The Global Carbon Cycle

"The more people there are on the planet, the less each of us can use the atmosphere for waste disposal without contributing to further global warming." - Population Action International, 2000

"One hundred and fifty years ago humans started a grand, uncontrolled experiment with carbon on earth. We don't know exactly how the experiment will turn out, but it will certainly change our climate and our lives." *- from Lecture*

28 Nov 2010

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1. Introduction

Although we don't usually think of carbon in our day to day lives, carbon plays the central role in the "reduction-oxidation battlefield" that we call life. On the one side of the battlefield you have the photosynthetic organisms that use light energy and atmospheric CO2 to produce a pool of reduced organic compounds with high potential energy, plus a reservoir of oxygen. On the other side of the battlefield you have the heterotrophic creatures, like ourselves, that are trying to release this stored energy by oxidizing the reduced organic compounds, consuming O2 and adding CO2 to the atmosphere in the process. What humans have done is to accelerate this oxidation through fossil fuel burning and land use changes, so much so that we have started a grand, uncontrolled experiment with carbon on earth. We now recognize that this experiment will change our climate, and the potential effects on people's lives have stimulated some of the largest public and policy debates of any scientific topic today. In this lecture we will learn more about the carbon cycle, how it functions on earth, and how it is controlled by natural and anthropogenic processes.

The carbon cycle has been linked to the changes in climate that we have recently observed on earth, especially the increases in temperature shown in *Figure 1* (below). The rapid rise in temperature compared to the last 1000 years in the bottom panel of *Figure 1* has been called the "hockey stick" because of the long period of similar temperatures (the handle) versus the sharp upturn of the blade. The Intergovernmental Panel on Climate Change (IPPC) in its most recent report (2007) states that

“Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level.”

and that

"The understanding of anthropogenic warming and cooling influences on climate has improved…, leading to very high confidence that the global average net effect of human activities since 1750 has been one of warming.”

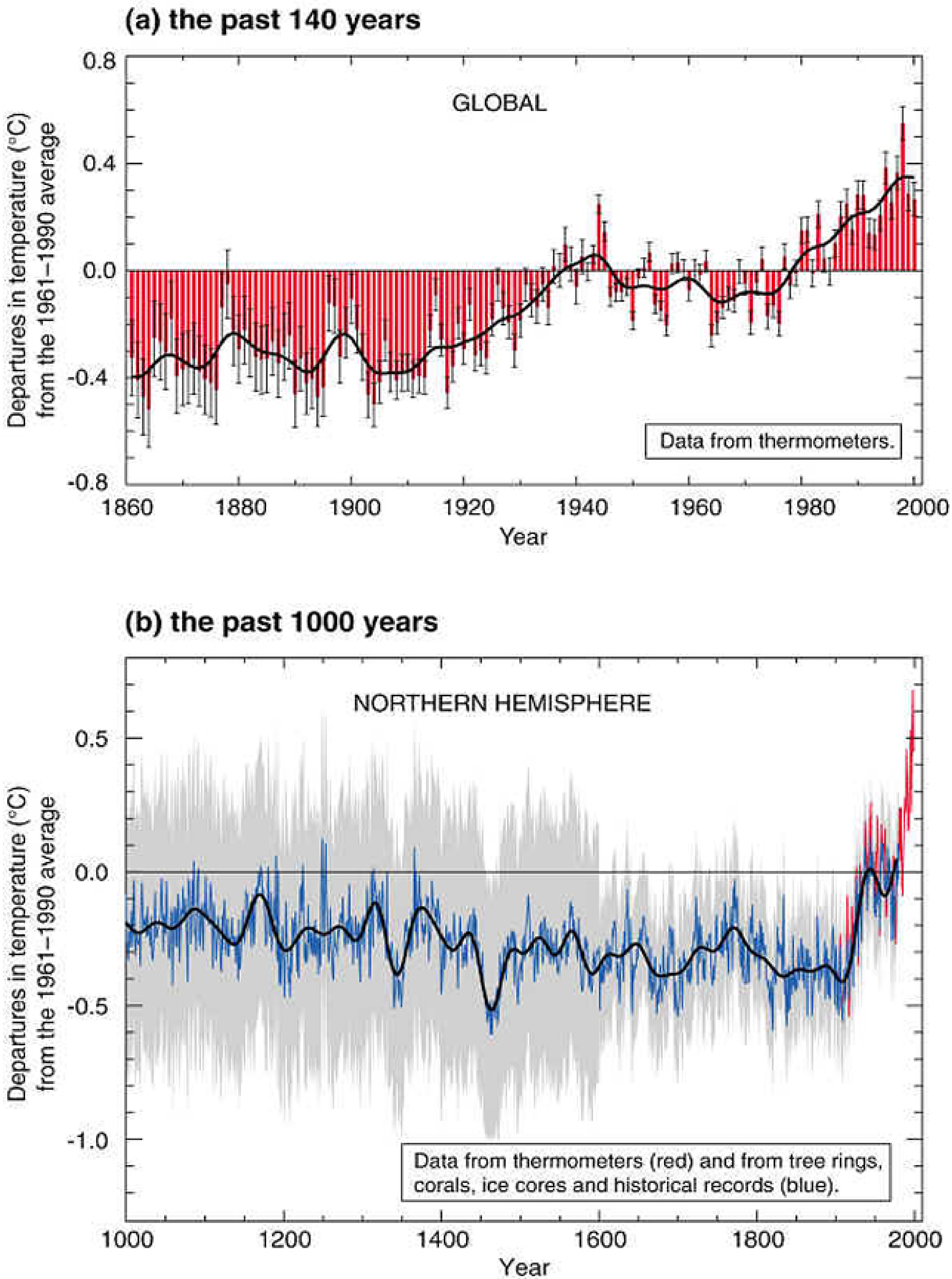


Figure 1. *Changes in the Earth's surface temperature for the last 140 (above) and the change in temperature for the northern hemisphere for the last 1000 years (below).*

These changes in CO2 are shown below (*Figure 2*) for the record of atmospheric concentration at the Mauna Loa Observatory in Hawaii. The concentrations have been increasing steadily since measurements began in 1958, and other records indicate that these increases in atmospheric CO2 began in the middle 1800s at the start of the human industrial revolution.

