IS CARBON DIOXIDE FROM FOSSIL FUEL CHANGING MAN'S ENVIRONMENT?

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(Read April 25, 1969, in the Symposium on Atmospheric Pollution: Its Long-term Implications)

I ORIGINALLY proposed as the title of this talk: "If carbon dioxide from fossil fuels is changing man's environment, what will we do about it?" It was my meaning to inquire into what might be the response of scientists, philosophers, and decision-makers if specialists assert that accelerated use of fossil fuels may be harmful. I was requested to modify the title to read "Is CO_2 from fossil fuel changing man's environment?" either because a shorter title might suggest a shorter, more acceptable talk, or because I obviously cannot answer the first question. I cannot answer the second question either; but I will now give you my views on both questions.

Atmospheric carbon dioxide as a factor in man's environment has been so clearly described by Roger Revelle in a report which he prepared in 1965 for the President's Science Advisory Committee that I shall not attempt to improve on his words (Revelle, 1965: p. 112):

> Only about one two-thousandth of the atmosphere and one ten-thousandth of the ocean are carbon dioxide. Yet to living creatures, these small fractions are of vital importance. Carbon is the basic building block of organic compounds, and land plants obtain all of their carbon from atmospheric carbon dioxide. . . .
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> Over the past several billion years, very large quantities of carbon dioxide have entered the atmosphere from volcanoes. The total amount was at least forty thousand times the quantity of carbon dioxide now present in the air. Most of it . . . was precipitated on the sea floor as limestone or dolomite. About one-fourth of the total quantity, at least ten thousand times the present atmospheric carbon dioxide, was reduced by plants to organic carbon compounds and became buried as organic matter in the sediments. A small fraction of this organic matter was transformed into the concentrated deposits we call coal, petroleum, oil shales, tar sands, or natural gas. These are the fossil fuels that power the worldwide industrial civilization of our time.
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> Throughout most of the . . . [million or so] years of man's existence on earth, his fuels consisted of wood and other remains of plants which had grown only a few years before they were burned. The effect of this burning on the content of atmospheric carbon dioxide was negligible, because it only slightly speeded up the natural decay processes that continually recycle carbon from the biosphere to the atmosphere. During the last few centuries, however, man has begun to burn fossil fuels that were locked in the sedimentary rocks, . . . and this combustion is measurably increasing the atmospheric carbon dioxide.
>
> The present rate of production from fossil fuel combustion is about a hundred times the . . . [rate of natural removal by] weathering of silicate rocks. . . . Within a few short centuries, we are returning to the air a significant part of the carbon that was slowly extracted by plants and buried in the sediments during half a billion years.
>
> Not all of this added carbon dioxide will remain in the air. Part of it will become dissolved in the ocean, and part will be taken up by the biosphere, chiefly in trees and other terrestrial plants, and in the dead plant litter called humus. The part that remains in the atmosphere may have a significant effect on climate: carbon dioxide is nearly transparent to visible light, but it is a strong absorber and back-radiator of infrared radiation, particularly in the wave lengths from 12 to 18 microns; consequently, an increase of atmospheric carbon dioxide could act, much like the glass in a greenhouse, to raise the temperature of the lower air.

The annual input to the atmosphere of CO_2 from fossil fuels can be estimated within an accuracy of about 20 per cent from records of the production of coal, petroleum, and the other fossil fuels (Revelle, 1965: p. 116). The rate of input has risen rapidly since 1850 with a doubling time of fifteen to twenty years except for a noticeable slowing during the economic depression, 1930–

TABLE 1

Decade or Year	Rate of input of fossil fuel CO_2 (ppm y^{-1})
1860–69	0.06
1880–89	0.14
1900–09	0.33
1940–49	0.72
1950	0.87
1966	1.77
1970 (estimate)	2.0

