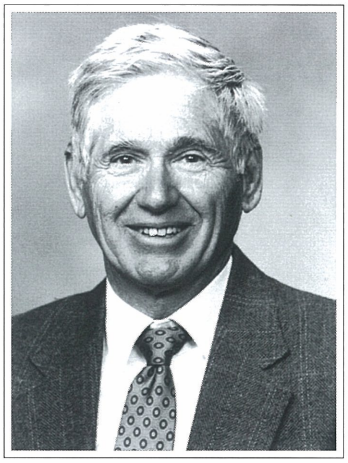
The Winners of the Blue Planet Prize
1993

1993

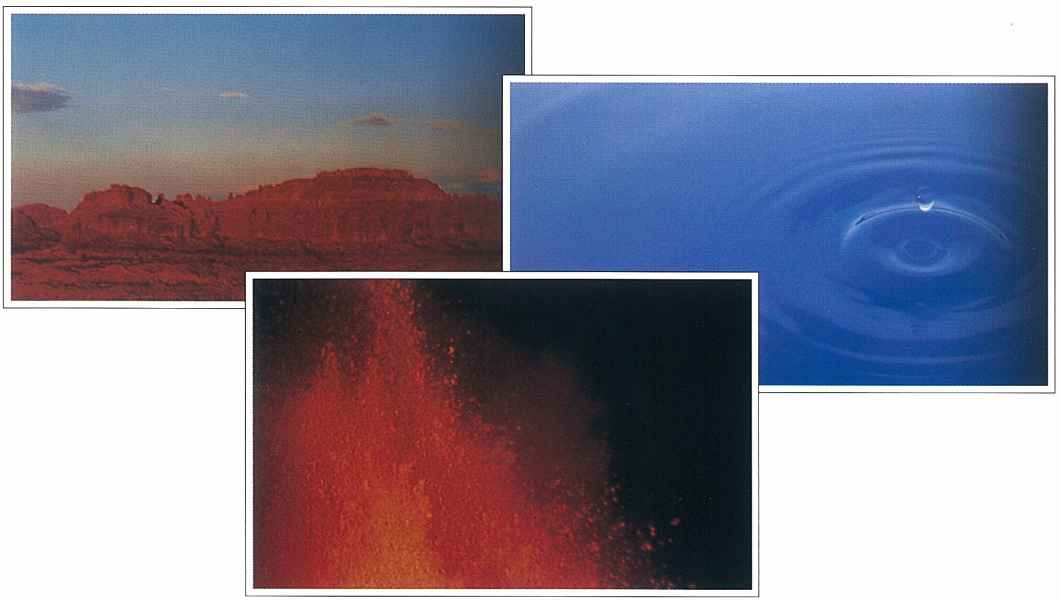
Blue Planet Prize

Dr. Charles D. Keeling (U.S.A.)

Professor, Scripps Institution of Oceanography at the University of California, San Diego



IUCN–The World Conservation Union (Headquartered in Switzerland)



The 1993 awards ceremony opened with a slide presentation showing the essential beauty of nature and how human beings are a part of life on Earth.

His Highness Prince Akishino and Her Highness Princess Kiko attend the awards ceremony for the 1993 Blue Planet Prize.

Prince Akishino and Princess Kiko toast the laureates.

Dr. Keeling accepts the 1993 Blue Planet Prize.

Dr. Holdgate, representing the IUCN, accepts the 1993 Blue Planet Prize.

Professor Takashi Mukaibou, chairman of the Presentation Committee, describes the Blue Planet Prize selection process.

Jeno C. A. Staehelin (left), Switzerland's ambassador to Japan, and Michael A. G. Michaud, minister counselor for environment, science and technology at the U.S. embassy in Japan, listen as His Highness Prince Akishino addresses the audience.

Seated in the audience during the symposium, which focused on population-related problems, the winners add their views on the population debate.

Profile

Dr. Charles David Keeling

Professor, Scripps Institution of Oceanography at the University of California, San Diego

Education and Academic and Professional Activities

1948 B.A., University of Illinois
1953–56 Research Fellow, California Institute of Technology
1954 Ph. D., Northwestern University
1956–64 Assistant Research Chemist, Scripps Institution of Oceanography, University of California, San Diego
1961–62 Guggenheim Fellow, Meteorological Institute, University of Stockholm
1964–68 Associate Professor of Oceanography, Scripps Institution of Oceanography, University of California
1968 Professor of Oceanography, Scripps Institution of Oceanography, University of California
1969 Guest Professor, Zweiten Physikalisches Institut of the University of Heidelberg
1981 Half-Century Award of the American Meteorological Society
1986 Fellow, American Academy of Arts and Sciences
1990 Fellow, American Association for the Advancement of Science
1991 Maurice Ewing Medal, American Geophysical Union

Dr. Keeling has also been Scientific Director of the Central Carbon Dioxide Laboratory of the World Meteorological Organization since 1976.

Dr. Charles D. Keeling is an earth scientist who has conducted pioneering research into carbon dioxide levels of the atmosphere and ocean, as well as the global carbon dioxide gas cycle. The first to recognize the importance of scientifically measuring atmospheric carbon dioxide levels, Dr. Keeling in 1958 began precise measurements using nondispersive infrared analysis at the Mauna Loa Observatory in Hawaii and started atmospheric observation at the South Pole. Continuing his research for more than 30 years, Dr. Keeling has amassed a great deal of useful data. This long record of atmospheric carbon dioxide levels has provided the international scientific community with an invaluable body of data that today forms the basis for an ongoing discussion of global warming.