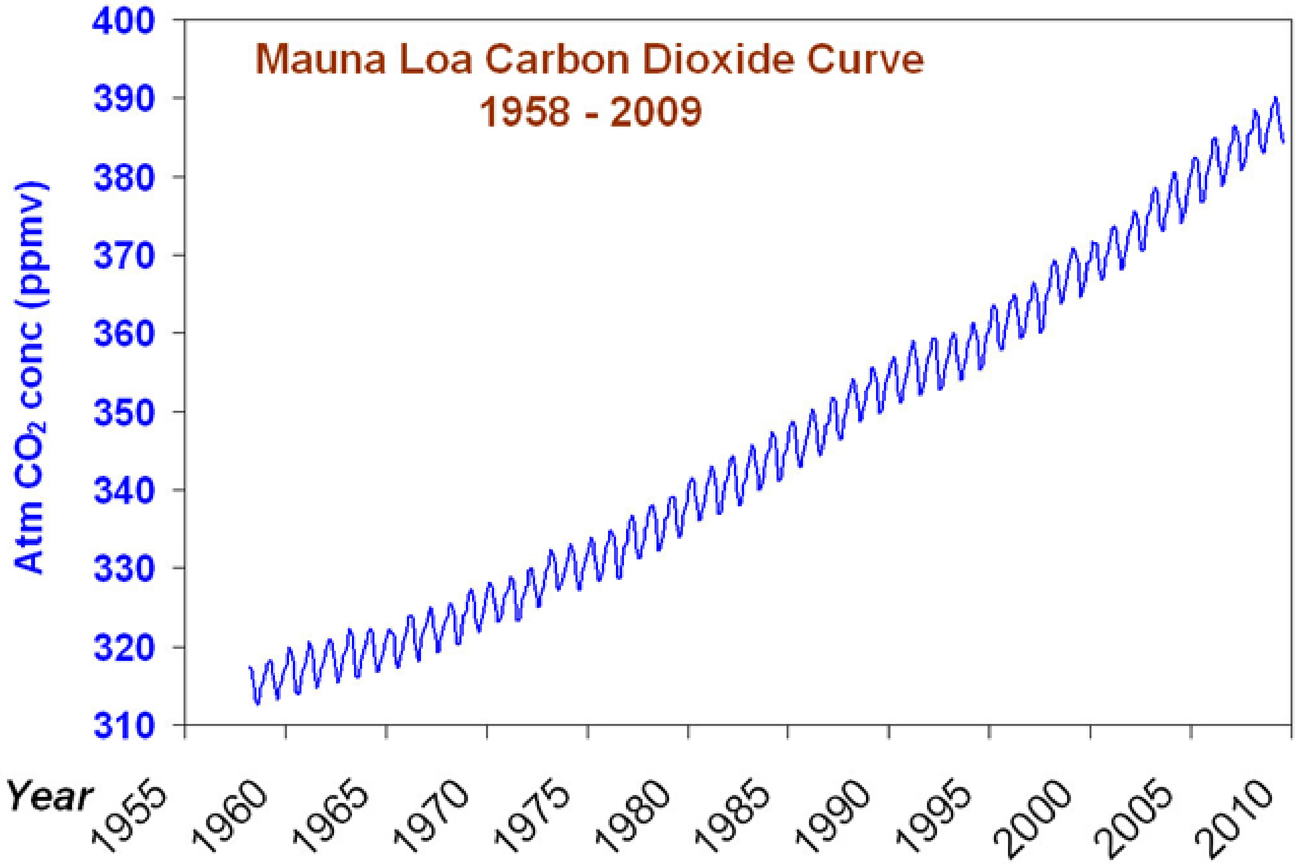


Figure 2. *Changes in the concentration of CO2 over time in the Earth's atmosphere, taken from the Mauna Loa Observatory (above; from D. Keeling; //ftp.cmdl.noaa.gov/ccg/co2/trends/co2_mm_mlo.txt).*

In addition to the changes in CO2, human influence has contributed to changes in other greenhouse gases in the atmosphere as well, as shown in *Figure 3* below. It is this evidence of consistent changes in greenhouse gases correlated with human activity which has led to the IPCC conclusions that humans are increasing greenhouse gas concentrations and that those gases are in large part driving climate change.

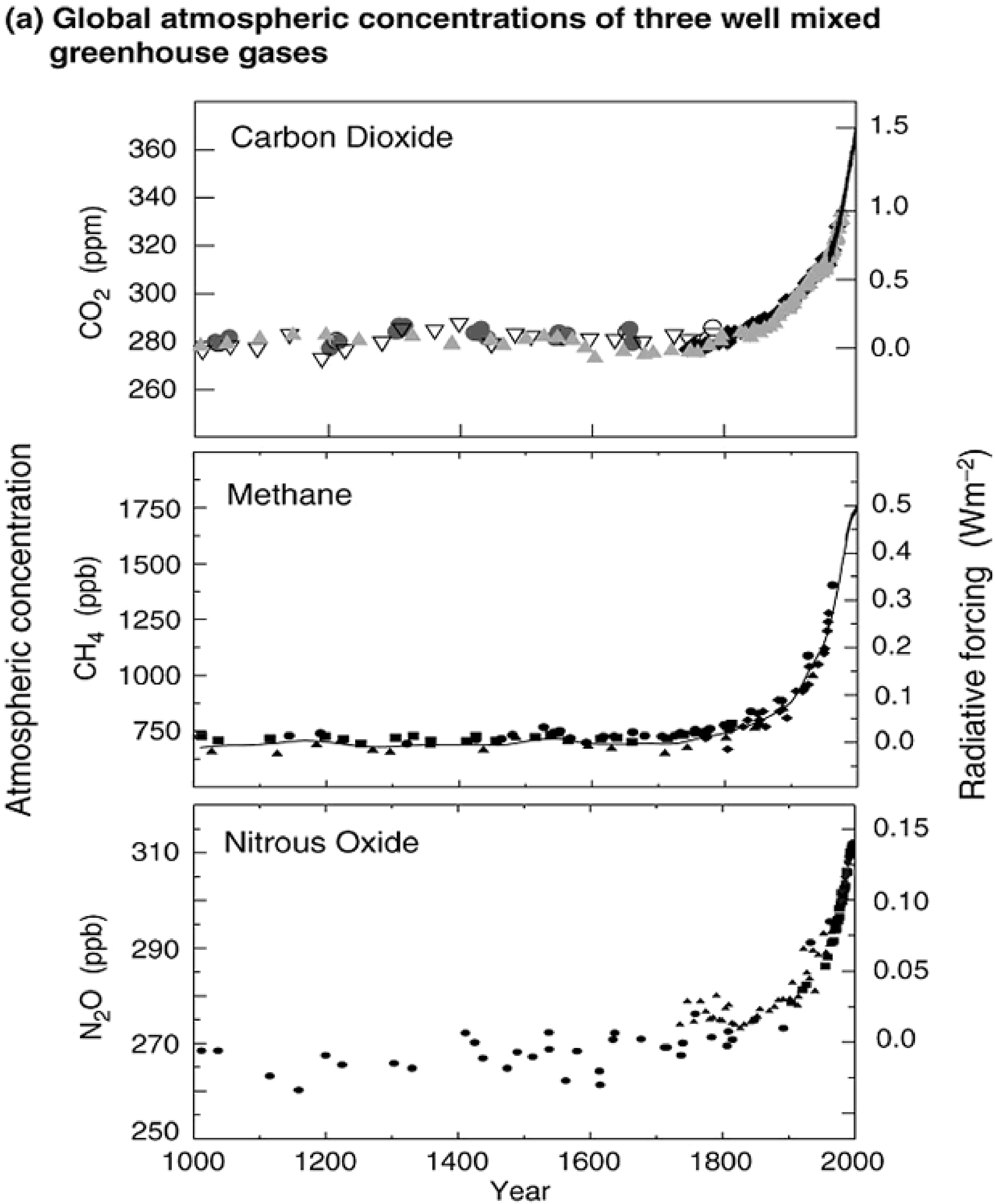


Figure 3. *Relationship between increases in greenhouse gases over time. Note the consistent increases in the mid 1800s at the start of the industrial revolution.*

