Charles Keeling & Measuring Atmospheric CO_2

by John Leaf

Enjoying the Great Outdoors

Charles Keeling loves the great outdoors. That poses a challenge.

The year is 1953 and the post-World War II economy is booming. People across the nation are starting families and buying homes. They are equipping them with new technologies, such as dishwashers, frozen foods and televisions. The air is filled with a sense of scientific progress.

Just out of chemistry graduate school in Illinois, Keeling is looking for a job. With a background in studying polymers (used to make plastics), he has plenty of opportunities. However, Keeling will not take any job that comes his way. In tune with the outdoors, he wants to find something on the West Coast. Keeling's advisor thinks he is a fool to turn down multiple East Coast jobs offering good pay.

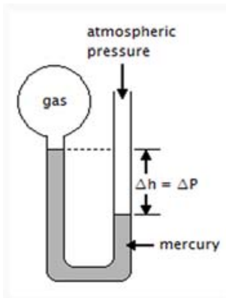
> **OPTIONAL THINK (A**). Would you sacrifice good jobs for something you loved? What do you think are the chances Keeling will succeed?

Keeling writes letters to Geology departments in the West, presenting his services as a chemist. Most politely decline. But Keeling gets two offers. He accepts a postdoctoral position at the California Institute of Technology in southern California.

Although Keeling has some knowledge of geology he is inexperienced. He is unsure what research to pursue, so he is assigned to a project on extracting uranium from granites to use for nuclear power. The fit seems logical for a chemist like Keeling. His first task is to crush rocks for two weeks. The goal of the study interests Keeling enough, but rock crushing frankly doesn't inspire him.

While chatting with some colleagues one day, Keeling hears his advisor mention an idea about estimating the amount of carbonate (CO_3) in surface water. If one assumed that that the carbonate levels in the water reached an equilibrium with the carbonate rock below it and the atmosphere above, one could calculate a value from other known factors. This interests Keeling. With his advisor's consent, he sets out to test it. However, he quickly realizes that in order to carry out his experiment, he needs a reliable measurement for carbon dioxide (CO_2) in the air. Other scientists had already attempted to measure this and reported wildly different results (from 150ppm to 350ppm, at least a twofold difference!). Many concluded that carbon dioxide in the atmosphere wasn't consistent throughout the world. Any given day could be different than the next depending on the local conditions.

One problem with measuring carbon dioxide in the atmosphere is that there simply isn't much to measure. It constitutes less than 1% of the gases in air. Even a small mistake could lead to large differences in the measured value. Keeling does some background research and rigs together a manometer to measure the gas.



How a Manometer Works

A manometer works much like a straw. It is a tube and with changes in pressure, the liquid in it is either drawn up or pushed out. The key differences are that the tube is bent into a J-shape and one end is closed.

In determining the quantity of a gas, the object is to measure how much of the pressure of the air is due just to the one gas: its partial pressure. Depending on how much gas is present, it forces the liquid in the manometer to rise or fall.

Steps:

1. Collect an air sample of known volume.
2. Remove its water vapor by passing the gas through an appropriate liquid.
3. Measure the pressure.
4. Extract CO_2 and other gases by freezing them.
5. Re-thaw them and measure the gas pressure again.
6. Calculate the volume from pressure with a simple formula (PV=nRT).
7. Substract other gases (such as N2O) of known concentration.

The entire process takes more than two hours: quite an undertaking for a "simple" CO_2 measurement.

Running his initial tests in Pasadena, a suburb of Los Angeles, Keeling finds the device works well, but his results vary widely.

> **THINK (1)**. Identify some reasons for his results varying so much. Identify some further tests whereby Keeling could confirm or disconfirm each suspicion.

Intent on getting a good measurement, Keeling is able to get money to travel up the coast to Big Sur State Park to gather more data. He is beginning to believe that perhaps there might not be a global "base level" for atmospheric CO_2, thereby making results for his study unobtainable. However, he is just as interested in experiencing the scenic Big Sur coast — the dramatic cliffs, the undulating coastline, the inspiring redwood trees, the crashing surf. So regardless of what data he collects, he is all for an outing in the great outdoors.

Arriving at Big Sur, Keeling follows his plan to rigorously measure carbon dioxide in the air every few hours, as well as take samples in the river and ground water. Most geochemists at the time would scoff at such tediousness for such a simple task, but Keeling does so partly for the sake of fun. If he is going to drive halfway up the coast of California, he might as well get as much data as he can, even if it requires getting out of the tent a few times each night.

Keeling's results indicate that his advisor's hope was misplaced. Carbon dioxide in the water is much more concentrated than in the air. However, he also notices an intriguing daily pattern. The measured level in air hovers around 310 parts per million fairly consistently. But it rises at night and sinks in the day. Perhaps, like Keeling, you are already beginning to consider reasons why.