Born in 1928 in Scranton, Pennsylvania, Dr. Keeling received his undergraduate degree from the University of Illinois. In 1954, he earned his doctorate from Northwestern University. Dr. Keeling joined the Scripps Institution of Oceanography at the University of California, San Diego, in 1956 and became the Professor of Oceanography in 1968, a title which he holds to this day.

Lecture

A Brief History of Atmospheric Carbon Dioxide Measurements and Their Impact on Thoughts about Environmental Change

Dr. Charles D. Keeling

Introduction

More than a few people have wondered why I have spent 40 years focused mainly on a single chemical molecule: carbon dioxide. I would like to explain to you how it was possible to maintain an interest in this simple molecule for so long. I will start by taking you back to the beginnings of science when neither this molecule, nor any other molecule, was known to anyone. Then, after sharing with you some of the early developments of science which led to the discoveries of carbon dioxide and its importance to life and to the Earth's environment, I will explain how I more or less accidentally became interested in studying this substance, and inadvertently joined a long succession of scientists who have investigated its role in nature.

Early History of Carbon Dioxide

Let us contemplate the world as seen by people living before the birth of modern science. We can imagine that the most curious among them attempted to understand the nature of air, water, and the matter which makes up living plants and animals. For example, people could perceive that strong winds involved some kind of invisible substance. Perhaps it was the same substance that caused bubbles under water. But lacking means to probe further into causes, and lacking any understanding of how matter was made up of tiny molecules, they were unable to make any great progress in understanding nature better. Thus, they had no real idea of why plants have leaves, or how climate might be influenced by a changing composition of an atmosphere made up of individual gases mixed together. Indeed, the notion that climates could change was not thought about.

Because people then had no idea that plants exchange substances with the air and that air contains substances that influence climate, the topic which became my life work could not have been conceived before modern science laid the groundwork for understanding the chemistry of gases. Of course, people were free to speculate, and, as an example, Stephen Hales, born in the late 1600s, asked in an essay on vegetables in 1727 whether the leaves of plants might not be there because the plants drew some part of their nourishment from the air.

The discoveries which led to an understanding of the nature of air began in 1754 with the observations in Scotland by Joseph Black, who found that something in air could be precipitated in water containing lime to make a milky solid material. This substance he called "fixed air." It was actually carbon dioxide gas, but he had no idea that it was composed of car-

Table 1 Early Measurement of CO_2 in Air

	Approximate Time	Mean Concentrations Found
Alexander von Humboldt	1797	circa 1% (10,000 ppmv)
Theodore de Saussure	1815	596 ppmv
	1827	506 ppmv
	1828	447 ppmv
	1829	403 ppmv
	1830	373 ppmv
Jules Reiset	1870	290 ppmv

bon and oxygen as the modern name implies, because these chemical elements had not yet been identified.

During the next 30 years, a time shorter than I have been measuring carbon dioxide, the chemistry of the atmosphere was worked out by the great "pneumochemists," as they were called at the time. The discovery was made that liquid water could be separated into two gases, one of which was a new gas that was called "inflammable air," but is now called hydrogen. The other was later called "oxygen." Soon afterwards that gas was discovered to be part of air, where it is mixed with a nonreactive gas that later came to be called nitrogen. Fixed air, the gas discovered by Joseph Black, was shown to consist of oxygen and another element that came to be called carbon. Lavoisier, who discovered this a short time later, proposed the theory of oxidation by which elements, in general, combine to form molecular compounds.

With this tantalizing insight into a basic premise of modern chemistry, the discovery of many more elements and of many chemical reactions soon took place. Meanwhile, other naturalists, led mainly by sheer curiosity as had been the first pneumochemists, began to probe the process by which plants grow.

Even before Lavoisier had positively identified oxygen as a gas and given it its present name, an Englishman named Priestly had found that vegetables grown in a confined space caused the air to change in some way that supported combustion. He thus came close to realizing that plants give off oxygen when they grow, although he mistakenly thought the plants were removing something from the air called "phlogiston." Soon after Priestly's discovery, a Dutchman named Jan Ingen-Housz found that plants do what Priestly discovered only in the presence of sunlight. In the dark they appeared to "poison" the air, as he said. A Frenchman, Senebier, further noticed that plants grew better if they were supplied with "poisoned air," which he recognized to be not a poison at all but fixed air, that is, carbon dioxide. In 1796 Ingen-Housz then carried Senebier's idea even further by proposing that the organic matter of plants comes from the carbon that Lavoisier had found to be part of fixed air; that is, plants don't just transform carbon dioxide into some other gas, they utilize part of it, as well. Ingen-Housz also suggested that this carbon is absorbed by plants through the leaves, not from the ground as most people had previously supposed. Ingen-Housz cited the evidence of Alexander von Humboldt that air typically contains 1% carbon dioxide.

Von Humboldt's first measurements of carbon dioxide in air were much too high. This didn't matter to Ingen-Housz's theory, but it established a bad precedent. It took many years before the amount present in the air was correctly measured, as indicated in the summary shown in Table 1.

