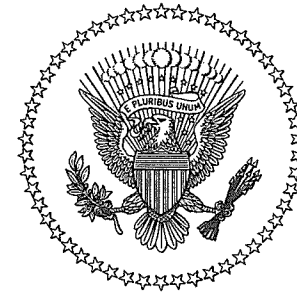


RESTORING THE QUALITY  
OF  
OUR ENVIRONMENT



*Report of The  
Environmental Pollution Panel  
President's Science Advisory Committee*

THE WHITE HOUSE

NOVEMBER 1965

THE WHITE HOUSE

WASHINGTON

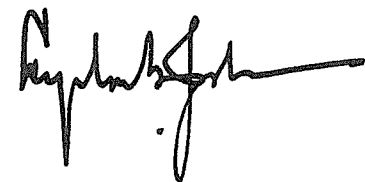
November 5, 1965

Ours is a nation of affluence. But the technology that has permitted our affluence spews out vast quantities of wastes and spent products that pollute our air, poison our waters, and even impair our ability to feed ourselves. At the same time, we have crowded together into dense metropolitan areas where concentration of wastes intensifies the problem.

Pollution now is one of the most pervasive problems of our society. With our numbers increasing, and with our increasing urbanization and industrialization, the flow of pollutants to our air, soils and waters is increasing. This increase is so rapid that our present efforts in managing pollution are barely enough to stay even, surely not enough to make the improvements that are needed.

Looking ahead to the increasing challenges of pollution as our population grows and our lives become more urbanized and industrialized, we will need increased basic research in a variety of specific areas, including soil pollution and the effects of air pollutants on man. We must give highest priority of all to increasing the numbers and quality of the scientists and engineers working on problems related to the control and management of pollution.

I am asking the appropriate Departments and Agencies to consider the recommendations and report to me on the ways in which we can move to cope with the problems cited in the Report. Because of its general interest, I am releasing the report for publication.



## PRESIDENT'S SCIENCE ADVISORY COMMITTEE

DONALD F. HORNIG, *Chairman*, Special Assistant to the President for Science and Technology  
HERBERT F. YORK, Jr., *Vice Chairman*, Professor of Physics, University of California, San Diego  
Lewis M. Branscomb, Chairman, Joint Institute for Laboratory Astrophysics, Boulder  
Melvin Calvin, Professor of Chemistry, University of California, Berkeley  
Richard L. Garwin, Thomas J. Watson Research Center, International Business Machines Corporation, Yorktown Heights  
Marvin L. Goldberger, Professor of Physics, Princeton University  
Philip Handler, Chairman, Department of Biochemistry, Duke University Medical Center  
Franklin A. Long, Vice President for Research and Advanced Studies, Cornell University, Ithaca  
Gordon J. F. MacDonald, Chairman, Department of Planetary and Space Physics, Institute of Geophysics and Planetary Physics, University of California, Los Angeles  
William D. McElroy, Chairman, Department of Biology, The Johns Hopkins University  
George E. Pake, Provost, Washington University, St. Louis  
John R. Pierce, Executive Director, Research—Communications Sciences Division, Bell Telephone Laboratories  
Kenneth S. Pitzer, President, Rice University  
Edward M. Purcell, Professor of Physics, Harvard University  
Frederick Seitz, President, National Academy of Sciences

## ENVIRONMENTAL POLLUTION PANEL

JOHN W. TUKEY, *Chairman*, Professor of Mathematics, Princeton University, and Associate Executive Director, Research—Communications Sciences Division, Bell Telephone Laboratories  
Martin Alexander, Associate Professor of Soil Science, New York State College of Agriculture, Cornell University, Ithaca  
H. Stanley Bennett, Dean, Division of Biological Sciences, University of Chicago  
Nyle C. Brady, Director of Office of Science and Education, U.S. Department of Agriculture (until August 31, 1965), Director of the Cornell University Experiment Station, Director of Research, New York State College of Agriculture, Cornell University, Ithaca  
John C. Calhoun, Jr., Science Advisor to the Secretary of the Interior (until February 5, 1965), Vice President for Programs, Texas A & M University System, College Station  
John C. Geyer, Chairman, Department of Sanitary Engineering and Water Resources, The Johns Hopkins University, Baltimore  
Aarie J. Haagen-Smit, Professor of Biochemistry, California Institute of Technology, Pasadena  
Norman Hackerman, Vice Chancellor for Academic Affairs, University of Texas, Austin  
James B. Hartgering, Director of Research and Education, American Hospital Association, Chicago  
David Pimentel, Head, Department of Entomology and Limnology, New York State College of Agriculture, Cornell University, Ithaca  
Roger Revelle, Director, Center for Population Studies, Harvard University  
Louis H. Roddis, President, Pennsylvania Electric Company, Johnstown  
William H. Stewart, (member until June, 1965) Office of the Secretary, U.S. Department of Health, Education, and Welfare, Washington  
James L. Whittenberger, Professor of Public Health, Harvard School of Public Health  
John L. Buckley, *Staff*, Technical Assistant, Office of Science and Technology, Washington

# Contents

	<i>Page</i>
Acknowledgements . . . . .	ix
Introduction . . . . .	1
The Effects of Pollution . . . . .	3
Health Effects . . . . .	3
Excessive air pollution for short periods . . . . .	3
Prolonged exposure to ordinary urban air pollution . . . . .	3
Water-borne pollutants and health . . . . .	4
Pesticides and human health . . . . .	4
Effects on Other Living Organisms . . . . .	5
Why do we care? . . . . .	5
Kinds of effects on organisms other than man . . . . .	5
Impairment of Water and Soil Resources . . . . .	7
Excess fertility in waters . . . . .	7
Soil pollution . . . . .	7
Polluting Effects of Detergents . . . . .	8
Deterioration of Materials and Urban Environments . . . . .	9
Climatic Effects of Pollution . . . . .	9
The Sources of Pollution . . . . .	10
Municipal and industrial sewage . . . . .	10
Animal wastes . . . . .	10
Urban solid wastes . . . . .	11
Mining wastes . . . . .	11
Consumer goods wastes . . . . .	11
Unintentional Releases . . . . .	12
In Which Directions Should We Go? . . . . .	13
Recommendations . . . . .	16
A. Principles . . . . .	16
B. Actions . . . . .	17
C. Coordination and Systems Studies . . . . .	23
D. Baseline Measurement Programs . . . . .	25
E. Development and Demonstration . . . . .	26
F. Research . . . . .	29
G. Manpower . . . . .	33
H. Incompleteness of Recommendations . . . . .	38
Appendixes:	
X1. Challenging Tasks for the Men and Women Who Can Improve the Quality of Our Environment . . . . .	39
X2. Organizational Questions . . . . .	48
X3. A "General" Index of Chemical Pollution . . . . .	57
X4. Standards Development . . . . .	59
X5. Metropolitan Problems . . . . .	62
X6. Air Problems . . . . .	66
X7. Water Quality . . . . .	70

## Subpanel Reports

	<i>Page</i>
Y1. Soil Contamination . . . . .	74
Y2. Health Effects of Environmental Pollution . . . . .	91
Y3. Benchmark Surveillance . . . . .	102
Y4. Atmospheric Carbon Dioxide . . . . .	111
Y5. Solid Wastes . . . . .	134
Y6. Combined Sewers . . . . .	157
Y7. Effects of Chlorinating Wastes . . . . .	168
Y8. Agricultural Wastes . . . . .	170
Y9. Aquatic Blooms . . . . .	173
Y10. Effects of Pollutants on Living Organisms Other Than Man . . . . .	192
Y11. Improved Pest Control Practices . . . . .	227
Index . . . . .	293

## Acknowledgements

The study was conducted under the general supervision of Colin M. MacLeod, Deputy Director, Office of Science and Technology.

The Panel drew on scientists and engineers from within the Federal Government, from state governments, universities and industry to form subpanels of experts, each of which explored a different problem. These busy men put in, on the average, several weeks of their time talking to scientists, studying and evaluating information published and unpublished, and writing reports. The reports are included as the "Y" Appendixes.

The members of the subpanels are listed on the following pages.

