

From Isotopes to Temperature, & Influences of Orbital Forcing on Ice Core Records

Overview

This module provides a hands-on learning experience where students will review ice core isotope records to determine the isotope-temperature scaling and their relationship to orbital variations. The objective of this module is for students to learn how water isotopes are used to infer temperature changes back in time, and how orbital variations (Milankovitch forcing) control the multi-millennial scale climate variability. In addition, students will learn about how climate feedbacks (CO₂, sea ice, iron-fertilization) can amplify/moderate temperature changes that cannot be explained solely by orbital forcing.

The module is divided into three independent parts, allowing teachers to pick and choose the sections they wish to cover when. An overview of the three labs is described below.

Lab 1: From Isotopes to Temperature: The students will begin by finding ice core/snow pit locations in Antarctica and making predictions about how temperature might change with elevation and distance from the ocean. First they will determine the lapse rate (change in temperature with elevation) for the region. They will find the annual oxygen isotope data for the region and calculate the relationship between the isotopes and temperature. Next they will use the isotope-temperature scaling to determine the amount of temperature change at Vostok or Dome C. Each group/student can present their findings from their Antarctic ice core and the class can evaluate regional differences. In this lab, students practice calculating slopes and determining relationships between elevation, temperature, and isotopes.

Lab 2 (Optional): Isotope Fractionation and Rayleigh Distillation: In this lab students will use the Rayleigh Distillation equation to simply model how hydrogen and oxygen isotopes fractionate in the hydrologic cycle en-route to the ice sheets. Students will learn *delta* notation, and determine the relationships between temperatures, fraction of vapor remaining, and isotopic abundance.

ATM 211 UWHS Climate Science

UW Program on Climate change

Unit 3: Natural Climate Variability

B. Paleoclimate on Millennial Timescales
(Ch. 12 & 14)

a. Recent Ice Ages

b. Milankovitch Cycles

Grade Level 9-12

Time Required

Preparation

- 4-6 hours to become familiar with Excel data, Online Orbital Applet, and PowerPoint

3-5 hours Class Time (All three labs)

- 5 minute pre survey
- 25 min PowerPoint topic background & Lab 1 introduction
- 25 min Lapse Rate exercise
- 40 min Compile class data and apply to Dome C ice core
- 30 min Lab 2 (Excel calculations for Rayleigh Distillation) OPTIONAL
- 50 min Lab 3 Worksheets on Orbital changes and Milankovitch
- 30 min Lab 4 (Excel calculations for CO₂ and Orbital temp changes)
- 5 minute post survey

Materials Needed

Reference textbook: Kump LR, Kasting JF, Crane GC (2010) The Earth System. Pearson

Excel: Students should have prior experience using excel to make graphs and calculations

The results from this exercise provide a physical understanding for why isotopic values in Antarctica are so depleted (more negative).

Lab 3: Milankovitch Cycles as Primary Orbital Forcing for Temperature Variations: In this lab, students will use the Vostok ice core record, and online applet, to identify how orbital configurations (eccentricity, obliquity, and precession) initiate glaciations, as well as initiate deglaciations. The lab uses an interactive online website that allows students to select a number of time periods, and identify the insolation effects due to the exact orbital parameters during that same time period. The changes in insolation are then used to identify periods where the isotopes respond to reflect temperature increases or decreases.

Lab 4: Orbital Driven Temperature Variations Amplified by CO₂ Concentrations (in progress): In this lab students will investigate the contributions of *insolation* and CO₂ radiative forcings responsible for the reconstructed temperature changes observed in the ice core records (Lab 2). The differences in orbital incoming radiation (i.e. insolation) between the glacial and interglacial periods can account for only about a fifth of the temperature changes recorded in the ice cores. This is because the orbital changes produce responses in other components of the climate system that amplify the changes. These include changes in the carbon cycle (CO₂ feedback) and changes in the planetary albedo from more or less ice cover (ice-albedo feedback). Here, students will make basic calculations to determine the relative contribution of radiative forcing from orbital and CO₂ differences between the glacial and present day.

Focus Questions

1. How do we infer temperatures from isotope data in an ice core?
2. What is the lapse rate and how does it work in the troposphere?
3. How does Rayleigh Distillation effect water isotopes in the hydrological cycle?
4. How do the three Orbital Parameters change the amount of incoming insolation?
5. What configuration of the Milankovitch Cycles is most likely to initiate a glaciation?
6. How does CO₂ amplify or dampen the Earth's temperature response?

Learning Goals

Students should be able ...

1. To understand how paleoclimate scientists infer local temperature change from Antarctic ice core data.
2. To determine the present day isotope/temperature relationship and understand how this is done.
3. To understand how isotopes fractionate in the hydrological cycle.
4. To get a sense for how Earth's orbital parameters influence the long-term climate variability.
5. To observe that the CO₂ changes track temperature changes, and contribute to both additional temperature increases (high ppm) or decreases (low ppm) relative to that expected from orbital forcing only.

