Charles Keeling & Measuring Atmospheric CO_2
TEACHING NOTES

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Overview

The Keeling Curve is now an icon of climate science. This case study considers the origin and development of this famous graph, illustrating how "science-in-the-making" looks very different than it does in retrospect. It follows Keeling from his introduction to measuring carbon dioxide in a strictly geological context through successive stages as the relevant context shifts. The episode also highlights the uncertainty of funding, with five major crises over three decades.

Major NOS features include:

- the role of long-term data
- funding science
- role of measurement (accuracy, precision, calibration of instruments)
- cultural and political contexts of science
- the role of collaboration
- science as a career/human dimension of science

THINK Exercises

The primary purpose of these questions is for students to develop scientific thinking skills and to reflect explicitly on the nature of science. The questions are open ended, and the notes here are only guides about the possible diversity of responses. In many cases, there is actual history as a benchmark (which can be shared after the students' own work), but by no means does it indicate an exclusively "correct" answer. Accordingly, avoid overt clues or "fishing" for answers, implying that a particular response is expected or considered "more right." The case study should be illustrating the blind process of science-in-the-making. To help promote thinking skills, the teacher should encourage (and reward) thoughtful responses, well articulated reasoning, and respectful dialogue among students with different ideas or perspectives.

Where the case study here echoes NOS features students have encountered in other case studies, the relationships should be noted and perhaps contribute to deeper discussion. This form of repetition and integration with prior knowledge significantly deepens the NOS lessons.

OPTIONAL THINK (A)

A primary role for these simple introductory questions is to engage listeners in the case study and its main character. The simple yes-or-no questions, with responses easily expressed by a show of hands, allow everyone to participate, and do so without much reflection or risk of being "wrong."

The series of questions A-D highlight the human dimension of science and science as a career.

THINK (1)

This question requires a bit more consideration than the previous one-- but as an early question it is still designed to be relative simple. Responses may be just one or a few words. The teacher can "reward" one response (perhaps ask how many other students were ready to suggest the same thing) and quickly invite another response, and another, leading to a brief cascade able to involve many students. The exercise implicitly models the value of creative thinking. One may elect to list responses on a board, as many of the variables students identify may become relevant later in the story. The instructor should comment positively on all the responses (as an ensemble) before moving on, to affirm the value of participation.

Some possible variables in Keeling's measurements might include:

- poor sample taking (for example, not fully replacing the old air in the flask with the local air)
- poor measuring system
- other variable local sources of CO_2: car exhaust? industrial burning of fuel? backyard incinerators?
- actual changes in environmental CO_2 concentration: height from the ground? time of day? temperature? plants photosynthesizing?
- local factors that "interfere" with the samples or measurements themselves: temperature? humidity? wind?
- the researcher's own breath! (laden with CO_2)

This THINK exercise is a good introduction to the challenge behind the "simple" task of making a series of accurate measurements. Much of Keeling's scientific challenge in the years to come involve such attention to precise and accurate measurements, so this discussion helps set the stage for later parts of the story (THINK 2, 3, 4, 8).

THINK (2)

This may be an opportune occasion to introduce the distinction between accuracy and precision. Here, one may imagine an imprecise measurement of CO_2 as not having the last digit, only the first two (one may also elect to introduce the related concept of significant digits).

Because the gases are measured here in parts per million, even small mistakes could distort the measured values.

Students may be reminded that others had failed to find a consistent base level of CO_2. Keeling's results similarly include a range of values, but also may indicate why. In this case, we know the method of measurement is consistent in the different locations: observed differences, although relatively small, may be interpreted as "real." Without precision, one could not discern these differences at all: only very low levels overall.

THINK (3)

Keeling can test the *same sample* in both the manometer and the infrared analyzer and compare the data. In this case, one already knows that the measurement with the manometer can be trusted and used *as a standard*. This is the essence of *calibration*, a central concept in this case study.

Further, to ensure that the analyzer provides a reliable measurement *each time it is used*, the standard samples are used again, and the reference standards themselves are checked regularly.

For standardizing the results at different sites, one may set up *a set of identical reference samples.* All are calibrated using the same manometer, to ensure that they are indeed similar. By using the reference gases, the calibration of the different infrared analyzers will thus also be based on a common standard.

THINK (4)

As in the case of daily CO_2 variation from the West Coast, lack of precision might not have shown clearly the seasonal differences. For Mauna Loa, the differences are no more than 1½ % of the measured values.

THINK (5)

As needed, help students stay focused on Keeling's particular case, rather than on vague generalities.

Benefits include: sources for CO_2 data from around the globe; cost savings from sharing resources; access to sites otherwise not available. Costs and problems include: possible different processes for collecting the gas; leading to results that cannot be compared; non-standardized measurement methods; long term collection threatened by any shifting alliance.

THINK (6)

Remember that the reference year is 1964.

