



A  
“Toy”  
Model  
of the  
Earth  
System

EARTH  
[carbon]

*Intended for education, explanation, experimentation,  
exploration, and even entertainment!*

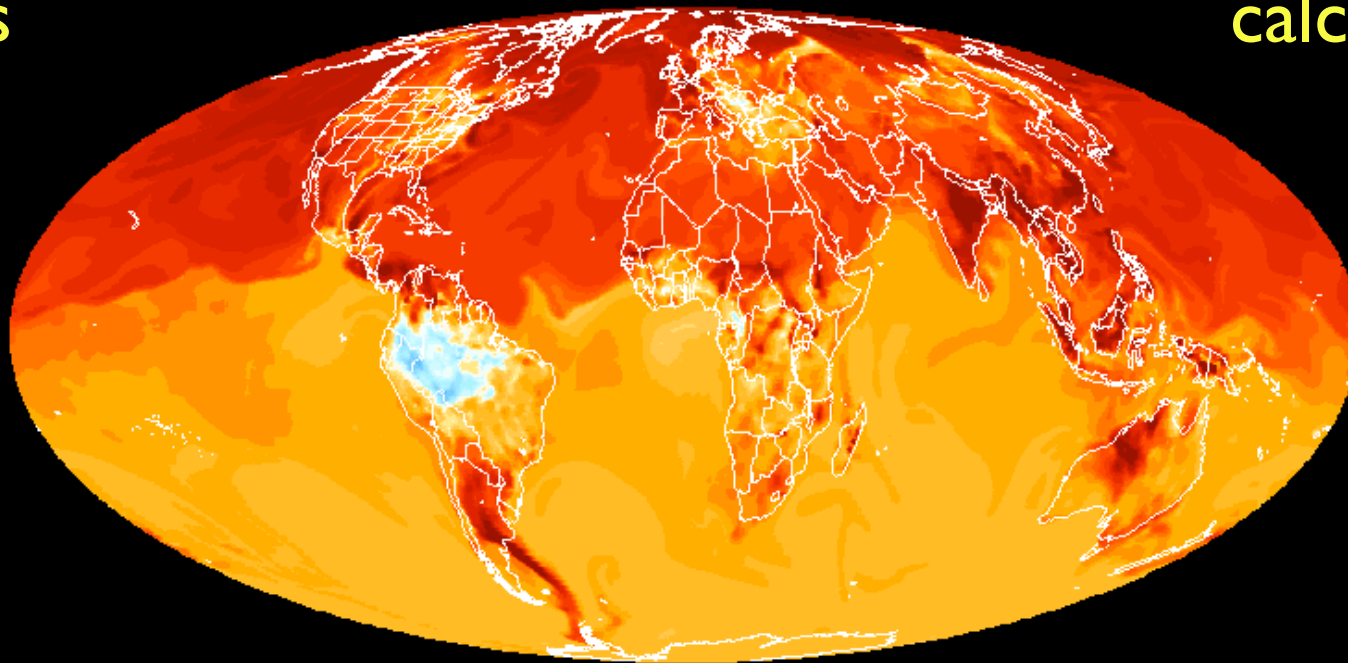
# The Breathing of the Earth

3-Hourly [CO<sub>2</sub>] 500m AGL