In 1804, Theodore de Saussure showed that water was also an essential chemical in photosynthesis, combining with carbon to make actual living matter. He also demonstrated more clearly than Ingen-Housz that the carbon involved in plant growth came from the air. Curious about the carbon dioxide in the air, he made the first detailed measurements of its concentration there, measuring it near Geneva, Switzerland, under different wind conditions, different hours of the day and different months of the year. The mean value that he found was roughly 0.04% by volume, which I will put in modern units as 400 parts per million by volume (ppmv). This value was much less than von Humboldt had found, but still in considerable error.

De Saussure's *Memoires*, published in 1830, nevertheless ushered in a period of increasingly precise measurements of atmospheric carbon dioxide, culminating in some nearly correct measurements in the 1880s by a Belgian named Jules Reiset. Reiset's data were the first to show correctly the seasonal cycle in atmospheric carbon dioxide. These data indicated that summer values on the Atlantic Coast of Belgium were lower than winter values by about 10 ppmv. This seasonal difference we now know to be due mainly to the uptake of carbon dioxide by plants, which gradually reduces the amount of carbon dioxide in the air over the whole Northern Hemisphere from May to September, and over the Southern Hemisphere from November to March. Unfortunately, none of the other investigators of carbon dioxide reproduced the seasonal cycle even approximately correctly, casting doubt on all of their data.

After the 1880s, interest in carbon dioxide diminished for reasons which I have not been able to establish. Indeed, a quick and easy but not very precise 19th century technique of measurement, called Pettenkofer's Method, became the most common method for measuring carbon dioxide, so that measurements actually became less precise than the best of those of the 19th century. The 20th century data were generally higher than the correct concentrations, although of course this wasn't known at the time.

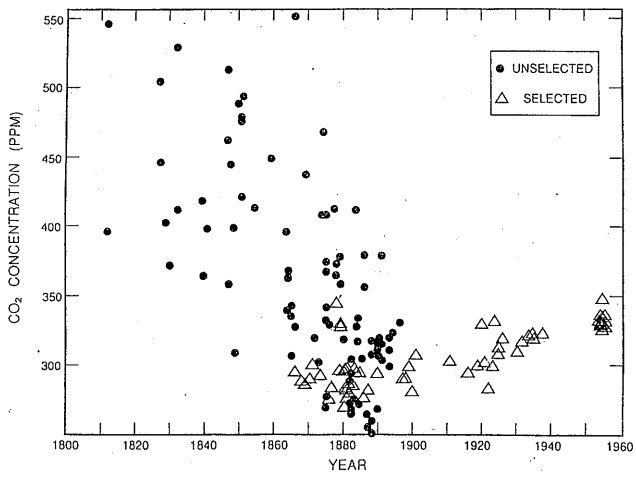


Figure 1 Measurement of the concentration of atmospheric CO_2 in the Earth's atmosphere. Measurement selected by G. S. Callendar as the most reliable are shown as open triangle. Concentration is expressed in parts per million (ppm) by volume.

In the 1930s, in the midst of this period of low interest in atmospheric carbon dioxide, a steam technologist named G. S. Callendar made a personal hobby of carbon dioxide. In a series of papers, he summarized what was known about atmospheric carbon dioxide and its likely effect on climate. He attempted to select the most reliable measurements from the past for study. I have plotted these observations in Fig. 1, distinguishing the ones that he considered most reliable. From these he came to the conclusion that the combustion of coal, along with the other major fossil fuels, methane and petroleum, was probably responsible for causing atmospheric carbon dioxide to increase, as the observations indicated. He correctly perceived that ocean water contains a vast reservoir of bicarbonates and carbonate salts which react chemically with carbon dioxide. He thus supposed that the world oceans had absorbed some of the carbon dioxide produced by combustion. However, on the basis of the direct carbon dioxide observations, he was misled into concluding that the rise in carbon dioxide actually exceeded the amount that had been added to the air by fuel combustion. His most detailed article on the subject was published in 1938 but he continued to publish articles on the subject until 1958, thus overlapping with my first studies. Indeed, we exchanged letters just before his last article was written.

This brings my talk to where I will discuss my own work. From this point on I will call carbon dioxide by its chemical name, CO_2.

A Career Measuring Carbon Dioxide

My interest in atmospheric CO_2 came about quite accidentally. As a student I had studied the irradiation of polymeric films by high-energy neutrons from a nuclear reactor, a subject having little to do with environmental science. After receiving my doctoral degree I decided to change fields and study geological processes, from the viewpoint of a chemist. At the California Institute of Technology, in Pasadena, California, my supervisor, Dr. Harrison Brown, allowed me to choose a topic to study, and I decided to determine how the acidity of natural waters is influenced by contact with CO_2 gas in the atmosphere. The rivers and lakes that I visited all happened to be near forests. As part of my experiments, which began in 1954, I measured the pressure exerted by CO_2 dissolved in the water, and the amount of CO_2 in the air. Since I didn't know how constant the CO_2 concentrations in air might be, I made measurements every few hours for a day at a time, thus obtaining measurements during both dark and light periods. Inadvertently I was measuring the diurnal cycle of CO_2 in forest air.

