EXAMINING LONG-TERM GLOBAL CLIMATE CHANGE ON THE WEB

Jacqueline E. Huntoon — Department of Geological Engineering and Sciences, Michigan Technological University, 1400 Townsend Drive, Houghton, MI. jeh@mtu.edu

Robert K. Ridky — Department of Geology, University of Maryland, College Park, MD. ridky@umd.edu

ABSTRACT

Students can use web-based data sets to investigate long-term global change. By accessing, graphing, and interpreting available greenhouse gas, population, oxygen isotope, and temperature data sets, students can compare data that span two distinct time intervals: the last few hundred years, and the last few hundred thousand years. Data for the last 250 years can be examined to investigate relatively recent trends in atmospheric CO_2, population, and temperature. Data for the last 250,000 and 450,000 years demonstrate the use of isotopes as a proxy for temperature, the existence of climate cycles, and long-term changes in atmospheric CO_2 and temperature. The activity begins by posing an open-ended question that makes study of global change relevant to students. Students complete the activity by using their interpretations to compose a brief written report. Technical, problem solving, and communication skills are all emphasized in this inquiry-based activity.

Keywords: Education – Geoscience, Education – Computer Assisted, Geoscience – Teaching and Curriculum

INTRODUCTION

The activity described in this paper begins by posing the question: "Should the U.S. and other countries limit emissions of greenhouse gases to reduce global warming?" to students. As the students work through the main body of the activity, they learn about global climate change by accessing and interpreting web-based data sets. Students are asked to compose a brief written report at the end of the activity in which they respond to the initial question using data they have collected, graphed, and interpreted. Because students are generally aware of the controversy surrounding global warming, it is an ideal problem to motivate them to work with real data and formulate their own hypotheses. Different students who work through the activity may reach different conclusions; the activity is designed to encourage use of the scientific method and independent thinking. The activity supports inquiry-based instruction because students learn new material as they work to solve a problem.

Research scientists are investigating the global warming question using a wide variety of data that can be used to reconstruct conditions in the past, or predict future temperature changes on Earth. Like many problems investigated by scientists, different data sets lead researchers to different conclusions. In the activity described here, students are first asked to investigate the relationship between the concentration of greenhouse gases in the atmosphere, human population, and average global temperature during the last 250 years. Students are then asked to examine data that are used to document climate change over longer time intervals: the last 250,000 and 450,000 years. Humans have probably not had a significant impact on climate prior to about 10,000 years ago, so most of the long-term dataset reflects natural (rather than anthropogenic) climate variability. In comparing data covering the different time intervals, students, like researchers, may come to different conclusions about the causes of climate change.

Climate change is an ideal topic for study using web-based data and computer-based software. Datasets available on the web are easily accessed and can be analyzed using spreadsheet programs (e.g., Roof and Savoy, 1996). Students who work through the activity described in this paper become fully engaged in the scientific process by investigating a real-world problem using real data. They also become more informed about the types of data and methods used by researchers. By integrating and interpreting the diverse types of real data accessed in this activity they become aware of the problems faced by scientists who are asked to make interpretations that affect the general public.

The activity provides meaningful context to support instruction in topics such as climate, Milankovitch cycles, population growth, greenhouse gases, and oxygen isotopes. The information presented in the activity is self-explanatory for students with a strong background in geology or other earth science field. Students who lack such background may benefit from some instruction about one or more topics as they work through the activity. Students who are proficient with spreadsheet programs will have no trouble working through the exercise, but some students will require personalized assistance. Sophomore and junior-level undergraduates majoring in science and non-science disciplines tested the activity and found it interesting and informative. The relevance of the initial question and the open-ended nature of the activity stimulated some students to conduct additional research on their own.

THE ACTIVITY

The activity for investigating climate change using web-based data is presented in its entirety in this article. The websites used in the activity all present high-quality data and are maintained by U.S. government agencies. Governmental maintenance insures the sites will continue to be available in the future. Although modern students are typically adept at using the web, they are not always careful about ascertaining the accuracy of web-based information. By selecting websites that are appropriate for use in research we hope to demonstrate to students how to avoid the pitfalls of using information distributed by organizations or individuals promoting specific agendas. The remainder of this paper, excluding the Discussion section, is written so that it can be used directly by students.

Introduction - The results of many scientists' research suggest that the Earth is warming (e.g., Levitus et al., 2001). The potential effects of warming include a decrease in the amount of snow cover on land and floating ice on water in the northern hemisphere, global sea level rise, and an increase in the frequency of extreme rainfall events in the U.S. (USEPA, 2001). The press is aware that the public is increasingly concerned about the possible effects of global warming and sensational information is published regularly. Although evidence of global warming is abundant, policy makers, the general public, and even some scientists disagree about the magnitude, effects, and causes of warming. Most atmospheric and earth scientists think that production and combustion of fossil fuels releases greenhouse gases to the atmosphere (e.g., carbon dioxide, methane, and nitrous oxide) that result in warming. A position statement issued by the American Geophysical Union (AGU, 1998) indicates that its membership agrees that the Earth's atmosphere is currently warming and that greenhouse gases in the atmosphere contribute to warming. The policy statement also indicates that pronounced changes in the Earth's climate have occurred in the past, long before human activities could have had an influence on climate. It is therefore difficult for scientists to conclusively state that modern-day global warming is solely an anthropogenic effect. Despite the uncertainty, most scientists are urging caution and advocating reducing emissions of greenhouse gases (AGU, 1998). Some scientists, however, suspect that warming due to natural climate variations will outweigh anthropogenic effects during the next several centuries (Gerhard et al., 2001).

Before you begin working through this activity think about the question: "Should the U.S. and other countries limit emissions of greenhouse gases to reduce global warming?" Throughout most of the activity you will collect data from scientifically respected web-based sources that relate to this question. The text that follows will guide you through the activity; specific directions for obtaining and interpreting data are provided in text boxes. At the very end of the activity you will be asked to prepare a brief report in which you respond to the question and support your response using graphs and interpretations based on the data you accessed earlier in the activity. Questions posed in the text boxes should be answered as you work through the activity because they will help you outline and formulate your final report.

What is climate? - It is helpful to get a sense of what climate is and how climate in any local area has changed in the recent past before examining potential causes of climate change. Climate is defined as an area's average weather over decades or longer periods of time. In contrast to climate, weather is short-term (minute- to month-long) variations in parameters like temperature, humidity, precipitation, cloud cover, and wind (Considine, 1976). Weather affects our daily lives. One can easily describe how the weather changed in the last few days, or how the weather at this time of year differs from that during the preceding season. It is difficult to notice climate change however, because one cannot accurately recall what the weather was like years or decades ago.

Do you think you have a good memory about past weather conditions? Try to remember how temperatures have changed since the beginning of the last decade, or over a longer period of time. Have temperatures become warmer? Cooler? After you decide, compare your recollections with data from the National Climatic Data Center (NCDC, 2001) (Text Box 1).

What causes climate to change? - Data obtained from the NCDC likely show some sort of change through time. Local climate change may result from a variety of factors, even changes in agricultural practices or urbanization. Global climate change occurs in part due to changes in the amount of solar energy reaching the surface of the Earth. The amount of solar energy received by a site on the Earth's surface is controlled both by the chemistry of the Earth's atmosphere and the geometry of the Earth/Sun system. The effect of the chemistry of the Earth's atmosphere on climate is investigated in Part I of this activity. The effect of the geometry of the Earth/Sun system is the focus of Part II.

Part I: GREENHOUE GASES, POPULATION, AND TEMPERATURE

What are greenhouse gases and how do they influence global climate? - When energy from the Sun hits the Earth's atmosphere, some of the energy is reflected back to space and some is either absorbed by the Earth's atmosphere or transmitted to the Earth's surface (Figure 1). Incoming radiation helps to warm the surface of the Earth, and as the Earth warms it emits heat energy at infrared wavelengths (greater than 700 nm). Heat energy can be absorbed and reemitted by certain gases in the atmosphere known collectively as "greenhouse gases". The main greenhouse gases are water (H_2O) and carbon dioxide (CO_2). Other greenhouse gases include methane (CH_4), nitrous oxide (N_2O), hydro-fluorocarbons, perfluorocarbons, and sulfur hexafluoride (USEPA, 2001). Greenhouse gases

Log on to the website: http://lwf.ncdc.noaa.gov/oa/climate/climateresources.html

This text box will help you obtain data about short-term climate change in your local area.

Click on ***Get/View Online Climate Data***.

Select ***Graphs***, where that option appears on the line that begins with Surface Data.

Click on ***Climate Visualization (CLIMVIS)***.

Click on ***Time Series*** below the heading Global Historical Climatological Network Data.

Select ***Version 2 Temperature Data: Regularly Updated Max/Min Temperature Data**** by clicking on the sample graph below the heading.

The next page contains the terms to which you must agree before using the data. Read the terms, and if you agree to them, click on ***I Agree to These Terms (continue).***

Choose ***Display Two Parameters For One Station*** from the scroll down list. Then select your geographic location by clicking on the world map. Select your state or country from the scroll-down list that appears, and click on ***Okay*** once you make your selection.

