Module 6 - Lecture 16a

This is the first of two lectures on climate change. This is a complex and contentious subject. In this lecture, we will concentrate on evidence that humans may be changing climate by causing the earth to warm. In the next lecture, we will look at predictions for the next 100 years or so and also at some of the consequences that climate change may bring.

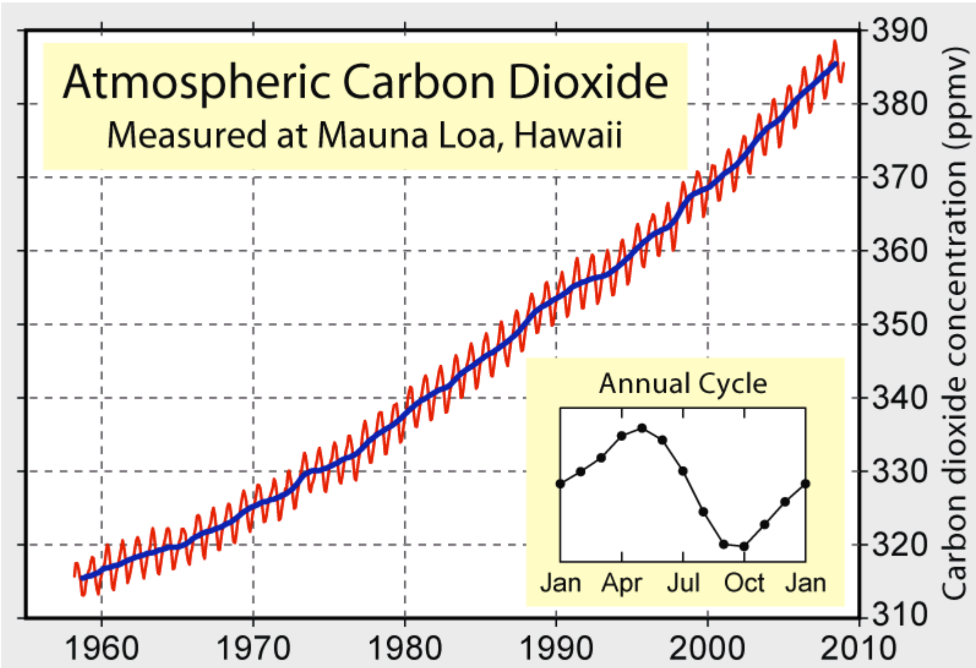
Before we look at the enhancement of the greenhouse effect, it is important to remember that the greenhouse effect has a beneficial side. You might refer to this as the natural greenhouse effect (i.e. one that has not been affected or influenced by human activities). If the earth's atmosphere did not contain any greenhouse gases, the global annual average surface temperature would be about 0^oF, which is pretty cold. The presence of greenhouse gases raises this average temperature to about 60^oF and makes the earth a much more habitable place.

The current concern centers on the increasing atmospheric concentrations of greenhouse gases and how this may affect the earth's energy balance. Carbon dioxide is probably the best known of the greenhouse gases. Other greenhouse gases include water vapor, methane, chlorofluocarbons and ozone. Much of what we will say about carbon dioxide applies to the other greenhouse gases as well.

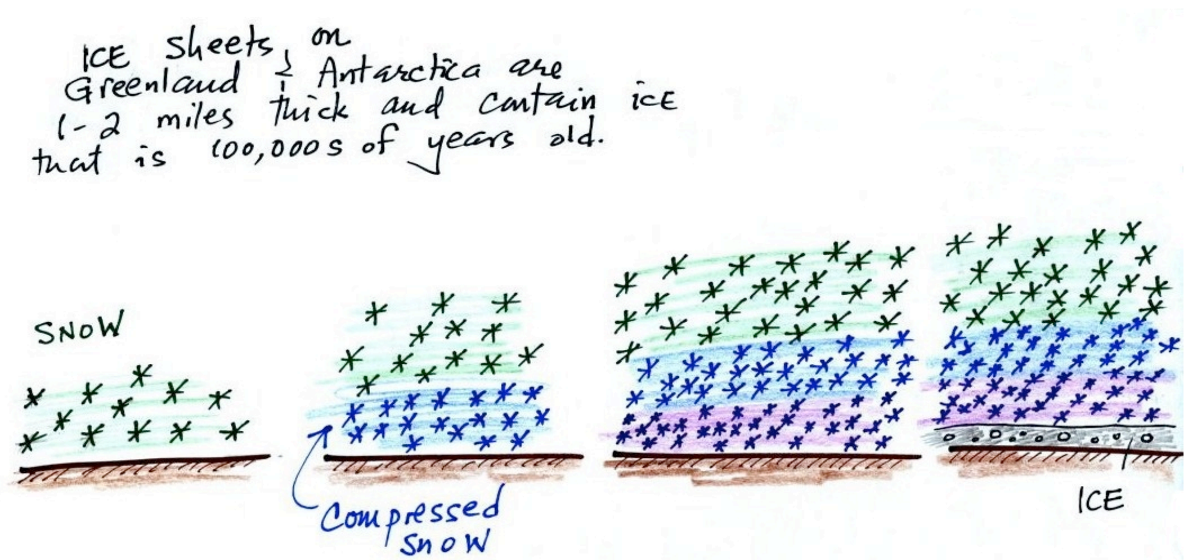
Here are some main points to consider.

- Atmospheric CO_2 concentrations are increasing, largely as a result of human activities. This is generally accepted as fact. We will look at some of the evidence below.
- Increasing greenhouse gas concentrations will strengthen the greenhouse effect and cause the earth's surface to warm. This is a hypothesis, but many (perhaps the vast majority of) scientists regard this as fact and believe that enhanced greenhouse effect warming is already underway.
- Even a small change in the global average temperature could melt polar ice and cause a rise in sea level that may pose an environmental threat to coastal areas. Warming may change weather patterns and bring more precipitation to some areas and prolonged drought to other places (like Arizona). Vectors that carry serious tropical diseases, such as malaria & dengue fever, may extend their range into more temperate areas. Plant and animal species could become extent if they cannot adapt to the changed conditions.

The Keeling Curve consists of carbon dioxide measurements made on top of the Mauna Loa volcano in Hawaii. Mauna Loa is a good location for measuring background levels of carbon dioxide because it is remote from cities. This famous graph is named after Charles Keeling, who began these measurements in 1958. Carbon dioxide concentrations have increased from 315 ppm in 1958 to about 385 ppm today. The small wiggles (one wiggle per year) show that the carbon dioxide concentration changes slightly during the course of a year. For more information, see the Scripps Institution of Oceanography site.