## SOIL CONTAMINATION

H. Stanley Bennett, *Chairman*  
Dean, Division of Biological Sciences  
University of Chicago

Martin Alexander  
Associate Professor of Soil Science  
New York State College of Agriculture  
Cornell University, Ithaca

Sterling B. Hendricks  
Soil and Water Conservation Research  
Division  
Agricultural Research Service  
U.S. Department of Agriculture  
Beltsville, Maryland

H. L. Lucas  
Professor and Director of Biomathematics  
Training Program  
Institute of Statistics  
North Carolina State University, Raleigh

Thomas J. Sheets, *Staff*  
Crops Research Division  
Agricultural Research Service  
U.S. Department of Agriculture  
Beltsville, Maryland  
(Present address) Associate Professor of  
Entomology and Crop Science  
North Carolina State University, Raleigh

HEALTH EFFECTS OF ENVIRONMENTAL  
POLLUTION

James L. Whittenberger, *Chairman*  
Professor of Public Health  
Harvard School of Public Health

Aarie J. Haagen-Smit  
Professor of Biochemistry  
California Institute of Technology,  
Pasadena

Lincoln E. Moses  
Executive Head  
Department of Statistics  
Stanford University

William H. Stewart (member until  
June 1965)  
Office of the Secretary  
U.S. Department of Health, Education,  
and Welfare, Washington

John R. Bagby, Jr., *Staff*  
Communicable Disease Center  
Public Health Service  
U.S. Department of Health, Education,  
and Welfare, Atlanta, Georgia

H. Bruce Dull, *Staff*  
Communicable Disease Center  
Public Health Service  
U.S. Department of Health, Education,  
and Welfare, Atlanta, Georgia

## BENCHMARK SURVEILLANCE

Aarie J. Haagen-Smit, *Chairman*  
Professor of Biochemistry  
California Institute of Technology  
Pasadena

Louis H. Roddis, *Vice Chairman*  
President  
Pennsylvania Electric Company  
Johnstown

Nyle C. Brady  
Director of Science and Education  
U.S. Department of Agriculture  
(until August 31, 1965)  
Director of the Cornell  
University Experiment Station  
Director of Research  
New York State College of Agriculture  
Cornell University, Ithaca

Raymond J. Jessen  
Professor of Business Statistics  
Graduate School of Business  
Administration  
University of California, Los Angeles

James L. Whittenberger  
Professor of Public Health  
Harvard School of Public Health

W. J. Youden  
4821 Upton Street NW.  
Washington

John L. Buckley, *Staff*  
Technical Assistant  
Office of Science and Technology  
Washington

## ATMOSPHERIC CARBON DIOXIDE

Roger Revelle, *Chairman*  
Director, Center for Population Studies  
Harvard University

Wallace Broecker  
Professor of Geology  
Columbia University, New York

Harmon Craig  
Professor of Geochemistry  
Department of Earth Sciences  
University of California, La Jolla

Charles D. Keeling  
Scripps Institution of Oceanography  
La Jolla, California

J. Smagorinsky  
Weather Bureau  
Environmental Sciences Services  
Administration  
U.S. Department of Commerce  
Suitland, Maryland

## SOLID WASTES

John C. Calhoun, Jr., *Chairman*  
Science Adviser to the Secretary  
U.S. Department of the Interior  
(until February 5, 1965)  
Vice President for Programs  
Texas A & M University System  
College Station

Patrick Conley  
Senior Fellow  
Mellon Institute, Pittsburgh

Aarie J. Haagen-Smit  
Professor of Biochemistry  
California Institute of Technology  
Pasadena

Norman Hackerman  
Vice Chancellor for Academic Affairs  
University of Texas, Austin

Leonhard Katz  
President  
Astro Dynamics, Inc.  
2d Avenue, Northwest Industrial Park  
Burlington, Massachusetts

George J. Maslach  
Dean, College of Engineering  
University of California, Berkeley

Louis H. Roddis  
President  
Pennsylvania Electric Company  
Johnstown

James E. Hill, *Staff*  
Bureau of Mines  
U.S. Department of the Interior  
Washington

## COMBINED SEWERS

John C. Geyer, *Chairman*  
Chairman  
Department of Sanitary Engineering  
and Water Resources  
The Johns Hopkins University  
Baltimore

Leonhard Katz  
President  
Astro Dynamics, Inc.  
2d Avenue, Northwest Industrial Park  
Burlington, Massachusetts

## EFFECTS OF CHLORINATING WASTES

Martin Alexander, *Chairman*  
Associate Professor of Soil Science  
New York State College of Agriculture  
Cornell University, Ithaca

John C. Geyer  
Chairman  
Department of Sanitary Engineering and  
Water Resources  
The Johns Hopkins University, Baltimore

Deric O'Bryan, *Staff*  
Geological Survey  
U.S. Department of the Interior  
Washington

## AGRICULTURAL WASTES

Martin Alexander, *Chairman*  
Associate Professor of Soil Science  
New York State College of Agriculture  
Cornell University, Ithaca

Nyle C. Brady  
Director of Science and Education  
U.S. Department of Agriculture  
(until August 31, 1965)  
Director of the Cornell University  
Experiment Station  
Director of Research, New York State  
College of Agriculture  
Cornell University, Ithaca

Deric O'Bryan, *Staff*  
Geological Survey  
U.S. Department of the Interior  
Washington

## AQUATIC BLOOMS

Martin Alexander, *Chairman*  
Associate Professor of Soil Science  
New York State College of Agriculture  
Cornell University, Ithaca

John B. Moyle  
Department of Conservation  
St. Paul, Minnesota

Ruth Patrick  
Academy of Natural Sciences  
Philadelphia, Pennsylvania

Leon Weinberger  
Division of Water Supply  
and Pollution Control  
Public Health Service  
U.S. Department of Health, Education,  
and Welfare, Washington

Deric O'Bryan, *Staff*  
Geological Survey  
U.S. Department of the Interior  
Washington

## EFFECTS OF POLLUTANTS ON LIVING ORGANISMS OTHER THAN MAN

David Pimentel, *Chairman*  
Head, Department of Entomology  
and Limnology  
New York State College of Agriculture  
Cornell University, Ithaca

Don W. Hayne  
Professor of Experimental Statistics  
Institute of Statistics  
North Carolina State University  
Raleigh

Louis A. Krumholz  
Professor of Biology  
University of Louisville

John T. Middleton  
Director, Air Pollution Research Center  
University of California  
Riverside

Lionel A. Walford  
Director, Sandy Hook Marine Laboratory  
Bureau of Sport Fisheries and Wildlife  
U.S. Department of the Interior  
Highlands, New Jersey

John L. Buckley, *Staff*  
Technical Assistant  
Office of Science and Technology  
Washington

## IMPROVED PEST CONTROL PRACTICES

David Pimentel, *Chairman*  
Head, Department of Entomology and  
Limnology  
New York State College of Agriculture  
Cornell University, Ithaca

Donald A. Chant  
Chairman, Department of Biological  
Control  
University of California, Riverside

Arthur Kelman  
Professor of Plant Pathology and Forestry  
North Carolina State University, Raleigh  
Present Address—  
Chairman, Department of Plant  
Pathology  
University of Wisconsin, Madison

Robert L. Metcalf  
Vice Chancellor  
University of California, Riverside

L. D. Newsom  
Head, Department of Entomology  
Louisiana State University, Baton Rouge

Carroll N. Smith, *Staff*  
Entomology Research Division  
Agricultural Research Service  
U.S. Department of Agriculture  
Gainesville, Florida

## Introduction

Environmental pollution is the unfavorable alteration of our surroundings, wholly or largely as a by-product of man's actions, through direct or indirect effects of changes in energy patterns, radiation levels, chemical and physical constitution and abundances of organisms. These changes may affect man directly, or through his supplies of water and of agricultural and other biological products, his physical objects or possessions, or his opportunities for recreation and appreciation of nature.

The production of pollutants and an increasing need for pollution management are an inevitable concomitant of a technological society with a high standard of living. Pollution problems will increase in importance as our technology and standard of living continue to grow.

Our ancestors settled in a fair and unspoiled land, easily capable of absorbing the wastes of its animal and human populations. Nourished by the resources of this continent, the human inhabitants have multiplied greatly and have grouped themselves to form gigantic urban concentrations, in and around which are vast and productive industrial and agricultural establishments, disposed with little regard for state or municipal boundaries.

Huge quantities of diverse and novel materials are dispersed, from city and farm alike, into our air, into our waters and onto our lands. These pollutants are either unwanted by-products of our activities or spent substances which have served intended purposes. By remaining in the environment they impair our economy and the quality of our life. They can be carried long distances by air or water or on articles of commerce, threatening the health, longevity, livelihood, recreation, cleanliness and happiness of citizens who have no direct stake in their production, but cannot escape their influence.

Pollutants have altered on a global scale the carbon dioxide content of the air and the lead concentrations in ocean waters and human populations. Pollutants have reduced the productivity of some of our finest agricultural soils, and have impaired the quality and the safety of crops raised on others. Pollutants have produced massive mortalities of fishes in rivers, lakes and estuaries and have damaged or destroyed

commercial shellfish and shrimp fisheries. Pollutants have reduced valuable populations of pollinating and predatory insects, and have appeared in alarming amounts in migratory birds. Pollutants threaten the estuarine breeding grounds of valuable ocean fish; even Antarctic penguins and Arctic snowy owls carry pesticides in their bodies.