Keeling wants to pursue these measurements further. He gets approval to travel to other remote areas to complete similar tests. He is very intent on getting accurate, uninterrupted data even while other scientists don't believe such precision is necessary. Imagine Keeling's typical work. For each visit, he drives several hours to some remote location, unpacks all his camping and research gear, and collects samples every few hours while he is there. Sometimes, he brings his family with him. He returns to Cal Tech hauling numerous air samples. Collecting and analyzing this data takes him the better part of two years.

> **ACTIVITY 1**. Review Keeling's results. Compare the testing sites: the locations (map), the local ecology (images), and the measurements made at each site. Is there a consistent baseline CO_2 level? Identify any other important similarities or differences. Suggest some possible explanations for any pattern you observe.
>
> **THINK (2)**. In what ways did Keeling's precision contribute to his findings?

Job Offers

As his data accumulate, Keeling sees that the CO_2 levels are not fully consistent from place to place and time to time. Perhaps his methods are flawed? Yet as he continues to collect data, he gains confidence with his findings. Three years after beginning his carbon dioxide study at Big Sur, he is convinced enough to discuss his results with other colleagues.

Keeling talks to Gilbert Plass, working nearby at Lockheed Martin. Plass is researching infrared radiation for the military in connection with the possibility of heat-seeking missiles. As a side topic, he had become interested in the ability of carbon dioxide in the atmosphere to absorb heat. Plass has read an old study by Swedish chemist Svante Arrhenius.

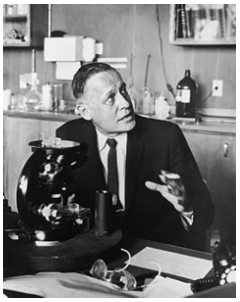
A few gases in our atmosphere absorb some of Earth's dissipating heat. This keeps the Earth at warmer average temperatures. The phenomenon is thus known as the greenhouse effect. In the late 1800s, Arrhenius proposed that adding carbon dioxide to the atmosphere would amplify the greenhouse effect. He was concerned that the carbon dioxide released from burning fuels (wood, coal, oil, gas) might increase temperatures even more. He even calculated some hypothetical rises in temperature that would result.

Plass had begun to look at the discredited issues of the study and enlisted one of the newly developed computers to help with the complex calculations. His results showed that human activity might raise the global temperature of the earth by 1.1 C per century [7]. While the calculations weren't certain enough to make any huge waves in the scientific community, Keeling takes note of the work as a context for researching atmospheric carbon dioxide further. Perhaps he, too, can use absoprtion of infrared radiation to measure amounts of CO_2?

News of Keeling's work also reaches Harry Wexler, the head of the National Weather Bureau. Interested in his findings, Wexler invites Keeling to visit him in Washington D.C. Keeling is flown out to D.C., and presents the case for an extended study on his newly found global base level of CO_2. Taking a gamble, Keeling also proposes to measure CO_2 with infrared analyzers as a more reliable and efficient — but also more expensive — method. While these had been used extensively by the military in designing heat seeking missiles, no one had ever tested them with low concentrations of gas such as carbon dioxide. Indeed, although Keeling had played around with an infrared analyzer for several days in the lab, he is taking a huge leap of faith that they will actually work on a gas as dilute as atmospheric carbon dioxide.

Wexler seems to like the idea. He informs Keeling that the Weather Bureau was already planning to measure global CO_2. After World War II the global presence of the U.S. grew and military officials wanted to know more about the Earth's processes. Already an upcoming 18 months in 1957-1958 had been designated as the International Geophysical Year (IGY), a government sponsored effort to gain deeper understanding of the globe and to promote international cooperation through science.

Wexler's department had received massive funding for the IGY and he is interested in Keeling's input on possible remote locations to measure CO_2. In addition, Wexler invites Keeling to meet with a U.S. Air Force representative to discuss the possibility of using their routine reconnaissance missions: allowing sampling of air at high altitudes and in remote locations. Wexler is impressed with Keeling and offers him a position for carrying out the global CO_2 sampling program. The overcrowded weather offices are full, but he shows Keeling the basement of the Naval Observatory, where he would have ample office space for his research.



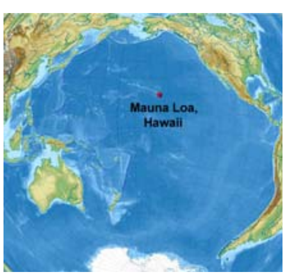
Upon returning to California, Keeling finds that another renowned scientist has taken interest in his findings. Oceanographer Roger Revelle, head of the Scripps Institution, had been alerted by one of Keelling's colleagues. He invites Keeling down to Scripps and they discuss his work over lunch, overlooking the glittering Pacific Ocean as a cool sea breeze drifts off the water. At the end of the meeting, Revelle offers a position to Keeling.