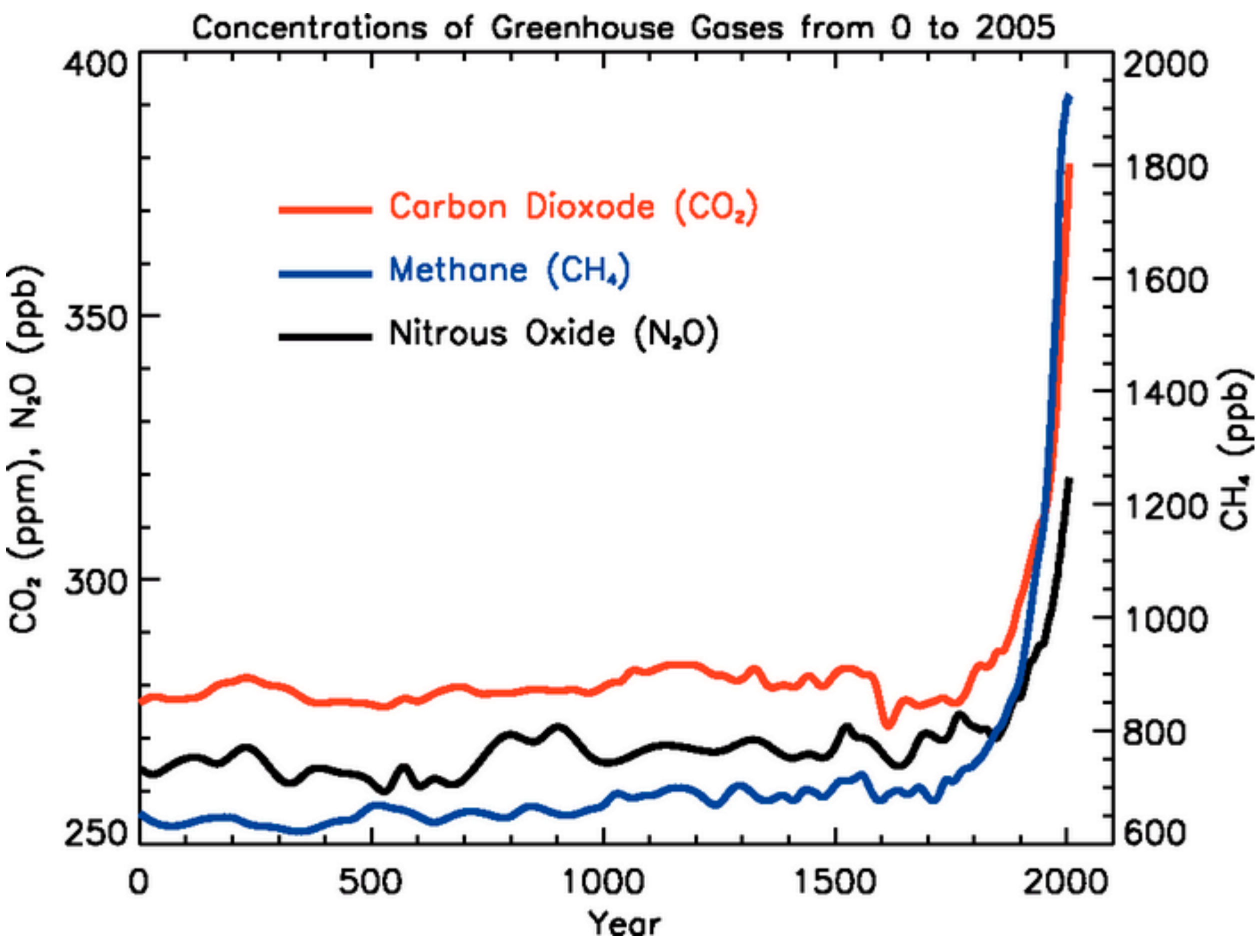


Once scientists saw this data, they wanted to determine the concentration of atmospheric carbon dioxide in the past. Scientists devised a very clever method to accomplish this. They collected core samples from the Antarctica and Greenland ice sheets that are thousands of years old. As layers of snow are piled on top of each other year after year, the snow at the bottom is compressed and eventually turns into a thin layer of solid ice. The ice contains small bubbles of air trapped in the snow, which are samples of the atmosphere at the time the snow originally fell. Scientists are able to date the ice layers, remove air from these bubbles and measure the carbon dioxide concentration. The technique is challenging because the layers are very thin, the bubbles are small and it is hard to avoid contamination.



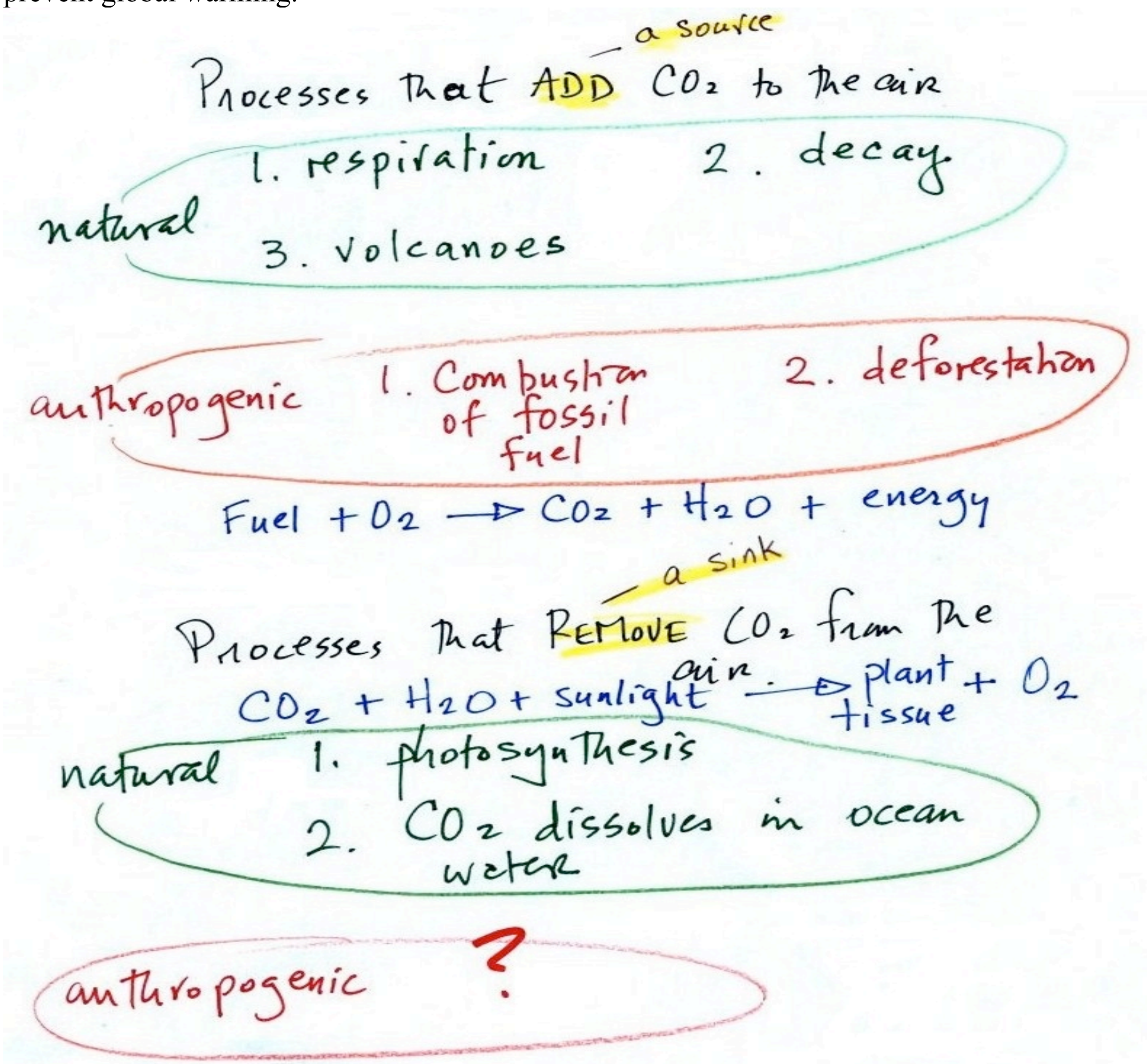
From ice core measurements scientists have determined that the atmospheric carbon dioxide concentration remained fairly constant at about 280 ppm from 0 AD until the mid-1700s, which marked the beginning of the Industrial Revolution. Fossil fuel combustion to power factories began to add significant amounts of Carbon dioxide to the atmosphere. The figure (from Climate Change 2007, IPCC 4th Assessment Report) shows that concentrations of two other greenhouse gases, methane and nitrous oxide, show a very similar trend.