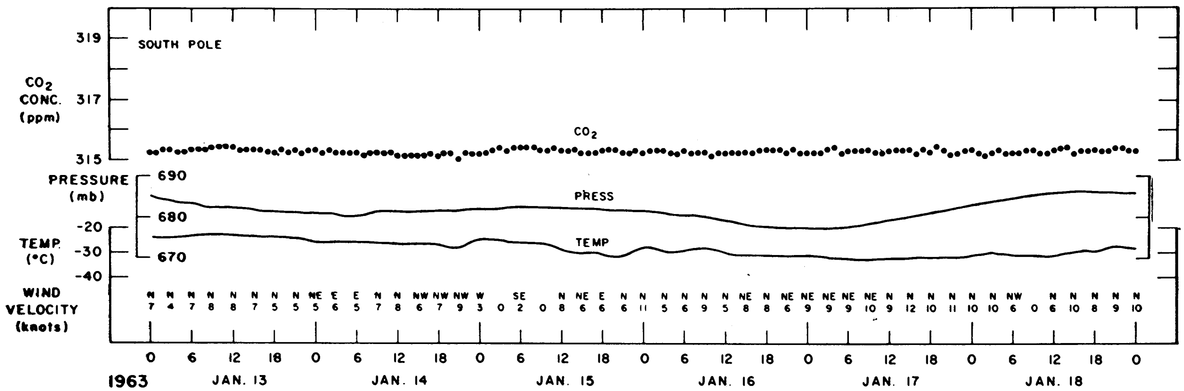

FIG. 1. A typical record of the hourly average concentration of atmospheric CO_2 at the South Pole versus universal (Greenwich) time.

1940, and during the two world wars. Table 1 shows a sample of the data expressed as the rate of increase in concentration of atmospheric CO_2 in parts per million of dry air (p.p.m.) per year, neglecting any possible removal.

Since 1957 the Scripps Institution of Oceanography, in cooperation with the Environmental Sciences Services Administration of the United States government has monitored the increase in atmospheric CO_2 at two remote stations, Mauna Loa Observatory, Hawaii, and the South Pole, to find out what proportion of the CO_2 from fossil fuel is accumulating in the atmosphere. I shall now briefly describe these measurements (Pales and Keeling, 1965; Brown and Keeling, 1965).

Air is sucked by a diaphragm pump through aluminum tubing from a mast upwind from local sources of CO_2. The air then passes through a trap to remove water vapor and into the cell of an infrared analyzer, where the concentration is

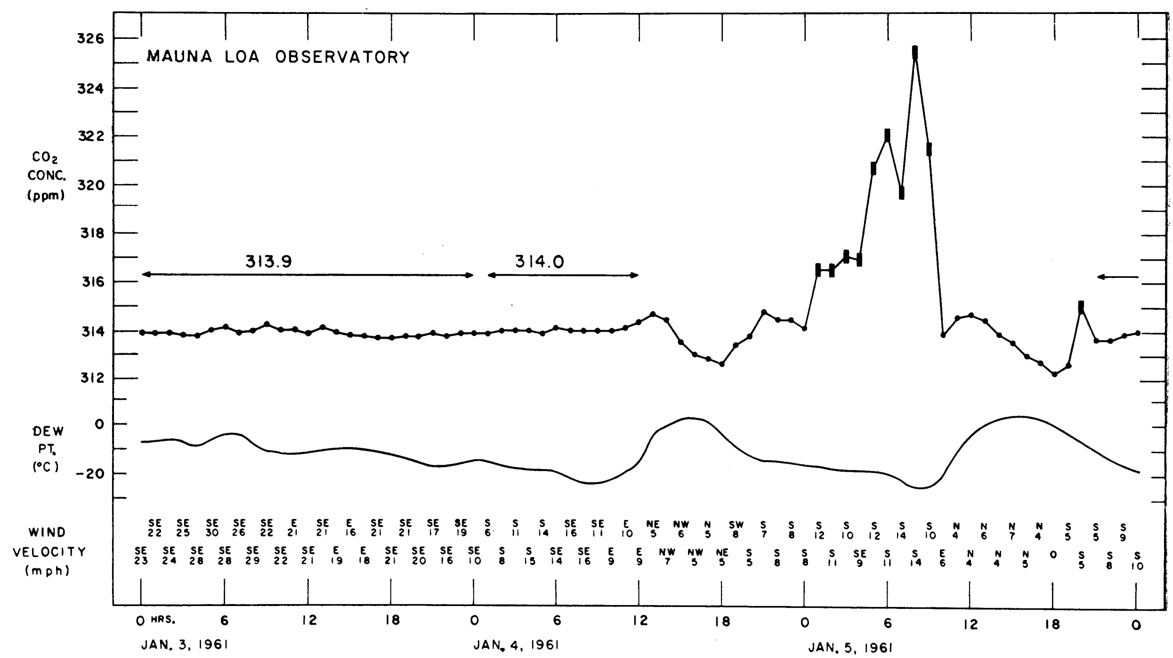

FIG. 2. An illustration of the hourly average concentration of atmospheric CO_2 at Mauna Loa Observatory versus local time. From the beginning of the plot until 12 hr. on January 4 the concentration is steady. During the afternoons of January 4 and January 5 the concentration dips owing to the uptake by vegetation. During the early hours of January 5 the concentration was high and variable owing to volcanic contamination.