With so much evidence for the increases in greenhouse gases due to human activities, and the simple physics of how greenhouse gases trap heat at the Earth's surface, it is somewhat surprising that there are still so many skeptics about climate change and the role of humans. Two consistently heard arguments against climate change are that it is all due to sunspot activity, and it is all due to volcanoes. In the last lecture on Climate Models we dissected each of these arguments to show that they are insufficient to explain the rise in global temperatures (in fact, volcanoes actually cool the globe over short time scales that we are now examining). When confronted with these facts, skeptics often turn to two additional ploys to divert people's attention away from the science. They say that scientists need to get funding for their research, and that they are deliberately hyping climate warming for their own personal gain. The problem with this argument is that scientists are not famous to begin with (name a scientist, any scientist, living today... now name a movie start living today...), and scientists are not rich (your average clerk on Wall Street probably makes more than a college professor). There is very little if any "personal gain" for a scientist to reap in hyping the real facts of climate warming. An additional ploy that skeptics use is to "cherry pick" data, which is the selective use of data which fits their argument. A brilliant example of that is seen in a White House press statement by Tony Snow followed by an open letter from the White House bragging that the U.S. was doing better than Europe at controlling greenhouse gases:

Open Letter on the President's Position on Climate Change, 7 February 2007:

"Our emissions performance since 2000 is among the best in the world. According to the International Energy Agency, from 2000-2004, as our population increased and our economy grew by nearly 10%, U.S. carbon dioxide emissions increased by only 1.7%. During the same period, European Union carbon dioxide emissions grew by 5%, with lower economic growth."

The problem with this statement is that it uses only a small bit of the data available, chosen very carefully (dishonestly?) to highlight the point the politicians wanted to make. If you looked at the full record of data since 1990 (*Figure 4*) you see that in fact the U.S. has increased its greenhouse gas emissions by 15% over the full period of record, while Europe's emissions have decreased by 1%. The artificial reference period selected by the White House after the 9/11 recession, is circled in *Figure 4 (2001-2004).*

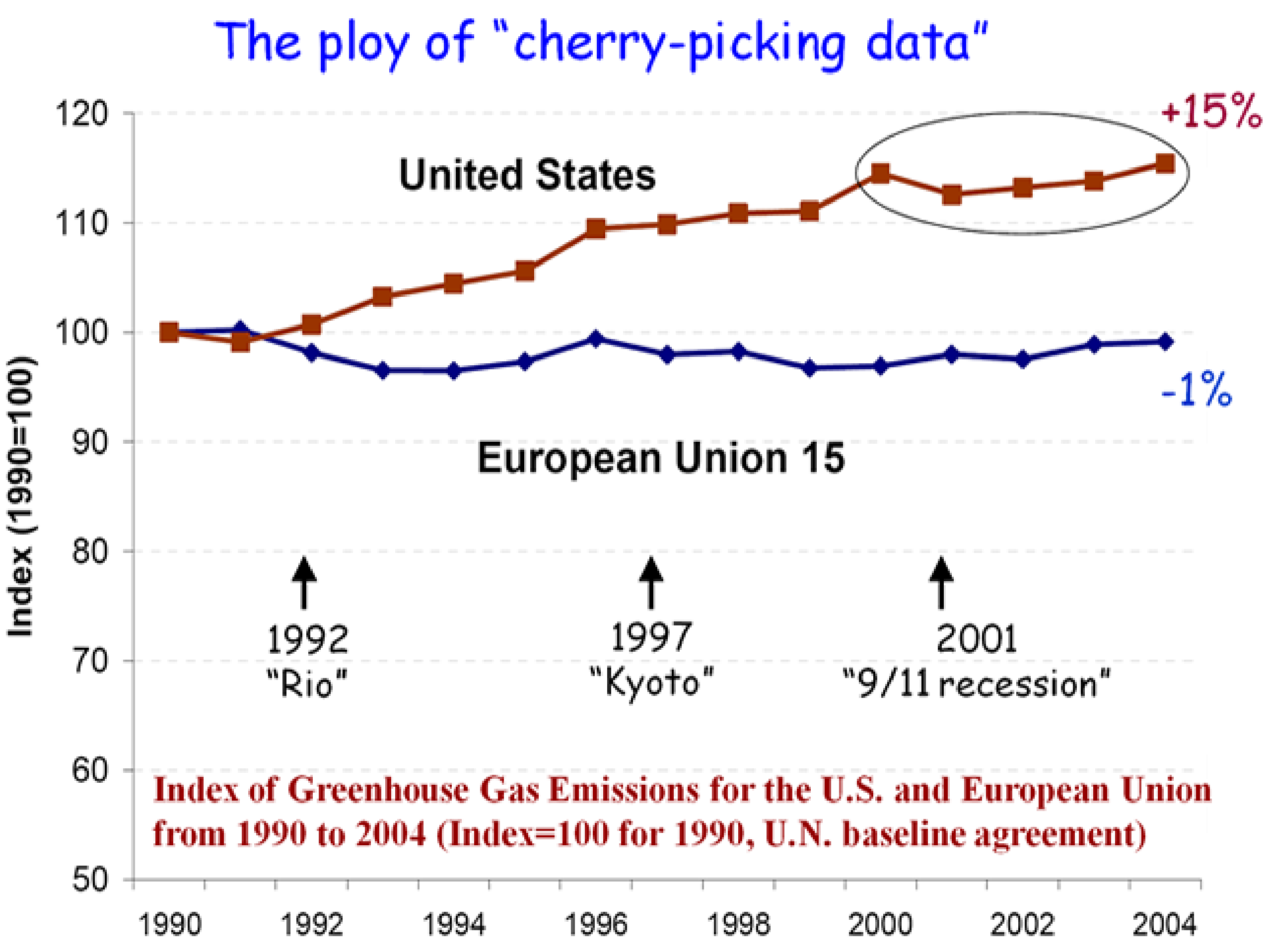


Figure 4. *Plot showing the index of greenhouse gas emissions for the U.S. and the European Union from 1990 to 2004. The full record of data clearly shows that the U.S. is not doing better than Europe, as the White House claimed in 2007 based on only 4 years of data they selected artificially to try and confuse the public about the realities of climate warming and our role as humans. References: http://www.whitehouse.gov/news/releases/2007/02/20070207-1.html ; http://www.whitehouse.gov/news/releases/2007/02/20070207-5.html ; Pacific Institute data.*

Such politically-motivated ploys to confuse the public about climate warming not always so easy to uncover, and yet they are common and should be realized and confronted.

Despite the claims that increasing greenhouse gas emissions by humans could not cause a change in global temperatures, there is a strong correlation between CO2 concentration in the atmosphere and global temperatures for the past. *Figure 5* below shows this correlation over the last 160,000 years, and it is clear that the temperature and CO2 concentrations in the atmosphere are linked. This is consistent with our current understanding of how the greenhouse effect operates.