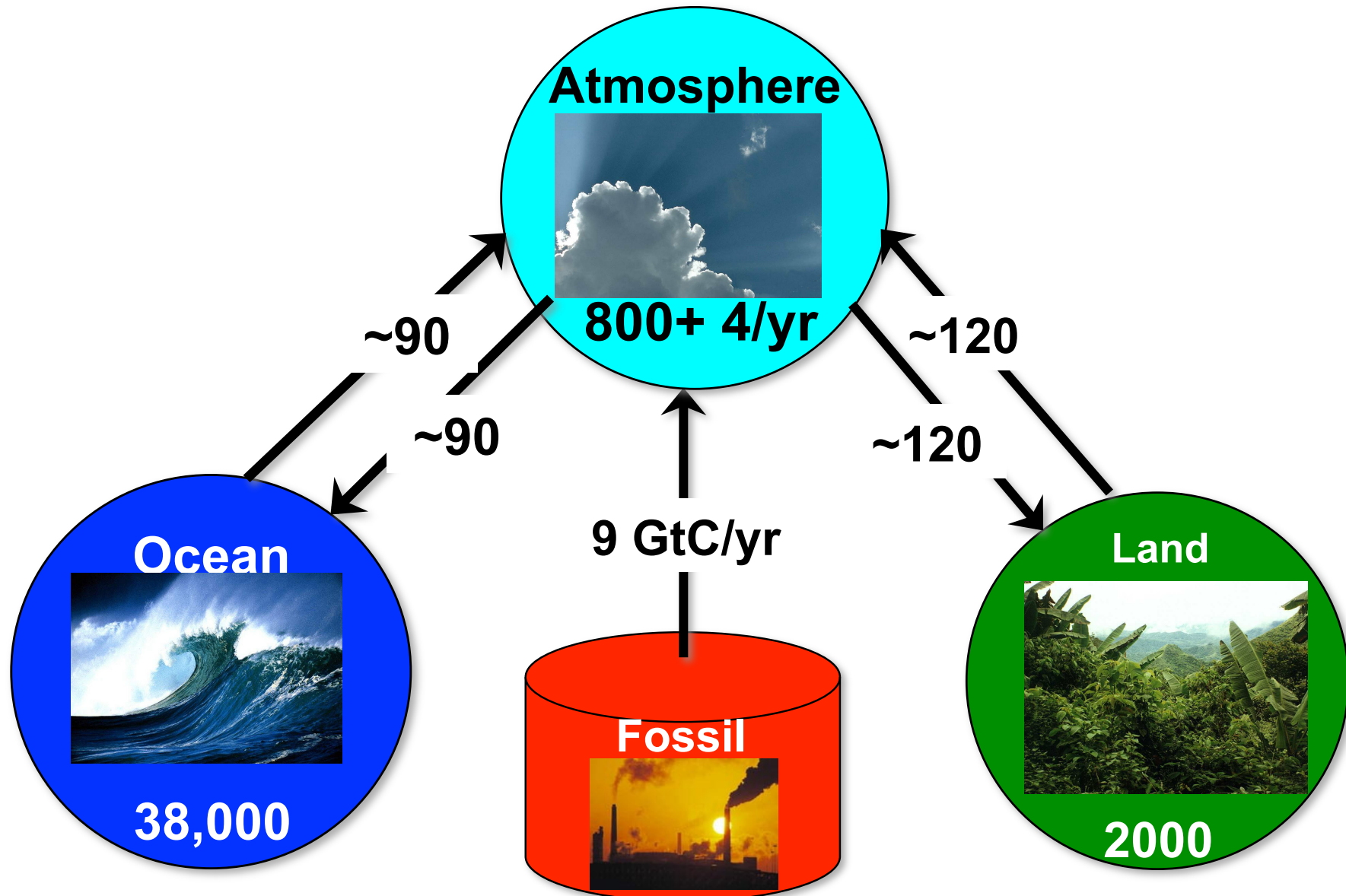
Month=Jun, Day=1, Year=2004

10 million  
boxes

lots of  
calculations



# Boxes of Carbon





# The Oceans

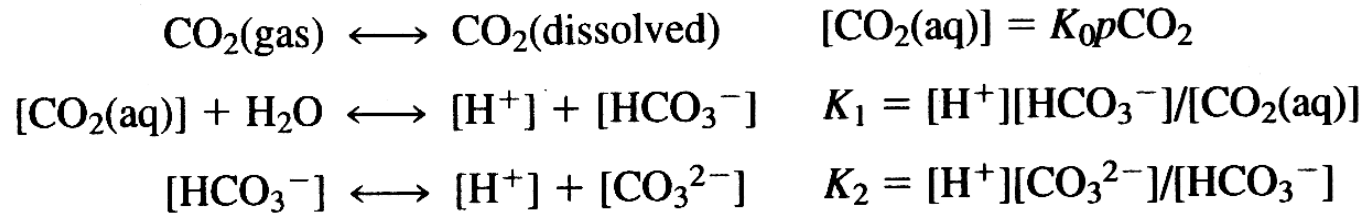


# Planetary Titration

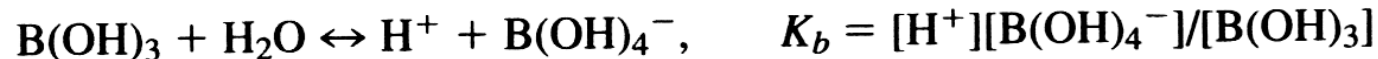
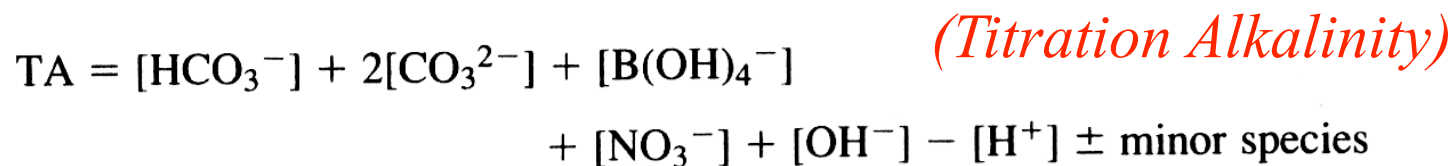