On the next page, first select the station that most closely matches your location. Second, choose the units you wish to use on a graph of the data that is being made for you. Third, make sure that the graph will show the correct information. Make sure that the First Parameter is ***Max Temperature***, the Second Parameter is ***Min Temperature***, and ***All Months*** is chosen in the Months column. Also make sure that the Start Year precedes the End Year, and that both the Start Year and the End Year lie within the time period covered by data from the station you have chosen. You can review the time period for which data are available for the station by going back up to the list of stations.

After you make sure all the parameters are correct for the graph, click on ***Graph Data***.

Look at the graph you just made. The top curve is the maximum monthly temperature recorded at the station. The bottom curve is the minimum temperature. The vertical axis on the plot is temperature, in either ^{o}F or ^{o}C (depending on the choice you made when constructing the graph). The horizontal axis corresponds to time. In each entry along the horizontal axis, the first two numbers indicate the year and the second two numbers indicate the month. For example, July 1985 is represented as 8507.

Do the data show an identifiable increase or decrease in temperature through time? If so, what processes might be responsible for the observed changes in temperature?

Even if you don't see a trend, one may actually exist. If you want to investigate the data more fully, you could calculate a long-term mean for each month. You could then calculate a deviation from the long-term mean for each month of record. You could then calculate an annual average departure from the long-term monthly means and plot these values as a function of time. Although this process sounds complicated, it can be completed relatively quickly using a spreadsheet.

Text Box 1. Directions for accessing and manipulating measured temperature data from sites in the U.S. from NCDC (NCDC, 2001).

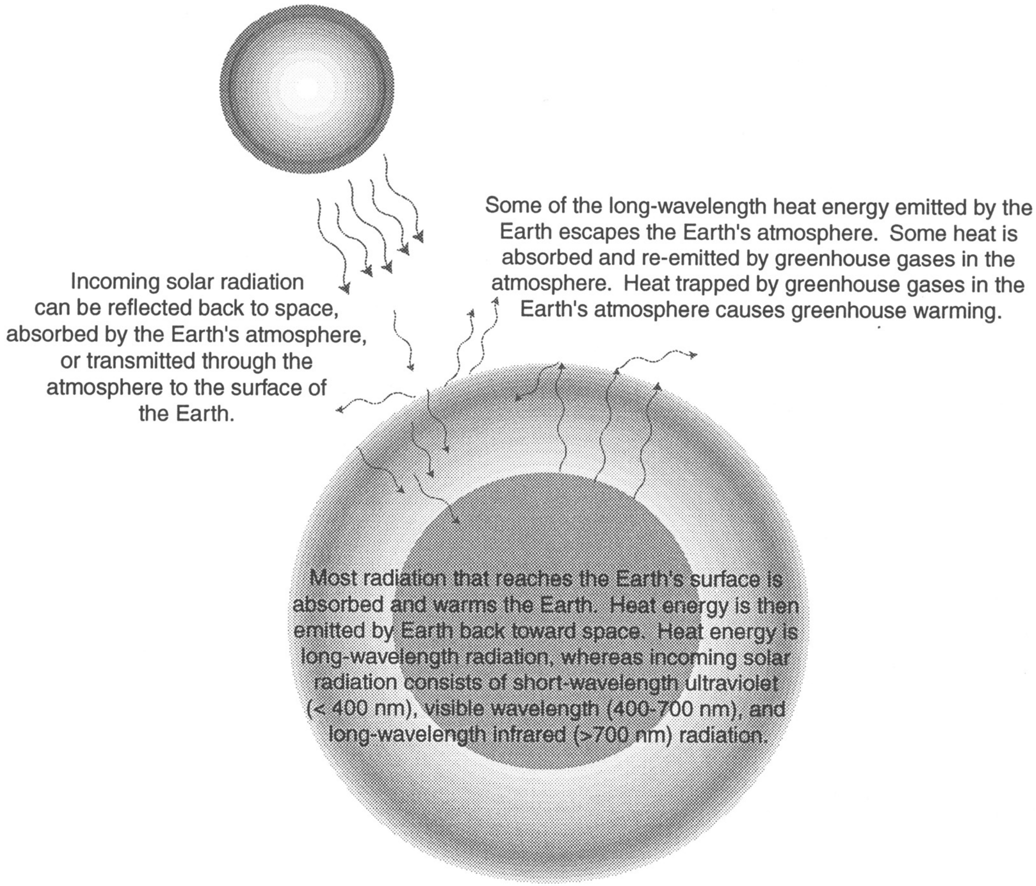

Figure 1. Interaction of incoming solar radiation and outgoing heat energy emitted by the Earth with greenhouse gases in the Earth's atmosphere. Modified from USEPA (2001).

allow most incoming solar radiation to pass through the Earth's atmosphere because it consists mainly of energy in the visible (400-700 nm) and ultraviolet (< 400 nm) spectra. Only 40% of incoming solar radiation occurs at infrared wavelengths (Kump et al., 1999).

Some greenhouse gases are naturally occurring (e.g., H_2O, CO_2, CH_4, N_2O) and were present long before human activities could have modified the chemistry of the atmosphere. The naturally occurring greenhouse gases kept the Earth's temperature from fluctuating wildly in the past, and made it possible for diverse life forms to inhabit the Earth's surface. The concentration of these gases in the atmosphere is currently increasing. Since the beginning of the Industrial Revolution, use of fossil fuels (coal, oil, and natural gas) and deforestation have resulted in significant increases in atmospheric concentrations of CO_2, CH_4, and N_2O (USEPA, 2001). Industrial activities, agriculture, and mining also release greenhouse gases to the atmosphere.

How have the levels of greenhouse gases in the atmosphere changed in the past 250 years? - A great deal of information about the concentration of greenhouse gases in the atmosphere is available from a website maintained by the Carbon Dioxide Information Analysis Center (CDIAC, 2001a). In this activity we investigate change in the atmosphere's CO_2 content over time. Air samples have been retrieved for about the last 40 years from high elevation stations located far from any significant anthropogenic emission of greenhouse gases. These samples are thought to represent accurately the composition of the lowermost part of the Earth's atmosphere (the troposphere). At the same website CO_2 data are available for times preceding establishment of direct monitoring stations. These data are obtained by analyzing air bubbles trapped in ice sheets located far from population centers. Ice cores extracted from the Greenland and Antarctic ice sheets are used extensively in climate research.

CO_2 data collected since 1959 at Mauna Loa, a 4170 m high volcano on the island of Hawaii, are used to identify relatively recent changes in the composition of the

Log on to the website: http://cdiac.esd.ornl.gov/

This text box contains instructions that will help you access and graph atmospheric CO_2 data obtained through direct monitoring on Mauna Loa, and through analysis of Antarctic ice cores.

Click on ***Products*** in the large triangle.

Click on ***Atmospheric Trace Gases, Carbon Isotopes, Radionuclides, and Aerosols*** in the Subject Areas list.

Click on ***Atmospheric Carbon Dioxide and Carbon Isotopes*** from the Atmospheric Carbon Dioxide List.

Click on ***Historical CO_2 record from the Siple Station ice core***.

Click on ***Digital Data*** at the top of the page.

Highlight all of the data in the second table and copy the data. Do not copy the column titles at the top of the table, or the reference information that follows the table.

Open a spreadsheet program with graphing capability (e.g., Microsoft Excel) on your computer.

Paste the data you have copied into your open spreadsheet. Your spreadsheet program will probably put all of the data into one long column. You must separate the data into different columns. To do this in Microsoft Excel, select the first column (which contains all of the data). Go to the Data pull-down menu and choose Text to Columns. The Convert Text to Columns Wizard will appear. Choose Fixed Width from the first Wizard screen and go to the next screen. The second screen should show your data properly aligned in columns. If the data are not properly aligned, move the column boundaries as necessary and then go to the next screen. Review the format of the data on the third Wizard screen and when you are satisfied that the entries are shown correctly, choose Finish to complete the reformatting process.

Delete the first column of data (average depth). In Excel you can easily delete entire columns by highlighting column headers (A, B, C, etc.) and choosing Delete from the Edit pull-down menu.

Go back to the website: ***http://cdiac.esd.ornl.gov/trends/co2/contents.htm***.

Click on ***Mauna Loa*** under Atmospheric CO2 records from sites in the SIO air-sampling network.

Click on ***Digital Data*** at the top of the page.

Copy the data in the table to a new sheet in the spreadsheet program. Delete all columns except the year and the annual average columns. An entry of –99.99 in the annual average column indicates that data are not complete for that year. Delete all rows with –99.99 in the annual average column. You can delete entire rows in Excel by highlighting the row leader (1, 2, 3, etc.) and choosing Delete from the Edit pull-down menu.

Now combine the two data sets by copying and pasting data from the second sheet (for the years 1959-2000) to the first sheet (years 1744-1953) below the entry for 1953.

Note that all of the CO_2 values are in ppmv (parts per million by volume).

To graph the data in Excel you should click on the Chart Wizard icon and choose XY (Scatter) from the menu. Then pick a graph type that connects the data points with a line.

Make sure your graph is scaled so that the horizontal axis runs from the year 1750 on the left to the year 2000 on the right.

Text Box 2. Directions for accessing and manipulating CO_2 data from Friedli et al. (1986), Neftel et al. (1994), CDIAC (2001b), and Keeling and Whorf (2001).

Log on to the website: http://www.census.gov/ipc/www/world.html

This text box will help you access and graph population data.

