LIMITS ON GLOBAL WARMING[1]

A. S. Dennis

U.S. Bureau of Reclamation

Denver, CO 80225

Abstract. Consideration of the earth's carbon reservoirs and carbon exchanges among them indicates that the concentration of carbon dioxide (CO_2) in the atmosphere will increase markedly over the next 100 years and more. A doubling of atmospheric CO_2, along with anticipated feedback effects on atmospheric water vapor, will be roughly equivalent in radiative terms to an increase of 5 percent in the intensity of solar radiation at the top of the atmosphere. The laws of physics predict a resultant global warming, which likely will average around 3 to 4 °C, unless it is modified by other feedback effects. Concern about global warming is heightened by evidence that the average temperature at the earth's surface has risen about 0.5 °C over the last century. Global warming will be limited in intensity as the atmosphere approaches total opacity in the CO_2 radiation bands and will be ended by advection of excess CO_2 into the ocean depths, a process which will take several centuries. Possible measures to offset global warming include restrictions on fossil fuel consumption and active measures, such as the introduction of artificial dust clouds into the stratosphere to scatter solar radiation.

1. INTRODUCTION

The temperature at the surface of the earth is a function of the atmospheric concentrations of greenhouse gases, particularly water vapor and CO_2, as well as several other variables. As early as the 1860s, some scientists speculated that changes in the composition of the atmosphere due to widespread use of coal to fuel the Industrial Revolution eventually could affect the weather. Arrhenius (1896) calculated that doubling the concentration of carbon dioxide (CO_2) in the atmosphere would raise surface temperatures by about 5 to 6 °C depending on latitude.

Global warming, if it proves real, will surpass in importance all other cases of inadvertent weather and climate modification to date. Interest in it and other aspects of global climate change has been increasing in the scientific community over the past 25 years. However, most Americans paid little attention until 1988. That year brought to much of North America a searing drought, which climaxed a series of hot summers in the 1980s. It also brought TV newscasts combining pictures of drought-stricken fields with ominous speculations that the drought was merely a taste of an imminent climate change. Almost immediately "the greenhouse effect" and "global warming" became household words.

Among the hundreds of articles and reports that have appeared in the last few years dealing with various aspects of climate change, I have not found one that brings together in a few pages all of the factors that are likely to determine the intensity and duration of global warming due to an enhanced greenhouse effect. This paper does that. It describes no original research and it references, for the most part, reviews rather than original sources. It is intended to provide a perspective on the anticipated global warming and some ability to judge the merits of various methods that have been proposed to offset its impacts. No attempt is made to assess the potential impacts of global climate change on agriculture, commerce, or any other human activity.

2. CARBON RESERVOIRS AND CARBON CYCLES

2.1 An Inventory of Carbon Reservoirs

Any assessment of the possibility of global warming due to changes in the composition of the atmosphere must consider present and future trends of CO_2 concentrations. Carbon is stored in the earth's crust, ocean and atmosphere, and moves freely among the three reservoirs. Because carbon is a constituent of many inorganic compounds and is also a key element in the composition of all organisms, tracking it involves consideration of geological, physical, chemical, and biological processes.

While the quantities of carbon in its various locations are subject to considerable uncertainty, various authors have produced useful inventories; an example is that of Berner and Lasaga (1989), which is the basis of table 1. Nearly all the earth's carbon is tied up in sedimentary rocks, many of which were laid down on the seafloor as shells ages ago and subsequently lifted above sea level by geologic processes.

[1]Based on a presentation at the Fortieth Anniversary Meeting of the Weather Modification Association, Ontario, California, May 9, 1991.

Table 1. - Distribution of the earth's carbon among principal reservoirs.*

Reservoir	Mass stored (gigatons)**	Mass stored (Relative to atmosphere)
All biota	560	0.8
Atmosphere as CO_2	720	1.0
Dead surficial carbon	3,000	4
Recoverable fossil fuels	4,000	6
Ocean (as CO_2, H_2CO_3, bicarbonate and carbonate ions)	42,000	58
Sedimentary organic matter	15,000,000	21,000
Calcium-magnesium carbonate (mostly in sedimentary rocks)	25,000,000	35,000
Calcium carbonate (mostly in sedimentary rocks)	35,000,000	49,000

* Based on Berner and Lasaga (1989).
** 1 gigaton (Gt) = 10^9 metric tons = 10^{15} g = 1 petagram (Pg). Dr. Arnold Court has pointed out to me that 1 Gt is the mass of 1 km^3 of water, a fact that helps one to visualize the quantities listed in this table.

2.2 Short-term Carbon Cycles

The observed increase in atmospheric CO_2 over the past few decades has resulted from a small net difference between opposing processes (Houghton and Woodwell 1989). Large transfers of carbon relative to the atmospheric reservoir take place each year (fig. 1). Every year some 100 Gt is removed from the atmosphere by photosynthesis and sequestered as plant tissue, mostly wood, while a like amount is replaced by respiration by plants and animals and the decay of organic matter in the soil. Every year just over 100 Gt of carbon is removed as atmospheric CO_2 dissolves in the ocean, and a slightly smaller amount diffuses from the ocean back into the atmosphere. The relatively small annual contributions of carbon to the atmosphere from burning of fossil fuels (5 Gt) and from deforestation (2 Gt) are important because there are no known offsetting effects. However, the amount of carbon in the atmosphere is going up by "only" 3 to 3.5 Gt per year and the net absorption into the ocean is roughly 2 Gt annually, which leaves 2 Gt (some authorities say 4 Gt) per year unaccounted for.

