The Mauna Loa Carbon Dioxide Record: Lessons for Long-Term Earth Observations

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The Mauna Loa carbon dioxide record is an iconic symbol of the human capacity to alter the planet. Yet this record would not have been possible without the remarkable work of one man, Charles David Keeling. We describe three emergent themes that characterized his work: (1) his desire to study and understand the processes that control atmospheric CO_2 and the global carbon cycle, (2) his campaign to identify and minimize systematic measurement error, and (3) his tenacious efforts to maintain continuous funding despite changing government priorities and institutions. In many ways, the story of the Mauna Loa record demonstrates that distinctions between research and "routine" measurements are not very useful in long-term monitoring of Earth properties and processes.

1. INTRODUCTION

Charles David Keeling, who passed away in June 2005, directed a program to measure the concentrations of CO_2 in the atmosphere that continued under his direction from the late 1950s until his passing in 2005. This program, operated out of Scripps Institution of Oceanography in collaboration with the National Oceanographic and Atmospheric Administration (NOAA), is responsible for the Mauna Loa CO_2 record, which is almost certainly the best known icon illustrating the impact of humanity on the planet as a whole (Figure 1). Informally, this plot is known as the "Keeling Curve" throughout the scientific community.

This chapter emphasizes lessons learned about making long-term measurements based on the experiences of the Scripps atmospheric CO_2 program. Readers are referred to C. D. Keeling's autobiographical article, "Rewards and penalties of monitoring the Earth" [*Keeling*, 1998], which recounts many of the efforts, some quite exceptional, necessary to sustain the Scripps CO_2 measurements at Mauna Loa and elsewhere for a period of decades. It is clear that a nearly unbroken record over such a long time frame would not have been possible without the singular talents and persistence of an extraordinary scientist, and it is doubtful that a single individual could accomplish similar lifetime achievements within the constraints of today's science infrastructure. Nevertheless, we believe that the story of the Mauna Loa CO_2 record offers fundamental lessons for current and future planning and implementation of long-term Earth observations. The need to monitor the Earth is now more acute than ever, and the development and implementation of useful long-term global observations is one of the major scientific challenges of our time.

This chapter draws on the authors' familiarity with the published papers of C. D. Keeling (whom we will call CDK

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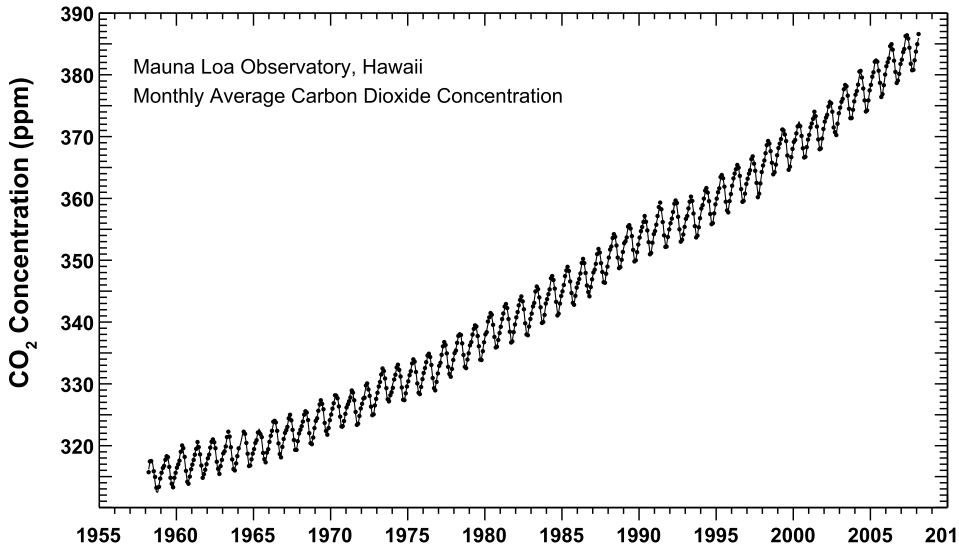

Figure 1. Monthly average CO_2 concentration at Mauna Loa Observatory, Hawaii, 1958–2005.

here) and on our experience as close observers of his work during the latter part of his professional career. We have also reviewed extensive documentation available in his files at Scripps. We focus here on three emergent themes.