Click on ***Historical Estimates of World Population***

When the data come up on your screen, copy all of the data (including the year column and all of the estimated population columns) to a spreadsheet program with graphing capability on your computer.

Separate the data into different columns in your spreadsheet.

Refer back to the website and decide which column of data you would like to plot. Once you have made your choice, delete all of the data columns except the year column and the column that contains the population data you will plot.

The data you have just downloaded are in millions, that is, the number "5" indicates a population of 5 million. These data cover the time period from 12,000 years ago to 1950.

Go back to ***http://www.census.gov/ipc/www/world.html*** and click on ***World Population: 1950 to 2050*** to obtain more population data.

When the data appear on your screen, copy the entries for the years 1950 to 2000 and paste these data into a new sheet in your open spreadsheet program. If the data are imported as a single column, reformat the data. You may need to manually add some blank spaces at the beginning of the first row before you reformat the data to get all of the columns to align properly. Resize the column widths if necessary to show the data. Delete the last two columns (annual averages). You should now have two columns: one containing the year, and one containing the population.

Before you can combine the data for 1950-2000 with the data from –10,000 to 1950 you must convert the 1950-2000 data to population in millions. To do this divide each of the 1950-2000 population values by one million in your spreadsheet. Enter the new values in the third column of the 1950-2000 sheet.

You can now combine the two data sets. Copy the years from the second sheet (1950-2000) to the first sheet (-10,000-1950), overwriting the 1950 row. When you copy and paste the population values in Excel, use Paste Special (from the Edit pull-down menu) to paste only the values (not the formulas) from the second sheet into the first sheet.

Before you graph the population data, delete any rows that do not contain population values. This will make your graph look better when it is complete. Try plotting the graph with both a linear and logarithmic vertical (population) axis.

Change the horizontal scale on the population graph so that you only show the years 1750-2000. In Excel you can do this by double clicking on the horizontal axis, choosing Scale from the Format Axis dialogue box, and changing the Minimum to 1750, the Major unit to 50, and the Minor unit to 10.

Compare the population graph to the CO_2 graph. How are the graphs similar? How are they different?

Text Box 3. Directions for accessing and manipulating population data from the United Nations (1973) and U.S. Census Bureau (1999).

Log on to the website: http://cdiac.esd.ornl.gov/

This box will help you obtain temperature data for the last 150 years.

Click on ***Products*** in the large triangle.

Click on ***Climate*** in the Subject Areas List.

Click on ***Temperature*** in the Global Temperature, Precipitation, Sea Level Pressure, and Station Pressure Data list.

Click on ***Global and hemispheric temperature anomalies-land and marine instrumental records***.

Click on ***Digital Data*** at the top of the page.

Click on ***Table – Global Monthly and Annual Temperature Anomalies, 1856-1999***.

Copy all of the information in the table and paste the information into a spreadsheet.

Note that these data are temperature anomalies. That is, they are the deviations from the average temperatures measured between 1961 and 1990.

Delete all columns except the first (year) and last (annual average temperature anomaly).

Graph the data. Although the data do not extend back to 1750, set the minimum value on the horizontal axis to 1750 and the maximum value to 2000 so that the graph will plot at the same scale as the CO_2 versus time and population versus time graphs.

Does there appear to be a relationship between temperature, greenhouse gas concentration, and population? What data might be useful in further investigations of the potential relation?

Text Box 4. Directions for accessing and manipulating temperature data from Jones et al. (2000) and CDIAC (2001a).

Earth's atmosphere (Keeling and Whorf et al., 2001). CO_2 data obtained from the Siple Station Antarctic ice core (Friedli et al., 1986; Neftel et al., 1994) provide information about the atmosphere's CO_2 content from 1744-1953. Follow the instructions in Text Box 2 to access, graph, and interpret data from these sources.

How do the levels of greenhouse gases in the atmosphere relate to human population? - Humans tend to produce greenhouse gases, even in prehistoric societies, through use of fossil fuels for heating and cooking, and clearing of land for agriculture. Although rates of production of greenhouse gases by humans today is not evenly distributed internationally (modern industrialized societies produce greater amounts of greenhouse gases than do developing nations), one way to qualitatively test the hypothesis that recent increases in atmospheric greenhouse gases are related to human activities is to compare the concentrations of greenhouse gases through time to human population levels (Text Box 3). Graph the population data using the same horizontal (time) scale as used for the CO_2 data so that the two graphs can be easily compared.

If greenhouse gas concentrations show no relation to human population, the hypothesis should be discarded. If, however, CO_2 and population do appear to be related, the hypothesis is not proven to be true, it simply warrants additional testing. Whenever scientists develop a hypothesis, they also collect data that can be used to test the hypothesis. They do not specifically try to collect data that support their hypothesis; rather they try to collect data that might force them to reject their hypothesis. If the population data do not contradict the hypothesis that recent increases in atmospheric greenhouse gases are related to human activities, what additional data might be collected to test the hypothesis further?

How is temperature related to greenhouse gas concentrations and population? - To investigate how temperature might be influenced by greenhouse gas concentrations in the atmosphere, access temperature data from the CDIAC website (Jones, et al., 2000; CDIAC, 2001a) (Text Box 4). These temperature data should be plotted using the same horizontal (time) scale as the CO_2 and population data and then compared with the other data.

Log on to the website: http://aa.usno.navy.mil/

This box contains instructions on how to obtain information about how the number of daylight hours changes with latitude and time of year.

Click on ***Data Services***.

Click on ***Table of Sunrise/Sunset, Moonrise/Moonset, or Twilight Time for an Entire Year***.

Follow instructions on the page and access data for sites at different latitudes.

Determine the number of hours between sunrise and sunset at each site on the current date. Record this information as well as the latitude of each of the sites.

For one of the sites, look at data for one full year to determine how the number of daylight hours changes through the year.

Plot the number of daylight hours at each of the four sites on the current date as a function of latitude. Plot latitude on the vertical (y) axis and number of daylight hours on the horizontal (x) axis.

Is the relationship between the number of daylight hours and latitude in agreement with the theory?

Text Box 5: Directions for accessing and manipulating day-length and latitude data from the U.S. Naval Observatory Astronomical Applications Department (U.S. Naval Observatory, 2001).

Part II: ASTRONOMICAL CONTROLS ON CLIMATE

How does the geometry of the Earth/Sun system influence climate? - A partial answer to this question is found in the origin of the word 'climate', which comes from the Greek word 'klima'. Klima means inclination in Greek, and the inclination of the Earth's rotational axis relative to the plane that contains the Earth's orbit around the Sun determines how the length of the day changes with latitude and time of year (Figure 2). Because Earth's surface temperatures are largely controlled by the amount of energy received from the Sun, inclination strongly influences climate.

The number of consecutive hours during which the Sun can be observed from a location on Earth changes with latitude and time of year in a predictable way. For example, the northern hemisphere summer begins on the summer solstice (on or about June 21). This day is the longest of the year in the northern hemisphere. Above the Arctic Circle, at latitudes within about 23.5^{o} of the North Pole, the Sun never sets on the summer solstice. On the same day, the Sun never rises within the Antarctic Circle (latitudes within about 23.5^{o} of the South Pole), and the southern hemisphere experiences the shortest day of the year.

Because the United States covers a large area, you can look at data from it alone to verify that the amount of sunlight received at a site varies with the site's latitude and time of year. The U.S. Naval Observatory maintains a website that contains the information you need (Text Box 5).

What other aspects of the Earth's orbit around the Sun influence climate? - The influence of the Earth's inclination on climate is pronounced, but inclination, also referred to as obliquity, is just one aspect of the geometry of the Earth/Sun system that controls the amount of incoming solar energy (insolation) reaching the Earth. Cyclic changes in three parameters (eccentricity, obliquity, and precession) that describe the configuration of the Earth/Sun system are typically identified as potential causes of long-term climate change.

What is eccentricity? - The path that the Earth takes as it moves around the Sun describes an ellipse (the ecliptic) that lies within a single plane (Figure 2). When the Earth is at perihelion (located closest to the Sun) on about January 2 (U.S. Naval Observatory, 2000) it is 147 million km from the Sun (Rosenberg, 1998). When the Earth is at aphelion (farthest from the Sun) on about July 6 (U.S. Naval Observatory, 2000) it is 152 million km from the Sun (Rosenberg, 1998). Thus the present-day maximum annual difference in distance between the Earth and the Sun is about 5 million kilometers. Because the Earth is closest to the Sun at perihelion, it receives more incoming solar radiation at that time. Currently the Earth receives about 6% more insolation at perihelion than at aphelion (NASA, 2000).

