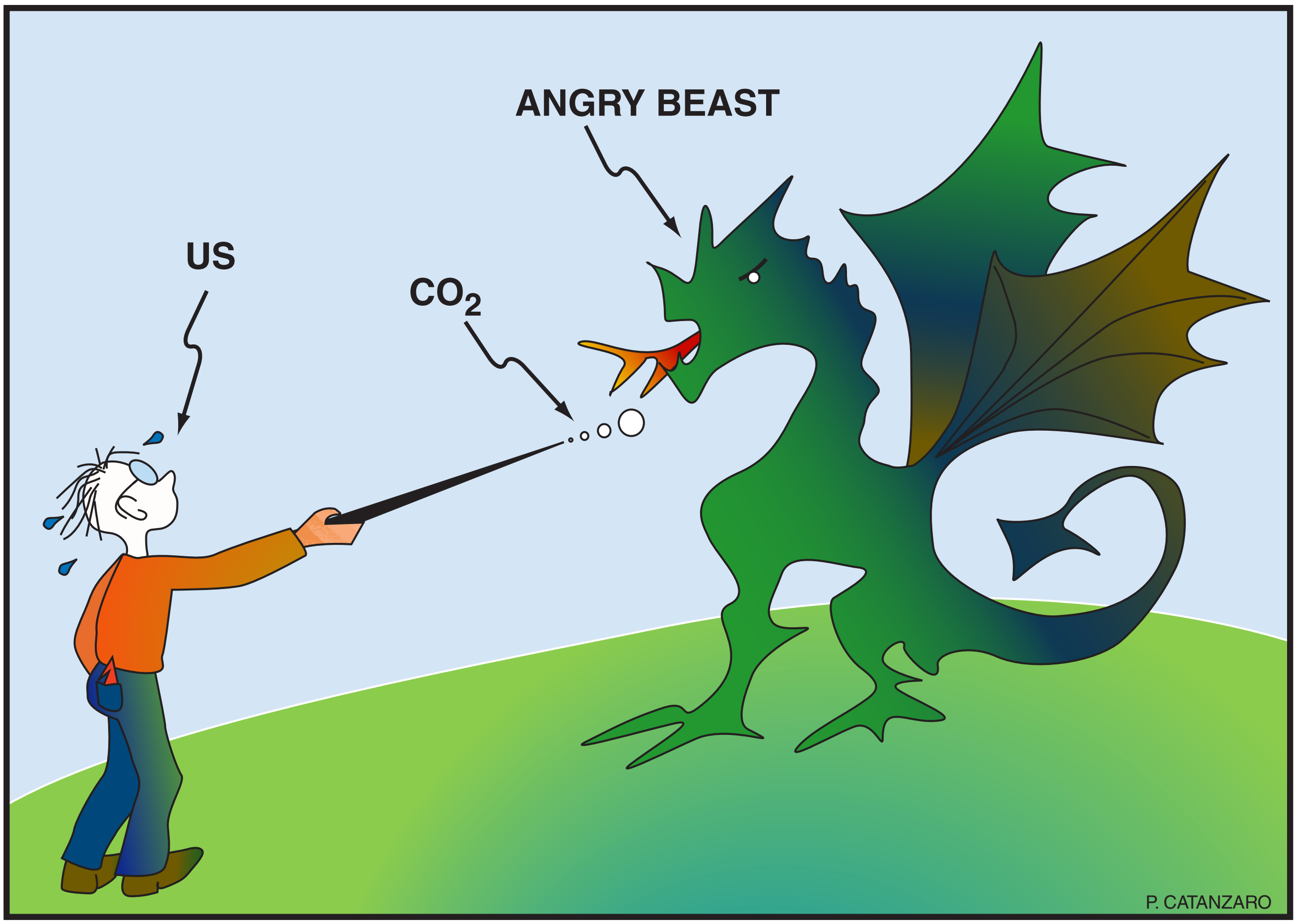
FOSSIL FUEL CO2
AND
THE ANGRY CLIMATE BEAST



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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.