1. The Scripps CO_2 measurements were sustained above all by a multidecade research quest to understand the processes that control the long-term global mass balance and partitioning of carbon.

2. The quality and utility of the Mauna Loa CO_2 data set and the other Scripps CO_2 measurements depended on CDK's career-long campaign to identify and minimize systematic error.

3. The Mauna Loa CO_2 record and other Scripps CO_2 measurements could not have been sustained without extraordinary efforts to maintain continuous funding despite the vagaries of government priorities and institutions.

2. UNDERSTANDING THE CONTROLS ON ATMOSPHERIC CO_2

The idea of making measurements at Mauna Loa arose while CDK was doing postdoctoral studies at Cal Tech. In the course of studying carbon in river water, a project that incidentally required making measurements of CO_2 in air, he made the key discovery that when he sampled the air in places remote from cities and other obvious sources or sinks for CO_2, he always got almost the same value of about 310 ppm [*Keeling*, 1958]. Previous measurements of CO_2 in the atmosphere did not show such constancy, but those measurements had been made by wet chemical methods considerably less accurate than the dry manometric method he employed. This postdoctoral experience taught him two key lessons that were to guide his entire career: (1) the Earth system might behave with surprising regularity, and (2) highly accurate measurements are necessary to reveal this regularity.

The discovery of this stable background CO_2 concentration begged the question of how stable was stable? Were there small fluctuations? Was the background rising because of human influences? Discussions ensued with Harry Wexler of the U.S. Weather Bureau, who suggested that CO_2 concentrations be measured on a continuing basis at the newly created stations in Antarctica and near the summit of Mauna Loa. Rather than accepting an offer to join Wexler in Washington, D.C., CDK instead chose to move to the Scripps Institution of Oceanography, where Roger Revelle was interested in starting a CO_2 measurements program. Revelle was independently interested in the question of rising CO_2 and was working at the time on a landmark paper with Hans Suess on this topic. Revelle believed the right approach to resolving changes over time was to make large surveys of CO_2 concentrations at many locations in the atmosphere and ocean at, say, decadal intervals. Wexler and Revelle both recognized that CDK's methods and preliminary measurements held promise for obtaining a global "snapshot" of global CO_2 levels during the International Geophysical Year of 1957–1958. By maintaining the interest and support of Wexler at the Weather Bureau, CDK was ultimately able to set up measurements at Antarctica and Mauna Loa while initiating an airborne and shipboard sampling program under Revelle at Scripps. Remarkably, by age 30, CDK had established the basic analytical techniques, sampling strategies, and calibration methods that would sustain his career-long contributions to understanding the nature and causes of variations in atmospheric CO_2. This approach involved using a nondispersive infrared analyzer to compare samples from flasks or in situ measurements with calibration gases and employing a high-accuracy manometer for the absolute calibration of the calibration gases.

During the late 1950s, a growing number of scientists became interested in studying effects of human activities on the global carbon cycle—that is, the ongoing cyclic exchange of the element carbon in various forms among plants, animals, air, water, and earth [see *Sundquist et al.*, this volume]. This interest was perhaps best exemplified by the Revelle and Suess manuscript. Published in 1957, that paper [*Revelle and Suess*, 1957, pp. 19–20] contained perhaps the most often quoted lines in the immense body of literature concerning human impacts on the global carbon cycle:

> Thus 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. This experiment, if adequately documented, may yield a far-reaching insight into the processes determining weather and climate. It therefore becomes of prime importance to attempt to determine the way in which carbon dioxide is partitioned between the atmosphere, the oceans, the biosphere and the lithosphere.