OPTIONAL THINK (B). As Keeling, you now have two job offers: which would you choose? (Which do you think Keeling will choose?)

Keeling pictures the dingy East Coast office of the Weather Bureau and readily accepts Revelle's offer. Wexler, in Washington, accepts Keeling's decision and even promises a large sum of the Weather Bureau's IGY money, as well as offering to assist in establishing various sampling sites. Keeling now has a job at a distinguished oceanographic research institute. He is able to reflect on his good fortune. He had taken a chance on deciding to work only on the West Coast and had pursued his personal interests in taking measurements at Big Sur State Park. How much of his current status did he owe to luck, how much to his own skills and effort?

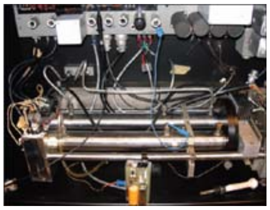
Leading a Global CO_2 Program

Time moves fast for Keeling after accepting the job at Scripps. In August of 1956, age 28, he officially moves to San Diego. While writing up his baseline CO_2 data for publication, he begins to prepare for the IGY, scheduled to begin the following July. He checks possible sites for measuring CO_2 around the globe.

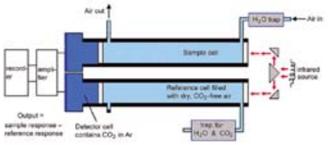


One location is on Mauna Loa in Hawaii, a former military site obtained by the Weather Bureau for taking meteorological measurements during the IGY. Located in the middle of the Pacific Ocean at an elevation above the tree line, it is a pristine location for measuring atmospheric concentrations.

Keeling trains others to take measurements here at Mauna Loa so he can continue work in California. He must impart the need for measuring as precisely as possible and transfer his skills. He also coordinates assistants at other sites the Weather Bureau and Scripps have picked for monitoring, including one in Antarctica. He helps get the planes set up for sampling CO_2.



With his new wealth of funding, Keeling also orders infrared analyzers — at a pricey $6,000 each — and begins to get them working properly.



How an Infrared Gas Anaylzer Works

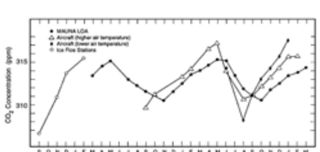
An infrared analyzer is based on the ability of carbon dioxide to absorb infrared radiation as heat. To test an air sample, infrared radiation is passed through it. Some radiation will be absorbed by the carbon dioxide, so less radiation reaches the detector at the end of the sample chamber. More carbon dioxide means more radiation absorbed.

At the same time, a second measurement is taken for reference of a known sample without CO_2. The two measurements are compared. The difference between the test sample and the reference gas indicates the extra amount of radiation absorbed, and thus the amount of CO_2 in the sample.

THINK (3). How will Keeling know that the new infrared analyzers give the same results as the earlier manometer, already known to be accurate? How will he know if the instrument at Scripps is working exactly the same as the instrument at Mauna Loa or other sampling sites?

Progress setting up the stations is slow. Sampling must occur around the clock at each site. The IGY starts formally in July, 1957, but Keeling and crew manage to get only their California and Antarctica sites fully functional. Due to technical troubles, the Mauna Loa site opens three months late. When the site does start yielding results, Keeling is surprised with good news. Their first results are within one part per million of what he had predicted. Roger Revelle had not been convinced that consistent levels existed, but Keeling now felt vindicated. Not long after, however, a power failure shuts down the remote site and delays further measurements. The generators are fixed, but subsequent CO_2 values begin to drift. Is the equipment faulty? Several months later the power fails again. Keeling visits Mauna Loa himself. Regular measurements resume. But now unexpected new results trouble Keeling even more.

ACTIVITY 2. Students graph Keeling's data from the Mauna Loa site from 1957 to 1960 and interpret its meaning.



Having gone to remote locations to avoid plants and secure mixing of air, Keeling had hoped to eliminate the sources of variation that he had found earlier. He thus expected to find a consistent baseline CO_2 level. His results now indicate a seasonal variation in CO_2 levels.

THINK (4). Reviewing Keeling's data, how is precision important for reaching conclusions about patterns in global CO_2 levels?