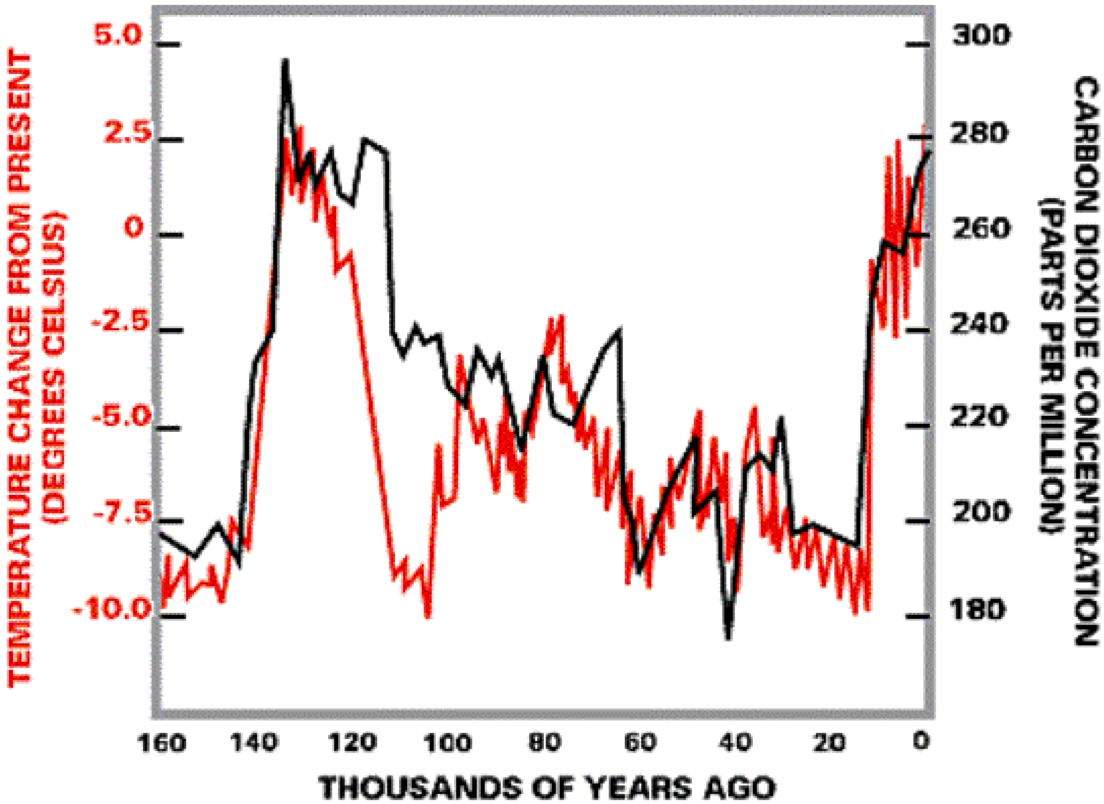


Figure 5. *Plot showing how CO2 concentrations (estimated from measurements of CO2 trapped in ice cores) are correlated with global temperature (estimated from indicators such as isotopes in organic matter of ocean sediments) over the last 160,000 years (and we know that this correlation now extends at least 400,000 years back in time).*

Although the CO2 concentrations shown in *Figure 5* are all below today's concentration of ~385 ppm, there have been times on earth in the past when the CO2 concentration of the atmosphere has also been greater than it is today (see *Figure 7*). If it has been greater, then one might ask "why are we so worried, the CO2 concentrations were greater than they are today and we still survived?" The answer to that question lies in the fact that the rate of change of CO2 in the atmosphere is faster today than at anytime in earth's history. It is this rapid increase in CO2, not necessary the final CO2 concentration that may be reached, which is causing much of our concern. For example, because organisms (and certainly all of the human cultures on earth) have never been exposed to such rapid rates of CO2 increase, we don't know how they will respond and whether they will be able to adapt quickly enough to survive. These are the questions that science and society are struggling with today. While we know that CO2 concentrations are increasing, there have been several plans or ideas on how to control them "naturally", such as plant more trees to take up the excess CO2. Later in the lecture we will examine two of these ideas and determine if they could be real solutions to global warming.

2. Carbon Accounting

In order to understand the carbon cycle we must understand first the "accounting" of where the pools of carbon are located, second the "pathways and cycling" of how the carbon is moving from one pool to another, and third the "controls" on how much carbon is cycled.

There are several different forms of carbon that we have to keep track of in learning about the carbon cycle. The main forms are (a) Inorganic-C in rocks (such as bicarbonate and carbonate); (b) organic-C (such as found in organic plant material); and (c) carbon gases such as CO2, (carbon dioxide), CH4, (methane), and CO (carbon monoxide). "Carbon cycling" is really all about the movement of C from one of these forms to another form.

Table 1 gives an accounting of where these different forms of carbon are located on earth (note that 10^{15} g = 1 billion tons = 1 gigaton = 1 Pedagram):

LOCATION	**Amount ($\times 10^{15}$ gC)**
Rocks	65,000,000
Oceans	39,000
Soils	1,580
Atmosphere*	750
Land plants	610

* In the atmosphere, CO2 is 99.6% of the total (i.e., the amount of CH4 is small).

