Luxuriant plant life sank beneath water, locking up carbon that otherwise would have drawn off oxygen used in evolving life.

THE FRAGILE BREATH OF LIFE: HOW IT CAME TO BE

THE ROLE OF THE OCEANS

By ROGER REVELLE

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; plants obtain all of their carbon from atmospheric or oceanic carbon dioxide; marine and terrestrial animals, including man, either directly or indirectly procure the substance of their bodies from the carbon compounds made by plants.

For most of the past billion years, the two fundamental processes of life on the planet earth have been photosynthesis and respiration. In photosynthesis, plants use the energy of sunlight to break down water and combine its hydrogen with carbon dioxide to form organic matter in their own tissues. The oxygen freed from the water escapes into the air or into the oceans.

Plants gain energy for their vital activities through respiration—in effect, the reverse of photosynthesis; that is, they combine free oxygen with the organic matter in their own tissues to produce carbon dioxide and water. All animals and most bacteria ultimately obtain all their energy in the same way. On an earth-wide basis, both photosynthesis and respiration are rapid processes: an amount of oxygen equal to the total in the atmosphere is freed by photosynthesis of marine and land plants every few thousand years, and all the atmospheric carbon dioxide is cycled through land plants in about thirty years. The rate of respiration would just equal the rate of photosynthesis, and no free oxygen would accumulate, were it not for one remarkable fact about the earth—it has oceans.

Earth is sometimes called the water planet because of the large quantities of liquid water on its surface, unlike all the other members of our solar system. To permit free oxygen to accumulate in the atmosphere, it is essential that this water, instead of being spread in a uniform film over the surface, is gathered together in deep basins surrounding the huge islands we call continents. The reason is as follows.

Ever since continents and oceans have existed on earth, the land surfaces have been continually worn by wind and running water. The debris from this destruction has been washed and blown downward to the ocean floor. Deposited there as oceanic sediment, some of this debris later became cemented into rock and was uplifted to help rebuild the continents.

FROM the standpoint of the formation of oxygen in the atmosphere, the most important components of the oceanic sediments were the carbon-containing remains of plants and animals. At any one time, the amount of carbon being deposited was only a very small fraction of the living and dead organic matter on the earth, but over a billion years the total deposition was very large. If this carbon had not been withdrawn from the cycle of photosynthesis and respiration, it would have combined with and locked

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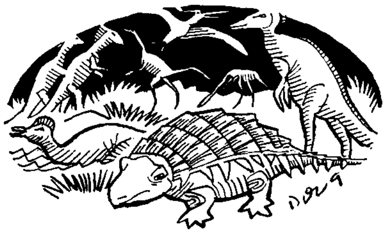
up oxygen as the oxygen was produced by photosynthesis; withdrawal of the carbon permitted oxygen to accumulate in the atmosphere.

Oxygen makes up 20 per cent of the volume of the atmosphere and carbon dioxide only three-hundredths of 1 per cent; but if, as seems likely, nearly all the oxygen has been produced by the photosynthesis of green plants during much of the past billion years, then the total amount of carbon dioxide that has passed through the air during this time must be at least equal to the amount of oxygen now present in the air.

The geologic evidence of the rocks shows that in fact volcanoes and volcanic springs have brought very much larger quantities of carbon dioxide to the surface. The total amount of carbon dioxide released during the lifetime of the earth was at least 40,000 times the quantity of carbon dioxide now present in the air. Most of this combined with calcium or magnesium freed by the weathering of silicate rocks and was precipitated on the sea floor as limestone or dolomite. About one-fourth of the total quantity, at least 10,000 times the present atmospheric carbon dioxide, was reduced by plants to organic 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 world-wide industrial civilization of our time. The carbon in every barrel of oil and every lump of coal, as well as in every block of limestone, was once present in the atmosphere as carbon dioxide.

Throughout most of the half-million 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 being 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 the fossil fuels that were locked in the sedimentary rocks over 500 million years, and this combustion is measurably increasing the atmospheric carbon dioxide.