The land, water, air and living things of the United States are a heritage of the whole nation. They need to be protected for the benefit of all Americans, both now and in the future. The continued strength and welfare of our nation depend on the quantity and quality of our resources and on the quality of the environment in which our people live.

The pervasive nature of pollution, its disregard of political boundaries including state lines, the national character of the technical, economic and political problems involved, and the recognized Federal responsibilities for administering vast public lands which can be changed by pollution, for carrying out large enterprises which can produce pollutants, for preserving and improving the nation's natural resources, all make it mandatory that the Federal Government assume leadership and exert its influence in pollution abatement on a national scale.

We attempt here to describe the problem, to distinguish between what is known and what is not, and to recommend steps necessary to assure the lessening of pollution already about us and to prevent unacceptable environmental deterioration in the future.

U  
di  
ef  
in  
ta  
  
fr  
ep  
ua  
de  
ce  
fr  
co  
at  
oc  
ca  
  
th  
  
fe  
po  
to  
thi  
th  
po  
de  
be  
tol  
ma  
Th  
cit  
con  
spe  
kn



an adequate number to start with. They should be selected by use of modern probability methods.

The waters of a single drainage area may vary from small trickles to large lakes. In sampling these waters, however, we can take advantage of the way in which the waters flow from smaller streams into larger ones, and from larger ones into rivers and lakes.

The lands of a drainage area may vary even more widely: highly cultivated farm lands may grade through rangelands to rocky mountains and deserts. All are part of the general environment; the pollution of all must be considered in the overall result. We can take advantage of what we know about the likelihood of pollution of different kinds of land in planning the details of the sampling, but we must give all lands their appropriate chance to contribute to the final result.

## APPENDIX Y4

## Atmospheric Carbon Dioxide

ROGER REVELLE, *Chairman*WALLACE BROECKER  
HARMON CRAIGC. D. KEELING  
J. SMAGORINSKY

## Contents

	<i>Page</i>
Section I. Carbon Dioxide From Fossil Fuels—The Invisible Pollutant . . . . .	112
Introduction . . . . .	112
The Recent Increase in Atmospheric Carbon Dioxide . . . . .	114
Partition of Carbon Dioxide Among the Atmosphere, the Ocean, and the Biosphere . . . . .	117
Probable Future Content of Carbon Dioxide in the Atmosphere . . . . .	119
Possible Effects of Increased Atmospheric Carbon Dioxide on Climate . . . . .	121
Other Possible Effects of an Increase in Atmospheric Carbon Dioxide . . . . .	123
Melting of the Antarctic Ice Cap . . . . .	123
Rise of Sea Level . . . . .	123
Warming of Sea Water . . . . .	123
Increased Acidity of Fresh Waters . . . . .	124
Increase in Photosynthesis . . . . .	124
Other Possible Sources of Carbon Dioxide . . . . .	124
Oceanic Warming . . . . .	124
Burning of Limestone . . . . .	125
Decrease in the Carbon Content of Soils . . . . .	125
Change in the Amount of Organic Matter in the Ocean . . . . .	125
Changes in the Carbon Dioxide Content of Deep Ocean Water . . . . .	125
Changes in the Volume of Sea water . . . . .	125
Carbon Dioxide From Volcanoes . . . . .	126
Changes Due to Solution and Precipitation of Carbonates . . . . .	126
Conclusions and Findings . . . . .	126
Section II. Detailed Computations . . . . .	128
References . . . . .	131

## Section I. CARBON DIOXIDE FROM FOSSIL FUELS—THE INVISIBLE POLLUTANT

### INTRODUCTION

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. Marine plants obtain carbon from the dissolved carbon dioxide in sea water, which depends for its concentration on an equilibrium with the carbon dioxide of the atmosphere. Marine and terrestrial animals, including man, procure, either directly or indirectly, the substance of their bodies and the energy for living from the carbon compounds made by plants.

All fuels used by man consist of carbon compounds produced by ancient or modern plants. The energy they contain was originally solar energy, transmuted through the biochemical process called photosynthesis. 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.

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 became 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 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 world-wide industrial civilization of our time.

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 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 the fossil fuels that were

locked in the sedimentary rocks over five hundred million years, and this combustion is measurably increasing the atmospheric carbon dioxide.

In the geologic past, the quantity of carbon dioxide in the atmosphere was determined by the equilibrium between rates of weathering and photosynthesis, and the rate of injection of volcanic carbon dioxide. On an earthwide average, both weathering and photosynthesis must speed up when the carbon dioxide content of the air is increased, and slow down when it is diminished; consequently, over geologic time the carbon dioxide in the air must have risen when volcanic activity was high, and must have gone down when volcanoes were quiescent. On a human scale, the times involved are very long. The known amounts of limestone and organic carbon in the sediments indicate that the atmospheric carbon dioxide has been changed forty thousand times during the past four billion years, consequently the residence time of carbon in the atmosphere, relative to sedimentary rocks, must be of the order of a hundred thousand years.

The present rate of production of carbon dioxide from fossil fuel combustion is about a hundred times the average rate of release of calcium and magnesium from the weathering of silicate rocks. As long as this ratio holds, precipitation of metallic carbonates will be unable to maintain an unchanging content of carbon dioxide in the atmosphere. 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. [Water vapor also absorbs infrared radiation, both in the range of the CO<sub>2</sub> band centered at 15 microns, and at wave lengths near 6.3 microns. With the average concentration of water vapor in the lower air at mid latitudes, the effect of carbon dioxide absorption is reduced to about half that which would exist in an absolutely dry atmosphere. (Möller, 1963.) Ozone, which is an important constituent of the upper air, also absorbs some infrared at wave lengths around 9.6 microns, but its principal effect on air temperature is due to its absorption of ultraviolet and visible sunlight.]

The possibility of climatic change resulting from changes in the quantity of atmospheric carbon dioxide was proposed independently by the

American geologist, T. C. Chamberlain (1899) and the Swedish chemist, S. Arrhenius (1903), at the beginning of this century. Since their time, many scientists have dealt with one or another aspect of this question, but until very recently there was little quantitative information about what has actually happened. Even today, we cannot make a useful prediction concerning the magnitude or nature of the possible climatic effects. But we are able to say a good deal more than formerly about the change in the quantity of atmospheric carbon dioxide, and about the partition of carbon dioxide from fossil fuel combustion among the atmosphere, the ocean, and the biosphere.

### THE RECENT INCREASE IN ATMOSPHERIC CARBON DIOXIDE

During the five years from 1958 through 1962,  $5.3 \times 10^{16}$  grams of carbon dioxide were produced by the combustion of coal, lignite, petroleum and other liquid hydrocarbons, and natural gas (see Tables 1 and 2).

TABLE 1.—Carbon Dioxide Produced by Fossil Fuel Combustion, 1950–62  
[ $10^{16}$  grams]

Year	Coal <sup>1</sup>	Lignite <sup>2</sup>	Liquid Hydrocarbons <sup>3</sup>	Natural Gas <sup>4</sup>	Total	As % of Atmospheric CO <sub>2</sub> in 1950
1950.....	0.37	0.09	0.17	0.04	0.67	0.29
1951.....	.38	.09	.20	.05	.72	.31
1952.....	.38	.09	.21	.05	.73	.31
1953.....	.38	.09	.22	.05	.74	.32
1954.....	.38	.09	.23	.06	.76	.32
1955.....	.41	.10	.25	.06	.82	.35
1956.....	.44	.11	.27	.07	.89	.38
1957.....	.45	.13	.29	.07	.94	.40
1958.....	.46	.14	.29	.08	.97	.41
1959.....	.48	.14	.32	.09	1.03	.44
1960.....	.50	.14	.34	.10	1.08	.46
1961.....	.48	.15	.36	.10	1.09	.46
1962.....	.50	.15	.39	.11	1.15	.49
Total.....	5.61	1.51	3.54	.93	11.59	4.93

<sup>1</sup> Assumed carbon content, coal=75 percent.

<sup>2</sup> Assumed carbon content, lignite=45 percent.

<sup>3</sup> Assumed carbon content, liquid hydrocarbons=86 percent.

<sup>4</sup> Assumed carbon content, natural gas=70 percent. (Corresponding to a mixture by volume of 80 percent CH<sub>4</sub>, 15 percent C<sub>2</sub>H<sub>6</sub> and 5 percent N<sub>2</sub>.)

Source: Computed from Table 2.