Keeling is sufficiently confident with his initial results and calibrations that he presents his findings at a geophysics conference in Helsinki in August, 1960. He also publishes his data. However, with the IGY winding down, Keeling has also lost a major source of funding for continuing his studies. He has to scramble now to find more money. Impressed with his results, a colleague and collaborator of Revelle, Hans Suess, transfers some of his own IGY money to Keeling [8].

In addition, Keeling applies for a grant from the National Science Foundation (NSF). Although NSF has been around for a decade, it has subsisted with minimal funding. In 1957, however, the Soviets launch the first satellite in space, Sputnik. Many Americans, wary of Soviet power, worry about supremacy in science and technology. Amid fears of falling behind, funding pours into NSF. Keeling receives a grant from the foundation to continue his research through 1962. In addition to Suess and the NSF, the Weather Bureau supplies technicians to operate the measuring stations at the South Pole and Mauna Loa, and on the ships at sea and the planes in flight.

With all this data, however, Keeling needs some time away to sort through it all. Taking a break from data collecting in 1961, Keeling travels to Sweden to work with Bert Bolin, whom he met earlier in Helsinki. Together they begin working through the data. They find that all Northern Hemisphere sites exhibit a clear seasonal cycle, while the Southern ones follow a much weaker one. This follows the earlier patterns based on vegetation, but on a more extended time scale. There is more plant life in the Northern Hemisphere, leading to larger swings in CO_2 uptake (spring, summer) and release (fall, winter). With such variation, they begin to consider other potential sources that might significantly increase or decrease the amount of carbon dioxide. They calculate potential "sinks" for removing atmospheric carbon dioxide, as well as "sources" from humans burning fuels. They present these results at a conference in the Netherlands. Overall, the trip ends successfully. But Keeling also returns home to learn that Harry Wexler (from the Weather Bureau) has passed away.

Funding Woes

Returning to the U.S. in 1963, Keeling presents his findings again at a geology conference in Berkeley. Scientists are beginning to take interest in his work, but not so in Congress. Late in 1963, looking to make budget cuts, they cease funding anything in the Weather Bureau not related to weather forecasting. Without Wexler to defend Keeling's work, Keeling himself travels to Washington to present his case. But to no avail. His Antarctic stations are cut, as are his ship and aircraft measurements.

As funding cuts set in during 1964, Mauna Loa is threatened with closure. With $100,000 a year needed to stay open, the station is shut down in May [8]. Through strenuous efforts, Keeling scrapes together enough support from the NSF to open Mauna Loa again. In addition, he collaborates with a former technician to set up a collection program at the South Pole, with flasks being brought back to Scripps for analysis.

Meanwhile, the Scripps Institute of Oceanography promotes Keeling to a junior faculty member. While Keeling feels honored, the extra responsibilities further burden his already tight schedule for overseeing his CO_2 program. Yet Keeling uses his growing network of colleagues to muster assistance in measuring global carbon dioxide levels. He now has gas samples from Point Barrow, Alaska, New Zealand, sites in the remote Eastern Pacific, and planes flying in Sweden.

> **THINK (5)**. Identify some benefits of Keeling collaborating with other scientists on such studies. Also identify some potential costs or problems.

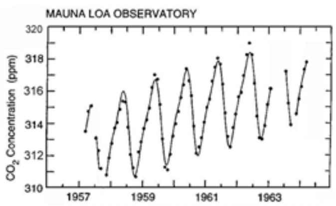
From Weather to the History of Climate

Balancing his duties as a faculty member at Scripps, eking out enough funding to keep Mauna Loa operating, and coordinating with colleagues who are providing air samples from around the world, Keeling manages to get away to a conference in Boulder on "Causes of Climate Change." Scientists from many different fields have convened here, mainly to discuss the fascinating topic of historical glacial periods: vast changes in climate occurring over a relatively short period of geologic time. Scientists are studying the nature of glaciers. They have cored lake bottoms for pollen that indicates what plants once lived in the area. They have studied rocky moraine deposits left by the movement of giant ice sheets. While the existence of Ice Ages has been known for over a century, investigators are realizing now just how fast climate can change. But what causes the sudden shifts is still unknown, along with the uncertain prospect of such conditions returning again soon.

Scientists and the public alike are also realizing more and more the impacts humans can have on their environment. In the late 19th and early 20th centuries urban smokestacks symbolized industrial progress and jobs. Now, scientists are beginning to reveal the serious damages and health problems caused by water and air pollution. Some people have even died from the heavy smog in major cities, further amplifying fears. Cold War tensions between the United States and the Soviet Union continue. With the new potential to "seed" clouds, some people wonder if the Soviets will summon deadly blizzards on the U.S. The two superpowers sign a treaty in 1963 banning atmospheric testing of nuclear weapons, but concerns about radioactive fallout persist.