From 1860 to 1959, the amount of carbon dioxide produced by combustion of fossil fuel, chiefly coal, was equal to nearly 14 per cent of the atmospheric carbon dioxide. The accuracy of estimates of the total carbon dioxide content of the world atmosphere before 1958 was too low to allow satisfactory calculation of what fraction of this carbon dioxide from fossil-fuel combustion remained in the atmosphere. In the middle 1950s, however, new instruments utilizing the infrared spectrum of carbon dioxide were developed. These allowed rapid and very accurate measurement of the carbon dioxide content of air samples. As part of the program of the International Geophysical Year, a study was made of the total carbon dioxide content of the atmosphere and the changes in it from year to year. The two most successful sets of observations were supervised by Dr. Charles David Keeling of the Scripps Institution of Oceanography: one at the U.S. Weather Bureau Station near the top of Mauna Loa mountain on Hawaii, the other at the U.S. Scientific Station at the South Pole. Some 15,000 measurements were carried out near these centers of vast atmospheric mixing, far from uncontrollable sources of contaminants. Because of the nearly ideal locations, together with the high precision of the instruments, and the extreme care with which the samples were taken, it was possible to estimate the trend of atmospheric carbon dioxide with an accuracy greater by two orders of magnitude than ever before.



The data show clearly and conclusively that, from 1958 through 1962, the carbon dioxide content of the atmosphere increased by 1.15 per cent. The increase from year to year was quite regular. During the same five years, United Nations' statistics show that fifty-three billion tons of carbon dioxide were produced by the combustion of coal, lignite, petroleum and other liquid hydrocarbons, and natural gas. This is 2.26 per cent of the 2,350 billion tons of carbon dioxide present in the atmosphere in the early 1950s. We see from these figures that almost exactly half of the fossil-fuel carbon dioxide remained in the air.

The other half of the carbon dioxide released by fossil fuels was taken up in the ocean and in the biosphere, that is, mainly in trees and other living plants and in oceanic and soil humus.

If the carbon dioxide produced by burning fossil fuels during the last hundred years was divided among the air, the sea, and the biosphere in the same proportions as in the five years from 1958 through 1962, then the quantity of carbon dioxide in the air at the beginning of the present decade was about 7 per cent higher than in the middle of the nineteenth century.

The United Nations Department of Economic and Social Affairs has projected world energy requirements up to the year 2000. The required fossil fuel combustion would give an amount of atmospheric carbon dioxide 25 per cent greater than the amount present during the nineteenth century. The uncertain rates of world economic development and of introduction of atomic energy as a substitute for fossil fuels raise doubts about the reliability of this estimate. We can with greater confidence say what would be the total amount of carbon dioxide injected into the air if all recoverable reserves of fossil fuels were consumed. At present rates of expansion in fossil fuel consumption, this condition would be approached within the next 150 years. If all the estimated 3,000 billion tons of reserves were recovered and burned, 7,850 billion tons of carbon dioxide would be produced—about 340 per cent of the amount now present in the atmosphere.

Although the date when it may occur is somewhat uncertain, a 25 per cent increase in atmospheric carbon dioxide within the next few decades is not, therefore, an unreasonable prediction. Such a rise might be sufficient to produce significant effects on climate; it would almost certainly cause marked changes in the temperature and other properties of the stratosphere.

Carbon dioxide is nearly transparent to visible light, but at all levels in the atmosphere the carbon dioxide molecules absorb infrared radiation and reradiate it in all directions, partly downward and partly upward. In the lower atmosphere, some of the downward emission of infrared from the carbon dioxide molecules reaches the earth's surface and must be reradiated again. Thus the total amount of infrared radiation from near the ground is increased. To maintain a heat balance, the temperature near the ground must be higher than it would be in the absence of carbon dioxide. This is the so-called "greenhouse effect."

CARBON dioxide and water vapor absorb and emit infrared radiation at nearly the same wave lengths. Hence an increase in either carbon dioxide or water vapor will result in an increase of the temperature of the lower air. A rise in temperature due to an increase in water vapor will not affect the atmospheric carbon dioxide; but a rise in temperature from added carbon dioxide tends to increase evaporation, accelerated evaporation tends to raise the water vapor content of the lower air, augmentation of water vapor means increased absorption of infrared, and the magnified infrared radiation brings about a still further rise in temperature. We have here a classic example of a feedback mechanism.

In the stratosphere, the effect of an increase in carbon dioxide is exactly the opposite of the effect of an increase near the ground. The amount of water vapor is very low, and the temperature is mainly determined by the balance between warming due to absorption of sunlight by ozone and cooling due to emission of infrared radiation by carbon dioxide. Since the total infrared radiation is constant and equal to the incoming sunlight, the temperature must go down when the number of carbon dioxide molecules increases.