Because the difference between annual averages is less than the difference one can find even between seasons in the same year, one may doubt that the pattern is anything more than such natural variation, already known. The regularity of the increase -- found *each and every year* over 7 years -- lends some credence to a consistent pattern or “trend.” On the other hand, the increase is not the same from year to year, indicating that whatever is causing the increase is not regular or predictable. Still, if one observes the data graphed month by month (Keeling’s graph), it is not just the averages that increase: the minimum seasonal values each increase and the maximum seasonal values each increase. Namely, the seasonal variation seems visibly independent of the annual increases, indicating one should not conflate them or regard them in same category.

Ultimately, this is a fine example where informed scientists might legitimately disagree. Science often addresses uncertainty, only to be resolved by further investigation.

Strategies for working from uncertainty may vary. *Scientists* tend to be cautious in judgments and conservative in supporting new claims until evidence is quite secure. Their primary concern is whether the justification of the scientific claims is sound. They may thus withhold judgment because there is limited context for taking action, besides doing more research. In the face of uncertainty, *policy makers*, by contrast, cannot responsibily abdicate action. They must institute concrete prudent plans. Accordingly, they need to consider and accommodate the possibility of multiple alternatives at the same time. Their version of conservative judgment is thus to imagine scenarios that may, at the time, be based on only limited evidence. That is, they must take into account a wider range of possibilities and crudely assess their likelihood. This strategy of hedging against possible adverse outcomes that are not yet certain is known as the Precautionary Principle and is a core challenge in environmental management. Here, it is important to note that the scientist’s epistemic conservatism is not necessarily appropriate for guiding public policy or action.

THINK (7)

Remember that the reference year is 1969.

Compared with 1964, the trend of increase is much more visible, especially in its regularity. Notably, the most recent minimum now exceeds the earlier maximums. An overall increase of approximately 1% since 1958 is documented. What is still not clear from Keeling’s data alone, however, is whether this has a corresponding, or “significant,” effect on temperature.

THINK (8)

This is partly an opportunity to review the central concept of calibration and its significance for both *accurate* and *precise* measurements.

Several years later, Keeling described the precision he was striving for:

> The concentration of atmospheric CO_2 deduced from the infrared measurements at Mauna Loa depends directly on the concentration of CO_2 attributed to the reference gases used to calibrate the analyzer. For this reason, considerable effort has been taken to suppress both random and systematic errors arising from use of these gases.

Each working reference gas used at the observatory in the determination of CO_2 in air was routinely compared *twenty or thirty times* during its period of use with semi-permanent standard reference gases kept at the observatory and thirty times with similar semi-permanent standards kept at the Scripps central laboratory. The comparisons at Scripps were made partially before and partially after use at the observatory to assure detection of any significant long term drift in working gas concentration. Also, the semi-permanent standards held at the observatory were compared with the semi-permanent standard gases at Scripps at least *fifty times* after use in the field. Certain semi-permanent standards at Scripps in turn were closely compared (at least *150 times*) with a special set of manometrically calibrated standard gases also kept at the Scripps laboratory.

THINK (9)

Remember that the reference year is 1976.

An overall increase of approximately 3½ % since 1958 is now documented. Again, the significance for average temperature is not clear from these data alone. Also, while the CO_2 increase now seems more significant, one cannot be sure what is the source of the increase. (Those questions are addressed and resolved in subsequent research.)

THINK (10)

As before, help students stay focused on Keeling's particular case, rather than on vague generalities, which will easily be shaped by students' personal political views (for example, their impressions of Reagan as a President). The aim is to *not* have a political debate, but to reflect more analytically on the influence of politics -- any politics -- on scientific research and the growth of knowledge.

NOS Reflection Questions

These reflective function partly for recall and review but also to help consolidate and thus complete the central NOS lessons of the case study. They are essential to "closing" the lessons and making the NOS thinking explicit and articulate.

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

Some phenomena exhibit patterns only over the long term. Evidence of those patterns only becomes clear with extended periods of data. These patterns are not always obvious in advance, yet may be of immense importance: for example, the seasonal variation of CO_2 levels; the southern oscillation/El Niño climate cycles; the gradual (but continuous) increase in global CO_2 levels. The Keeling Curve is one of the most vivid examples of the significance of a long-term data set, whose value is acknowledged mostly in retrospect, after much of the data has already been collected.

Long-term data requires not only sustained funding, but also institutional continuity. Long-term projects are vulnerable to changes in local science administrators and to their shifting whims. Also, there must be individuals motivated and skilled enough to do the research. Methods must be consistent to allow later findings to be compared with earlier ones.

Note that Keeling ultimately used the importance of having a long term data set from one source as an argument for continued funding.

