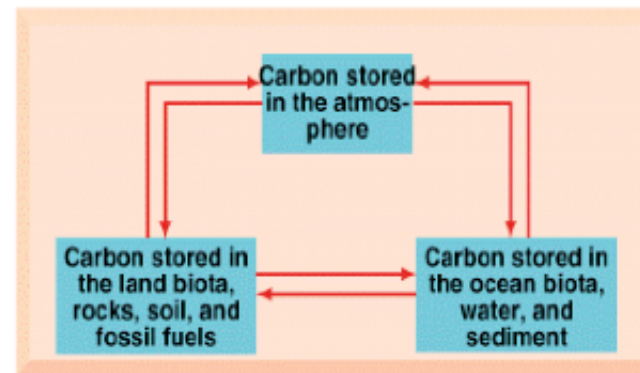
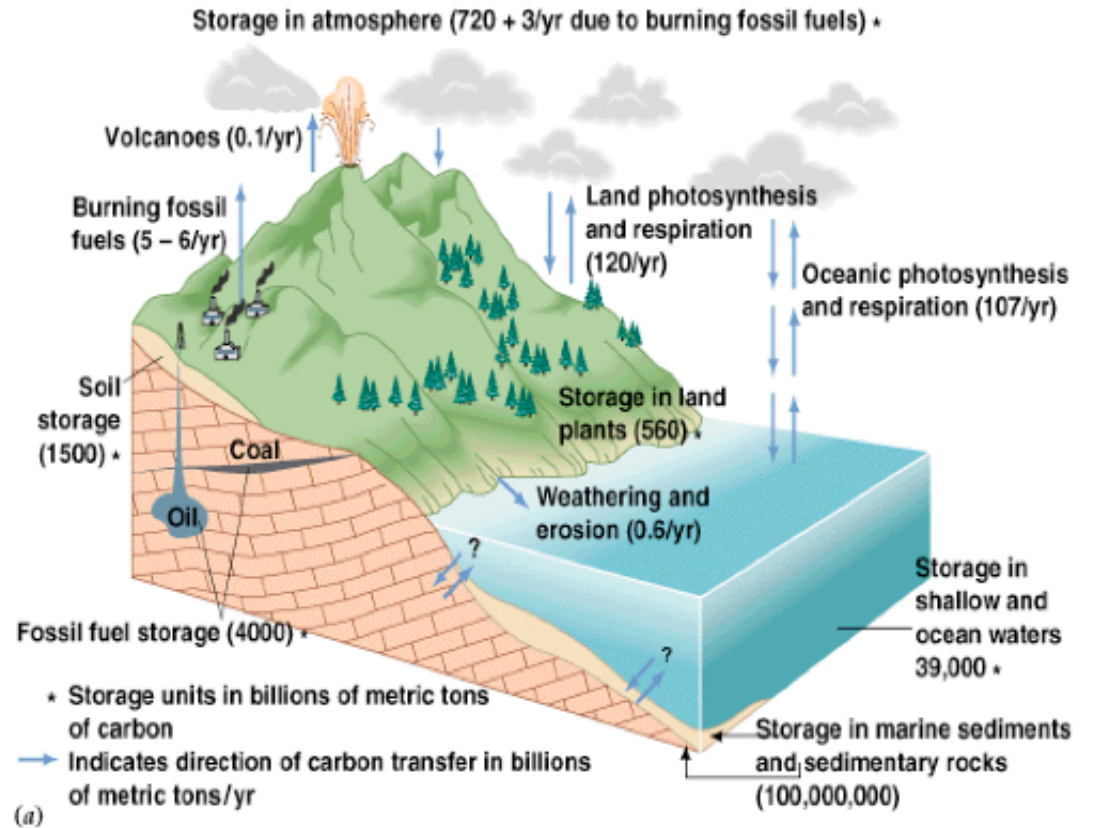


# Carbon Cycle

# Simple carbon cycle



(a) Generalized global carbon cycle. (b) Parts of the carbon cycle simplified to illustrate the cyclic nature of the movement of carbon. (SOURCE: Modified after G. Lambert, 1987, *La Recherche*: 18, pp. 782-783.)

# Reservoirs fluxes and residence times

**Reservoirs:** pools of carbon that can be uniquely defined

**Fluxes:** the rate of movement of carbon from one reservoir to another

**Residence time:** the average time that carbon spends in a given reservoir

**Fluxes:** (in billions of metric tons/year)

Land Plants

Photosynthesis	120
Plant respiration	60
Soil respiration	60
Plants to soils	60
Fossil fuel formation	0.0001
Fossil fuel burning	6
Deforestation	2

Ocean

Dissolving from atmosphere	107
Exsolving to atmosphere	105
Carbonate formation	0.3
Weathering	0.6

<u>Volcanoes</u>	0.1
------------------	-----

# Seasonal cycles vs. annual changes

The big fluxes are seasonal

- Land: photosynthesis and respiration (120 each way)
- Ocean: dissolving and exsolving (about 110 each way)
- These are in balance averaged over one year most of the time
- Both are slightly out of balance now due to fossil fuel inputs... more later
- So the big fluxes on a year to year basis are fossil fuel burning and deforestation

# Other notes on fluxes

-- flux of carbon out of fossil fuels is 60,000 times faster than flux into fossil fuels

-- the ocean exchange works by diffusion...