TABLE 2.—World Production of Fossil Fuels—1950–62

[Millions of Metric Tons]

Year	Coal	Lignite	Liquid Hydrocarbons <sup>1</sup>	Natural Gas <sup>2</sup>	Total
1950.....	1,340	530	540	155	2,565
1951.....	1,375	550	620	180	2,725
1952.....	1,375	550	655	200	2,780
1953.....	1,380	555	690	210	2,835
1954.....	1,375	550	725	220	2,870
1955.....	1,500	630	790	240	3,160
1956.....	1,595	665	860	260	3,380
1957.....	1,625	765	905	285	3,580
1958.....	1,665	825	930	305	3,725
1959.....	1,730	845	995	345	3,915
1960.....	1,810	875	1,075	375	4,135
1961.....	1,760	900	1,140	405	4,205
1962.....	1,805	905	1,235	440	4,385
Total.....	20,335	9,145	11,160	3,620	44,260

<sup>1</sup> Includes Petroleum and Natural Gasoline.

<sup>2</sup> Assumed density of  $8 \times 10^{-4}$  gm cm<sup>-3</sup> (1000m<sup>3</sup>=0.8 ton).

Source: World Energy Supplies. Statistical Papers, Series J, United Nations, New York.

This is 2.25 percent of the  $2.35 \times 10^{18}$  grams of carbon dioxide present in the atmosphere in 1950 (assuming an atmospheric carbon dioxide concentration of 300 ppm by volume—445 ppm by weight—and a mass of  $5.2 \times 10^{21}$  grams for the entire atmosphere.) On the average during 1958–1962, the CO<sub>2</sub> produced each year by fossil fuel combustion was 0.45 percent of the quantity in the atmosphere.

Beginning in 1958 and extending through 1963, two nearly continuous series of measurements of atmospheric CO<sub>2</sub> content were made. One of these series was taken at the U.S. Weather Bureau station near the top of Mauna Loa Mountain in Hawaii (Pales and Keeling, 1965), the other at the United States scientific station at the South Pole (Brown and Keeling, 1965). The measurements were carried out on an infrared gas spectrometer, with a relative accuracy for a single measurement of about  $\pm 0.1$  ppm. The observing stations are located near the centers of vast atmospheric mixing areas, far from uncontrollable sources of contaminants. Because of these nearly ideal locations, together with the high precision of the instruments, and the extreme care with which the samples were taken, these measurements make it possible to estimate the secular trend of atmospheric CO<sub>2</sub> with an accuracy greater by two

orders of magnitude than ever before. Some fifteen thousand measurements were carried out during the five-year period.

The data show, clearly and conclusively, that from 1958 through 1963 the carbon dioxide content of the atmosphere increased by 1.36 percent. The increase from year to year was quite regular, close to the average annual value of 0.23 percent. By comparing the measured increase with the known quantity of carbon dioxide produced by fossil fuel combustion, given in Table 4, we see that almost exactly half of the fossil fuel CO<sub>2</sub> apparently remained in the atmosphere.

Tables 3 and 4 show that between 1860 and 1940 the amount of CO<sub>2</sub> produced by fossil combustion, chiefly coal, was 7.9 percent, and by 1950, 10.3 percent, of the estimated atmospheric CO<sub>2</sub> content in 1950. By 1959, the total CO<sub>2</sub> production was equal to 13.8 percent of the atmospheric CO<sub>2</sub>. Unfortunately, the accuracy of measurements of atmospheric CO<sub>2</sub> before 1958 is too low to allow estimates of the secular variation, and it is therefore impossible to compute directly whether the fraction of fossil-fuel CO<sub>2</sub> remaining in the atmosphere throughout the past hundred years has been constant, or slowly or rapidly changing.

TABLE 3.—Carbon Dioxide Produced by Fossil Fuel Combustion, 1860–1959

[10<sup>16</sup> grams]

Decade	Coal <sup>1</sup>	Lignite <sup>2</sup>	Liquid Hydrocarbons <sup>3</sup>	Natural Gas <sup>4</sup>	Total	As % of Atmospheric CO <sub>2</sub> in 1950
1860–69.....	0.46	0.01	.....	.....	0.47	0.20
1870–79.....	0.70	.03	.....	.....	.73	.31
1880–89.....	1.06	.05	0.02	.....	1.13	.48
1890–99.....	1.49	.08	.04	0.01	1.62	.69
1900–09.....	2.33	.15	.10	.02	2.60	1.11
1910–19.....	3.10	.21	.19	.04	3.54	1.53
1920–29.....	3.26	.31	.48	.07	4.12	1.75
1930–39.....	3.16	.35	.74	.12	4.37	1.86
1940–49.....	3.74	.49	1.14	.25	5.62	2.39
1950–59.....	4.11	1.07	2.44	.62	8.24	3.49
Total.....	23.41	2.75	5.15	1.13	32.44	13.81

<sup>1</sup> Assumed carbon content, coal=75 percent.

<sup>2</sup> Assumed carbon content, lignite=45 percent.

<sup>3</sup> Assumed carbon content, liquid hydrocarbons=86 percent.

<sup>4</sup> Assumed carbon content, natural gas=70 percent. (Corresponding to a mixture by volume of 80 percent CH<sub>4</sub>, 15 percent C<sub>2</sub>H<sub>6</sub> and 5 percent N<sub>2</sub>).

Source: Computed from Table 4.

TABLE 4.—World Production of Fossil Fuels, 1860–1959

[Millions of Metric Tons]

Decade	Coal	Lignite	Liquid Hydrocarbons <sup>1</sup>	Natural Gas <sup>2</sup>	Total
1860–69.....	1,660	85	5	.....	1,750
1870–79.....	2,560	180	15	.....	2,755
1880–89.....	3,850	285	55	10	4,200
1890–99.....	5,405	495	140	40	6,080
1900–09.....	8,455	880	310	80	9,725
1910–19.....	11,240	1,270	590	155	13,255
1920–29.....	11,850	1,875	1,510	285	15,520
1930–39.....	11,500	2,135	2,335	485	16,455
1940–49.....	13,570	2,995	3,605	970	21,140
1950–59.....	14,960	6,465	7,710	2,400	31,535
Total.....	85,050	16,665	16,275	4,425	122,415

<sup>1</sup> Includes petroleum and natural gasoline.

<sup>2</sup> Assumed density of  $8 \times 10^{-4}$  gm cm<sup>-3</sup> (1000m<sup>3</sup>=0.8 ton).

Sources: From 1860 to 1949, United Nations, Department of Economic and Social Affairs: "World Energy Requirements". Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Vol. 1, pp. 3–33, 1956. For 1950–59, United Nations, World Energy Supplies. Statistical papers, Series J, United Nations, New York.

There are measurements of a somewhat different kind, which can give us useful information however. These are determinations of the so-called "Suess Effect."

#### PARTITION OF CARBON DIOXIDE AMONG THE ATMOSPHERE, THE OCEAN, AND THE BIOSPHERE

Because the fossil fuels have been buried for millions of years, they contain no Carbon 14. (This radioactive isotope is produced in the atmosphere by cosmic ray bombardment of nitrogen, and it has a half-life of only about six thousand years.) Consequently, the addition to the atmosphere of CO<sub>2</sub> from fossil fuel combustion, and its subsequent partition among the atmosphere, the ocean, and the biosphere will cause the ratio between radioactive and nonradioactive carbon to decrease. This manifests itself as a measurable reduction in the amount of radioactive carbon, for example, in tree rings grown in recent years compared with rings that grew during the 19th Century. This reduction, due to fossil fuel combustion, is called the "Suess Effect," after Professor Hans Suess, who first observed it (see Revelle and Suess, 1956).

The measurement of the "Suess Effect" is beset with many difficulties, the chief among them being that the Carbon 14 content of the atmosphere—more precisely the ratio of  $C^{14}$  to  $C^{12} + C^{13}$ —varies by 1 or 2 percent from century to century apparently depending on the long-term variations in sunspot intensity. Tree ring measurements show that this ratio went up during the 15th and 17th Centuries, and down during the 16th and 18th, in each case by about 2 percent (Suess, 1956). Prior to the atomic weapons tests of the mid-Fifties, the ratio was lower by between 1 and 2 percent than in the middle of the 19th Century. This change during the past hundred years was apparently largely due to the "Suess Effect."

Taking the "Suess Effect" as between 1 and 2 percent over the period from 1860 to 1950, during which time the total carbon dioxide produced from fossil fuels was 10% of the atmospheric  $CO_2$ , and assuming that presently occurring changes in the magnitude of the "Suess Effect" are in the same proportion to  $CO_2$  from fossil fuel combustion as in the past, we can compute both the relative sizes of the oceanic and biosphere reservoirs that are taking up part of the added  $CO_2$ , and the partition of  $CO_2$  between these reservoirs. The amount taken up in the biosphere will be different if there are two or more sources of additional carbon dioxide, than if fossil fuels are the only source, but the amount absorbed by the ocean will not vary. Implied in the calculation is the further assumption that any  $CO_2$  from other sources will have about the same ratio of  $C^{14}$  to total carbon as the atmosphere. Details are given in Section II.