The large annual exchanges between the ocean and the atmosphere indicated in figure 1 arise mainly from the fact that the equilibrium concentration of CO_2 at the ocean surface varies from place to place, principally because the ability of water to hold a gas in solution decreases with increasing temperature. Because atmospheric concentrations are quite uniform, the general tendency is for CO_2 to be given off by surface seawater that is being warmed and absorbed by water that is cooling. For example, degassing is likely along the equator west of South America, as cold upwelling water from the coast

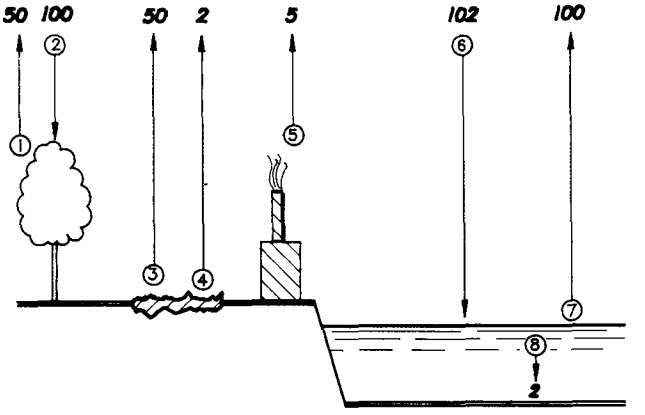

Figure 1. - Short-term carbon transfers (gigatons per year) among the atmosphere, ocean and the earth's crust (adapted from Houghton and Woodwell, 1989).

moves westward and warms under the tropical sun (fig. 3.4 of Brewer 1983). However, the tendency toward degassing from seawater that is being warmed can be reversed by rapid growth of plankton in nutrient-rich water.

Short-term exchanges of CO_2 between the ocean and the atmosphere are almost in balance, as figure 1 indicates. The apparent net absorption by the ocean over the past few decades has been driven by the rapid increase in the atmospheric concentration, which either speeds CO_2 absorption or suppresses its escape depending on local conditions. If the ocean warms as a result of global climate change, its ability to absorb atmospheric CO_2 will be diminished slightly. Keeling et al. (1989) have calculated that a slight observed warming of the sea surface from 1978 to about 1988 reduced the total CO_2 uptake over the decade by roughly 3 Gt.

Short-term exchanges of CO_2 between the ocean and the overlying atmosphere involve only the ocean's mixed layer. Convection and turbulence distribute dissolved CO_2 in its various forms rather uniformly throughout the mixed layer in a few months. The depth of the mixed layer varies, depending mainly on wind speed and vertical density gradients, but averages around 75 m (Keeling et al. 1989). The mixed layer reaches its maximum depth in areas where loss of heat from the sea surface to overlying cold airmasses leads to convective overturning within it. At high latitudes during winter, convective currents of chilled surface water can penetrate downward as much as 1 km, but mixing to that depth is incomplete.

2.3 Carbon in Seawater

In order to discuss CO_2 in seawater quantitatively it is necessary to consider the various forms that it assumes. The CO_2 dissolved in seawater is hydrated to form a weak solution of carbonic acid (H_2CO_3), which dissociates in two stages to yield bicarbonate (HCO_3^-) and then carbonate ($CO_3^=$) ions. The relative abundance of the various ions is controlled by a number of buffering reactions, of which the most important is

$$2\ HCO_3^- \leftrightarrow H_2CO_3 + CO_3^= \qquad (1)$$

The equilibrium constants for the various reactions vary with temperature and the pH value (acidity). According to a review by Archer (1990), only 1 percent of the carbon in seawater remains as CO_2 or undissociated H_2CO_3, 88 percent of it exists as bicarbonate ions, and the other 11 percent as carbonate ions. Some writers use the expression "total CO_2" to mean the total of dissolved CO_2 gas, H_2CO_3, and bicarbonate and carbonate ions.

The fact that CO_2 forms H_2CO_3, which then dissociates, makes it possible for seawater to hold about 30 times more CO_2 under present conditions than it could otherwise. Although oxygen is about 600 times as plentiful as CO_2 in the atmosphere, it is only about 20 times as plentiful in the ocean as the CO_2 equivalent of the carbon in the ocean. However, there is resistance to further additions of CO_2 to seawater. This resistance is expressed as a buffer factor, which is sometimes called the Revelle factor (Brewer 1983). The Revelle factor is a function of temperature, alkalinity and salinity, and so varies from place to place. Its present values are around 10, which means that changes in the total concentration of carbon in seawater, expressed as a percentage of the existing concentration, are only 0.1 times the corresponding changes in the partial pressure of CO_2 gas in the overlying atmosphere (Brewer 1983). Even so, seawater still is taking up about 3 times more CO_2 than it would if CO_2 did not dissociate.

Numbers quoted in table 8 of Keeling et al. (1989) can be combined to show that the ocean's mixed layer now holds roughly the same amount of carbon as does the atmosphere. Using that result and the current Revelle factor of 10, one can estimate the final apportionment between the atmosphere and the mixed layer of incremental amounts of atmospheric CO_2. As an increase of 10 percent in the atmospheric concentration of CO_2 will produce only a 1 percent increase in the total carbon content of the mixed layer, equilibrium is reached once the mixed layer takes up 0.09 Gt of each additional gigaton of carbon, leaving the remaining 0.91 Gt in the atmosphere.

2.4 Intermediate Cycles: Carbon in the Deep Ocean

It has been estimated that the CO_2 released from fossil fuels since the beginning of the Industrial Revolution has been divided about equally between the ocean and the atmosphere; yet the result just quoted in section 2.3 shows that the mixed layer can not absorb and hold more than one-tenth of the excess carbon being released to the atmosphere each year. The mixed layer's ability to continue to draw down atmospheric CO_2 depends on exchanges with the deep ocean, which holds about 98 percent of the carbon listed for the oceanic reservoir in table 1. Exchanges of carbon between the mixed layer and the ocean depths are brought about by ocean currents, large-scale turbulence and biological processes.

All of the oceans share a common circulation. It is characterized by regions where cold water sinks into the depths, especially in the Weddell Sea near Antarctica and between Greenland and Norway in the North Atlantic, and by regions where cold water from the depths reappears at the surface. Upwelling is marked along the west coast of South America, for example. The deep-ocean circulation proceeds very slowly, with complete circuits taking hundreds or thousands of years. Tritium released by nuclear bomb testing in 1962 and carried downward in the North Atlantic circulation still had not penetrated south of 30° N in the deep Atlantic by 1981 (Brewer 1983).

The cold water that sinks into the ocean depths tends to be rich in CO_2 and associated forms of carbon simply because it is cold. Its carbon content is enhanced further by biological processes. Organisms growing in the mixed layer deplete its CO_2 significantly, thereby making possible the uptake of more atmospheric CO_2, and ensuring that the sinking water carries significant amounts of carbon downward in organic as well as inorganic forms. On its long circuit in the deep ocean, the water is further enriched by organic waste falling from the mixed layer. Decomposition of this waste gives off CO_2, which leads to an increase of some 10 percent in the concentration of CO_2 and associated ions over the first kilometer downward from

the surface. Farther down, the concentration does not vary much with depth (Brewer 1983).