# Carbonate Equilibria in Ocean Water

Three equations (equilibria) in five unknowns



Add two more constraints

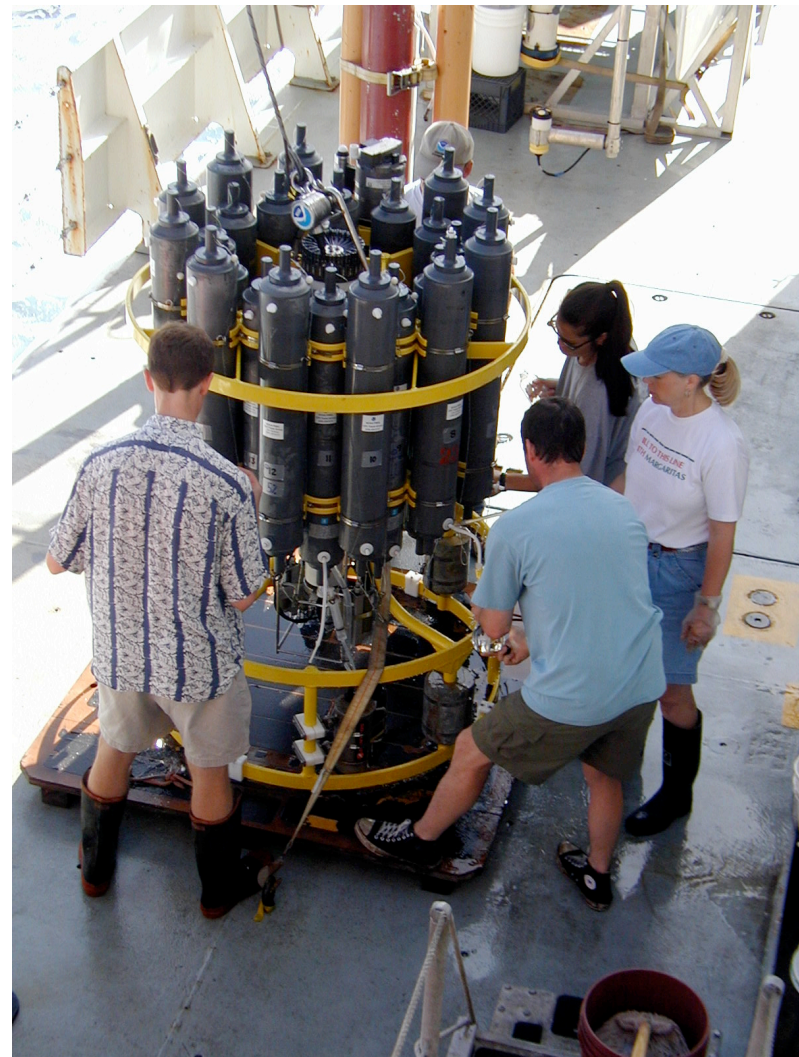
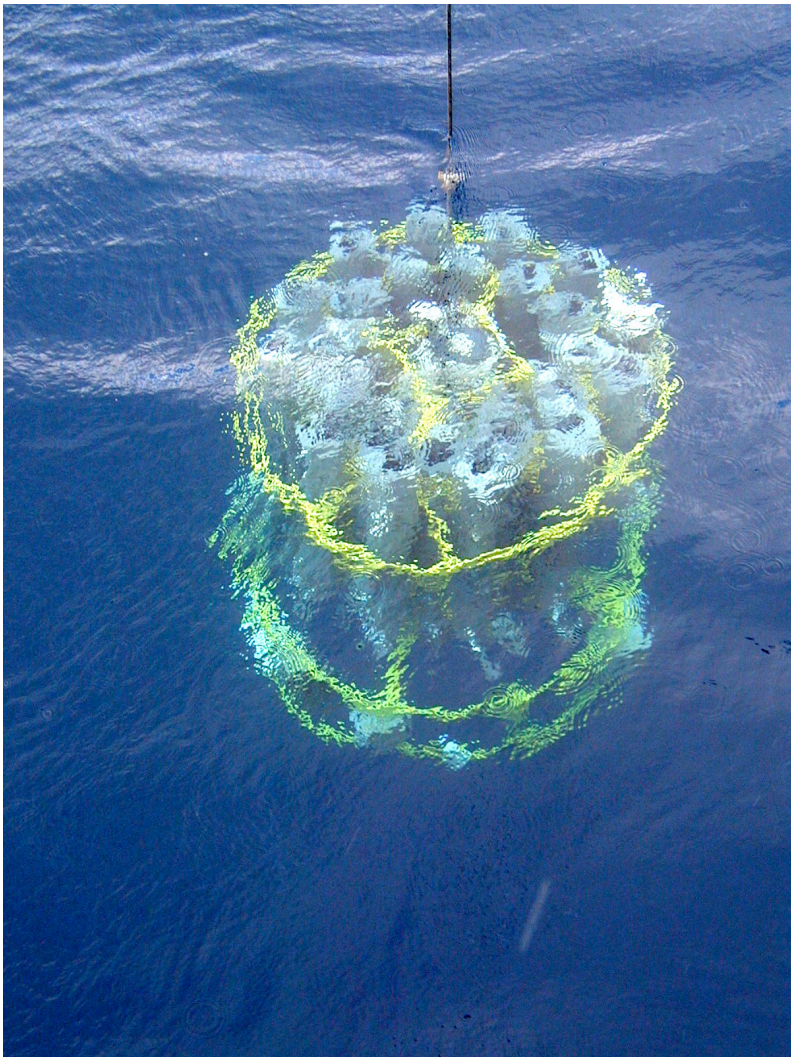