The calculation shows that if the oceanic layer mixing with the atmosphere is several hundred meters thick, the amount of exchangeable carbon in the biosphere is less than or about equal to that in the atmosphere. These are both "reasonable" values. On the other hand, if another significant source of  $CO_2$  is assumed for the last few decades, the amount of  $CO_2$  added to the biosphere becomes so large that it should have been observed. In fact, no increase in the biosphere has been noted. Perhaps the most striking result is that the ocean takes up a relatively small fraction of the total added  $CO_2$ , probably about 15%. In the past, the usual scientific belief has been that by far the larger part of any added  $CO_2$  would be absorbed in the ocean. This is undoubtedly true if we consider a sufficiently long time period, of the order of thousands or even, perhaps, hundreds of years, because the ocean as a whole contains nearly sixty times as much carbon dioxide as the atmosphere. But over shorter times, only the uppermost layers of the ocean take part in exchanges with the air. Moreover, most of the oceanic carbon dioxide is present as carbonate and bicarbonate, balanced against metallic cations,

and a marked increase in oceanic  $CO_2$  therefore requires an increase in cation concentration, which can be brought about only by rock weathering or solution of calcium-rich sediments. These are slow processes.

### PROBABLE FUTURE CONTENT OF CARBON DIOXIDE IN THE ATMOSPHERE

We can conclude with fair assurance that at the present time, fossil fuels are the only source of  $CO_2$  being added to the ocean-atmosphere-biosphere system. If this held true throughout the last hundred years, the quantity of  $CO_2$  in the air at the beginning of the present decade was about 7% higher than in the middle of the last century (see Table 3).

Throughout these hundred years, the rate of fossil fuel combustion, and thus of  $CO_2$  production, continually increased, on the average about 3.2 percent per year. The amount produced in 1962 was almost 25 times the annual production in the mid-1860's. The rate of increase may be accelerating. During the eight years from 1954 to 1962, the average rate of increase was 5%.

We can ask several questions about the future  $CO_2$  content of the atmosphere. Two of these questions are:

- (1) What will the total quantity of  $CO_2$  injected into the atmosphere (but only partly retained there) be at different future times?
- (2) What would be the total amount of  $CO_2$  injected into the air if all recoverable reserves of fossil fuels were consumed? At present rates of expansion in fossil fuel consumption this condition could be approached within the next 150 years.

The second question is relatively easy to answer, provided we consider only the estimated recoverable reserves of fossil fuels. The data are shown in Table 5. We may conclude that the total  $CO_2$  addition from fossil fuel combustion will be a little over 3 times the atmospheric content, and that, if present partitions between reservoirs are maintained, the  $CO_2$  in the atmosphere could increase by nearly 170 percent.

The answer to the first question depends upon the rate of increase of fossil fuel combustion. Table 6 shows that if this combustion remains constant at the 1959 level, the total  $CO_2$  injected into the atmosphere by the year 2000 will be about 28 percent of the atmospheric content in 1950. If the average rate of increase of combustion continues at 3.2 percent per year, the quantity injected into the atmosphere by the year 2000 will be about 42 percent; if the 5% rate of increase during the last 8 years persists, the quantity injected will be close to 60 percent. Assuming further that the proportion remaining in the atmosphere continues to be half the total quantity injected, the increase in atmospheric  $CO_2$  in the year 2000 could be somewhere between 14 percent and 30 percent.

Based on projected world energy requirements, the United Nations Department of Economic and Social Affairs (1956) has estimated an amount of fossil fuel combustion by the year 2000 that with our assumed partitions would give about a 25 percent increase in atmospheric CO<sub>2</sub>, compared to the amount present during the 19th Century. For convenience, we shall adopt this figure in the following estimate of the effects on atmospheric radiation and temperature.

TABLE 5.—*Estimated Remaining Recoverable Reserves of Fossil Fuels*

	10 <sup>9</sup> Metric Tons	Carbon Dioxide Equivalent, 10 <sup>18</sup> gms	As % of Atmospheric CO <sub>2</sub> in 1950
Coal and Lignite <sup>1</sup> .....	2,320	5.88	252
Petroleum and Natural Gas Liquids <sup>2</sup> .....	212	.67	29
Natural Gas <sup>3</sup> .....	166	.43	18
Tar Sands <sup>2</sup> .....	75	.24	10
Oil Shales <sup>2</sup> .....	198	.63	27
Total.....	2,971	7.85	336

<sup>1</sup> Assumed to be 20 percent lignite containing 45 percent carbon, and 80 percent bituminous coal containing 75 percent carbon.

<sup>2</sup> Assumed carbon content of petroleum, natural gas liquids, and hydrocarbons recoverable from tar sands and oil shales=86 percent.

<sup>3</sup> Assumed composition of natural gas by volume: CH<sub>4</sub>=80 percent, C<sub>2</sub>H<sub>6</sub>=15 percent, N<sub>2</sub>=5 percent.

Source: Computed from data given by M. King Hubbert, "Energy Resources, A Report to the Committee on Natural Resources of the National Academy of Sciences—National Research Council," NAS Publication 1000-D, 1962, pp. 1-141.

TABLE 6.—*Estimates of Carbon Dioxide From Fossil Fuel Combustion in Future Decades, Assuming Different Rates of Increase of Fuel Use*

Year	As percent of Atmospheric CO <sub>2</sub> in 1950		
	0	3.2	5.0
1959.....	13.80	13.80	13.80
1969.....	17.30	18.00	18.47
1979.....	20.79	23.79	26.15
1989.....	24.28	31.94	37.90
1999.....	27.77	41.96	58.75
2009.....	31.26	57.04	93.14

## POSSIBLE EFFECTS OF INCREASED ATMOSPHERIC CARBON DIOXIDE ON CLIMATE

One of the most recent discussions of these effects is given by Möller (1963). He considers the radiation balance at the earth's surface with an average initial temperature of 15°C (59°F), a relative humidity of 75 percent, and 50% cloudiness. We may compute from his data that with a 25 percent increase in atmospheric CO<sub>2</sub>, the average temperature near the earth's surface could increase between 0.6°C and 4°C (1.1°F to 7°F), depending on the behavior of the atmospheric water vapor content. The small increase would correspond to a constant absolute humidity, that is, a constant weight of water in the atmosphere. The larger increase would correspond to a constant relative humidity, that is, as the temperature rose, the water vapor content would also rise to maintain a constant percentage of the saturation value. A doubling of CO<sub>2</sub> in the air, which would happen if a little more than half the reserves of fossil fuels were consumed, would have about three times the effect of a twenty-five percent increase.

As Möller himself emphasized, he was unable to take into account the vertical transfer of latent heat by evaporation at the surface and condensation aloft, or of sensible heat by convection and advection. For this reason he was unable to consider the interactions between different atmospheric layers in a vertical column. In consequence, Möller's computations probably over-estimate the effects on atmospheric temperature of a CO<sub>2</sub> increase. A more comprehensive model is being developed by the U.S. Weather Bureau. This includes processes of convection and of latent heat transfer through the evaporation and condensation of water vapor. Meaningful computations should be possible with this model in the very near future. But climatic changes depend on changes in the general circulation in the atmosphere, and these will be related to the spatial distribution and time variation of carbon dioxide and water vapor. The ratio of CO<sub>2</sub> 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 CO<sub>2</sub> content. Without a comprehensive model incorporating both the fluid dynamics and the radiation transfer processes of the atmosphere it is not possible to predict how these effects will perturb the general circulation. Such a model may be available within the next two years.

Models of atmospheric thermal equilibrium in which vertical convection is allowed to maintain the observed vertical temperature gradient have recently been constructed by S. Manabe of the U.S. Weather Bureau (Manabe and Strickler, 1964; Manabe, 1965). These show that the effect of infra red absorption from the present atmospheric carbon dioxide at mid latitudes is to maintain a ground temperature about 10°C (18°F) higher than would prevail if no CO<sub>2</sub> were present. An increase in the CO<sub>2</sub> content without a change in absolute humidity would, according to these models, produce a somewhat smaller surface temperature rise than that estimated by Möller. But a considerable change would occur in the stratosphere, where the CO<sub>2</sub> concentration by volume is perhaps 50 times that of water vapor. A 25% rise in carbon dioxide would cause stratospheric temperatures to fall by perhaps 2°C (3.6°F) at an altitude of 30 kilometers (about 100,000 feet) and by 4°C (7°F) at 40 kilometers (about 130,000 feet).