Consideration of equation 1 shows that the presence of dissolved carbonates enhances the ability of seawater to handle more CO_2, because any increase in carbonate concentration drives the equation to the left, that is, it converts CO_2 already present into bicarbonate. Surface seawater is supersaturated with respect to calcium carbonate ($CaCO_3$); many marine creatures take advantage of this fact and precipitate it to form their shells. The precipitation of $CaCO_3$, proceeds mainly according to the following equation:

$$2HCO_3^- + Ca^{++} \rightarrow CaCO_3 + CO_2 + H_2O \qquad (2)$$

Although this process results in a release of CO_2, its ultimate effect is to remove carbon from seawater. The most spectacular product of this process is coral reefs, but it has other results of much greater importance. Over millions of years, seashells and other organic debris have accumulated on the seafloor, creating the vast reservoir of carbon in sedimentary rocks (table 1).

The solubility of carbonates in water varies directly with pressure and inversely with temperature and pH value. In the depths, the temperature is always near 2 °C, pressures run to thousands of bars, and the pH is lowered, that is, the acidity increased, by the CO_2 released by decaying organic matter. Below some level, the water is no longer supersaturated with respect to $CaCO_3$, which begins to dissolve and thereby increases the ability of the water to hold CO_2. This changeover occurs at a great depth, which has been estimated at 5 km for the North Atlantic Ocean (Brewer 1983), and does not prevent the accumulation of carbonates on much of the earth's seafloor.

2.5 Geochemical Carbon Cycles

Carbonates do not build up on the seafloor indefinitely; seashells, like almost everything in nature, are recycled. If the shells are converted to sedimentary rock (limestone) and elevated above sea level, the limestone is eventually attacked by H_2CO_3 and carried away to the ocean as calcium and bicarbonate ions. The H_2CO_3 can be formed as atmospheric CO_2 dissolves in rainwater or in surface water, or as CO_2 released by decaying organic matter in the soil enters groundwater. The simplified chemical equation for weathering of $CaCO_3$,

$$CaCO_3 + H_2O + CO_2 \rightarrow CaCO_3 + H_2CO_3 \rightarrow Ca^{++} + 2HCO_3^- \qquad (3)$$

is the converse of equation 1, which describes the precipitation of $CaCO_3$ as seashells.

It has been known for over a century (e.g., Arrhenius 1896) that volcanos release CO_2 to the atmosphere and that the weathering of rocks removes it. Thanks to the development of the theory of plate tectonics, it has been recognized in the last decade that the two processes just named and the carbonates on the seafloor are linked in a grand geochemical carbon cycle. According to Ruddiman and Kutzbach (1991), "Chemical weathering of continental rocks removes carbon dioxide from the atmosphere and carries it in dissolved chemical form to the ocean, where it is taken in by marine biota and deposited in sediments on the seafloor. Tectonic activity eventually frees this trapped carbon dioxide in the following manner. The motion of the earth's lithospheric plates transports the seafloor to ocean trenches, where subduction carries old crust and sediments down toward the earth's hot interior. At great depths, the sediments melt, releasing carbon dioxide, which emerges from the volcanic islands that overlie the buried crust and rejoins the atmosphere, completing the cycle." Additional information is given by Berner and Lasaga (1989), who emphasize that the weathering of silicates followed by precipitation of $CaCO_3$ in the sea produces *a net loss of CO_2 from the atmosphere.* The governing equations for the conversion of silicates to $CaCO_3$ are:

$$2CO_2 + H_2O + CaSiO_3 \rightarrow Ca^{++} + 2HCO_3^- + SiO_2 \qquad (4)$$

$$2HCO_3^- + Ca^{++} \rightarrow CaCO_3 + CO_2 + H_2O \qquad (5)$$

In the absence of offsetting processes, notably emissions from volcanos and ocean-atmosphere exchanges, the weathering of rocks could deplete the atmospheric CO_2 reservoir completely in about 10,000 years. Berner and Lasaga (1989) note that the processes in the magma under the earth's crust that break down carbonates result not only in the expulsion of CO_2 but in the recombination of calcium and silicon into silicate rocks, which also is required to close the geochemical carbon cycle.

2.6 CO_2 in the Atmosphere

Summarizing to this point, the concentration of CO_2 in the atmosphere is affected by many factors, including the growth and decay of plants and trees, the deposition and burning of fossil fuels, sea surface temperatures, volcanic activity, and topography. Topography enters in because the rise and fall of mountains and plateaus affect sea level and the rate of rock weathering (Ruddiman and Kutzbach 1991). An increased concentration of atmospheric CO_2 hastens weathering of silicates, which removes CO_2 from the atmosphere and deposits it in the ocean. This negative feedback effect may have set the outer limits on the CO_2 concentration over geologic time, but did not control the concentration very closely. Experimental data indicate wide ranges in the atmospheric CO_2 concentration in the distant past, as noted in a review article by Lorius et al. (1990). Air bubbles trapped in the famous Vostok ice core from Antarctica have been analyzed to estimate the atmospheric concentration back for some 150,000 years. The concentration during that time varied from 175 to 300 ppm by volume (fig. 2).

Estimates of the concentration of CO_2 in the atmosphere at the start of the Industrial Revolution, say in 1815, cluster around 270 ppm. These estimates are based on ice-core samples and on sporadic direct measurements during the nineteenth century. The concentration approached 300 ppm by 1900.

The concentration of CO_2 in the atmosphere has been measured systematically since 1958, which was the

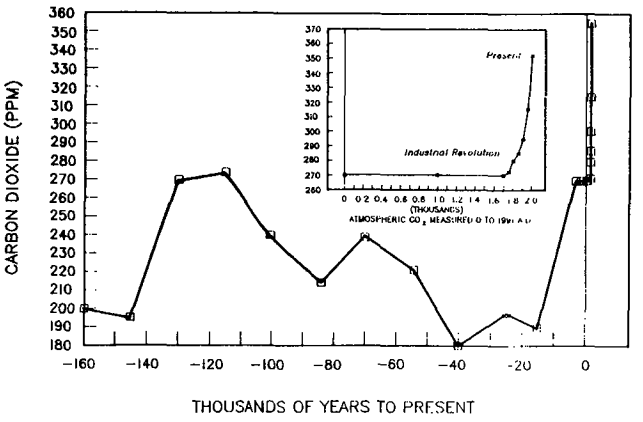

Figure 2. - Concentration of CO_2 in the atmosphere over the past 160,000 years.