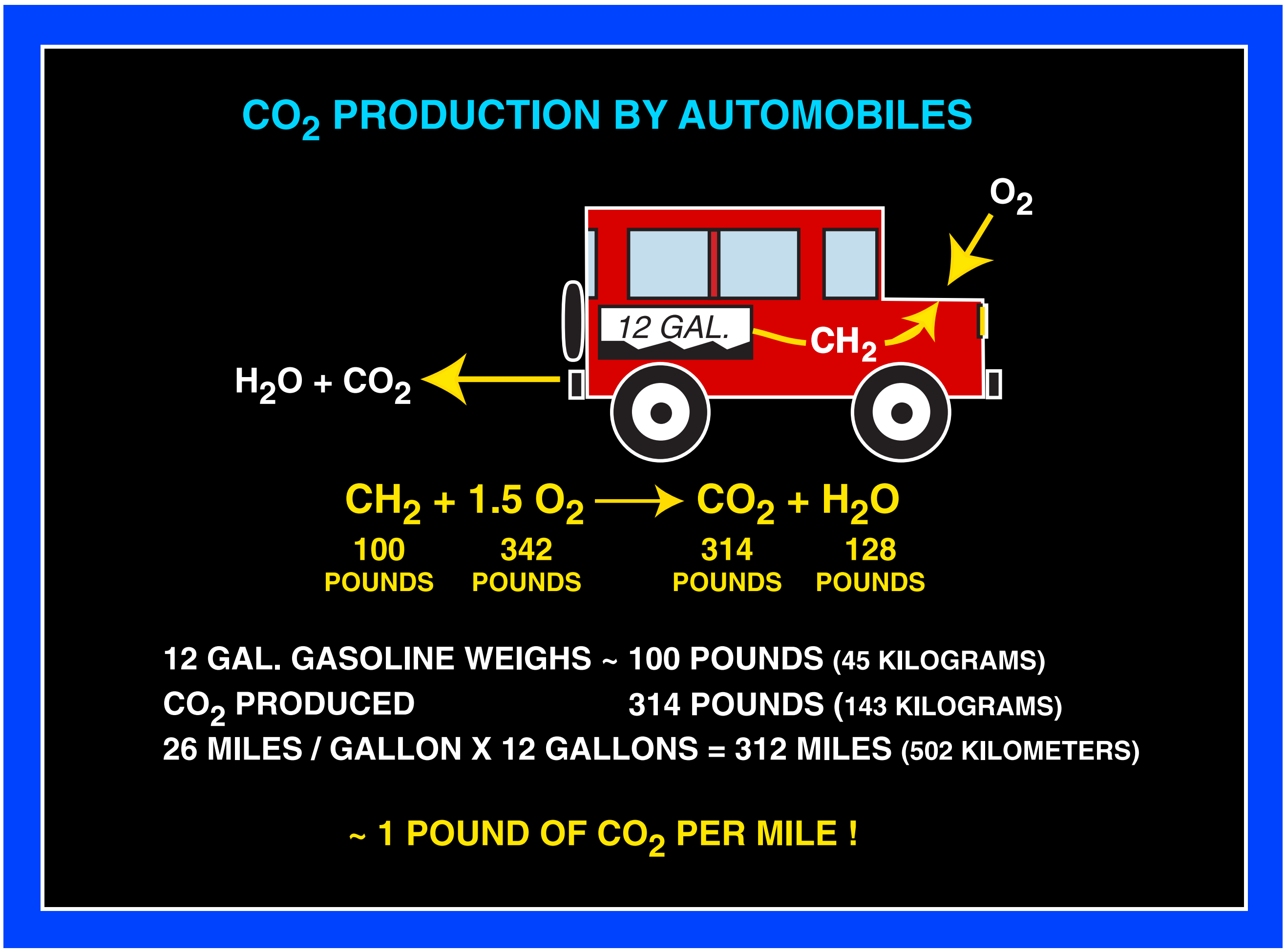
CO_2 PRODUCTION BY AUTOMOBILES
O_2
12 GAL.
CH_2
$H_2O + CO_2$
$CH_2 + 1.5\ O_2 \longrightarrow CO_2 + H_2O$
100 POUNDS
342 POUNDS
314 POUNDS
128 POUNDS
12 GAL. GASOLINE WEIGHS ~ 100 POUNDS (45 KILOGRAMS)
CO_2 PRODUCED 314 POUNDS (143 KILOGRAMS)
26 MILES / GALLON X 12 GALLONS = 312 MILES (502 KILOMETERS)
~ 1 POUND OF CO_2 PER MILE !

