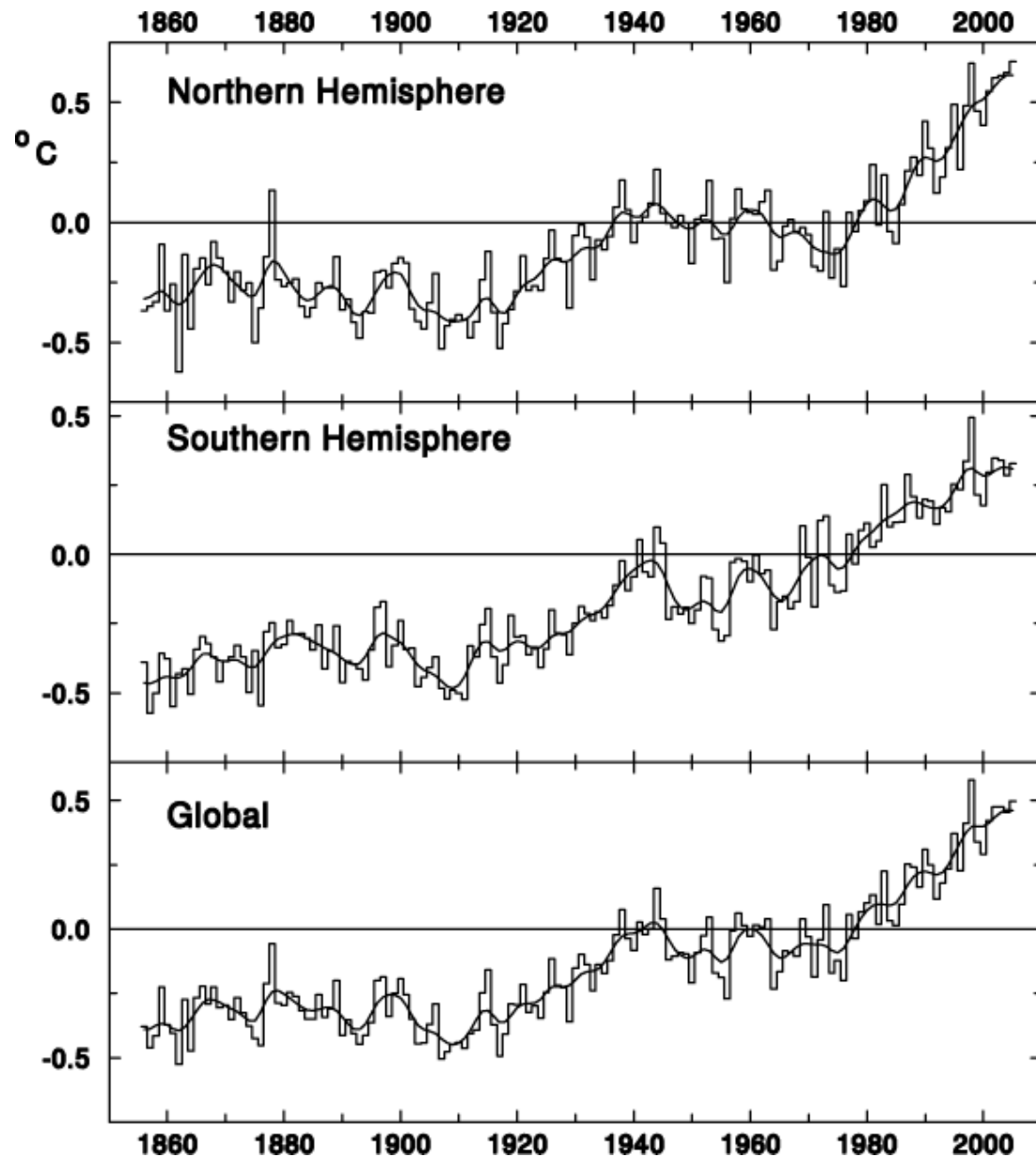
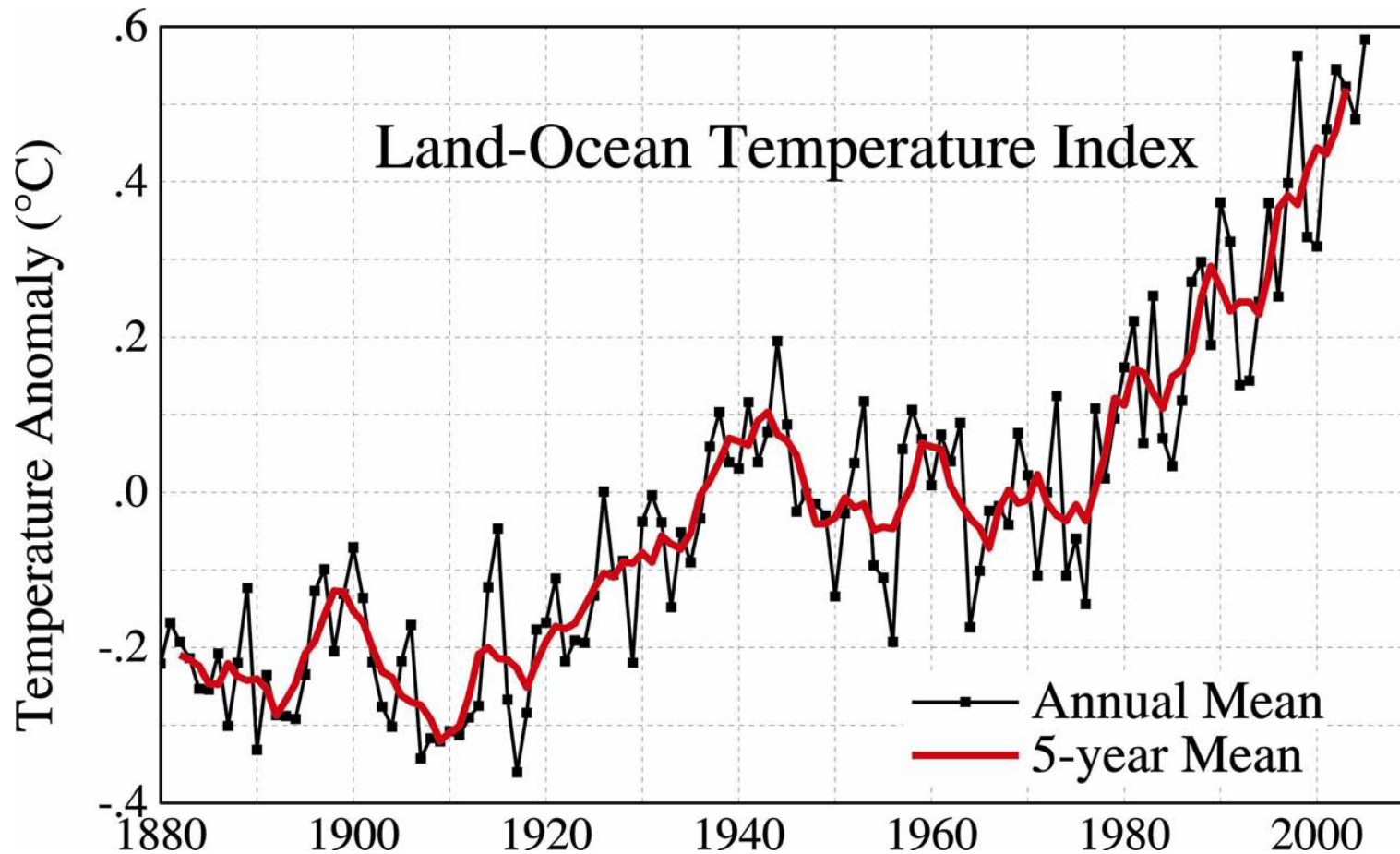
An aerial, black and white photograph of a city. In the foreground, a large, oval-shaped stadium with a tiered seating area is visible. The stadium is surrounded by a road and parking lots. Beyond the stadium, the city extends into the distance with a dense grid of buildings and streets. The text "Lecture 12" and "The Carbon Cycle and Climate Change" is overlaid in red on the left side of the image.

Lecture 12
The Carbon Cycle
and Climate Change



The global temperature rise over the course of the instrumental record

According to actual measurements from thermometers distributed around the globe, temperatures appeared stable until about 1900, when they began to rise. They cooled a bit from 1940 to 1970, then resumed their upward trend. This is the case for both the northern and southern hemispheres.

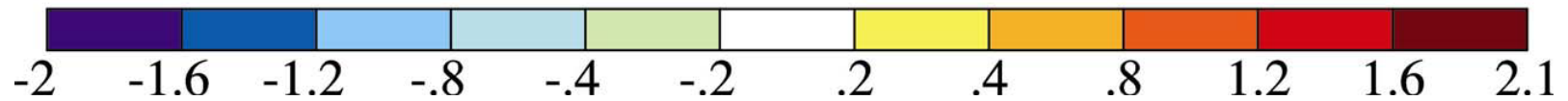
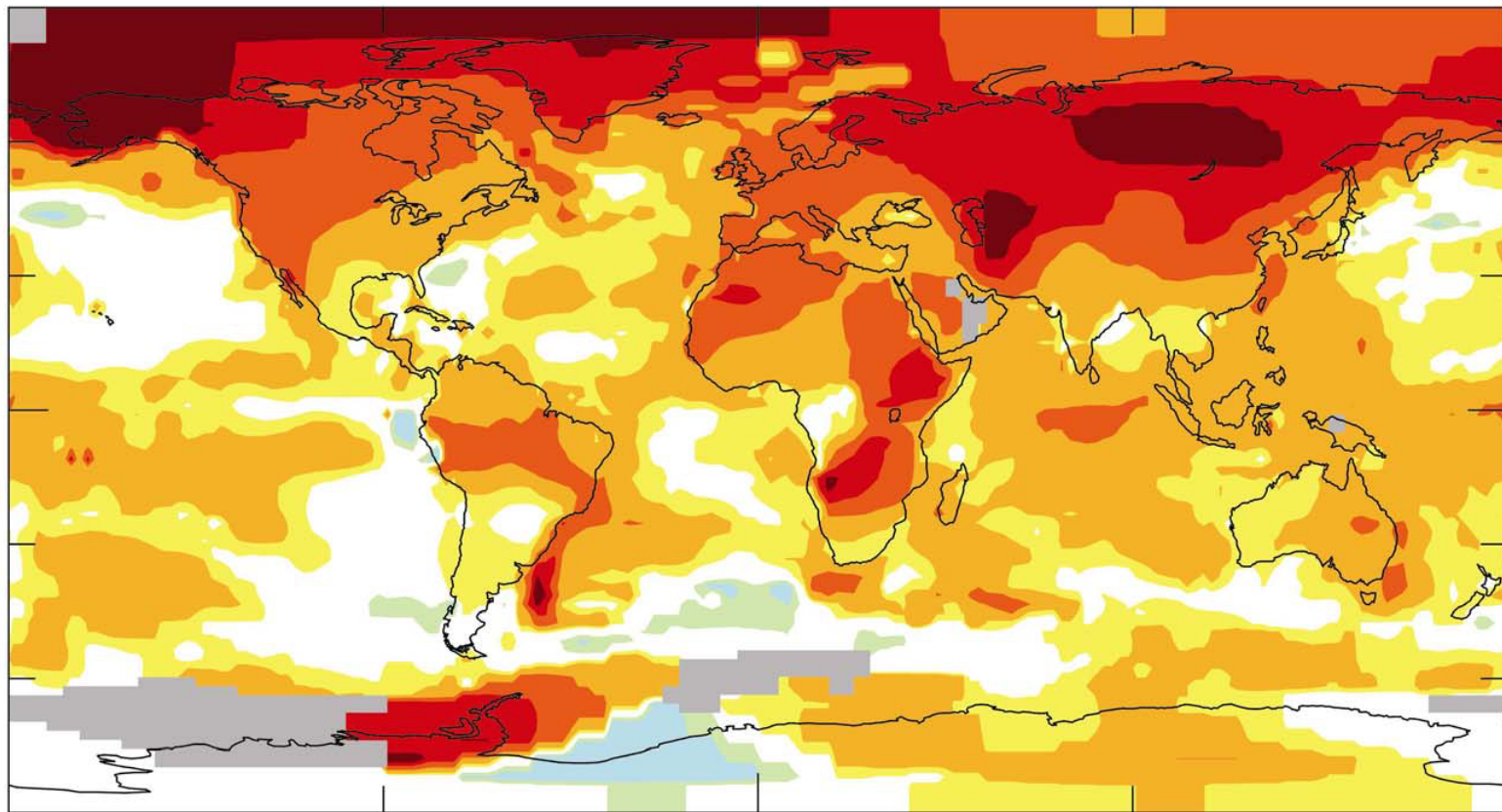


Global mean surface temperature change based on surface air measurements over land and SSTs over ocean. *Source:* Update of Hansen et al., *JGR*, 106, 23947, 2001; Reynolds and Smith, *J. Climate*, 7, 1994; Rayner et al., *JGR*, 108, 2003 (after James E. Hansen 2006).