International Geophysical Year. The concentration varies with both time and place. The continuous measurements since 1958 at Mauna Loa, Hawaii, show small diurnal variations, annual variations, which extend about 6 ppm from peak to trough, and irregular fluctuations, some of which can be related to large-scale weather disturbances, particularly the El Nino events. All of these are superimposed on a rising trendline, which was at 315 ppm in 1958 and reached 352 ppm in 1989 (Keeling et al. 1989). Land vegetation, which draws down the atmospheric supply of CO_2 in the Northern Hemisphere spring and releases CO_2, in the fall, accounts for about 90 percent of the annual fluctuation (Sellers and McCarthy 1990). The seasonal warming of the North Atlantic and North Pacific Oceans during Northern Hemisphere spring and summer tends to raise the atmospheric CO_2 concentration by degassing from the sea surface, but the biological processes predominate.

Mixing of air throughout the global atmosphere, including transequatorial exchanges, is accomplished on a time scale of about a year. As a result, the concentration of CO_2 is fairly uniform over the whole world, although minor variations exist. Ground-level concentrations over the Northern Hemisphere now exceed those over the Southern Hemisphere by almost 3 ppm, and the difference increased from 1958 to 1989. The size of the excess is correlated with annual global consumption of fossil fuels, which is concentrated in the industrialized countries of the Northern Hemisphere, although the correlation is not exact (Keeling et al. 1989).

The present rate of increase in the mean global concentration of CO_2 in the atmosphere far exceeds anything detected in the geologic record (fig. 2). Comparison of the sizes of the different carbon reservoirs (table 1) shows that the atmospheric concentration could continue to rise for some time as a result of fossil fuel consumption. Nordhaus and Yohe (1983) projected future levels under various assumptions about economic trends and associated fuel consumption; their median scenario suggests a doubling of the atmospheric CO_2 concentration from the 300 ppm that prevailed at the beginning of the twentieth century to 600 ppm around the year 2070 (fig. 3). Because of increases in other greenhouse gases, notably methane (CH_4) and chlorofluorocarbons (CFCs),

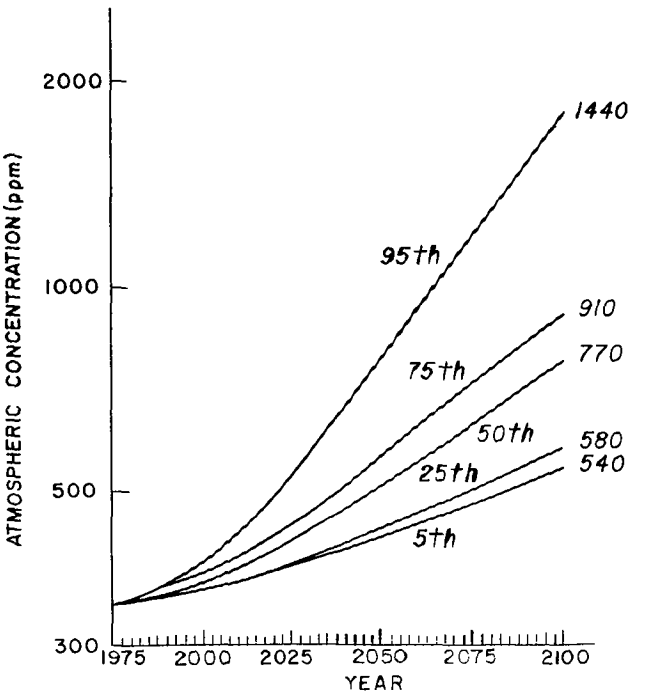

Figure 3. - Observed and predicted concentrations of CO_2 from 1975 to 2100 for indicated percentile runs of Nordhaus and Yohe (1983). The numbers on the right-hand side indicate concentrations in the year 2100.

the earth will experience the equivalence in radiative terms of a CO_2 doubling somewhat earlier, say around 2050.

3. PHYSICAL BASIS FOR THE GREENHOUSE EFFECT

Apart from a negligible amount of heat generated by radioactivity in its crust and other even smaller sources, all of the earth's heat comes from the sun. The incoming solar energy at the top of the atmosphere varies only by 0.1 percent or so; averaged over all latitudes, times of day, and seasons, it amounts to about 342 watts per square meter (W m^{-2}). Figure 4, which is based on Ramanathan et al. (1989), shows the disposition of the solar energy. About 105 W m^{-2} are reflected or scattered back into space, so the albedo of the earth is calculated as 105/342, or 0.31. The absorbed energy is transformed into sensible heat and latent heat. Eventually, some of it appears as the kinetic energy of the winds and much of it is reradiated from the surface or by the atmosphere as long-wave (infrared) radiation.[2]

Application of the Stefan-Boltzmann Law shows that the average outgoing IR at the top of the atmosphere, 237 W m^{-2}, is equivalent to that from a black-body radiator at 255 °K. The 33 °C difference between that number and the actual, average, surface temperature of the earth, which is about 288 °K, is due to the atmosphere's greenhouse

[2]In accordance with the *Glossary of Meteorology*, the abbreviation IR will be used to mean both "infrared" and "infrared radiation."