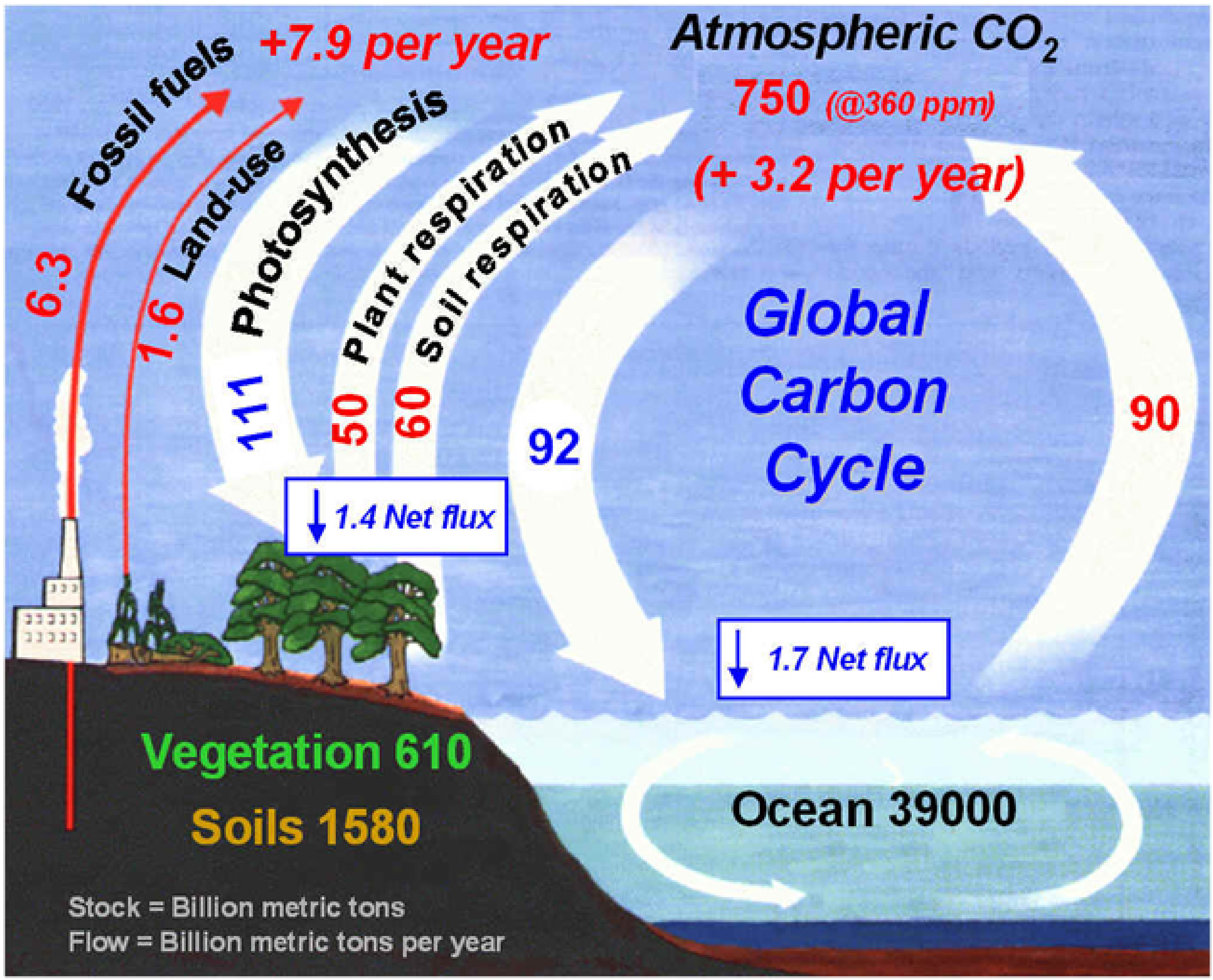


Figure 6. *Pathways, pools, and fluxes in the global carbon cycle. Note that the actual numbers vary slightly with different estimates, and are used here only as guides to the levels of fluxes and pools.*

3. Pathways & Cycling

There are several pathways in the carbon cycle that are of particular importance (*Figure 6 above*). The main pathways to and from the atmosphere are diffusion into and out of the ocean, photosynthesis which consumes CO2 from the atmosphere (an output from the atmosphere), respiration which produces CO2 (an input to the atmosphere), and the burning of fossil fuels and biomass which also produces and input of CO2 to the atmosphere.

Although the largest storage of carbon is in rocks (*Table 1*), the largest magnitudes of fluxes don't involve the rock pool directly on short time periods. The magnitudes of C fluxes are as follows (all in 10^{15} g of C per year):

- Net Ocean uptake = 1.7 (x 10^{15} g C / yr)
- Photosynthesis = 111
- Respiration = 110
- Fossil fuels = 6.3
- Biomass burning = 1.6

Mass Balance

As discussed in the lecture on Ecosystems, we can use biogeochemical principles to construct a mass balance for the atmosphere by knowing that the amount of C in the atmosphere increases by 3.2 x 10^{15} g C /yr, by knowing that the internal change in the atmosphere is zero, and by knowing the other fluxes into and out of the atmosphere:

NET CHANGE =	**INPUT + OUTPUT + INTERNAL CHANGE**
3.2 =	**(110 + 6.3 + 1.6) + (-111 -1.7) + (0)**
3.2 =	**5.2**

Given this analysis we find that there is an imbalance -- we need an additional "sink" of -2.2 (3 - 5.2) x10^{15} g C to balance the global C budget. In other words, we are "missing" over 2 billion tons of C each year; this shows how incomplete our understanding of the global carbon cycle is at present. Although it is possible that this missing sink could be found in any of the major pools of carbon on earth, it is most likely that the pools with a shorter residence time such as vegetation, soils or the ocean (compared to rocks) are most important. Recent models indicate that terrestrial ecosystems in the Northern hemisphere are the most likely repository of this carbon.

4. Controls

In order to fully understand how the carbon cycle operates, and to gain a better understand of issues such as the missing sink of C and slowing the rate of C increase in the atmosphere, we must examine the controls on carbon amounts and movement. There are several dominant controls on the flux rates of carbon between different carbon pools on earth, including the influence of volcanic activity and rock weathering, which are most important on long time scales. Human influence on the global carbon cycle has been very recent, but has altered the C-cycle in a dramatic way by adding CO2 and CH4 to the atmosphere.

(A). Volcanic activity: CO2 concentrations in the atmosphere are related to volcanic activity, as *Figure 7* illustrates. This shows that the concentration of CO2 has varied over a large range in our atmosphere in the geologic past. When volcanic activity is high the CO2 concentration in the atmosphere is also high due to the release of CO2 from volcanoes or fissures into the atmosphere. Large, single volcanic eruptions today have much less effect on the atmospheric CO2 concentration, but can release particles into the atmosphere that can cause a slight (but temporary) cooling of the Earth's surface, as was seen in the lecture on climate models.

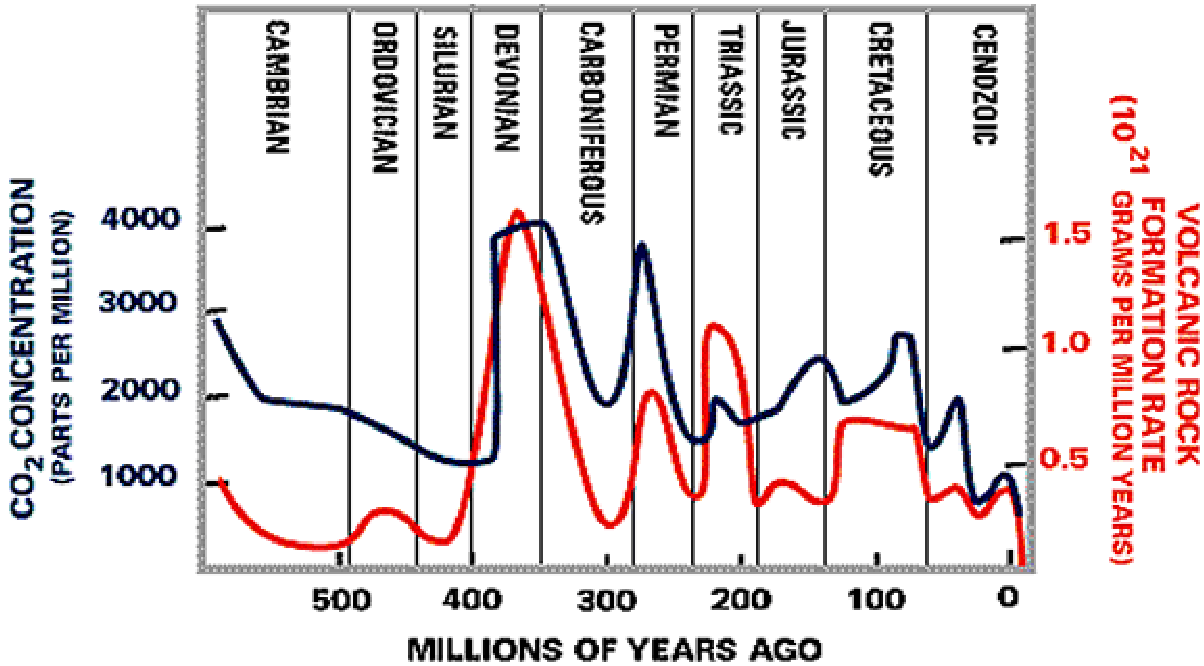


Figure 7. *The relationship between CO2 concentration in the atmosphere (black line) and volcanic activity on earth (red line).*

(B). Rock weathering: CO2 concentrations have been limited over geologic time to a range of about 200 - 6000 ppm in the atmosphere due to weathering of rocks and the formation of carbonate minerals. *Figure 8* shows that CO2 in the atmosphere is consumed in the weathering of many rocks. This weathering produces bicarbonate ($HCO3^-$), a form of inorganic carbon, and calcium (Ca^{2+}) that are then transported in river water to the oceans. Once in the oceans the calcium and bicarbonate are combined by organisms to form calcium carbonate, the mineral that is found in shells. When the organisms die this calcium carbonate mineral is buried in the sediments, where eventually it comes under great temperature and pressure and is melted during the process of "subduction", when one tectonic plate moves under another. The melted rock rises to the surface in the form of magma and is released back to the surface of the earth through volcanoes. This high-temperature process also converts some of the calcium carbonate back to CO2, which is released to the atmosphere to begin the cycle over again. Remember that this control acts over a time scale of millions to hundreds of millions of years.