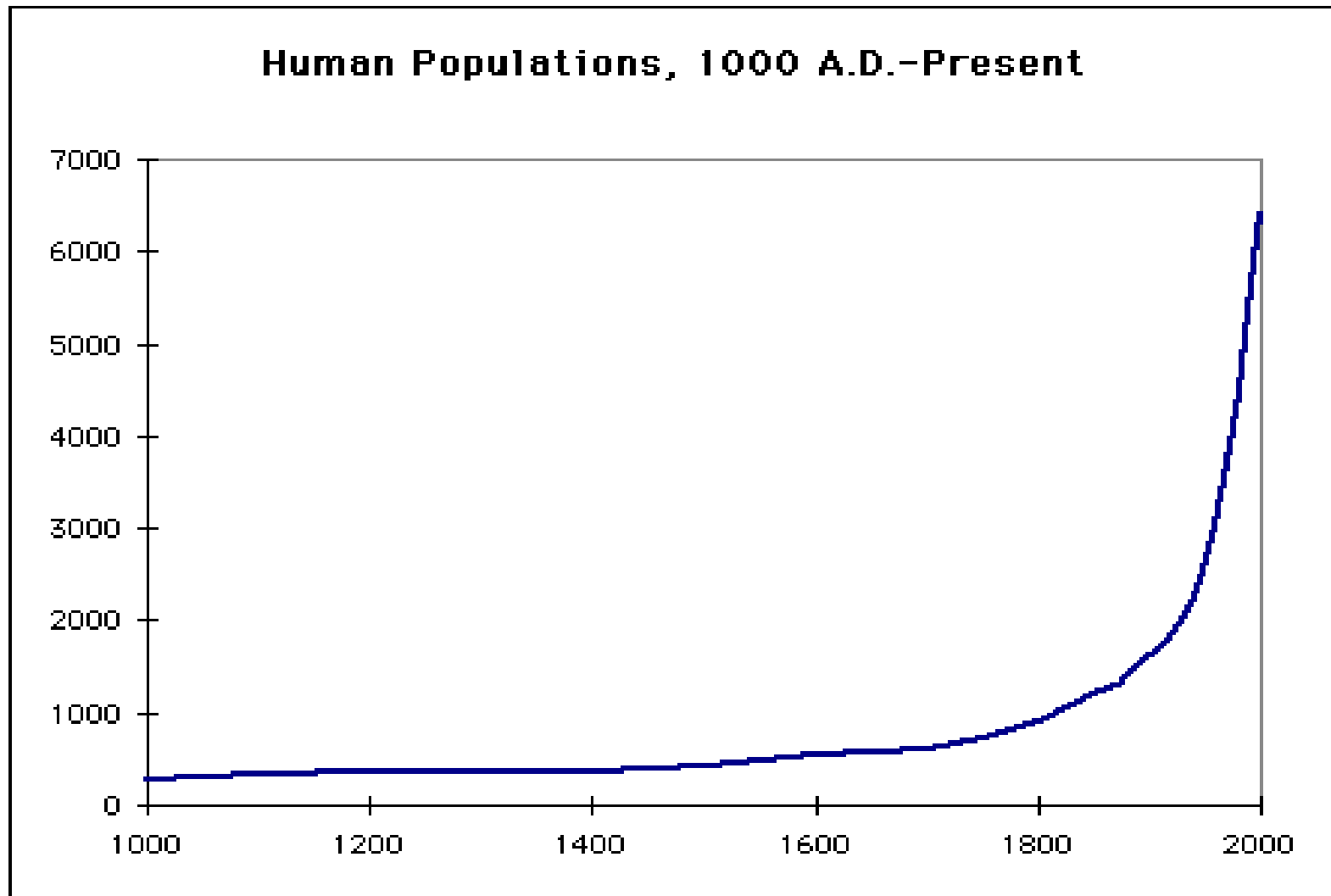
2001-2005 Mean Surface Temperature Anomaly ($^{\circ}\text{C}$)

Base Period = 1951-1980

Global Mean = 0.53

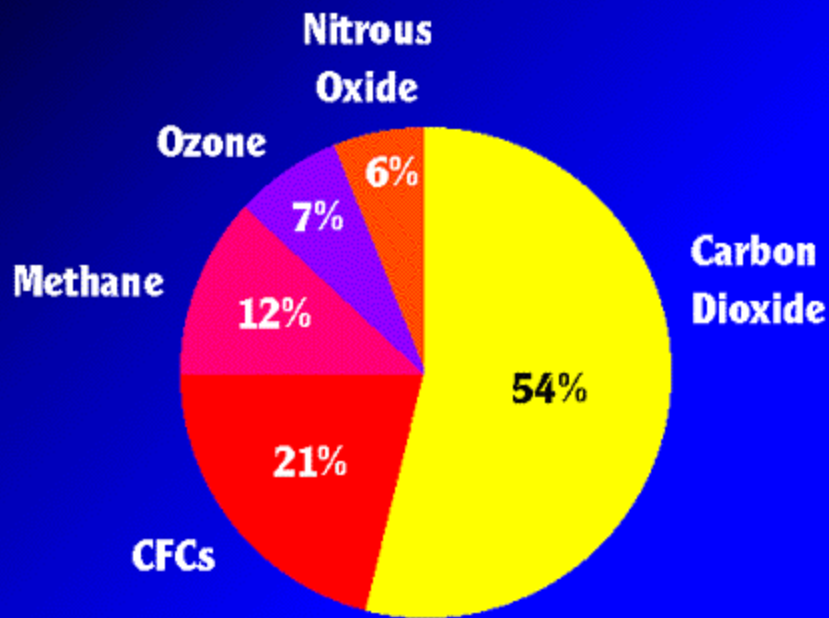


(After James E. Hansen 2006)



Anatomically modern humans emerged about 200,000 years ago. Human populations remained tiny relative to current levels until a few thousand years ago. In the last thousand years, global human population has begun to exhibit exponential growth, setting the stage for a massive global impact of humans on the natural environment.

Contributions to Global Warming by the Major Greenhouse Gases



1990 values

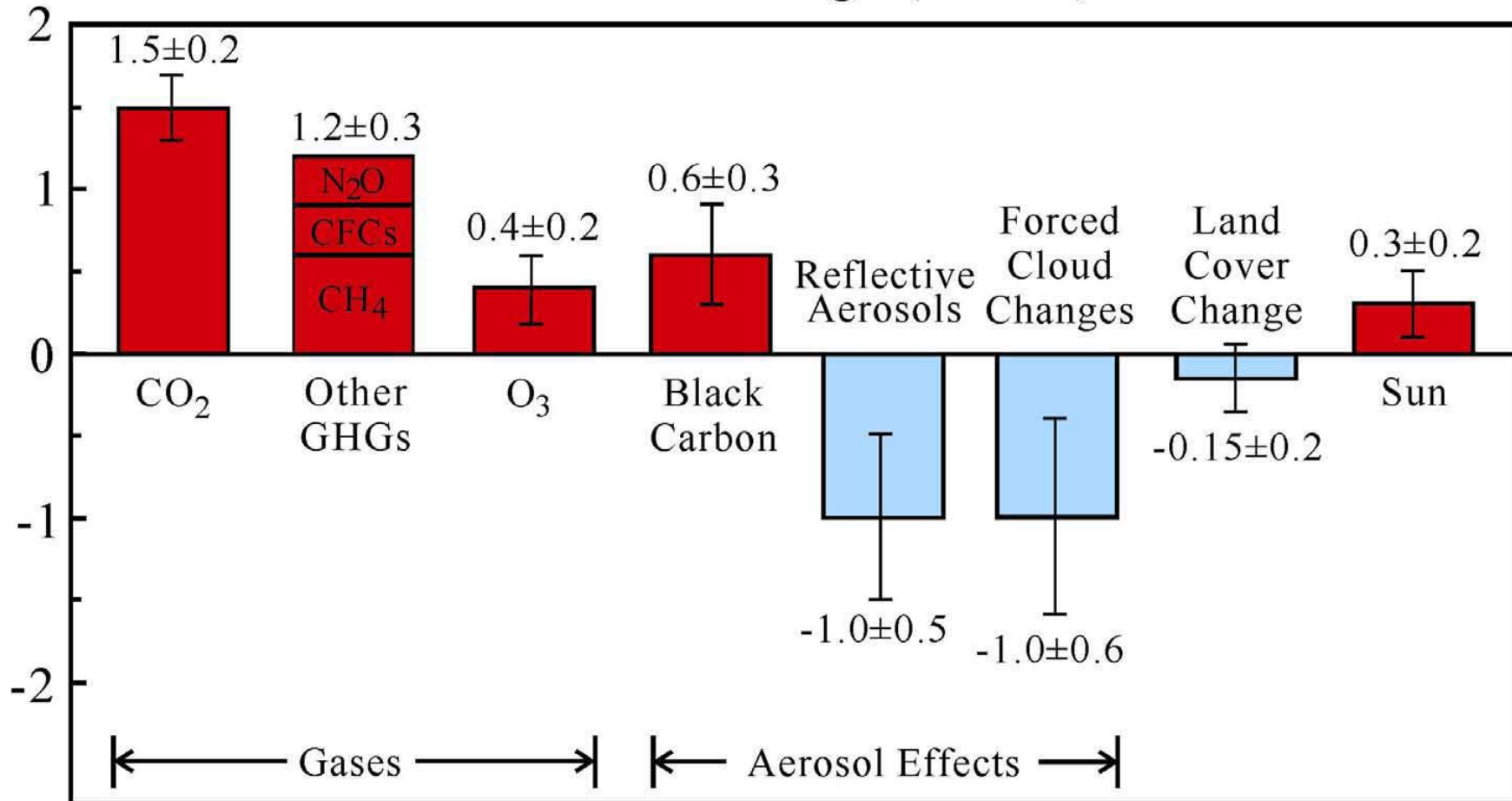
Source - *The Greenhouse Trap*, Francesca Lyman,
World Resources Institute, 1990



CG Figure-22

It is critical to understand what controls the CO₂ concentrations in the atmosphere, because the increase in CO₂ makes up more than half of the human enhancement of the greenhouse effect. This is the justification for studying the global carbon cycle. Note the CFCs reduction after 1987 Montreal Protocol.

Effective Climate Forcings (W/m^2): 1750-2000



Climate forcing agents in the industrial era. “Effective” forcing accounts for “efficacy” of the forcing mechanism

Source: Hansen et al., JGR, **110**, D18104, 2005.

Natural Source and Sink of Carbon Dioxide (Atm. Lifetime ~ 50-200 yrs)

Source

- ❑ Lithosphere: $C + O_2 \rightarrow CO_2$
- ❑ Other chemical reactions in the atm.

Sink

- ❑ CO_2 dissolves into the oceans (and returns to the atmosphere by a reverse process)
- ❑ Photosynthesis (land biota): $CO_2 + H_2O + \text{sunlight} \rightarrow CH_2O + O_2$

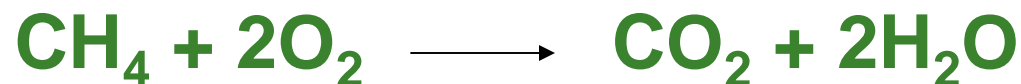
There are three main types of fossil fuels:

(1) Oil and its derivatives

(2) Coal

(3) Natural Gas

Fossil fuels are typically composed of compounds containing hydrogen and carbon atoms. The process of burning fossil fuels always results in carbon dioxide being emitted into the atmosphere. Take the example of natural gas (methane).



Water and carbon dioxide are the by-products.