$$\text{Flux by diffusion} = k (C_{\text{air}} - C_{\text{ocean}})$$

(C is concentration or amount, **k** is a constant)

if  $(C_{\text{air}} - C_{\text{ocean}})$  goes up, flux goes up

if  $(C_{\text{air}} - C_{\text{ocean}})$  goes down, flux goes down

if  $(C_{\text{air}} - C_{\text{ocean}})$  reverses, flux reverses

# Reservoirs

<u>Reservoirs:</u>	<u>billions of metric tons</u>
Atmosphere:	720
Ocean:	39,000
Carbonates:	100,000,000
Fossil fuels:	4,000
Land plants:	560
Soils:	1500

# Notes on reservoirs

- most carbon is in rocks (carbonates and other sediments)
- most carbon not in rocks is in the ocean
- about 3 times more carbon in soils than in land plants

# Residence times

Residence times:	(years)
<i>(all relative to sum of out fluxes)</i>	
Land plants	~ 5
atmosphere	~ 3
soils	~ 25
Fossil fuels	~ 650
oceans	~ 350
carbonates	~ 150 million

# Notes on residence times

-- some **in fluxes** are not balanced by **out fluxes**...the atmosphere and fossil fuels, for example... so RT's are slightly different (and reservoirs are growing... or shrinking)

-- the RT of carbon in the air is long enough that the air is well mixed (atmosphere mixes in about 1 year)... **China's CO<sub>2</sub> is our problem and vice versa**

-- the RT of fossil fuels reflects *all* FF's suspected to exist... RT's for recoverable supplies are lower

# Notes on residence times

-- ocean RT also reflects the average, which combines the **surface water** (short RT, few months to years) and **deep water** (long RT, 200 to 1000 years)... average is weighted towards deep water, as this is most of the water

-- ocean RT reflects the circulation of the ocean (**deep water formation**)

# Notes on residence times

Big issue...

Because reservoirs are interconnected, short residence times are underestimates.

Imagine if we clean up the atmosphere... the reservoirs with longer residence times, like the ocean, will give carbon back to the atmosphere.

Thus, the atmospheric residence time is more like 100 years.

# Notes on residence times

-- Anthropogenic flux (fossil fuels and deforestation) to atmosphere ~ 8 bmt/yr, but atmospheric increase is only ~ 4 bmt/yr

*Question:*

Where does the other 4 bmt/yr go?

Two possibilities:

Land Plant Uptake (Excess Photosynthesis) vs. Ocean uptake

*--Important to know which is more important because the residence times are so different... storage on land is far more temporary than storage in the deep ocean.*

# Notes on residence times

Carbon => plants recycles *quickly* (<70 yr) to atmosphere

Carbon => ocean recycles *slowly* (>300 yr) to atmosphere

We can separate these by measuring  $^{13}\text{CO}_2$  and well as  $\text{CO}_2$  in the atmosphere... plants discriminate against  $^{13}\text{CO}_2$ , the ocean does not.