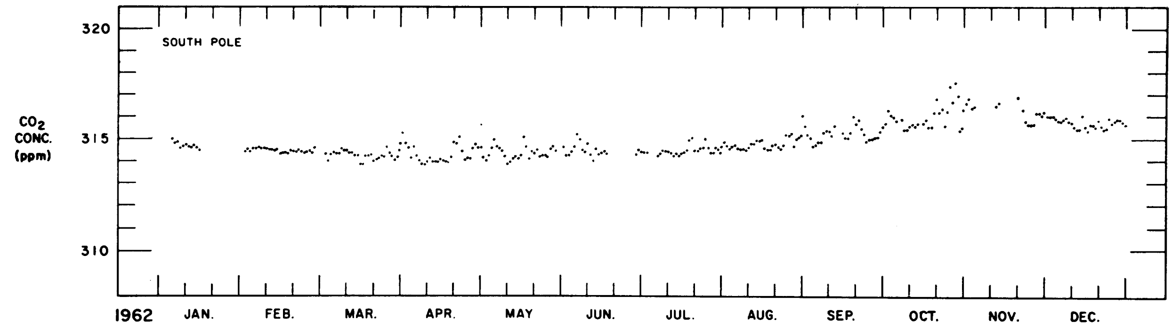

FIG. 3. The daily average concentration of atmospheric CO_2 versus time at the South Pole.

compared sequentially with a reference gas to a precision of 0.2 p.p.m. The data, here expressed as 60-minute averages, are for the South Pole monotonously steady (fig. 1) but at Mauna Loa sometimes show locally produced volcanic CO_2 or effects of vegetation 20 kilometers away (fig. 2). Only the steady portions of the record are used in the subsequent analysis.

Over a year both stations show a cyclic pattern owing to the seasonal variation in plant activity. At the South Pole the amplitude of oscillation is less than 2 p.p.m. (fig. 3) while at Mauna Loa it is nearly 6 p.p.m. (fig. 4). At the South Pole the oscillation is so small that it does not mask an increase of about 0.7 p.p.m. owing to the fossil fuel input. From ten years of a nearly uninterrupted record at Mauna Loa we clearly see an increase, superimposed on a remarkably regular annual pulse (fig. 5). We have not been able to separate the cyclic oscillation and secular trend with complete certainty, but by assuming that the cyclic portion repeats exactly each year, a variety of assumed trend functions all yield substantially the pattern shown in the figure (Bainbridge, 1969).

A surprising feature of the Mauna Loa record is the apparent falling off of the slope of the trend during a period when the rate of CO_2 input was increasing (fig. 6). Also surprising is the result of a calculation of the behavior of surface ocean water based on the simple but quite realistic assumption that the CO_2 is entering the oceans at a rate proportional to the CO_2 partial pressure difference produced at the sea surface. A plot of the difference between input and accumulation is nearly linear as though the surface water had maintained a constant CO_2 partial pressure of 311 p.p.m. since 1958.

These features suggest that the surface layer of ocean water has not been the principal agent for removing fossil fuel CO_2 from the air, at least during the past few years. In any case, the surface layer of ocean water is insufficient to hold more than about 10 per cent of the fossil fuel CO_2 which has left the atmosphere; because the depth of the layer which maintains good contact with the atmosphere is shallow, and because the CO_2 pressure of sea water rises nearly ten times as rapidly as the concentration of total carbon when CO_2 is added to the solution (Bolin and Eriksson,

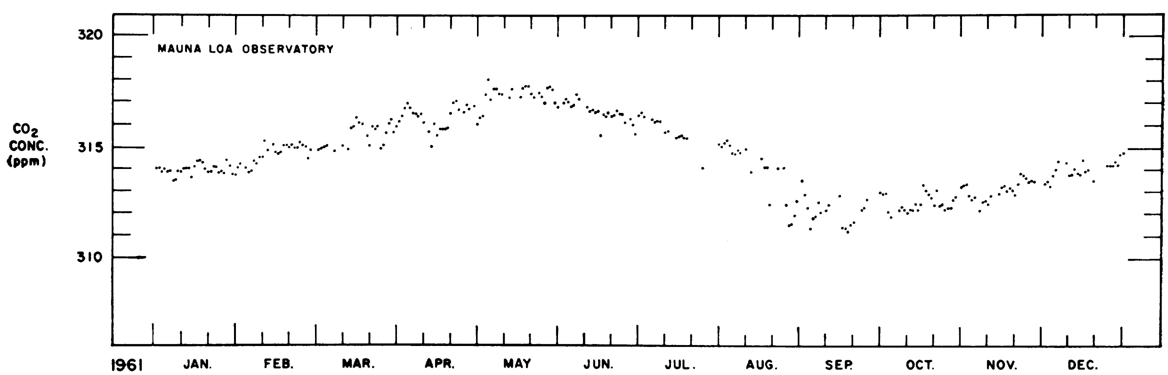

FIG. 4. The daily average concentration of atmospheric CO_2 versus time at Mauna Loa Observatory.