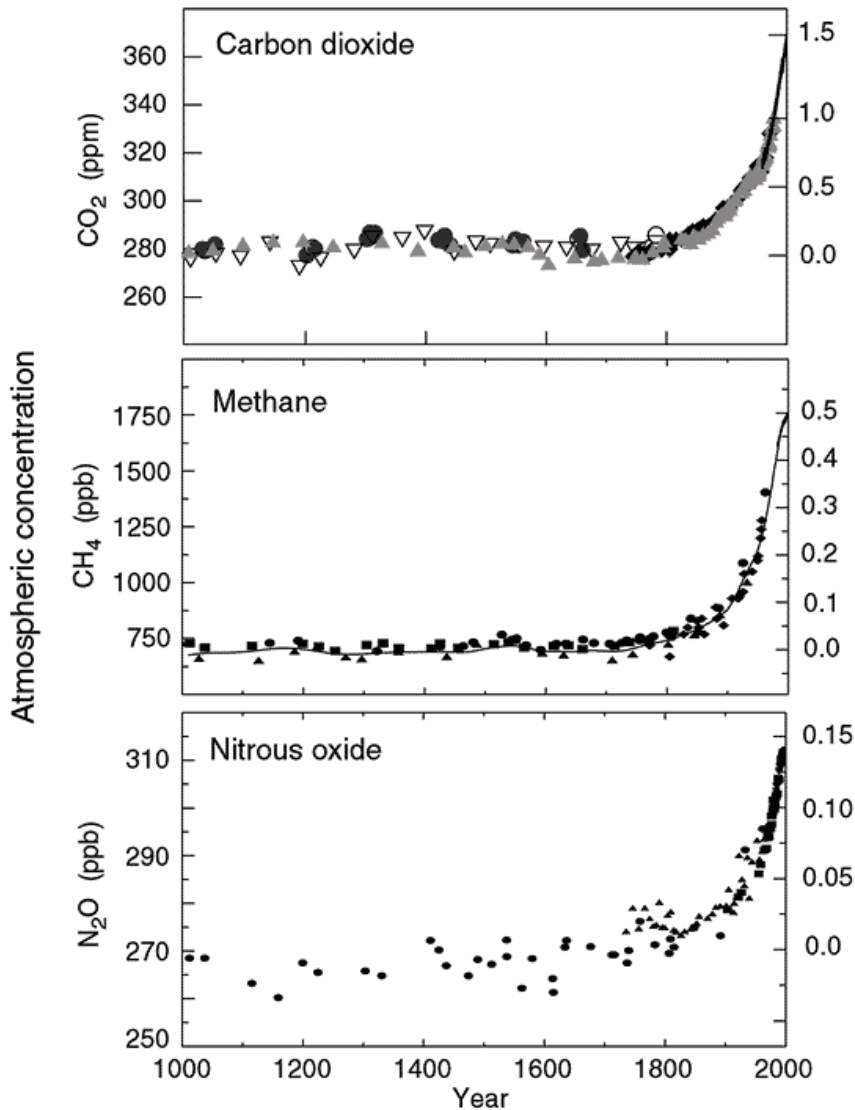
Let's begin our examination of the carbon cycle by focusing on emissions of CO₂.

Currently, about 6.3 gigatons (1 Gt = 10¹² kg) of carbon are released into the atmosphere as a result of fossil fuel burning.

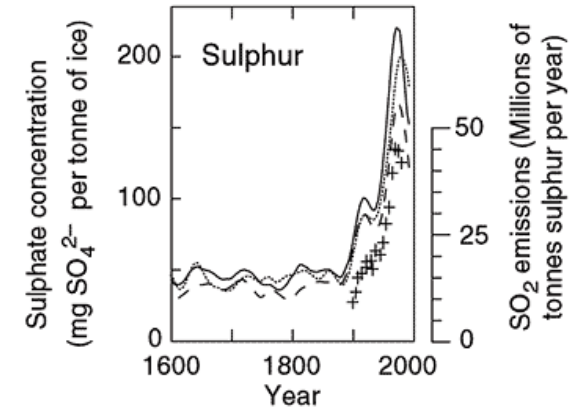
About 40% of this comes from coal burning, another 40% comes from burning of oil and oil derivatives (such as gasoline), and the remaining 20% comes from burning of natural gas (methane).

Indicators of the human influence on the atmosphere during the Industrial Era

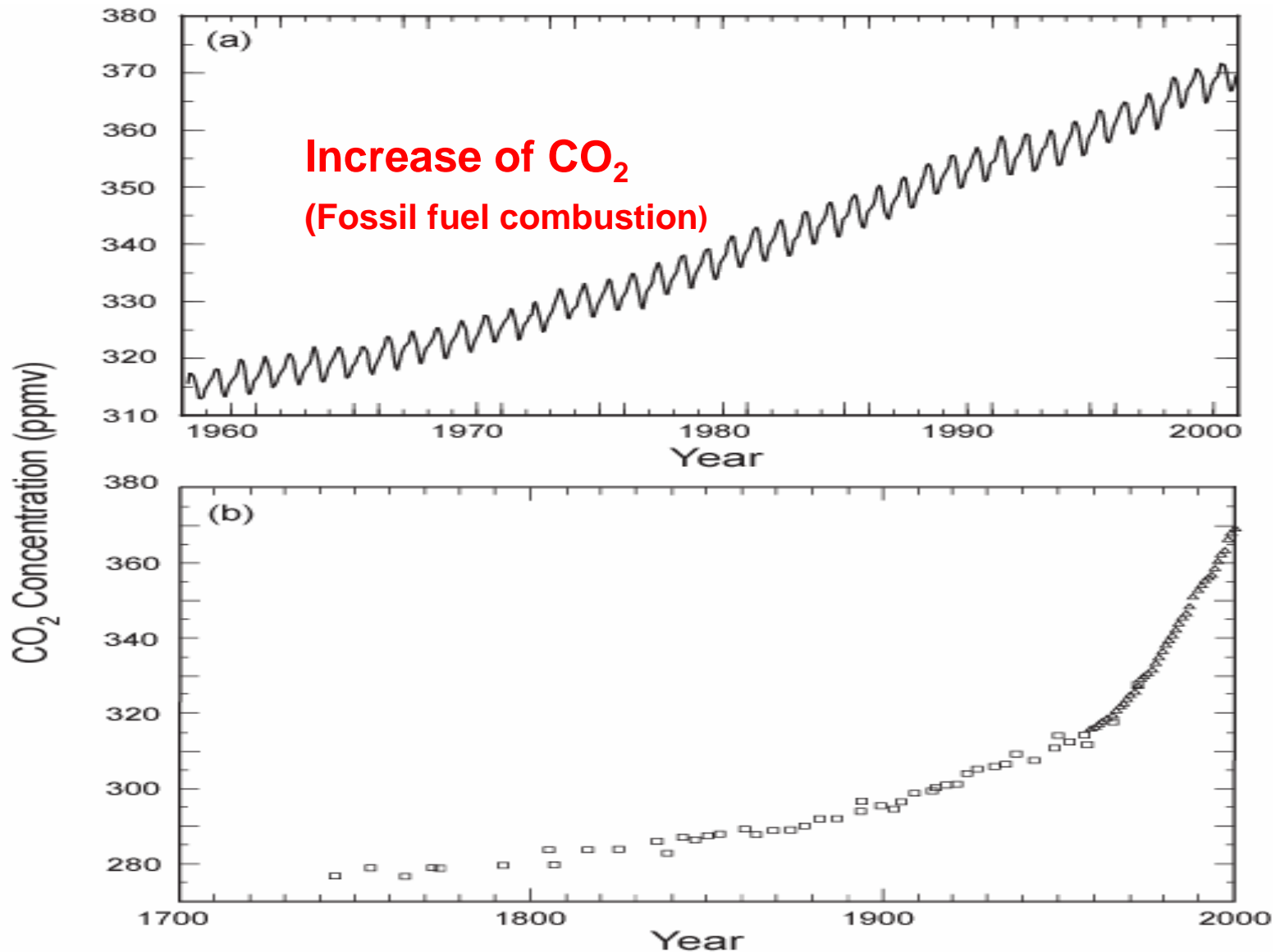
(a) Global atmospheric concentrations of three well mixed greenhouse gases



(b) Sulphate aerosols deposited in Greenland ice

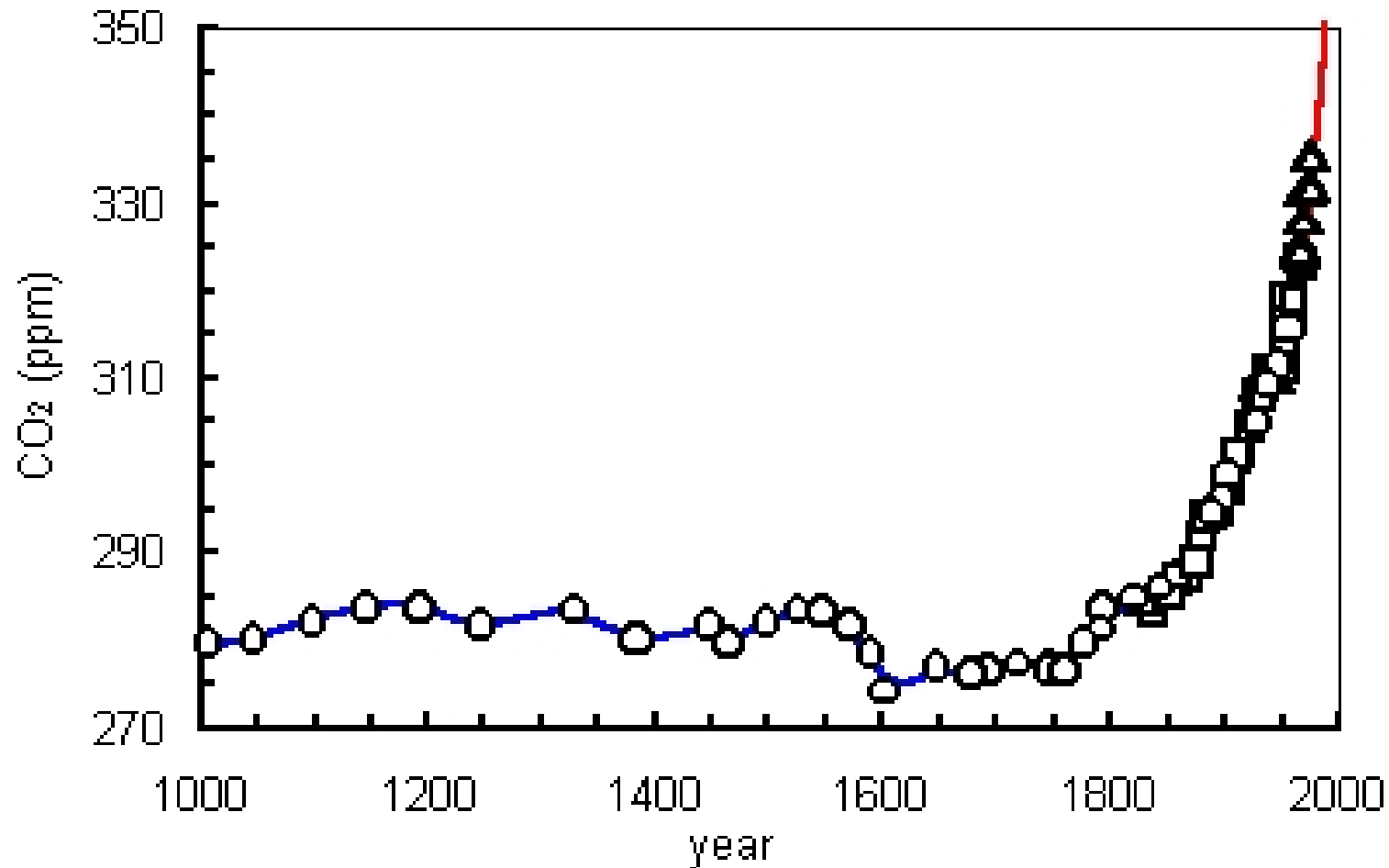


According to records of past atmospheric composition in ice cores, greenhouse gases, including carbon dioxide, methane, and nitrous oxide, have increased during the industrial era. So have sulfate aerosols.

