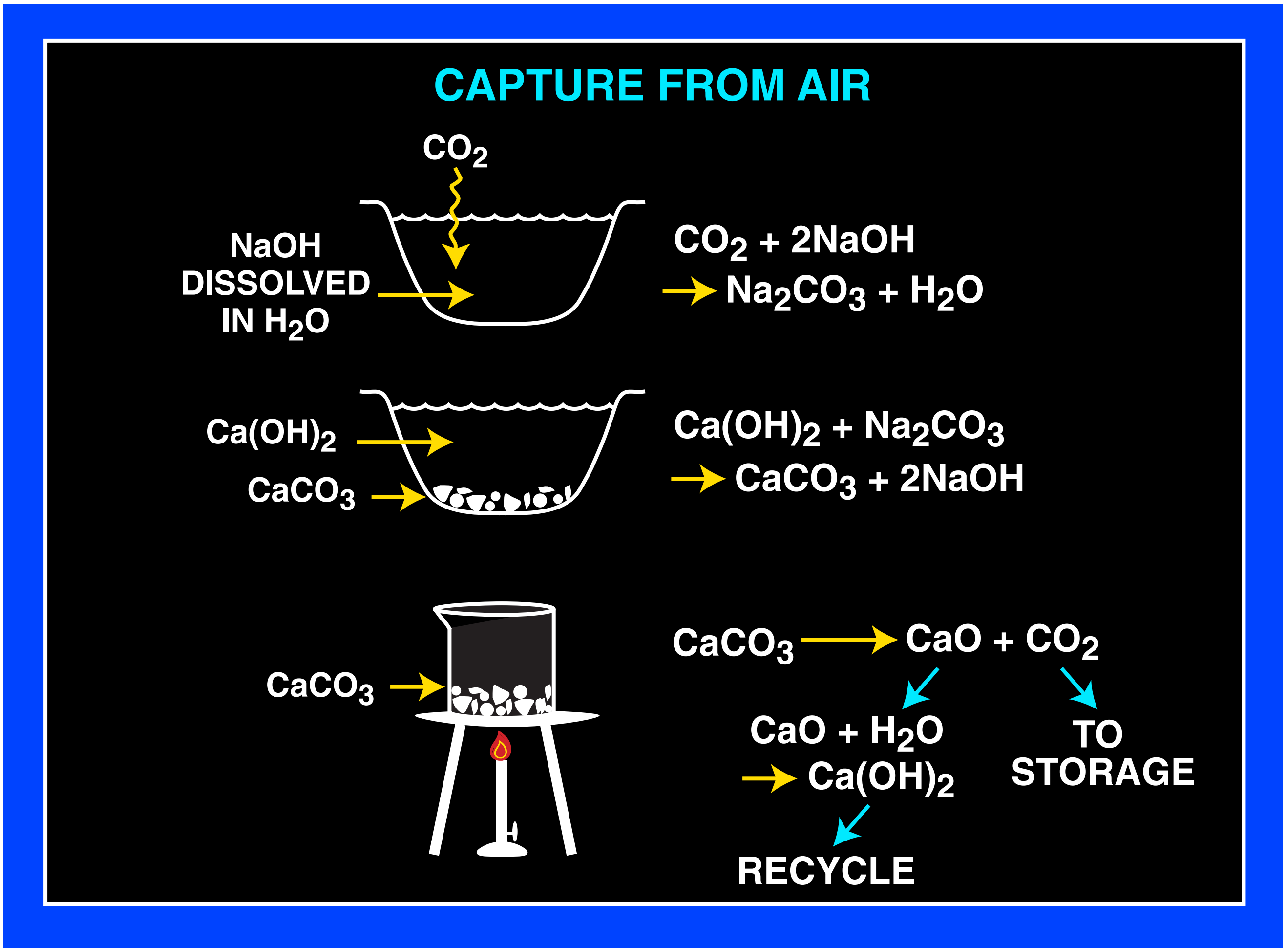
CAPTURE FROM AIR
CO2
NaOH
DISSOLVED
IN H2O
CO2 + 2NaOH
→ Na2CO3 + H2O
Ca(OH)2
CaCO3
Ca(OH)2 + Na2CO3
→ CaCO3 + 2NaOH
CaCO3
CaCO3 → CaO + CO2
CaO + H2O
→ Ca(OH)2
TO
STORAGE
RECYCLE