Figure 1

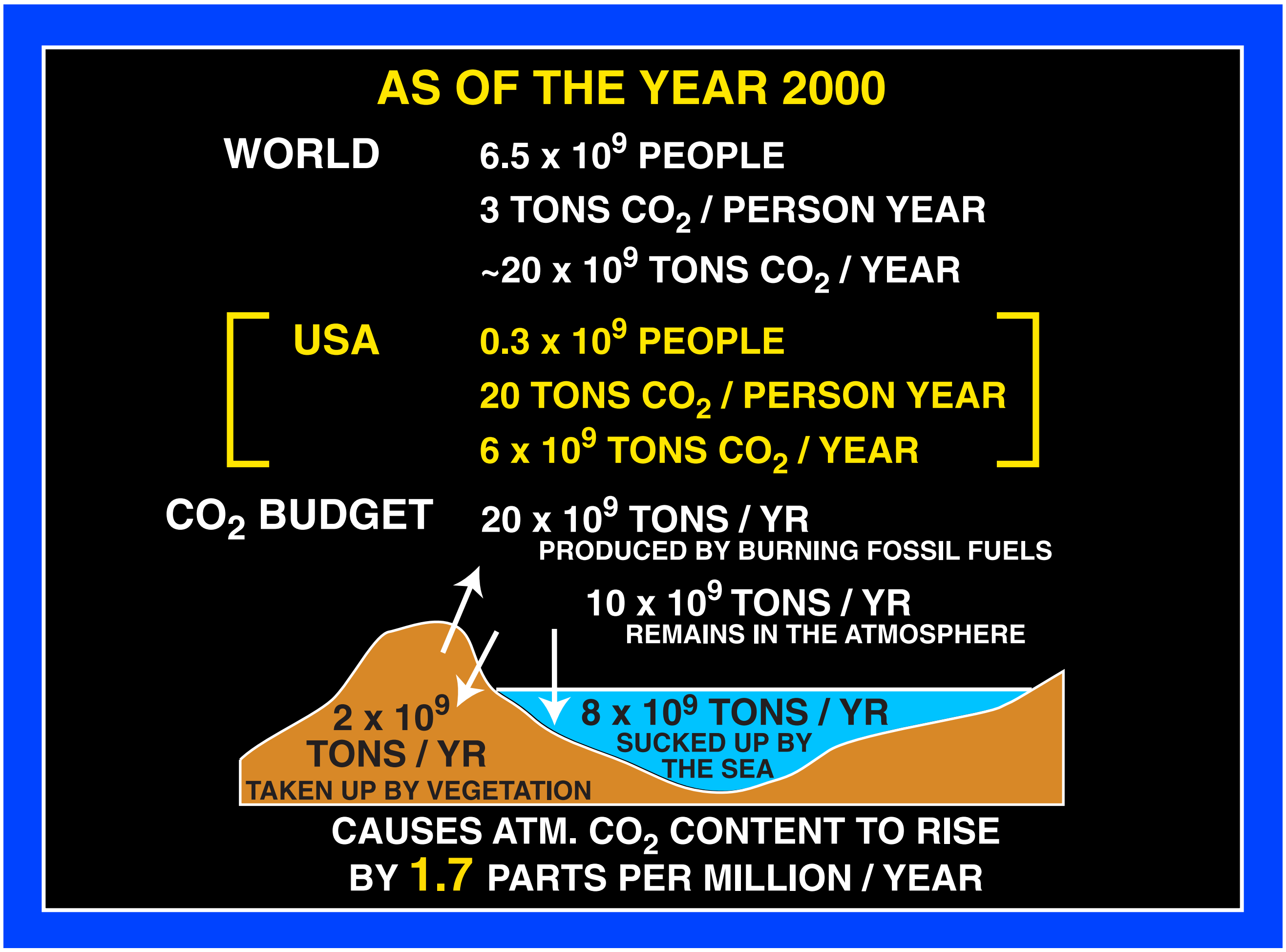
AS OF THE YEAR 2000
WORLD
6.5 x 10^9 PEOPLE
3 TONS CO2 / PERSON YEAR
~20 x 10^9 TONS CO2 / YEAR
USA
0.3 x 10^9 PEOPLE
20 TONS CO2 / PERSON YEAR
6 x 10^9 TONS CO2 / YEAR
CO2 BUDGET
20 x 10^9 TONS / YR
PRODUCED BY BURNING FOSSIL FUELS
10 x 10^9 TONS / YR
REMAINS IN THE ATMOSPHERE
2 x 10^9
TONS / YR
TAKEN 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 eighths of that expected. Two routes are available to get from the white dot to the