For more than half a century now, the words "large-scale geophysical experiment" have been a rallying cry for the need to understand human manipulation of atmospheric CO_2 as a profound global environmental change. In that single memorable paragraph, Revelle and Suess described the connections between human production of CO_2 and the full array of earth and biological processes that cycle carbon, extending over geologic time. The statement's reference to weather and climate is, of course, an allusion to the so-called greenhouse effect, a natural warming influence of the Earth's atmosphere that is enhanced by increasing concentrations of CO_2.

Against the background of this concern, the value of the Mauna Loa record quickly became apparent. The first year of measurements there was somewhat stressful, as measured CO_2 concentrations drifted unexpectedly, in contrast to the relatively stable values observed in Antarctica. Understanding the drifting values was complicated by power outages that interrupted measurements for weeks at a time. Nevertheless, the mean values recorded at Mauna Loa agreed closely with those measured in Antarctica and in samples taken from ships and planes. Within just a few years, CDK showed that the observed variations at Mauna Loa were part of a regular seasonal cycle, reflecting the seasonal growth and decay of land plants in the Northern Hemisphere, superimposed on a steady long-term rise that was also observed in Antarctica and attributed to the burning of fossil fuels [*Keeling*, 1960; *Pales and Keeling*, 1965; *Brown and Keeling*, 1965]. In fact, the annual mean CO_2 measurements at Mauna Loa turned out to be a very good representation of the global atmospheric average. These measurements provided not only the first global CO_2 "snapshot" sought by Revelle but also the first opportunity to use systematic trends in atmospheric CO_2 concentrations to understand the influence of global carbon cycle processes. In particular, the Antarctic and Mauna Loa records documented for the first time the year-to-year rise in global CO_2 due to burning fossil fuels.

CDK realized from the start that understanding the Mauna Loa record required comparison to measurements at other widely distributed locations. By the mid-1960s, he had analyzed air samples collected from ships, planes, and land stations extending from Antarctica to Point Barrow, Alaska. During a year in Sweden, CDK worked with Bert Bolin (later to become the first Chair of the Intergovernmental Panel on Climate Change) to evaluate how the observed CO_2 variations were affected by atmospheric circulation and by latitudinal and seasonal variations in industrial and natural uptake and release [*Bolin and Keeling*, 1963]. The long-term secular increase in atmospheric CO_2 was determined to occur at about one-half the rate of industrial CO_2 production [*Pales and Keeling*, 1965]. This crucial observation was quickly highlighted by the U.S. President's Science Advisory Council, which extrapolated the effects of rising fossil fuel consumption to predict future atmospheric CO_2 levels [*Revelle et al.*, 1965]. Thus, within the first decade of his postgraduate career, CDK established the first global CO_2 observation network, demonstrated that these observations are essential to discerning and anticipating trends in the natural and industrial processes that control atmospheric CO_2, and provided the key data used to support research recommendations at the highest level in the U.S. government.

CDK also realized that his measurement methods could be extended to analysis of CO_2 in gas samples equilibrated with ocean surface water. Knowing the importance of global air-sea CO_2 exchange, and taking advantage of previous publications and the availability of the Scripps research fleet, he undertook the first global map of ocean surface dissolved CO_2 concentrations [*Keeling*, 1968]. With Bolin, he developed numerical box models to simulate large-scale ocean-atmosphere exchange and mixing [*Keeling and Bolin*, 1967, 1968]. These efforts initiated CDK's considerable influence on oceanic CO_2 measurements, described in more detail by *Brewer* [this volume].