While most scientists attribute the current increase in carbon dioxide to human activities, natural processes can also cause fluctuations in atmospheric carbon dioxide concentration. Other ice core measurements (source) actually extend back several hundred thousand years and indicate that carbon dioxide concentrations varied between about 180 and 300 ppm. The current carbon dioxide increase is the largest and most rapid in the ice core record.

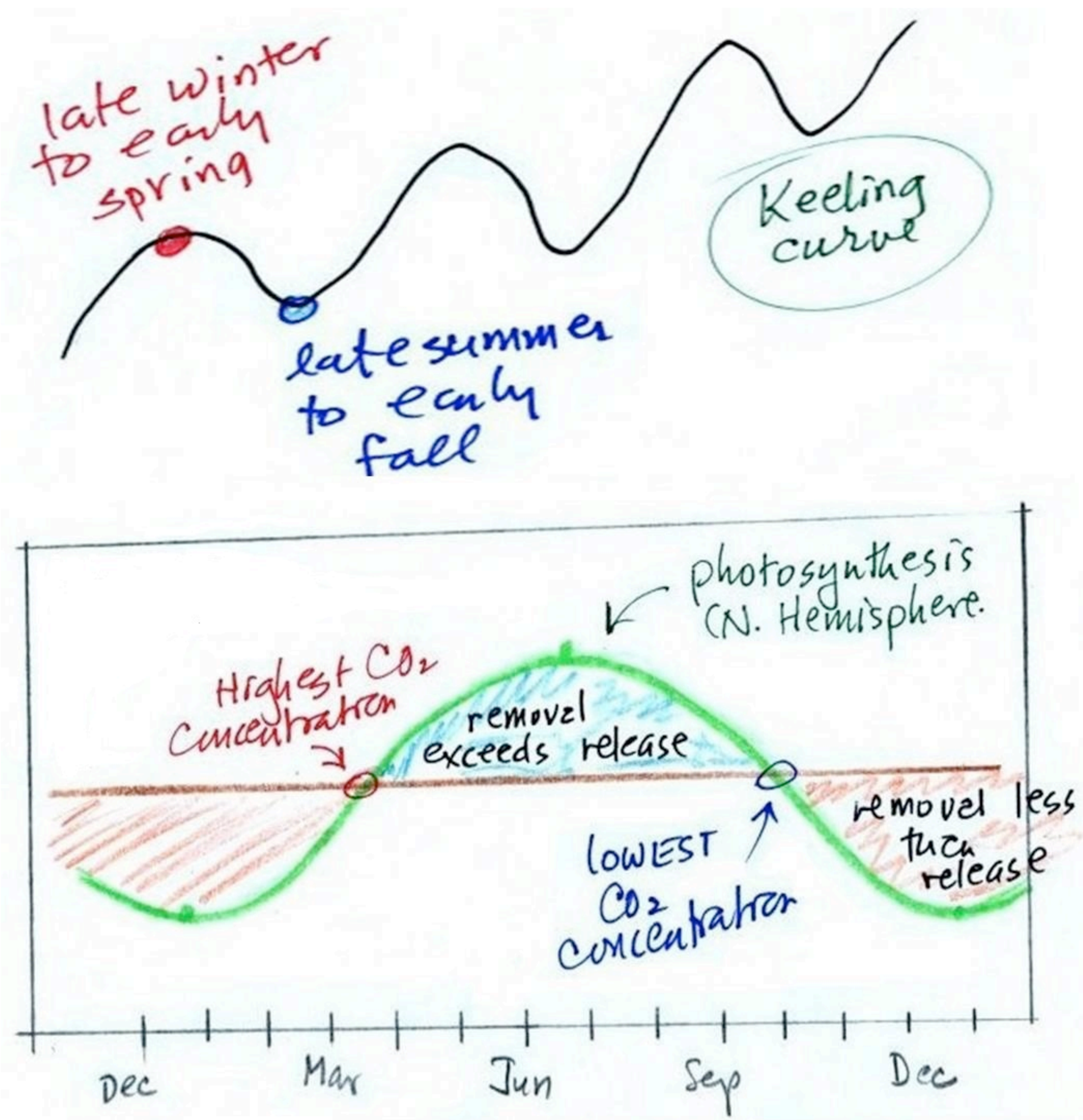


Now we will look at the sources and sinks of carbon dioxide in the atmosphere. Carbon dioxide is added to the atmosphere naturally by respiration (animals breathe in oxygen and exhale carbon dioxide), the decay of organic matter, and volcanoes. Combustion of fossil fuels, a human activity also adds carbon dioxide to the atmosphere. Photosynthesis removes carbon dioxide (the equation is shown below) and carbon dioxide dissolves in the oceans. Deforestation indirectly adds carbon dioxide to the atmosphere because cutting down and killing a tree prevents it from removing carbon dioxide from the air through photosynthesis.