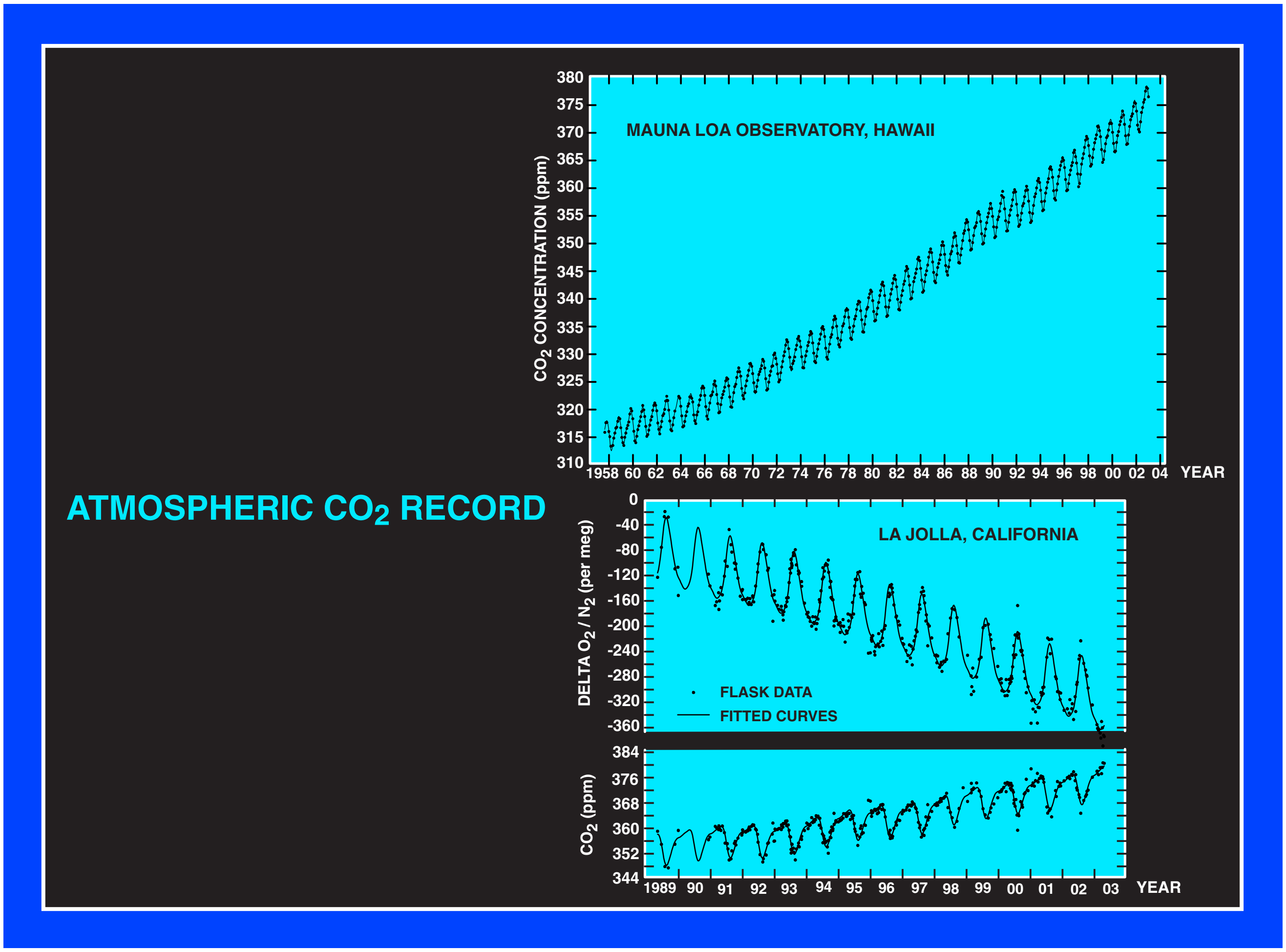
ATMOSPHERIC CO2 RECORD
MAUNA LOA OBSERVATORY, HAWAII
CO2 CONCENTRATION (ppm)
380
375
370
365
360
355
350
345
340
335
330
325
320
315
310
1958 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94 96 98 00 02 04
YEAR
LA JOLLA, CALIFORNIA
DELTA O2 / N2 (per meg)
0
-40
-80
-120
-160
-200
-240
-280
-320
-360
FLASK DATA
FITTED CURVES
CO2 (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

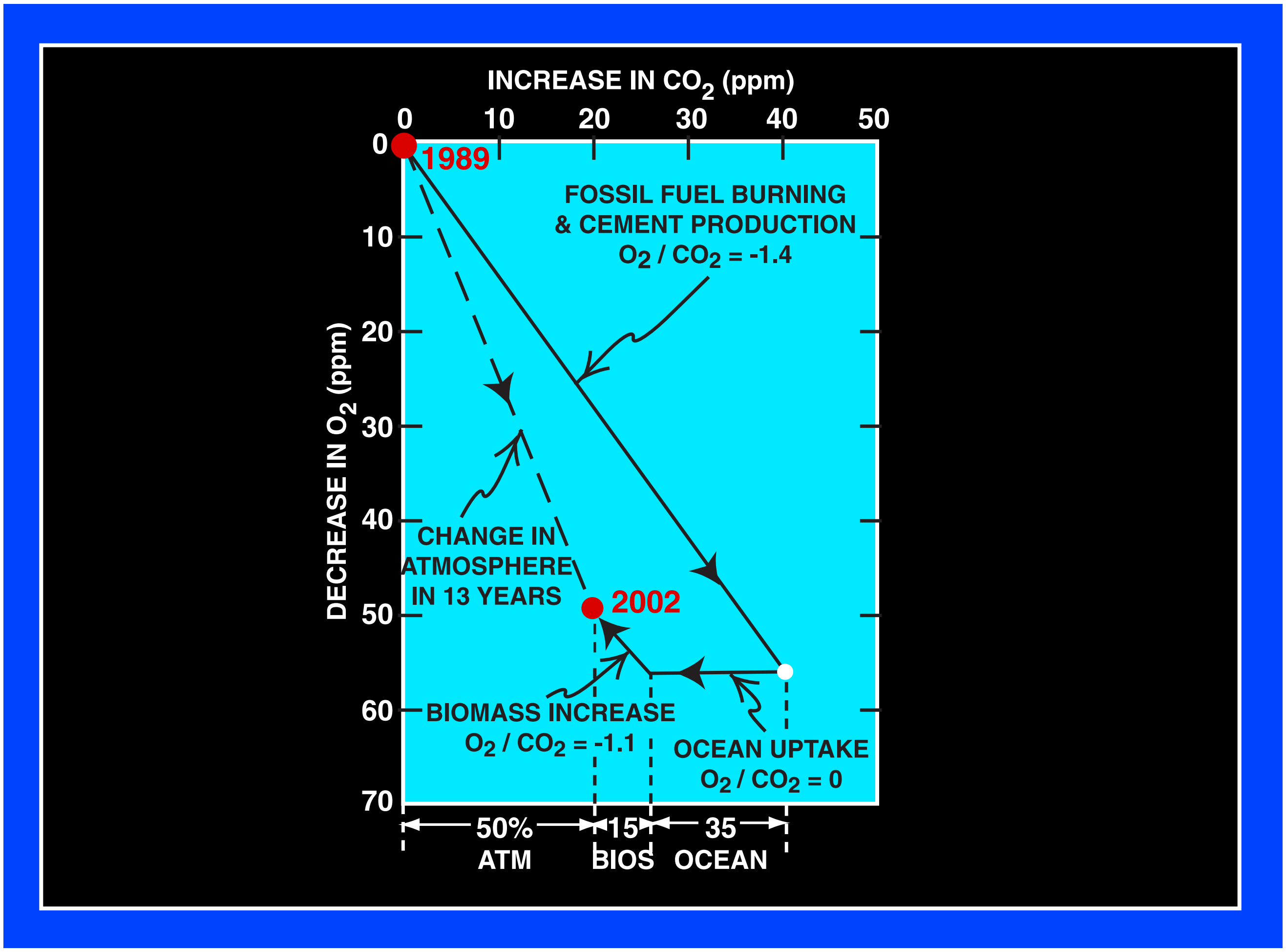
INCREASE IN CO2 (ppm)
0
10
20
30
40
50
DECREASE IN O2 (ppm)
0
10
20
30
40
50
60
70
1989
2002
FOSSIL FUEL BURNING
& CEMENT PRODUCTION
O2 / CO2 = -1.4
CHANGE IN
ATMOSPHERE
IN 13 YEARS
BIOMASS INCREASE
O2 / CO2 = -1.1
OCEAN UPTAKE
O2 / CO2 = 0
50%
ATM
15
BIOS
35
OCEAN