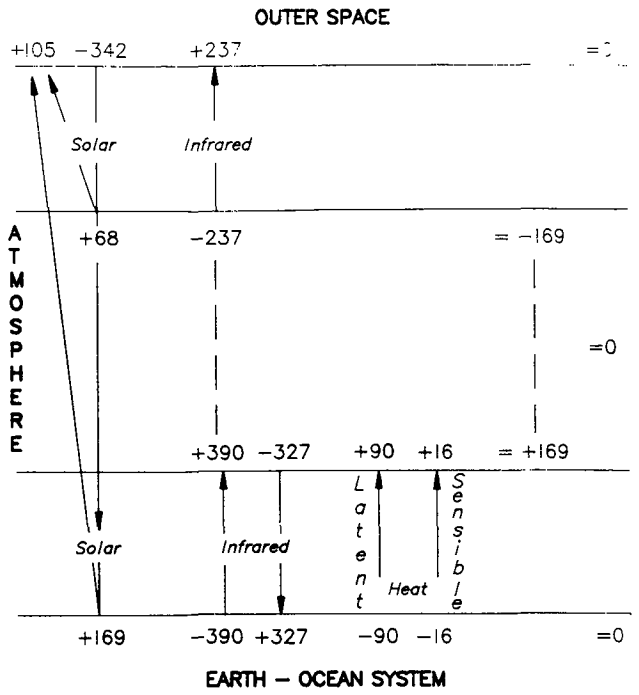

Figure 4. - Disposition of solar energy reaching the top of the atmosphere (based on Ramanathan et al. 1989). Amounts shown are in watts per square meter and are to be interpreted as yearly averages over the entire earth.

effect. The effective IR temperature of 255 °K suggests that IR sensors in space respond, on average, to IR emitted from the middle troposphere, say around the 400-mb level.

Many studies of possible climate change have dealt with the impacts of a doubled-CO_2 world. Barring changes in cloudiness, a doubling of the concentration to 600 ppm would have a negligible effect on the atmosphere's ability to absorb solar radiation, but would make it a more efficient absorber and radiator of IR. Ramanathan (1981) calculated that the increase in IR emissivity of the atmosphere by itself would increase the downward flux of IR energy at the earth's surface by 1.2 W m^{-2}, even if the temperature structure of the atmosphere remained as at present (fig. 5). However, the troposphere would warm up because it would absorb more of the outgoing IR from the surface, and this effect would increase the downward flux at the surface by another 2.3 W m^{-2}, so the total effect of CO_2 doubling would amount to 3.5 W m^{-2}. The warmer surface would result in additional evaporation from the ocean. As water vapor is itself a greenhouse gas, the troposphere would be warmed still further by absorption of IR by water vapor, as well as by the release of latent heat when the additional water vapor precipitated. Ramanathan calculated this positive feedback effect at 12 W m^{-2}, bringing the total impact of doubling CO_2 to 15.5 W m^{-2} (fig. 5). *Without the effects of the anticipated associated increase in water vapor, the impact of doubling the atmospheric CO_2 concentration would be so small that it would be very difficult to detect.*

The feedback factor for the effect of the increase in water vapor in this case can be calculated as 15.5/3.5, or

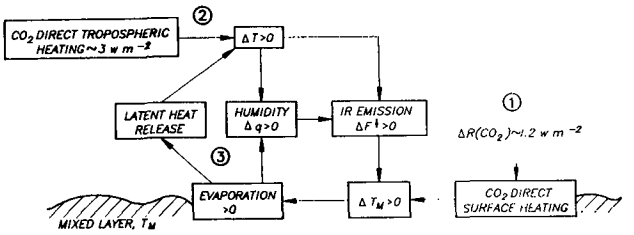

Figure 5. - Schematic illustration of the ocean-atmosphere feedback processes by which CO_2 increase warms the surface of the earth. All of the numbers correspond to hemispherically averaged conditions and apply to a doubling of CO_2 (after Ramanathan 1981, courtesy of the American Meteorological Society).

4.4. [Some previous authors have used different definitions of feedback factors.] As defined and calculated here, a feedback factor greater than 1 signifies positive feedback and a feedback factor less than 1 signifies negative feedback.

The 15.5 W m^{-2} calculated by Ramanathan (1981) as the total radiative impact of doubling CO_2 equals about 5 percent of the mean flux of solar radiation at the top of the atmosphere, so one would anticipate a substantial impact on the earth's climate. One crude way to estimate the impact of doubled CO_2 on the temperature at the surface is to apply the Stefan-Boltzmann equation with the outgoing IR increased from 237 to 252.5 W m^{-2} in line with Ramanathan's calculations. The result is about 259 °K, which suggests that global warming under doubled CO_2 conditions might amount to about 4 °C. It is surprising how well the 4 °C rise estimated by this simple method and the 5 to 6 °C calculated by Arrhenius in 1896 (!) agree with the results obtained by more complex models. [Arrhenius assumed that the *relative* humidity would stay the same as the earth warmed, and so caught the extremely important feedback due to increased *absolute* humidity.]

Of course, global warming will not affect the outgoing IR unless the earth's albedo is changed; an observer in space would still record 237 W m^{-2} of outgoing IR. The surface and lower atmosphere would be warmer than at present, but the IR sensors in space would be responding, on average, to higher layers of the atmosphere, leaving the outgoing IR the same. The highest levels of the atmosphere would actually cool, as the thickened blanket of CO_2 and water vapor in the troposphere would absorb some of the IR that presently reaches them from the surface and the lower atmosphere.

4. ANALOGS OF GLOBAL WARMING

Numerous scientists have examined climatological records and paleoclimatic data for clues to possible climate changes due to enhanced concentrations of greenhouse gases. According to Gleick's (1989) review, ". . . the Holocene optimum (about 6000 to 5000 years B.P.) is considered an analogue for a 1 °C warming; the last interglacial (about 125,000 years B.P.) is considered an

analogue for a 2 to 2.5 °C warming; and the Pliocene climatic optimum (about 3 to 4 million years B.P.) corresponds to a warming of 3 to 4 °C." Considerable effort has gone into studies of lake levels, types of vegetation, and so on during those eras for indications of what a warmer world might entail. However, Crowley (1990) has concluded that geologic records yield no completely satisfactory analogs of global warming because, among other things, the earth's orbit around the sun is different now than in the past, and nothing in the geologic record matches the current rate of increase in concentrations of greenhouse gases.

Although paleoclimatic data do not yield exact analogs of future climates, they are valuable in investigations of the physical mechanisms that control climate. Lorius et al. (1990) have calculated that between 40 and 65 percent of the variance in the Vostok temperature record can be explained by variations in the concentrations of CO_2 and CH_4 during the same period, and about 80 percent by a combination of orbital forcing (the Milankovitch effect) and greenhouse gas concentrations. They also employed multivariate analysis to deduce that the feedback factor that applied to temperature variations driven by variations in the concentrations of CO_2 and CH_4 over the 150,000 years before the present was somewhere around 3. This result is intriguing because it agrees fairly well with the theoretical calculations of Ramanathan (1981). It is also in reasonable agreement with recent output from general circulation models, which will be discussed next.