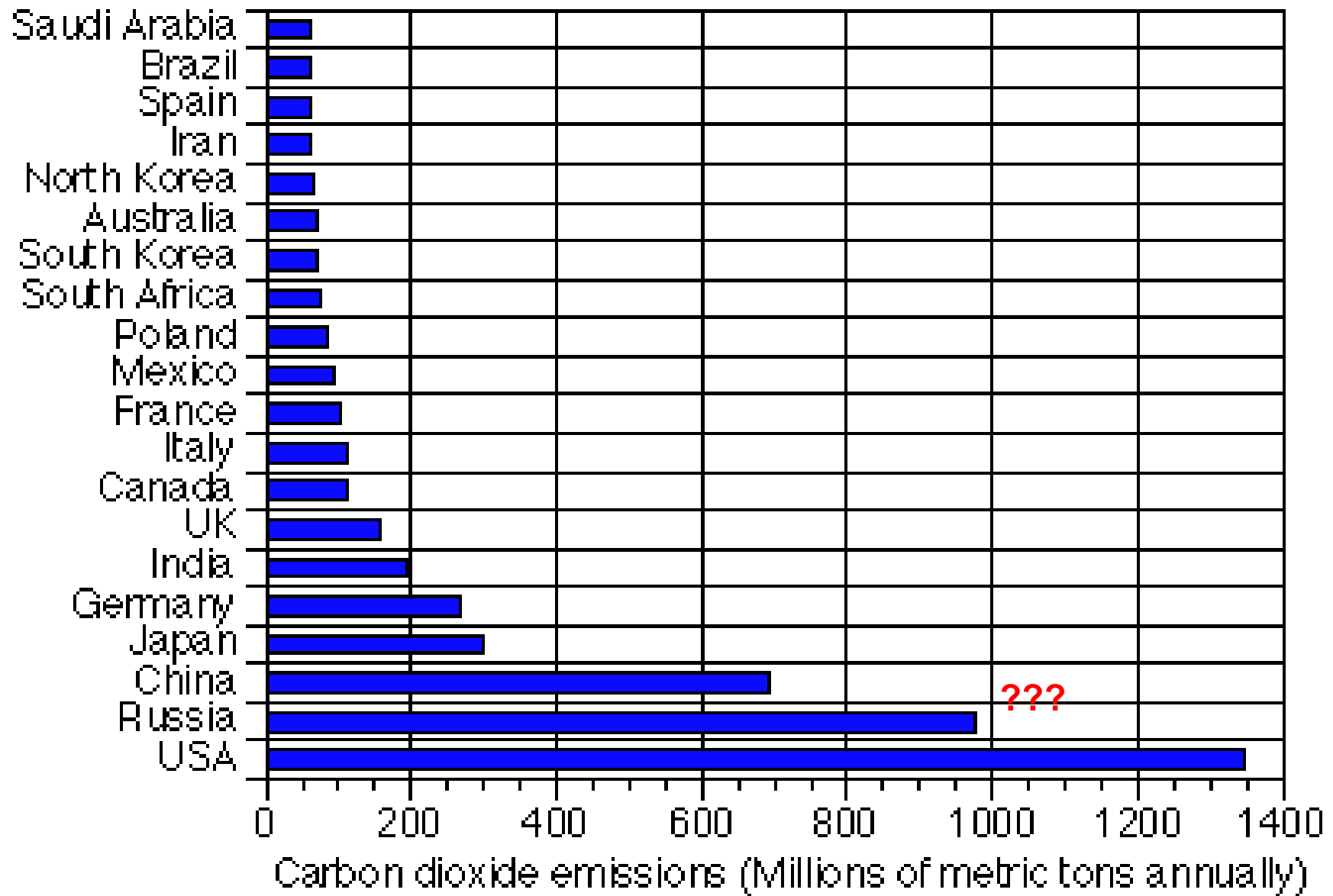


Concentration of atmospheric CO₂ at Mauna Loa Observatory, Hawaii, expressed as a mole fraction in parts per million of dry air for the period 1958-2000 (courtesy of Pieter Tans, Geophysical Monitoring for Climate Change, Environmental Research Laboratory, National Oceanic and Atmospheric Administration). (b) **Atmospheric CO₂ concentration for the past 250 years** as indicated by measurements in air trapped in ice core from Antarctica determined by Neftel et al. (1985) and extended to the present using the Mauna Loa recorded displayed in (a).

The carbon dioxide record in the Greenland Ice Core



The current increase in CO₂ amounts to 3.2 gigatons of carbon being put into the atmosphere every year.



Here's how the total emissions break down by country.

1997 total fossil CO₂ production by country

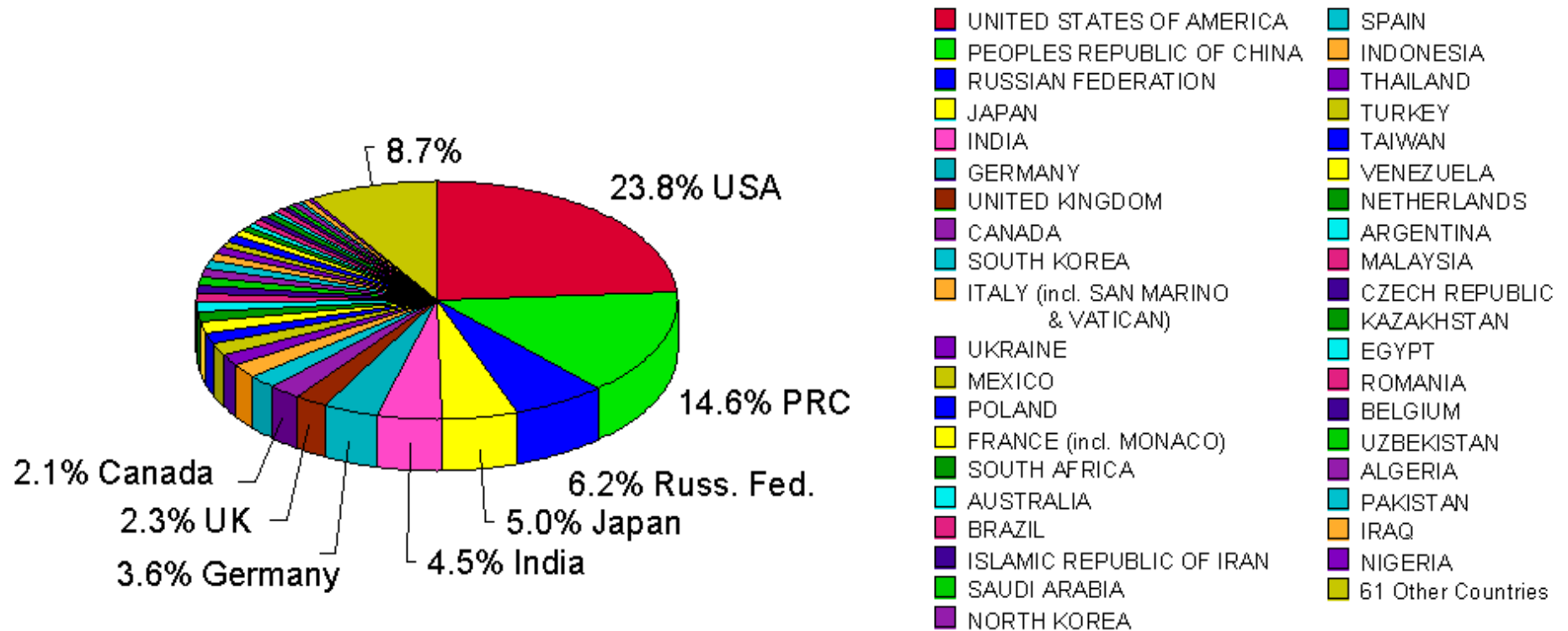
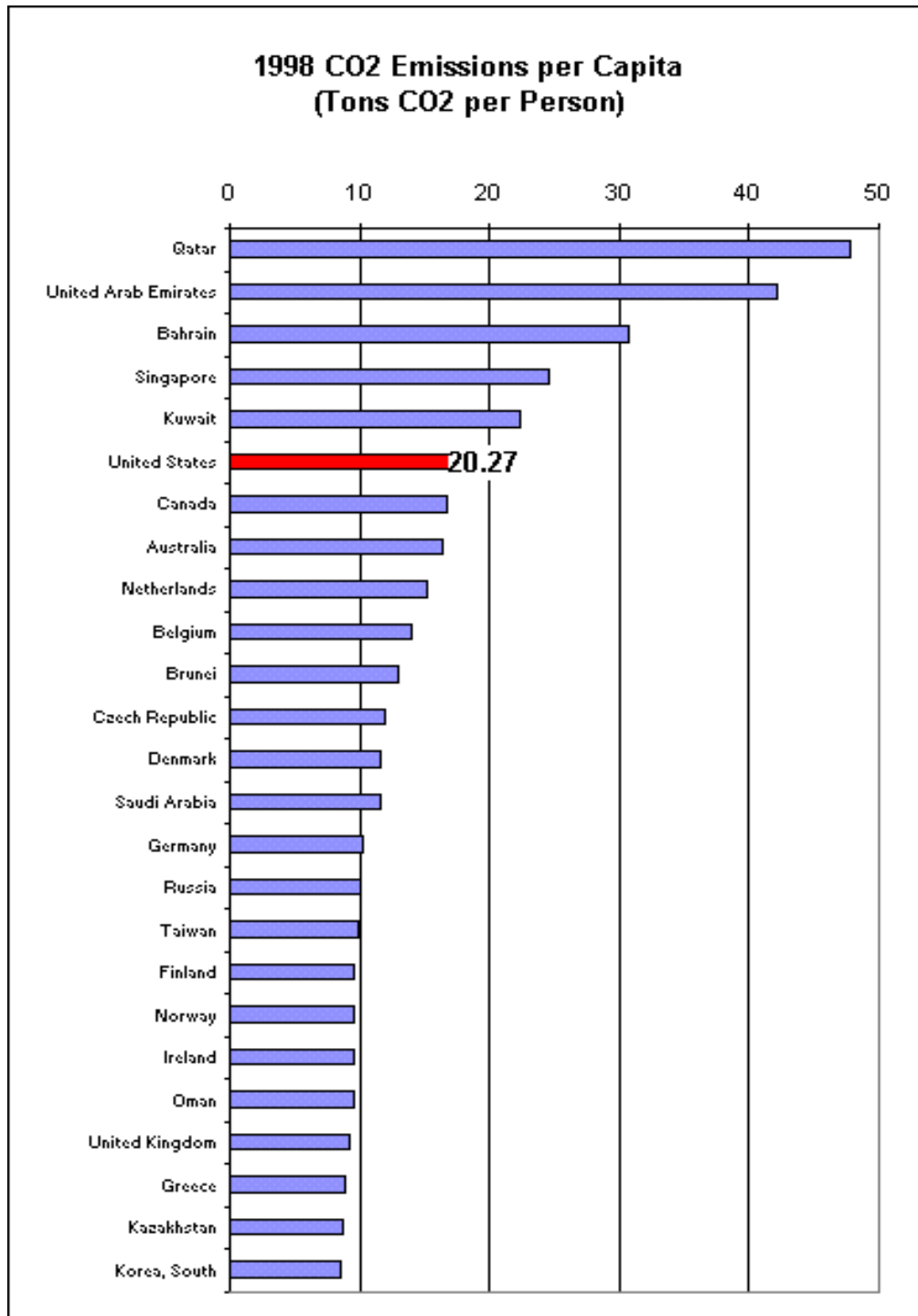


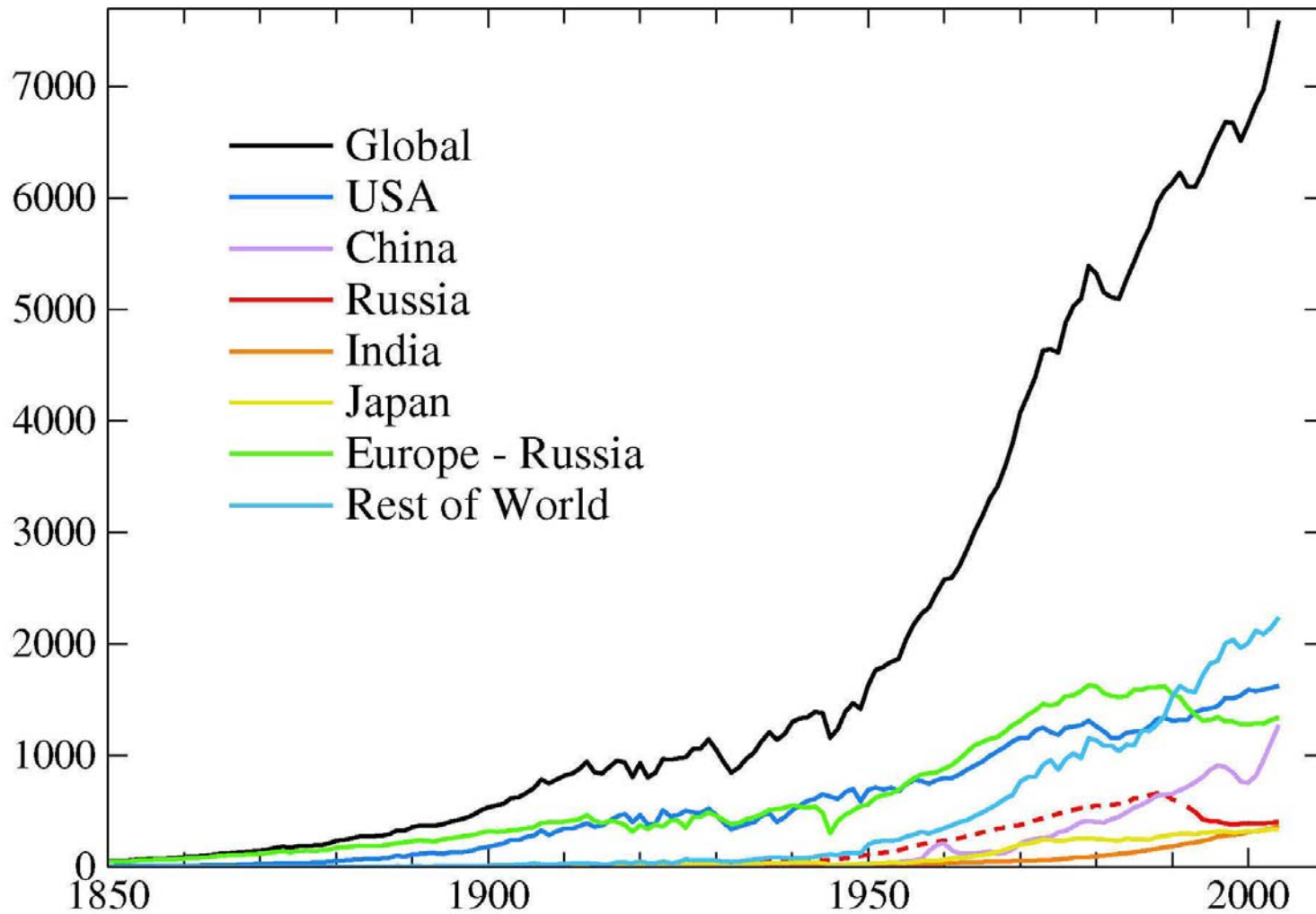
Figure by M. Horning based on Data from Gregg Marland and Tom Boden (Oak Ridge National Laboratory) and Bob Andres (University of North Dakota), available from the Carbon Dioxide Information Analysis Center (<http://cdiac.esd.ornl.gov/>)

Here's how each country's emissions break down as a percentage of the total.