Figure 4

	O_2/CO_2	PERCENT OF CO_2 EMISSIONS
SOLID FUELS	1.17	36.8
COAL, LIGNITE...		
LIQUID FUELS	1.44	41.6
GASOLINE, KEROSENE....		
GASEOUS FUELS	1.95	18.0
METHANE, PROPANE		
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.

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[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 21st century (see Figure 6).

Climatic impacts of fossil fuel CO_2

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

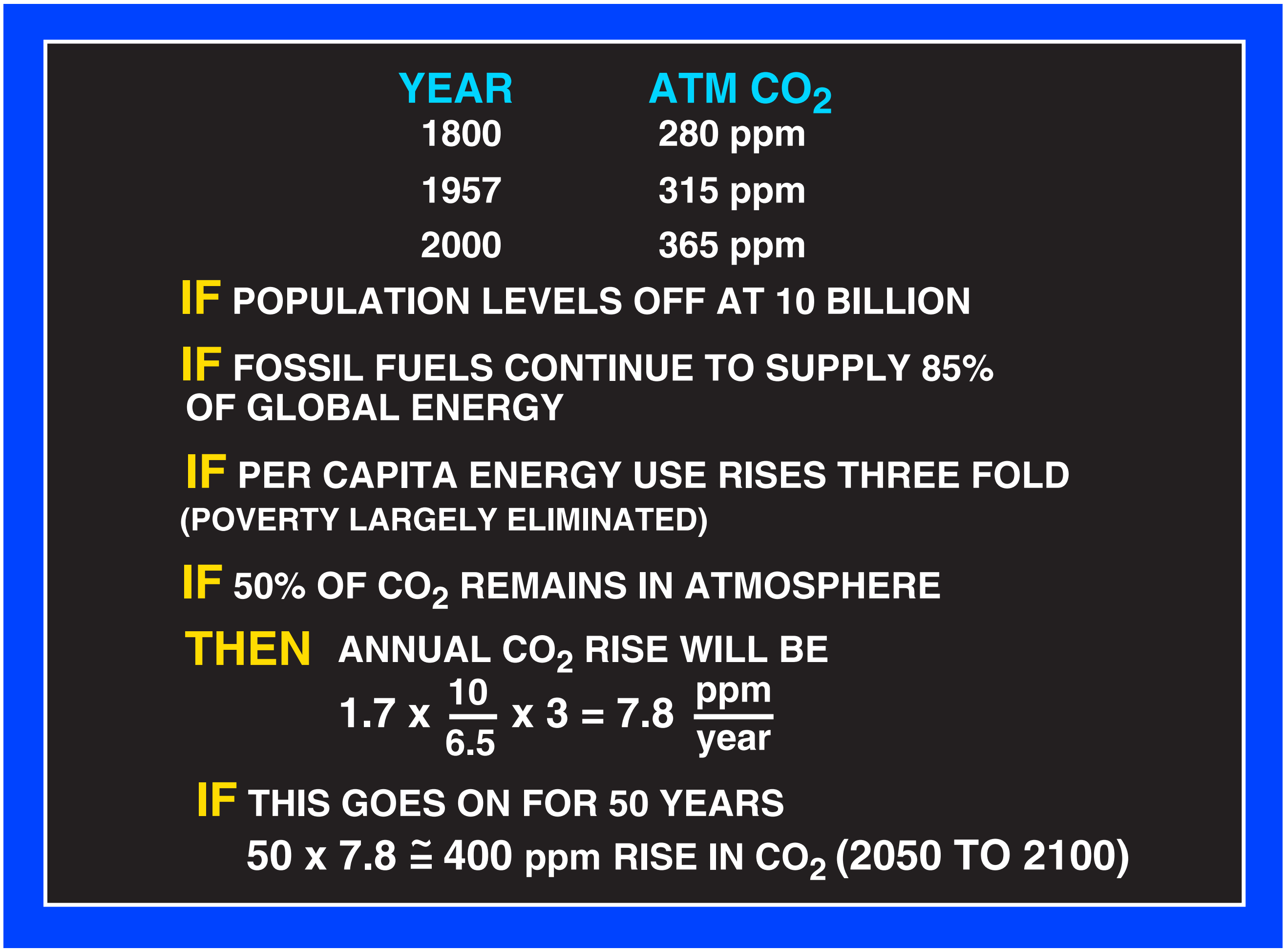
YEAR ATM CO_2
1800 280 ppm
1957 315 ppm
2000 365 ppm
IF POPULATION LEVELS OFF AT 10 BILLION
IF FOSSIL FUELS CONTINUE TO SUPPLY 85% OF GLOBAL ENERGY
IF PER CAPITA ENERGY USE RISES THREE FOLD (POVERTY LARGELY ELIMINATED)
IF 50% OF CO_2 REMAINS IN ATMOSPHERE
THEN ANNUAL CO_2 RISE WILL BE
$1.7 \times \frac{10}{6.5} \times 3 = 7.8 \frac{ppm}{year}$
IF THIS GOES ON FOR 50 YEARS
$50 \times 7.8 \cong 400$ ppm RISE IN CO_2 (2050 TO 2100)

