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Atmospheric CO_2 Consequences of Heavy Dependence on Coal

by Ralph M. Rotty*

Accurate and regular measurements of the concentration of CO_2 in the atmosphere during the past 20 years show an accelerating increase. Although clearing of tropical forests has released large amounts of carbon to the atmosphere, evidence is strong that a major contributor is the combustion of fossil fuels. Future energy demands of the world will require extensive further exploitation of fossil fuels, and projections show that without major development of nonfossil fuel alternatives, the atmospheric concentration will double within the next 75 years.

Four issues require serious attention. The developing countries will require vastly increased amounts of energy. Major efforts to develop suitable (inexpensive) nonfossil energy sources to meet at least a portion of this demand are required. The distribution of carbon released from fossil fuels and from other anthropogenic sources among the reservoirs of the carbon cycle must be better defined. Uncertainties regarding the effect of the increased concentration of CO_2 in the atmosphere on global climate must be reduced. Possible political and social responses to a substantial climate change must be studied in order to more fully understand all of the implication of increased atmospheric CO_2.

The release of carbon as CO_2 as a result of fossil fuel use has been increasing at an exponential rate for more than 100 years. If this expansion continues, the concentration of CO_2 in the atmosphere may be doubled in the next 60 years or so. The effects on global climate may well become apparent suddenly, and because of the great momentum developed by the machinery that produces man's energy, could grow out of control before remedial actions become effective.

Because the amount of carbon contained in easily accessible fossil fuels is so vast, there is great temptation to use these resources as a source of energy which could last for nearly two more centuries. However, the very vastness of this carbon reserve is what causes the deep concern within the climatological community. The amount of carbon in recoverable fossil fuels reserves is ten times the amount now in the total global atmosphere as carbon dioxide.

As these reserves are used, an increase in concentration of CO_2 in the atmosphere will surely result; and because CO_2 absorbs a portion of the infrared radiation emitted by the Earth, it is generally believed that a warmer global climate will result. Although the amount of warming produced by a given increase is uncertain, the impact of increased atmospheric CO_2 on man's environment could be quite large. The potential CO_2 problem may present a challenge of unprecedented scope and difficulty.

Observed Atmospheric CO_2 Concentration

Since 1958, when accurate and regular monitoring began at Mauna Loa Observatory in Hawaii, the concentration of CO_2 in the atmosphere has shown an accelerating increase (Fig. 1). While there are large annual fluctuations from seasonal effects, the current yearly average value has grown to about 330 ppm, compared to the estimated preindustrial value of 298 (+4/−6) ppm (*1*). Measurements made at Point Barrow, Alaska, from aircraft over Sweden, and at the South Pole all show the same secular increase (*2*). The ultimate constraint on fossil fuel burning may be the climatic impact of this atmospheric CO_2 buildup.

The concentration of carbon dioxide in the atmosphere is a global problem which depends on emissions from all parts of the world. Unilateral actions

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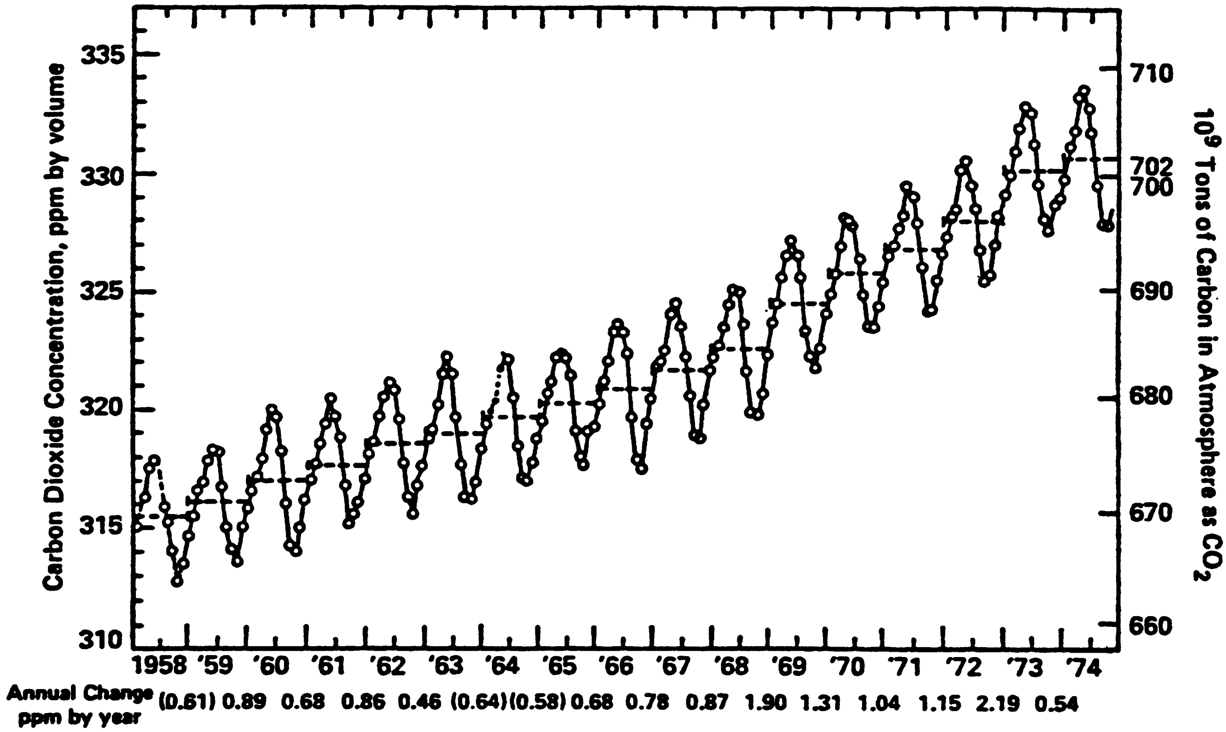

FIGURE 1. CO_2 observations. Monthly average values at Mauna Loa Observatory.

taken by the United States are of limited consequence, because other regions of the world, including the developing areas, are contributing large and increasing quantities as well. Therefore, it is important in planning to consider not only the actual contribution of CO_2 which might result from continued dependence by the United States on fossil fuels (which must mean coal as the oil and gas reserves are depleted), but also the impact that a U.S. policy will likely have on other nations, especially those in the developing world where the rate of growth in fossil fuel use has recently been the greatest.