Unfortunately, our present understanding of the physical processes that determine weather and climate is not sufficient to allow us to make very useful predictions about the effect of an increase in atmospheric carbon dioxide, except to say that the average rise in temperature over the earth would probably not be large. The best and most recent calculations have been made by the German meteorologist, F. Möller, and the American, Syukuro Manabe. Dr. Manabe was able to compute the transfer of heat through a vertical column of the atmosphere with different carbon dioxide contents. He concluded that a doubling of carbon dioxide would result in a temperature increase of about 4 degrees Fahrenheit, provided that the relative humidity remained constant. With a 25 per cent increase in carbon dioxide and a constant relative humidity, the rise in temperature would be about 1.2 degrees Fahrenheit. Considerably larger changes would occur in the stratosphere. A 25 per cent increase in carbon dioxide would cause stratospheric temperatures to fall about 3.5 degrees Fahrenheit at an altitude of 100,000 feet, and 7 degrees Fahrenheit at 130,000 feet.

CLIMATIC changes depend both on changes in vertical heat-transfer and on the general circulation of the atmosphere. The latter should be related to the spatial distribution and time variation of carbon dioxide and water vapor content. The ratio of carbon dioxide to water vapor is higher in the polar regions than in low latitudes, higher in winter than in summer, and much higher in the stratosphere than near the ground. For example, the volume of carbon dioxide in the atmosphere at high latitudes is about half the volume of water vapor, while near the equator it is less than a tenth of the water vapor volume. As a result, the radiation balance of the earth will be affected differently at different seasons, latitudes, and heights by changes in the atmospheric carbon dioxide content.

Without a more comprehensive model of the atmosphere than we now possess, it is impossible to make quantitative predictions. But in general we should expect that the effect of the differential distributions of carbon dioxide and water vapor would make the atmospheric circulation more sluggish as the carbon dioxide content rises.

Some meteorologists have argued that the world-wide atmospheric warming between 1885 and 1940 was brought about by the increase in atmospheric carbon dioxide. During this period, the mean annual air temperature over the entire earth rose by nearly 1 degree Fahrenheit. Warming occurred in both hemispheres and at all latitudes, but the largest rise was observed between 40 degrees and 70 degrees north latitude, where the average winter temperature rose by nearly 3 degrees Fahrenheit.

There are two difficulties with this argument: One, prior to 1940 the increase in atmospheric carbon dioxide from fossil-fuel combustion was only 4 per cent, and this was probably too small to produce the observed temperature changes; two, the warming of the surface air did not continue much beyond 1940. Between 1940 and 1960, additional warming occurred in Northern Europe and North America, but for the world as a whole, and also for the northern hemisphere, there was a slight lowering of about 0.2 degrees Fahrenheit in mean annual air temperature. Yet during this period more than 40 per cent of the total carbon dioxide increase from fossil fuel combustion occurred.

In general, our attitude toward the changing content of carbon dioxide in the atmosphere that is being brought about by our own actions should probably contain more curiosity than apprehension. Human beings are now carrying out a large-scale geophysical experiment which, if adequately documented, may yield a far-reaching insight into the processes determining weather and climate. We must not forget, however, that even a relatively small rise in the average annual temperature of the atmosphere might be accompanied by other more serious changes, for example, shifts in the position or the width of belts of low rainfall.

The possible future changes in climate that may be brought about by increases in atmospheric carbon dioxide give a unique justification to research and development on ways of modifying climate by deliberate human action. Man-made climatic modifications that might benefit some regions could be deleterious to others, and this raises serious ethical and legal objections to projects for carrying out such modifications. But these objections do not apply to attempts to bring about climatic changes that would counteract those that might be produced by an increase in the amount of atmospheric carbon dioxide.

FOR example, a change in the radiation balance in the opposite direction could be produced by raising the albedo, or reflectivity, of the earth. Such a change in albedo could be brought about by spreading very small reflecting particles over large oceanic areas. The particles should be sufficiently buoyant so that they will remain close to the sea surface, and they should have high reflectivity, so that even a partial covering of the surface would be adequate to produce a marked change in the amount of reflected sunlight. A fine powder of latex or of a light-colored opaque plastic, dispersed by a machine something like the smoke generators used in World War II, might do the job very well. Rough estimates indicate that enough particles to cover a square mile effectively could be produced for perhaps $100. A 1 per cent change in reflectivity might be brought about for about $500 million a year, particularly if the reflecting particles were spread in low latitudes, where the incoming radiation is concentrated. Considering the extraordinary economic and human importance of climate, costs of this magnitude do not seem excessive. An early development of the needed technology might be useful in inhibiting the formation of hurricanes in tropical oceanic areas by partly preventing the absorption of sunlight in the subsurface ocean waters, thereby depriving these storms of the energy they need to build up and maintain their ferocious intensity.