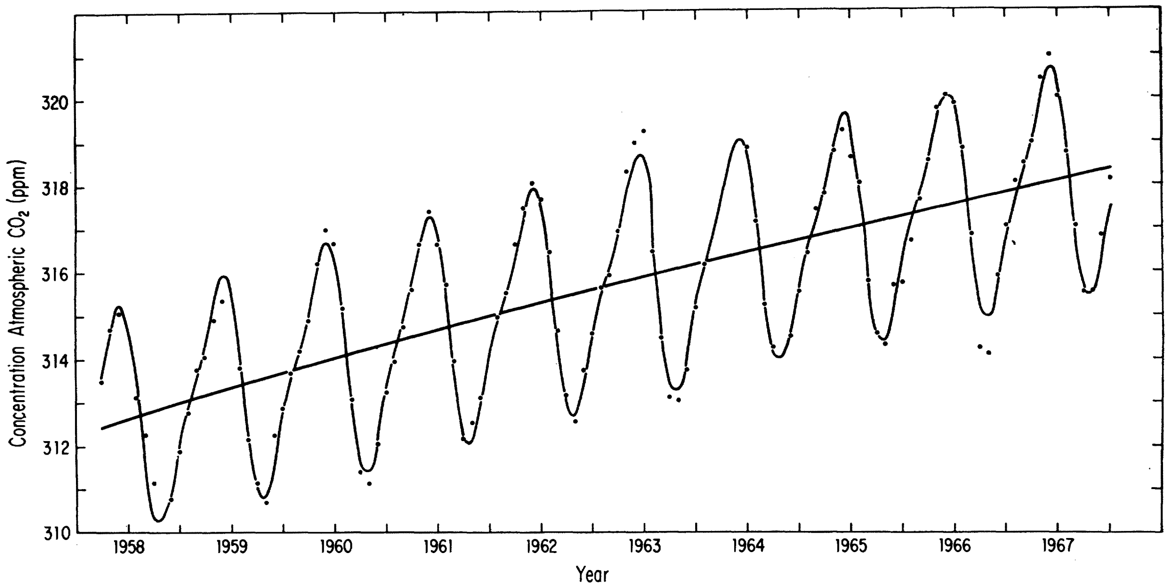

FIG. 5. Long-term variations in the concentration of atmopheric CO_2 at Mauna Loa Observatory. The dots indicate the observed monthly average concentrations. The oscillating curve is a least squares fit of these averages based on an empirical equation containing 6 and 12 month cyclic terms and a trend function. The slowly rising curve is a plot of the trend function, chosen to contain powers of time up to the third.

1959: p. 133; their value of 12.5 has been corrected for the influence of boric acid).

It is thus of little consequence to the overall problem of disposing of CO_2 from fossil fuel whether this surface layer has, in fact, taken up CO_2 since 1958 or not—the principal sink for CO_2 must lie in the deep oceans or not be oceanic at all. Our present analysis cannot go much farther: we do not, at the present time, understand how the deep ocean can effectively remove such a large flux of CO_2 because about one thousand years are required for deep water to be renewed by exchange with surface water.

Perhaps land plants, by growing more rapidly by a process plant physiologists call "CO_2 fertilization," are now removing this excess CO_2. But we must put into our balance sheet the large-scale alteration of virgin lands by cultivation and forest fires, which, since 1900, have released so much CO_2 that a net removal of carbon from the land biosphere seems as likely to have occurred as a net increase (Hutchinson, 1954: p. 390). Thus the true situation is not clearly established, and we are unable, as yet, to predict from our knowledge of the carbon cycle the redistribution of CO_2 from fossil fuel over the coming decades and centuries. From the record so far it appears that about 40 per cent of the CO_2 from fossil fuel is remaining in the atmosphere (fig. 7). Until we obtain better information, I suggest using this figure as a reasonable empirical factor for prediction.