By the early 1970s, the Mauna Loa record had played a key role in launching international research programs to understand the effect of rising CO_2 on climate [*Keeling*, 1998]. As the Scripps CO_2 observations expanded to new sites and extended in time, the growing record continued to reveal the influence of global processes. The steady rate of increasing CO_2 levels became a primary benchmark for refining models to predict the effects of burning fossil fuels on the global carbon cycle and climate. CDK was in the vanguard of this research. Not content with previous estimates of historical industrial CO_2 production, he compiled and published his own estimates [*Keeling*, 1973], which stood as a standard data set for many years. With his Scripps colleagues Robert Bacastow and Charles Ekdahl, CDK used his CO_2 measurements to constrain a predictive numerical box model of the global carbon cycle [*Ekdahl and Keeling*, 1973; *Bacastow and Keeling*, 1973]. This model was so well explained and meticulously documented that it became a carbon cycle "tutorial" for generations of younger scientists (including the authors of this chapter).

Continued measurements and modeling of the global CO_2 budget in the 1970s and 1980s indicated that the cumulative fraction of industrial CO_2 remaining in the atmosphere (the "airborne fraction") was between 50% and 60% [*Keeling et al*., 1976b, 1985]. This observation was consistent with improved ocean models that showed that CO_2 absorption by the oceans (perhaps combined with some uptake by terrestrial plants) could account for the rest of the industrial CO_2 [*Siegenthaler and Oeschger*, 1978, 1987]. These conclusions were supported by measurements of the isotope ratio $^{13}C/^{12}C$ in samples of atmospheric CO_2 collected by CDK in 1955–1956 and 1977–1978 [*Keeling et al.*, 1979]. Thereafter, carbon isotope analyses were added to the suite of Scripps CO_2 measurements in collaboration with Wim Mook of Groningen University.

As the atmospheric CO_2 record extended in time, CDK and his colleagues observed important spatial and temporal variations that revealed further information about controlling processes. Much of this work was summarized in two book-length collections of papers [*Keeling et al.*, 1989, 2001]. An increasing latitudinal concentration gradient reflected the effects of atmospheric mixing and the "piling up" of industrial CO_2 near its predominant sources in the Northern Hemisphere. These relationships provided a basis for model-based inferences about other CO_2 sources and sinks. The correlation of climatic trends with subtle interannual and interdecadal variations in atmospheric CO_2 also became an important focus. Bob Bacastow discovered that the secular rise in CO_2 levels was modified by interannual variations correlating with global meteorological variations known as El Niño events [*Bacastow*, 1976; *Bacastow et al*., 1980]. The amplitude of the well-defined seasonal CO_2 cycle was observed to be increasing in the Northern Hemisphere in a manner that correlated with rising regional land temperatures [*Bacastow et al*., 1985; *Keeling et al*., 1996]. These observations regarding climate-CO_2 interactions foreshadowed increasing concern about potential positive CO_2 feedbacks to global warming.

Looking ahead, international organizations such as the Intergovernmental Panel on Climate Change are engaged in research to determine the potential effects of future fossil fuel burning and counteractive measures, including deliberate carbon sequestration. Throughout his career, CDK had a strong sense of the "big picture" of the global carbon cycle and its perturbation by human activities. He shared this view through the powerful lens of his research on systematic variations in atmospheric CO_2. Whatever future actions and policies are taken concerning fossil fuels and climate change, their impacts will be directly reflected in continued measurement and understanding of atmospheric CO_2 concentrations.

3. IDENTIFYING AND MINIMIZING SYSTEMATIC ERROR

Just as CDK's work was driven by his desire for understanding, it was defined by his passion for identifying and minimizing systematic error in his measurements. Until his development of a constant-volume manometer for calibration of reference gases, atmospheric CO_2 measurements had yielded erratic values that defied systematic interpretation [*Keeling*, 1998]. Before his adaptation of an infrared analyzer to provide precise and continuous monitoring, sources of sample variation and contamination had been very difficult if not impossible to distinguish.

