Mauna Loa in the Classroom

Ideas for use of the Mauna Loa Observatory carbon dioxide record in middle school and high school earth science, mathematics and social science teaching
Use with permission of Dr. Karen Bice. Original information can be found at http://www.whoi.edu/science/GG/people/kbice/maunaloa_text.pdf

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In my opinion, the use of these data provides an excellent opportunity to integrate applied math, earth science and social science teaching. However, note that nowhere here do I get into the issue of *climate change* forced by the anthropogenic carbon dioxide increase or its societal implications. This is intentional. There is a tremendous amount of information on this available in textbooks and on reputable web sources. If you need help finding or understanding web sources, contact me by email. For earth science teaching, the ideas offered below serve best as an introduction to the problem of anthropogenic climate change, or as part of a discussion of the controls on atmospheric chemistry.

Primary data source: Atmospheric CO2 concentrations (ppmv) derived from in situ air samples collected at Mauna Loa Observatory, Hawaii, C.D. Keeling and T.P. Whorf. Carbon Dioxide Research Group, Scripps Institution of Oceanography, University of California, La Jolla, California 92093-0444, U.S.A.
Downloaded 11/1/04 from **http://cdiac.esd.ornl.gov/trends/co2/sio-mlo.htm**

When were these data collected?

March 1958- December 2003.
Atmospheric carbon dioxide concentration data collection is ongoing at the Mauna Loa Observatory and at sites across the globe.

What data are provided in the accompanying spreadsheets?

The spreadsheet **maunaloa_co2_monthly.xls** contains the monthly atmospheric carbon dioxide concentration expressed in parts per million by volume (ppmv). The monthly values have been adjusted to the 15th of each month. Missing values are denoted by - 99.99.

The spreadsheet **maunaloa_co2_annual.xls** contains two sets of annual CO2 data.

Columns A-B contain the annual arithmetic means of the monthly values from Mauna Loa. In years with one or two missing monthly values, annual values were calculated by substituting a fit value (4-harmonics with gain factor and spline) for that month and then averaging the twelve monthly values.

Columns O-P of the spreadsheet show the Mauna Loa annual data preceded by the concentration of CO2 in air bubbles trapped in ice cores (see below).

The spreadsheet also contains U.N. world population data (see below).

How were the Mauna Loa data collected?

The following description of methodology is modified from the CDIAC web address given above. See the original source for references and more detail.

Methods

The Mauna Loa Observatory, Hawaii, is located near the summit of the active Mauna Loa volcano, 19°32' N, 155°35' W, 3397 m above mean sea level. You can view photos of the facility at http://www.mlo.noaa.gov/. Air samples at Mauna Loa are collected continuously from air intakes at the top of four 7-m towers and one 27-m tower. Four air samples are collected each hour for the purpose of determining the CO_2 concentration. Determinations of CO_2 are made by using a Siemens Ultramat 3 nondispersive infrared gas analyzer with a water vapor freeze trap. This analyzer registers the concentration of CO_2 in a stream of air flowing at ~0.5 L/min. Every 30 minutes, the flow is replaced by a stream of calibrating gas or "working reference gas". In December 1983, CO_2-in-N_2 calibration gases were replaced with the currently used CO_2-in-air calibration gases. These calibration gases and other reference gases are compared periodically to determine the instrument sensitivity and to check for possible contamination in the air-handling system.

Hourly averages of atmospheric CO_2 concentration, wind speed, and wind direction are plotted as a basis for selecting data for further processing. Data are selected for periods of steady hourly data to within ~0.5 parts per million by volume (ppmv); at least six consecutive hours of steady data are required to form a daily average. The Mauna Loa atmospheric CO_2 measurements constitute the longest continuous record of atmospheric CO_2 concentrations available in the world.