*(Boric acid dissociation)*

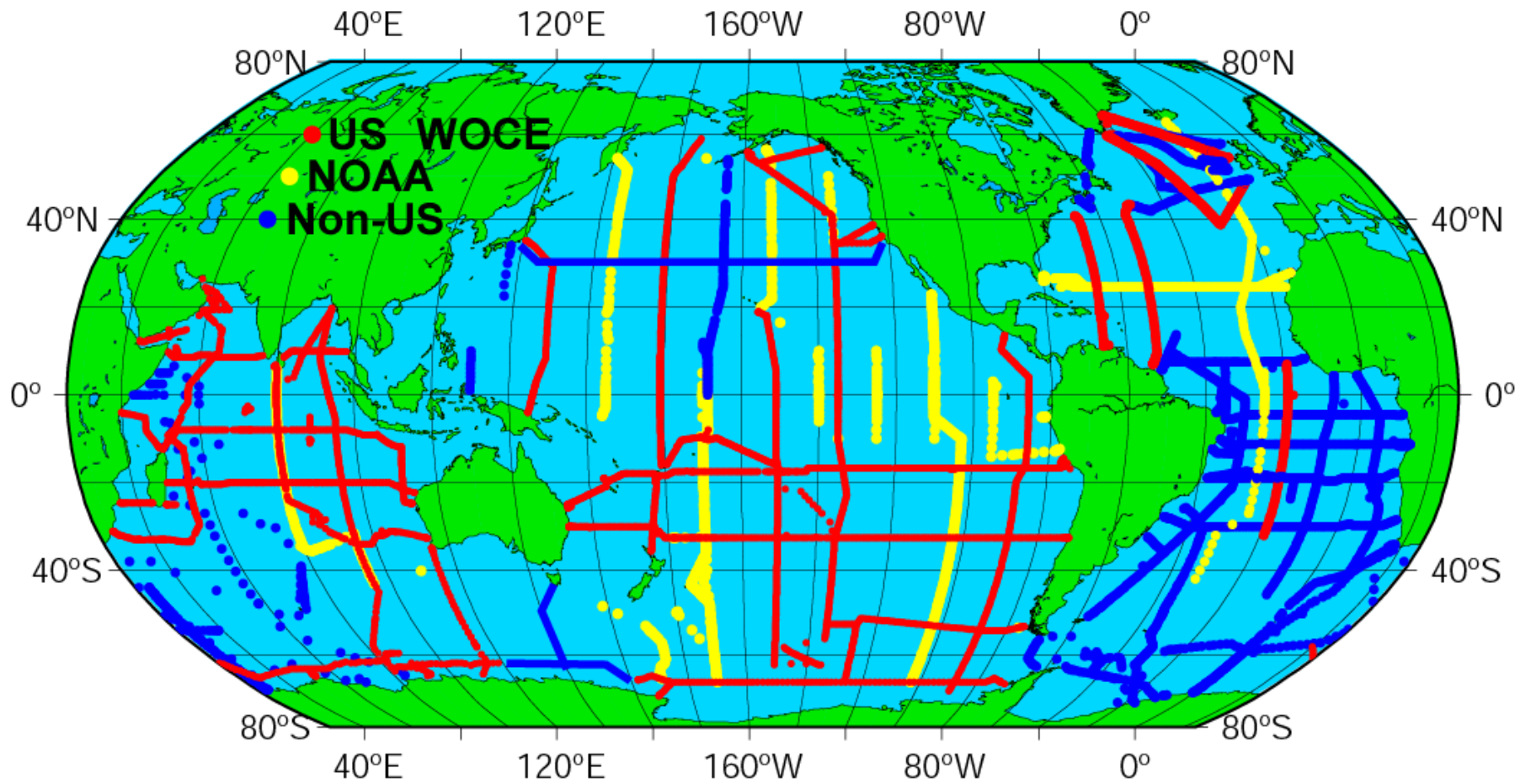
$$\Sigma B = 1.179 \times 10^{-5} S \text{ mol/kg}$$