5. PREDICTIONS FROM GENERAL CIRCULATION MODELS

The results of Ramanathan (1981) were based on a one-dimensional ocean-atmosphere model. The actual ocean-atmosphere system is three-dimensional, which allows the transport of heat from place to place by winds and ocean currents. The only models capable of handling the three-dimensional system are the general circulation models (GCMs). There is an extensive literature describing the various GCMs developed at different institutions and providing sample results; space does not permit any description of the models in this paper.

Most of the simulations of global warming using GCMs have modeled a world in which the atmospheric concentration of CO_2 is steady near 600 ppm, approximately double that of the year 1900. The results indicate that doubling CO_2 will raise the average surface temperature of the earth by some amount in the range of 1.5 to 5 °C. Recent estimates are clustering around 3 to 4 °C. Most of the models indicate that warming in the polar regions will be more pronounced than warming at lower latitudes. One comforting fact is that the changes in precipitation predicted by the models are within the range of the rainfall fluctuations that have occurred from natural causes over the past few hundred years. Unfortunately the models do not simulate natural precipitation patterns very well, and they do not agree concerning regional impacts on either temperature or precipitation (Grotch and MacCracken 1991).

Most doubled-CO_2 model runs simulate an earth whose climate has stabilized following a sudden doubling of the atmospheric CO_2 concentration, with no further increase thereafter. Such model runs do not correspond to the actual earth, with its steadily increasing concentration of greenhouse gases. Doubled-CO_2 scenarios can be viewed as rough estimates of a condition through which the earth may pass on its way to even higher concentrations of greenhouse gases. As noted in section 2, the combined effect of increases in CO_2, CH_4, and CFCs is likely to produce the equivalence of a doubled-CO_2 atmosphere around 2050, but the onset of global warming will be moderated by the tremendous thermal inertia of the ocean. As some recent papers put the time constant for adjustment of the temperature of the ocean's mixed layer to a thermal forcing function at roughly 50 years, it appears that the theoretical predictions of climate for a doubled-CO_2 world should be most applicable to some time around 2100. However, upwelling of cold, deep-ocean water that has never been exposed to an enhanced greenhouse effect will continue for centuries and prevent the establishment of a true equilibrium condition.

Critics of GCMs often refer to their coarse spatial resolution, with grid points typically separated by a few hundred kilometers in the horizontal, which precludes representation of mesoscale and local phenomena except through parameterization. However, the crude representation of physical processes in the models is probably a more serious deficiency. At this time, the key physical uncertainties center around ocean-atmosphere interactions, the radiative effects of clouds, and the albedos of surfaces covered by ice or snow. As all three factors involve the possibility of significant feedback effects, their correct representation is of critical importance.

The first ocean-atmosphere GCMs which modeled the ocean at all treated it as a swamp, that is, a wet surface with no capacity to store heat. More recent versions (e.g., Meehl and Washington 1990) treat the ocean as consisting only of its mixed layer. That allows the ocean to store heat. Models that treat exchanges of heat between the mixed layer and the ocean depths are just beginning to appear.

Clouds are sites where latent heat is transformed into sensible heat (and sometimes vice versa), and they are important to the earth's radiation budget (Fouquart et al. 1990; Arking 1991). Because the dimensions of individual clouds are much smaller than a typical GCM grid spacing, clouds must be parameterized in the models, and several parameterization schemes are in use (Randall 1989). A recent intercomparison of 19 different GCMs concluded that most of the variation in results was attributable to differences in the models' depiction of cloud feedback (Cess et al. 1990).

Clouds simultaneously cool the earth by scattering solar radiation and warm the earth by intercepting IR from the ground and reradiating some of it downward as well as to outer space. The relative importance of the two effects varies with time of day, latitude, and cloud characteristics. Important cloud characteristics in this regard include

cloud-top temperature, thickness, and the physical state and size distribution of the particles constituting the cloud. Shallow clouds with warm tops are thought to exert a net cooling effect because they radiate considerable IR into space, while clouds with cold tops warm the earth because they are weak IR radiators. Calculations based on satellite data of the annual global mean effect of all clouds have shown that, on balance, clouds cool the earth. Estimates of the net cooling effect have ranged from near zero to 40 W m^{-2} (Fouquart et al. 1990), while recent results generally fall between 17 and 27 W m^{-2} (Ramanathan et al. 1989; Arking 1991).

Because clouds exert a net cooling effect, it is likely that any increase in cloudiness associated with a warmer earth would exert a negative feedback effect, while a decrease would exert a positive feedback effect. GCMs do not agree on what the changes in cloud cover would be, so they can not agree on the feedback effects. A comparison of 19 different GCMs under perpetual July conditions found about one-third of them exhibiting a negative feedback effect and the other two-thirds a positive effect (Cess et al. 1990; Arking 1991). In summary, there is currently no way to tell whether the modification of the earth's clouds by the enhanced greenhouse effect will lead to a positive or a negative feedback effect upon surface temperatures.

Multiple runs with the same GCMs have shown that the results of doubled-CO_2 runs are also quite sensitive to the albedos assigned to polar sea ice and seawater at low sun angles (Meehl and Washington 1990). Varying these assigned parameters within reasonable limits can lead to an Arctic Ocean that becomes mostly ice-free in summer or to one that stays icebound year round. The difference produces noticeable effects on globally averaged temperature and has serious implications for the climates of northern North America and Eurasia.

6. EVIDENCE OF GLOBAL WARMING

The appreciable increases in CO_2 that have occurred already have prompted searches for a corresponding warming of the earth's surface. The statistical problems encountered in this approach parallel those involved in detecting inadvertent weather modification and changes in local weather produced by operational cloud seeding programs. Obviously, the special methods developed to evaluate randomized cloud seeding projects are not applicable to the global warming issue.