In CDK's first (1956–1957) proposals for U.S. Weather Bureau support to initiate monitoring at Mauna Loa and Antarctica, substantial fractions of the budget were for purchase of infrared analyzers and construction of the calibration laboratory at Scripps. The value of these investments became quickly apparent. The calibrated measurements confirmed and extended to global scale CDK's postdoctoral observations of uniform concentrations in samples from remote locations. The deployment of continuous infrared analyzers made it possible to reveal secular variations (such as the initial discovery of seasonal cycles) after eliminating sources of local contamination. Preliminary results were presented at scientific meetings and published [*Keeling*, 1960; *Bolin and Keeling*, 1963], with immediate impact as described earlier in this chapter.

A full account of CDK's sampling and calibration procedures was not published until 1965 [*Brown and Keeling*, 1965; *Pales and Keeling*, 1965]. These remarkable papers provided the first detailed description of the level of care that CDK had taken to minimize sources of systematic error. As an indication of his respect for the importance of attention to detail in field measurements, CDK published these seminal papers with first authorships given to Craig Brown and Jack Pales, his on-site technicians at Antarctica and Mauna Loa, respectively.

The 1965 papers included diagrams and an aerial photo showing field station facilities, sampling sites, and potential sources of contamination. Sample lines for the continuous analyzers were located at compass quadrants to allow comparison of source effects based on prevailing wind directions. Although no local sources were apparent in the measurements at Antarctica, the continuous analyzer at Mauna Loa showed periods of short-term variability that appeared to be associated with wind direction and diurnal events. The Mauna Loa observations required that data be selected only from periods when measurements were stable for periods of several hours. (This procedure was affirmed by later analysis in which short-term variations at Mauna Loa were attributed to contamination by vegetation, car exhaust, and volcanic CO_2 vents, in combination with diurnal variations in prevailing winds. Many of these problems were minimized by deployment in 1972 of a 27-m-high tower with two intakes.) Flask samples were also collected at both sites and analyzed at Scripps. Comparison of results from the flask analyses with values from the continuous analyzers revealed a flask storage artifact attributed to photooxidation of stopcock grease during long exposure to sunlight at Antarctica. The subsequent improvements in storage procedures soon became crucial because funds for the continuous analyzer at Antarctica ran out.

Further analyses of variability and other sampling and calibration issues were published in 1976 [*Keeling et al.*, 1976a, 1976b]. As always, attention to detail was conspicuous. Despite many precautions (see below), contaminated flask samples were not uncommon, and iterative statistical screening procedures were developed based on standard errors observed in control groups of uncontaminated samples taken at Scripps. The papers also described how CDK had instituted a hierarchy of reference gases, in which each "working" reference gas was compared in the field 20 to 30 times with "semipermanent" reference gases during its period of use and compared 30 times with semipermanent reference gases at Scripps both before and after use in the field. The semipermanent reference gases used in the field were, in turn, compared with the semipermanent reference gases kept at Scripps at least 50 times both before and after use in the field. Finally, some of the semipermanent reference gases at Scripps were compared at least 150 times with manometrically calibrated standard gases. Repeated manometric calibrations over the period 1959–1974 had documented a slight (0.06 ppm) drift over time in the Scripps semipermanent reference gases.

More importantly, the 1976 papers described a significant carrier gas effect on analyses made by the infrared analyzers. From the beginning of CDK's monitoring program, the reference gases used in calibration had been prepared as mixtures of CO_2 and nitrogen to minimize possible degradation resulting from the presence of oxygen. In the early 1970s, a comparison of several different kinds of infrared analyzers revealed discrepancies that could be explained only by different infrared absorption sensitivities to oxygen in air. Exhaustive experiments confirmed that the entire Scripps CO_2 data set required upward adjustment between 2.5 to 4 parts per million to account for this effect. Because most uses of the data had relied on concentration differences rather than absolute values, previous conclusions based on the data set remained intact. New standard gases of CO_2 in air were prepared, while the CO_2-in-nitrogen standards were retained to assure the long-term continuity of the data set.