Figure 6

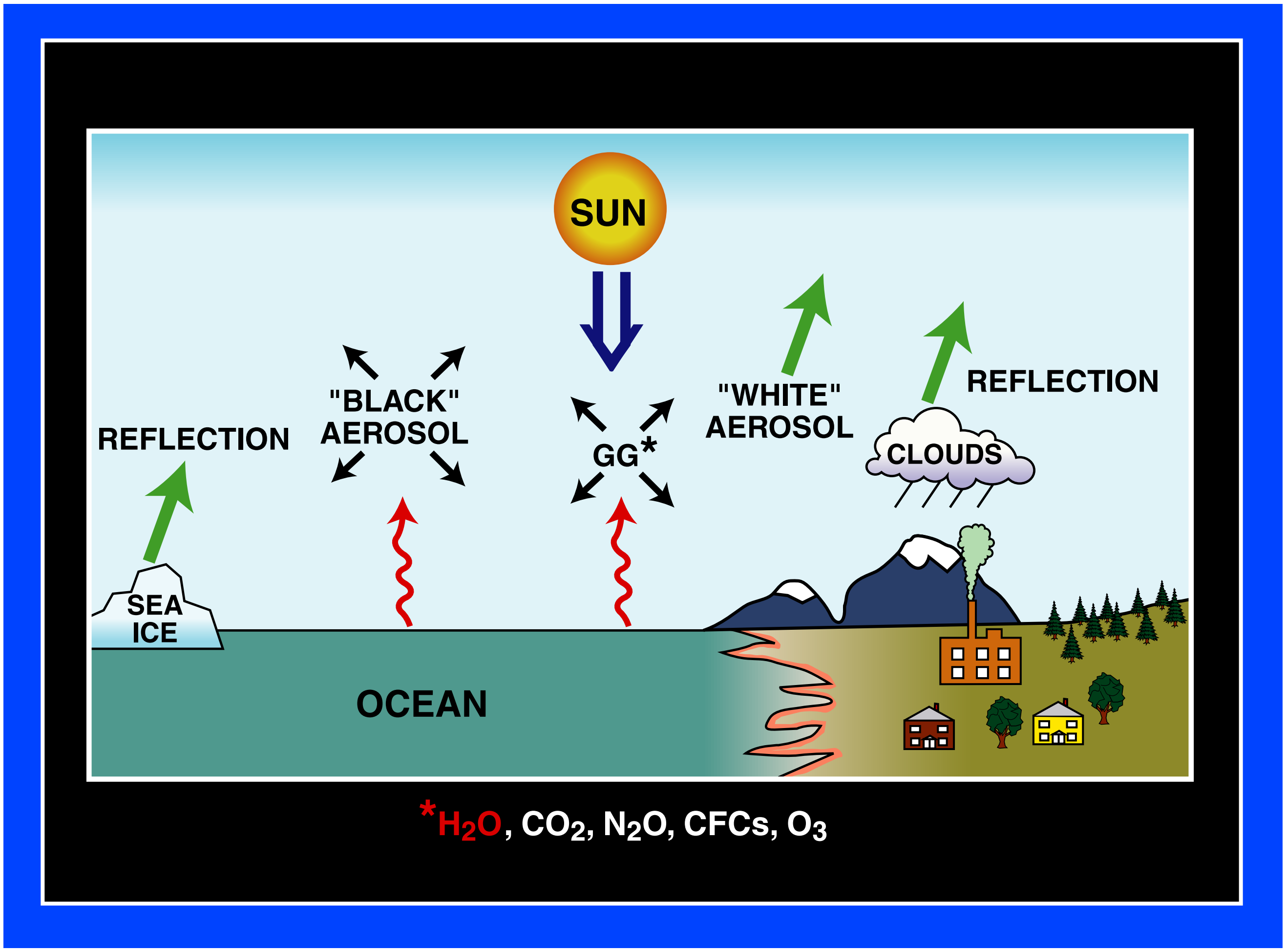
SUN
"BLACK"
AEROSOL
GG*
"WHITE"
AEROSOL
REFLECTION
CLOUDS
REFLECTION
SEA
ICE
OCEAN
*H_2O, CO_2, N_2O, CFCs, O_3