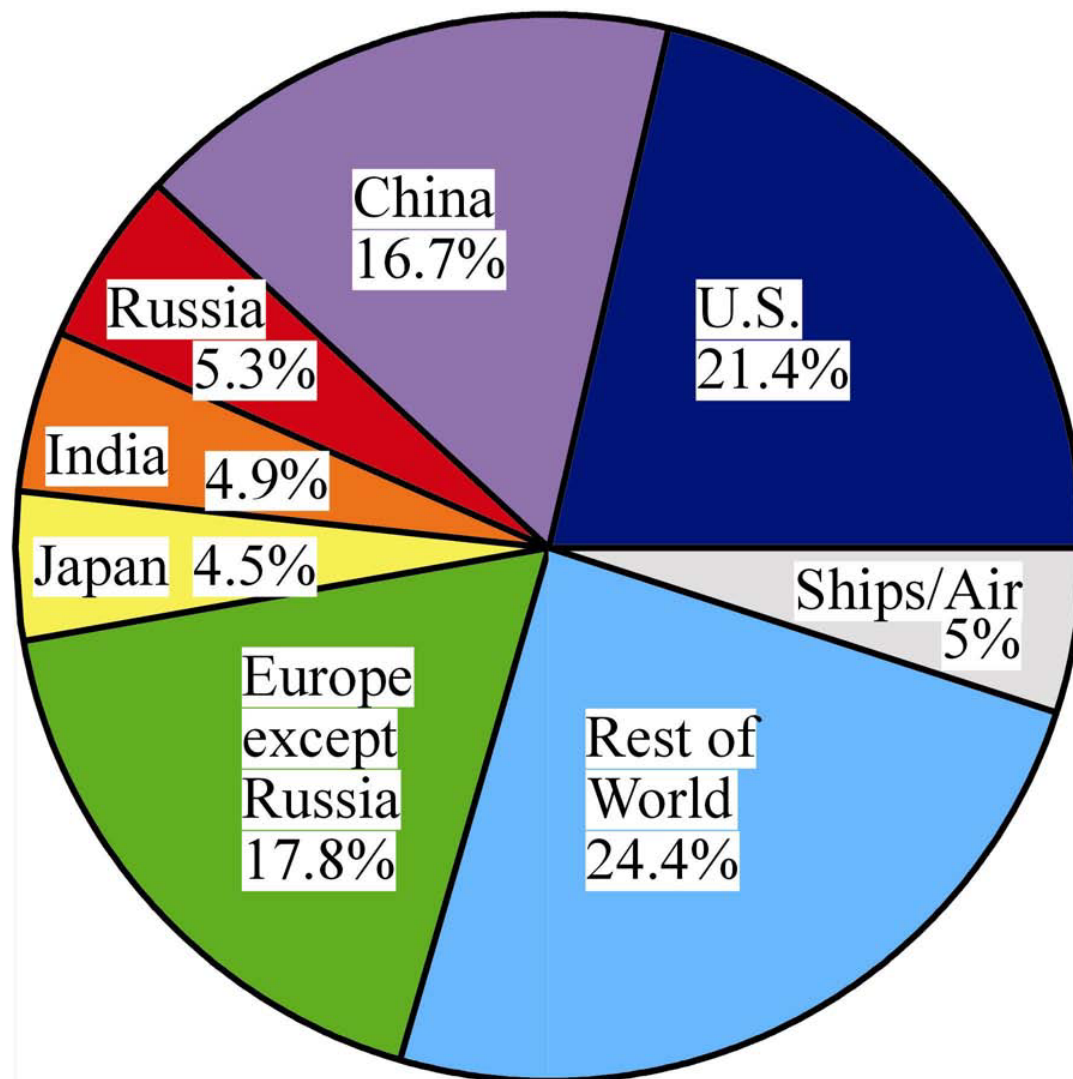
We've seen that the U.S. produces by far the most emissions of CO₂ of any country in the world. How does the U.S. compare to other countries on a per capita basis?

Country/Region Fossil Fuel CO₂ Annual Emissions



After Hansen, 2006

2004 Portions of CO₂ Emissions



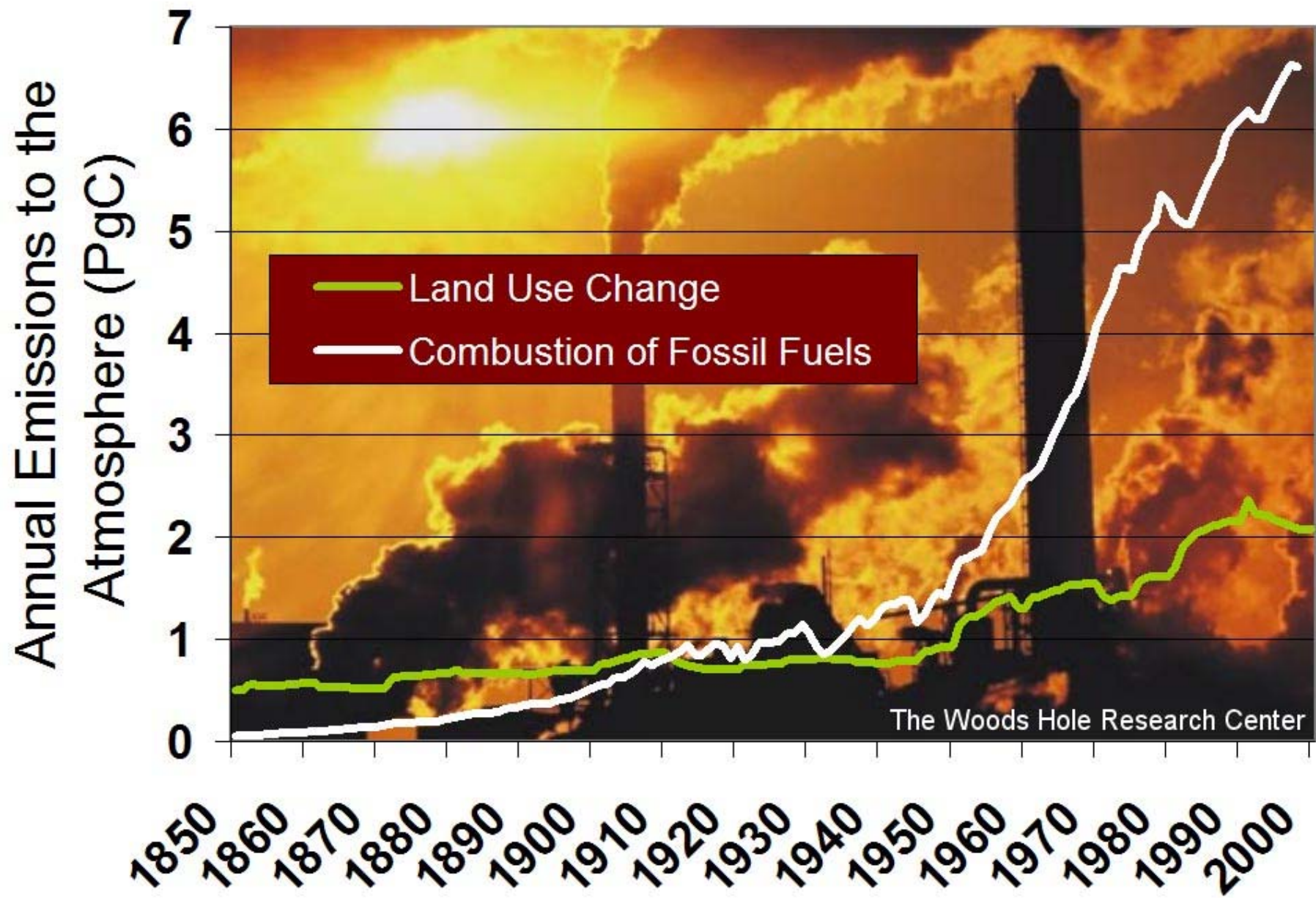
Source: Hansen et al, J. Geophys. Res., to be submitted

Human activity is also adding CO₂ to the atmosphere through deforestation.

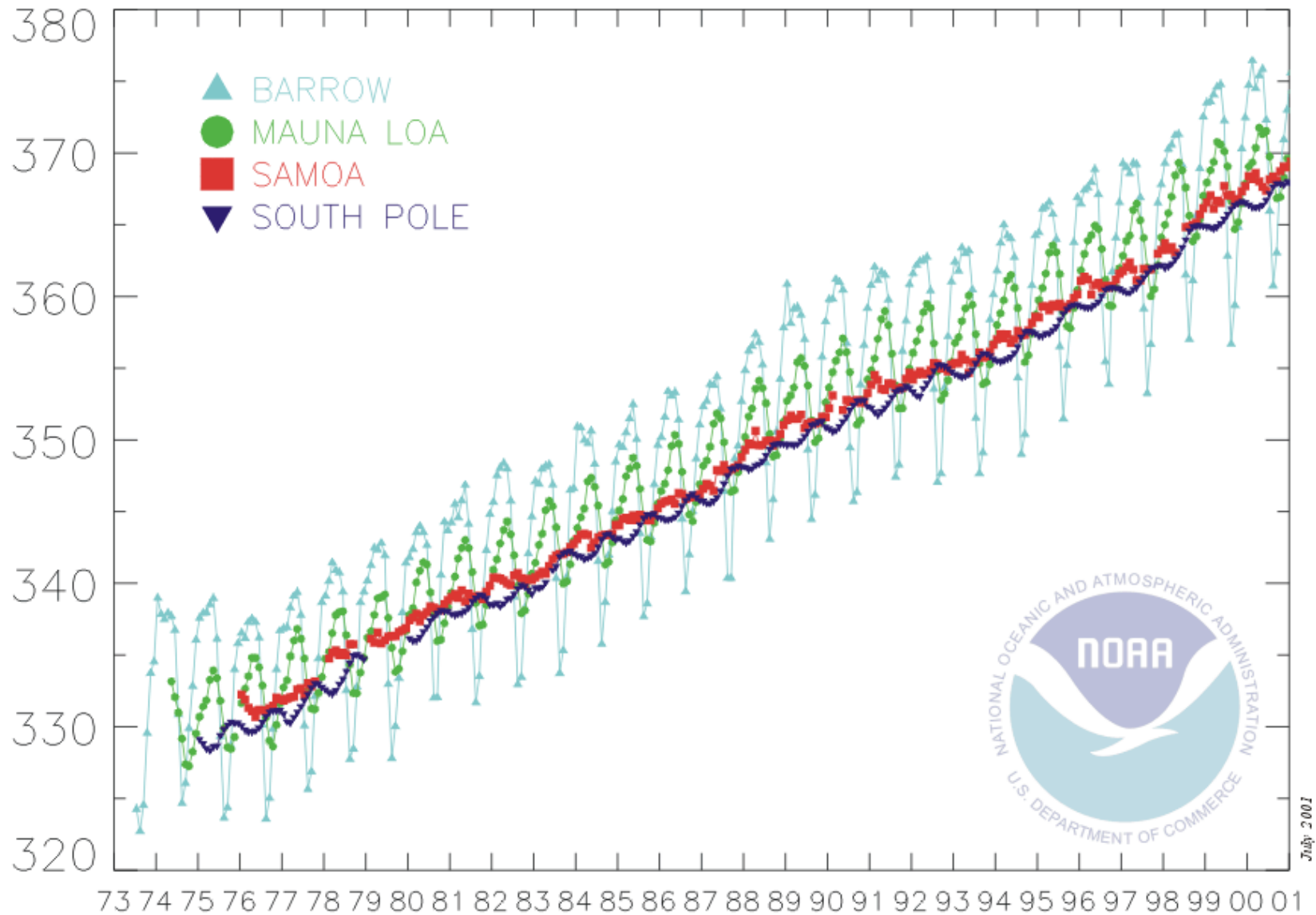
When tropical forests are clear cut, the land is typically converted to pasture.

The original forest and its soil have a much higher carbon content than the pastureland, so the **process of burning the forest must result in a significant release of carbon to the atmosphere.**

Deforestation is thought to be releasing about **2.2 gigatons** of carbon every year into the atmosphere.



The role of the terrestrial biosphere carbon dioxide measurements



Facts about DEFORESTATION

Deforestation occurs at a rate of 150,000 square km per year worldwide (every 2.5 years, an area equivalent to the state of California disappears).