Many scientists at Boulder discuss the possible reasons for Ice Ages and the potential for another. But Keeling and others also weigh in on the potential for a warming trend, due, as Arhennius had envisioned, to cumulative carbon dioxide "pollution" and the greenhouse effect. They urge more funding to study it. However, most believe that if there are any sort of changes, they will be in the distant future — a hundred years or more. Keeling's recent data [7], however, makes many uneasy.

ACTIVITY 3. Add Keeling's data from 1960-1964 to the graph from Activity 2.

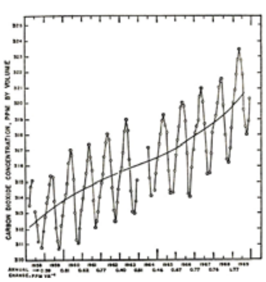


THINK (6). Keeling's graph shows a steady increase from 1957 to 1964. Yet does it represent a significant increase or just natural variation? Identify several reasons both for taking this limited data seriously and for considering any firm conclusions as premature. In a case of uncertainty such as this, what principles should guide one's decisions?

Many scientists are aware of the concept of the greenhouse effect and acknowledge that humans are releasing carbon dioxide into the atmosphere. Yet most assume that the oceans will absorb the excess carbon dioxide. Keeling's data, however, seems to match calculations by Suess, Revelle and others about how much CO_2 is produced by burning and how much is absorbed by vegetation and by the oceans.

With the public concern about humans affecting the Earth growing, the President asks his Science Advisory Committee to consider the mounting environmental issues. They recognize the importance of greenhouse warming and recommend monitoring CO_2 for at least the next few decades [8]. The U.S. Weather Bureau, too, plans to begin measuring CO_2 at various locations.

ACTIVITY 4. Add Keeling's data from 1964-1969 to the graph from Activity 3.



It is now 1969. The slight increase in CO_2 levels that was visible in 1964 has continued.

THINK (7). How should one interpret the significance of these data now, five years later? What specific factors are relevant to your assessment? Compare this with your assessment for 1964 (THINK 6).

Keeling began recording CO_2 mainly to establish a background level for the atmosphere. Now the steady increase seems to indicate a significant trend. As awareness of air pollution grows, with the U.S. Congress increasing government powers to enforce clean air in 1967, the earlier speculations about the role of burning carbon fuels loom much larger. In 1969, Keeling talks to the American Philosophy Society on the implications of the steadily rising CO_2. He ponders the significance of human impact on the environment and the effects of releasing carbon that was removed from the atmosphere 500 million years ago in the production of coal:

The rise in CO_2 is proceeding so slowly that most of us today will, very likely, live out our lives without perceiving that a problem may exist. But CO_2 is just one index of man's rising activity today. We have rising numbers of college degrees, rising steel production, rising costs of television programming and broadcasting, high rising apartments, rising numbers of marriages, relatively more rapidly rising numbers of divorces, rising employment, and rising unemployment. At the same time we have diminishing natural resources, diminishing distract-free time, diminishing farm land around cities, diminishing virgin lands in the distant country side ...

[Viewed over thousands of years] I am struck by the obvious transient nature of the CO_2 rise. The rapid changes in all factors I [have just] mentioned, including the rapid rise in world population, are probably also transient; these changes, so familiar to us today, not only were unknown to all but the most recent of our ancestors but will be unknown to all but the most immediate of our descendants. [5]

Meanwhile, new data from ice sheets and sea beds indicate that Earth's climate can change far more quickly than previously believed [7].

Challenges from NOAA and NSF

Late in 1969, Keeling takes another year of leave and travels to Germany with his family. There he studies the recent achievements of the European scientific community and serves on a committee to develop standards on how to measure carbon dioxide for the recently formed World Meteorological Organization (WMO).

When he returns, he learns that the U.S. Weather Bureau has been reorganized under a new name, the National Oceanic and Atmospheric Administration, or NOAA. In addition, they had tried to purchase one of Keeling's own analyzers with the intention of taking their own CO_2 measurements alongside the Scripps program at Mauna Loa.

NOAA's intentions worry Keeling a great deal. They indicate that NOAA plans to relieve Keeling of his monitoring duties. Keeling does not necessarily object to NOAA measuring CO_2, but he does not trust them to do it with adequate precision. However, with backing of the WMO (whose support he secured in Germany), Keeling's funding does not appear to be in danger. He even opens another sampling station in the remote Pacific.