Eccentricity is a parameter used to quantify the degree to which the Earth's orbit differs from a circle. Eccentricity is calculated as the distance from the center of the ellipse to one of its foci divided by half of the length of the longest (or major) axis of the ellipse. The eccentricity of the Earth's orbit is currently 0.017. It varies through time however, from a minimum of 0.0 to a

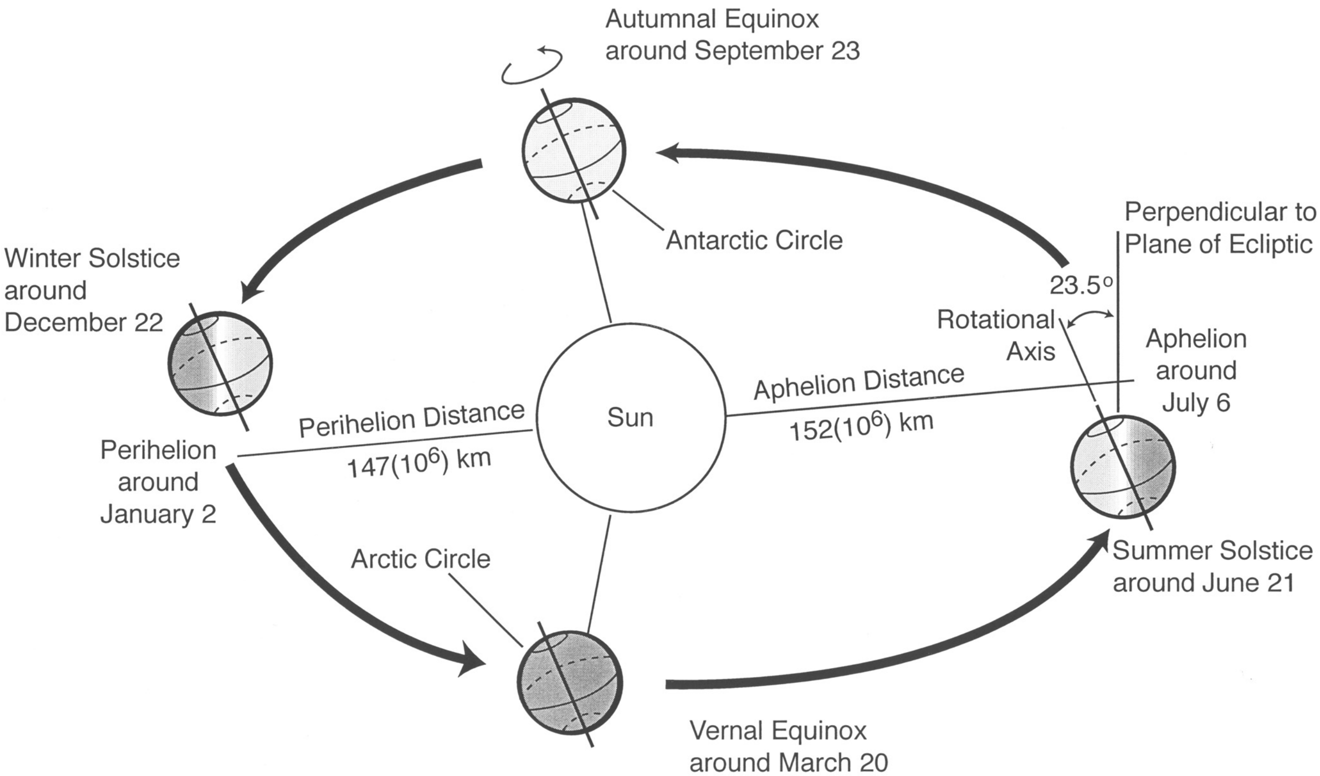

Figure 2. Present-day configuration of the Earth-Sun system. The Earth's rotational axis is tilted at an angle of 23.5° relative to a line perpendicular to the plane that contains the Earth's path around the Sun (the ecliptic). The Earth is closest to the Sun (perihelion) on about January 2. At the same time the southern hemisphere of the Earth is tilted toward the Sun. Incoming solar radiation is most concentrated at its most southerly latitude (23.5° South, Tropic of Capricorn) on the winter solstice (about December 22). The winter solstice is the beginning of northern hemisphere winter and southern hemisphere summer. On the winter solstice, latitudes above the Arctic Circle (within 23.5° of the North Pole) experience 24 hours of darkness, while latitudes above the Antarctic Circle (within 23.5° of the South Pole) experience 24 hours of daylight. The Earth is farthest from the Sun (aphelion) on about July 6. Aphelion occurs at approximately the same time as the summer solstice (about June 21) at which time the northern hemisphere of the Earth is pointed toward the Sun. The equinoxes occur when the plane containing the Earth's equator (the perpendicular to the rotation axis) crosses the ecliptic. At those times the Sun appears to be located directly above the equator at mid-day. The Earth's orbit around the Sun is elliptical, but its shape is greatly exaggerated in this figure (modified from Duxbury et al., 2000).

maximum of 0.06. When the eccentricity is 0.0, the Earth's orbit around the Sun is circular, and the same amount of energy reaches the Earth every day of the year. When the eccentricity is high, the amount of insolation that reaches the Earth varies throughout the year and is highest when the Earth is at perihelion. The total amount of insolation that reaches the Earth during any single year is also a function of eccentricity. When the Earth's orbit is at maximum eccentricity, the Earth receives about 2% more insolation during a year than it does at minimum eccentricity (Kump et al., 1999).

What is obliquity? - The plane of the Earth's equator does not lie within the ecliptic, but is inclined to the ecliptic at an angle of about 23.5° (Figure 2). The angle between the ecliptic and the equator is known as the obliquity. On the summer solstice, the northern hemisphere of the Earth points most directly toward the Sun. On this day, the Sun appears to be positioned directly overhead when viewed from the Earth at latitude 23.5° north. In contrast, the winter solstice occurs when the Sun appears to be located directly above 23.5° South latitude. Throughout the rest of the year, the Sun appears to move from one of these two positions to the other.

At two times during the year, on the autumnal and vernal equinoxes, the Sun appears to be located directly above the equator when viewed from the Earth. The equinoxes occur when the Earth's equator crosses the plane of the ecliptic. On the equinoxes, days and nights

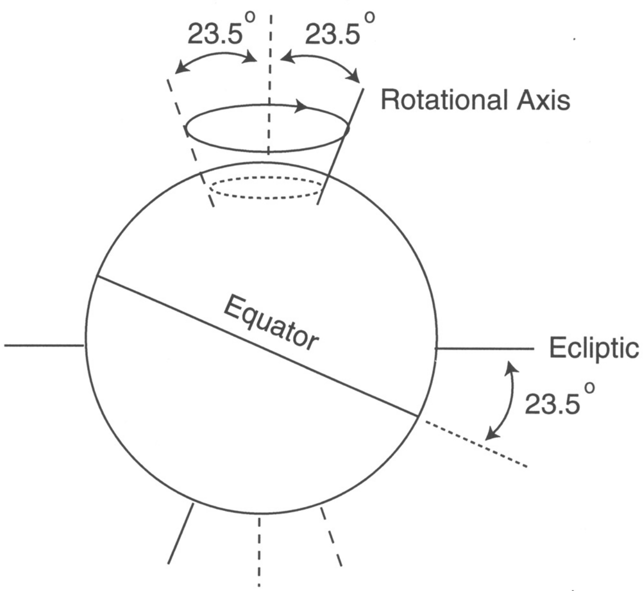

Figure 3. Precession of the Earth's rotation axis. The angle between the rotational axis and the normal to the plane of the ecliptic does not change during precession, but the orientation of the rotational axis does change. Figure modified from Crowley and North (1991).

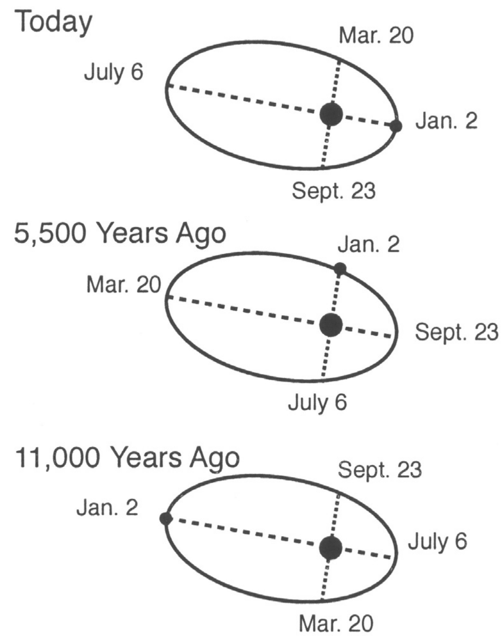

Figure 4. Precession of the equinoxes, see text for explanations. Figure modified from Imbrie and Imbrie (1986).

are of equal duration (hence the name equi=equal and nox=night). Because perihelion currently occurs at about the same time as the winter solstice, the Earth's southern hemisphere receives more incoming solar energy during its summer than does the northern hemisphere. In contrast, the northern hemisphere receives more energy during its winter than does the southern hemisphere, and northern hemisphere winters are relatively mild compared to those experienced in the southern hemisphere.

Although the plane containing the Earth's equator is currently inclined at an angle of 23.5° relative to the ecliptic, obliquity varies through time from 22° to 24.5°. When obliquity is high, the contrast between the seasons is enhanced. If the obliquity were to ever reach 0°, there would be no difference between summer and winter, and both the northern and southern hemisphere polar regions would receive the same amount of insolation that they currently receive on the equinoxes throughout the year.

What is precession? - The Earth's rotational axis precesses (Figure 3), so that the direction in which the Earth's rotational axis trends changes though time. Precession is distinct from changes in obliquity because the angle between the Earth's rotational axis and a perpendicular to the ecliptic remains constant when only precession occurs. To visualize precession and obliquity, imagine a spinning top. When the top begins spinning, its rotational axis is nearly perpendicular to the surface upon which it rotates. When the top slows down, the orientation of the rotational axis changes. First, the rotational axis is no longer vertical (its 'obliquity' increases), and second, the direction in which the rotational axis points changes (it precesses).