Figure 57

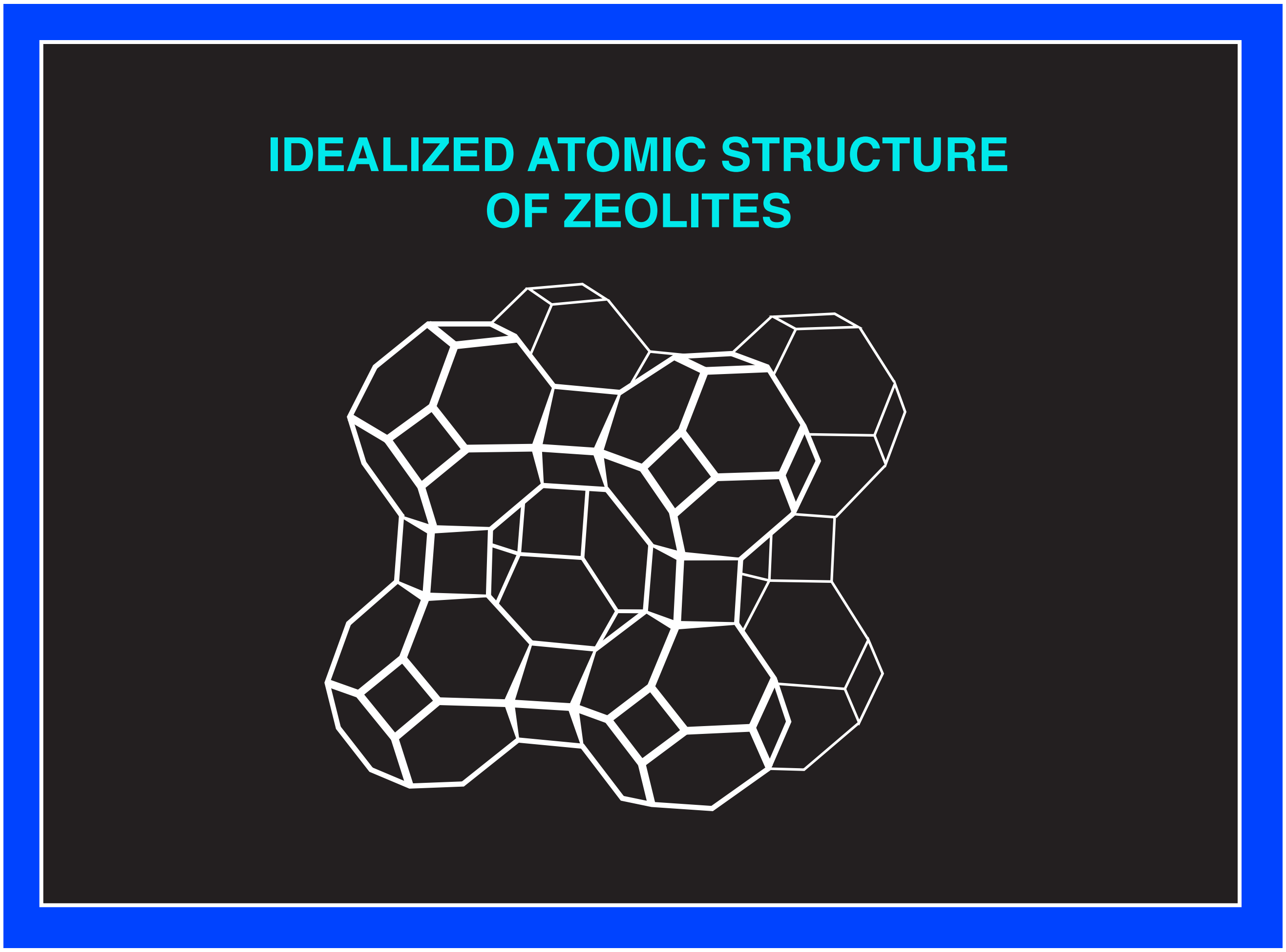

Figure 58

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. 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 cooling coil placed within the chamber to pull the CO_2 off the zeolite converting 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 liquified 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.