Meanwhile, Keeling faces a major problem in the lab. One of Keeling's technicians has found that results from the infrared analyzers vary depending on the type of gas used to dilute the CO_2 sample (nitrogen versus regular air). This could jeopardize the results for nearly all of their sampling sites. They calculate the necessary correction factor. Fortunately for Keeling, the correction is modest. The mishap does not threaten the existing data. Nevertheless, new calibrated gas samples are needed for both CO_2 in air and in nitrogen. The NOAA investigators, not wanting to wait for new calibration, go ahead with the formation of their own CO_2 monitoring program.

> **THINK (8)**. Discuss whether Keeling's concerns about calibration are justified. Explain how you think Keeling should respond to NOAA's decisions.

Within a relatively short time span Russia, the United States and Africa all experience severe droughts. Crops die. Lack of monsoon rains in Southern Asia reduce yields there, as well [7]. Increasing environment awareness helps further spur a growing environmental movement, marked by events under the banner of Earth Day, 1970.

Despite the growing public awareness of environmental problems, Keeling finds his funding at risk again. No sooner does the NSF award Keeling another two-year grant than they began to backpedal on dispersing such funds. They regard his work as "routine" and would rather fund ground-breaking research. The not-so-subtle gesture indicates to Keeling that he should begin transferring the measurement stations to suitable government agencies (such as NOAA).

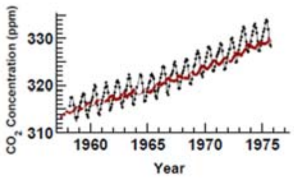
> **OPTIONAL THINK (C)**. As Keeling, how would you respond to NSF's implicit threat?

Keeling argues that he and his collaborators are still making new discoveries from the data. Indeed, soon after the confrontation, a physicist who worked at Mauna Loa finds that after removing the influence of fossil fuels, the CO_2 data record exhibits variation over the decades, possible evidence of yet unknown natural cycles. With further research, they find that the data match and help confirm an emerging theory about a weather pattern, known for several decades, called the "southern oscillation," or sometimes El Niño.

Also in Keeling's favor are his reference and standard gases. In 1975, the WMO hosts a meeting at Scripps to standardize methods and references for measuring CO_2. NOAA advocates economizing on costs using less stringent standards. The group as a whole, however, concludes that Keeling's laboratory should calibrate the gases for the programs worldwide. To assist, the newly launched United Nations Environmental Program (UNEP) provides two years of funding to assist with calibrating the standards.

Progress moves slower with less staff, but Keeling is still able to publish his next set of data. This also shows the adjustments for the "gas carrier" effect (the measurement differences due to the dilution gas).

> **ACTIVITY 5**. Add Keeling's data from 1969-1976 to the graph from Activities 2-4.



THINK (9). How should one interpret the significance of these data, now another seven years later? Compare to your assessments for 1964 and 1969.

Funding Woes, Again

A new governmental organization is also beginning to take notice. The Energy Research and Developmental Agency (ERDA) is formed by piecing together parts of other organizations. Its director, Alvin Weinberg, is interested in supporting the study on the effects of carbon dioxide on the environment. A strong supporter of nuclear energy, he is interested in casting fossil fuels in an unfavorable light.

Soon thereafter, ERDA becomes part of a new Department of Energy (DOE). Climate scientists meet to decide what to do with the money now available for studying CO_2. NOAA reiterates its desire to take over the monitoring. But they admit they are not quite prepared to take over Keeling's stations. They decide to continue Keeling's funding, but only for the next two years.

NSF also notifies Keeling again that his work is routine and advise him that they will discontinue support in 1977. In addition, officials from UNEP send word that their funding for Keeling and Scripps will last just two more years, as they were only allocated to start up the international program.

In the midst of these funding woes, aid comes from Keeling's colleague and friend, and his earlier host in Germany, Karl Otto Muennich. Realizing Keeling's troubles with generating exciting new conclusions to impress the governmental organizations, Muennich proposes a look at the carbon isotopes in their gas samples over time. Atoms can have varying number of neutrons, affecting the element's weight. Carbon is no exception. In addition, different sources of carbon (such as fossil fuels or the atmosphere) tend to have distinctive percentages of "normal" carbon atoms and heavy or light atoms. This will enable them to track the specific sources responsible for the increase in CO_2 levels.

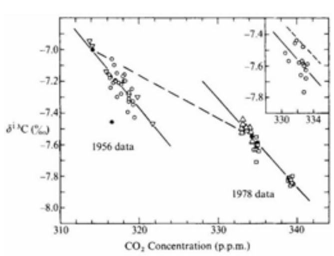
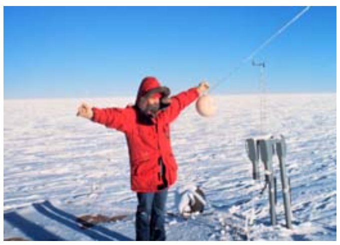


Fig. 1 Change in the relation between carbon isotopic ratio $\delta^{13}C$, and concentration of atmospheric CO_2 over 22 yr.