To carry out my measurements of CO_2, I built a manometer, which is a device that measures the pressure of CO_2 gas in a confined volume. By measuring the temperature of the gas as well as the pressure, and by calibrating the confining volume, the manometric determination of CO_2 gave a higher precision than had been attained previously by chemical methods. I also similarly measured the quantity of air by the same technique beforehand, and I separated the CO_2 from the air using a new method that I had read about, freezing it out in a trap cooled with liquid air.

My first measurements were made with only a brief prior investigation of the scientific literature. But soon I began to search this literature to learn about atmospheric CO_2. I found out, of course, that it was reported to be quite variable in concentration. For example, only a

Table 2 CO_2 Concentration in Different Types of Air (Buch, 1948)

High Arctic:	150 – 230 ppmv
Modified Arctic:	283 – 316 ppmv
Maritime Polar:	309 – 345 ppmv
Tropical:	319 – 349 ppmv

ppmv: parts of CO_2 per million parts of dry air by volume

short time previously, in 1953, a comprehensive book on the geochemistry of all of the Earth's elements was published. The chapter on carbon quoted extensive CO_2 data by a scientist from Finland named Kurt Buch. As shown in Table 2, Buch had decided that air from different regions of the Earth showed characteristic concentrations that varied from below 200 ppmv in the Arctic, to nearly 350 ppmv in tropical regions. At first I could see no reason to question these data.

Neither did Karl Gustav Rossby, a world famous meteorologist who had pioneered weather forecasting in America and had recently returned to his native Sweden to establish an institution of meteorology there. He decided to include chemical measurements in the study of meteorological processes at his new institute. To do so, he helped to establish a network of some 50 locations in Scandinavia. Measurements of CO_2 at these locations began the same year that I made my first measurements. The Scandinavian data appeared in each issue of a new Swedish journal of geophysics called *Tellus*. The measurements evidently confirmed that large variations of atmospheric CO_2 occurred even in the open air away from plants and major cities, just as Buch's data had indicated.

Since I had been measuring CO_2 in forested areas which might be expected to promote large variations, I was surprised to find that measurements which I made in the afternoon had nearly the same CO_2 concentration everywhere that I went, contrary to the Scandinavian data. Afternoon is when the heating of the ground by the sun causes the air near the ground to mix with air above the trees, so that the effect of photosynthesis on the concentration of CO_2 should not be very strong. I decided that I was probably measuring the same CO_2 concentration as was occurring above the trees. To confirm this, I made additional measurements away from trees, on beaches of the Pacific Ocean during sea breezes, on high mountains at elevations too high for trees to grow, on deserts near my home where there were hardly any plants at all and, with the help of a professor at the Scripps Institution of Oceanography, in air collected on a ship in the eastern Pacific Ocean near the equator. In all cases I found the concentration of CO_2 in the afternoon to be close to 315 ppmv. I came to the conclusion that the published 20th century data generally were in error and that the CO_2 concentration, when not locally influenced, was nearly the same at least from the equator to the northern limits of the United States, and perhaps everywhere.

It took me two years to reach this conclusion. The year was 1956. I learned that plans were being made for a large international study of the environment called the International Geophysical Year, and that this study was to include measurements of atmospheric CO_2. These were to be patterned after the Scandinavian program already operating. I expressed my con-

cerns to several planners of the International Geophysical Year that the data might not be very useful if the Scandinavian method were to be used. One of these planners was Dr. Harry Wexler, director of research for the U.S. National Weather Service. I showed him my best open-air measurements of CO_2 which suggested that the concentration of CO_2 varied only slightly with the previous location of the air, contrary to the Scandinavian data. His response was to tell me about a new remote station where such measurements could be made over long time periods. The location was called the Mauna Loa Observatory on the island of Hawaii. The observatory had been constructed the year before, high on the mountain of Mauna Loa. He was eager to see the observatory used during the International Geophysical Year, and he encouraged me to try to make measurements there.

I also talked with Roger Revelle, director of the Scripps Institution of Oceanography. From his own examination of the existing measurements of CO_2 over the past century, he still accepted the idea that CO_2 varied from place to place. He argued that the best way to decide whether CO_2 was increasing in the air was to obtain a limited number of measurements in many places so as to establish an average "benchmark" value of the global average concentration. Then in 10 or 20 years one could remeasure CO_2 to see if it had increased in the air. He proposed that I make extensive CO_2 measurements from ships and airplanes.

In the summer of 1956 I moved to the Scripps Institution of Oceanography and with the urging of both Revelle and Wexler I followed both of their approaches. The scope of the study is shown in Fig. 2.