The orientation of the Earth's orbit around the Sun also precesses so that the perihelion's location in space changes. The perihelion is the point on the Earth's elliptical path around the Sun at which the Earth is located closest to the Sun. Precession of the perihelion and precession of the Earth's rotational axis combine to produce precession of the equinoxes (Figure 4). Axial precession determines which hemisphere of the Earth points toward the Sun at different locations along the Earth's path around the Sun. Precession of the perihelion determines how far the Earth is from the Sun at different locations along the Earth's path around the Sun. Our calendar is based on the seasons, so that northern hemisphere winter always occurs when the northern hemisphere of the Earth is pointed away from the Sun. Currently the perihelion occurs during the early part of northern hemisphere winter, just after the winter solstice. In the future, precession of the equinoxes will result in the perihelion occurring later in the calendar year. Because the proximity of the Earth to the Sun at the time of the summer and winter solstices can strongly influence the amount of insolation reaching the northern

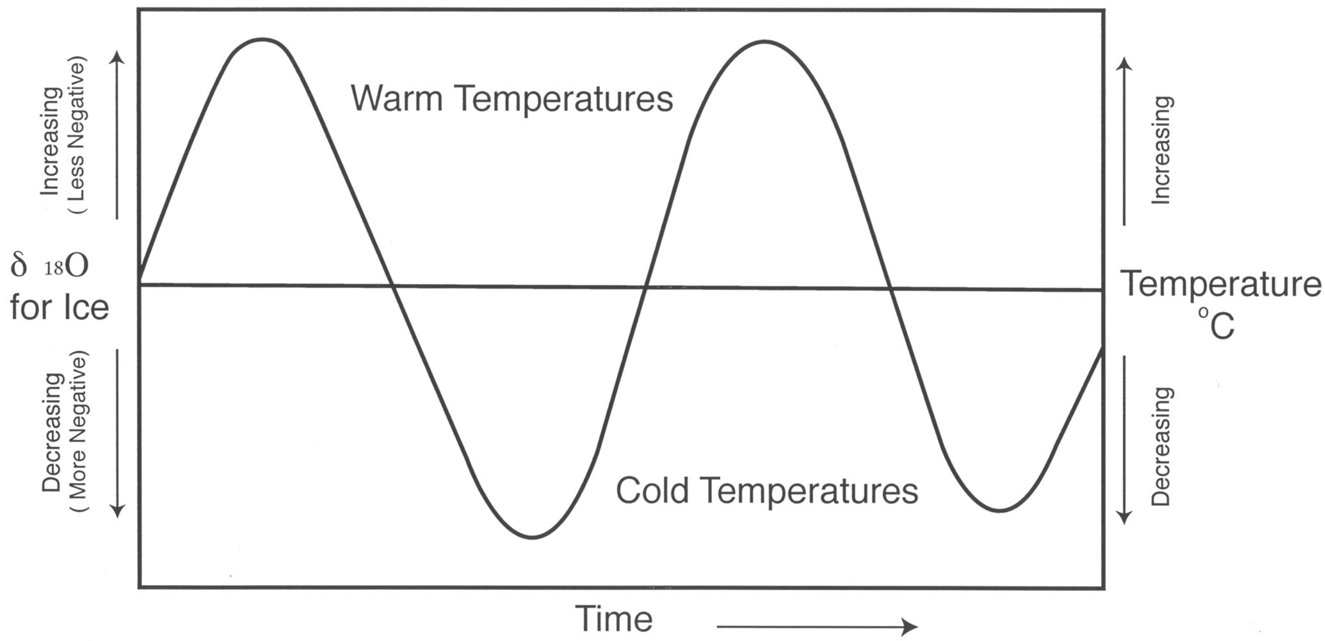

Figure 5. Schematic diagram showing the basic relationship between oxygen isotopic composition of ice and temperature. The source of the moisture that forms the precipitation that eventually becomes ice has a more significant influence on the ratio of oxygen isotopes in ice than does temperature, but the general relationship between isotopic composition and temperature is as shown.

and southern hemispheres, precession can have a strong influence on climate.

What is Milankovitch Theory? - Milutin Milankovitch was a Serbian astrophysicist and mathematician who lived from 1879-1958. Milankovitch fully developed the mathematical tools necessary to determine how eccentricity, obliquity, and precession influence Earth's climate. Milankovitch used his skills to generate a plausible explanation for the cause of ice ages. Milankovitch's work built on the work of others; as early as 1842, a French mathematician, Joseph Adhemar, proposed precession of the equinoxes as the mechanism that produced ice ages on Earth (Imbrie and Imbrie, 1986). In 1864, a Scottish scientist named James Croll expanded upon Adhemar's theory by incorporating the effects of eccentricity. During the first half of the 20th century, Milankovitch developed a way to calculate the amount of insolation received on Earth as a function of latitude and season. His calculations showed that orbital variations were sufficient to cause ice ages. It took Milankovitch's elegant mathematics to convince the scientific community that astronomical processes could control climate.

Because of the work of Milankovitch and others it is now accepted that changes in eccentricity, obliquity and precession are cyclic. As such, their behavior varies throughout time in a predictable way. The eccentricity cycle repeats approximately every 100,000 and 400,000 years. The obliquity cycle repeats about every 41,000 years. The precession cycle has periods of 19,000 and 23,000 years. Interpreting data to determine which of the cycles is dominant is difficult because effects of these parameters, and potentially others, are superimposed on one another.

Milankovitch and others determined that the onset of ice ages is favored when the amount of insolation reaching high latitudes is reduced. Cool summertime temperatures seem to be the most important factor controlling the onset of glaciation because snow that accumulates in winter is less likely to melt in summer. Accumulation of snow enhances cooling because snow reflects more incoming solar radiation than bare ground (Imbrie and Imbrie, 1986; NASA, 2000).

What is the geologic evidence of global climate change prior to the Industrial Revolution? - Although many people think that climate has changed during their lifetime, geologists and other scientists have long accepted the fact that climate has changed radically during the last 10,000-100,000 years. During the late 1700s and early 1800s, geologists pondered the importance of large boulders that were scattered across otherwise featureless plains. Comparisons of rock types showed that the boulders had been carried far from their sources by some mechanism. Geologists also observed deep scratches and gouges on the boulders' and other rocks' surfaces, particularly near mountain ranges and in the northernmost parts of Europe and the United States. Huge piles of poorly sorted materials – clay, sand, and boulders – all randomly mixed together - were also a puzzle. In 1837, Louis Agassiz, the president of the Swiss

Log on to the website: http://www.ngdc.noaa.gov/

This box provides instructions on how to access and manipulate oxygen isotope data from the GRIP ice core.

Click on ***Paleoclimate***.

Click on ***Paleoclimate Data***.

Click on ***Ice Cores*** under Obtaining Data by Discipline.

Click on ***Download Ice Core Data*** under Obtaining Data at the WDC-A.

Click on ***Listed by Data Type*** at the top of the page

Click on ***GRIP*** under Isotopes to get to the directory you need.

Click on ***GRIP Oxygen Isotopes*** to see the data file.

The data you need is in the file gripd18o.dat.

You can get the data onto your own computer by cutting and pasting.

In Excel use Paste Special, under the Edit pull-down menu. Identify the data as Unicode Text and choose Space as the text delimiter. This will properly align the data in columns.

Note that the first data entry is:
0.0 -35.04 -39.000
The data include depth in meters (1^{st} column), $\delta^{18}O$ values (2^{nd} column), and age (3^{rd} column). Note that the ages of the uppermost layers are negative. That is because all of the ages are referenced to 1950. Layers that were deposited since 1950 are negative. All other ages are in years before 1950. Thus 1951 would be assigned an age of –1 on this scale and 1949 would be assigned an age of +1.

Note that although the maximum age is 248,763 years, almost all of the data (lines 1-4966 out of a total of 5425 lines) are for the last 100,000 years. The data were sampled at a regular interval (every 55 cm). Why are there more data for the upper part of the core than for the lower part?

Delete the first column so you are left with age and $\delta^{18}O$ values only.

Graph the data. Plot age on the horizontal axis and $\delta^{18}O$ on the vertical axis. This may require you to reverse the way the columns were automatically assigned by the spreadsheet program. In Excel's Chart Wizard Chart Source Data box you can switch the column headers (A and B) in the X and Y series definitions.

Connect the data points with a smooth line. Scale the vertical axis ($\delta^{18}O$) so that it ranges from –45 to –30. Once you get a plot you like, print a copy.

After you plot the data, start to interpret what it means.

Describe qualitatively what your graph tells you about long-term temperature variation during the last 250,000 years. The easiest way to do this is to put the words 'warmer' and 'colder' at the appropriate ends of the graph's y-axis.

Do the data show any cyclicity? That is, do warm periods and cold periods alternate with any sort of regular frequency? Is there any evidence of a 100,000 yr eccentricity cycle? Is there evidence of the 41,000 yr obliquity cycle? Is there evidence of the 19,000-23,000 yr precession cycle?

Look at the data for the last 250 years in more detail. To do this, make a new graph that covers the last 250 years.