With collaboration from Muennich and his assistants, Keeling finds that the isotope ratio has indeed shifted with the burning of fossil fuels. Moreover, they are able to correlate them. This indicates that the increase of carbon dioxide in the atmosphere is indeed due to fossil fuels burned by humans. It is not due to "natural" variation or cycles. Keeling is confident this breakthrough will secure more funding for his program. But he soon learns that DOE has agreed to fund the NOAA's CO_2 measurement program instead. In addition, NOAA has begun collaborating with the U.S. Geological Survey to study the isotopes in their samples: another not so subtle message that they are assuming responsibility for monitoring global carbon dioxide. By championing his new studies, however, Keeling manages to scrape together another two years of funding from the NSF, provided he agrees not to seek funding again.

> **OPTIONAL THINK (D)**. Has Keeling's work finally become routine? Has NOAA exhibited its ability to maintain the program effectively? Discuss whether Keeling is justified in defending his program scientifically or seems just to be protecting his own personal interests.

Taking a risk, Keeling again takes a leave from Scripps and travels to Europe to learn more about the Earth's climate. This time he goes to Switzerland, where researchers are refining measuring techniques for CO_2 trapped in ice bubbles from glaciers. The trip is a success in terms of the research project and new ideas for studying his own collection of data. But he is forcefully reminded of his challenges at home when he receives a letter from NOAA on how to transfer his program to them when his funding runs out.



Keeling had spent nearly three decades honing methods for collecting CO_2. He still does not think that NOAA will adopt adequate levels of precision and accuracy. He fears that departure from his methods will invalidate new data, while ruining the capacity to make long-term comparisons. By this time, the experience and expertise of Keeling and his technicians was unparalleled worldwide. Keeling expressed his exactitude in a 1976 paper:

> *The sample taker, to minimize contamination from his own breath, was instructed to sample only when the wind was at least 5 knots. After first breathing normally near the site for some moments, he exhales, then inhales slightly, and finally without exhaling again, walks 10 steps into the wind, where he takes the sample … Only one member of the South Pole field party was designated each year to take samples. Prior to arrival in Antarctica, he received two days of instruction from Scripps personnel. The results of his practice sampling were determined by gas analysis while he was still undergoing training.* [6]

In 1981 Keeling meets with the head of DOE (David Slade), the director of the NOAA CO_2 program and the head of Scripps to discuss funds for measuring CO_2. He argues that new breakthroughs continue and that because the NOAA and USGS data do not match his own, they are unreliable substitutes. The arguments seem to fall on deaf ears. Then during the wrap up session Slade offhandedly states that the DOE can still pick up the tab for Keeling's work. Not long after, Keeling learns that the director of Scripps had contacted one of Slade's advisors and put in a special word on the importance of keeping Keeling's program going. Slade had thought it over and ultimately taken the advice.

Political Woes

Soon after Keeling is guaranteed funding for two more years, Ronald Reagan is elected President. A strong critic of the environmental movement and of climate change claims, he moves swiftly to cut any research in these fields [8]. Shakeups in the scientific adminstration are immediate. Slade (who had helped rescue Keeling's program) is out at DOE. Replacing him is Fred Koomanoff, who announces that he will withhold any funds for CO_2 research that have not already been dispersed.

> **THINK (10)**. Here, the basis for a funding decision seems based on criteria other than scientific merit or skills. Should science be wholly independent of culture, or is it appropriate that scientists respond to social values? Does this seem to be a fair reflection of cultural values, or is it "just politics"? Using this case as an example, how could one insulate scientific research from unwarranted political influence or short-term shifts in culutral values?

Rallying support for the environment and for research on the greenhouse effect, a junior Congressman named Al Gore holds hearings on the environmental issue now known as "global warming." The testimony of leading climate researchers such as Revelle, Keeling's former mentor [7], hits the major news media. Swamped by the attention, the Reagan administration relents, sparing at least some of the climate research funding. Regardless, tight budgets force Keeling to once again look for other sources of support.

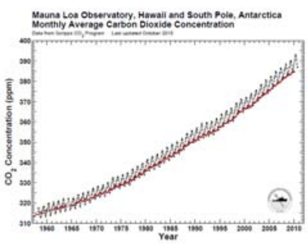
Re-applying for funding from the NSF, Keeling argues that his data does not match NOAA's new findings and that the WMO is still using Scripps' gases for standards. He also comments now on the importance of having long term data from the same source. While NOAA had urged WMO to switch to the new U.S. government gas standards, WMO resists, implicitly endorsing Keeling's precision and accuracy. NOAA and DOE concede to fund Keeling and Scripps for one more year -- but only with an agreement that they help transfer the Mauna Loa station to NOAA.