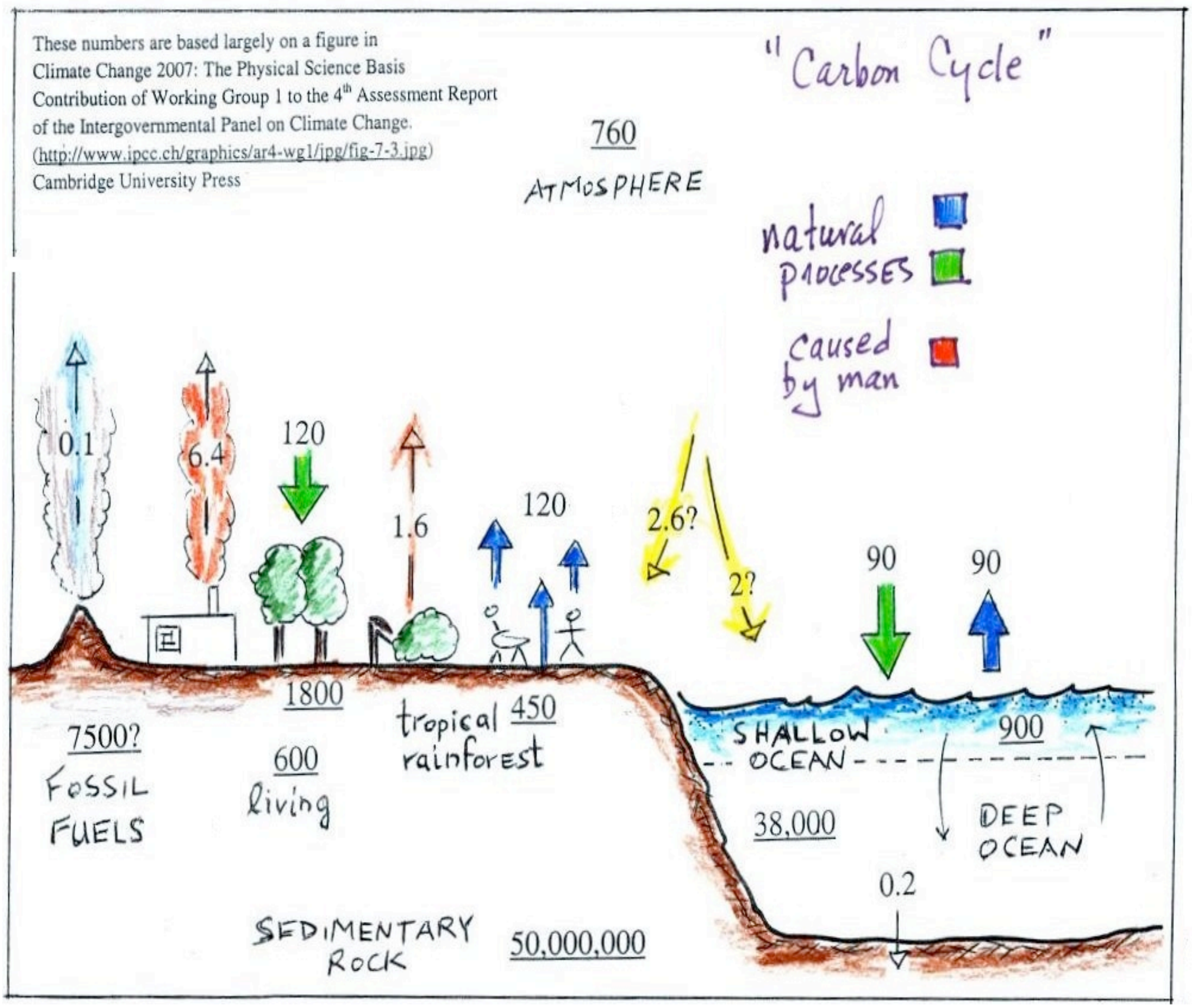
The ? in the figure below means your instructor is not aware of any anthropogenic process that removes significant amounts of carbon dioxide from the air. Carbon sequestration (the capture/removal of carbon dioxide from the air and storing it) is being considered to lessen or prevent global warming.



We are now able to better understand the yearly variation in atmospheric carbon dioxide concentration or the "wiggles" on the Keeling Curve (the top panel of the figure below). The annual photosynthesis cycle is shown in the bottom panel of the figure below (green curve). Atmospheric carbon dioxide concentrations are lower in the summer when the rate of photosynthesis is highest because photosynthesis consumes carbon dioxide. In the winter, more fossil fuels are burned for heating homes and photosynthetic activity is also at a minimum, which causes higher atmospheric carbon dioxide concentrations.



To understand why human activities are causing atmospheric carbon dioxide concentrations to increase, we need to look at the relative amounts of carbon dioxide being added to and being removed from the atmosphere. The carbon balance in the atmosphere can be compared to the balance in a bank account. The carbon cycle shows the movement of carbon through the atmosphere, land and the ocean. A simplified version of the carbon cycle is shown below.



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Here are the main points to take from this figure, which rely on computer models to predict or estimate how much warming there will be and how the amount of warming might depend on location).

1. The underlined numbers show the amount of carbon <u>stored</u> in "reservoirs." For example 760

units* of carbon are stored in the atmosphere, predominantly in the form of carbon dioxide, but also in small amounts as methane (CH_4), chlorofluorocarbons and other gases containing carbon. Note that the atmosphere is a small reservoir compared to the ocean. The other numbers show "fluxes," the amount of carbon moving into or out of the various reservoirs (actually just into and out of the atmosphere). Over land, respiration and decay add 120 units* of carbon to the atmosphere every year. Photosynthesis (primarily) removes 120 units every year.

2. Note the natural processes (color-coded blue and green) are more or less in balance over land (120 units added to the atmosphere and 120 units removed) and over the oceans (90 units added and 90 units of carbon removed). If these were the only processes present, the atmospheric concentration (760 units) would not change.

3. Anthropogenic (human-caused) emissions of carbon into the air are small compared to natural processes (orange in the figure). About 6.4 units are added during the combustion of fossil fuels (and during the manufacture of cement) and 1.6 units are added every year because of deforestation. (When trees are cut down they decay or are burned and add carbon dioxide to the air. They are also not able to remove carbon dioxide from the atmosphere through photosynthesis.)