*(Salinity)*

# Observing The Ocean Interior

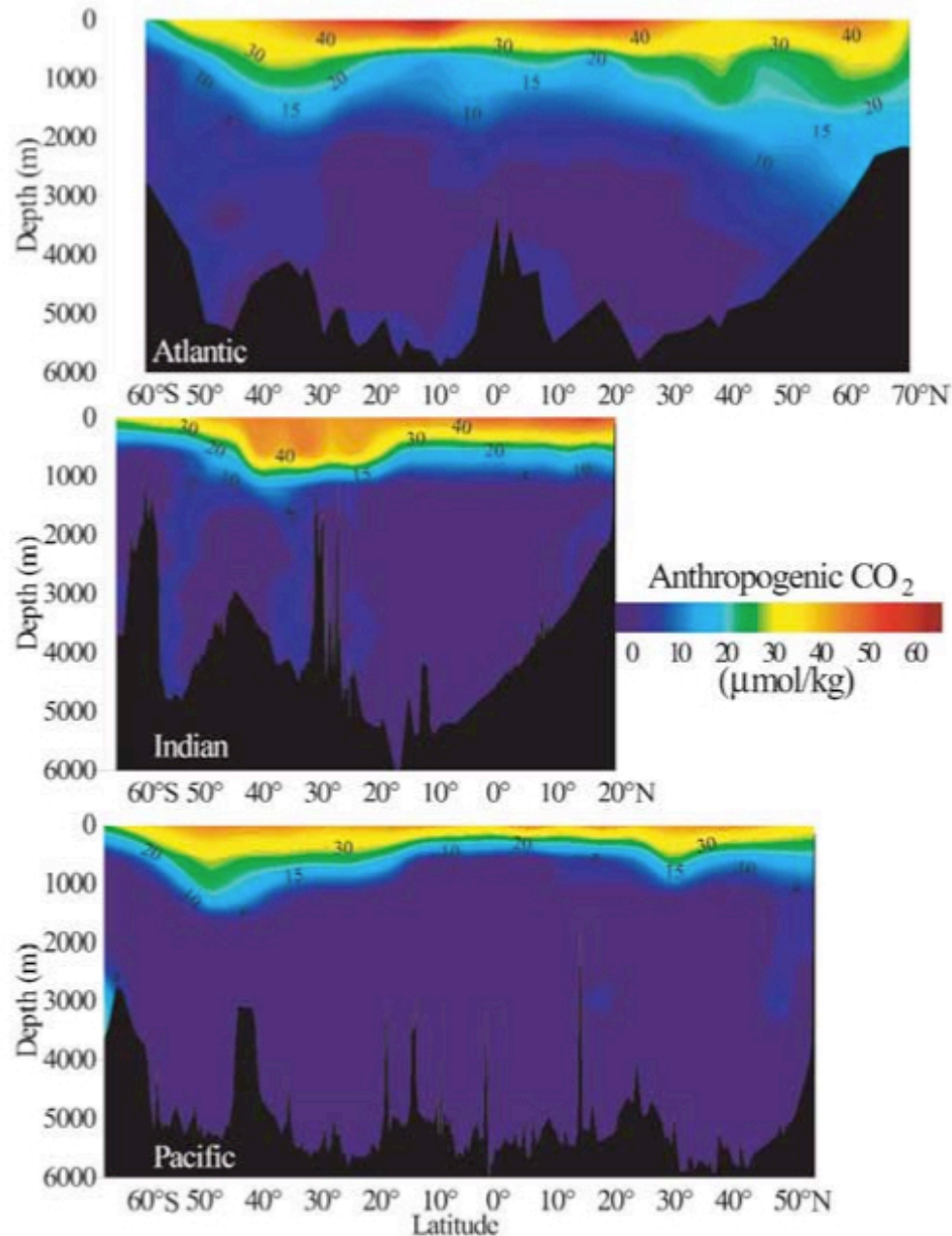


# WOCE/JGOFS/OACES Global Survey Data





# Anthropogenic Carbon in the Oceans

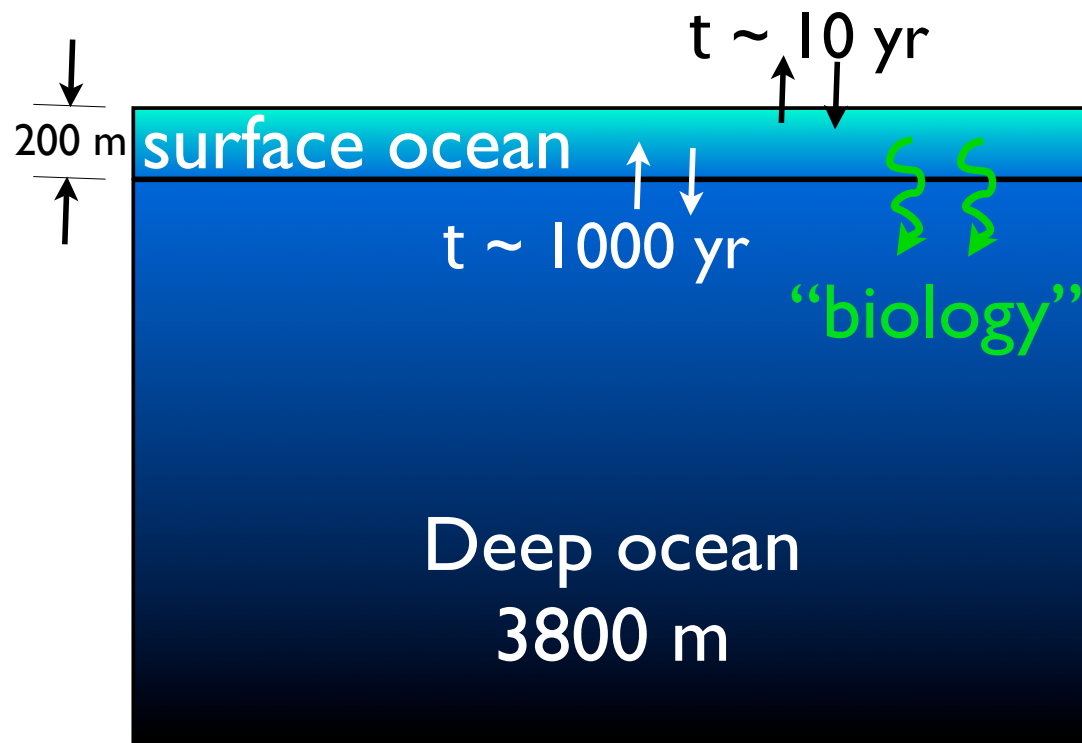


- Estimated from total observed DIC using stoichiometry
- Most anthropogenic DIC confined to top few 100 m
- “Shoaling” in tropics, convection at higher latitudes
- Some “contamination” of bottom water in Atlantic (both hemispheres)

Figure 8. Zonal mean distributions of estimated anthropogenic CO<sub>2</sub> concentrations (in units of  $\mu\text{mol kg}^{-3}$ ) along north-south transects in the Atlantic, Indian and Pacific oceans. The Pacific and Indian Ocean data are from the Global CO<sub>2</sub> Survey (this study), and the Atlantic Ocean data are from Gruber (1998).