Ultimately, DOE continues to fund Keeling in varying amounts over the next few years. Keeling also cobbles together other amounts from NSF and WMO. The head of Scripps, in another unexpected but welcome show of support, lines up funding from a private organization.

Keeling manages to sustain the program through the eight years of the Reagan Presidency. In the subsequent adminstration, DOE becomes receptive again to Keeling's pleas and funds his work. When the Presidency changes again in 1994, the new DOE administrators decide to fund climatological research only where relevant to land-based carbon processes (crops and forestry). Challenged yet again, Keeling is able to persuade them of the importance of the global monitoring of CO_2 to measure plant absoprtion of CO_2. As the signficance of the data and its relevance to climate change policy becomes clearer in subsequent years, funding, ironically, finally becomes more routine.

Epilog

Both the NOAA and Scripps continue to monitor CO_2 levels at Mauna Loa with Keeling's standards for accuracy -- ultimately adopted by NOAA. In 1988 an international group of scientists (the Intergovernmental Panel on Climate Change, or IPCC) began to assemble a more systematic and synoptic view of climate change and its potential global impacts. The data from Keeling and his colleagues -- now documenting three decades of increasing carbon dioxide levels -- became part of an undeniable connection between humans and rising global tgemperatures and the changing of the Earth's climate pattern.



The graph is now widely known, fittingly, as the "Keeling Curve." Global carbon dioxide continues to rise. It currently measures 390 ppm, more than 25% higher than when Keeling began measuring in 1953.

THINK: NOS Reflection Questions

Discuss how the case of Charles Keeling & Measuring Atmospheric CO_2 illustrates the following features of the nature of science:

> the role of long-term data (THINK 6, 7, 9)

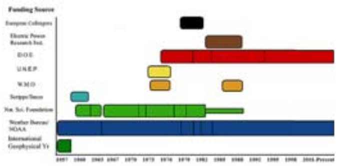
Consider again the Keeling Curve. While Arhennius speculated about global warming in the late 1800s, and Revelle, Suess and others calculated crude estimates in the late 1950s, concerted attention to global change did not emerge until the late 1970s. By that time, Keeling had already accumulated more than 2 decades of measurements. Recall also the ability to "mine" the data in later studies. Compare your own assessments of the data in 1960, 1964 and 1969 with our present knowledge. Discuss the role of long-term data, both their use and the task of generating them.

In 1969 Revelle (Keeling's mentor) commented on the prospect of global warming:

> *Human beings are now carrying out a large scale geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future. Within a few centuries, we are returning to the atmosphere and oceans the concentrated organic carbon stored in sedimentary rocks over hundreds of millions of years.* [6]

How does this claim appear different now than to a listener in the 1960s?

What is the role of Keeling's long term data on issues that were once considered uncertain?



> funding science (THINK 10)

Review the many organizations that funded Keeling's research. Recall, too, Keeling's major funding crises: in 1958 (completion of IGY), in 1964 (all funding cut), in 1973 (NSF against routine funding, NOAA creating their own program), in 1977-1980 (NSF, DOE, NOAA striving to streamline the process under NOAA), and in 1981 (political context). What factors shape funding in science? Are some more important than others?

In retrospect, do you think the system functioned well in this case? Can you propose any revisions (beyond just wishing for more money!) that might improve how funds are allocated, especially in cases of developing long-term data?

> role of instruments (accuracy, calibration and precision) (THINK 1, 2, 3, 4, 8)

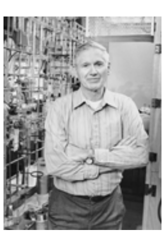
Keeling was always concerned about the quality of the measurements, including proper calibration. How was calibration -- assessing an instrument's performance against known standards -- important to the results and the conclusions based on them? How was precision -- the ability to confidently discern small differences in measurements -- important in detecting patterns in Keeling's data and the conclusions based on them (especially in the early studies)?

> cultural and political contexts of science (THINK 10)

Review your earlier reflections on politics and science in light of subsequent events. In what ways should science respond to cultural values and changes in cultural values, and in what ways should it be independent and "insulated" from such concerns?

> role of collaboration (THINK 5)

Recall all the persons who assisted Keeling personally or who worked as collaborators. How did they shape the scientific outcome?



> science as a career/human dimension of science (OPTIONAL THINK A, B, C, D)

Consider again the personal decisions and actions that shaped Keeling's career. In what ways did his motivations and interests contribute to science, and in what ways did they limit it? What do you regard as a proper balance between personal and professional concerns?

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