How do the oxygen isotope data for the last 250 years compare to the temperature data for the last 250 years?

Text Box 6. Directions for accessing and manipulating oxygen isotope data from Dansgaard et al. (1989; 1993), GRIP Members (1993), Grootes et al. (1993), Johnsen et al. (1997), and NCDC (2001).

Table 1: Outline for preparing a description of the activities and results of a short research project.

Section Heading	*Contents of Section*
Title	The title should be a concise phrase that gives a reader a sense of what material is present within the report.
Statement of Problem	What problem(s) did you address?
Methods	How did you work toward developing a hypothesis in response to the problem? What data were used? Where did the data come from? Did you have to manipulate the data in some way before you were able to analyze it?
Results and Interpretation	What hypothesis or hypotheses were you able to generate in response to the problem, based on your analysis of the data? How were data used to develop interpretations? Include graphs or figures as necessary because it is much easier to describe something to a reader if the reader can actually see it. If you consulted other materials (for example, journal articles that describe the activities of other researchers) this is a good place to describe the information (with appropriate references) that you obtained from outside sources.
Summary	Summarize the results of your work.
References	Give credit, in a standard format, to those from which you obtained information.

Society of Natural Sciences, asserted that all of these features could be attributed to only one cause – glaciers.

Agassiz's interpretation was not well received because most scientists at the time attributed the problematic features to the worldwide, catastrophic flood described in the Bible (Imbrie and Imbrie, 1986). With time, however, the evidence for glaciers, even at low elevations, became unquestionable. As geologists collected more and more data they demonstrated that at the height of glaciation, most of Canada and much of the northern half of the United States were covered with ice.

Once glaciers were recognized as responsible for the haphazard placement of large boulders and other paradoxical features, a new question arose: what caused glaciers to form and then disappear? Until the 1970s no clear answer to this question existed. Since that time geologists have recognized that the Earth's geography exerts a fundamental control on climate. Because most insolation reaches the Earth near the equator, the poles are warmed primarily by heat that is transported to them by oceanic currents or atmospheric circulation. Ice ages occur only when a continental landmass is located within the Arctic or Antarctic Circle, as Antarctica is today. Variations in the geometry of the Earth/Sun system (Milankovitch cycles) are favored as the explanation for the waxing and waning of glaciers when the world is primed by its geography for the presence of ice.

What other data are available that provide evidence of long-term climate change? - Data that can be used to infer long-term changes in the Earth's climate are typically collected from sediments that accumulate on the ocean floor or from cores removed from ice sheets. In this activity, data obtained by the Greenland Ice Core Project (GRIP) at its site on the Greenland Ice Sheet (Dansgaard et al., 1989; Dansgaard et al., 1993; GRIP Members, 1993; Grootes et al., 1993; and Johnsen et al., 1997) obtained from the NCDC (2001) website are compared to data from Vostok site in Antarctica (Jouzel et al., 1987; Jouzel et al., 1993; Jouzel et al., 1996; Barnola et al., 1999; Petit et al., 1999; Petit, et al., 2000) from the CDIAC (2001a) website. Although data collected from either the marine realm or ice cores do not provide temperature information directly, they do contain proxy information from which it is possible to infer temperature. Stable isotope ratios are among the best indicators of long-term climate change.

How are isotopes used to infer temperature change? - There are three naturally occurring common isotopes of oxygen (^{16}O, ^{17}O, ^{18}O). Each isotope has the same number of protons (eight), but differs in the number of neutrons in its nuclei. ^{16}O has only eight neutrons, while ^{18}O has ten neutrons. ^{16}O is the most abundant isotope of oxygen (99.789%), followed by ^{18}O (0.204%), and ^{17}O (0.037%). Because the ocean contains most of the Earth's water, the ratio of the concentration of ^{18}O to ^{16}O in the ocean is used as a standard to which the ratio of the concentrations of these two isotopes in other samples can be compared. The symbol "$\delta^{18}O$" is used to indicate how any sample's ratio differs from the ratio in Vienna Standard Mean Ocean Water (VSMOW). A negative $\delta^{18}O$

Log on to the website: http//cdiac.esd.ornl.gov/

This box contains instructions on how to obtain and manipulate information about temperature and CO_2 levels from Antarctic ice cores.

Click on ***Products*** in the large triangle.

Click on ***Climate*** in the Subject Areas list.

Click on ***Historical Isotopic Temperature Record from the Vostok Ice Core*** in the Global Temperature, Precipitation, Sea Level Pressure, and Station Pressure Data list.

Click on ***Digital Data*** at the top of the page.

Copy the data in the table and paste it into a spreadsheet.

Delete the first and third columns of data (depth and deuterium content of the ice).

All of the years in this data set are referenced to 1998. To make the years in this data set correspond to those in the oxygen isotope data set, first insert a new column between the year column and the temperature variation column. Subtract 48 from each of the year values in the first column and place the result in the new second column. Forty-eight is subtracted because that is the difference between 1950 and 1998.

Note that the temperatures that are shown are deviations from the modern surface temperature (-55.5 °C) at Vostok.

Graph the last two rows of the data (corrected year and temperature variation). These data cover a much longer time period than the GRIP oxygen isotope data.

You may want to scale the horizontal axis for Vostok data so that only the time period –50,000 to 250,000 years before 1950 is shown before comparing the Vostok and GRIP data.

How do the Vostok data compare to the GRIP data?

If you want to investigate the relationship between CO_2 and temperature further, go to the website: ***http://cdiac.esd.ornl.gov/trends/co2/contents.html*** and click on ***Historical CO_2 record from the Vostok ice core***.

Click on ***Graphics*** at the top of the page and view the long-term CO_2 record. How does the long-term CO_2 record compare to the long-term temperature record? Does it seem likely that temperature and atmospheric CO_2 concentration are correlated? Do changes in CO_2 concentrations precede or postdate temperature changes?

Text Box 7. Directions for accessing and manipulating temperature and CO_2 data from the Vostok ice core. Data from Jouzel et al. (1987; 1993; 1996), Barnola et al. (1987), Petit et al. (1999; 2000), and CDIAC (2001a).

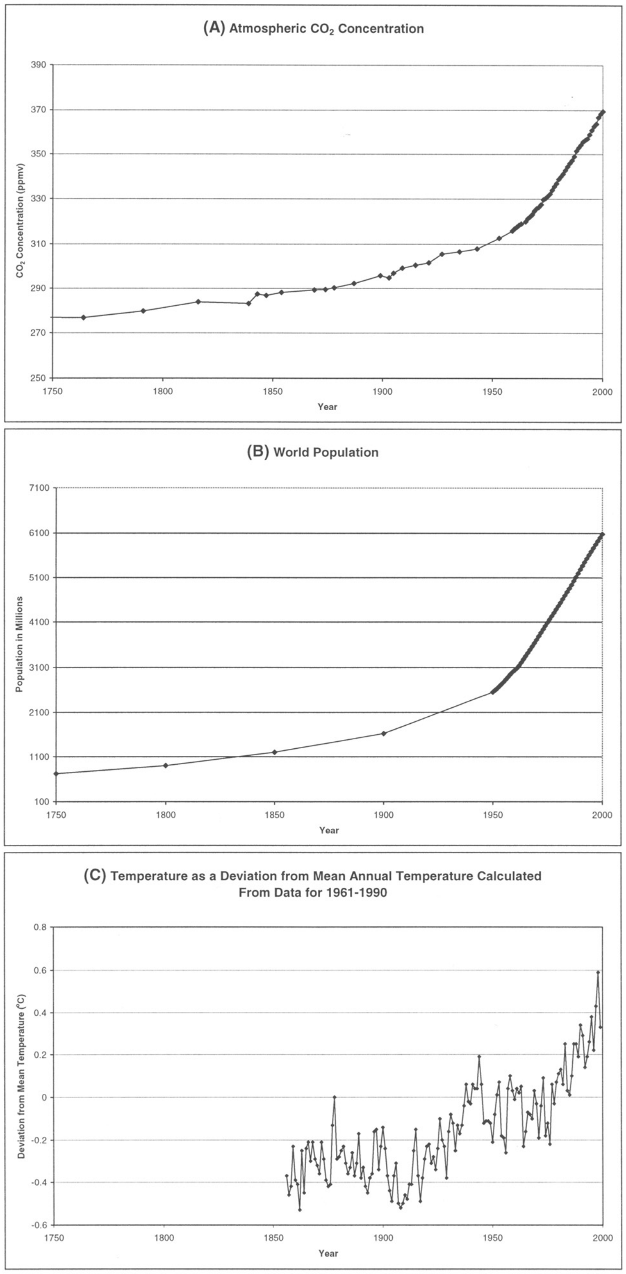

Figure 6: Atmospheric CO_2 concentration, population, and temperature for the last 250 years. (A) Atmospheric CO_2 data from Friedli et al. (1986), Neftel et al. (1994), CDIAC (2001a), and Keeling and Whorf (2001). (B) Population data from the United Nations (1973) and U.S. Census Bureau (1999). (C) Temperature data from Jones et al. (2000) and CDIAC (2001a).

