***Lamont-Doherty Earth Observatory of Columbia University / Earth Institute***

***Earth2Class*** Saturday, October 22, 2016

**Activity: Ice Core – Dust and climate reconstruction**

1. **I. Introduction**

Every year, snow falls on the Earth’s polar regions (e.g. Greenland and Antarctica). The next year, more snow falls on top of the old snow, and the year after that the same thing happens: over time, these layers of snow compress down into an ice sheet. The annual layers, though, remain discrete (more or less), unless they are destroyed by the flow of the ice or any melting events. These annual layers provide a record of the Earth’s past climate (i.e. paleoclimate), and such records can reach back for hundreds of thousands of years. By drilling deep into the ice sheet, long ice cores can be recovered. Paleoclimate records derived from these cores provide the most direct and detailed way to identify changes in past climate and atmospheric conditions. In this exercise, we will look at recent ice core data from East Antarctica at the European Project for Ice Coring in Antarctica (EPICA) site Dome Concordia (Dome C).

Several different climate indicators can be measured from samples of the ice:

* *The amount of dust* in each annual layer can tell us about the state of the environment at the time that the dust was deposited. Various kinds of fallout from the atmosphere, including airborne continental dust, biological material, volcanic debris, sea salts, cosmic particles, and isotopes produced by cosmic radiation, are deposited on the ice sheet surface along with the snow. They mix with the snow, and also sometimes act as a distinctive barrier between different ice layers.
* *The composition of bubbles of air* trapped in the ice actually represents the composition of the atmosphere in ancient times. With increasing pressure from subsequent snow deposition on an ice cap or glacier, the snow becomes compacted: air gets trapped within tiny bubbles in snow/ice layer. This entrapment of air occurs essentially with no differentiation of the atmospheric gas components. However, carbon dioxide has different chemical properties from other atmospheric gases. Therefore, the carbon dioxide concentration in the air-filled spaces might be affected by interaction with the ice or with trapped impurities.
* *The isotopic composition of water, and in particular the concentration of the heavy isotope of oxygen*, 18O, relative to 16O, as well as heavy 2H (deuterium) relative to 1H, is indicative of the temperatures of the environment. Water that incorporates heavier isotopes evaporates less readily and condenses more easily in the atmosphere than its lighter isotopic analogues. During cold (dry) periods, then, the isotopic composition of evaporated water gets lighter (more negative) than it is during warm periods as the heavy isotope is preferentially left behind (more positive). This evaporated water gets turned into ice at the poles. Therefore, the isotopes in polar ice store this hydrological signal.

**Background about Dome C:**

The EPICA program (1996-2006) is an ambitious, multinational European project set out to provide the longest ice-core climate record in two different regions of Antarctica: Dome C and Dronning Maud Land. The drilling has taken 5 years from January 1996 to December 2000, and was extended for a further 6 years from January 2001 to December 2006. At Dome C, a core was drilled from 3,270 m thick ice, encompasses a complete Antarctic climate record over the past 800,000 years and atmospheric methane and carbon dioxide records from 650,000 years ago to the present. The scientific team’s finding to date has significantly advanced our understanding of the Earth’s climate over the past eight glacial cycles. Many analyses have been performed on the drill-core ice samples. For instance, researchers have measured the amount and isotopic composition of gases trapped in the ice, like methane and carbon dioxide, as well as the amount and composition of dust. The profiles of 2H, methane, and carbon dioxide concentrations all show a story about past climates: a short “interglacial” stage (the Holocene, the warm period we currently are experiencing) at the top, a long “glacial” stage below that, and the last interglacial stage further down near the bottom of the core. Here we will analyze the complete ice core records of climate, atmospheric methane, carbon dioxide and dust concentration over the past 800,000 years, *with the aim to understand how climate has changed in the past and these changes may be related to variations in greenhouse gas concentrations in the past.*

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*Note:* Years Before Present (yrBP) refers to years before 1950 because the years are based off radiocarbon dating, which is set to a year (1950) before bomb carbon accumulated. CO2 units are PPMV = parts per million volume which reflects the concentration of CO2 in an air sample.

The ratio of heavy to light isotopes of hydrogen and oxygen are reported in the “del notation” (δD), which in ice are typically negative. This is because they are reported in relation to the reference standard Vienna Standard Mean Ocean Water (VSMOW), as below for D/H.

$$δD= \frac{(D/H)\_{ice }–(D/H)\_{VSMOW}}{(D/H)\_{VSMOW}}$$

**Activity**

The EPICA Dome C core from central East Antarctica goes back 800,000 years, and we will look at the entire ice core record. Use Microsoft Excel or equivalent for the following exercises.

**Note: The age of the ice at any level and the gas in the bubbles within it are not the same!**

**(We will discuss this)**

Helpful hint: Always **use a scatter plot** if you want to look at the relationship between two variables, e.g. how temperature changes with time or ice age varies with depth. For aesthetic reasons, choose to use the smooth lined scatter unless there are more than one data series on the same plot, in which case use the marked lined scatter to display each data series with different marker points. Additionally, it is helpful to include the equation when you are asked to plot the trendline on the graph. Remember, all graphs should have a title, axis labeled (with units if applicable), a legend if more than one data set is plotted, title, and a caption. It is possible that Excel has a hard time handling large datasets when plotting the data; in this case, create plots one at a time, save them as an image, and delete them before creating the next plot to reduce the computer processing that is required.