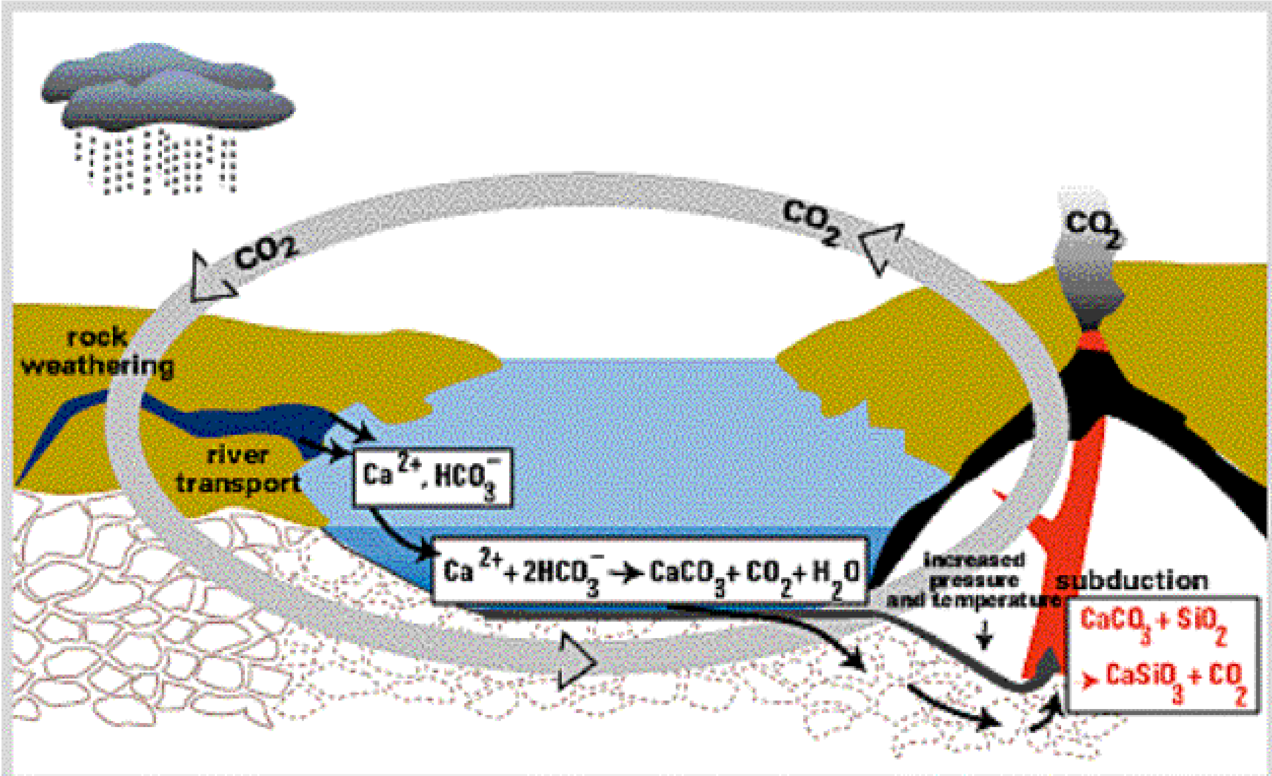


Figure 8. *The global carbon cycle from the perspective of its long-term control by weathering.*

(C.) Biological Activity: Some of the patterns we see in carbon distribution and movement on Earth are controlled by short-term biological reactions, such as photosynthesis, respiration, and the production of greenhouse gases such as CH4 by bacteria. *Figure 9* shows the general trend of increasing CO2 and CH4 concentrations in our atmosphere over time, and the differences in concentration in the hemispheres is due to the greater land mass in the Northern hemisphere. The seasonal cycles of concentration change are also shown, which highlight the strong control of biological processes. As illustrated in our accounting and fluxes of carbon discussed above, the gross fluxes of carbon from these biological processes can be large, but the net changes tend to be small compared to the human influence on today's carbon cycle.