Tropical forests once occupied 16 million square kilometers of the earth's surface, but now cover only 9 million.

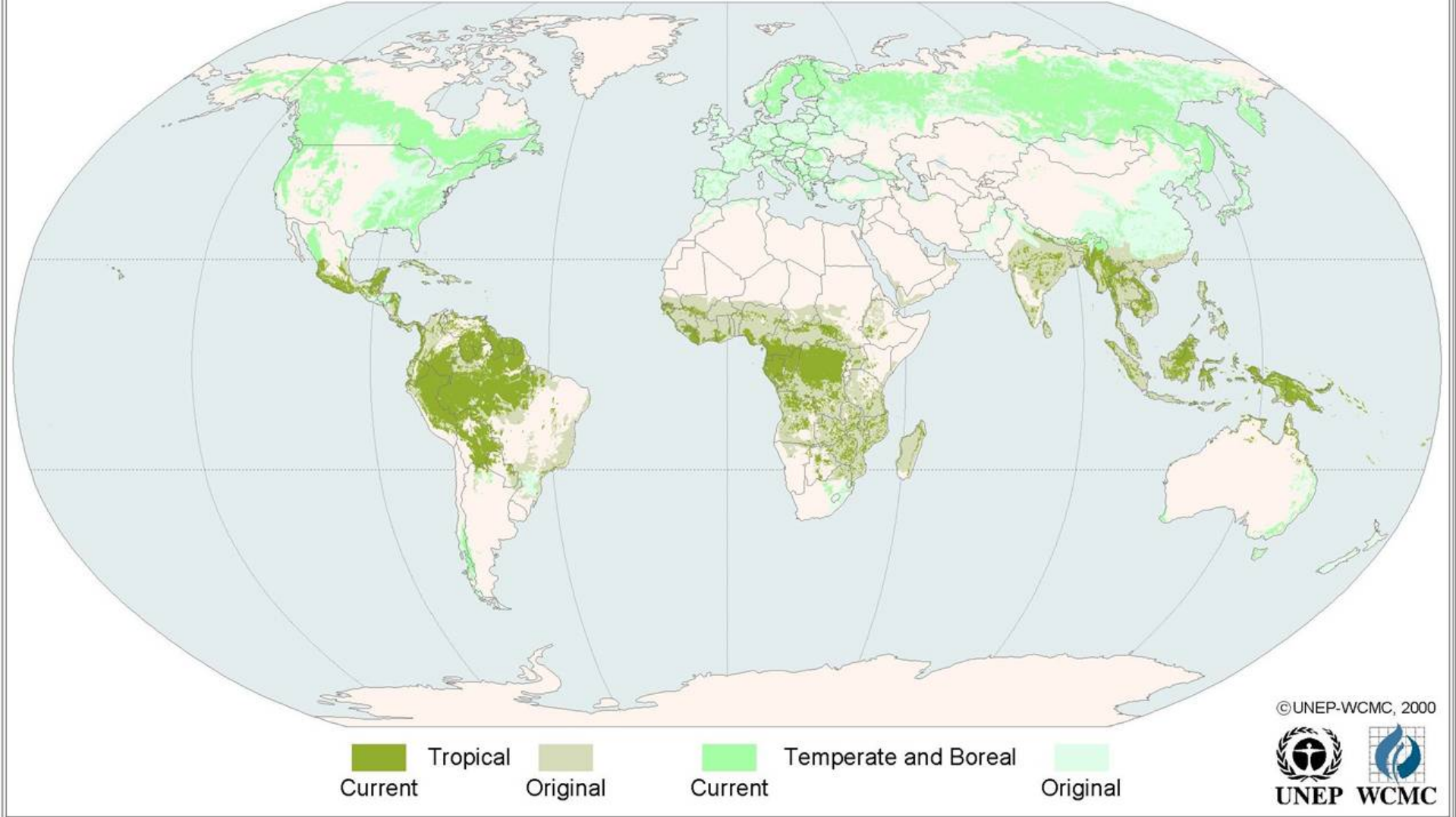
It is estimated that Latin America and Asia have already lost 40% of their original forest; Africa a little more than half.

In many countries the rate of deforestation is accelerating. For example, most of the forested areas of Bangladesh, India, the Philippines, Sri Lanka and parts of Brazil's rain forest could be gone by the end of the century.

Only in the Congo Basin and some of the more isolated areas of the Amazon Basin does the forest remain largely intact.

2 20 98

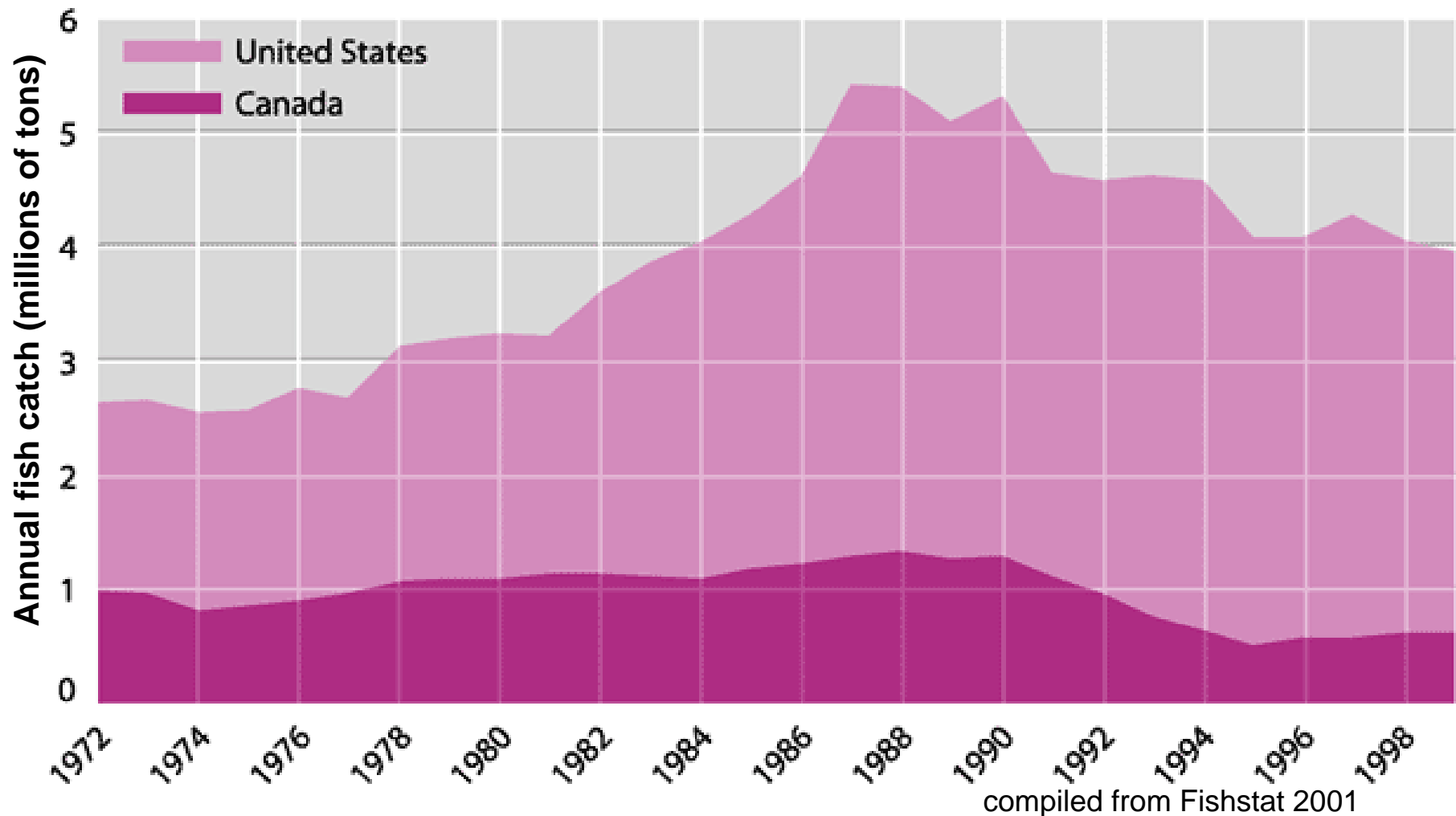
Global Distribution of Original and Remaining Forests



Human impact on forest distribution as of the year 2000

Implications of DEFORESTATION

- **Species loss:** The majority of earth's species live in the tropics. The majority of the species in the tropics have very limited ranges, increasing the importance of small patches of land for overall biodiversity.
 - **Global carbon cycle:** The burning of the forests releases carbon dioxide into the atmosphere, contributing to the increase in greenhouse gas concentrations.
 - **Local climate change:** The loss of rain forest alters precipitation and cloud patterns.
-



Ocean ecosystems are also coming under increasing stress due to human activity. Evidence comes from records of total fish catch in the oceans surrounding North America, shown above. Fish catch rose until the late 80s, then has declined precipitously. This has been attributed to overfishing. Fisheries around the world have behaved similarly.



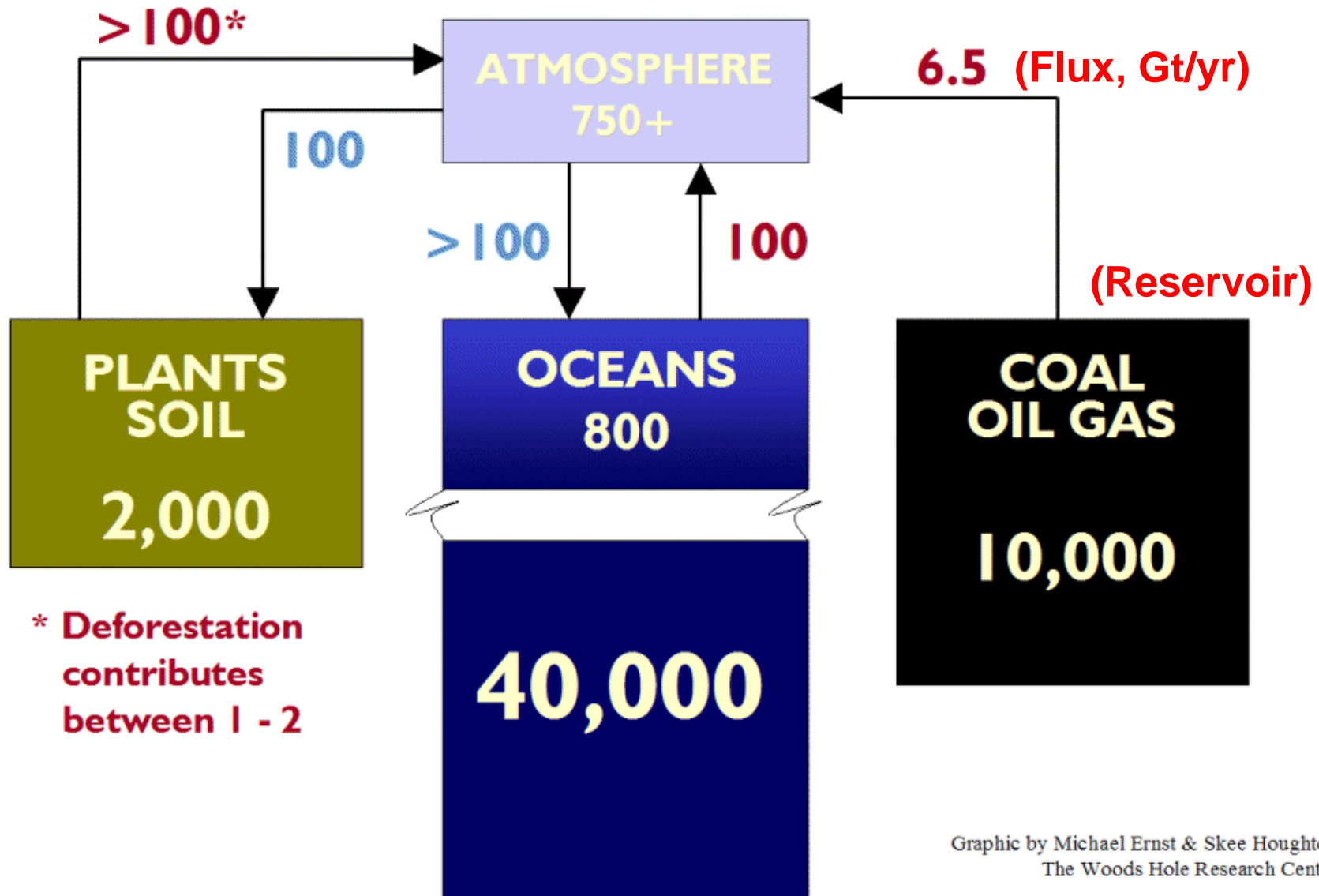
Examples of drastically declining fish populations

- **New England groundfish and flounder**
- **Southeast Spiny Lobster**
- **Atlantic Bluefin Tuna and Swordfish**
- **Main Hawaiian Island Bottomfish**
- **Large Coastal Sharks**
- **Gulf of Mexico King Mackerel and Pink Shrimp**
- **Atlantic/Gulf of Mexico/Caribbean Reef Fish Complex**
- **Pacific Ocean Perch**
- **North Pacific Albacore**
- **Oysters, Hard Clams, and Abalones**

Global Flows of Carbon



1 Gt = 10^{12} kg (Petagrams of Carbon/Year)



Graphic by Michael Ernst & Skee Houghton
The Woods Hole Research Center

Let's consider what happens to all that CO₂ that is emitted into the atmosphere.