To What Extent Has Use of Fossil Fuels Been Responsible for Atmospheric CO_2 Increases?

Carbon dioxide emissions from fossil fuels have been calculated from United Nations fuel production data given in World Energy Supplies (*3-5*). In 1973 Keeling estimated the amount of carbon released by fossil fuel burning (*3*). Annual values for the global emission of CO_2 from fossil fuel sources (adding a small contribution from the manufacture of cement — about 2% of that from fossil fuels — and including estimates from flared natural gas), have subsequently been calculated by Rotty (*4, 5*) (Fig. 2).

The exponential trend in CO_2 production is quite evident (Fig. 2). Except for the world wars and the great economic depression of the 1930s, a growth rate of 4.3% per year provides an excellent fit to the data. While it might be suspected that the rate of growth might now be leveling off, an examination of the current decade offers little encouragement for such optimism.

The upper part of Figure 3 shows global CO_2 production rates, and the lower shows the annual rate of energy use in the United States. The relatively sharp decline in U.S. energy use in 1974 and 1975 was accompanied by a proportionally much smaller decrease in global CO_2 production. This suggests that conservation in the United States cannot be counted on to arrest the growing CO_2 production on a global scale.

The tie between the observed increase in CO_2 concentration in the atmosphere and the release of CO_2 by the combustion of fossil fuels is strengthened by the recent analysis of Rust et al. (*1*). A model consisting of an exponential growth term and periodic functions of various frequencies was fitted to the monthly averages of the Mauna Loa CO_2 observations (216 points), and the computer was used to determine the exponential growth rate and the

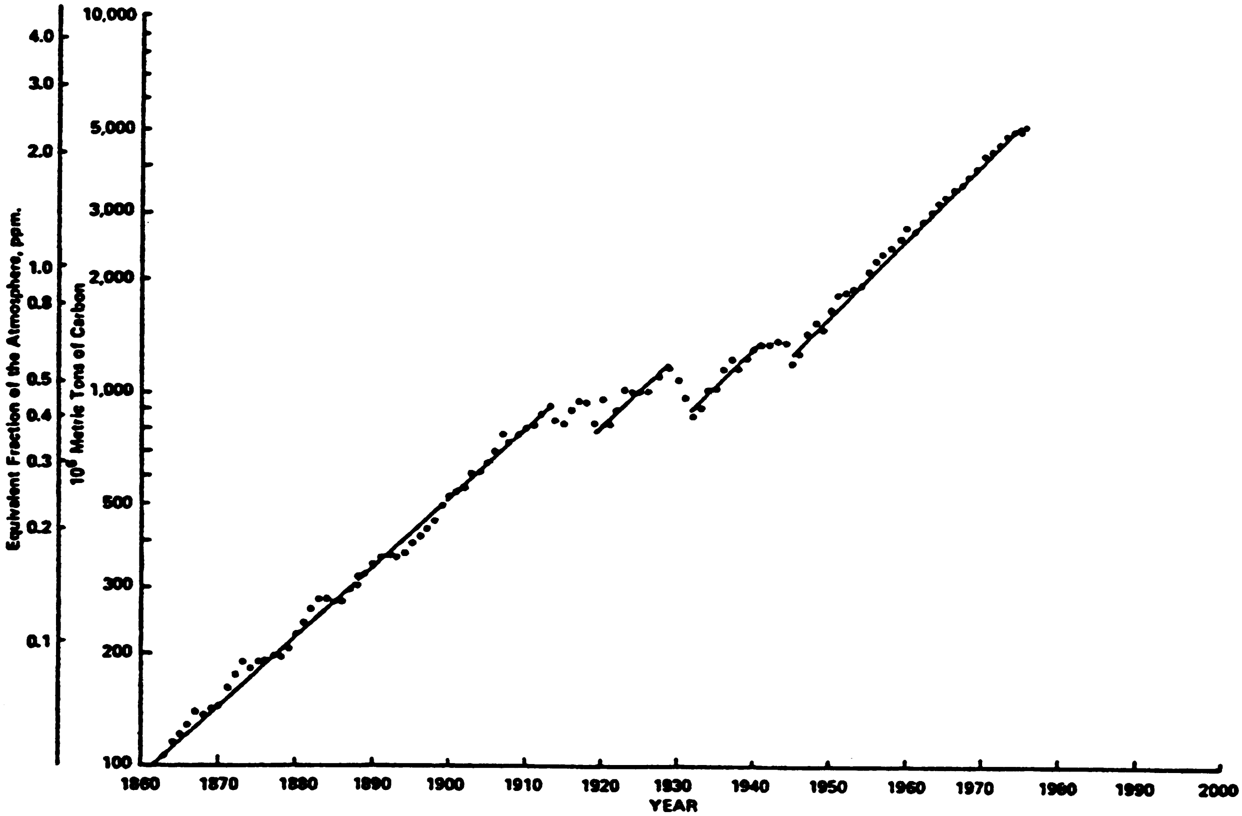

FIGURE 2. Global production of CO_2 from fossil fuels and cement (1860-1976).

frequencies of the periodicities which gave the "best fit". The significant point for the present argument is that the exponential growth rate has a value of 0.00329 per month (0.04 per year), and this nearly matches the 0.043 annual growth rate of CO_2 production from use of fossil fuels. The amount of carbon accounted for by the atmospheric CO_2 increase since 1958 is about 53% of the amount released during the same time span by fossil fuel production. Evidently the remainder has been sequestered in other reservoirs of the natural carbon cycle.