"Which side of the moon do you like best?"

Saturday Review

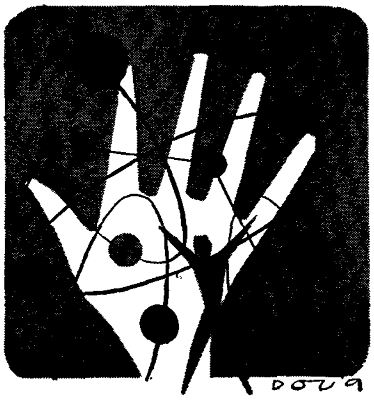
The Third Culture

TEN YEARS AGO, *SR* initiated a monthly supplement on science, edited by John Lear. It was *SR's* second magazine-within-a-magazine venture, the first being devoted to recordings, under the editorship of Irving Kolodin. Subsequent supplements on education, edited by Paul Woodring and James Cass, and on communications, edited by Richard L. Tobin, rounded out the monthly cycle.

The purpose of the supplements was to deal with primary aspects of creativity and systematic thought in the modern world. A more particularized purpose in instituting the science section was to open up a direct channel of communication between scientist and non-scientist. It seemed to the editors that the existing lines of separation were arbitrary and unreal. There was a degree of artistic and humanistic concern in science that many non-scientists tended to ignore, and a degree of discipline and systematic thought in the arts that many scientists tended to deny. This lack of effective communication served as the basis, some years later, for C. P. Snow's original Rede Lecture on "Two Cultures and the Scientific Revolution."

The wall of separation today between the formal scientific community and the rest of the intellectual community is far less formidable than it was a decade ago. There is at least a vocabulary for discourse between scientist and non-scientist. Rapport no longer requires special indulgence. The man of the liberal arts has lost much of the old sense of mystification about the laboratory and engineering world. And the scientist has gained a new respect for the intangibles and the individualistic course of the artist.

With full respect for C. P. Snow, however, the main problem of the two cultures is not now, nor has it been for some time, the absence of communication between scientist and non-scientist. The problem has to do with what is being communicated. The scholars or artists and the scientists are talking to each other but not about the right things. Here we come to the real failure of the two cultures. Creative brainpower and advanced skills are not being directed to the largest need of the human species. The common and tragic failure of both the arts and the sciences is that they have given most of their energy and focus to the immediates and intermediates and very little to the ultimates. They have advanced the human condition without necessarily safeguarding the human estate. Each has served its own tradition without expanding it to encompass the essentially new problem of a world that has become one before it has become whole. In this sense, the problem is not what happens between the two cultures. The problem is what happens between the two cultures in history.



There is no doubt that the worlds of the systematic thinker and the creative artist have been productive and, in many respects, prosperous. But there is still a question of total relevance, a question concerning the uses to which brainpower and scholarship and artistry are put, and the directions they take; a question involving the safety of the world environment. If the two cultures don't understand the requirements of world peace, and if they fail to serve world peace in the most fundamental sense, they become detached from their most important function—no matter how firmly they may be attached to everything else.

In his second Rede Lecture in 1963, C. P. Snow sought to correct the impression given by the earlier lecture that he was more concerned about communication than about human problems and politics. He made it clear that he *was* concerned and indeed optimistic about the potentialities of science. And he was most eloquent and persuasive in calling for the full release of human intelligence in closing the gap between the world's rich and poor. This is all to the good, but the struggle against poverty needs a framework of possibilities. No fundamental progress against poverty is possible so long as a large proportion of the world's energies and reserves goes into things that can be used only for destructive purposes. And no poverty this earth has known will have greater dimensions than that which will follow the general collapse of peace in an atomic age.

Sir Charles spoke of the significance of the Industrial Revolution and gave emphasis to the untapped possibilities of applied science. But the central significance of the Industrial Revolution transcends economic change or the possibilities for good. The central significance of the Industrial Revolution is that it created engines for world destruction without creating the instruments for control. The reach of science and engineering has superseded the capacity for social and political organization. The betterment of human society depends even more on the conditions of an enforceable peace than on an ingenious technology.

The need today is for a Third Culture —one concerned with the total connection between total cause and total effect, one which recognizes that human destiny cannot be served or assured until tribalism, however elevated its station or sophisticated its language, gives way to a world view. —N.C.