**A. δD as a proxy for temperature**

Next you will calculate the temperature based on the isotopic composition of the ice, specifically deuterium ratios (δD) in unit of per mille or ‰. Calculate the temperature at Dome C using the following formula, which describes the empirical relationship between temperature and deuterium concentration, from Jouzel et al. (2007) [supplementary online material](http://www.sciencemag.org/content/suppl/2007/07/03/1141038.DC1/Jouzel.SOM.pdf):

$$Temperature \left(°C\right)= \frac{δD ‰-5.5 ‰}{6.2 ‰/℃}$$

1. Plot **temperature vs. ice age** using a scatter plot.
2. List sources of uncertainty for this paleoclimate record (Hint: how does scientist determine the ice age).
3. How long ago did the last maximum temperature occur (in other words, when was the last “interglacial” period)? How long ago did the last minimum temperature occur (in other words, when was the “last glacial maximum”)?
4. Compare these temperatures to recent mean annual temperatures at Dome C (-50°C). [Annual average temperature at Dome C, Antarctica](http://www.tutiempo.net/en/Climate/DOME_C_II/898280.htm)

**B. CO2, CH4, and Dust**

1. Plot **CO2** as a function of **gas age** as a scatter plot.
2. How closely does the plot of CO2 resemble that of temperature?
3. Now make a scatter plot of **CO2** (y axis) vs **temperature** (x axis). This time use a “marked scatter” since we are interested in finding out the correlation between these two variables rather than their trends with time/depth. Add a trendline (report equation) and record the r2 value.
4. Comment on the statistical significance of this correlation.
5. Make the same plots for **CH4**. (CH4 as a function of gas age; CH4 (yaxis) vs. temperature (x axis), adding a trendline and recording the R2 value).
6. Is CO2 or CH4 more closely correlated with temperature? Why do you think that is?
7. Make a plot of **dust** as a function of **ice age**. Compare this to the temperature vs. ice age plot.

**C. Comparison with the modern conditions**

According to the data from Carbon Dioxide Information Center (CDIAC), the present atmospheric CO2 is about 401.2 ppmv. Insert today's CO2 concentration into the linear regression equation from task B (step c) to determine what the past relationship between CO2 and temperature predicts that today's temperature should be at Dome C.

1. How does your calculated temperature compare with the known temperature (about -50)?

You can calculate the rate of change of temperature in units of °C per thousands of year (°C/kyr) by subtracting one temperature from the next oldest and dividing by the ice-age difference:

*(younger temp - older temp)/(older ice age - younger ice age) = rate of change*

The rate is positive for warming and negative for cooling. “Younger” means “shallower” here.

1. Calculate the warming **rate** over the entire record and plot warming rate vs. **ice age**.
2. What is the most **rapid** warming rate that occurred? When was it?
3. Calculate the rate of change in greenhouse gas concentrations (both CO2 and CH4) as done above, but this time use the **gas age and calculate the rate of change between each data point.** What is the maximum and range of rates observed for both gases?
4. Calculate the modern rate of change (from 18th century to 2005) in CO2 and CH4 using the inserts in Figure 2 A and B below (on the following page).
5. Compare the modern rate of change (calculated in d) to past rates (calculated in c).

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| **A**http://cses.washington.edu/cig/figures/ipccar4co2big.gif | **B**ipccar4ch4big |
| **Figure 2:** Changes in greenhouse gases from ice core and modern data. Atmospheric concentrations of CO2 and CH4 over the last 10,000 years (large panels) and since 1750 (inset panels). Measurements are shown from ice cores (symbols with different colors for different studies) and atmospheric samples (red lines). Figure adapted from [IPCC 2007 WG1 SPM](http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-spm.pdf%22%20%5Ct%20%22_blank).  |
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**Discussion Questions**

1.     Why do ice age and gas age change with depth in the core? Why does the thickness of annual layers change?

2. Why were CO2, CH4, anddust concentrations different during the glacial time? How did conditions during the glacial period differ from today's conditions?

3.     How do the changes in temperature, carbon dioxide, and methane in glacial/interglacial time scales compare to the changes since the 18th century?

4.Why are these ice core paleoclimate records so important to our understanding and prediction of climate change? Also discuss the importance of seeing if changes in greenhouse gases occur before or after temperature change.

**VI. Additional Reading**

*Nature* has a web focus on Dome C ice core studies providing some of the previous Dome C ice core papers and a collection of related articles, as well as a podcast. <http://www.nature.com/nature/focus/epica/>

* Brook, Ed. "Palaeoclimate: Windows on the greenhouse." *Nature* 453, no. 7193 (2008): 291-292.
* J. Jouzel et al, “Orbital and Millennial Antarctic Climate Variability over the Past 800,000 Years” *Science* (2007): 317 (5839), 793-796.
* McManus, Jerry F. "Palaeoclimate: A great grand-daddy of ice cores." *Nature* 429, no. 6992 (2004): 611-612.
* Walker, Gabrielle. "Palaeoclimate: Frozen time." *Nature* 429, no. 6992 (2004): 596-597.