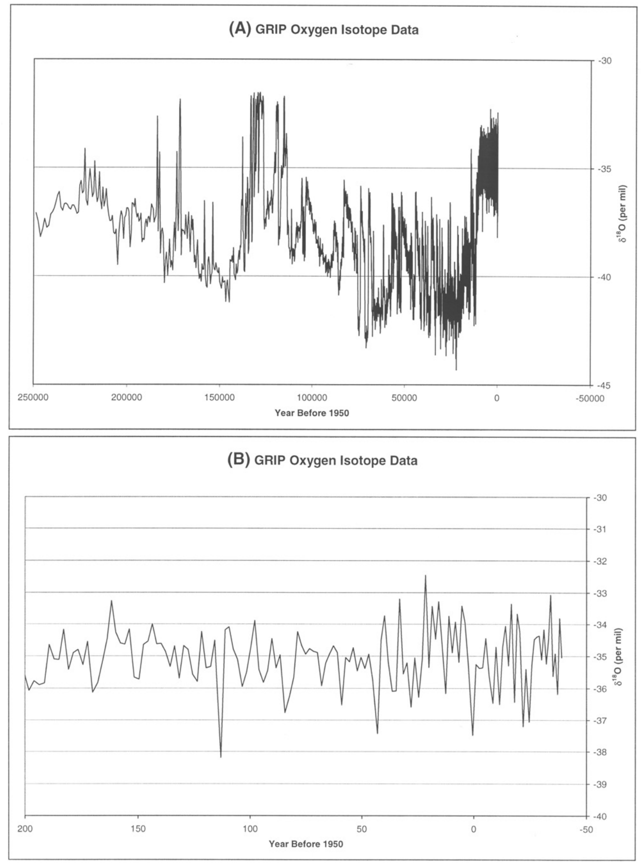

Figure 7: Oxygen isotope data from the Greenland Ice Sheet Project for the last 250,000 years (A), and the last 250 years (B). Temperature can be inferred from the isotope data: colder temperatures are associated with increasingly negative isotopic values. Data from Dansgaard et al. (1989; 1993), GRIP Members (1993), Grootes et al. (1993), Johnsen et al. (1997), and NCDC (2001).

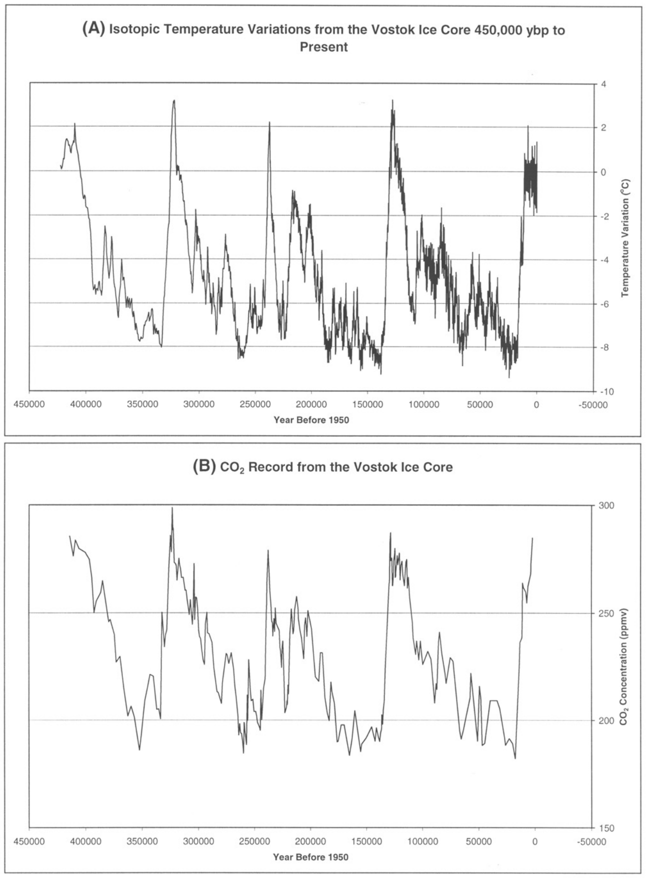

Figure 8: CO_2 and Temperature data from the Vostok ice core. (A) Temperatures inferred from deuterium content of the complete Vostok core for the last 450,000 years. (B) CO_2 data for the complete Vostok core for the last 450,000 years. Data from Jouzel et al. (1987; 1993; 1996), Barnola et al. (1987), Petit et al. (1999; 2000), and CDIAC (2001a).

value means that a sample has less ^{18}O than VSMOW, while a positive $\delta^{18}O$ value indicates that is has more ^{18}O. Fresh water (including rain or snow) always has less ^{18}O than VSMOW, and it therefore has a negative $\delta^{18}O$ value. When global climate cools, $\delta^{18}O$ values for snow and ice become increasingly negative (Figure 5). $\delta^{18}O$ data obtained from ice cores can be used to infer long-term climate change because they reflect the climate at the time the ice was deposited. Oxygen isotope data from the GRIP site can be accessed on the web (Text Box 6).

There are 2 stable isotopes of the element hydrogen, (protium and deuterium). Most hydrogen atoms are protium (99.98%); only 0.02% of hydrogen is deuterium. Like oxygen, the ratio of hydrogen isotopes in ice and snow is in part temperature dependent. At Vostok, Antarctica the relationship between the deuterium content of snow and average annual temperature has been determined theoretically and experimentally (Jouzel et al., 1993; Jouzel et al., 1996; Petit et al., 1999; Petit et al., 2000). Because a relationship between deuterium content and temperature exists, it is possible to infer temperatures from the deuterium content of the Vostok ice core (Text Box 7). The Vostok data set contains the longest continuous proxy temperature record available to scientists.

PART III: REFLECTING ON THE PROBLEM

After working through the web-based activity, respond to the question: "Should the U.S. and other countries limit emissions of greenhouse gases to reduce global warming?" using the data you have collected. Responses can be as short as one paragraph or as long as several pages. Table 1 contains an outline that can be used to guide preparation of a brief research report. The research report is intended to provide a format for integrating the interpretations made based on individual data sets. It is possible to interpret the results of the entire activity in many ways, so it is important to justify your conclusions using logic and data. The graphs prepared as part of the preceding portions of the activity should be used as figures in the report.

DISCUSSION

After students complete the exercise, it is worthwhile to discuss the data and their interpretations. Atmospheric CO_2 concentration, population, and global temperature all show similar trends for the last 150 years (Figure 6). Plotting the three data sets at the same scale makes it is possible to readily compare the different data. Both atmospheric CO_2 concentration and population show a steady increase from 1750 to about 1950. From 1950 to 2000, both atmospheric CO_2 concentration and population increased more rapidly. Temperature data (Figure 6c) show more variability, but there is a rapid increase in temperature during the last half of the 20^{th} century. This analysis does not prove a relationship between population, atmospheric greenhouse gas concentrations, and global warming; rather it suggests a relationship may exist.

Although the graphs shown in Figure 6 may initially cause students to conclude that human activities are producing global climate change, the purpose of the rest of the exercise is to show that significant climate changes have occurred in the past, before humans had an impact. Data from two distinct time periods are examined in the exercise to demonstrate how one might reach disparate conclusions by using different types of data to study a problem. As mentioned within the exercise, scientists collect data to test a hypothesis, not to prove that a hypothesis is true. The process of hypothesis testing is not well understood outside of the academy, and politicians and the media typically cite preliminary results of research projects to justify policy decisions. Students and the public at large need to become more familiar with the scientific process in order to critically evaluate those policy decisions and the data on which they are based. By asking students to make a decision based on data that lead them to contradictory interpretations, this exercise presents them with a real-world problem faced by many scientists whose research addresses issues of interest to the general public. After it is completed, the exercise can be used to stimulate classroom discussions about the scientific method, the need for scientific literacy among the general public, and the relation between scientific research and public policy decisions.

Long-term $\delta^{18}O$ data from the Greenland Ice Sheet show evidence of climate change during approximately the last 250,000 years (Figure 7a). This long-term dataset shows no significant change during the recent past (Figure 7b) in contrast to the data in Figure 6. The oxygen isotope data in Figure 7b do not directly correlate with temperature data (Figure 6c) because temperature is only one of the factors that control the ratio of oxygen isotopes in ice. The source of the moisture that becomes the ice has a more significant influence on the isotopic composition of the ice than temperature. Oxygen isotopes are used to infer long-term climate change because significant changes in climate result in variations in the sources of moisture. The long-term data show cyclicity at a variety of scales, consistent with the basic tenets of Milankovitch Theory.

Temperature information derived from the deuterium content of the Vostok ice core for the last 250,000 years (Figure 8a) shows the same basic trend as the oxygen isotope data from Greenland (Figure 7a). Consistency between the two data sets lends credibility to the assumption that isotopes can be used to infer global climate change. Temperature and CO_2 data (Figure 8b) for the complete Vostok ice core show obvious cyclicity.

Three important aspects of greenhouse gases are not highlighted in the activity. First, greenhouse gases remain in the atmosphere for long periods of time, and their present-day effects are minor compared to those predicted for the long-term by atmospheric scientists. The atmospheric lifetime of CO_2 is 120 years, but other greenhouse gases have longer lifetimes. For example, sulfur hexafluoride (a relatively minor greenhouse gas) has a lifetime of 3,200 years (CDIAC, 2001b; Houghton, et al., 2001). Secondly, all greenhouse gases have different potentials to warm the atmosphere. Sulfur hexafluoride has 22,200 times the global warming potential of CO_2 (CDIAC, 2001b; Houghton, et al., 2001). Thirdly, the effect of water vapor in the atmosphere on global climate is not addressed.