The method of measuring CO_2 that I had used at the California Institute of Technology had allowed me to analyze about 500 samples in two years. To accomplish a much more exten-

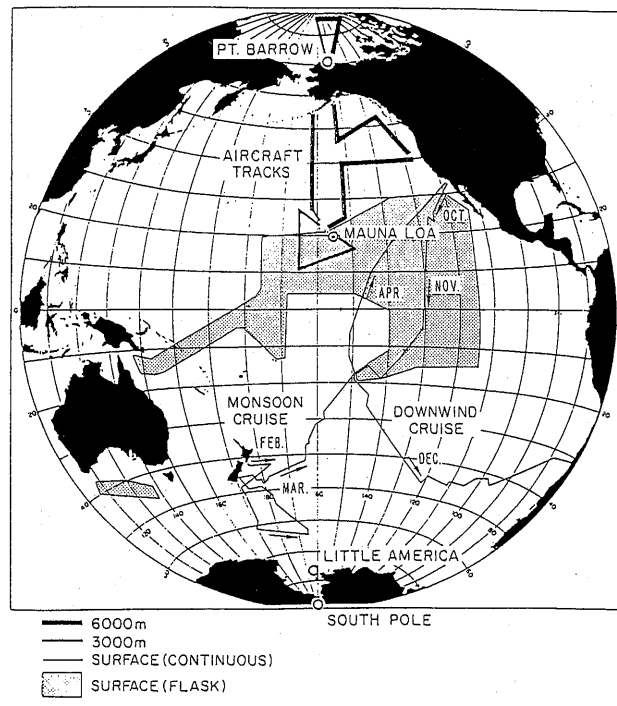


Figure 2 Locations of stations and ship tracks for sampling atmospheric CO_2. Stippled (gray) areas indicate regions where sampling took place along multiple ship tracks, not shown individually.

Table 3 CO_2 Concentration in Different Regions in 1962

Arctic:	313 – 325 ppmv
Pacific Ocean at 20 °N:	315 – 321 ppmv
Equatorial Pacific:	317 – 321 ppmv
South Pole:	317 – 319 ppmv

Measurements by the Scripps Institutions of Oceanography

sive program for the International Geophysical Year, I took advantage of semiautomatic infrared gas analyzers which had become commercially available. None of them had been used to measure atmospheric CO_2 precisely, but at least one model seemed likely to be capable of doing so. After testing this one, I was able to purchase several, including one unit for the Mauna Loa Observatory, one for Antarctica, one to be put on a ship, and one for my laboratory in La Jolla. They had to be calibrated, and for this purpose I built a new and more precise manometer. This manometer was completed in 1959; it is still the basis of calibrating the gas analyzers in my program and since 1975 has been the primary basis for calibrating atmospheric CO_2 analyzers internationally.

At the close of the International Geophysical Year in 1959, it became clear that the gathering of data to fulfill Dr. Revelle's benchmark study should not be shut down and started up again only after 10 to 20 years, as he had first suggested. Especially the data from the Mauna Loa Observatory and the South Pole showed interesting features never seen before in any CO_2 data. These became more and more interesting as the records became longer. A clearly marked seasonal oscillation had shown up in the data from the Mauna Loa Observatory in the first year of uninterrupted measurements, beginning in the final months of 1958 and extending through 1959, as shown in Fig. 3. We know now that a similar cycle appears everywhere in the Northern Hemisphere. Thus, it seems astounding that this cycle was never clearly seen in earlier measurements, since the methods available in the 19th century were already adequate to show it. The times of fall and rise in CO_2 corresponded to the expectations of when plants absorb CO_2 during the active growing season, and release it through decay processes, as de Saussure had anticipated a century and a half earlier. As indicated in Table 3, the spatial variations in CO_2, even when the seasonal cycle was taken into account, were much smaller than earlier 20th century data had indicated.

An increase in atmospheric CO_2 concentration from year to year, already hinted at by data obtained during the International Geophysical Year, became ever more clearly seen as the records at the Mauna Loa Observatory and elsewhere became longer. By 1963 the average rate of increase was well enough established by these data to be compared with the rate of CO_2 injection into the air by fossil fuel combustion. The data showed that the fraction of fossil-fuel-derived CO_2 which apparently remains in the air was about 50%. This fraction has remained nearly the same up to the present time, suggesting a steady mechanism for its removal from the air. This mechanism is absorption by the oceans, the same mechanism that Callendar had described in the 1930s, but had then questioned because the existing CO_2 data appeared to disprove it.

I should not, however, imply that the removal rate has remained perfectly steady. Let us

now turn to a consideration of the entire record of atmospheric CO_2 for the Mauna Loa Observatory, from the first measurements in 1958 until early this year (1993). Interannual variations in the rate of rise of CO_2 are quite clearly evident in the record, and seem to be caused by natural oscillations that do not affect the average fraction of CO_2 remaining in the air from fossil-fuel combustion on longer time scales. The accompanying series of diagrams serves to illustrate this.

The first of these is a plot of monthly data, shown by dots in Fig. 4. The seasonal cycle, as shown previously just for 1958 and 1959, is clearly seen every year, superimposed on the long-term rise. The average cycle, combined with the rise, is shown by a smooth curve through the data. The seasonal cycle is obviously quite regular, since the dots and the curve agree closely. If the average seasonal cycle is removed from both the data and from the curve, thus "seasonally adjusting" the data, the long-term trend in CO_2 is seen more clearly, as in Fig. 5.

To compare this rising trend with the amount of CO_2 injected into the air by fuel combustion, I have calculated the amount of CO_2 injected each year and summed it with all amounts injected earlier. In this way I obtain the cumulative increase shown in Fig. 6. The units are gigatons of carbon contained in CO_2, where one gigaton is equal to a thousand million metric tons. As indicated, about 80 gigatons were released up to 1959, rising to 230 gigatons in 1993. By adjusting the plotting scale, this curve can be compared to the previous plot of the seasonally adjusted atmospheric CO_2 data. When this is done (see Fig. 7), the patterns of the rise in CO_2 and of fossil-fuel CO_2 emissions are seen to be remarkably similar. This comparison is one of the most convincing indicators that the rise in atmospheric CO_2 is closely related to the injection of CO_2 from fossil fuels.