Of the 6.3 gigatons of carbon being put into the atmosphere every year by fossil fuel burning and the 2.2 gigatons being put there by deforestation (total **8.5 gigatons**), only about **3.2 gigatons** actually remains there.

The amount remaining can be calculated directly from the increase in atmospheric CO₂.

So where is all the excess CO₂ going?

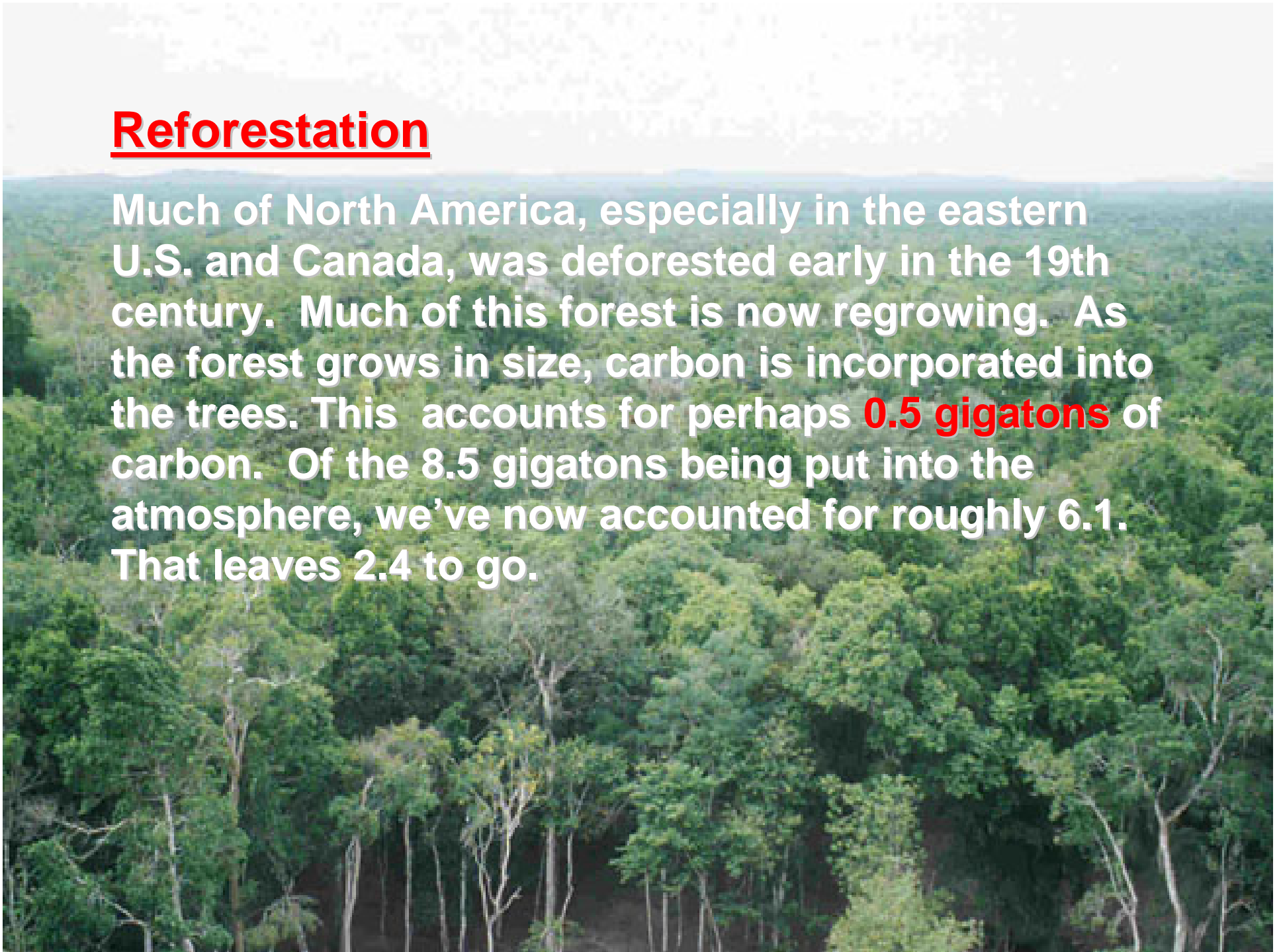
Uptake by the Ocean

The main way anthropogenic CO₂ is removed from the atmosphere is through oceanic uptake. This occurs because CO₂ dissolves in seawater. The excess carbon is eventually incorporated into the skeletons of marine organisms and buried in deep sea sediments as the organisms die and fall to the bottom of the ocean.

This process is thought to remove about **2.4 gigatons** of carbon per year from the atmosphere. So we started with 8.5 gigatons, 3.2 are in the atmosphere, 2.4 are taken up by the ocean, leaving us with **2.9 gigatons still** to be accounted for.

Reforestation

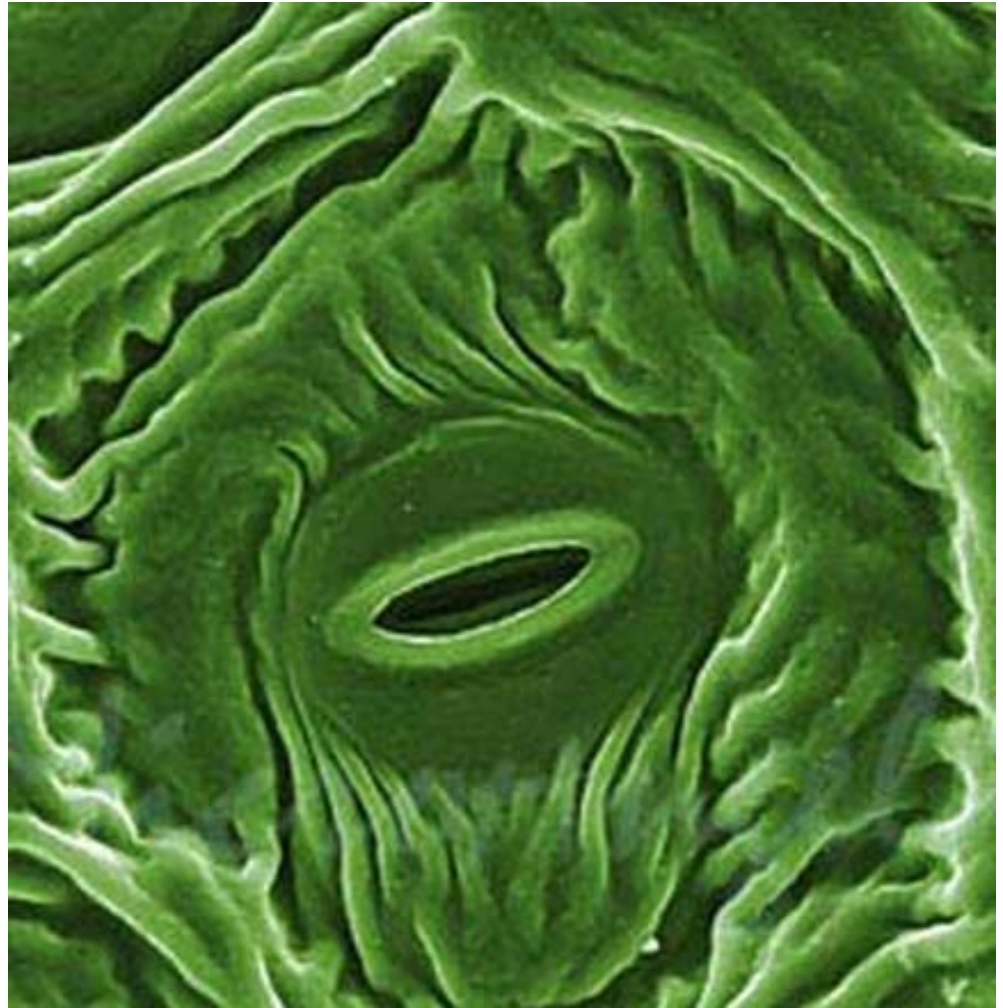
Much of North America, especially in the eastern U.S. and Canada, was deforested early in the 19th century. Much of this forest is now regrowing. As the forest grows in size, carbon is incorporated into the trees. This accounts for perhaps **0.5 gigatons** of carbon. Of the 8.5 gigatons being put into the atmosphere, we've now accounted for roughly 6.1. That leaves 2.4 to go.



CO₂ fertilization

Plants need CO₂ for photosynthesis. They generally obtain this CO₂ through stomata, small openings on their leaves. But plants also lose water, another critical substance for their survival, through their stomata. This makes it essential that they be able to control the size of the stomata. When the CO₂ concentration is increased, the stomata do not have to be as large to take in the same amount of CO₂. So the plants can survive and continue to grow under drier conditions.

It is possible that increased CO₂ levels in the atmosphere are leading to **enhanced growth rates of terrestrial plants, accounting for some of the missing carbon.**



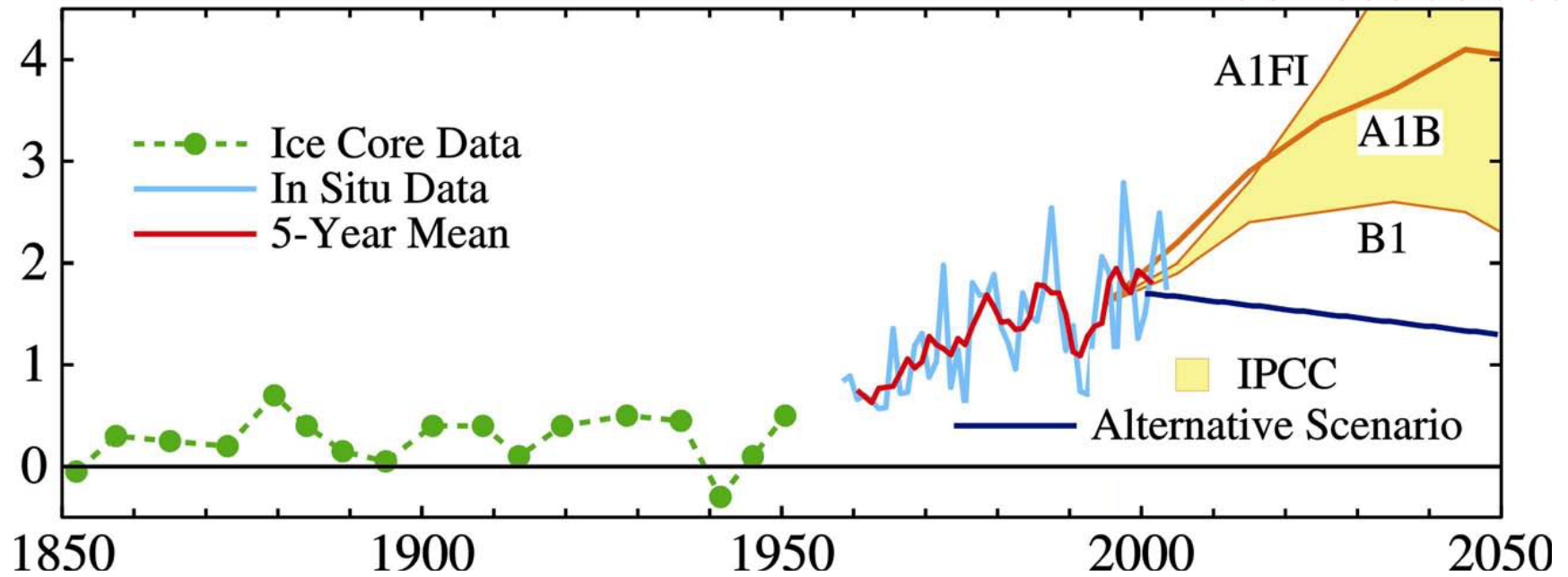
Microscopic view of the underside of a leaf surface

Summary

- ❑ Many questions still remain unanswered on the carbon cycle.
- ❑ However, it is quite clear that humans have produced a significant amount of carbon dioxide and other greenhouse gases in the atmosphere based on unequivocal observations since the era of Industrial Revolution. Their productions continue to this date.
- ❑ A new scientific field called “Biogeoscience” has emerged in recent years for the study of the distributions of greenhouse gases in the atmosphere, the oceans, and the land biota.