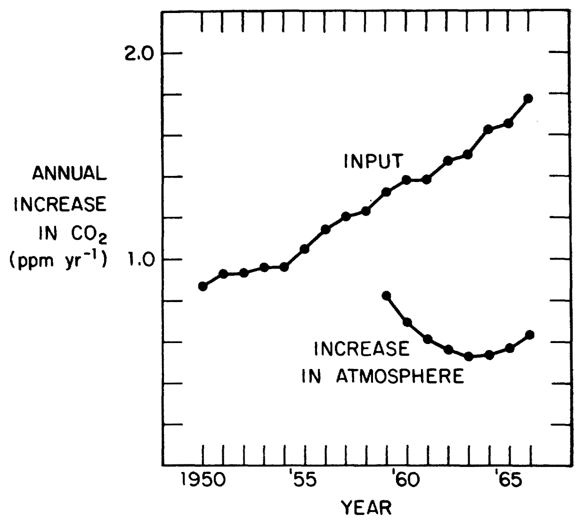

FIG. 6. *Upper curve*: The annual input of fossil fuel CO_2 in the atmosphere versus time expressed as an annual increase in concentration of atmospheric CO_2 neglecting any possible removal. *Lower curve*: The annual increase of atmospheric CO_2 according to the trend function shown in figure 5.

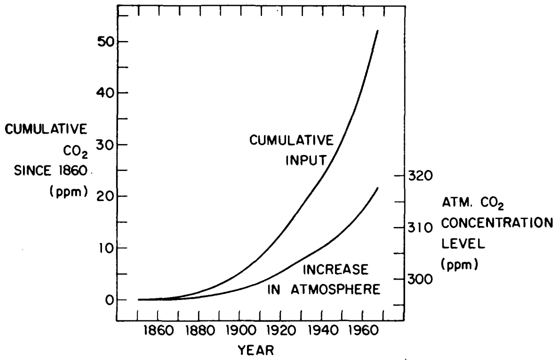

FIG. 7. An estimate of the input of fossil fuel CO_2 into the atmosphere and the increase of atmospheric CO_2 since the mid-nineteenth century.

Concerning the apparent anomaly that a larger proportion of the CO_2 from combustion has been removed in 1965–1967 than in 1958–1960 (see fig. 6), our record is still too short to decide whether the anomaly is real.

I will now discuss the possible climatic response to an increase in atmospheric CO_2, passing by some calculations based on static models of the atmosphere (Plass, 1956; Kaplan, 1960; Möller, 1963) to consider the calculations of Manabe and coworkers (Manabe and Strickler, 1964; and Manabe and Wetherald, 1967) which, for the first time, take into account all the major atmospheric factors except circulation. The model calculates the state of thermal equilibrium as the asymptotic steady state approached in an initial value problem. Water vapor; ozone; low, middle, and high clouds; and albedo are considered as well as CO_2.

If all the CO_2 were to vanish from the atmosphere, the earth's surface temperature would be reduced substantially: 10 to 20° C, depending on whether the water vapor content remains constant, or decreases to preserve the same relative humidity. If the amount of CO_2 were to rise by a factor of 2, from 300 to 600 p.p.m., the change would be less dramatic but still climatically significant: 2.8° C rise in temperature if the relative humidity is fixed. These calculations are not accurate predictions, however, because they are based on an assumption that other environmental factors do not change when the temperature changes by the predicted amount. The model is especially sensitive to changes in clouds. For example, a 30 p.p.m. increase in CO_2 (approximately what has occurred since 1850) would be compensated for by a 0.3 per cent increase in low clouds or a 0.6 per cent increase in middle clouds. How the amount of clouds would in reality change in response to warming triggered by a CO_2 increase is still a guess, because we lack any dynamic model to predict clouds. Consequently, we are left without a clear prediction. Nevertheless, I believe that no atmospheric scientist doubts that a sufficiently large change in atmospheric CO_2 would change the climate: we need only compare our atmosphere with the very hot CO_2-laden atmosphere of Venus to guess the consequences of an unrestricted CO_2 increase. We just do not yet know what increase in CO_2 the earth's atmosphere will accept without warming noticeably.

My assessment of the situation is that the increase in CO_2 is of no special concern to our immediate well-being. The rise in CO_2 is proceeding so slowly that most of us today will, very likely, live out our lives without perceiving that a problem may exist.

But CO_2 is just one index of man's rising activity today. We have rising numbers of college degrees, rising steel production, rising costs of television programming and broadcasting, high-rising apartments, rising numbers of marriages, relatively more rapidly rising numbers of divorces, rising employment, and rising unemployment. At the same time we have diminishing natural resources, diminishing distraction-free time, diminishing farm land around cities, diminishing virgin lands in the distant countryside. The event described in the following newspaper quotation could not have occurred fifteen years ago (*Los Angeles Times,* Oct. 27, 1968):

> SAN DIEGO—Memorial services will be held Monday for Dr. Robert W. Pidd, ranking authority on thermionics and senior scientist at Gulf General Atomics.
>
> Dr. Pidd, 47, was killed Friday in a one-car traffic accident while driving to Borrego Springs. His family said he was going to the desert resort to escape recent heavy smog in San Diego that had aggravated an asthmatic condition.