In subsequent publications, CDK continued to place utmost priority on the long-term integrity of sampling and calibration. Data selection procedures were reexamined for both the entire Mauna Loa data set [*Keeling et al.*, 1982] and the entire flask dataset [*Keeling et al.*, 1989]. Small adjustments were applied to be consistent with ongoing examination of the drift observed in calibration of reference gases [*Keeling et al.*, 1982]. CDK continued his reexamination of long-term sampling and calibration issues until the time of his death.

We conclude this section with two quotes that exemplify CDK's determination to minimize systematic error. His attention to detail could be mind-boggling, as in the following description of flask sampling procedures for Antarctica [*Keeling et al.*, 1976b, p. 553]:

> The sample taker, to minimize contamination from his own breath, was instructed to sample only when the wind was at least 5 knots (2.6 m sec^{-1}). 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.

CDK also fully recognized that his constant hunt for systematic errors was often unattractive to readers and reviewers. In 1973, near the end of a long letter detailing calibration and data reduction procedures, he wrote (CDK, letter to Frank Eden, 6 March 1973) "the topics so far discussed all relate to essentially technical operations. At this time they are by no stretch of the imagination routine, but they are extremely tedious. They may never be all properly solved simply because they bore people."

CDK never regarded any aspect of his work as routine, least of all his continual quest to identify and minimize systematic error in his measurements. As the time span of the Scripps CO_2 data set grew longer, this quest never diminished. The particular challenges of long-term calibration and data reduction continued to occupy much of his attention.

4. STRUGGLING TO MAINTAIN CONTINUOUS SUPPORT

In his autobiographical memoir [*Keeling*, 1998], CDK made it clear that he regarded the "penalties" of his work to be his many difficulties in dealing with federal program managers who sought to cut his funding, take over his measurements, or both. To his published account of these problems, we add a graphical representation (Plate 1) of the challenges he faced in maintaining continuous support for his 50-year record of global atmospheric CO_2 concentrations. Despite the relentless increasing trend shown in the Mauna Loa CO_2 record, there was nothing inevitable about obtaining the record itself. The record was interrupted briefly in 1964 after congressionally mandated budget cuts and staff reductions at both Scripps and Mauna Loa. The record probably would have been discontinued at that time had CDK not pushed hard to keep it going. The program also endured a series of threats through the 1970s and 1980s associated with coordinated efforts by program officers at the National Science Foundation (NSF) and NOAA to transfer full responsibility for global CO_2 observations to NOAA. Important additional support was eventually obtained from the U.S. Department of Energy (DOE), but this support was subject to occasionally bizarre requirements, such as a "mandated convergence" with NOAA and a requirement that new discoveries be made at a pace of two per year [*Keeling*, 1998].

One incident, not reported by CDK in his autobiography, is worth recounting because it illustrates the extent to which his work was considered worthy of replacement by a federal program from the moment it received attention in high policy circles. As described above, in 1965 CDK coauthored an important Presidential Advisory Committee report [*Revelle et al.*, 1965]. This report included a recommendation that "a series of precise measurements of the CO_2 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" [*Revelle et al*., 1965, p. 127]. This was a clear reference to the Weather Bureau–supported Scripps CO_2 program.

Within weeks after publication of this report, a Weather Bureau program manager formally invited a Swedish CO_2 expert to spend a year or more in the United States to help start "an enhanced program of world-wide monitoring of CO_2." The invitation letter stated that "a committee of the highest scientific body in the U.S. Government" had "specifically charged" the Environmental Science Services Administration (ESSA, which housed the Weather Bureau) "with continuing the surveillance of background CO_2" (L. Machta, letter to W. Bischof, 23 December 1965). The letter omitted the report's recommendation concerning the Weather Bureau "and its collaborators," which had obviously been a reference to CDK and the Scripps CO_2 program. The Swedish scientist was offered the assistance of a Weather Bureau employee who had previously worked in CDK's laboratory.