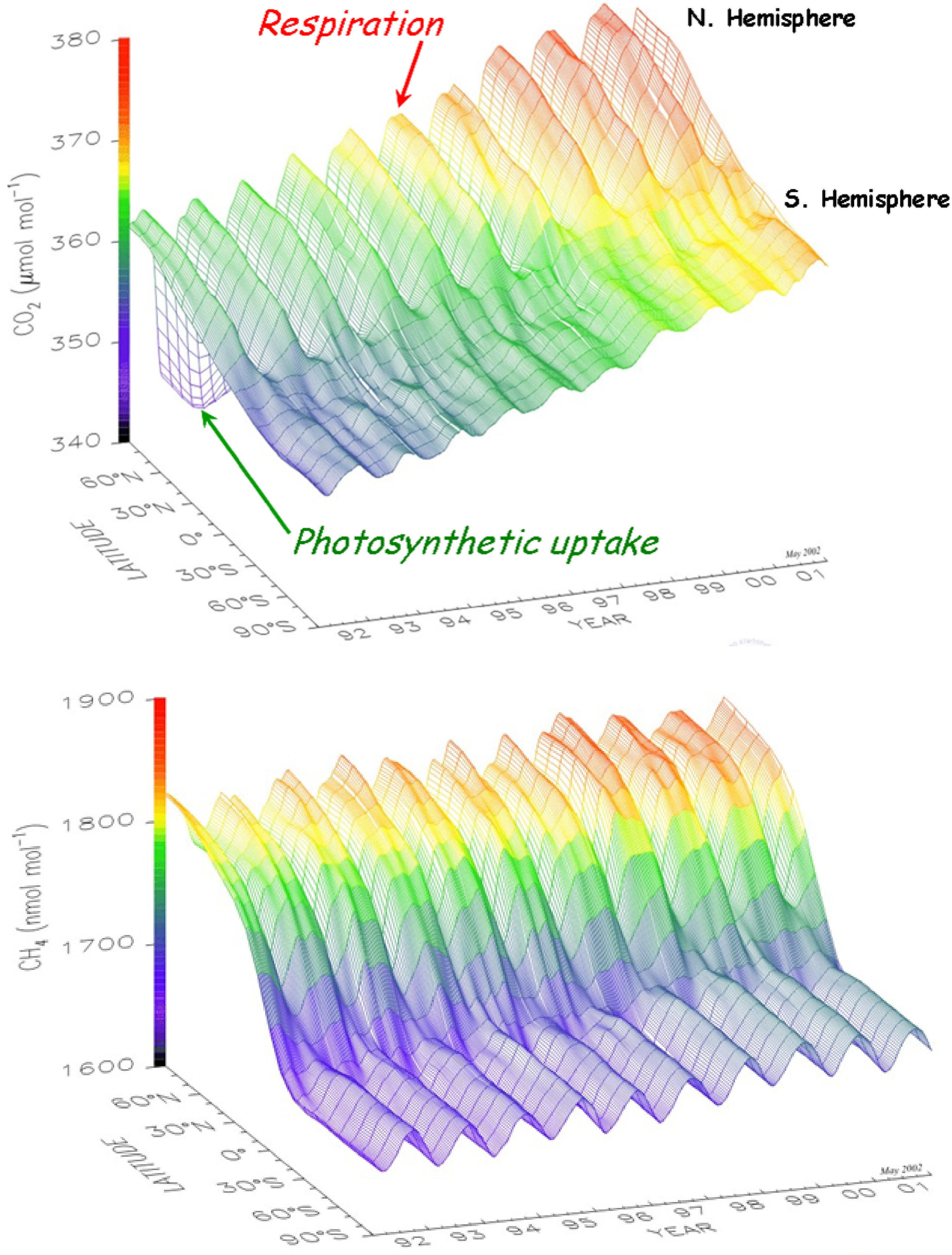


Figure 9 (above). *The global distribution and increases in carbon dioxide (top) and methane (bottom). The graphs show (1) the trend of increasing atmospheric concentrations over time, (2) the differences in concentration in the Northern and Southern hemispheres, and (3) the seasonal changes due to processes such as photosynthesis consuming CO2 and respiration producing CO2..*

(D.) Human Activity: Humans are dramatically changing the CO2 cycle by burning fossil fuels and biomass (e.g., forests). These increases in CO2 are linked to increased warming in our atmosphere, as discussed above; for example, the CO2 level in our atmosphere was only about 280 ppm before humaninduced changes began occurring about 150 years ago. Since humans started to pump CO2 into the atmosphere there has been a large increase in atmospheric CO2, and this increase will undoubtedly continue in the future as indicated by the following graph (*Figure 10*). The CO2 concentration in our atmosphere will likely double with only a modest 1% growth over the next 100 years (note that global population growth is much greater than that at the present). This rise in CO2 will increase the Earth's temperature even as soon as 2050 as shown in *Figure 11*, and will impact the climate that we actually "feel" in the future (*Figure 12*).

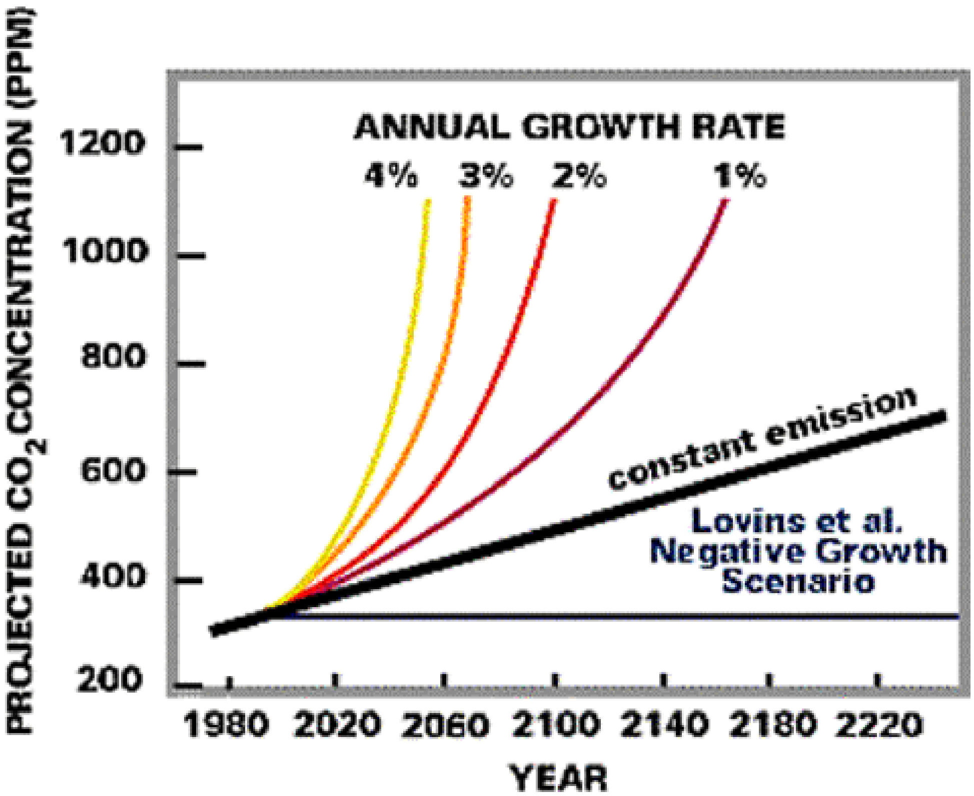


Figure 10 (above). Projected CO2 increases in the atmosphere given different scenarios of population growth.