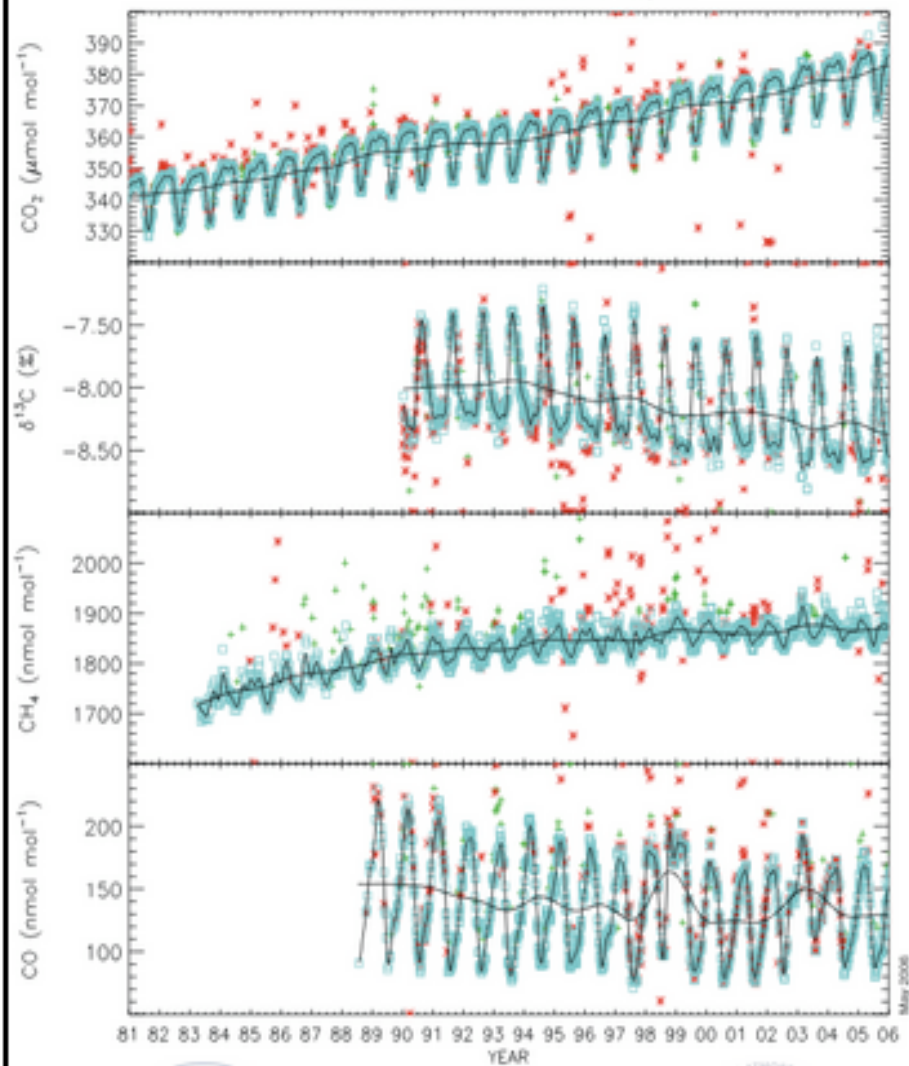
# Reconstructing the Carbon cycle

- Use a network of CO<sub>2</sub> observation sites and models of atmospheric circulation
- Over time and space we compare how much is in the atmosphere with what was upstream and with what was there earlier
- The difference tells us the net flux into or out of the atmosphere



## Barrow, Alaska

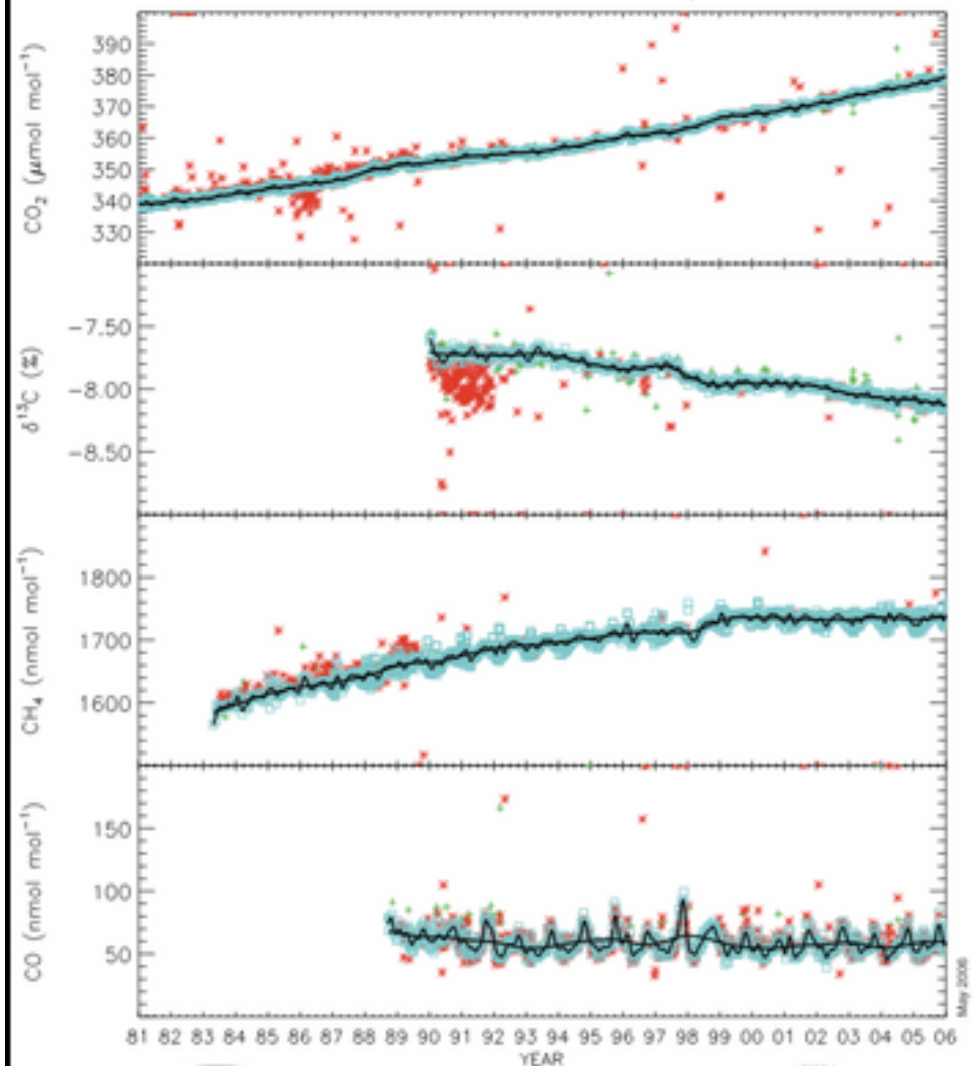
NOAA ESRL GMD Carbon Cycle



Time series showing atmospheric carbon dioxide, the carbon-13/carbon-12 isotopic ratio of carbon dioxide, methane and carbon monoxide from air collected weekly in glass containers. The isotope measurements are made at the University of Colorado INSTAAR, all others are made at NOAA. Samples that are regionally representative (square), influenced by local effects (plus), and rejected due to sample collection or analytical problems (asterisk) are shown. A smooth curve and long-term trend are fitted to the representative measurements (square). Contact: Dr. Pieter Tans, NOAA ESRL GMD Carbon Cycle, (303) 497-6678 (pieter.tans@noaa.gov, <http://www.cmdl.noaa.gov/ccgg/>).