Now it just happened that the very same day I drove my family to the desert to escape that smog attack. My judgment of the seriousness of the attack was supported by measurements of atmospheric CO_2 at the Scripps Institution of Oceanography which indicate that during the past year La Jolla has sometimes enjoyed levels of contaminated air comparable to severe smog in Los Angeles. Severe air pollution is new to La Jolla. During two years of nearly continuous measurements of CO_2 at Scripps during 1959–1961, the CO_2 level never reached the concentrations observed recently. The smog build-up at La Jolla is the inevitable consequence of more and more people driving automobiles in the still rapidly expanding metropolitan area of Los Angeles, 100 miles to the northwest of La Jolla.

It may be instructive to compare plots of past and predicted increases in CO_2 and population (figs. 8 and 9). I am struck by the the obvious transient nature of the CO_2 rise. The rapid changes in all factors I mentioned, including the rapid rise in world population, are probably also transient; these changes, so familiar to us today, not only were unknown to all but the most recent of our ancestors but will be unknown to all but the most immediate of our descendants.

Thus we are privileged to live in exciting times. For many scientists it has been a period of unprecedented opportunity. Burgeoning populations bring about greater interaction of man and nature. By observing the stimulating and powerful new connections of man with his total environment, indeed even occasionally by manipulating nature

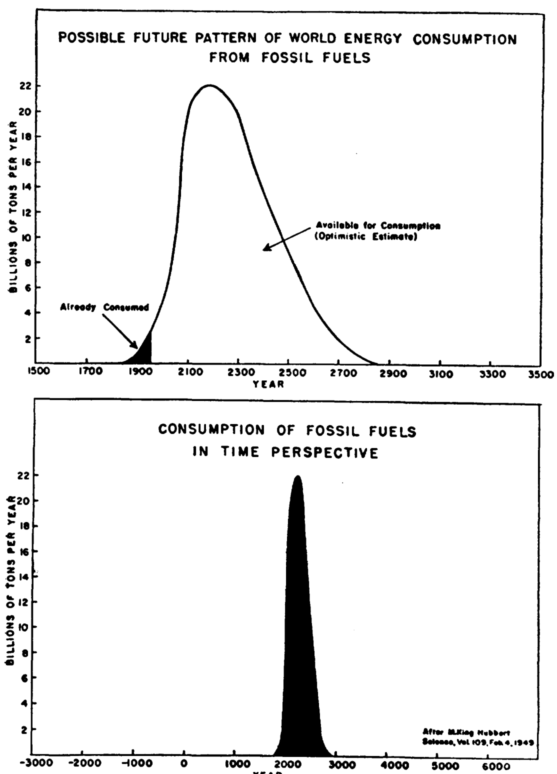

FIG. 8. Possible future patterns of energy consumption from fossil fuels. Two time scales are shown (from Brown, 1954, p. 169).

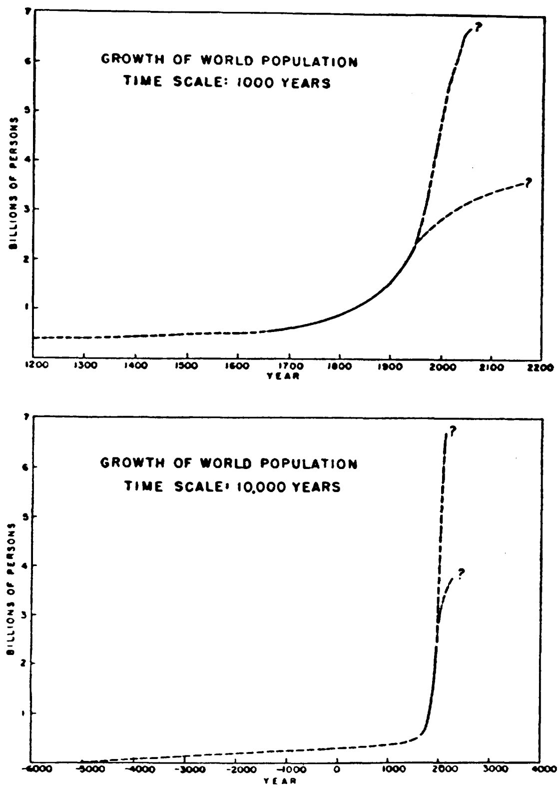

FIG. 9. Growth of world population on two time scales (from Brown, 1954, p. 49).

deliberately and scientifically, mankind may gain far-reaching insight into nature's secrets.