One might suppose that the increase in atmospheric CO<sub>2</sub> over the past 100 years should have already brought about significant climatic changes, and indeed some scientists have suggested this is so. The English meteorologist, G. S. Callendar (1938, 1940, 1949), writing in the late 1930's and the 1940's on the basis of the crude data then available, believed that the increase in atmospheric CO<sub>2</sub> from 1850 to 1940 was at least 10%. He thought this increase could account quantitatively for the observed warming of northern Europe and northern North America that began in the 1880's. From Table 2 and our estimate of the CO<sub>2</sub> partition between the atmospheric, the ocean, and the biosphere, we see that the actual CO<sub>2</sub> increase in the atmosphere prior to 1940 was only 4%, at least from fossil fuel combustion. This was probably insufficient to produce the observed temperature changes. [But it should be noted that up to 2.5% of the atmospheric carbon dioxide (after partition with the ocean and the biosphere) could also have been added by the oxidation of soil humus in newly cultivated lands.]

As Mitchell (1961, 1963) has shown, atmospheric warming between 1885 and 1940 was a world-wide phenomenon. Area-weighted averages for surface temperature over the entire earth show a rise in mean annual air temperature of about 0.5°C (0.9°F). World mean winter temperatures rose by 0.9°C (1.6°F). Warming occurred in both hemispheres and at all latitudes, but the largest annual rise (0.9°C or 1.6°F) was observed between 40° and 70° N latitudes. In these latitudes, the average winter temperatures rose by 1.6°C (2.8°F).

The pronounced 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 0.1°C (0.2°F) in mean annual air temperature (Mitchell, 1963). Yet dur-

ing this period more than 40% of the total CO<sub>2</sub> increase from fossil fuel combustion occurred. We must conclude that climatic "noise" from other processes has at least partially masked any effects on climate due to past increases in atmospheric CO<sub>2</sub> content.

#### OTHER POSSIBLE EFFECTS OF AN INCREASE IN ATMOSPHERIC CARBON DIOXIDE

*Melting of the Antarctic ice cap.*—It has sometimes been suggested that atmospheric warming due to an increase in the CO<sub>2</sub> content of the atmosphere may result in a catastrophically rapid melting of the Antarctic ice cap, with an accompanying rise in sea level. From our knowledge of events at the end of the Wisconsin period, 10 to 11 thousand years ago, we know that melting of continental ice caps can occur very rapidly on a geologic time scale. But such melting must occur relatively slowly on a human scale.

The Antarctic ice cap covers 14 million square kilometers and is about 3 kilometers thick. It contains roughly  $4 \times 10^{16}$  tons of ice, hence  $4 \times 10^{24}$  gram calories of heat energy would be required to melt it. At the present time, the poleward heat flow across 70° latitude is  $10^{22}$  gram calories per year, and this heat is being radiated to space over Antarctica without much measurable effect on the ice cap. Suppose that the poleward heat flux were increased by 10% through an intensification of the meridional atmospheric circulation, and that all of this increase in the flow of energy were utilized to melt the ice. Some 4,000 years would be required.

We can arrive at a smaller melting time by supposing a change in the earth-wide radiation balance, part of which would be used to melt the ice. A 2% change could occur by the year 2000, when the atmospheric CO<sub>2</sub> content will have increased perhaps by 25%. Since the average radiation at the earth's surface is about  $2 \times 10^5$  gram calories per square centimeter per year, a 2% change would amount to  $2 \times 10^{22}$  calories per year. If half this energy were concentrated in Antarctica and used to melt the ice, the process would take 400 years.

*Rise of sea level.*—The melting of the Antarctic ice cap would raise sea level by 400 feet. If 1,000 years were required to melt the ice cap, the sea level would rise about 4 feet every 10 years, 40 feet per century. This is a hundred times greater than present worldwide rates of sea level change.

*Warming of sea water.*—If the average air temperature rises, the temperature of the surface ocean waters in temperate and tropical regions could be expected to rise by an equal amount. (Water temperatures in the polar regions are roughly stabilized by the melting and freezing of ice.) An oceanic warming of 1° to 2°C (about 2°F) oc-

curred in the North Atlantic from 1880 to 1940. It had a pronounced effect on the distribution of some fisheries, notably the cod fishery, which has greatly increased around Greenland and other far northern waters during the last few decades. The amelioration of oceanic climate also resulted in a marked retreat of sea ice around the edges of the Arctic Ocean.

**Increased acidity of fresh waters.**—Over the range of concentrations found in most soil and ground waters, and in lakes and rivers, the hydrogen ion concentration varies nearly linearly with the concentration of free  $\text{CO}_2$ . Thus the expected 25% increase in atmospheric  $\text{CO}_2$  concentration by the end of this century should result in a 25% increase in the hydrogen ion concentration of natural waters or about a 0.1 drop in pH. This will have no significant effect on most plants.

**Increase in photosynthesis.**—In areas where water and plant nutrients are abundant, and where there is sufficient sunlight, carbon dioxide may be the limiting factor in plant growth. The expected 25% increase by the year 2000 should significantly raise the level of photosynthesis in such areas. Although very few data are available, it is commonly believed that in regions of high plant productivity on land, such as the tropical rain forests, phosphates, nitrates and other plant nutrients limit production rather than atmospheric  $\text{CO}_2$ . This is probably also true of the oceans.

Biological processes are speeded up by a rise in temperature, and in regions where other conditions are favorable higher temperatures due to increased  $\text{CO}_2$  might result in higher plant production.

#### OTHER POSSIBLE SOURCES OF CARBON DIOXIDE

We are fairly certain that fossil fuel combustion has been the only source of  $\text{CO}_2$  coming into the atmosphere during the last few years, when accurate measurements of atmospheric carbon dioxide content have been available. Carbon dioxide may have been produced by other sources during earlier times but it is not now possible to make a quantitative estimate. However we can examine the order of magnitude of some of the possible inputs from other sources, on the basis of our knowledge of the processes that might be involved.

**Oceanic warming.**—The average temperature of the ocean cannot have increased by more than  $0.15^\circ\text{C}$  during the past century, since any greater warming would have caused a larger rise in sea level than the observed value of about 10 centimeters. A more probable upper limit is  $.05^\circ\text{C}$ , because most of the sea level rise can be accounted for by glacial melting. An average  $.05^\circ\text{C}$  rise would correspond to  $0.5^\circ$  in the top 400 meters. This would cause a nearly 3% rise in the  $\text{CO}_2$  partial pressure.

After equilibration with the atmosphere, the partial pressure in both the air and the uppermost ocean layer would be higher by about 2.5%.

**Burning of limestone.**—Annual world production of carbon dioxide from the use of limestone for cement, fluxing stone, and in other ways, is about 1% of the total from fossil fuel combustion, or  $4 \times 10^{-5}$  of the atmospheric  $\text{CO}_2$  content per year.

**Decrease in the carbon content of soils.**—Since the middle of the Nineteenth Century, the world's cultivated farmland has been enlarged by about 50%. This is an increase of close to a billion acres or 1.6 million square miles, corresponding to 2.7% of the land area of the earth, and perhaps to 5% of forests and grass lands. Most soil humus is believed to be concentrated in forests and grassy areas. Assume that the total humus is equal to twice the amount of carbon in the atmosphere and that half the carbon in the humus of the newly cultivated lands has been oxidized to carbon dioxide. The total injected into the atmosphere from this source becomes less than 5% of the atmospheric  $\text{CO}_2$ .

**Change in the amount of organic matter in the ocean.**—About 7% of the marine carbon reservoir consists of organic material. Since a 1% change in the carbon dioxide content of the ocean changes the  $\text{CO}_2$  pressure by 12.5%, a decrease by 1% in the marine organic carbon (which would increase the total oceanic carbon dioxide by .07%) would raise the carbon dioxide pressure of the ocean and the atmosphere by about 1%. An increase in the temperature of water near the surface, during the past one hundred years, could have speeded up the rate of oxidation of organic matter relative to its rate of production by photosynthesis. Measurements of the content of organic matter in the ocean are neither accurate enough nor sufficiently extended over time to allow a direct estimate of this possibility. A change of several percent could have occurred without detection.

**Changes in the carbon dioxide content of deep ocean water.**—The deep ocean waters contain about 10% more carbon dioxide than they would if they were at equilibrium with the present atmospheric content. This is a result of the sinking of dead organic remains from the surface waters and their subsequent oxidation in the depths. The combination of biological and gravitational processes can be thought of as a pump that maintains a relatively low carbon dioxide content in the surface waters and in the atmosphere. If the pump ceased to act, the atmospheric carbon dioxide would eventually be increased five fold. Variations in the effectiveness of the pump could have occurred without detection during the past 100 years, and could have caused notable changes in the atmospheric carbon dioxide content.

**Changes in the volume of sea water.**—During the Ice Age the volume of sea water varied by about 5%. Changes of this magnitude would change the carbon dioxide content of the atmosphere by 10 to 15%.