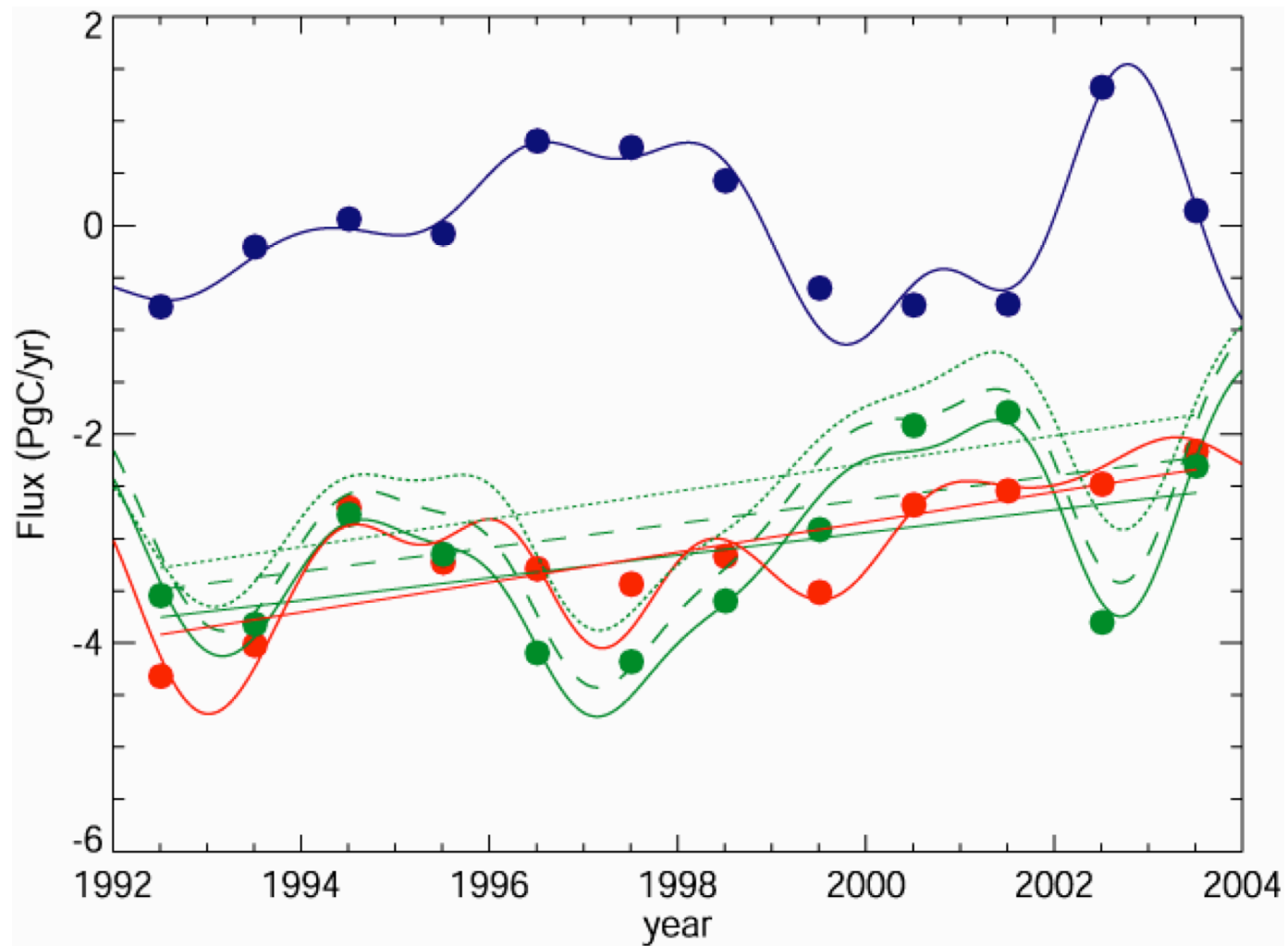
## American Samoa

NOAA ESRL GMD Carbon Cycle



Time series showing atmospheric carbon dioxide, the carbon-13/carbon-12 isotopic ratio of carbon dioxide, methane and carbon monoxide from air collected weekly in glass containers. The isotope measurements are made at the University of Colorado INSTAAR, all others are made at NOAA. Samples that are regionally representative (square), influenced by local effects (plus), and rejected due to sample collection or analytical problems (asterisk) are shown. A smooth curve and long-term trend are fitted to the representative measurements (square). Contact: Dr. Pieter Tans, NOAA ESRL GMD Carbon Cycle, (303) 497-6678 (pieter.tans@noaa.gov, <http://www.cmdl.noaa.gov/ccgg/>).