Recently the arguments have been advanced that other anthropogenic activities—e.g., clearing of tropical forests for agricultural land — could be contributing to the total CO_2 emitted to the atmosphere. Revelle and Munk (6) suggest that the carbon from forest clearing could total about half that from fossil fuels, but to avoid assuming that more must be sequestered in the oceans than seems likely, they assume it returns to a different part of the terrestrial biota. Thus the fractional division of carbon storage among the reservoirs may be different from what was earlier supposed, and the fraction remaining in the atmosphere may be nearer to 40% than to the calculated 53%. A full understanding of the carbon cycle is necessary before an accurate accounting of the excess carbon can be made with confidence.

The Natural Carbon Cycle

At the current concentration of 330 ppm of CO_2, the atmosphere contains about 700 billion tons of carbon (Fig. 4). Baes et al. (7) discuss the carbon cycle and point out that this is substantially less than the carbon stored in living and dead biomass on land (about 1,800 billion tons), somewhat more than that stored mostly as inorganic carbon in the well-mixed surface waters of the ocean, and much less than that stored in the deep oceans (about 32,000 billion tons). The fluxes of carbon between the land and the atmosphere via photosynthesis in one direction and respiration, decay, and fires in the other are estimated to be about 113 billion tons per year; and the fluxes between the oceans and atmosphere are estimated at about 90 billion tons per year. Since substantial portions of the carbon in the atmosphere, in the surface waters of the oceans, and on land are circulated among these reservoirs each year, the relatively

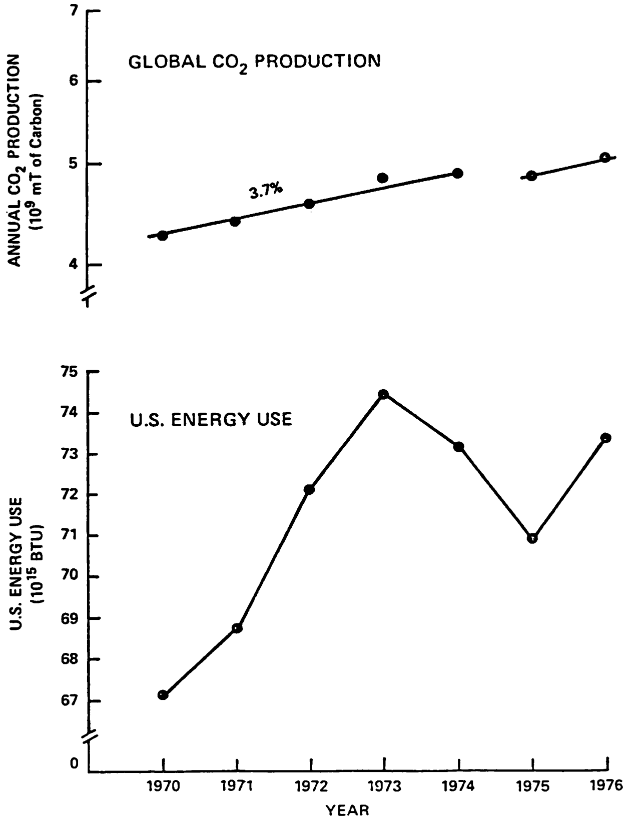

FIGURE 3. Global CO_2 production and U.S. energy use (1970-1976).

small amount in the atmosphere can be appreciably influenced by changes in the major fluxes of the natural carbon cycle.

Most land biomass is material which exchanges carbon relatively slowly: humus, recent peat, long-lived stems and roots of vegetation. Only a relatively small fraction is present as material that exchanges rapidly: small stems and roots, litter, leaves, etc.

Baes et al. (7) suggest that man can have a significant influence on the fluxes between the land and the atmosphere. If, for example, we could cause the living biomass (which contains about 680 billion tons of carbon) to increase at a rate of 1% per year, the current annual production of CO_2 from fossil fuels would be more than counterbalanced. Since forests store more carbon per hectare than grassland or agricultural land, this 1% increase in living biomass could be accomplished by conversion of more land to forests. However, the maximum increase in biomass that could be realized is small compared to the total mass of fossil carbon available in recoverable reserves.

Actually, living biomass is probably being reduced by the activities of man. As suggested earlier, a net conversion of woods to nonwoods may be taking place in the tropical areas of the world. It is quite possible that as much as 1% of the area of tropical forests is being converted to agriculture each year; because of the lower concentration of carbon, this could amount to an annual flux of more than 1 billion