CDK had little choice but to go along with this arrangement, but he expressed his concerns about the quality of the planned ESSA program in a meeting the following spring. In response, the program manager wrote that "You may have gathered that I hope to have ESSA scientists relieve you … from any need to study the secular changes. Creative scientists such as yourself could devote your time fully to other important aspects of the carbon dioxide cycle in the atmosphere." (L. Machta, letter to CDK, 10 March 1966). A year earlier, the same program manager (L. Machta, letter to CDK, 30 April 1965) had sent another letter "to inquire into your views for having the National Bureau of Standards accept responsibility for providing standard CO_2 gas samples." This letter offered the view,

> What worries me most about your accepting this responsibility, as you have in the past, are the possible lack of continuity should you change your interest or otherwise be unable to continue to supply tanks and the fact that as more organizations become interested in the problem your research efforts might be diluted with operational burdens.

At the time of these initiatives, neither ESSA nor the National Bureau of Standards had demonstrated any independent capability to conduct an atmospheric CO_2 program. Thus, in the flush of his early rise to scientific prominence (and several years before what he described in his autobiography as "first signs of trouble"), CDK was exposed to the frustration of federal program proposals that jeopardized his research on the basis of false dichotomies between "creative" and "operational" activities, and questioned his commitment to long-term continuity of the effort.

Over the last decade, the Scripps CO_2 program has coexisted peacefully alongside a much larger effort by NOAA. In hindsight, one wonders why the growth of the NOAA program necessarily was viewed as requiring a complete cessation of CDK's monitoring and calibration activities. The benefits of retaining a Scripps effort seem clear enough. First, core expertise and experience resided in CDK's program. As long as there was a desire on his part to continue these efforts, why was this not welcomed? Having two programs was also arguably very important for long-term continuity. As CDK stated: "There was no guarantee that NOAA's program might not have problems in the future.