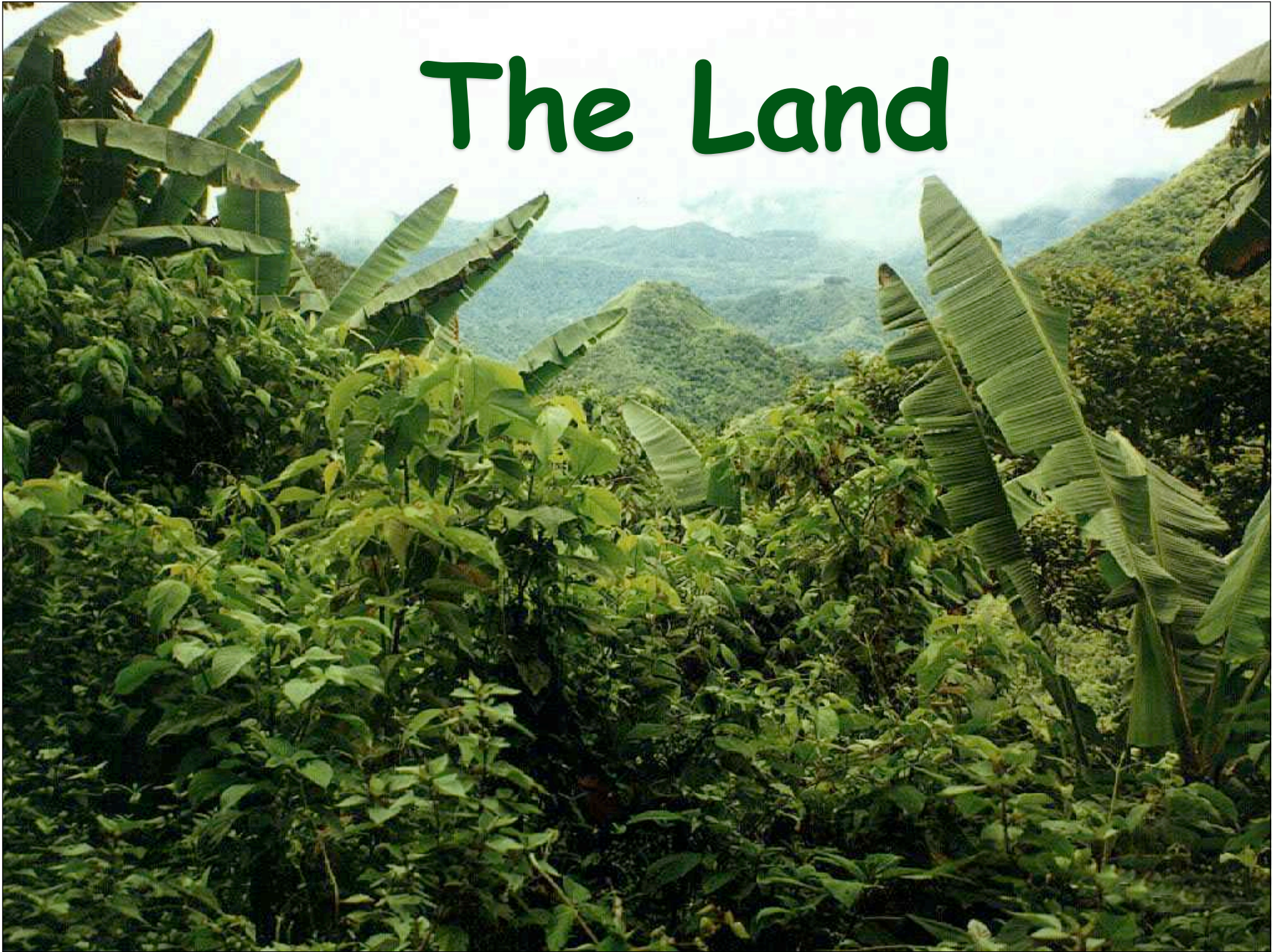
(Sabine et al, 2004)