Figure 59

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 liquified, 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 probably 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 inhabitants 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 15 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


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 63

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, 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


A HUGE TASK
IF ONE UNIT WERE REQUIRED TO REMOVE 1000 PEOPLE'S CO_2
THEN FOR 10 BILLION PEOPLE
300 THOUSAND EXTRACTORS WOULD BE NEEDED

Figure 61

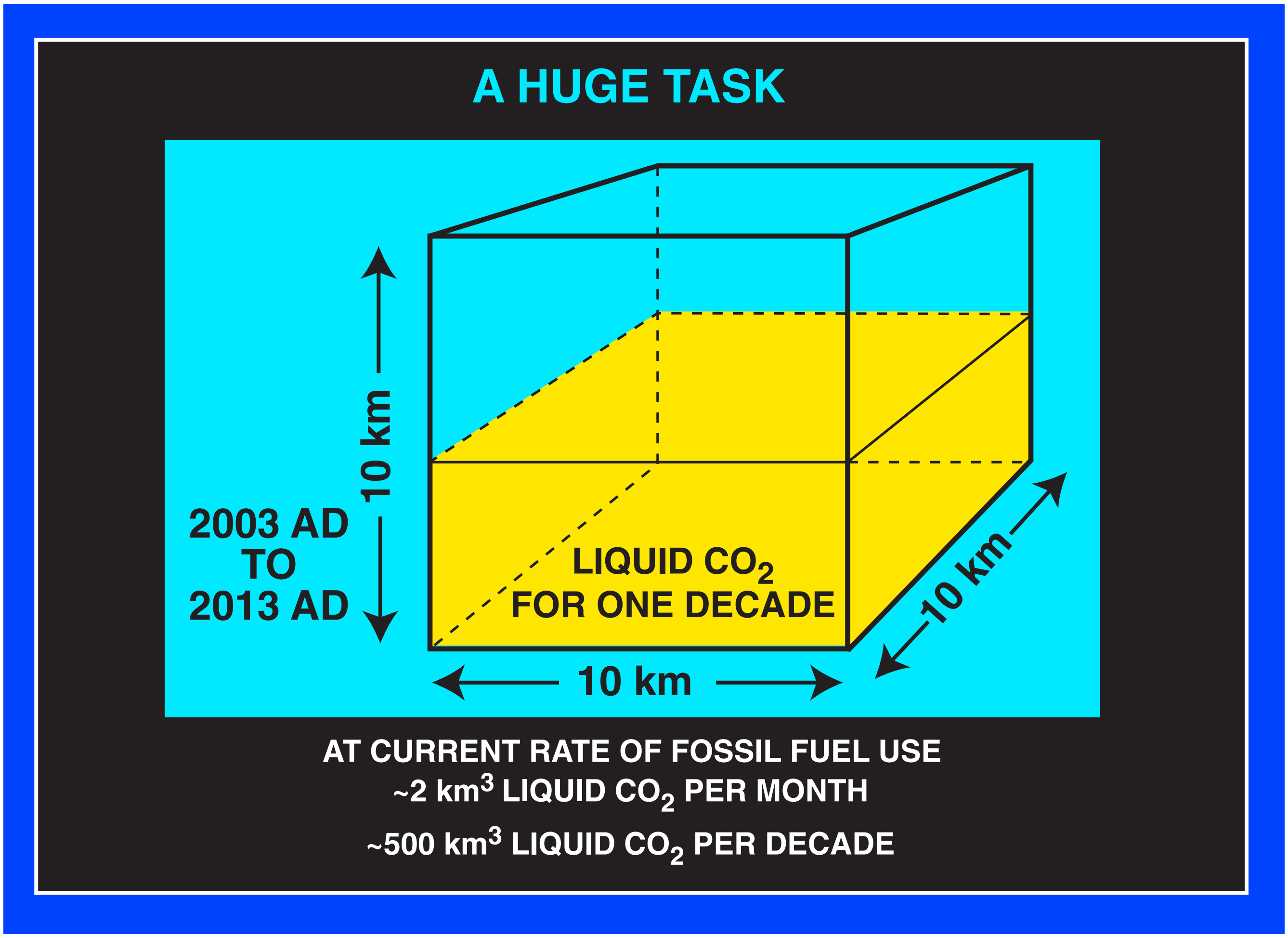
A HUGE TASK
10 km
2003 AD
TO
2013 AD
LIQUID CO_2
FOR ONE DECADE
10 km
10 km
AT CURRENT RATE OF FOSSIL FUEL USE
~2 km^3 LIQUID CO_2 PER MONTH
~500 km^3 LIQUID CO_2 PER DECADE