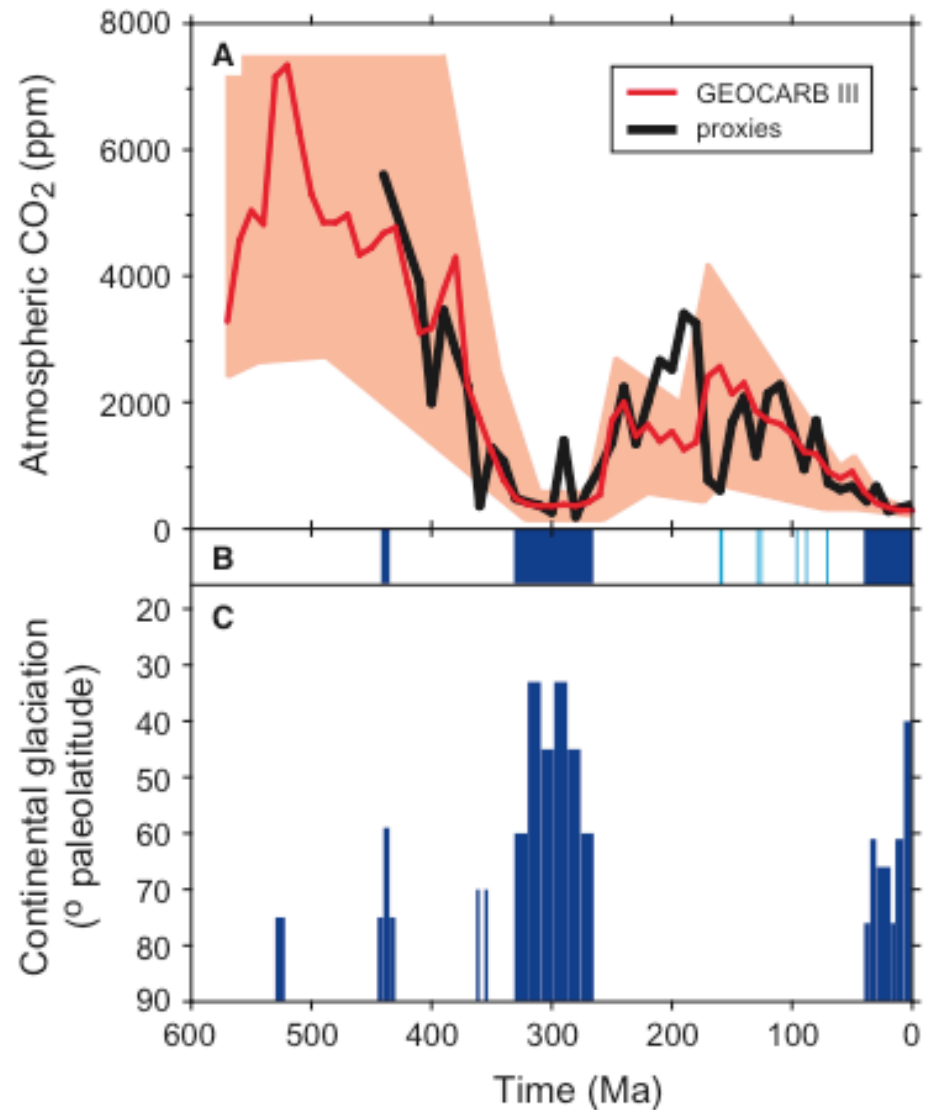
# Reconstructions of fluxes



# CO<sub>2</sub> levels over time

CO<sub>2</sub> levels have been much higher at times in the past... and climate was warmer

Royer, GSA Today



**Figure 2.** CO<sub>2</sub> and climate. **A:** Comparison of model predictions (GEOCARB III; Berner and Kothavala, 2001) and proxy reconstructions of CO<sub>2</sub>. 10 m.y. time-steps are used in both curves. Shaded area represents range of error for model predictions. **B:** Intervals of glacial (dark blue) or cool climates (light blue; see text). **C:** Latitudinal distribution of direct glacial evidence (tillites, striated bedrock, etc.) throughout the Phanerozoic (Crowley, 1998).