For example Thomas Jukes has felt this excitement. While a research biochemist at American Cyanamid Company, Jukes (1963: p. 335) wrote:

> The story of the world-wide population increase . . . is a tale of events that have spread through all countries; a story of the changes wrought by science and technology; of the effects of . . . public health education, farm machinery, vitamins, agricultural genetics, fertilizers, synthetic fibers, and, above all, pesticides. It concerns millions of people whose hopes and aspirations have been increased. . . .
>
> The insecticide DDT . . . has probably had a greater effect on disease and hunger than has any other man-made chemical substance . . . it has killed billions of insects. . . . The sociological effects have been far-reaching, including reclamation of land for agriculture and urban expansion, decreases in absenteeism, higher earnings and improved economic status. The population of Madagascar, which had been stationary for many years, doubled between 1947 and 1959 following the initiation of an antimalaria campaign in 1949.

Jukes (1963: p. 360) states further:

The best hope for coping with the need for food throughout the world lies in extending the superb agricultural technology of the United States into use in other countries . . . the issue is not one that merely involves 2 per cent of the sales of the chemical industry; at stake is no less than the protection of the the free world from hunger and disease.

Coming closer to my own profession of oceanography is the following quotation from an editorial by Athelstan F. Spilhaus (1964: p. 993):

Man *is* going to colonize the oceans, and it might just as well be *our* men. To compete successfully, we must be able to move faster in the sea, to go deeper, to stay down longer, than anyone else. We must understand more about the sea. . . .

Already phosphorites and diamonds are being taken commercially from the shelves in the sea, and nodules may be an inexhaustible source of other minerals in the future.

This quotation may, indeed, be one of the last times a scientist ever speaks of inexhaustible resources.

In our academic establishments enthusiasm may be tempered by the reflective powers of the scholarly mind. Kenneth Boulding (1964: p. 18) in a book on *The Great Transition*, as he calls it, states:

Attitudes toward the transition can range from rejection, through a grudging acceptance, to a cautious and critical acceptance, and to an enthusiastic and uncritical acceptance. . . I take my stand somewhere about the third of these positions. I welcome the transition as an event of enormous evolutionary potential in line with the general development of the universe as we know it.

These scientists who, I might say, are intoxicated with the success of twentieth-century science, show a deep faith that science and science-led technology may pull us out of any environmental predicament.

There also exist scientists who are alarmed, especially the ecologists whose natural environment is being so transformed recently that many find their professional work hindered. They are joined by hikers, fishermen, and other throw-backs to Cro-Magnon man who see recreational land disappearing and by scholars like Harrison Brown who, without obvious personal motives, nevertheless register concern.

For example, F. E. Egler (1964: p. 119), a sarcastic ecologist, calls the recent ecological changes such as the CO_2 increase, a Revolution in the Environment. He believes that "in general we have acted with remarkable arrogance to the whole nature of which we are a part" in allowing this revolution to take place without restraint. Now we must direct this revolution so

that we here and after thrive and survive in it. The problem is not one of growing and selling at a suitable profit this year's surplus crop of wheat. The problem is not in destroying the rats in your cellar, the cockroaches in your kitchen, the mosquitoes on your lawn, or even the bats in your belfry. The problem is not in growing timber on a 70-year rotation. The problem is not in saving your child from a lethal disease, or the unreasonable perpetuation of your own life. The problem is not in the continuing growth of our national economy. The problem is not in the balance of payments for a nation, or whether that nation and all nations are to survive under communism or under capitalism. The problem is whether the entire earth, man and the environment he is modifying can persist successfully and happily, generation after generation, meaningfully, without man either destroying himself, or losing himself in a whirling dervish of economic prosperity, linked with individual nonentity made tolerable only by perpetual tranquilization.

Harrison Brown (1954: p. 222) writes:

Our ancestors had available large resources of high-grade ores and fuels that could be processed by the most primitive technology—crystals of copper and pieces of coal that lay on the surface of the earth, easily mined iron, and petroleum in generous pools reached by shallow drilling. Now we must dig huge caverns and follow seams ever further underground, drill oil wells thousands of feet deep, many of them under the bed of the ocean, and find ways of extracting elements from the leanest of ores—procedures that are possible only because of our highly complex modern techniques, and practical only to an intricately mechanized culture which would not have been developed without the high-grade resources that are so rapidly vanishing.

. . . We are quickly approaching the point where, if a machine civilization should, because of some catastrophe, stop functioning, it would probably never again come into existence.