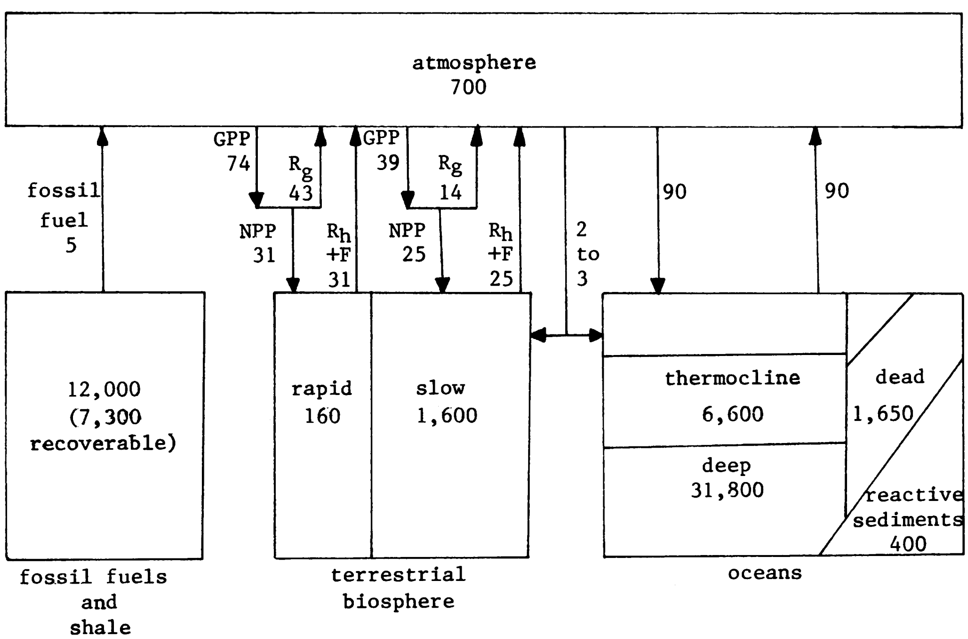

FIGURE 4. The carbon cycle. Fluxes in billions of tons/yr and reservoirs in billions of tons. Fluxes include gross primary production (GPP), green plant respiration (R_g), net primary production (NPP = GPP − R_g), respiration by hetrotrophy (R_h) and fires (F).

tons of carbon to the atmosphere. Other effects in the opposite direction are also suggested; controlled studies of plant growth show that photosynthetic production rate is enhanced when CO_2 concentration is increased, if other nutrients are not limiting (*8*).

Another major exchange of carbon indicated in Figure 4 is that between the atmosphere and the oceans. The oceans can be regarded as consisting of three separate layers: a relatively well-mixed surface layer of thickness about 70 m, the thermocline, a stagnant region stabilized by decreasing temperature and increasing density to a depth of about 1000 m, and the much larger region of the cold (<5°C) deep ocean. The capacity of the ocean surface waters to take up atmospheric CO_2 is determined largely by the reaction of CO_2 with carbonate ion to form bicarbonate ion. The amount of neutral "carbonic acid" (H_2CO_3) that can form is small, and other basic substances that can react with this weakly acidic gas are present in even smaller amounts.

Thus the capacity of the surface waters alone to take up CO_2 is quite limited because of the small supply of CO_3^{2-} ion present. Since the surface waters contain an amount of carbon comparable to that in the atmosphere, and because of the equilibrium chemistry of the carbonate to bicarbonate reaction, less than a tenth of the current fossil carbon flux can be taken up by the surface waters alone, and this fraction should decrease as the carbonate ion is consumed.

Clearly, for the oceans to sequester a substantial part of the fossil carbon flux, the surface waters and the deep waters must mix. The distribution of ^{14}C in the oceans indicates that the average residence time of water in the deep oceans is in the range of 500 to 2,000 years (*9, 10*). This is equivalent to only 2 to 8% of the surface water circulating to the deep ocean per year. Although the amounts of Ca^{2+} and HCO_3^- ion and $CaCO_3$ solid in all the oceans are far in excess of that required to deal with all the fossil carbon that mankind may wish to use, the natural control mechanism may be far too sluggish to cope with the high rate of fossil fuel use (*11, 12*).

Climate Change from Atmospheric CO_2 Increases

If mankind were to burn a major fraction of the fossil fuel reserves (mainly coal) at a rate in excess of what the carbon cycle can remove from the atmosphere, what consequences can be expected from the increased atmospheric concentration? By altering the energy exchange of the planet the global climate will be changed, but the global climate has always been changing! Geologic evidence leaves little doubt that the prevailing climate of the Earth during the past billion years was warmer than today's by as much as 10°C and almost totally free of polar ice. Beginning about 50 million years ago, something happened to cause a low transition of climate until about 2 million years ago, when a new mode of global climate was established. During these more "recent" years (the past 1 or 2 million years), there have been cyclic variations on several different time scales, but only during the past century or so have direct measurements of temperature been recorded systematically.

In the last several decades of quantitative meteorological documentation, rapid variations of global climate have been identified. Since these fluctuations are the ones which will primarily determine the course of global climate in the years and decades immediately ahead, it is important to note that they are not demonstrably periodic in character and therefore not predictable. The average temperature of the Earth has varied during the past century from a minimum in the 1880s (perhaps a consequence of strong volcanic activity) to a maximum around 1940, with a cooling tendency from 1940 to the present time. The 1940 maximum gave a Northern Hemisphere average temperature about 0.6°C higher than 1880, and half that increase has been lost since 1950. Whether these changes are fluctuations within the natural variations in climate, or whether they are attributable to some as yet unexplained cause, need not confuse the CO_2 picture. Up to the present, the CO_2 increases have been so small that they should have contributed only one- or two-tenths of a degree warming — an amount which could easily be masked within the natural variability.

Basically, the global climate is determined by the balance between the energy received from the sun and the long wavelength radiation from the Earth. The number of minute details that give local and time variations different from the global averages is enormous, and it is likely that by altering one (or a few) of the details on a global scale, man can affect the global climate. In addition to the effect of increased CO_2, there is the growing direct production of heat that results from man's use of energy, but this is presently an insignificant 0.01 percent of the solar flux and important only in localized areas of high energy utilization. There is the local effect of paved areas that alter the reflectivity (albedo) of the Earth's surface, but at present and for the foreseeable future this effect, too, will be localized and not global. Another anthropogenic effect is that of airborne particulates which, it has often been suggested, might produce a cooling by backscattering solar radiation. The magnitude of this effect, and even whether it is one of cooling or warming, depends on many factors

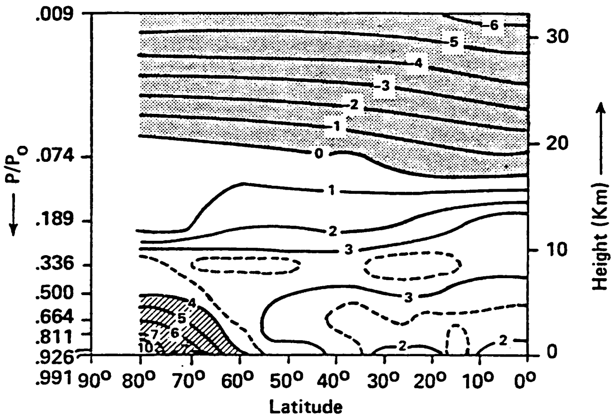

FIGURE 5. Temperature changes (in °C) with doubling of CO_2 concentration in atmosphere. Shading gives emphasis to large temperature increases in high latitudes and to cooling in the stratosphere.