Another interesting feature of the Mauna Loa record is seen in the previous plot of the actual monthly data (see again Fig. 4). The seasonal cycle is seen to be larger in the latter part of the record than in the earlier part by about 15%. This increase is probably not entirely a result of any single cause, but the main reason is likely to be that the growth rate of plants has

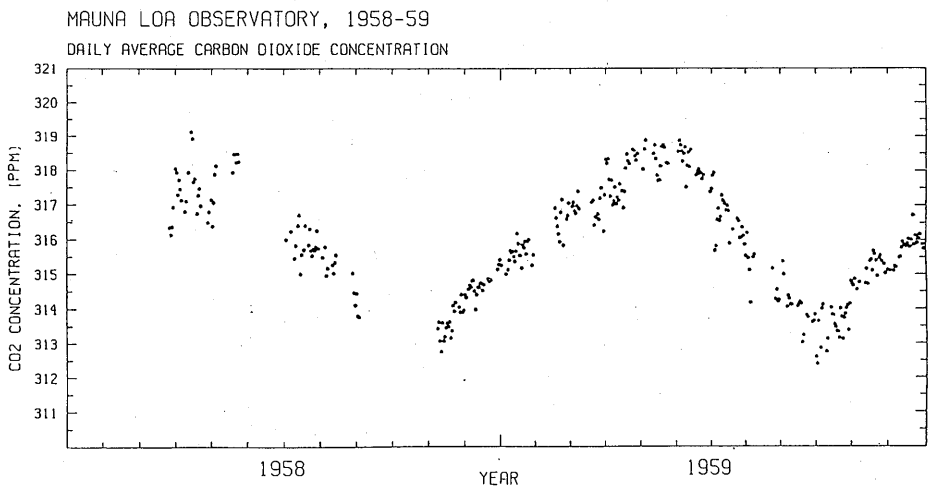


Figure 3 Daily average measured concentration of CO_2 in air at the Mauna Loa Observatory, Hawaii, measured during the first two years of sampling at this station. Concentration is expressed in ppm by volume.

increased since 1958. Perhaps this has occurred because the growing season of plants on land has become longer or because of improvements in agriculture, but part of the reason may be that the plants are responding to the increase in atmospheric CO_2, which has risen 13% since 1959. If so, this is a fulfillment of the original suggestion of Senebier that plants grow better when they are supplied with more fixed air, as CO_2 was known in the 18th century.

A close look at the comparison of seasonally adjusted CO_2 data to the curve for fossil fuel emissions (Fig. 7) shows that the actual CO_2 data tend to migrate from above to below the fossil-fuel curve and back every few years. To see this pattern better, I show in Fig. 8 a plot of the difference between the two curves, in effect what the seasonally adjusted CO_2 record would have looked like if burning of fossil fuels had not caused the CO_2 to increase year after year. I call this a CO_2 "anomaly." The vertical scale is expanded in the plot to see the fluctuating pattern of the anomaly more distinctly. The times when the CO_2 anomaly was rising correspond generally to times when large changes in weather have occurred in connection with a tropical phenomenon called El Niño. The times of the latter are shown by vertical arrows. The same patterns are seen globally in CO_2 records from near the North Pole to the South Pole. Processes involving both oceans and vegetation contribute to the oscillations but appear to do so in opposite ways, that is, the exchange of CO_2 between the air and the oceans oppose variations in uptake and release of CO_2 by plants on land. Thus, even larger CO_2 oscillations would have occurred during El Niño events if growing plants alone had caused the patterns.

I do not have time to describe many additional details about how atmospheric CO_2 measurements may help us to understand the cycling of carbon in nature. Thus, I now come to the