# CO<sub>2</sub> levels over time

CO<sub>2</sub> levels over the past 80 million years

Royer 2006

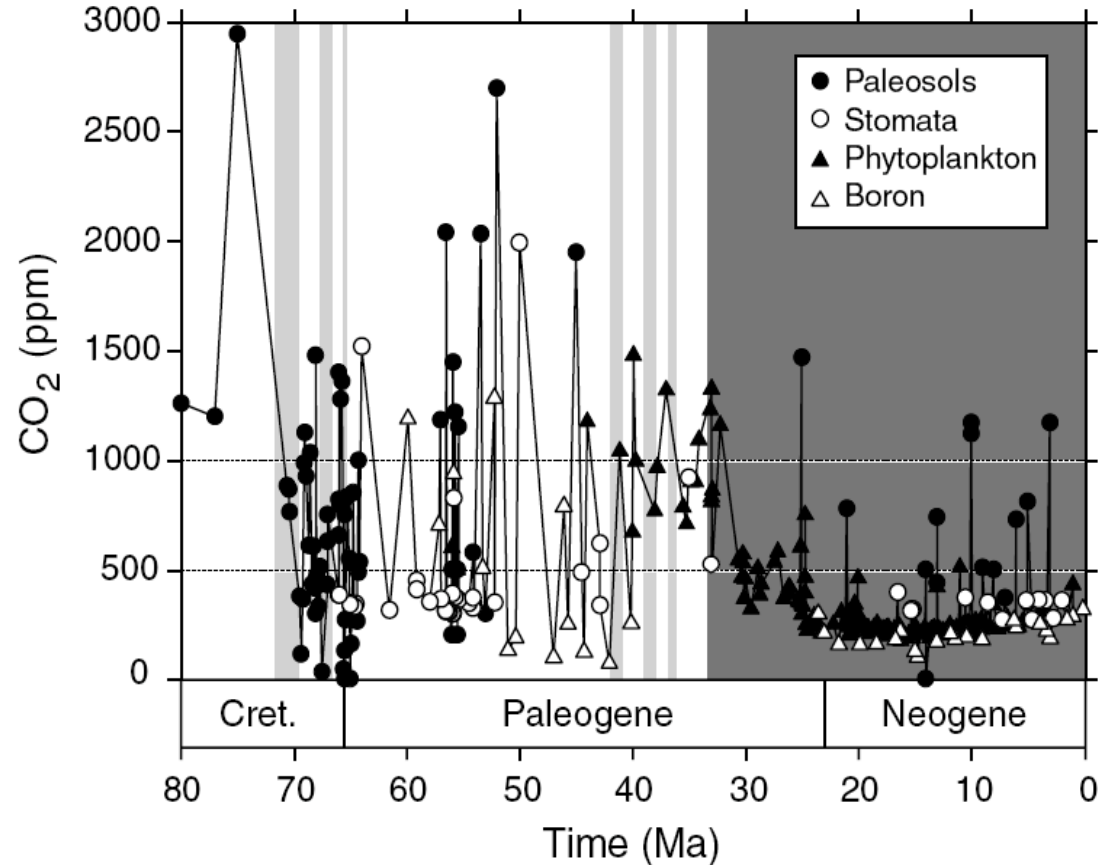
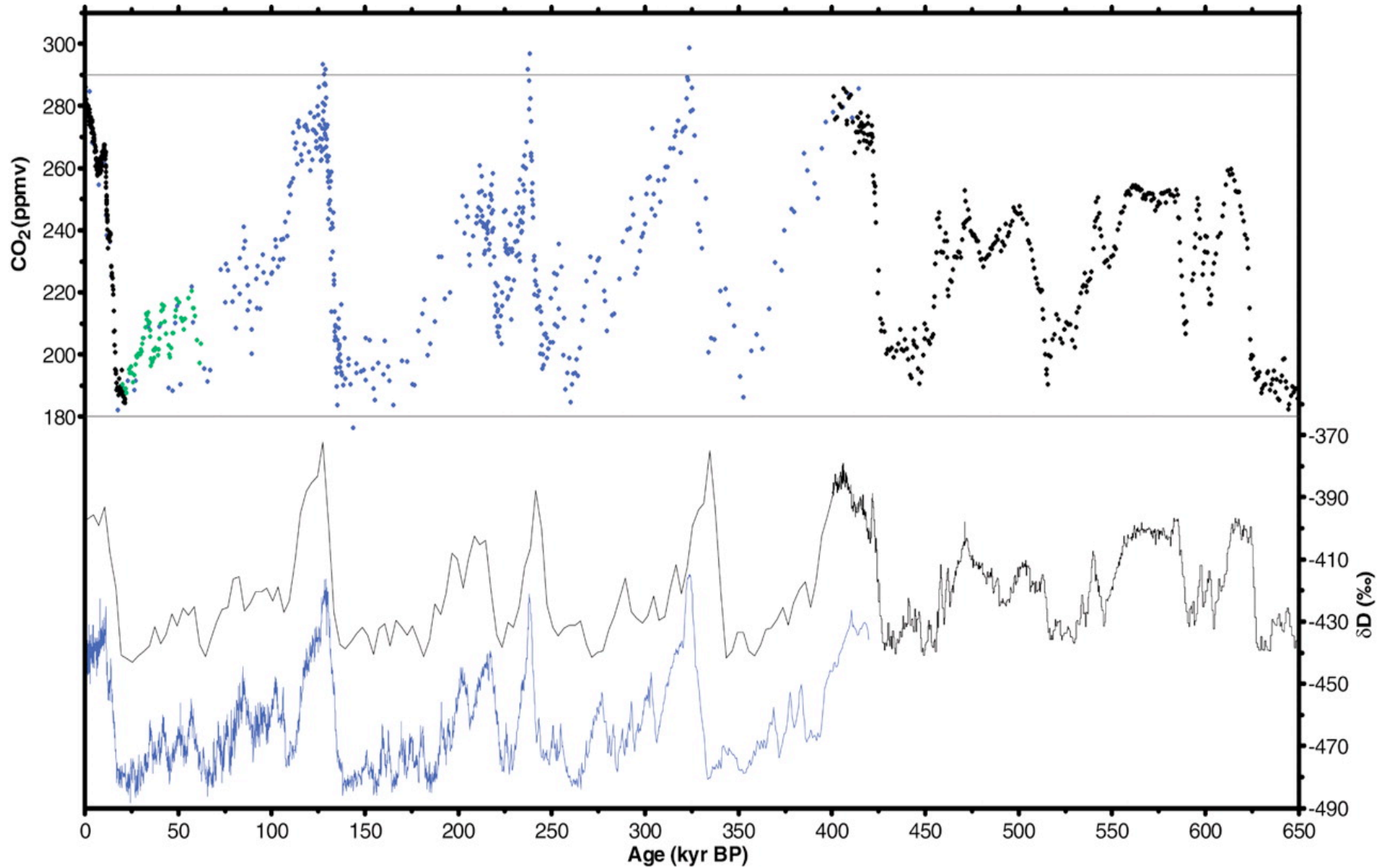
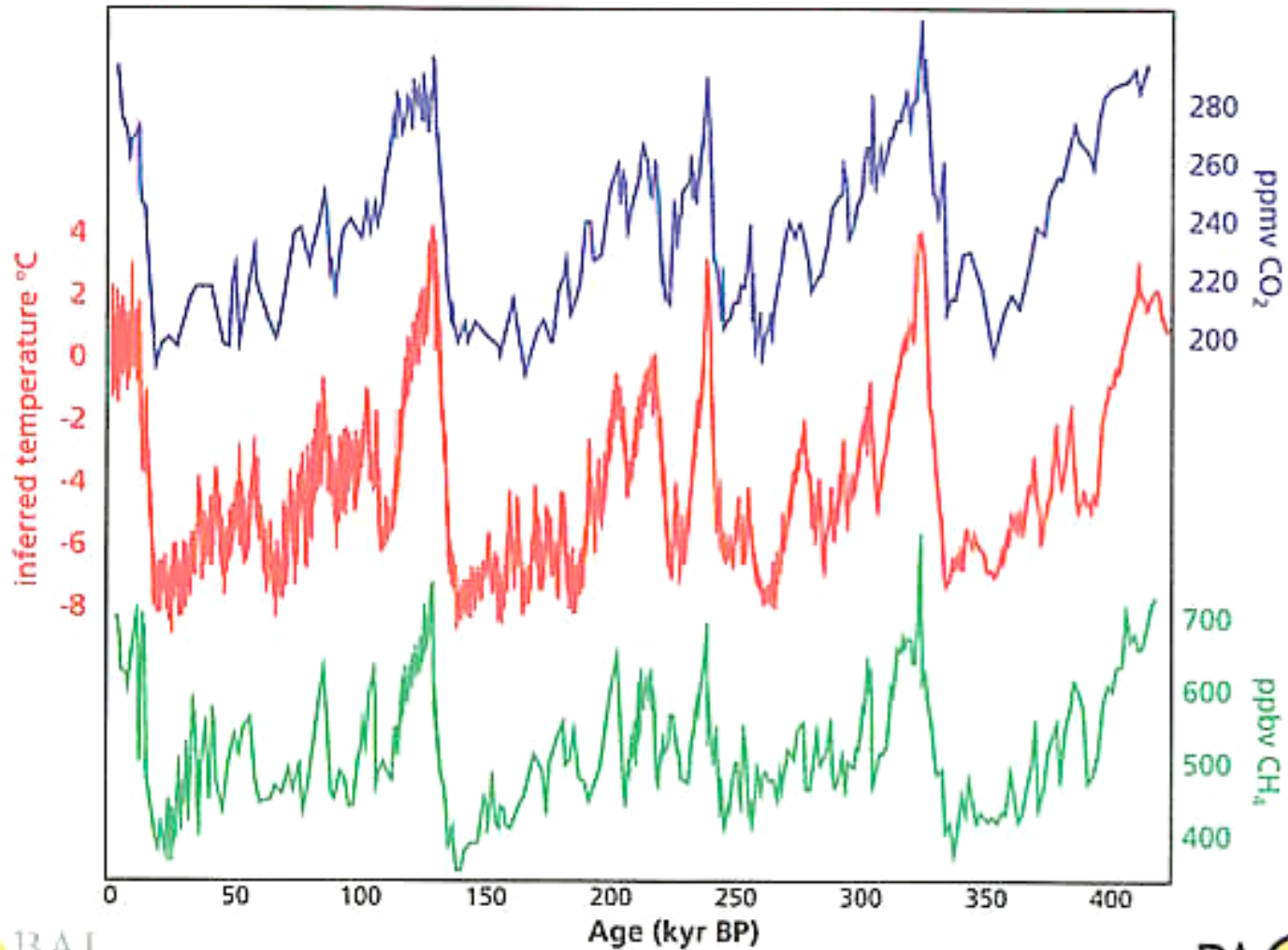