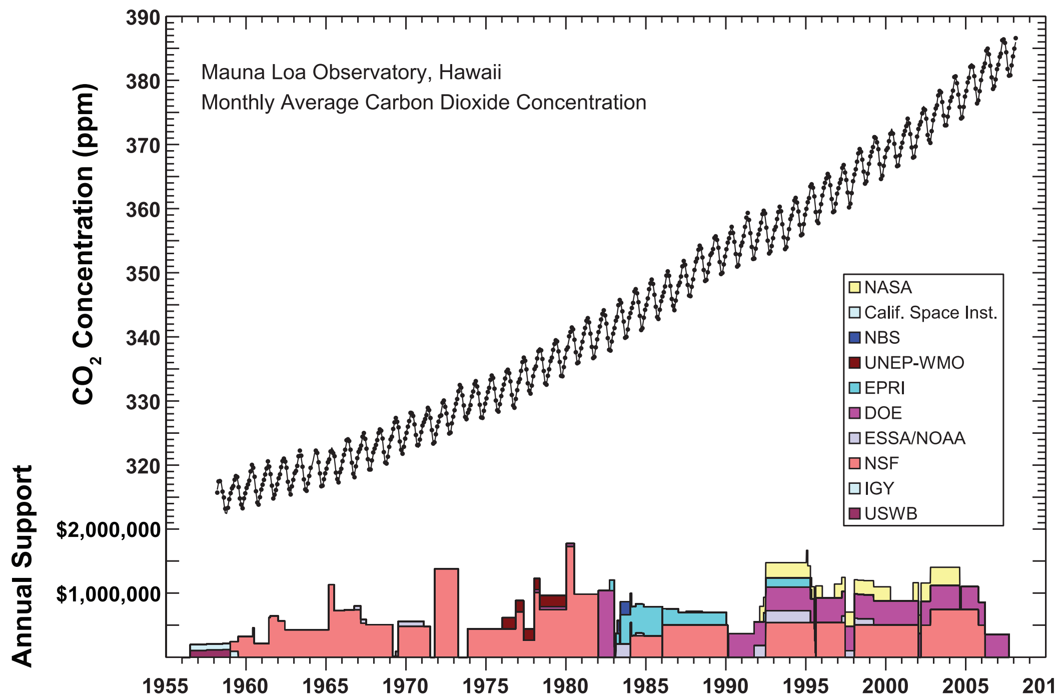

Plate 1. Funding sources for CDK atmospheric CO_2 measurements, 1956–2005. Funded amounts are adjusted for inflation to 2007 U.S. dollars. The funding data shown in this graph were compiled from CDK's files, including correspondence, proposals, and final reports of funded projects. Separate funding for ocean measurements is not included. Actual funding (often reported as existing research support in concurrent proposals), as opposed to proposed funding, is shown to the extent possible. Some joint funding arrangements were not documented in the files, and may be represented incorrectly as funding from the single "host" agency. Spikes and some gaps are artifacts of proposed funding periods that may have been adjusted in arrangements not described in the files. Costs borne directly by the U.S. Weather Bureau, NOAA, NSF, and numerous international partners for sustaining operations at remote sites are not included. Also not included is support in the form of Weather Bureau staff stationed at Scripps, a practice that ended in August 1963. Acronyms: NASA, National Aeronautic and Space Administration; Calif. Space Inst., California Space Institute; NBS, National Bureau of Standards; UNEP-WMO, United Nations Environment Programme–World Meteorological Organization; EPRI, Electric Power Research Institute; DOE, Department of Energy; ESSA/NOAA, Environmental Science Services Administration/National Oceanic and Atmospheric Administration; NSF, National Science Foundation; IGY, International Geophysical Year; USWB, U.S. Weather Bureau.

The CO_2 program," he argued, "was important enough that at one spot on the Earth two parallel sets of measurements were justified" [*Keeling*, 1998, p. 61].

CDK's commitment to long-term continuity is no longer questioned. Plate 1 shows his remarkable ability to keep his program going, one peer-reviewed proposal at a time. The most continuous source of his support was a series of 2- to 3-year grants from the NSF, but other agencies and private funding played key roles. The regular endorsement of peer reviewers was critical to sustaining the Scripps CO_2 program. Each successful proposal demonstrated the scientific community's approval of the research, monitoring, and calibration activities that together were necessary to produce and understand the record of CO_2 concentrations at Mauna Loa and elsewhere.

5. LESSONS FROM THE MAUNA LOA CO_2 EXPERIENCE

What lessons can be drawn from these experiences? One of us has recently summarized several suggestions on the occasion of the 50th anniversary of the start of the Mauna Loa CO_2 record [*R. F. Keeling*, 2008]. The central conclusion is that distinctions between research and "routine" measurements are not very useful in long-term monitoring of Earth properties and processes. This perspective comes from both practical and philosophical arguments. On the practical side, "Finding and correcting for the inevitable systematic biases is a job for scientists who understand the measurement technology, are passionate about data integrity, and are motivated to unravel how the Earth system operates" [*R. F. Keeling*, 2008, p. 1771]. On the philosophical side, the Earth is full of surprises, and the scientific literature abounds with reports of "routine" processes discovered to be not so routine. For example, another long-term monitoring effort that began during the International Geophysical Year of 1957–1958 was the British Antarctic Survey's ozone program. Nearly 30 years later, scientists working for this program discovered the ozone hole [*Farman et al*., 1985]. Being vigilant for surprises is especially important when we know that fundamental Earth processes are changing in response to human activities. The "large-scale geophysical experiment" is not routine!

Our understanding of how the Earth is changing draws heavily on the record of a small number of variables that have been measured very carefully over long periods of time. These time series are the cornerstone of our understanding as well as symbolic icons with which we can communicate to the wider public. As we contemplate a future in which measurements can be made with much higher density by using sensors in situ and space-based methods, one might easily imagine that the Earth science of the future will take a rather different form. We suggest that new understanding will be possible only if these expanded efforts can be sustained at high quality over long periods of time.

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