Annual CO₂ Growth (ppm/year)

Business as usual

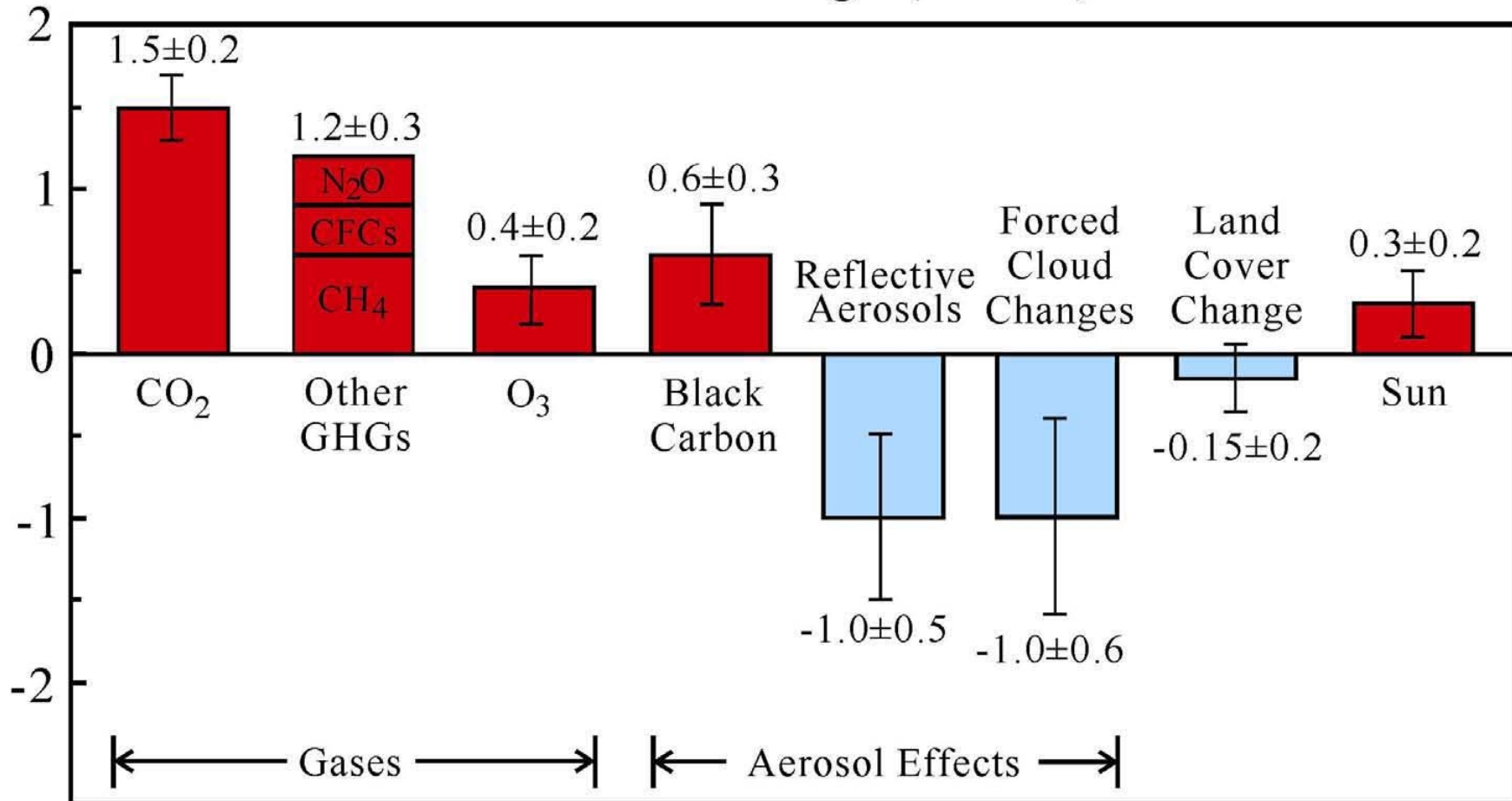


Growth rate of atmospheric CO₂ (ppm/year).

Source: Hansen and Sato, PNAS, 101, 16109, 2004.

IPCC: Intergovernmental Panel on Climate Change

Effective Climate Forcings (W/m^2): 1750-2000



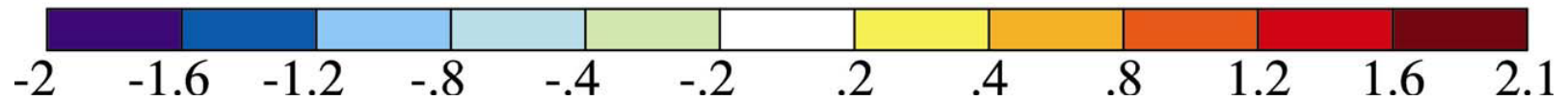
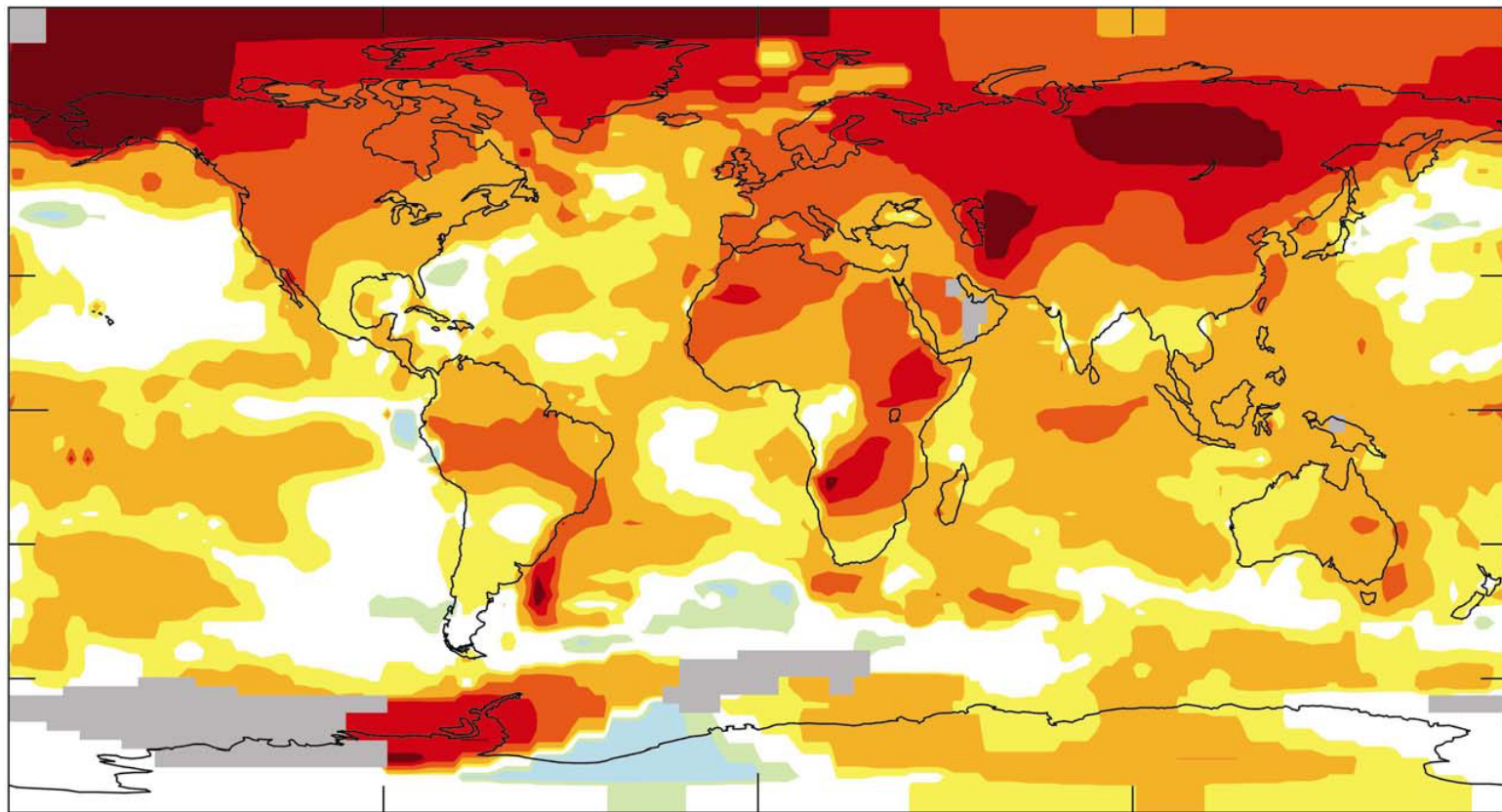
Climate forcing agents in the industrial era. “Effective” forcing accounts for “efficacy” of the forcing mechanism

Source: Hansen et al., JGR, **110**, D18104, 2005.

2001-2005 Mean Surface Temperature Anomaly ($^{\circ}\text{C}$)

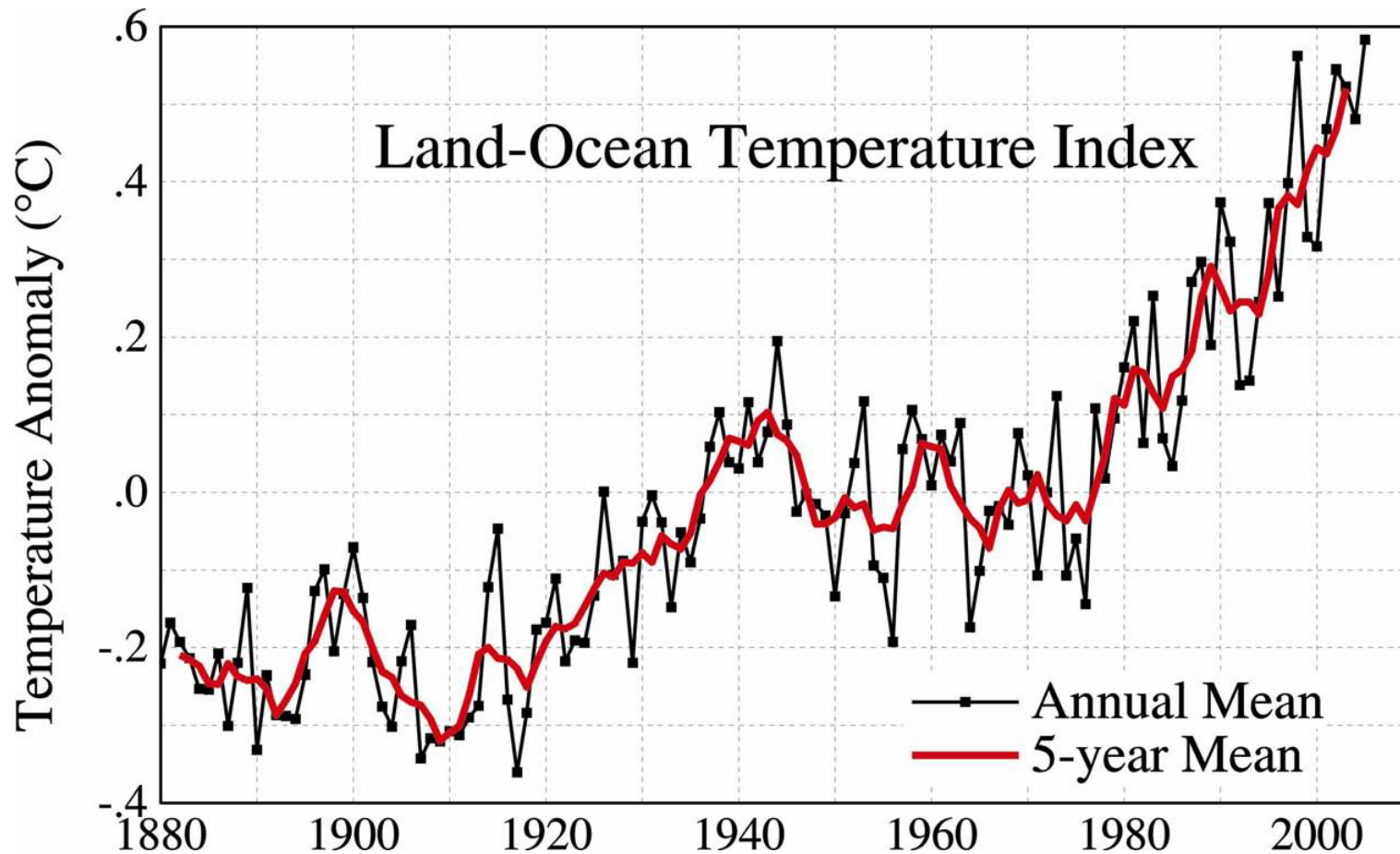
Base Period = 1951-1980

Global Mean = 0.53



(After James E. Hansen 2006)

Projection to the future? (globe and regions)



Global mean surface temperature change based on surface air measurements over land and SSTs over ocean. *Source:* Update of Hansen et al., *JGR*, 106, 23947, 2001; Reynolds and Smith, *J. Climate*, 7, 1994; Rayner et al., *JGR*, 108, 2003 (after James E. Hansen 2006).