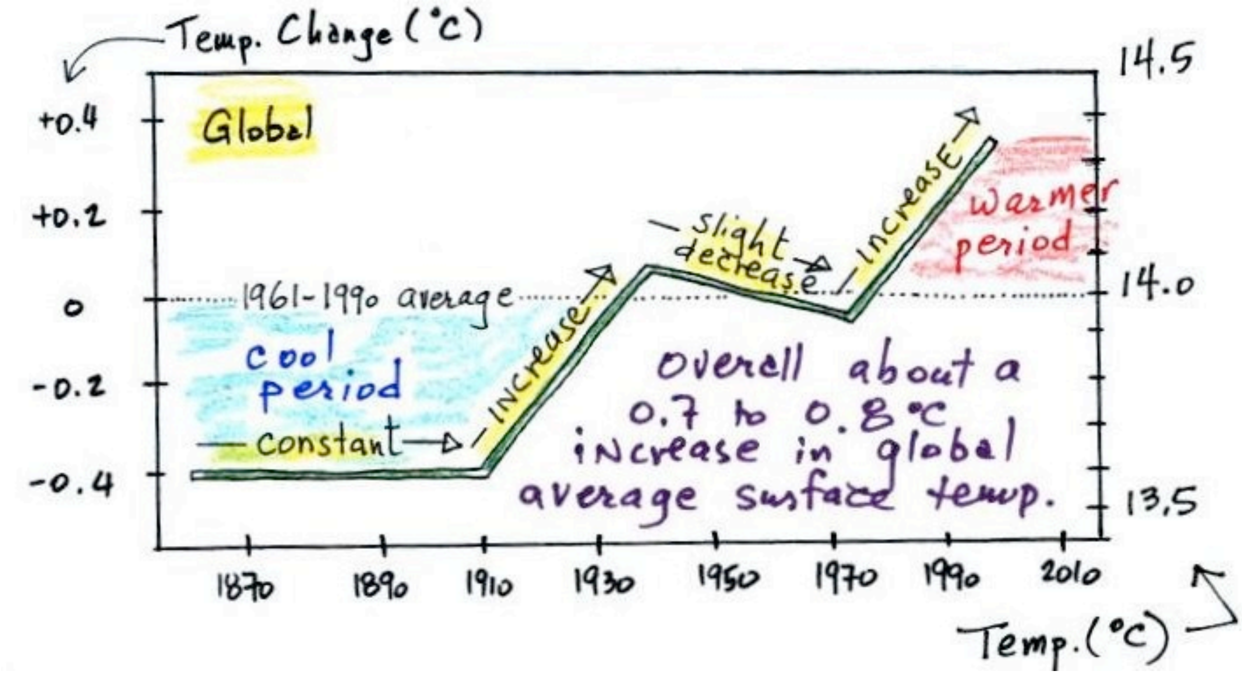
4. The rate at which carbon is added to the atmosphere by man is not balanced by an equal rate of removal. Only about half (4.6 of the 8) units added every year are removed (highlighted in yellow in the figure). This small imbalance (8 - 4.6 = 3.6 units) of carbon are added to the atmosphere every year, which explains why atmospheric carbon dioxide concentrations are continuing to increase. Note also that more carbon dioxide is added to the oceans every year than is removed. The addition of carbon dioxide to the oceans could increase the acidity of the ocean and make it more difficult for coral and sea shells to form. Shells and coral are made of calcium carbonate ($CaCO_3$).

4. In the next hundred years or so, the 7500 units of carbon currently stored in the fossil fuels reservoir (lower left hand corner of the figure) may be dug up or pumped out of the ground and burned. That would add 7500 units of carbon to the air. The big question is how will the atmospheric concentration change and what effects will that have on climate? Carbon dioxide can move into and out of the atmosphere fairly quickly, but movement through the other reservoirs is slower. The ocean may take a thousand or more years to reach a new equilibrium. Thus it is difficult to say precisely how quickly the picture will change when it is perturbed.

*Do not worry about the units, but here they are just in case you are interested.
Reservoirs - Gtons
Fluxes - Gtons/year
A Gton = 10^{12} metric tons. (1 metric ton is 1000 kilograms or about 2200 pounds)

Here is what we have learned so far. The atmospheric carbon dioxide concentration was fairly constant between 0 AD and the mid 1700s and it has been increasing since the mid 1700s. The obvious question is, what has the temperature of the earth been doing during this period? In particular has there been any warming associated with the increases in greenhouse gases that have occurred since the mid 1700s?

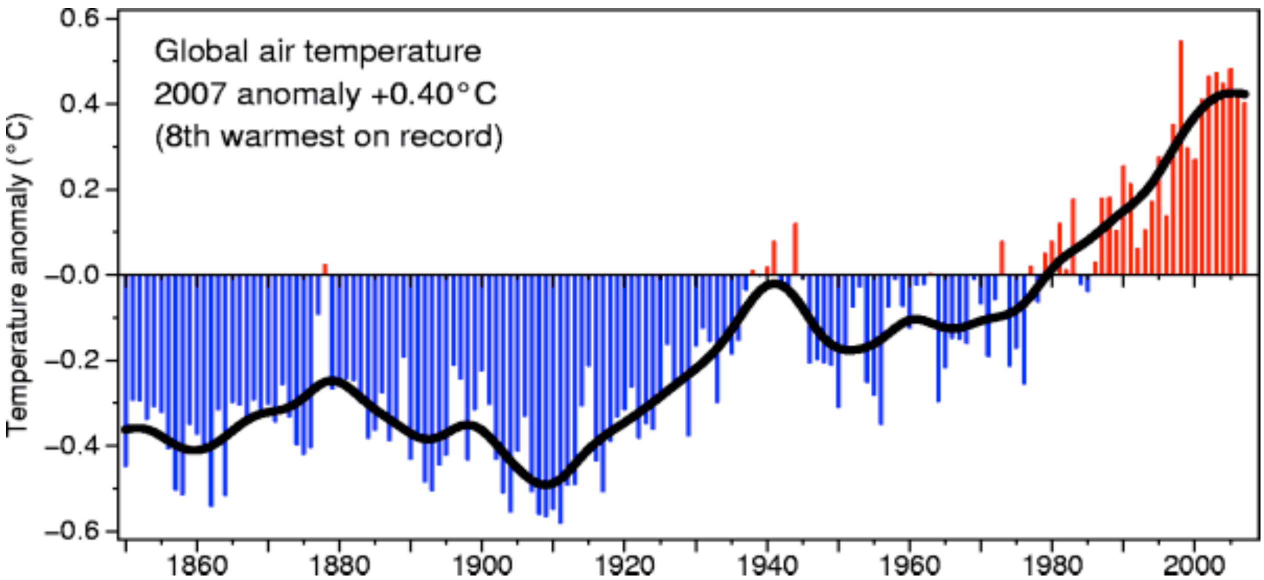
First we must take inventory of the accurate temperature data that we have. The figure below is based on actual temperature measurements using reliable thermometers at many locations on land and sea around the globe. The left side of the figure shows how average temperatures at various times compared with the 1961 to 1990 average. The vertical axis on the right side of the plot shows actual global average surface temperature values.



The temperature appears to have increased 0.7° to 0.8° C during this period. The increase has not been steady as you might have expected given the steady rise in carbon dioxide concentration (assuming that increasing carbon dioxide levels is the cause of the warming trend). The temperature also decreased slightly between about 1940 and 1970.