Background Information

Ice cores record climatic variations on numerous timescales. On 20,000-100,000 year timescales, ice cores record variations in Earth's temperature driven by orbital variations (Milankovitch cycles) in the distribution of incoming sunlight reaching the planet. Specifically, the water molecules in the precipitation reaching the poles are preferentially depleted of the heavier water isotopes based on the temperature gradient between the moisture origin and condensation site (Antarctica). This process is called Rayleigh Fractionation. When it's colder, more of the heavier water molecules are removed en-route to the

Polar Regions, resulting in lighter isotopic water (more negative δD or $\delta^{18}O$). The present day relationship of the surface temperature and isotopic content of snow samples can be determined from various transects into the Antarctic interior. This present-day relationship can be assumed to be similar to that in the past (geologic concept of uniformitarianism), and therefore provides a reconstructed temperature of past climate. There are some obvious assumptions that are made; for example, location of Antarctica was the same, ice sheet elevation must be more or less constant, moisture source region relatively constant, etc., all of which are considered reasonable, and thereby provide a range of temperature estimates that vary by ~20%. The ice core records also provide other proxy data including CO₂, methane, and dust among others. The Dome C ice core data provided in this lab allows students to investigate the positive or negative relationships between the isotopes (temperature) and other proxies. The millennial variability recorded in the ice core data reflect the integrated influence of orbital forcing (eccentricity, obliquity, & precession), and can be compared to the direct insolation (incoming radiation) curves calculated based on earth's astronomical position. The closest correlation with the orbital forcing occurs when comparing the rate of change of ice volume (derived from Benthic foraminifera $\delta^{18}O$ in ocean sediments), but for this lab we will look at how the oxygen isotope record from ice relates to the insolation curves. There are clear periods (~20,000, 40,000 & 100,000 years) when both the ice core record and orbital forcing data align. To first order the large amplitude, long-term fluctuations are driven by the orbital forcing, however there are other aspects of the climate system (thermal inertia of the oceans, feedbacks (e.g. sea-ice albedo)) that influence the actual isotopic variations, superimposed on the orbital variations.

Prior Knowledge and Learning Assets

Your students should be familiar with the basic concepts of solar radiation distribution and its seasonal cycle (see review on orbital influences on seasons), isotopes and isotopic abundance, and the hydrological cycle (evaporation, condensation, precipitation). Students will need to have a working understanding of how to calculate slopes (or gradients) and use exponential equations for the Rayleigh Distillation formulation. Familiarity with Excel spreadsheets is important. Students should also be aware of the concept of an atmospheric lapse rate (this should have been covered earlier in the Global Energy Balance chapter).

Anticipated Challenges

It may be difficult for students to grasp isotopes, natural abundances, and how we use delta notation. There is a review of isotopes in the Kump Earth System (p. 15, Ch. 14, and Useful Concepts p. 102), which will be helpful for understanding the Rayleigh Fractionation. Using Excel to make plots, averages, and manipulate data (columns, etc) will be an important skill for students to learn, but depending on the skill level, students can either make the plots themselves, or just interpret the pre-made figures.

Assessment Elements/Evaluation

Evaluation for this laboratory can take several forms. One evaluation method would be to use the Ch.14 Pleistocene Glaciation Homework. Students could be asked to explain (in groups) specific features of the Vostok/Dome C Ice Core Data from different time periods based on the Milankovitch Forcing. Students could also be evaluated based on their responses to the Lab worksheet questions. It is also important to include questions related to the key concepts and learning goals in the Ch14 Teacher's Summary for longer-term evaluations such as Unit quizzes or tests.

Conducting the Lesson

PART 1: INTRODUCING THE LAB

PRE SURVEY: Please have each student fill out the Pre Lab Survey

Lab 1: From Isotopes to Temperature:

This is the first component of the module where students will find the present day Antarctic Lapse Rate and Isotope/Temperature relationship. Have the students work in groups of 2-4, each with their own worksheet. Since color copying is expensive, I would recommend projecting the maps of Antarctic data on the screen. Then have students work together to determine the lapse rate, and isotope/temperature relationship for Dumont d'Urville to Dome C. Once each group has finished the Lab1 worksheet, take time to have each group report their values into the Lapse Rate spreadsheet, and calculate the average change in elevation, temperature, lapse rate, and isotope/temperature relationship from all groups. After the Group Lapse tab page has been filled out, review the Understanding the Data tab so that students know what the record they are looking at it is based on, and what the axes indicate. Now, the entire class will have an isotope/temperature relationship to plug into the next tab (Temperature Conversion) of the UWHS_DomeC_Lab1 spreadsheet. The students should continue to follow the worksheet, completing the instructions and interpreting the various figures comparing the isotope data with greenhouse gases (CO₂, CH₄) and dust

Lab 2: Isotope Fractionation and Rayleigh Distillation: (optional)

If you would like to go into how the heavier isotopes in water are preferentially removed by the process of fractionation (similar to distillation), it would be worthwhile but it will take some effort to review delta notation and have them practice using the simple Rayleigh exponential function in Excel for calculating various scenarios of water evaporation.