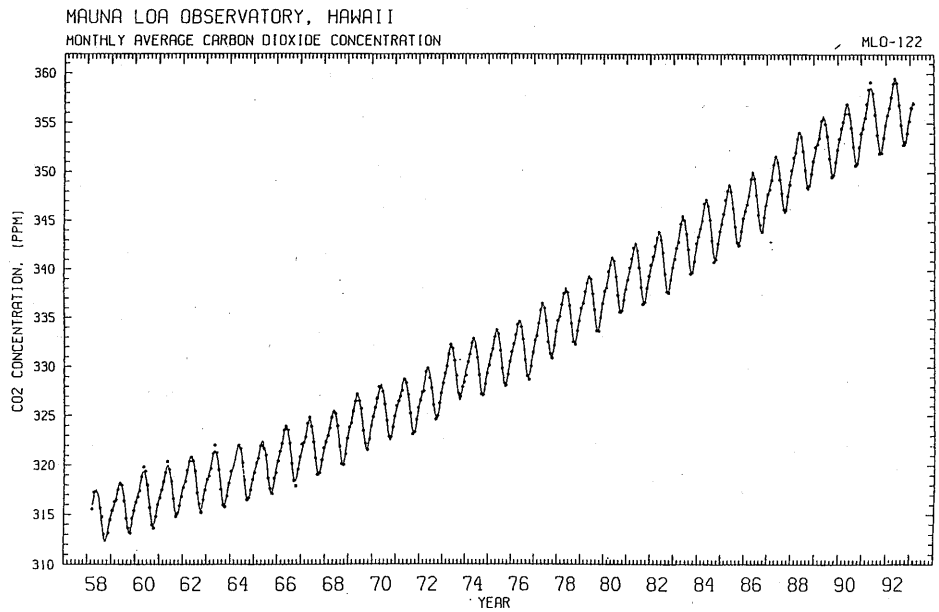


Figure 4 The concentration of CO_2 in air, in ppm, at the Mauna Loa Observatory from 1958 to 1993. Monthly averages are shown as solid dots. A smooth curve indicates the seasonal cycle superimposed on a long-term upward trend.

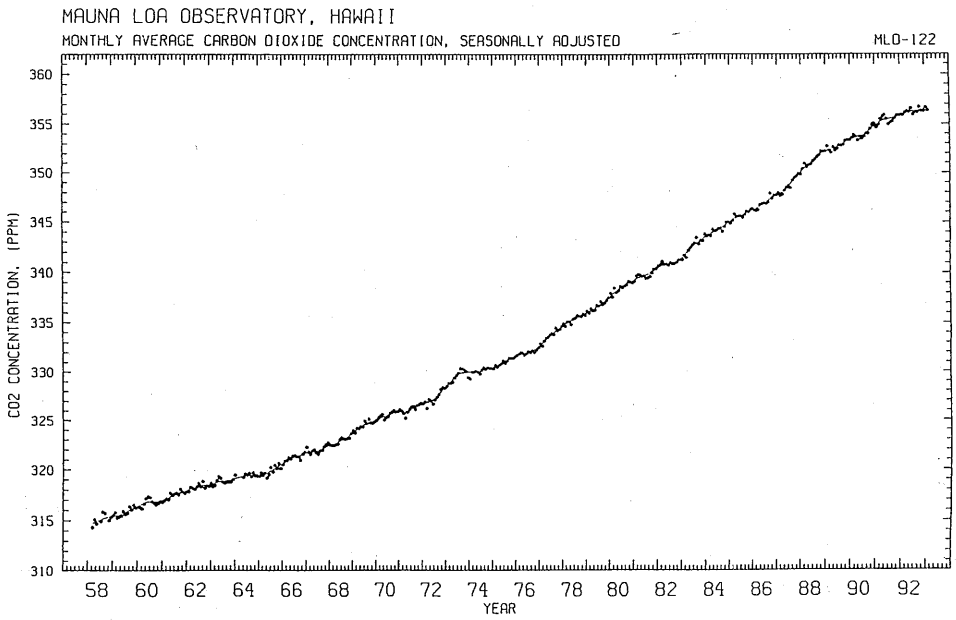


Figure 5 The same plot as Figure 4, except that the seasonal cycle is removed.

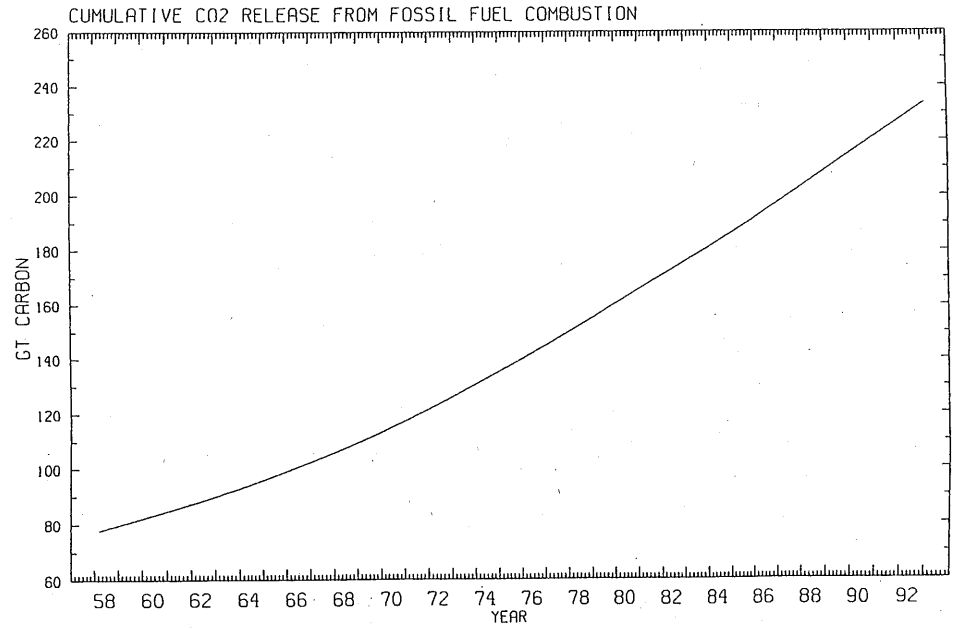


Figure 6 A plot of carbon in the fossil fuel that has been released to the atmosphere, expressed in gigatons (thousands of millions of metric tons). Amounts are cumulative, i.e., the amount for each year includes all of the previously released carbon.

close of my lecture.