(*13*). At present there is no evidence that particulates will have an effect comparable with that of atmospheric CO_2, nor can we count on particulates to be a compensating factor.

The impact of the atmospheric CO_2 increases on climate has been deduced from models of the climate system developed by Rasool and Schneider (*14*), Manabe and Wetherald (*15*), Ramanathan (*16*), Sellers (*17*), and others. Although the predictions of the models vary, critical examination of the existing models (*18*) suggests "the global average surface temperature increase from a doubling of atmospheric CO_2 content is between 1.5 and 3°C". However, Schneider conceded that "this estimate may prove to be high or low by severalfold"; this uncertainty must be recognized.

An increase in average surface temperature of 1.5 to 3.0°C is sufficient to change the global climate in major (but largely unknown) ways. More significant than the average surface temperature change is the distribution of atmospheric temperature change as shown in Figure 5 [taken from Manabe and Wetherald (*15*)]. The cooling of the stratosphere and especially the pronounced warming (~7°C) near the surface in higher latitudes are highly significant. The effects of warming the Earth's surface north of 70°N by more than 7°C will be extreme.

The changes in the temperature distribution in the atmosphere will cause changes in the general atmospheric circulation patterns, and thus result in changes in other climate variables (precipitation, cloudiness, winds, humidity, etc.). The terrestrial biosphere and also the ocean circulation and marine life can be vitally affected by these changes. The implications that such changes have on global agriculture and the economic and political balance of the world are enormous.

It must be conceded that the current models do not adequately account for all possible feedback mechanisms that can affect the precision of the results. Mechanisms not adequately accounted for include: (1) decreased snow and ice coverage, (2) change in cloud cover and in the temperature of cloud tops, (3) ocean coupling, and (4) land coupling. It is very difficult, however, to imagine that any (or all) these mechanisms could alter the model results so drastically that a climate warming with significant changes in the temperature distribution would not still be the result.

Calculations of Past, Present, and Future CO_2 from Fossil Fuels

Can we predict when the CO_2 concentration might reach alarming levels? The definition of "alarming levels" will depend on greater climatological knowledge than we now have, but also the time when a given concentration of CO_2 in the atmosphere will be reached depends on fossil fuel use (and on resiliency of the natural carbon cycle).

Keeling (*3*) has estimated the amount of carbon that is released as CO_2 for each unit of fossil fuel removed from the ground. By using Keeling's values, which assume a global average value for the carbon content of each fossil fuel, it is possible to estimate the amount of carbon dioxide released per unit of energy obtained by simply assuming similar average values for the energy content of each fuel. The results of such calculations are given in Table 1, and these factors make it relatively easy to estimate the amount of CO_2 released to the atmosphere for a given energy scenario, whether the energy demand (and the CO_2 produced) is for the United States or for the world.

Since the United States now uses a little less than one-third of the world's energy, its contribution to the buildup of atmospheric CO_2 is hardly decisive. Moreover, the rate of increase of energy demand during the next three to five decades is likely to be greater in many parts of the world than that in the United States. Therefore, the fraction of CO_2 contributed by the United States will likely drop irrespective of U.S. emphasis on coal.

Table 1. CO_2 Produced from fossil fuels per million BTU.

Fuel	C, kg/10^6 BTU	Ratio to natural gas
Coal	25.4	1.74
Oil	19.0-21.7	1.32-1.51
Natural gas	14.4	1.0
Synthetic fuel (75% efficient conversion)	33.8	2.35

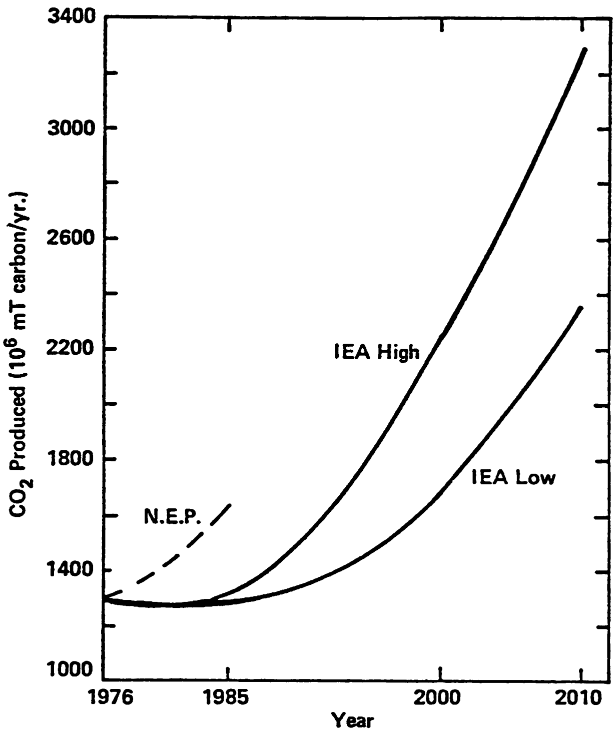

FIGURE 6. U.S. production of CO_2 from fossil fuels.