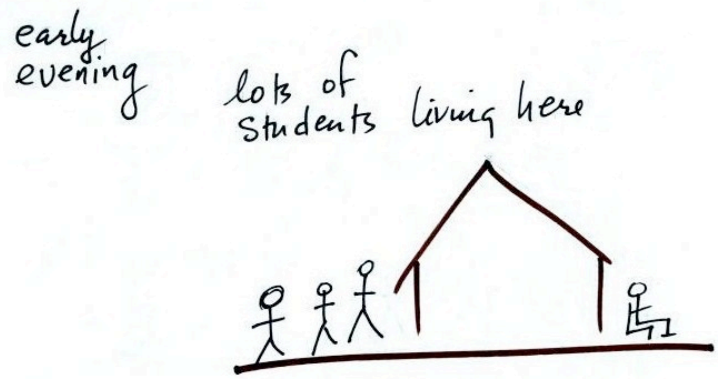
It is very difficult to detect a temperature change this small over this period of time. The instruments used to measure temperature have changed. The locations at which temperature measurements have been made have also changed (imagine what Tucson was like 130 years ago). About two thirds of the earth's surface is ocean and measurements were pretty sparse during much of this time period (sea surface temperatures can now be measured using satellites). Average surface temperatures also naturally change a lot from year to year.

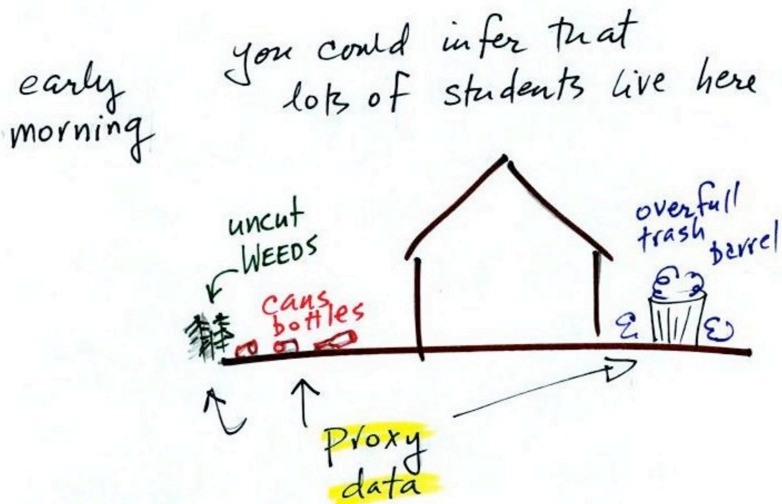
Here is another plot of global temperature change over a slightly longer time period from the University of East Anglia Climatic Research Unit. We should mention that the observed warming has not been uniformly distributed over the surface of the earth. Data from the 2000-2009 period shows the that greatest warming occurred in the Arctic.



Now it would be interesting to know how temperature changed prior to the mid-1800s. To measure carbon dioxide concentrations in the past, scientists were able to go back and analyze air samples from the past (air trapped in bubbles in ice sheets). A similar technique would not work with temperature because the trapped air bubbles would eventually reach the temperature of the surrounding ice. To determine past temperatures, you need to look for something else whose presence, concentration, or composition depended on the temperature at some time in the past. This is called proxy data.

Here is a proxy data "example." Suppose you want to determine how many students are living in a house near a university. You could walk by the house late in the afternoon when the students are most likely be outside and count them. That would be a direct measurement like measuring temperature with a thermometer. There could still be some errors in your measurement because some students who live in the house might be inside while some people outside may not live in the house. If you were to walk by early in the morning it is likely that the students would be inside sleeping. In that case you might look for other clues (such as the number of empty bottles in the yard) that might give you an idea of how many students lived in that house. You would use these proxy data to come up with an estimate of the number of students inside the house.





Scientists use a wide variety of proxy variables to estimate temperature.

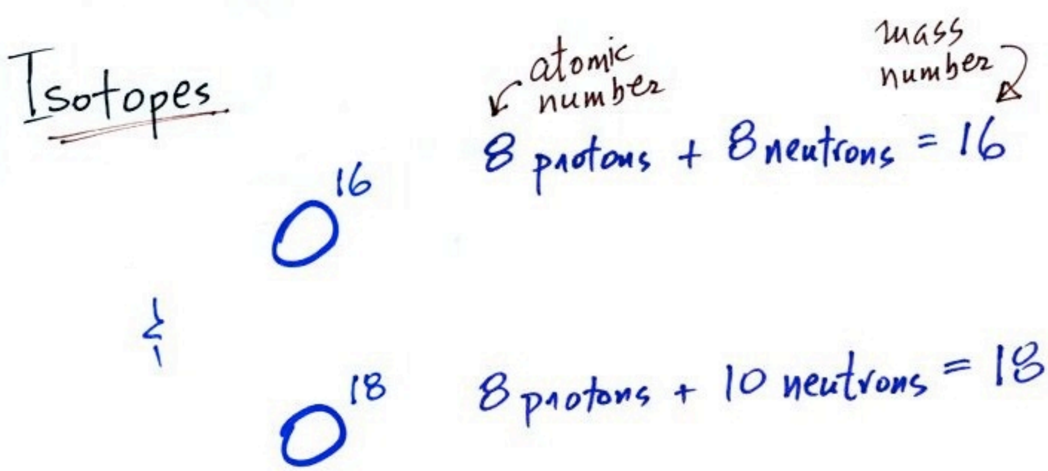
Tree Rings
The width of each yearly ring depends up the temperature and precipitation at the time the ring formed.

Coral
Coral is made up of calcium carbonate, which contains oxygen. The relative amounts of the oxygen^{-16} and oxygen^{-18} isotopes depend upon the temperature that existed at the time the coral grew.

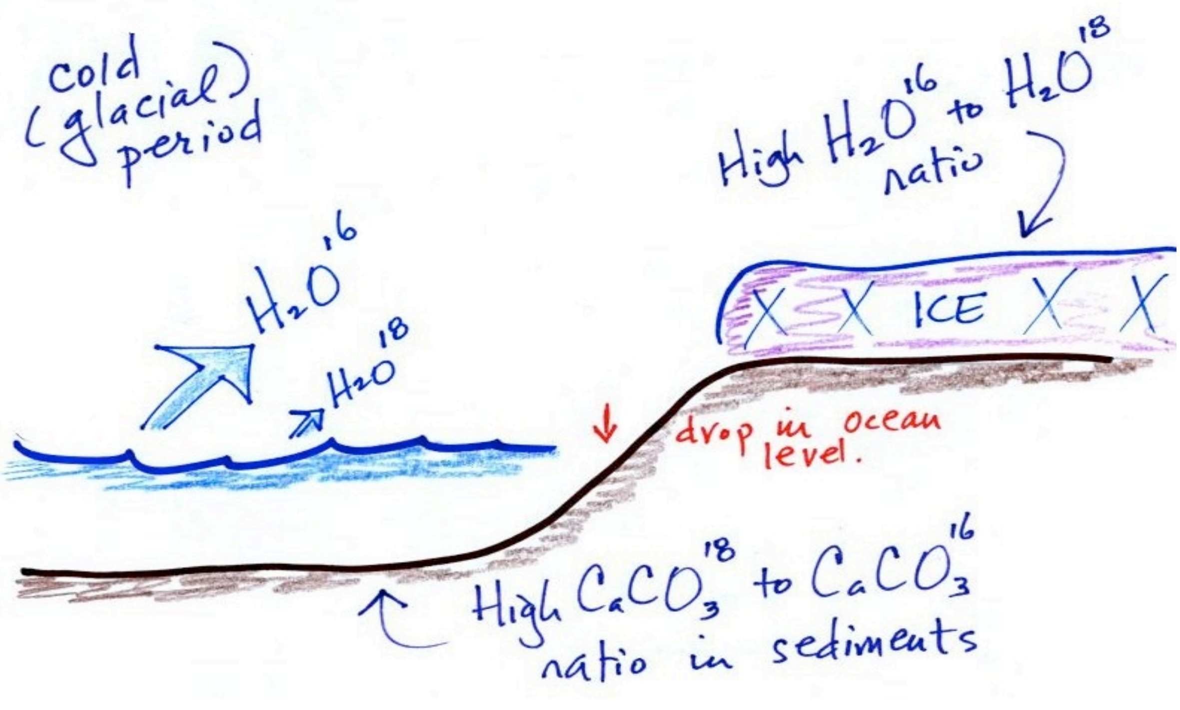
Lake and Ocean Sediments
Scientists can analyze lake bed and ocean sediments. The types of plant and animal fossils that they find depend on the water temperature at the time.