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

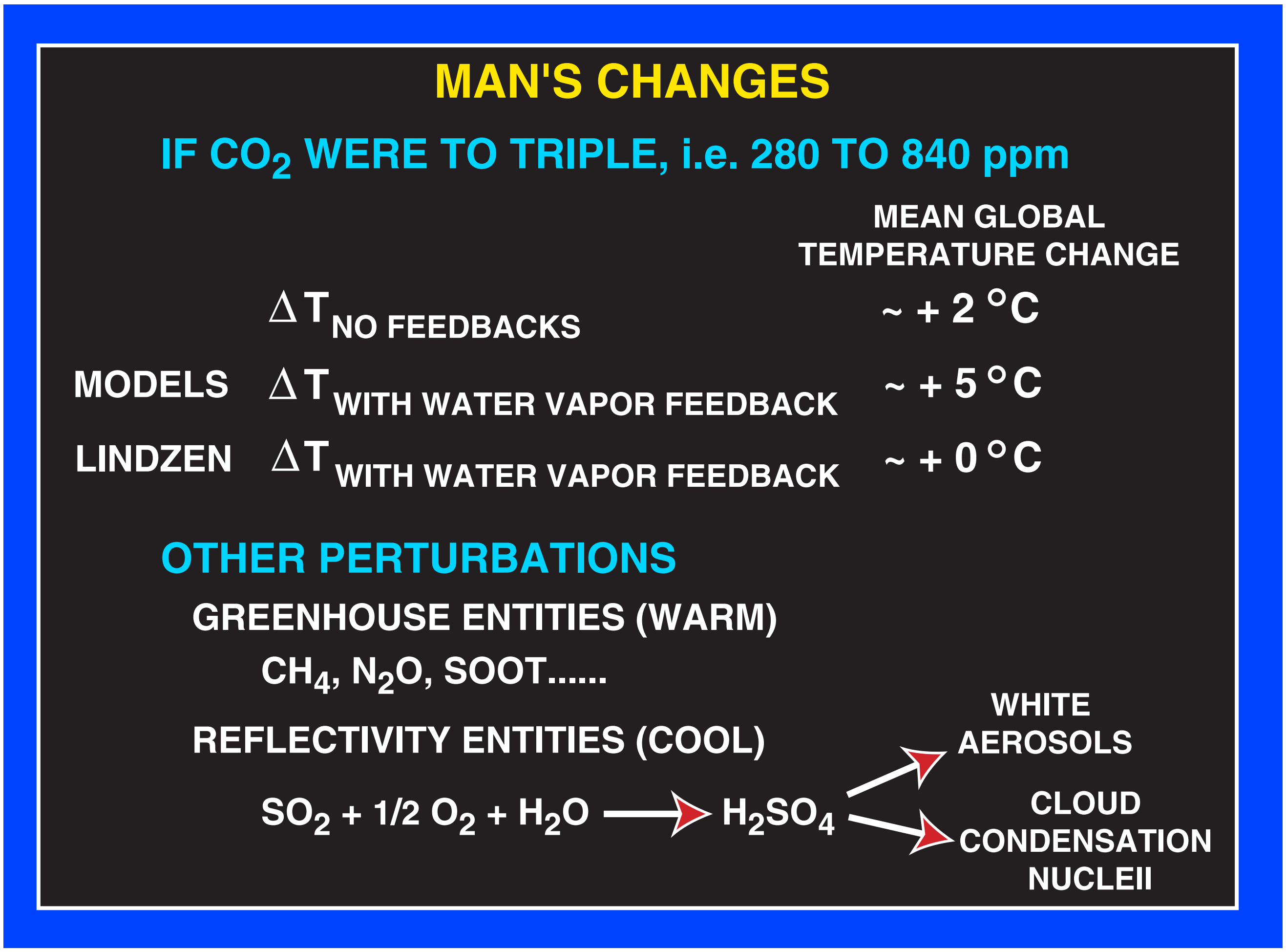
MAN'S CHANGES
IF CO_2 WERE TO TRIPLE, i.e. 280 TO 840 ppm
MEAN GLOBAL TEMPERATURE CHANGE
$\Delta T_{NO\ FEEDBACKS}$ ~ + 2 °C
MODELS $\Delta T_{WITH\ WATER\ VAPOR\ FEEDBACK}$ ~ + 5 °C
LINDZEN $\Delta T_{WITH\ WATER\ VAPOR\ FEEDBACK}$ ~ + 0 °C
OTHER PERTURBATIONS
GREENHOUSE ENTITIES (WARM)
CH_4, N_2O, 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