Composing a written response at the end of the activity serves three main purposes. First, it requires students to reflect on the data, and to integrate all available information. Second, it gives students the opportunity to sharpen their technical writing skills. Third, by presenting and justifying interpretations, students participate in all phases of research: identification of a problem, data collection and interpretation, and dissemination of the results of the study. Classroom discussions conducted after completion of the exercise are typically informative and enlightening for both students and faculty.

ACKNOWLEDGEMENTS

The authors thank Dr. William P. Patterson and an anonymous reviewer who took the time to critically evaluate this paper and offer many constructive suggestions. This paper also benefited from helpful discussions with Michigan Tech students Katie Keranen, Len Mankowski, and Kristi Gerber. Kristi Gerber also helped to prepare several of the graphics for the paper. Drs. Sue Beske-Diehl and Matt Peterson provided excellent ideas and constructive criticism. Dr. William Ruddiman reviewed an early draft of the manuscript. Funding provided by the American Geological Institute and the State of Michigan made this paper possible.

REFERENCES

American Geophysical Union, 1998, Climate Change and Greenhouse Gases: Position Statement, website: http://www.agu.org/sci_soc/policy/climate_change_position.html, site visited on September 21, 2001.

Barnola, J.M., Raynaud, D., Lorius, C., and Barkov, N.I., 1999, Historical CO_2 record from the Vostok ice core, *in*, Trends: A Compendium of Data on Global Change: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, TN, U.S.A., website: http://cdiac.esd.ornl.gov/trends/co2/vostok.htm, site visited on October 30, 2001.

Considine, D., 1976, Van Nostrand's Scientific Encyclopedia: New York, Van Nostrand Reinhold Company, 5th Edition, 2370 p.

Carbon Dioxide Information Analysis Center, 2001a, Carbon Dioxide Information Analysis Center, website: http://cdiac.esd.ornl.gov/, site visited on October 30, 2001.

Carbon Dioxide Information Analysis Center, 2001b, Current Greenhouse Gas Concentrations, website: , site visited on October 30, 2001.

Crowley, T.J. and North, G.R., 1991, Paleoclimatology: Oxford University Press, Oxford Monographs on Geology and Geophysics #18, p. 135.

Dansgaard, W., Johnsen, S.J., Clausen, H.B., Dahl-Jensen, D., Gundestrup, N.S., Hammer, C.U., Hvidberg, C.S., Steffensen, J.P., Sveinbjörnsdóttir, A.E., Jouzel, J., and Bond, G.C., 1993, Evidence for general instability of past climate from a 250 kyr ice-core record: Nature, v. 264, p. 218-220.

Dansgaard, W., White, J.W.C., and Johnsen, S.J., 1989, The abrupt termination of the Younger Dryas climate event: Nature, v. 339, p. 532-533.

Duxbury, A.C., A.B. Duxbury, and K.A. Sverdrup, 2000, Introduction to the World's Ocean: Madison, McGraw Hill, p. 32.

Friedli, H.H., Lotscher, H., Oeschger, H., Siegenthaler, U., and Stauffer, B., 1986, Ice core record of 13C/12C

ratio of atmospheric CO_2 in the past two centuries: Nature, v. 295, p. 220-223.
Gerhard, L.C., Harrison, W.E., and Hanson, B.M., 2001, Introduction and overview, *in* Gerhard, L.C., Harrison, W.E., and Hanson, B.M., eds., Geological Perspectives of Global Climate Change: Tulsa, OK, American Association of Petroleum Geologists, Studies in Geology, n. 47, p. 1-15.
GRIP Members, 1993, Climate instability during the last interglacial period recorded in the GRIP ice core: Nature, v. 364, p. 203-207.
Grootes, P.M., Stuiver, M., White, J.W.C., Johnsen, S.J., and Jouzel, J., 1993, Comparison of oxygen isotope records from the GISP2 and GRIP Greenland ice cores: Nature, v. 366, p. 552-554.
Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A., and Maskell, K., 2001, Climate Change 2001: The Scientific Basis: Cambridge, UK, Cambridge University Press, 944 p.
Imbrie, J. and Imbrie, K.P., 1986, Ice Ages Solving the Mystery: Cambridge, MA, Harvard University Press, 224 pp.
Johnsen, S.J., Clausen, H.B., Dansgaard, W., Gundestrup, N.S., Hammer, C.U., Andersen, U., Andersen, K.K., Hvidberg, C.S., Dahl-Jensen, D., Steffensen, J.P., Shoji, H., Sveinbjörnsdóttir, A.E., White, J.W.C., Jouzel, J., and Fisher, D., 1997, The ?18O record along the Greenland Ice Core Project deep ice core and the problem of possible Eemian climatic instability: Journal of Geophysical Research, v. 102, p. 26397-26410.
Jones, P.D., Parker, D.E., Osborn, T.J., and Briffa, K.R., 2000, Global and hemispheric temperatures anomalies – land and marine instrumental records, *in*, Trends: A Compendium of Data on Global Change: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, TN, U.S.A., website: , site visited on October 30, 2001.
Jouzel, J., Barkov, N.I., Barnola, J.M., Bender, M., Chappellaz, J., Genthon, C., Kotlyakov, V.M., Lipenkov, V., Lorius, C., Petit, J.R., Raynaud, D., Raisbeck, G., Ritz, C., Sowers, T., Stievenard, M., Yiou, F., and Yiou, P., 1993, Extending the Vostok ice-core record of palaeoclimate to the penultimate glacial period: Nature, v. 364, p. 407-412.
Jouzel, J., Lorius, C., Petit, J.R., Genthon, C., Barkov, N.I., Kotlyakov, V.M., and Petrov, V.M., 1987, Vostok ice core: a continuous isotope temperature record over the last climatic cycle (160,000 years): Nature, v. 329, p. 403-408.
Jouzel, J., Waelbroeck, C., Malaize, B., Bender, M., Petit, J.R., Stievenard, M., Barkov, N.I., Barnola, J.M., King, T., Kotlyakov, V.M., Lipenkov, V., Lorius, C., Raynaud, D., Ritz, C., and Sowers, T., 1996, Climatic interpretation of the recently extended Vostok ice records: Climate Dynamics, v. 12 p. 513-521.
Keeling, D.D., and Whorf, T.P., 2001, Atmospheric CO_2 records from sites in the SIO air sampling network, *in*, Trends: A Compendium of Data on Global Change: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, TN, U.S.A., website: , site visited on October 25, 2001.
Kump, L.R., Kasting, J.F., and Crane, R.G., 1999, The Earth System: Upper Saddle River, New Jersey, Prentice Hall, 351 p.
Levitus, S., Antonov, J.I., Wang, J., Delworth, T.L., Dixon, K.W., and Broccoli, A.J., 2001, Anthropogenic warming of the Earth's climate system: Science, v. 292, p. 267-270.
National Aeronautics and Space Administration, 2000 (actual posting date unknown), Milutin Milankovitch, *in*, On the Shoulders of Giants Series, website: http://earthobservatory.nasa.gov/Library/Giants/Milankovitch/, site visited on July 20, 2000.
National Climatic Data Center, 2001, Climate Resources, website: , site visited on October 31, 2001.
Neftel, A., Friedli, H., Moor, E., Lotscher, H., Oeschger, H., Siegenthaler, U., and Stauffer, B., 1994, Historical CO_2 record from the Siple Station ice core, *in*, Trends: A Compendium of Data on Global Change: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, TN, U.S.A., website: http://cdiac.esd.ornl.gov/trends/co2/siple.htm, site visited on October 26, 2001.
Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J.M., Basile, I., Bender, M., Chappellaz, J., Davis, M., Delayque, G., Delmotte, M., Kotlyakov, V.M., Legrand, M., Lipenkov, V.Y., Lorius, C., Pepin, L., Ritz, C., Saltzman, E., and Stievenard, M., 1999, Climate and atmospheric history of the past 420,000 years from Vostok ice core, Antarctica: Nature, v. 399, p. 429-436.
Petit, J.R., Raynaud, D., Lorius, C., Jouzel, J., Delaygue, G., Barkov, N.I., and Kotlyakov, V.M., 2000, Historical isotopic temperature record from the Vostok ice core, *in*, Trends: A Compendium of Data on Global Change: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, TN, U.S.A., website: , site visited on October 30, 2001.
Roof, S.R., and Savoy, L.E., 1996, Laboratory exploration of Pleistocene climate change, orbital forcing, and ocean-atmosphere interactions: Journal of Geoscience Education, v. 44, p. 300-308.
Rosenberg, M., 1998, Milankovitch Cycles: Changes in Earth-Sun Interaction, website: http://geography.about.com/library/weekly/aa121498.htm, site visited on July 22, 2000.
United Nations, 1973, The determinants and consequences of population trends: Population Studies, n. 50, p.10.
U.S. Census Bureau, 1999, World Population Information, website: , site visited on October 31, 2001.
U.S. Environmental Protection Agency, 2001, Global Warming, website: , site visited on October 31, 2001.
U.S. Naval Observatory, 2000, Astronomical Applications Department, Data Services, website: http://aa.usno.navy.mil/, site visited on July 22, 2000.