Fig. 4. CO<sub>2</sub> and temperature records for the late Cretaceous to present day (80–0 Ma). The CO<sub>2</sub> record is derived from Fig. 1B. Cold periods with strong evidence for geographically widespread ice are marked with dark shaded bands. Cool-to-cold periods with indirect or equivocal evidence for ice (see Section 2 for details) are marked with light shaded bands; such periods supported by only weak evidence are annotated with a question mark. The horizontal dashed lines at 1000 and 500 ppm CO<sub>2</sub> represent the proposed CO<sub>2</sub> thresholds for, respectively, the initiation of globally cool events and full glacials.

# Last 650,000 years: EPICA ice core



## 4 glacial cycles recorded in the Vostok ice core



GLOBAL  
T-G-B-P  
CHANGE

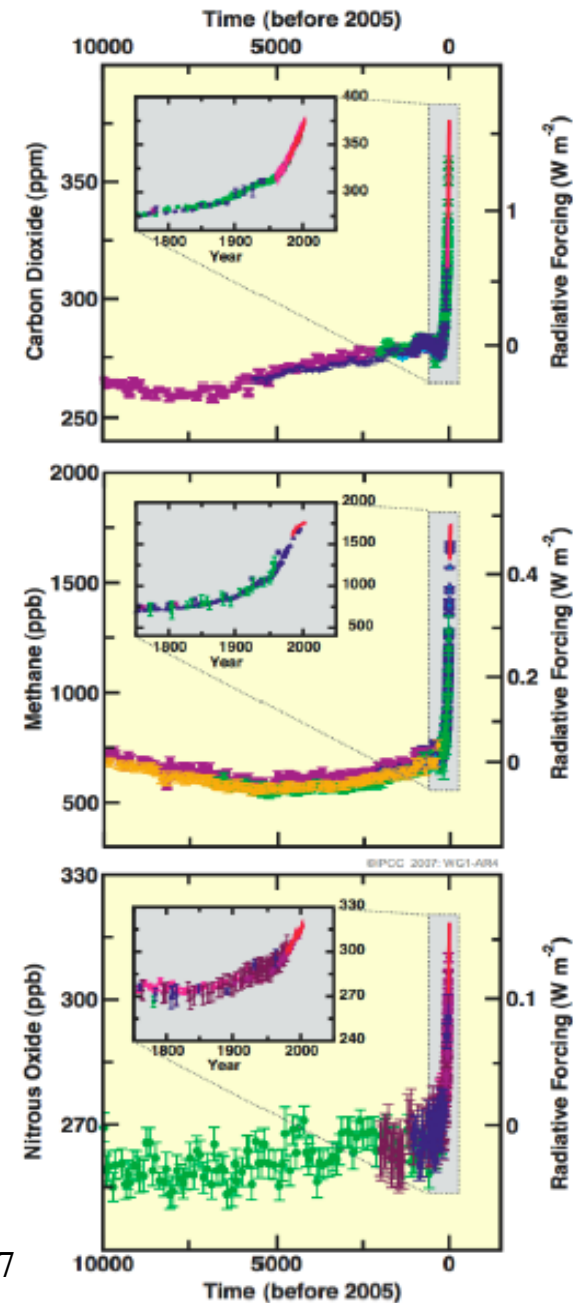
J.R. Petit et al., *Nature*, 399, 429–36, 1999.