- **funding science** (see THINK 10)

  Some factors shaping funding exhibited in this case include:
  - "routine" vs. novel research
  - social significance of results (IGY, military, long-term climate and weather forecasting, long-term environmental management)
  - social significance of research enterprise (international cooperation, international competition)
  - availability of surplus money (economic wealth)
  - political consequences of scientific results

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

  Recall the key conclusions, which all relied on recognizing patterns through fine-scaled differences (*precise* measurements, not just "crude" accurate ones): daily variation coupled to a relatively consistent CO_2 level, seasonal variation, El Niño variation, isotope analysis.

  Review the significance of managing or monitoring measuring instruments (calibration) to give consistent, comparable results. This is a sometimes tedious, but nonetheless essential task. Again, skilled calibration is a critical feature of the Keeling Curve as an effective long-term data set. This discussion may be an occasion to introduce the Bureau of Standards as an important scientific institution and resource.

- cultural and political contexts of science (see THINK 10)

  Retrospect allows us to see more clearly the suppression of certain scientific research initiatives that were deemed politically unfavorable during the Reagan Presidency. It is striking that these biases were widely noted at the time, but the criticisms had only limited sufficient politcal leverage in allocating funds. The general lesson is how science (and thus scientific knowledge) can bend under political forces, with bias and distortion of its claims if the political forces themselves are not balanced.

- role of collaboration (see THINK 5)

  One may recall all the persons who assisted Keeling personally: Wexler, Revelle, the head of Scripps, Muennich, and German colleagues. One may also note, for reference in discussion, Keeling's collaborators mentioned here: Weather Bureau, WMO, El Niño physicist; Muennich.

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

  One may reflect on Keeling's 1998 comments on the history of his own work, titled "Rewards and Penalties of Monitoring the Earth."

ACTIVITIES
The activities are largely to develop scientific skills -- here, in processing data (graphs) and interpreting it. They tend to engage students in a deeper level of detail that contributes to understanding the *scientific* concepts, rather than in understanding NOS .

ACTIVITY 1

Appropriate for pairs or small groups.

Each group receives:

- a map of the Western United States, labeled with the locations of Keeling's testing sites,
- a table of the measurements made at each site (including a brief designation of the local ecology), and
- an image of what each site generally looks like.

As indicated in the case study, invite students to look for patterns or meaningful relationships in the results. The instructor may manage integration of the results in their own style (group presentations, whole class discussion, jigsawing between groups, etc.).

Major observable trends:

- There is no consistent base level. (For example, the minimum at one location may be higher than maximum at another.)
- The highest maximum values are in heavily wooded areas.
- The lowest maximum values are on the beach, open water or air. Mountain tops and deserts are also low.
- The range of minimum values (Δ=28 ppm) is much smaller than the range of maximum values (Δ=94ppm).
- The largest differences between maximum and minimum (49-96 ppm) are in the forested areas, the smallest in the open-air, unvegetated areas (0-7 ppm).
- Elevation does *not* seem significant (except where it means lack of trees).

That is, any place with lots of vegetation and low wind are generally higher, and more highly variable. Drier and windier areas have much lower swings.

ACTIVITIES 2-5

Although these four activities involve sequential stages of the same graph, the instructor must resist the temptation to alert students to "save space" for later data: this is integral to depicting "science-in-the-making," as uncertain and unfolding unpredictably. Initially, *Keeling himself* did not expect to be measuring CO_2 levels for as long as he did. Students may well need to pull out an extra sheet of paper to extend their graphs: how much more they will likely learn the NOS lesson!

The periodic nature of the graphing also helps reinforce the NOS lesson about long-term data. Even when it seems to get routine, new surprises or insights may emerge.

While students might work together on graphing, the individual lessons will likely be stronger if each student engages in and "internalizes" their own individual graph.

As an option, one may economize on time by using selective data. On the data tables for Activities 3, 4 and 5, data for one month each quarter is highlighted in bold.

By Activity 5, the graph may be far less "surprising." In classes where students readily accept the trend, one may wish to omit the last segment of graphing. Still, there should be a sense that the scientific meaning of the data deepens each time.

ACTIVITY 2

Note that by averaging values over a whole month, Keeling reflects his expectations in determining a consistent "base level."

One option is to have students graph data in intervals — pausing every 3 or 4 months to assess the results as they are generated. At first, Keeling was quite concerned when he originally saw his data "drift." He thought that the measuring instruments might not be functioning properly, since the values did not remain relatively constant.

Optionally, they may also graph other sites, as shown in the subsequent figure from Keeling's publication.

In interpreting the data, whether individually, in groups or as an entire class, students should note the seasonal variation. Keeling learned from statisticians that one should not infer a cycle until it appears at least 5 times in succession. Here, there are barely two annual cycles. Still, Keeling was sufficiently confident in his measurement techniques that he was easily persuaded that the limited data reflected a natural cycle. In addition, it seemed a clear annual pattern and could be explained in much the same way as the daily cycles, observed earlier, by the varying photosynthetic activity of vegetation.