# Ocean Box Model

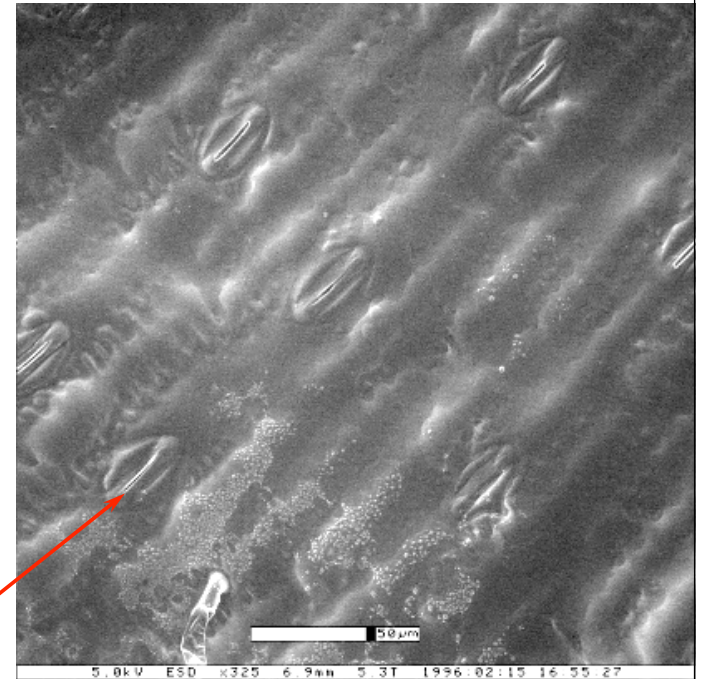
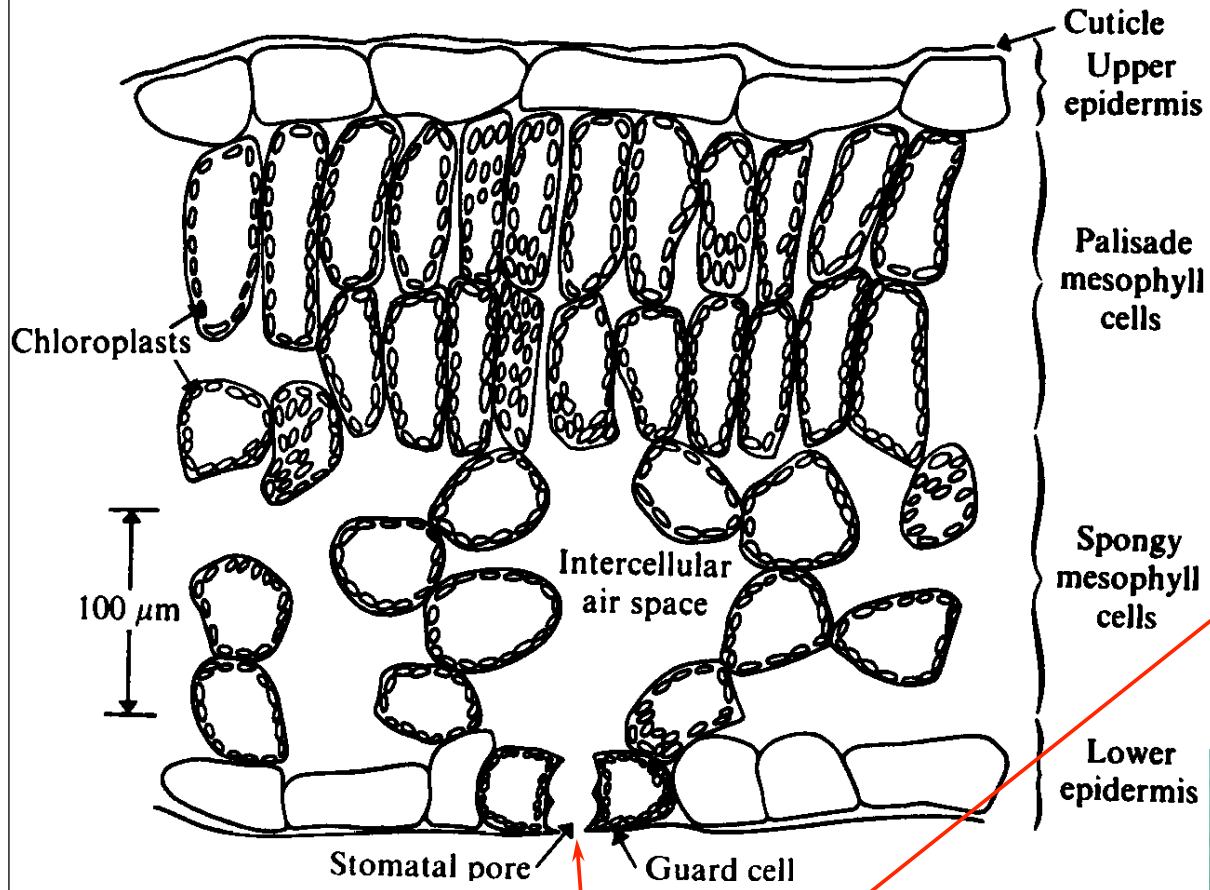


- Two reservoirs
- $p\text{CO}_2$ ,  $\text{HCO}_3^-$ ,  $\text{CO}_3^{2-}$ , pH, DIC from chemistry
- Temperature & salinity dependent equilibria
- Simple (adjustable) mixing between reservoirs
- Time invariant "biology"