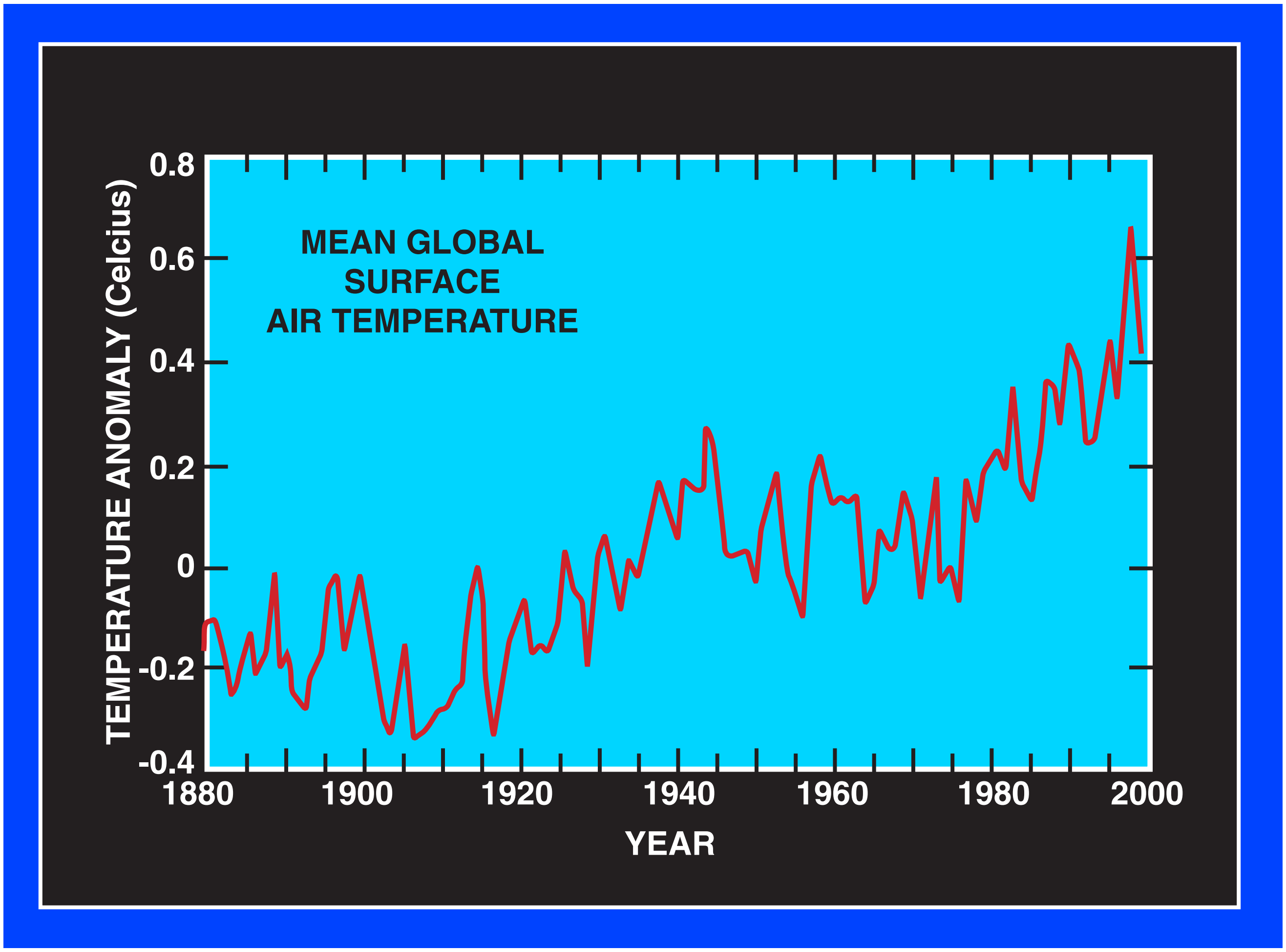
MEAN GLOBAL
SURFACE
AIR TEMPERATURE
TEMPERATURE ANOMALY (Celcius)
0.8
0.6
0.4
0.2
0
-0.2
-0.4
1880
1900
1920
1940
1960
1980
2000
YEAR

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