The Mauna Loa site is considered one of the most favorable locations for measuring undisturbed air because possible local influences of vegetation or human activities on atmospheric CO_2 concentrations are minimal and any influences from volcanic vents may be excluded from the records. The methods and equipment used to obtain these measurements have remained essentially unchanged during the 46-year monitoring program.

Because of the favorable site location, continuous monitoring, and careful selection and scrutiny of the data, the Mauna Loa record is considered to be a precise record and a reliable indicator of the regional trend in the concentrations of atmospheric CO_2 in the middle layers of the troposphere.

Ideas for use of these data in middle and high school teaching:

Using Monthly Data:
By plotting several years of monthly data, students should observe a regular cyclicity with a period of twelve months. Ask students to note during which months the slope of the CO2 curve is rising or falling.

- ***During what month do minimum values occur each year?*** (September-October)
- ***When do maximum CO2 values occur each year?*** (around May).
- ***What might the rising and falling parts of each annual cycle correspond to?*** The Mauna Loa Observatory is located in the northern hemisphere. The atmosphere is relatively well-mixed across the equator on the time period of a year or longer, but local variations in atmospheric composition will be reflected on the times scale of days, weeks and months. In other words, any seasonal cycle you can see at Mauna Loa must be reflecting a “local” (northern hemisphere) process. This seasonal cycle results from the growth (during Summer) and decay (during Winter) of trees and other plant matter in the northern hemisphere. Photosynthesis in Summer causes the removal (uptake) of CO2 from the atmosphere and the negative slope to the CO2 curve. The decay of leaves and green plants (the oxidation of labile organic matter) in Winter causes the release of CO2 to the atmosphere and the positive slope to the CO2 curve.
- ***What part of the biosphere might be most responsible for the seasonal pattern of CO2 observed at Mauna Loa?*** (It is primarily the northern hemisphere deciduous forests.)

More To Do: For upper level students, write out the photosynthetic reaction, roughly:

$$6CO_2 + 6H_2O \Leftrightarrow C_6H_{12}O_6 + 6O_2$$

As seen at Mauna Loa, the reaction goes left to right in June through October. November through May, the reaction goes to the left. An astute student will note that atmospheric oxygen should also show a seasonal cycle, one opposite to that of the CO2 seasonal cycle. Since the late 1980’s, it has been possible to make accurate measurements of changes in the O2/N2 ratio in air samples. These data show both the seasonal cycle expected from photosynthesis and respiration in terrestrial plants (opposite to that of the CO2 seasonal cycle) and a long term decrease in atmospheric O2 (opposite to that of the CO2 trend).

More To Do: On the web http://cdiac.esd.ornl.gov/trends/co2/sio-keel.htm, you can find similar datasets from collection sites in the southern hemisphere. These will show the opposite sense of positive and negative slopes to the seasonal cycles (i.e., they will be "out of phase" with the northern hemisphere sites) because the seasons are reversed in the southern hemisphere. Southern hemisphere records exhibit a smaller amplitude in the seasonal cycle because there are fewer forests in the southern than in the northern hemisphere.

Using Annual Data:

Have students plot the annual CO2 averages from Mauna Loa and try to fit a straight line to the 1958-2003 annual average values.

- ***On average, has CO2 been increasing or decreasing in Earth's atmosphere over the past half century?*** The slope to the line is positive, which indicates that the concentration of CO2 is increasing in the atmosphere. The Mauna Loa record shows an overall 18.8% increase in the mean annual concentration, from 315.98 parts per million by volume (ppmv) of dry air in 1959 to 375.64 ppmv in 2003. Students can calculate the rate of increase of CO2 in Earth's atmosphere.
- ***If a straight line is not a very good fit to the data, would you say that the slope of the curve is increasing or decreasing through time?*** Have students calculate the slope of a straight line fit to the 1958-1965 measurements.
- ***Compare this to the slope of a line fit to the 1994-2003 measurements. How different are they?*** The slope of the plot of annual average CO2 is increasing from 1958 to 2003, which means that the rate of increase of concentration of CO2 in Earth's atmosphere is increasing through time. In other words, the concentration of CO2 in the atmosphere is accelerating. As of December 2003, the 1997-1998 increase in the annual growth rate of 2.87 ppmv represented the largest single yearly jump since data collection at Mauna Loa began in 1958.