Finally, we might consider the view of college students. Here is a sample from the Berkeley campus of the University of California (Luten, 1964: p. 45):

The image which comes to my mind as applicable today is that of a Kafka-like toboggan, running down a slope at ever-increasing speed. Most of the passengers are completely unaware that the slope is becoming steeper; in the front, the official drivers are too busy quarreling over possession of the steering-bar to notice anything at all. Here and there among the passengers are a few individuals who recognize the danger. Some of these, convinced that a precipice lies ahead, shrilly exhort the others to

"Turn! Turn!"—how, they cannot say, and usually they indicate a direction somewhere along the receding track. Others knowledgeable in toboggan construction, offer wise expedients to hold the vehicle together for a few moments longer, in the hope that the slope will level off.

Whom shall we heed? The sober individuals with the bailing wire, just emerged from conference, speak with authority as they point out that, although the slope is becoming steeper, it cannot yet be considered a precipice. But it looks rather like a precipice to us, and we have just remembered that it was they who a few miles back told us how to grease the runners when we so wanted to feel the rush of crisp, winter air.

I recite these diverging points of view to illustrate that we hold widely divergent views concerning a possible peril. Have you noticed that practically all master plans do not project beyond the year 2000 A.D.? Our college students, however, today expect, or at least nourish the hope, to live beyond that date, and I predict that they will be the first generation to feel such strong concern for man's future that they will discover means of effective action. This action may be less pleasant and rational than the corrective measures that we promote today, but thirty years from now, if present trends are any sign, mankind's world, I judge, will be in greater immediate danger than it is today, and immediate corrective measures, if such exist, will be closer at hand. If the human race survives into the twenty-first century with the vast population increase that now seems inevitable, the people living then, along with their other troubles, may also face the threat of climatic change brought about by an uncontrolled increase in atmospheric CO_2 from fossil fuels.

REFERENCES

BAINBRIDGE, ARNOLD E. 1970. "The Secular Increase of Atmospheric Carbon Dioxide." To be submitted to *Jour. Geophy. Res.*

BOLIN, BERT, and ERIK ERIKSSON. 1958. "Changes in the Carbon Dioxide Content of the Atmosphere and Sea Due to Fossil Fuel Combustion." *Rossby Memorial Volume* (edited by B. Bolin, Rockefeller Institute Press, New York, 1959), pp. 130–142.

BOULDING, KENNETH E. 1964. *The Meaning of the Twentieth Century—The Great Transition* (New York, Harper and Row).

BROWN, CRAIG W., and CHARLES D. KEELING. 1965. "The Concentration of Atmospheric Carbon Dioxide in Antarctica." *Jour. Geophy. Res.* **70**: pp. 6077–6085.

BROWN, HARRISON. 1954. *The Challenge of Man's Future* (New York, Viking Press).

EGLER, FRANK E. 1964. "Pesticides—in our Ecosysem." *American Scientist* **52**: pp. 110–136.

HUTCHINSON, G. EVELYN. 1954. "The Biochemistry of the Terrestrial Atmosphere. *The Earth as a Planet* (chap. 8, edited by G. Kuiper, U. of Chicago Press), pp. 371–433.

JUKES, THOMAS H. 1963. "People and Pesticides." *American Scientist* **51**: pp. 355–362.

KAPLAN, LEWIS D. 1960. "The Influence of Carbon Dioxide Variations on the Atmospheric Heat Balance." *Tellus* **12**: pp. 204–208.

LUTEN, DANIEL B. 1964. "Numbers Against Wilderness." *Sierra Club Bull.* **49**: pp. 43–48.

MANABE, SYUKURO, and ROBERT F. STRICKLER. 1964. "Thermal Equilibrium of the Atmosphere with a Convective Adjustment." *Jour. Atm. Sci.* **21**: pp. 361–385.

MANABE, SYUKURO, and RICHARD T. WETHERALD. 1967. "Thermal Equilibrium of the Atmosphere with a Given Distribution of Relative Humidity." *Jour. Atm. Sci.* **24**: pp. 241–259.

MÖLLER, F. 1963. "On the Influence of Changes in the CO_2 Concentration in Air on the Radiation Balance of the Earth's Surface and on the Climate." *Jour. Geophy. Res.* **68**: pp. 3877–3886.

PALES, JACK C., and CHARLES D. KEELING. 1965. "The Concentration of Atmospheric Carbon Dioxide in Hawaii." *Jour. Geophy. Res.* **70**: pp. 6053–6076.

PLASS, GILBERT N. 1956. "The Carbon Dioxide Theory of Climatic Change." *Tellus* **8**: pp. 140–154.

REVELLE, ROGER. 1965. "Atmospheric Carbon Dioxide, Appendix Y4 of Restoring the Quality of Our Environment, a Report of the Environmental Pollution Panel." *President's Science Advisory Committee, The White House*, pp. 111–133.

SPILHAUS, ATHELSTAN F. 1964. "Man in the Sea." *Science* **145**: p. 993.