The increases in CO_2 from a heavily coal-based U.S. energy supply system are nevertheless significant. Based on the National Energy Plan, as issued by the Executive Office of the President on April 29, and on previous estimates of national energy demands developed at the Institute for Energy Analysis (*19*), production of CO_2 from fossil fuels in the United States can be expected to rise as indicated in Figure 6. According to the NEP, the 1976 United States energy use was 74.0 quads (1 quad equals 10^{15} BTU $\approx 1.05 \times 10^{18}$ joules $\approx 300 \times 10^9$ kilowatt-hour), of which 69.0 were derived from fossil fuels. Within the United States, 1,310 million tons of carbon were released as carbon dioxide — or about 27% of the world total. The NEP projects 92.8 quads for 1985, and with heavier dependence on coal, the CO_2 releases will rise to 1,638 million tons of carbon. The IEA projections for 1985 show both a lower overall energy demand and a slightly greater reliance on nonfossil energy and hence a substantially smaller CO_2 production. (Most of the difference between NEP and IEA is the lower demand for energy in the IEA scenarios.) The continued growth shown after 1985 is nearly all fueled by coal — as the oil and gas supplies continue to dwindle, and full utilization of uranium — i.e., in breeders — is precluded for political and social reasons. This results in dramatic increases in the carbon dioxide production reaching nearly 2.5 the present rate of production by the year 2010. Obviously, if this rate of rise occurs following the NEP's 1985 estimate, the United States production of CO_2 soon will approach the present global total CO_2 production.

Of even greater consequence is the probable growth in fossil fuel use in the rest of the world. I have attempted at least a rough assessment of the energy demands of various segments of the world as they are now and could be 50 years hence. Figure 7*A* shows the global CO_2 production as it is apportioned among the indicated 12 political-economic sectors (*20*). Clearly, North America, Western Europe, and centrally planned Europe (including the U.S.S.R.) are responsible for nearly three-fourths of the global total fossil fuel CO_2 — the United States, alone, for over one-quarter.

To develop a scenario for 50 years from now, the world was divided into six sectors — corresponding to combinations of the twelve sectors used in the present time analysis. The results of Figure 7*B* are based on the following assumptions: (1) U.S. energy requirements will be 125 quads with 15% nonfossil. (2) Western Europe's energy use will grow at 2% per year, and 15% percent will be nonfossil. (3) Centrally planned Europe (including the U.S.S.R.) will grow in energy use by 4%, with 15% nonfossil. (4) Japan and Australia will experience the same 2% per year growth as Western Europe, with 15% nonfossil. (5) Centrally planned Asia (largely China) will expand with an energy growth of 4.5%, nearly all fossil. (6) The developing world will have an average population growth rate of 1.5% and an increase in the per capita energy use to 53 × 10^6 BTU per year — the 1970 global average. (Although this requires a 5% average growth for 50 years, these countries have achieved an 8% annual growth during the past decade or so.)

Based on these assumptions, the calculations result in an annual fossil-fuel carbon dioxide release containing 23 × 10^9 tons of carbon. This is a total that is 4.5 times the 1974 amount. This represents a global energy dependence on fossil fuel equivalent to 1,090 quads. The sizes of the circles in Figure 7*B* (1974 and

Table 2. Estimated global energy demand in A.D. 2025.

Source (reference)	Demand, 10^{15} BTU
Perry and Landsberg (*21*)	1.173
WAES (extrapolated from the year 2000) (*22*)	710-1,000
Chesshire and Paritt (interpolation) (*23*)	550-1,500
Houthakker (*24*)	$\geq$ 1,000
Bloodworth et al. (extrapolated from the year 2020) (*25*)	815-1,110
Rotty (this paper)	1,090 (+ nonfossil – 100)