More: Climate change scientists talk about short term and long term sources and sinks for CO2.

By **SHORT term**, we mean time intervals on the order of several years or less.

LONG term means decades, centuries, millennia and longer.

A SOURCE is any process that results in the addition of CO2 to the atmosphere.

A SINK is any process that removes CO2 from the atmosphere.

Based on the monthly CO2 concentration data, students should infer that photosynthesis is a short term sink for CO2. The decomposition of organic in winter and early Spring is a short term source of CO2.

Older students may have heard of the following long-term sources of atmospheric CO2: fossil fuel burning and deforestation. The "long term" time scale in this case is decades, centuries and (likely) millennia. Fossil fuel (coal, oil, gas) burning and deforestation** are the cause of the positive trend in atmospheric CO2 over the past two centuries. On this time scale, the only viable natural sinks for CO2 are forest expansion and dissolution of carbon dioxide in seawater. However, the fact that the Mauna Loa data exhibit a trend (an increase) indicates that, for the past 200 years, there has been an imbalance between the sources and sinks for CO_2 on the time scale of decades to centuries.

In this case, the source is much greater than the sink, and so CO_2 "builds up" in the atmospheric reservoir. To illustrate the concept of sources, sinks and chemical reservoirs, you can use the analogy of a bath tub. The amount of water in the tub (the atmospheric CO_2 reservoir) is determined by the difference between the rate at which water is coming in through the faucet (CO_2 is being released by fossil fuel and forest burning) and the rate at which water is exiting through the drain or overflowing the sides (CO_2 is being taken up by new forest growth and by dissolution in the oceans). If the rate at which water flows in equals the rate at which water drains out, the system is said to be at "steadystate" and the water level in the tub will remain constant. For older students, a bank account analogy (with deposits, ATM withdrawals, and monthly balances) may be more interesting.

**Note that deforestation, which is often accomplished by burning, represents both a sort term source of CO_2 to the atmosphere (when the trees are burned) and a short- to longterm decrease in the size of the photosynthetic sink for CO_2 (when the forests are not there to grow larger). So, deforestation is *bad* in more ways than one! Once students understand this, have them go back to the monthly data and hypothesize what would happen to the atmospheric CO_2 curve if in, say July of some year, most of the forests in the northern hemisphere were cut and burned to make room for farming. What would scientists at Mauna Loa Observatory see almost immediately? What would the curve look like the next year? Ten years later? (Advanced students might research relative standing biomass in an acre of forest compared to an acre of farmland. This would be a natural lead-in to a discussion of *bioenergy.*)

On an even longer time scale (millennia and millions of years), volcanism is the primary source of atmospheric CO_2. The part of the CO_2 cycle with which students are likely to be least familiar is continental weathering - the long term sink for atmospheric CO_2. The chemical degradation of granites and similar Ca and Mg-rich silicate rocks, and the deposition of carbonate and carbonaceous sediments in the oceans, results in the removal of carbon from the atmosphere. Ultimately, it is this weathering/sedimentation cycle that will remove anthropogenic CO_2 from the atmosphere. However, because these processes proceed slowly (i.e., they operates on long time scales), atmospheric CO_2 concentrations will remain high long after humans take action to slow or cease the anthropogenic release of CO_2.

The possible effects of the next glacial period (if we experience one in a human time frame) on anthropogenic CO_2 are not easy to understand and are best suited for use in college teaching.

More To Do: The annual average values will be roughly the same in all sites across the globe because, as noted above, Earth's atmosphere is relatively well-mixed across the equator on the time period of a year or longer. You can have students determine this for themselves by comparing several southern hemisphere sites with several northern hemisphere sites. See http://cdiac.esd.ornl.gov/trends/co2/sio-keel.htm for other sites.