Surface temperature data from different sources have been combined and examined for evidence of global warming. There are numerous problems with surface temperature data, including station relocations, the heat-island effect of cities, and changes in procedures for measuring sea-surface temperature. Regional climate variations over periods of a few decades further confuse the issue. Still, there is good evidence that a net warming averaging 0.5 °C over the earth's entire surface (both land and sea) has occurred over the past century (Jones and Wigley 1990). The evidence from thermometer readings is reinforced by other types of evidence, including the shrinking of glaciers and the warming of some Canadian lakes (Houghton and Woodwell 1989). The latest satellite data indicate decreases in the extent of sea ice in the Arctic regions during the period 1978 to 1987, but show no significant trend in the extent of ice around Antarctica (Gloersen and Campbell 1991).

As cloud seeders have learned, finding a trend in meteorological data is just a starting point for discussions of possible causes. As climate has been varying for thousands of years, the observed warming during the twentieth century is not necessarily due to increased concentrations of greenhouse gases. Recently Balling (1991) has pointed out that desertification, which afflicts 30 percent of the land area of the globe to some degree, is producing a significant warming trend in the affected areas. Desertification may account for 0.05 °C or more of the total warming of 0.5 °C observed over the past century.

Skeptics point to the fact that the global warming was interrupted by a cooling trend in the Northern Hemisphere from 1940 to about 1965, during which period the CO_2 concentration was going up at an accelerated pace. Indeed, Gordon (1991) has shown that the observed warming during the past century may be only a manifestation of a random walk. Persons who believe that global warming has begun consider the cooling from 1940 to 1965 a temporary dip due to natural causes. The existence of the dip is a reminder that global warming due to enhanced concentrations of greenhouse gases could be masked at times by some combination of external driving forces promoting a cooling of the earth. For example, dust from the eruption of Mt. Pinatubo in the Phillipines in 1991 will exert a slight cooling effect on the earth's surface over the next several years. Global warming could also be masked by climate swings lasting a few decades and due only to internal feedbacks in the ocean-atmosphere system itself. Several experiments with GCMs have shown such swings, as exemplified in two recent 100-year simulations by Houghton et al. (1991).

Establishing that global warming is underway will require, for conservative scientists, a demonstration that changes have occurred that mimic, on a regional scale and at different levels in the atmosphere, those predicted by GCMs to accompany global warming. An announcement from Goddard Space Flight Center in mid-1991 that the temperature at 55 km altitude had *dropped* by 2.5 °C over the previous 10 years is worthy of attention, because it agrees with some GCM predictions of an enhanced greenhouse effect. However, proof of global warming according to the strict standard stated above is impossible at this time, because the available GCMs do not agree in their predictions of regional effects (Grotch and MacCracken 1991).

7. NATURAL LIMITS ON GLOBAL WARMING

There are numerous conceivable feedback effects in the ocean-atmosphere system, both positive and negative, that have not been mentioned so far in this paper. For example, warming of the ocean may release CH_4 presently locked up in sediments on continental shelves, thereby exacerbating the buildup of greenhouse gases (Revelle 1983). On the other hand, several authors have suggested

negative feedbacks that could limit the continued buildup of CO_2 in the atmosphere or, alternatively, the intensity of global warming in the presence of increased concentrations of greenhouse gases.

A negative feedback effect related to an increase in global cloud cover appears now as the most likely way for the earth to escape any serious global warming. Henderson-Sellers and McGuffie (1989), in an analog study using historical data, found a positive correlation between temperature and cloud cover. However, their data covered only a small fraction of the earth's surface and, as noted above, a majority of GCM runs have predicted a decrease in global cloud cover, rather than an increase, to accompany global warming.

Lindzen (1990) has argued that a negative feedback effect will arise as enhanced convection carries additional heat upward to be radiated into space from the upper troposphere and intensified subsidence between the convective cloud towers thins the water vapor shield between the surface and the top of the atmosphere. However, his calculations do not take account of the fact that convective clouds introduce large amounts of water into the upper troposphere, much of it as ice from anvil clouds. Randall (1989) has noted the need for improved parameterization of the high stratiform clouds induced by deep convection, which could be the basis of improved assessments of suggestions such as those of Lindzen.

It is possible that the human race will burn up nearly all the available fossil fuels in the next 200 to 300 years. Comparing the atmospheric and fossil fuel reservoirs (table 1) shows that, in theory, such rapid consumption of fossil fuels could push the atmospheric CO_2 concentration to almost unimaginable levels, say 1500 or 2000 ppm. The processes of rock weathering and advection into the deep ocean are much too slow to offset the effects of large increases in the global rate of fossil fuel consumption. Interaction with the biosphere poses the only possible limit in such a case. In particular, according to Sellers and McCarthy (1990), ". . . land vegetation is now thought likely to dominate the short-term biospheric response to increasing atmospheric CO_2".

Some persons have argued that very large increases in atmospheric CO_2 will be self-limiting because the growth of vegetation will accelerate in response to the increased concentrations of CO_2. There have been numerous investigations of the impacts of increased concentrations of CO_2 on plant growth, but mostly by persons interested in the potential impacts on crop yields (e.g., Waggoner 1983). In general, the effects are modest and some crops, corn for example, become saturated at CO_2 concentrations above 500 ppm. That is, further increases in the atmospheric CO_2 concentration will produce no further acceleration in their growth rates. However, Idso (1991) has provided some experimental evidence that the growth rates of trees are much more sensitive to increases in CO_2 than are the growth rates of crops. He reports that production of wood in one species increased by a factor of 2.8 when trees were exposed to a CO_2 concentration of 600 ppm. As trees account for well over half of the biospheric exchanges between the atmosphere and the earth's surface (both land and water), their sensitivity to increases in CO_2 concentrations could be very important. Idso's (1991) calculations indicate that, even in the face of a doubling of the present rate of fossil fuel emissions, trees could limit the concentration of atmospheric CO_2 to 700 ppm. There is much uncertainty associated with his numbers but, clearly, the potential of CO_2 removal by growing trees is important enough to justify further study.

If fossil fuel use continues to increase and accelerated tree growth fails to prevent a rise in the concentration of atmospheric CO_2 to over 1,000 ppm, could such a concentration lead to a runaway greenhouse effect, say another 6 °C warming over and above the 3 °C predicted by some models for a doubling to 600 ppm? Fortunately, the answer appears to be "No."