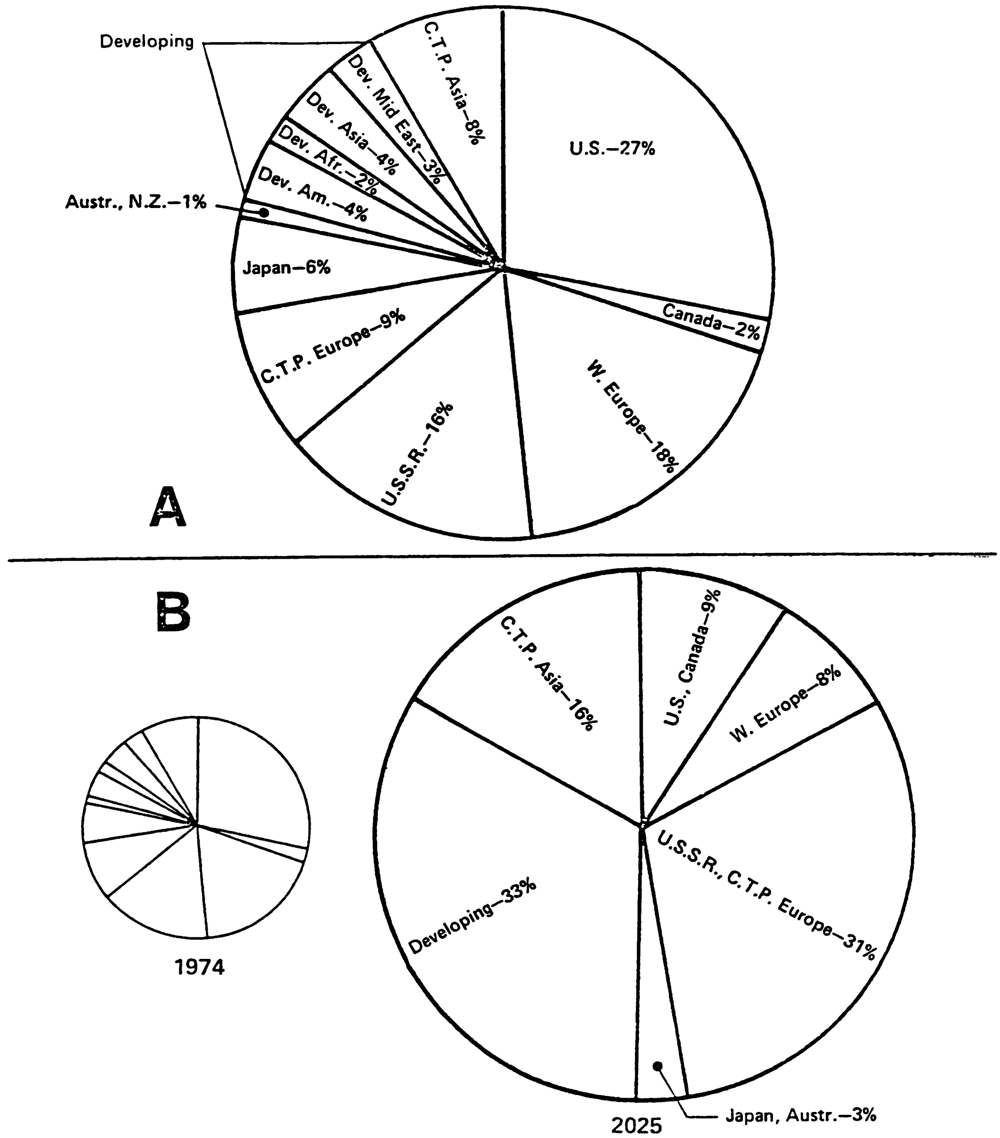

FIGURE 7. Global CO_2 production by world segments: (*A*) 1974; (*B*) 2025 scenario.

2025) are so proportioned that the areas on the figure represent the total quantity of carbon released from fossil fuel.

Others have estimated global energy demand for the future in a variety of ways and frequently for specific times other than the year 2025. In such cases I have extrapolated and interpolated to obtain an estimate for 2025. The resulting values are given in Table 2.

Perry and Landsberg (*21*) divided the world into segments similar to those used here, and although the totals are similar (for the Perry and Landsberg "low growth"), the distribution is markedly different. They show much larger energy growth in the United States and less in the "controlled economy" sections of the world (U.S.S.R. and China) and in the developing world. The level of agreement among the estimates is surprising considering the factors and time scale to be accounted for.

The previous analysis leads to the conclusion that the problem of avoiding the CO_2-triggered climate change becomes that of providing fuel for the developing countries to assure their progress without such heavy dependence on fossil fuels. Perhaps this is an area in which the United States can make a contribution through research and development on new energy supply systems and on small (decentralized) nonfossil systems.

One might suspect that growth to 1,090 quads (or 23×10^9 tons of carbon) for A.D. 2025 will heavily

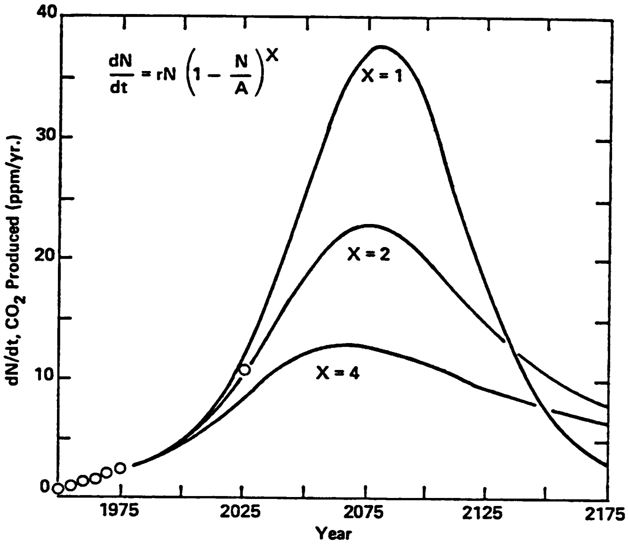

FIGURE 8. Global production of CO_2 from fossil fuels.

tax the fossil fuel reserves of the world. This is simply not true; recoverable fossil fuels (and shale oil) contain 7.3×10^{12} tons of carbon.

Several possible patterns for future CO_2 production from fossil fuel may be represented by the mathematical expression:

$$\frac{1}{N}\left(\frac{dN}{dt}\right) = 0.043\left(1 - \frac{N}{A}\right)^x$$

where N is a function of time t and represents the total cumulative amount of CO_2 produced from fossil fuel use up to that time, A is the quantity of CO_2 that would be produced from all of the fossil fuel ultimately recoverable ($\sim 7.3 \times 10^{12}$ tons C), and x is the parameter used to vary the emphasis on price, availability, etc., as the fraction of recoverable fossil fuels remaining is reduced. The quantity $[1 - (N/A)]^x$, which is always between zero and one, enables the cumulative use function to reflect a reduced rate of use as the resource approaches depletion, and the costs rise. In Figure 8 the historical fossil fuel use to the present is indicated by the open circles; the curve with $x = 1$ might represent "free and easy" access to remaining reserves along with early exhaustion of those readily available; the curve with $x = 4$ might represent lowered demand scenarios for fossil fuels resulting from high prices and low availability stimulating early extensive reliance on solar, nuclear, and other sources. In each case the total area under the curve (carried to infinite time) is the same and represents the total recoverable fossil fuel — mostly coal. The circle at the year 2025 corresponds to the quantity calculated in the previous paragraphs ($23{,}000 \times 10^6$ tons C or 10.9 ppm). The curves $x = 1$ and $x = 4$ can be regarded as error limits on the projections for future global fossil fuel use; they approximately bound the estimates of the scenarios of Table 2.