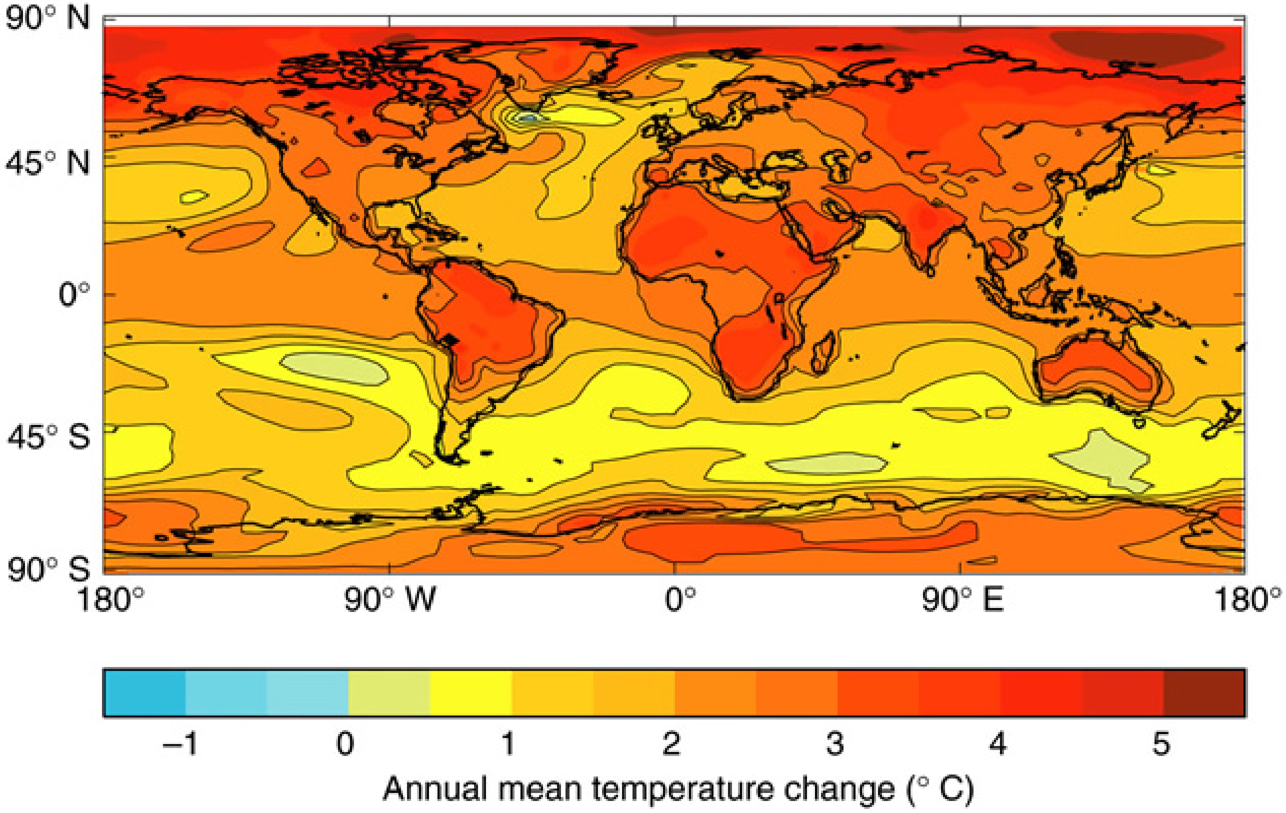
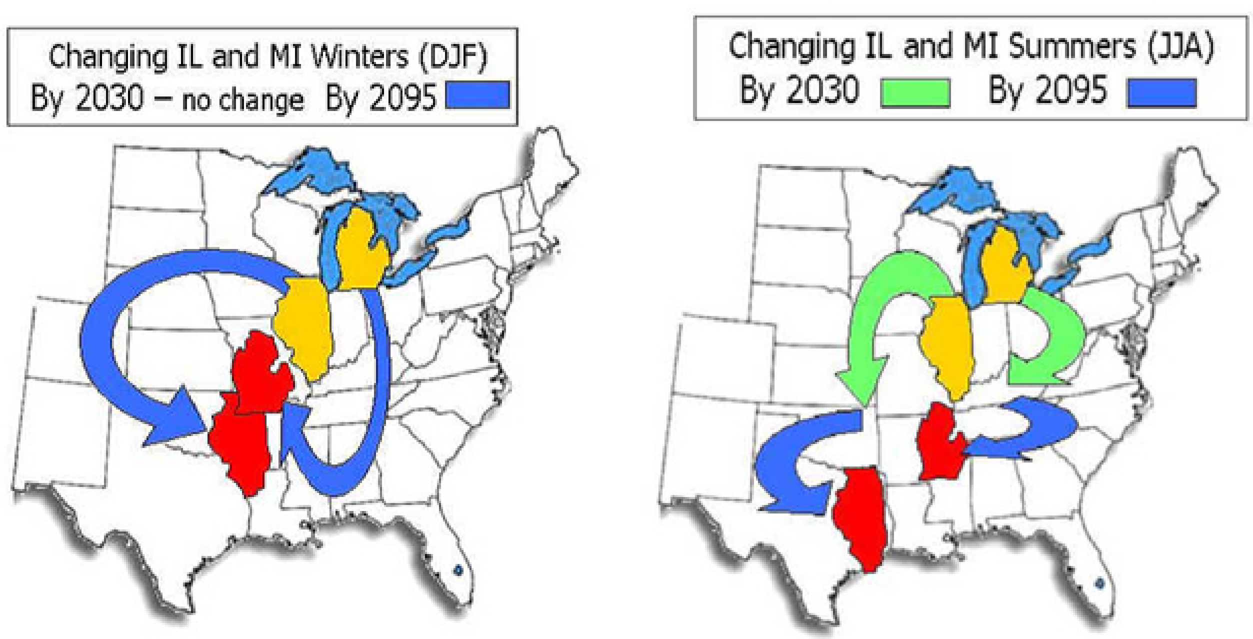


Figure 11 (above). Projected global surface temperatures by 2050 assuming a ~1% per year increase in equivalent CO_2.

Figure 12 (below). Illustration of the impacts of climate warming on the climate that we "feel" in Michigan and Illinois. By 2095, a typical Michigan summer will "feel" like a summer in northern Mississippi today (Wuebbles and Hayhoe, unpublished).



An important point to consider is that even if we stopped our emissions of CO_2 today, we would still experience climate change because of what has already been set in motion. This is because the lifetime (residence time) of several important greenhouse gases is fairly long in the atmosphere; thus, even if human-related emissions of CO_2 were totally halted right now, the atmospheric levels of CO_2 would decay very slowly over the coming decades. These long atmospheric lifetimes, and the biological realities of how life adapts to rapid climate change, add an urgency to the need to develop responses to reduce potential adverse impacts of climate change.

5. "Fixes"

Meeting the challenges associated with the combined impacts of climate change and direct human pressures on the environment involves three principal approaches:

1. Reducing the emissions of heat-trapping gases;
2. Minimizing human pressures on the environment. This will in turn lessen the future level of damage and reduce the vulnerability of ecosystems and societal systems to further stresses from climate;
3. Managing the impacts from climate change on ecosystems and on society through a variety of tools, including anticipation and planning, short-term adjustments, long-term adaptations, and risk-sharing.

All of these approaches are discussed in more detail in the Great Lakes Climate Change lecture later this semester, and especially in later semesters of our Global Change program (Global Change II), but in this lecture we will discuss the scientific aspects of several ideas about how we might slow the increase of CO2 in the atmosphere.

One of these potential "fixes" was known as the "Geritol Fix" (Geritol is a vitamin pill containing iron) and it involves the fact that algal growth in the southern oceans is limited by iron (Fe). If you add Fe you stimulate growth and the uptake of CO2 from the atmosphere by algae. In a careful biogeochemical analysis, however, this idea proved to be untenable because the algae would eventual run out of other limiting nutrients such as nitrogen and phosphorus according to the Redfield ratio discussed in the Ecosystems Lecture. The Geritol Fix could at most reduce our atmospheric CO2 concentrations by 10%.

Another idea has been that because land plants take up CO2 during photosynthesis, and CO2 stimulates their growth, we could solve the whole greenhouse gas problem by planting more trees. Once again, this solution runs up against some biogeochemical realities imposed by chemical stoichiometery (the Redfield ratio again). For example, where will the plants find the extra nitrogen in order to grow? We don't know the answer to this question, but this active area of research is gaining more knowledge on how the carbon and nitrogen cycles are linked, especially with respect to plants taking up excess CO2 in the atmosphere. In addition to planting trees to take up more CO2, there are different ways in which agriculture may also contribute to the solution of reducing the amount of CO2 in our atmosphere.

In the end, **the take-home message for today's lecture, is we must recognize that "There are no magic fixes for the CO2 problem"**, and that a variety of solutions will be required to minimize the impacts of our altered carbon cycle on earth's ecosystems and inhabitants.

6. Review and Self Test

- Review of main terms and concepts in this lecture.
- Self Test for this lecture.