Concluding Remarks

I have traced the history of carbon dioxide measurements over a period of nearly two and a half centuries, from the time of its first discovery to the early 1950s. After that I have talked mainly about my own investigations of CO_2 in the atmosphere. I should mention, however, that many other scientists have studied atmospheric CO_2 during the past 30 years. Some of the very best measurements are coming now from studies in Japan.

There is no likelihood that the study of CO_2 will slow down in the next few years as it did after the vigorous studies of the last century. There is much more that will be learned about the Earth's carbon cycle, and much of it will be as interesting as what we have already learned.

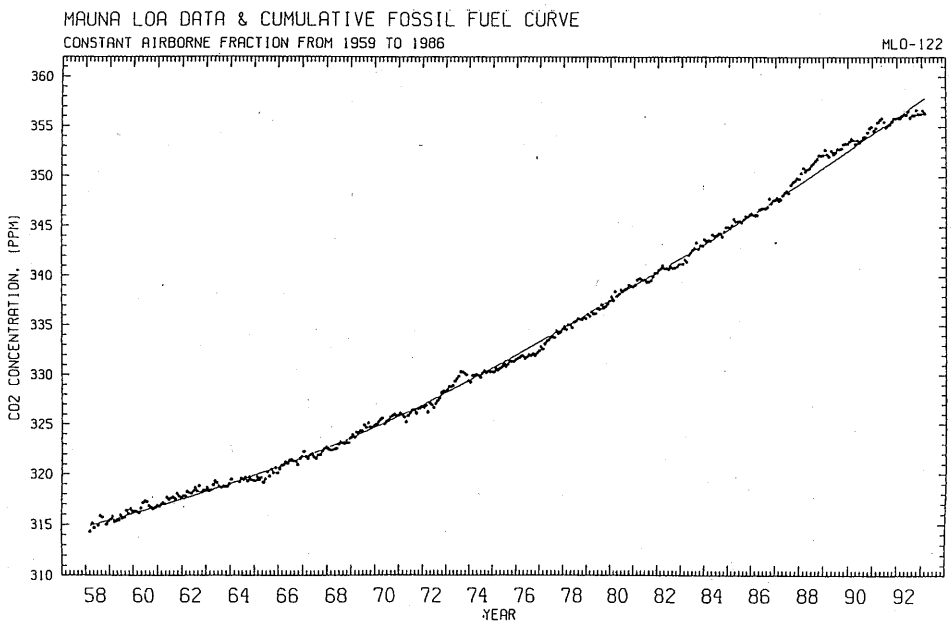


Figure 7 A comparison of the cumulative increase in carbon released by fossil fuel (shown in Figure 6) with the seasonally adjusted rise in atmospheric CO_2 at the Mauna Loa Observatory (shown in Figure 5).

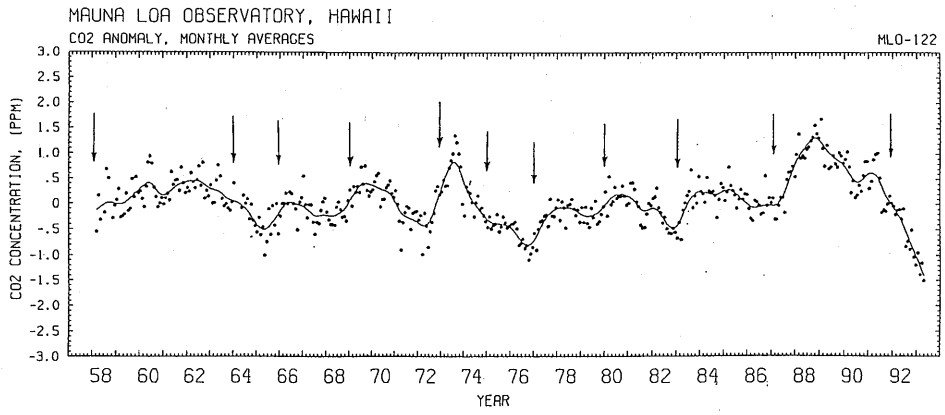


Figure 8 A plot of the anomaly in atmospheric CO_2 concentration at the Mauna Loa Observatory, expressed by the difference between two plots. Arrows denote El Niño occurrences.

Major Publications
Dr. Charles D. Keeling

Articles

Dole, M., C.D. Keeling, and D.G. Rose. "The Pile Irradiation of Polyethylene." *J. American Chemical Society*, 76 (1954), 4304–4311.

Keeling, C.D. and M. Dole. "A Viscometer for Solutions of High Polymers." *J. Polymer Science*, 14 (1954), 105–111.

Keeling, C.D. "The Concentration and Isotopic Abundances of Atmospheric Carbon Dioxide in Rural Areas." *Geochimica et Cosmochimica Acta*, 13 (1958), 322–334.

—. "Effect of Local Environment on the Isotopic Enrichment in Plants." *Comitato Nazionale per L'Energia Nucleare*, Laboratorio di Geologia Nucleare Pisa, (1960) 214–215.

—. "The Concentration and Isotopic Abundances of Carbon Dioxide in the Atmosphere." *Tellus*, 12 (1960), 200–203.

—. "The Concentration and Isotopic Abundances of Carbon Dioxide in the Rural and Marine Air." *Geochimica et Cosmochimica Acta*, 24 (1961), 277–298.

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