But during the last several thousand years, variations in oceanic volume have been small. During the past hundred years, world average sea level has varied by less than 10 centimeters. This very small volume change would have no appreciable effect on the atmospheric carbon dioxide.

*Carbon dioxide from volcanoes.*—Over geologic time, volcanic gases have been the principal sources of new carbon dioxide injected into the atmosphere. On the average the influx of volcanic CO<sub>2</sub> must have balanced the extraction from the atmosphere by rock weathering. The present rate of influx of volcanic CO<sub>2</sub> is close to a hundred fold less than that from fossil fuel combustion. No data exist on the worldwide level of volcanic activity over geologic time. It is conceivable that the level has fluctuated by two orders of magnitude, and that the fluctuations persisted for millenia, or even for millions of years.

*Changes due to solution and precipitation of carbonates.*—Calcium and magnesium carbonate precipitation on the sea floor lower the total CO<sub>2</sub> content of ocean water, but increase the carbon dioxide pressure and the free CO<sub>2</sub> content. Conversely, chemical weathering of limestone and dolomite on land lower the atmospheric CO<sub>2</sub> and the free CO<sub>2</sub> content of the sea, but increase the total oceanic CO<sub>2</sub>. The rates of these processes are about one order of magnitude lower than the present rate of production of carbon dioxide by fossil fuel combustion.

We conclude that the only sources of carbon dioxide comparable in magnitude to fossil fuel combustion during the last 100 years could have been a decrease in soil humus due to the increase in the area of cultivated lands, a decrease in the content of "dissolved" organic matter in the ocean, or a lowering of the carbon dioxide content of deep ocean waters. Marked changes in the oceanic regime would have been necessary for the latter two processes to have significant effects. As we have shown, none of the three processes are likely to be significant at the present time. Nor are any oceanographic data available which suggest that the required changes in the ocean occurred during the last hundred years.

## CONCLUSIONS AND FINDINGS

Through his worldwide industrial civilization, Man is unwittingly conducting a vast geophysical experiment. Within a few generations he is burning the fossil fuels that slowly accumulated in the earth over the past 500 million years. The CO<sub>2</sub> produced by this combustion is being injected into the atmosphere; about half of it remains there. The estimated recoverable reserves of fossil fuels are sufficient to produce nearly a 200% increase in the carbon dioxide content of the atmosphere.

By the year 2000 the increase in atmospheric CO<sub>2</sub> will be close to 25%. This may be sufficient to produce measurable and perhaps marked

changes in climate, and will almost certainly cause significant changes in the temperature and other properties of the stratosphere. At present it is impossible to predict these effects quantitatively, but recent advances in mathematical modelling of the atmosphere, using large computers, may allow useful predictions within the next 2 or 3 years.

Such predictions will need to be checked by careful measurements: a series of precise measurements of the CO<sub>2</sub> content in the atmosphere should continue to be made by the U.S. Weather Bureau and its collaborators, at least for the next several decades; studies of the oceanic and biological processes by which CO<sub>2</sub> is removed from and added to the atmosphere should be broadened and intensified; temperatures at different heights in the stratosphere should be monitored on a worldwide basis.

The climatic changes that may be produced by the increased CO<sub>2</sub> content could be deleterious from the point of view of human beings. The possibilities of deliberately bringing about countervailing climatic changes therefore need to be thoroughly explored. A change in the radiation balance in the opposite direction to that which might result from the increase of atmospheric CO<sub>2</sub> could be produced by raising the albedo, or reflectivity, of the earth. Such a change in albedo could be brought about, for example 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 a 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. Rough estimates indicate that enough particles partially to cover a square mile could be produced for perhaps one hundred dollars. Thus a 1% change in reflectivity might be brought about for about 500 million dollars 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 have other uses, for example in inhibiting the formation of hurricanes in tropical oceanic areas.

According to Manabe and Strickler (1964) the absorption and re-radiation of infrared by high cirrus clouds (above five miles) tends to heat the atmosphere near the earth's surface. Under some circumstances, injection of condensation or freezing nuclei will cause cirrus clouds to form at high altitudes. This potential method of bringing about climatic changes needs to be investigated as a possible tool for modifying atmospheric circulation in ways which might counteract the effects of increasing atmospheric carbon dioxide.

## Section II. DETAILED COMPUTATIONS

*Calculation of the Relative Sizes of the Ocean and Biosphere Reservoirs and the Probability of Other Sources of Carbon Dioxide at the Present Time*

A portion of the carbon dioxide coming into the atmosphere will be transferred to the ocean, and another part will enter the biosphere. We can test the possibility of carbon dioxide sources other than fossil fuel combustion by examining the relative sizes of the required ocean and biosphere reservoirs.

Let

$A = \text{CO}_2$  in atmosphere.

$B =$  equivalent  $\text{CO}_2$  in the part of the biosphere that exchanges with the atmosphere.

$M = \text{CO}_2$  in the oceanic reservoir that exchanges with the atmosphere.

$\Delta A, \Delta B, \Delta M =$  changes in  $\text{CO}_2$  content of these reservoirs.

$s = \frac{-\Delta C^{14}\text{O}_2}{C^{14}\text{O}_2}$  in the reservoir system,  $A + B + M$ .

$a = \frac{\Delta A}{A} =$  fractional change of atmospheric  $\text{CO}_2$  content.

$fA = \text{CO}_2$  produced by fossil fuel combustion.

$bA = \text{CO}_2$  produced by other processes.

Then, at equilibrium,

$$\Delta A + \Delta B + \Delta M = (f + b)A$$

$$\Delta A = aA$$

$\Delta M = oM$ , where  $o = \frac{a}{12.5}$ , owing to the buffer mechanism of sea water (Bolin and Eriksson, 1958).

And assuming that  $\text{CO}_2$  produced by other processes has approximately the same  $C^{14}$  content as the atmospheric  $\text{CO}_2$ , and knowing that fossil fuel  $\text{CO}_2$  contains no  $C^{14}$ .

$$A + B + M = \frac{f}{s}A$$

Solving for  $\Delta B$ ,  $M$ , and  $\Delta M$ , we find

$$\Delta B = A \left( o + f + b + os - \frac{of}{s} - a \right) \quad (1)$$

$$M = A \left( \frac{f}{s} - 1 - c \right) \quad (2)$$

$$\Delta M = oA \left( \frac{f}{s} - 1 - c \right) \quad (3)$$

Where

$$c = \frac{B}{A}$$

We know from measurements of tree rings grown during the middle of the Nineteenth Century, compared with those grown during the last few years, that for the period 1850–1950

$$0.02 \geq s \geq 0.01 \text{ (the "Suess Effect")}$$

During this same period,  $f = 0.1$ , hence

$$\frac{f}{5} \geq s \geq \frac{f}{10}$$

The series of atmospheric  $\text{CO}_2$  measurements at Mauna Loa and Antarctica from 1958–1963 show that during these years

$$a = \frac{f}{2}$$

Substituting in equations (1), (2) and (3) we find, for different values of  $b$  and  $\frac{B}{A}$ , the values shown in Table 7 for  $\frac{M}{A}$ ,  $\frac{\Delta M}{f}$  and  $\frac{\Delta B}{f}$ .

From this table we see that with a "Suess Effect" of 2% (the most probable value), with fossil fuel combustion as the sole source of additional  $\text{CO}_2$ , and with "effective" biosphere sizes of 2.5 to 0.5 times the atmospheric  $\text{CO}_2$ , the oceanic reservoir is 2.6% to 6.0% of the volume of the oceans, equivalent to a layer of water 100 to 240 meters thick just below the surface. The size of the oceanic reservoir varies inversely with the size of the biosphere. For a "Suess Effect" of 1% (probably too low), and the same range of biosphere sizes, the assumed layer of complete mixing contains 11% to 14% of the ocean volume, and has an effective thickness of 440 to 560 meters.