Figure 62

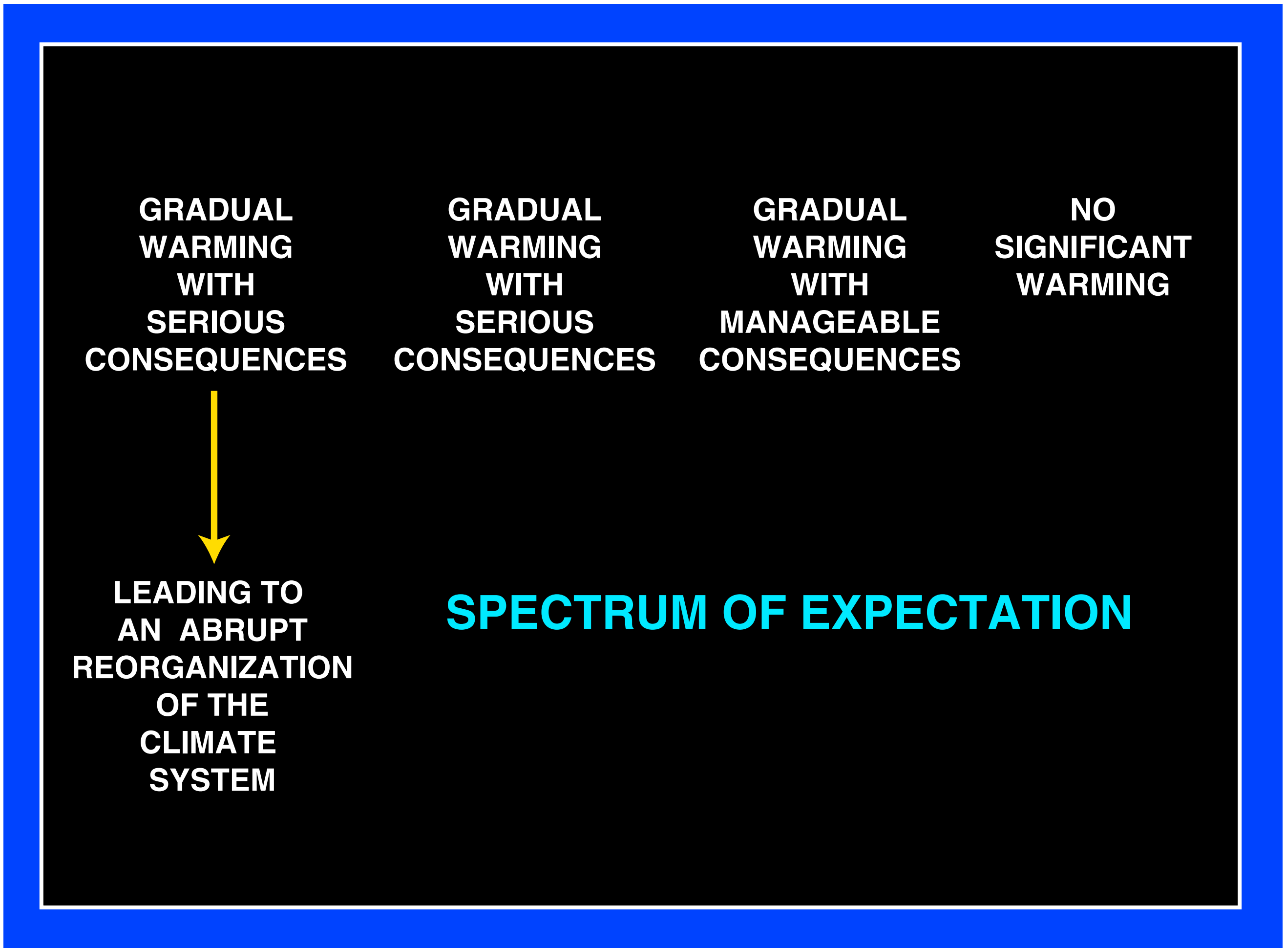
GRADUAL WARMING WITH SERIOUS CONSEQUENCES
GRADUAL WARMING WITH SERIOUS CONSEQUENCES
GRADUAL WARMING WITH MANAGEABLE CONSEQUENCES
NO SIGNIFICANT WARMING
LEADING TO AN ABRUPT REORGANIZATION OF THE CLIMATE SYSTEM
SPECTRUM OF EXPECTATION

Figure 63

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 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.