PAGES  
PAST GLOBAL CHANGES

# Last 10,000 years

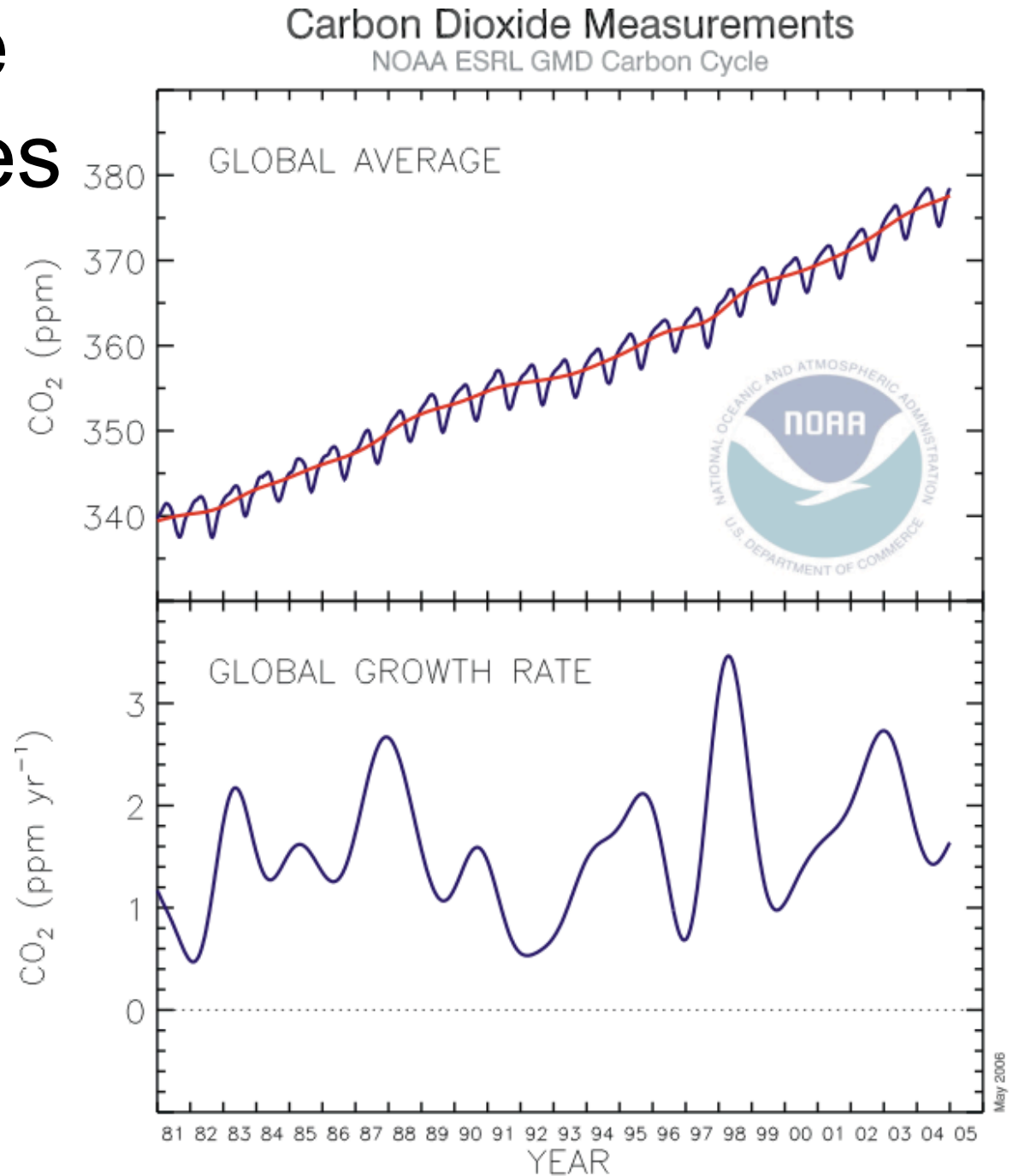
- Period of stable, “warm”, climate
- Some increase in last 5,000 years...
- **big increase in last 150 years**

Changes in Greenhouse Gases from ice-Core and Modern Data



# Greenhouse gas milestones

- Preindustrial level: **280 ppm**
- Full glacial level: **180 ppm**
- Today in 2006... **378 ppm... its almost party time!**



# Lessons

- The carbon cycle distributes carbon between the land, ocean and atmosphere
- CO<sub>2</sub> levels have been much higher than today in the far distant past
- CO<sub>2</sub> levels are much higher now than in the last 1,000,000 years