Ice Cores

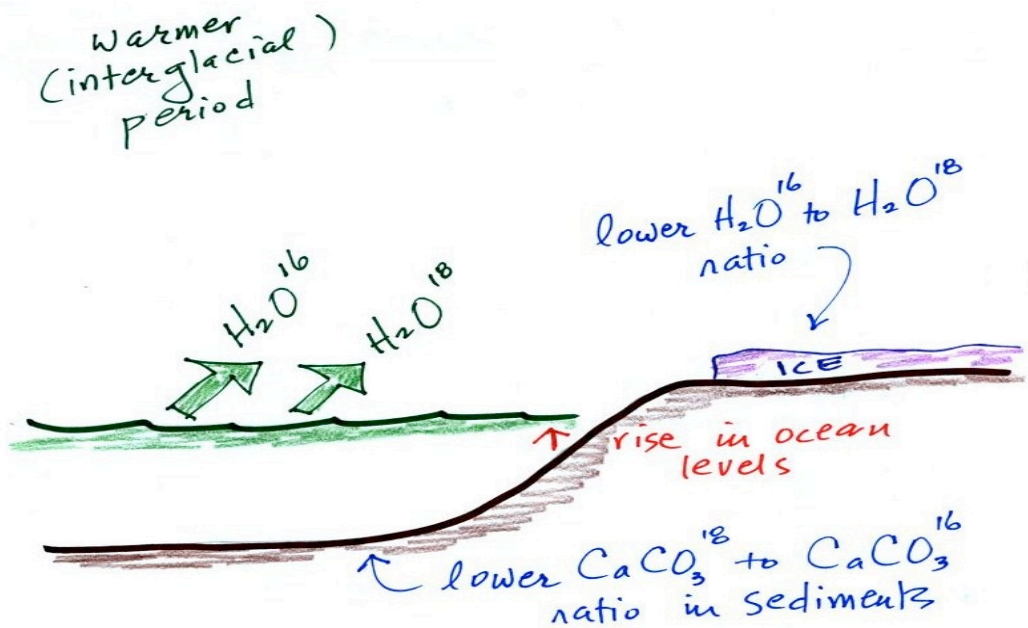
The relative amounts of oxygen and hydrogen isotopes depend upon the temperature at the time the ice fell from the sky as snow. Here is an idea of how oxygen isotope data can be used to determine past temperature.



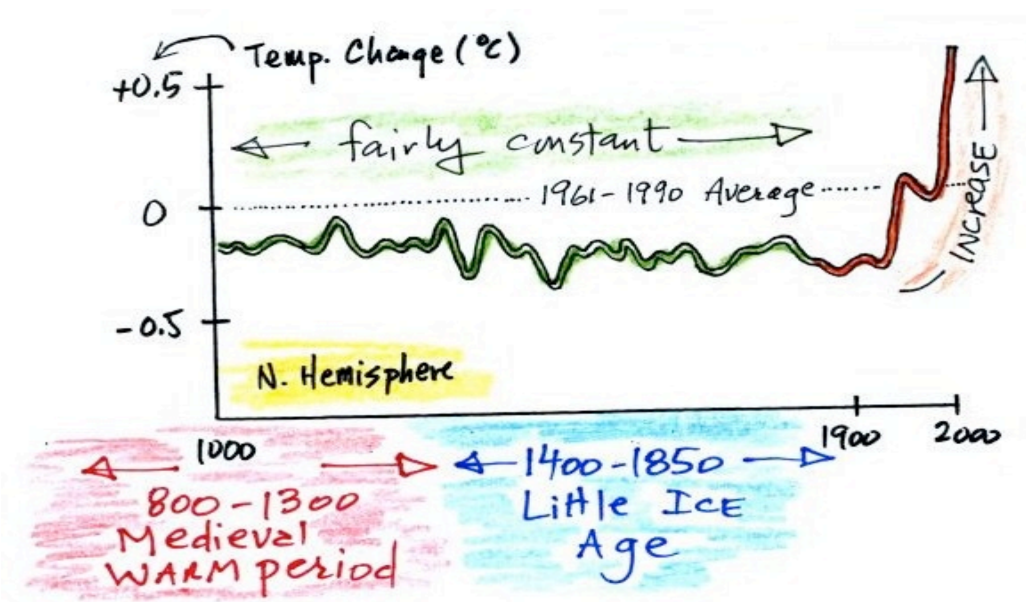
The two oxygen isotopes contain different numbers of neutrons in their nuclei. Both atoms have the same number of protons. During a cold period, the H_2O^{16} form of water evaporates more rapidly than the H_2O^{18} form. You would expect to find relatively large amounts of O^{16} in glacial ice. More of the H_2O^{18} remains in the ocean and the calcium carbonate of ocean sediments has relatively high amounts. Note also the drop in ocean levels during colder periods when much of the ocean water is found in ice sheets on land.