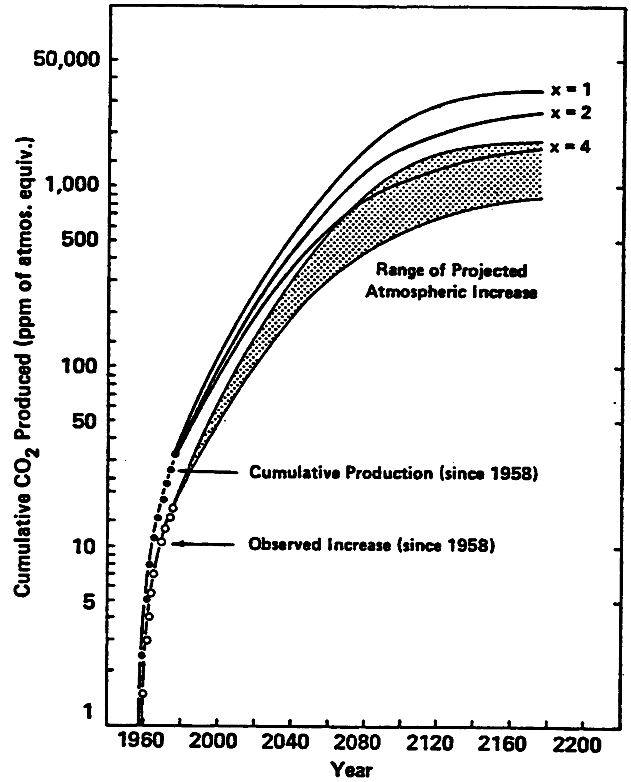

FIGURE 9. Projected cumulative CO_2 production and atmospheric CO_2 decreases.

In Figure 9, cumulative production of CO_2 since 1958 (as calculated above) is shown by the series of solid circles, and the projections along the lines $x = 1$, $x = 2$, and $x = 4$ correspond to the fuel-use curves of Figure 8. The projected atmospheric concentration of CO_2, starting with observations represented by the open circles, is based on 53% of the cumulative production remaining in the atmosphere. The atmospheric concentration increases rapidly after A.D. 2000 and for the 1,090 quad scenario developed here for 2025, it approaches a 150 ppm increase (over 1958) by 2025, 200 ppm increase by about 2035, and 300 ppm increase around 2050. Even low-growth scenarios (such as $x = 4$) are likely to result in observable climate change during the first half of the next century.

Of course, even lower fossil fuel-use scenarios are conceivable if the global society recognizes the potential environmental changes soon enough. Greater reliance on solar energy, even though more expensive, and on nuclear energy, even with its attendant risks, may become much more attractive; the fossil

fuel use curve could thus be brought even lower, and the magnitude of the potential climate change reduced.

What Does This All Really Mean?

The central question which ultimately must be addressed is: at what rate can we use the coal reserves before the resulting increased concentration of CO_2 in the atmosphere will cause an unacceptable climate change? This question probably oversimplifies the case since there are degrees of unacceptability and trade-offs of economic growth, social stability, etc., on the one hand, versus the serious impacts of climate change on the other. As suggested in the previous sections of this discussion and in many recent articles and papers on the subject, four principal areas of inquiry require serious consideration.

• Rates of fossil fuel use are critical. If all of the fossil resources were to be burned at a steady rate over a 10,000- to 100,000-year period, the atmospheric concentration would likely never rise to an unacceptable level. At such a low rate of utilization there would be enough time to sequester the carbon in the deep sea, and the problem would be nonexistent. Controlling the rate of fossil fuel use while maintaining hope within the impoverished masses of the world will require extremely careful planning and ability to deploy so-called inexhaustible energy sources effectively. A better understanding of the future energy requirements of the developing world and the alternatives for meeting these requirements are both essential in determining and possibly controlling rates of fossil fuel use.

• The distribution of the carbon dioxide produced from fossil fuel combustion and from other anthropogenic sources among the several reservoirs in the carbon cycle must be known. Without better information on the behavior of the terrestrial biosphere, we really cannot even say whether the biosphere is a source or a sink of CO_2. If the biosphere is supplying more CO_2 than it is absorbing, then behavior of the oceans must be different from what we believe. The ability of the ocean to act as a CO_2 sink is large, but the rate of possible sequestering of carbon is the important factor. Before we can estimate with confidence what fraction of the carbon dioxide from fossil fuels remains in the atmosphere, we must better understand the roles of both the biosphere and the oceans in the carbon cycle.

• Even if the concentration of CO_2 in the atmosphere could be accurately predicted for some given future time, there would remain vast uncertainty as to the effects on climate. The evidence is strong that additional atmospheric CO_2 will cause global warming; the "best guesses" are in the range of 2 to 4°C average temperature rise for a doubling of the CO_2 concentration. Of even greater uncertainty are the changes that will occur in the local climates of critical areas of the world. Will the areas of good agricultural soils continue to have climates conducive to good production? Since past major global climate shifts — e.g., glacials to interglacials — have occurred with temperature changes of about 5°C over many centuries, climate changes associated with a doubling of CO_2 concentration will be significant, and the rate with which they occur may be too great to allow for easy adjustment.

• We have little conception of how the world might manage a substantial climate change without drastic social dislocation. Granted that at the moment there is still uncertainty as to the magnitude of the CO_2-induced climate change, I believe it is not premature to examine possible global responses to such an eventuality that would preserve the stability of our social-political order.

Conclusions

Increases in the atmospheric concentration of CO_2 causes concern only when the quantities become large—i.e., several hundred billion tons of additional carbon. The direct contribution from emphasis on United States' coal use through 1985, as called for in the National Energy Plan, is of minor consequence. On the other hand, if such a policy continues into the next century, or if it serves as a model for major segments of the world, then the quantity of the resulting CO_2 could have serious consequences early in the next century. Further, if coal is used on a large scale as the base for liquid and/or gaseous synthetic fuels as the oil and natural gas reserves are depleted, the inefficiencies of conversion serve to increase the CO_2 produced per unit of delivered energy and further aggravate the problem.

It must be conceded, however, that great uncertainty pervades the estimates of the effect of increased CO_2 concentration in the atmosphere. It is of the highest importance that these uncertainties be resolved as expeditiously as possible, say by 1985. This will require a worldwide commitment of considerable scale. Only such aggressive effort is likely to lead to an estimate of the effect of CO_2 sufficiently robust to warrant the political, social, and economic measures that might be required to deal with unprecedented changes in the world's climate.

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