If the atmosphere becomes totally opaque in the CO_2 absorption bands, further additions will have no direct effect and at that point the feedback effects also would begin to stabilize. The atmosphere is already almost opaque in the middle of the CO_2 absorption bands, and increases in its concentration beyond 600 ppm will affect mainly the fringes of the bands. Therefore the additional warming for each unit increase in CO_2 concentration will drop off asymptotically toward zero, as noted by Arrhenius (1896). This comforting argument does not apply to additions of other greenhouse gases to the atmosphere, because each one has its own absorption bands.

Natural physical processes will limit the duration as well as the intensity of global warming. Increased rock weathering could draw down the excess atmospheric CO_2 over a few thousand years, but the dissolution of excess CO_2 in the ocean promises a quicker end to the enhanced greenhouse effect. The relative magnitudes of the various carbon reservoirs (table 1) suggest that the ocean depths can absorb without strain all the carbon in the world's fossil fuel reserves. Once the fossil fuel is exhausted, the atmospheric CO_2 concentration will begin to decrease as CO_2 continues to dissolve in the ocean's mixed layer and be advected into the depths. *Advection of CO_2-enriched seawater into the deep ocean promises an eventual end to the enhanced greenhouse effect.* It will take a few hundred years for enough upwelling and subsidence of ocean water to occur to bring the concentration down close to that of today, so global warming, if it proves real, will last through 10 or 20 generations of human beings. Note that, for reasons discussed earlier, the enhanced greenhouse warming would not relax its grip appreciably until the concentration of CO_2 fell to near the level of today, while the thermal inertia of the ocean would prove as effective in prolonging global warming as in tempering its onset.

It appears that the slight enhancement of carbon in the ocean, as excess atmospheric CO_2 is dissolved in the mixed layer and advected into the depths, will eventually be brought down by increased deposition of organic matter and shells on the sea floor. That process would also require centuries to work itself out. Roberts (1987) estimated that the "cleanup" of the ocean would not be complete before the year 3000.

8. POSSIBLE COUNTERMEASURES

Global warming would have serious effects on agriculture and many other human activities, and it is commonly assumed that nearly all of the effects would be undesirable. Ausubel (1991) has questioned that assumption, as well as several other pieces of prevailing wisdom about global climate change. Furthermore, the rates of change in temperature and precipitation predicted so far to accompany global warming fall within the range of natural regional variations experienced over the past few hundred years. Nevertheless, the idea persists that global climate change will be harmful, and considerable thought has been given to ways to mitigate its effects.

The most obvious countermeasure is a passive one, namely, to reduce emissions of greenhouse gases, thereby slowing, but not preventing, global warming. Control of emissions of CFCs is critical because, as already noted, they have absorption bands different from those of CO_2. There are now international agreements in place to control emissions of CFCs. An agreement to restrain emissions of CO_2 will be harder to come by, because of the close link between fuel consumption and the level of economic activity. Any reduction large enough to make a significant difference over the long term will require radical socioeconomic adjustments on a global scale. Nevertheless, inter-governmental committees are at work and hope to have an agreement covering all greenhouse gases ready for possible ratification at the United Nations Conference on Environment and Development (UNCED) scheduled for Rio de Janeiro, Brazil in June, 1992. The UNCED will consider climate change and a number of related problems, including ozone depletion and air pollution (Miller, 1991).

Many persons have suggested reforestation, or at least a halt to deforestation, as a way to slow global warming. Kulp (1990) has calculated recently that reforestation could remove a significant fraction of the expected net input of CO_2 to the atmosphere over the next 50 years. Idso's (1991) paper points to a similar conclusion; he emphasizes that deforestation not only adds to the CO_2 in the atmosphere but destroys a sink that could absorb future emissions from other sources. However, only growing trees take more carbon from the air than they release. A mature forest is in balance with the atmosphere; the only way to reduce its CO_2 output significantly would be to log the mature trees and preserve them from decay. Therefore taking lumber from a forest and using it to build houses, as opposed to letting it rot on the ground, is one way to combat global warming. Over the long haul, though, it does not appear practical to preserve enough wood to match the fossil fuel reservoir, which contains perhaps 7 times as much carbon as all the organisms that are alive at this moment (table 1).

As previously noted, marine organisms deplete CO_2 in the mixed layer and carry it down to the deep ocean as shells or organic carbon. There is evidence that the growth of marine organisms is limited in some areas by a lack of trace elements, notably iron (Archer 1990), so one could in theory deplete atmospheric CO_2 by fertilizing selected regions of the ocean surface. Enthusiasm for this suggestion should be tempered by the realization that marine biota contain only a small fraction of the total carbon stored in living organisms. One would also have to consider carefully the possible implications for all types of marine plant and animal life, to say nothing of possible effects on cloud droplet populations. Plankton give off dimethylsulfide, which contributes to the concentration of cloud condensation nuclei. Therefore promoting the growth of plankton could affect cloud albedos as well as deplete CO_2 levels in seawater. Foley et al. (1991) developed a simple model to test the effects of changes in cloud albedos related to variations in the output of dimethylsulfide by plankton. They concluded that the effect on global temperature is small compared to those that might be produced by changes in areal extent of cloudiness.

Cloud seeding has been suggested as a response to climate change. One can assume a continuation of weather modification projects designed to alleviate local effects of droughts. As it will not be possible to distinguish drought associated with global warming from droughts associated with natural climate fluctuations, such weather modification projects will not be identifiable as specific responses to climate change.

Cloud seeding to offset global warming could take a more active form. Increasing the areal coverage of shallow clouds, decreasing the coverage by deep clouds, or both would exert a cooling effect. While there is no established method to change the height distribution of existing clouds over any appreciable area or to increase the areal extent of low cloud decks, it might be possible to develop such techniques. It has also been proposed that changes in drop-size distributions be induced to make clouds better reflectors of sunlight. These suggestions are interesting, but so far I have not come across any detailed feasibility studies.

Dust in the atmosphere tends to cool the earth's surface by scattering solar radiation. Particulate matter in industrial pollution may be offsetting the expected greenhouse effect, at least in part. Artificial clouds of particulate matter could be generated for the express purpose of offsetting global warming. In order to avoid having the artificial clouds washed out by precipitation in a few weeks, they would have to be placed in the stratosphere. It has been suggested also that large mirrors could be placed in orbit around the earth to reflect part of the incoming sunlight. I have not seen any engineering studies for these two suggested responses to global warming, but am skeptical about them. There is no evidence to date of an impending climate change so catastrophic as to justify radical technological fixes.

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