More To Do (social science, as well as earth science): With higher level students, you might look at the Mauna Loa record in a bigger temporal context. Paleoclimatologists measure the concentration of CO2 in air bubbles trapped in glacier and ice-sheet ice. We therefore know that the concentration of CO2 in the atmosphere has been increasing since about the year 1800. Over the past 200 years, the rate of increase of CO2 in the atmosphere has also been increasing. (The spreadsheet **maunaloa_co2_annual.xls** includes a compilation of ice core CO2 data.)

Have students plot the composite ice core and Mauna Loa CO2 data together and then use the graph as the basis for an historical time line. Have students mark the events below (or use dates they are learning in their history class):

985 - establishment of the first European settlement in Greenland by Erik the Red
1066 - the Norman Invasion of England
1216 - beginning of the Middle Ages
1300 - abandonment of the Mesa Verde cliff dwellings in what is now Colorado
1492 - Columbus arrives in what is later called the Americas
1620 - English Separatists arrive at Cape Cod, then establish the Plymouth Colony
1653 - the first slave, Abraham van Batavia, arrives at the Dutch East India Company's Cape Colony, South Africa
1687 – Isaac Newton publishes what we know now as Newton's Laws of Motion
1698 – patent issued for the first crude steam engine

Note that, through the time represented above travel is by ship, horse and foot, most people live in small, agrarian-based settlements, manufacturing is done primarily by craftsmen and their apprentices.

1752 - American Benjamin Franklin offers the single fluid theory of electricity and led to the idea of the existence of positive and negative electrical charges
1763 - major improvements to the steam engine by the Scottish engineer James Watt
1769 – first self-powered road vehicle, built by French inventor Nicholas Cugnot
1780 - formulation of the Law of Combustion by the French scientist Antoine Lavoisier
1790 - invention of the electrical battery by the Italian scientist Luigi Galvani
1807 - development of commercial steamboats by the American inventor Robert Fulton
1816 – first U.S. energy utility company is founded and natural gas is used to light the streets of Baltimore
1851 - height of the New England whaling industry (by which time the Atlantic fishing grounds had been substantially depleted)
1886 – German mechanical engineer Karl Benz receives the first patent for a car driven by a gasoline-powered internal combustion engine
1903 – first sustained powered air flight, at Kill Devil Hills, North Carolina

Looking at the timing of these events (and knowing something about the Industrial Revolutions in Britain and America), students may be able to guess at the cause of the abrupt increase in CO2 in the atmosphere in the late 1790's: increased fossil fuel burning. The increase is caused by human activities, hence the expression "anthropogenic" carbon dioxide increase.

The wavy structure to the CO2 curve prior to ~1780 is the result of natural variability in the carbon system. Even larger amplitude natural variability in the atmospheric CO2 concentration has been caused by ocean temperature and chemistry changes associated with glacial-interglacial cycles. These glacial-interglacial cycles are caused by natural variations in solar insolation reaching the Earth. If you would like to work with those data, download the Vostok ice core CO2 record from the CDIAC Trends web site (http://cdiac.ornl.gov/trends/co2/vostok.htm).

Another social sciences exercise: Have students find global population data for the past 1000 years on the internet. Try http://www.census.gov/ipc/www/world.html or http://esa.un.org/unpp/. When does the slope of the global population curve change markedly? (The population data I found on the net are included in the spreadsheet **maunaloa_co2_annual.xls**.)

The atmospheric CO2 concentration began to increase dramatically at about the same time that global population began to increase. Technological and medical advances that accompanied the industrial revolution drove social changes and life expectancy increases that caused world populations to begin to increase dramatically. This increase continues to this day.

Feedback on Mauna Loa in the Classroom:

Share your suggestions to enrich, expand and improve this lesson. How did you use this lesson in your classroom?

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