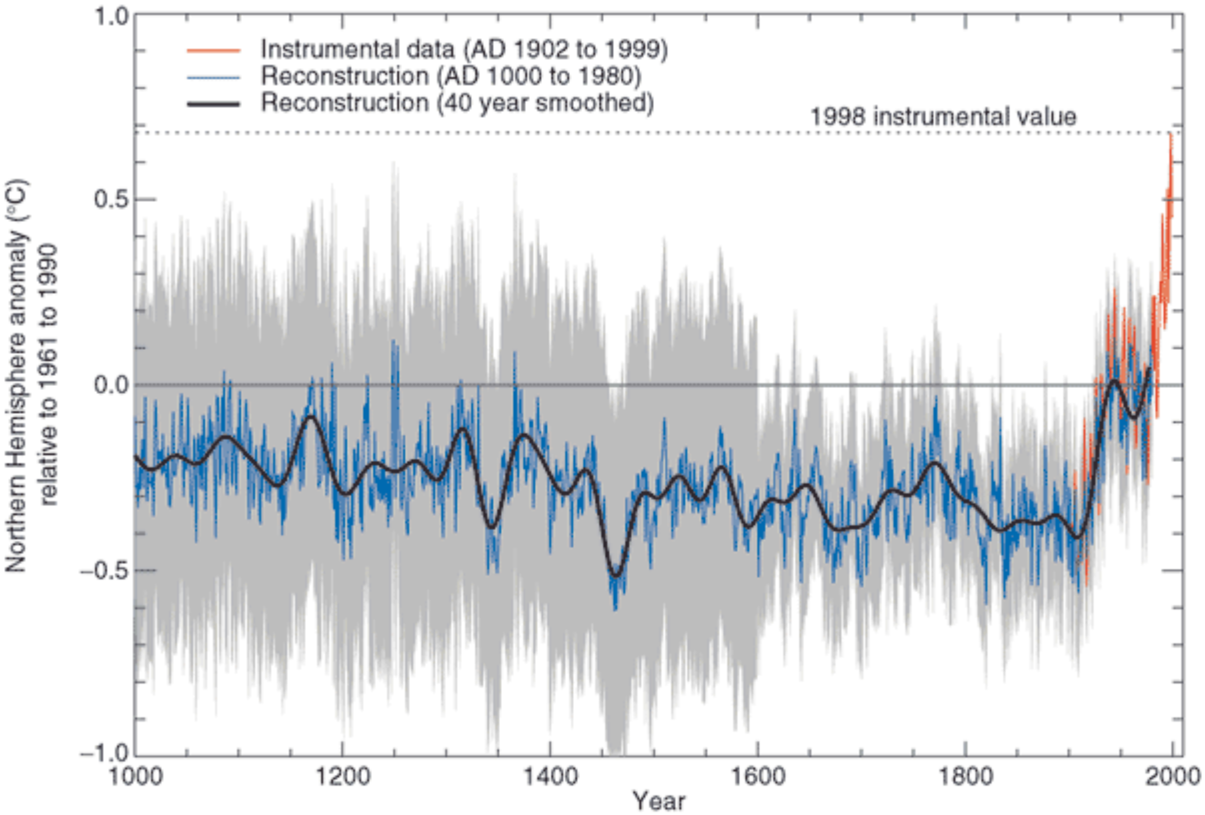
The reverse is true during warmer periods.



Using proxy data scientists have been able to estimate the average surface temperatures for hundreds of thousands of years into the past. The next figure shows average surface temperatures since 1000 AD. This is for the northern hemisphere only, not the entire globe. The major portion of the figure shows the estimates of temperature (again relative to the 1961-1990 mean) derived from proxy data. The instrumental measurements were made between about 1850 to the present day.



The actual data that the curve above is based upon is shown below. This is the so called "Hockey Stick Plot" originally published in 1999 by Mann, Bradley, and Hughes and included in Climate Change 2001 - The Scientific Basis, Contribution of Working Group I to the 3rd Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).

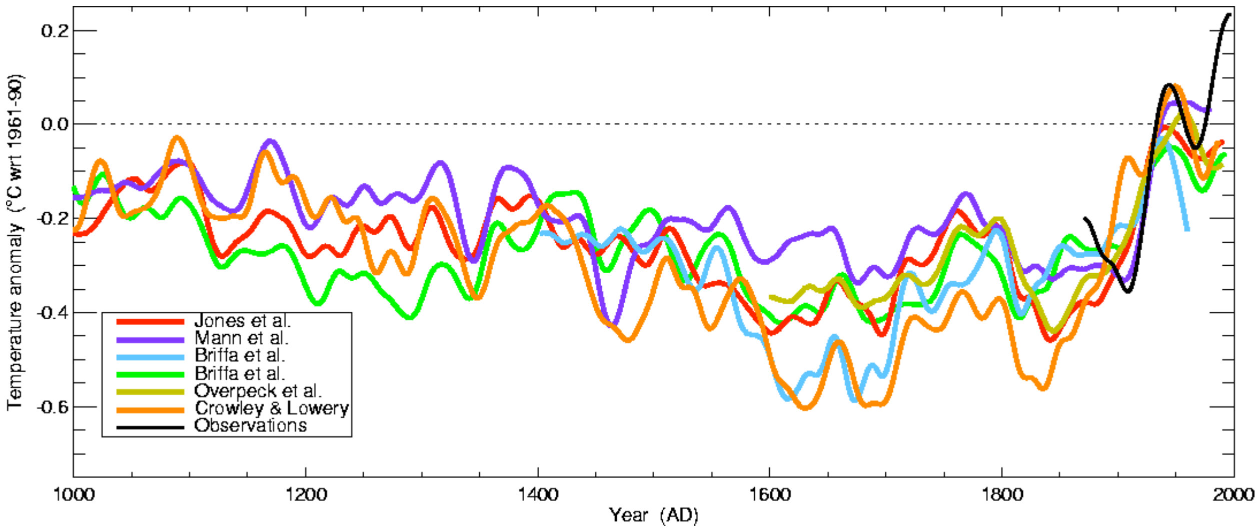


Many scientists would argue that this graph is strong support of a connection between rising atmospheric greenhouse gas concentrations and recent global warming. Early in this time interval when CO_2 concentration was constant, there were only modest changes in temperature. The largest overall change in temperature begins in about 1900 when we know that atmospheric carbon dioxide concentrations were increasing. The second half of the 20th century is the warmest period in at least the past 1000 years.

Some scientists have questioned the statistical methods used in the study. Additionally there is historical evidence in Europe of a medieval warm period lasting from 800 AD to - 1300 AD or so and a cold period, the "Little Ice Age", which lasted from about 1400 AD to the mid 1800s. These trends are not very prominent in the temperature plot above. This leads some scientists to question the validity of this temperature reconstruction. Scientists also suggest that if large changes in climate such as the Medieval warm period and the Little Ice Age can occur naturally, then perhaps the warming that is occurring at the present time also has a natural cause.

The so-called Year Without a Summer occurred in 1816, toward the end of the Little Ice Age. The unusually cold summer temperatures were apparently caused by a very large volcanic eruption the year before. Volcanoes have a temporary cooling effect on the global energy balance. Volcanic eruptions, such as the Mount Pinatubo eruption in 1991, inject large amounts of sulfate aerosols into the stratosphere where they reflect visible light back into space.

More recent temperature reconstructions have confirmed the overall trend shown in the hockey stick graph. In both figures again the late 20th century has the warmest temperatures in the period.



We will end this first lecture at this point. Here's a brief summary of what we learned.

- There is general agreement that atmospheric CO_2 and other greenhouse gas concentrations are increasing and that the earth is warming
- Not everyone agrees on the causes (natural or manmade) of the warming.
- In the next lecture we will look at estimates of how much additional warming there will be and some of the effects that the predicted warming will have.