Lab 3: Milankovitch Cycles as Primary Orbital Forcing for Temperature Variations:

This is the third component, which relates the isotope (temperature) variations observed in the Vostok ice core record to the orbital variations driven by the eccentricity (elliptical shape), precession (orientation of axis), and obliquity (tilt). Here, we use the online Applet designed by Tom Whittaker to get a sense for how each individual orbital component influences the Earth's temperature due to direct changes in insolation (sunlight). Lastly, we then combine the influences of all three orbital parameters and compare the insolation curves to the Vostok isotope record to determine which configurations favor glacial periods and which favor interglacial (warm) periods. The take away here is to understand why the Earth goes between glacial and interglacial states.

Lab 4: Orbital Driven Temperature Variations Amplified by CO₂ Concentrations (in progress):

This final component brings together the temperature changes reconstructed from the ice cores (Lab 2) and the orbital drivers of climate cycles (Lab 3) and investigates the effects of CO₂ on amplifying the temperature changes caused by the Milankovitch cycles. Here we will use a simple formula that determines the W/m² radiative forcing from increasing CO₂ from 190 ppm to 280 ppm between the glacial and present day, and then converts that into a change in temperature (ΔT) based on the Earth's climate sensitivity (the resultant change in global temperature per 1 W/m² radiative forcing). This can be compared with the change in incoming radiation between the glacial and present day and the predicted temperature change based on the Stefan Boltzmann equation. The key takeaway from this lesson is that the orbital changes alone cannot account for the full temperature changes recorded by the ice cores, and that feedbacks in the climate system amplify the amount of temperature. For Earth the CO₂ carbon cycle feedback is responsible for approximately one-third of the temperature change. Ice-albedo changes are mainly responsible for the last third.

POST SURVEY: Please have each student fill out the Post Lab Survey as thoroughly as possible and mail both surveys to:

Spruce Schoenemann, Dept. of Earth and Space Sciences, University of Washington Johnson Hall Rm-070, Box 351310, Seattle, WA 98195

Resources

- Introduction to Ice Core Climate Archives
 - <http://serc.carleton.edu/eslabs/cryosphere/6a.html>
- Similar data analysis activities based on the 400,000 year Vostok, Antarctica record
 - http://serc.carleton.edu/usingdata/datasheets/Vostok_IceCore.html
 - <http://serc.carleton.edu/introgeo/mathstatmodels/examples/Vostok.html>
 - <http://eesc.columbia.edu/courses/ees/climate/labs/vostok/>
- Teaching Climate Change with Ice Core Data & Ideas
 - <http://serc.carleton.edu/NAGTWorkshops/climatechange08/program.html>
 - http://serc.carleton.edu/NAGTWorkshops/climatechange/activity_ideas/index.html
- Another approach to making ice cores that study weather events during a winter season from NASA's Education Student Observation Network at
http://www.nasa.gov/audience/foreducators/son/winter/snow_ice/students/F_Snow_and_Ice_Students.html

Milankovitch Cycles

- Vostok Interactive: <http://itg1.meteor.wisc.edu/wxwise/climate/earthorbit.html>
- Seasonal Interactive (Review): <http://itg1.meteor.wisc.edu/wxwise/seasons/seasons.html>
- Lesson: <http://www.sciencecourseware.org/eec/GlobalWarming/Tutorials/Milankovitch/>
- Visualization: http://highered.mcgraw-hill.com/sites/0073369365/student_view0/chapter16/milankovitch_cycles.html

Paleoclimate

- Recent and Long Term Carbon Variations <http://www.esrl.noaa.gov/gmd/ccgg/trends/history.html>
- Paleoclimatology overview <http://serc.carleton.edu/microbelife/topics/proxies/paleoclimate.html>
- NOAA Paleoclimatology data portal <http://www.ncdc.noaa.gov/paleo/paleo.html>
- What's the connection between low sea level and big ice sheets? Deep Sea Paleoclimate
<http://oceanexplorer.noaa.gov/explorations/05stepstones/background/paleoclimate/paleoclimate.html>
- Where are ice cores stored? <http://niel.usgs.gov/about.htm>
- Antarctic marine sediment core lesson plan <http://serc.carleton.edu/eet/cores/index.html>
- NOAA timeline <http://www.ncdc.noaa.gov/paleo/ctl/index.html>
- Paleoclimate animations http://emvc.geol.ucsb.edu/1_DownloadPage/Download_Page.html