TABLE 7.—Possible Sizes of Oceanic and Biosphere Reservoirs and Partition of Added CO<sub>2</sub> Among Reservoirs $b=0; s=0.2f; a=0.5f$  $(f=0.1)$ 

$\frac{B}{A}$	$\frac{M}{A}$	$\frac{\Delta B}{f}$	$\frac{\Delta M}{f}$	$\frac{\Delta B}{B}$	$\frac{\Delta M}{M}$
0.5	3.5	0.36	0.14	0.072	0.004
1.0	3.0	.38	.12	.038	.004
1.5	2.5	.40	.10	.027	.004
2.0	2.0	.42	.08	.021	.004
2.5	1.5	.44	.06	.018	.004

 $b=0; s=0.1f; a=0.5f$ 

0.5	8.5	.16	.34	.032	.004
1.0	8.0	.18	.32	.018	.004
1.5	7.5	.20	.30	.013	.004
2.0	7.0	.22	.28	.011	.004
2.5	6.5	.24	.26	.010	.004

 $b=.5f; s=0.2f; a=0.5f$ 

0.5	3.5	.86	.14	.172	.004
1.0	3.0	.88	.12	.088	.004
1.5	2.5	.90	.10	.060	.004
2.0	2.0	.92	.08	.046	.004
2.5	1.5	.94	.06	.038	.004

A layer of water a few hundred meters thick would be acceptable to oceanographers as defining mixing over several decades. Hence, if the "Suess Effect" is close to 2%, the size of the biosphere reservoir is probably about equal to, or less than, that of the atmospheric reservoir. This coincides with other estimates that the effective size of the biosphere on land, including both living organisms and humus, ranges from 1/2 to one times the atmospheric carbon content. Possibly the organic content of the oceanic mixing layer should be included in the biosphere reservoir, but this is only a few tenths of the atmospheric CO<sub>2</sub>.

In terms of the amounts of carbon they contain, the biosphere reservoir is much smaller than the oceanic reservoir. However, over short times in the ocean, only the relatively small "free" CO<sub>2</sub> content (dissolved and hydrated carbon dioxide) needs to be taken into account. Most of the oceanic carbon dioxide is present as carbonate and bicarbonate, and because of the peculiar buffer mechanism of sea water they do not have a very large quantitative effect on the partition between the sea and the air.

The Table shows if sources other than fossil fuel combustion had contributed much carbon dioxide to the air within the last few decades,

the biosphere would have increased in size by what is probably an observable amount. Such an increase has not been noted. We can conclude that, at least during the recent past, fossil fuel combustion has been the only significant source of CO<sub>2</sub> added to the ocean-atmosphere-biosphere system. The available data do not rule out the possibility that in earlier decades carbon dioxide may have come from oxidation of marine or terrestrial humus, as well as from fossil fuels, but if so, more than half of the amount produced was re-absorbed in the biosphere and the ocean.

## REFERENCES

- Arrhenius, Svante, 1903: *Lehrbuch der kosmischen Physik 2*. Leipzig: Hirzel.
- Bolin, Bert, and Eriksson, Erik, 1958: Changes in the carbon dioxide content of the atmosphere and sea due to fossil fuel combustion. *Rosby Memorial Volume*, edited by B. Bolin, Rockefeller Institute Press, New York, 1959. pp. 130-142.
- Bolin, B., and Keeling, C. D., 1963: Large-scale atmospheric mixing as deduced from the seasonal and meridional variations of carbon dioxide. *Journal of Geophysical Research*, Vol. 68, No. 13. pp. 3899-3920.
- Broecker, Wallace S., 1963: C<sup>14</sup>/C<sup>12</sup> ratios in surface ocean water. *Nuclear Geophysics: Proceedings of conference NAS/NRC Publ. 1075*, Washington, D.C. pp. 138-149.
- Broecker, Wallace S., 1965: Radioisotopes and oceanic mixing. Manuscript Report, Lamont Geological Observatory, Palisades, New York.
- Brown, Craig W., and Keeling, C. D., 1965: The concentration of atmospheric carbon dioxide in Antarctica. Manuscript submitted for publication, Scripps Institution of Oceanography.
- Callendar, G. S., 1938: The artificial production of carbon dioxide and its influence on temperature. *Quarterly Journal Royal Meteorol. Soc.*, Vol. 64. p. 223.
- Callendar, G. S., 1940: Variations in the amount of carbon dioxide in different air currents. *Quarterly Journal Royal Meteorol. Soc.*, Vol. 66. p. 395.
- Callendar, G. S., 1949: Can carbon dioxide influence climate? *Weather* Vol. 4. p. 310.
- Callendar, G. S., 1961: Temperature fluctuations and trends over the earth. *Quarterly Journal Royal Meteorol. Soc.*, Vol. 87, No. 371. pp. 1-12.
- Chamberlin, T. C., 1899: An attempt to frame a working hypothesis of the cause of glacial periods on an atmospheric basis. *Journal of Geology*, Vol. 7. pp. 575, 667, 751.
- Conservation Foundation, 1963: Report of conference on rising carbon dioxide content of the atmosphere.
- Craig, Harmon, 1957: The natural distribution of radiocarbon and the exchange time of carbon dioxide between atmosphere and sea. *Tellus*, Vol. 9, No. 1. pp. 1-17.

- Eriksson, Erik, 1963: The role of the sea in the circulation of carbon dioxide in nature. Paper submitted to Conservation Foundation Conference, March 12, 1963.
- Eriksson, Erik, 1963: Possible fluctuations in atmospheric carbon dioxide due to changes in the properties of the sea. *Journal of Geophysical Research*, Vol. 68, No. 13. pp. 3871-3876.
- Hubbert, M. King, 1962: Energy resources; a report to the committee on natural resources of the National Academy of Sciences—National Research Council. Publication 1000-D, National Academy of Sciences—National Research Council, Washington, D.C.
- Kaplan, Lewis D., 1959: The influence of carbon dioxide variations on the atmospheric heat balance. *Tellus*, Vol. 12 (1960), No. 2. pp. 204-208.
- Kraus, E. B., 1963: Physical aspects of deduced and actual climatic change. *Annals of New York Academy of Sciences*, Vol. 95. pp. 225-234.
- Lamb, H. H., and Johnson, A. I., 1959: Climatic variation and observed changes in the general circulation. *Geografiska Annaler*, Vol. 41. pp. 94-134.
- Lamb, H. H., and Johnson, A. I., 1961: Climatic variation and observed changes in the general circulation. *Geografiska Annaler*, Vol. 43. pp. 363-400.
- Lieth, Helmut, 1963: The role of vegetation in the carbon dioxide content of the atmosphere. *Journal of Geophysical Research*, Vol. 68, No. 13. pp. 3887-3898.
- Lysgaard, L., 1963: On the climatic variation. *Changes of Climate*, Rome Symposium by UNESCO-WHO; Published in Arid Zone Research Volumes, 20, Paris. pp. 151-159.
- Manabe, Syukuro, and Strickler, Robert F., 1964: Thermal equilibrium of the atmosphere with a convective adjustment. *Journal of Atmospheric Sciences*, Vol. 21, No. 4. pp. 361-385.
- Manabe, Syukuro, 1965: Dependence of the climate of the earth's atmosphere on the change of the content of some atmospheric absorbers. Text of talk made at summer study session of NAS Panel on Weather and Climate Modification.
- Mitchell J. Murray, Jr., 1963: Recent secular changes of global temperature. *Annals of New York Academy of Sciences*, Vol. 95. pp. 235-250.
- Mitchell, J. Murray, Jr., 1963: On the world-wide pattern of secular temperature change. *Changes of Climate*, Rome Symposium by UNESCO-WHO; Published in Arid Zone Research Volumes, 20, Paris. pp. 161-181.
- Möller, F., 1963: On the influence of changes in the CO<sub>2</sub> concentration in air on the radiation balance of the earth's surface and on the climate. *Journal of Geophysical Research*, Vol. 68, No. 13. pp. 3877-3886.
- Pales, Jack C., and Keeling, C. D., 1965: The concentration of atmospheric carbon dioxide in Hawaii. Manuscript submitted for publication, Scripps Institution of Oceanography.
- Plass, Gilbert N., 1955: The carbon dioxide theory of climatic change. *Tellus*, Vol. 8 (1956), No. 2. pp. 140-154.

- Plass, Gilbert N., 1956: The influence of the 15 $\mu$  carbon-dioxide band on the atmospheric infra-red cooling rate. *Quarterly Journal Royal Meteorol. Soc.*, Vol. 82. pp. 310-324.
- Plass, Gilbert N., 1961: Letter to the editor concerning "The influence of carbon dioxide variations on the atmospheric heat balance," by L. D. Kaplan, *Tellus*, Vol. 12 (1960) pp. 204-208. *Tellus*, Vol. 13 (1961), No. 2. pp. 296-300.
- Revelle, Roger, and Suess, Hans E., 1956: Carbon dioxide exchange between atmosphere and ocean and the question of an increase of atmospheric CO<sub>2</sub> during the past decades. *Tellus*, Vol. 9 (1957), No. 1. pp. 18-27.
- Suess, H. E., 1965: Secular variation of the cosmic ray-produced carbon-14 in the atmosphere and their interpretations. Submitted for publication to *Journal of Geophysical Research*, Scripps Institution of Oceanography.
- United Nations Department of Economic and Social Affairs: World energy requirements in 1975 and 2000. Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, 1956. pp. 3-33.
- United Nations, 1961-64: World energy supplies. Statistical Papers, Series J. United Nations, New York.