# The Land



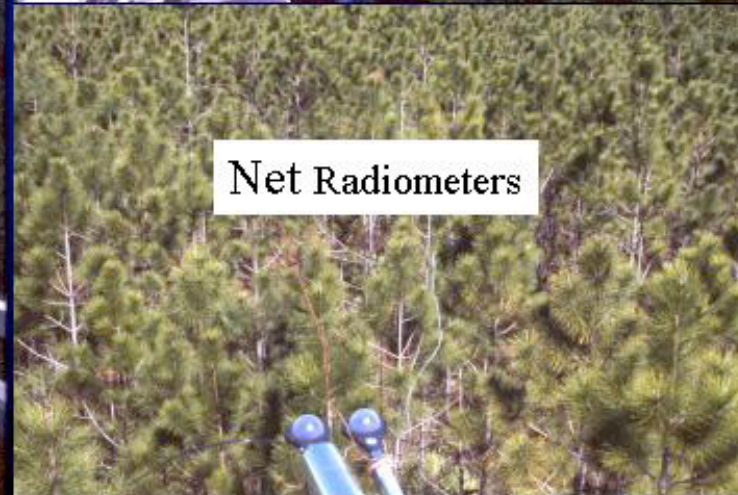
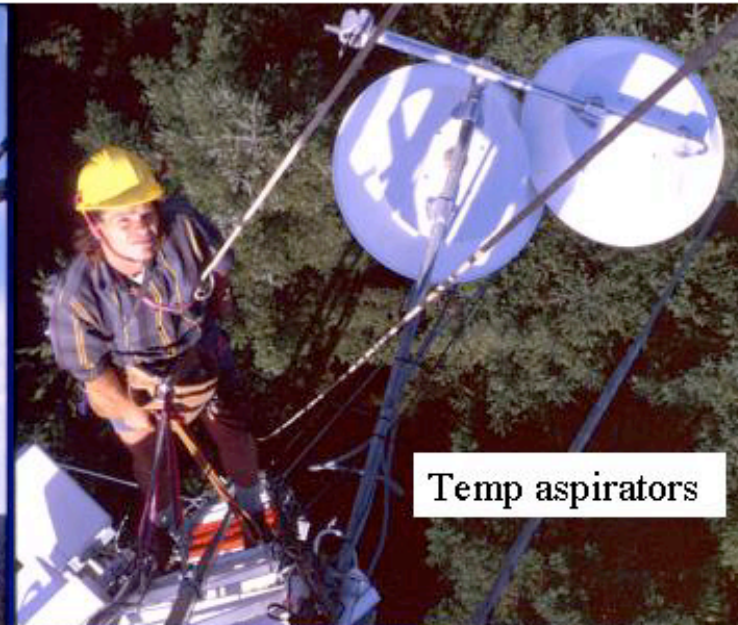
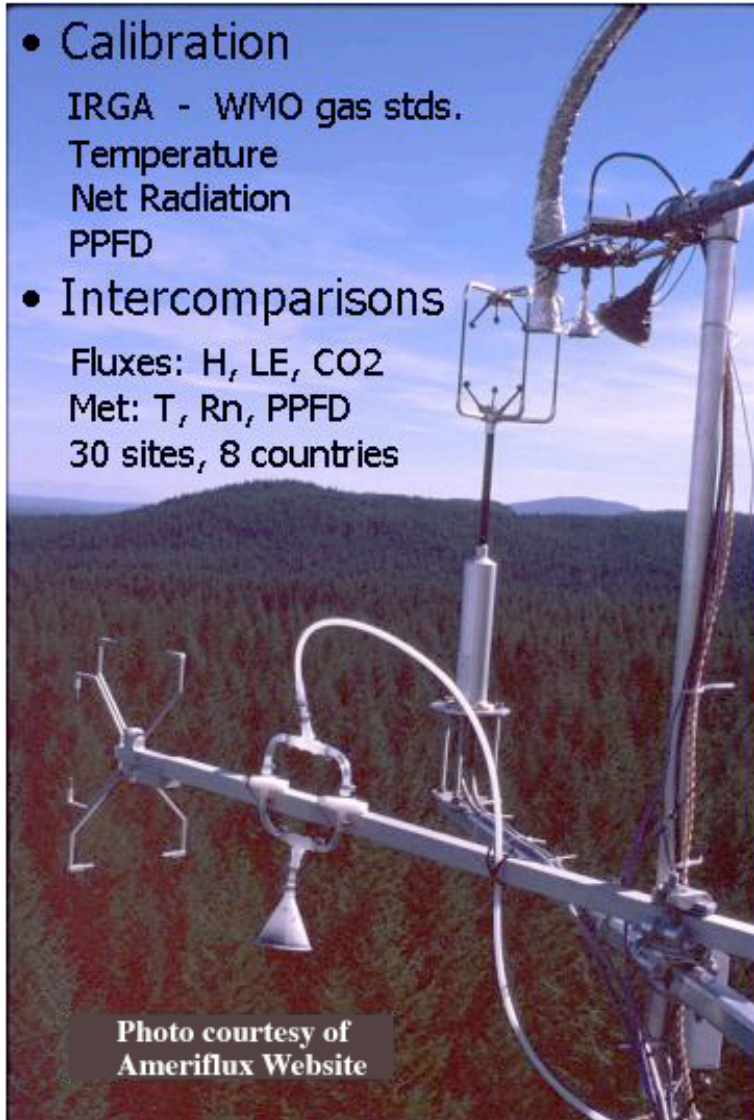
# Leaf Anatomy



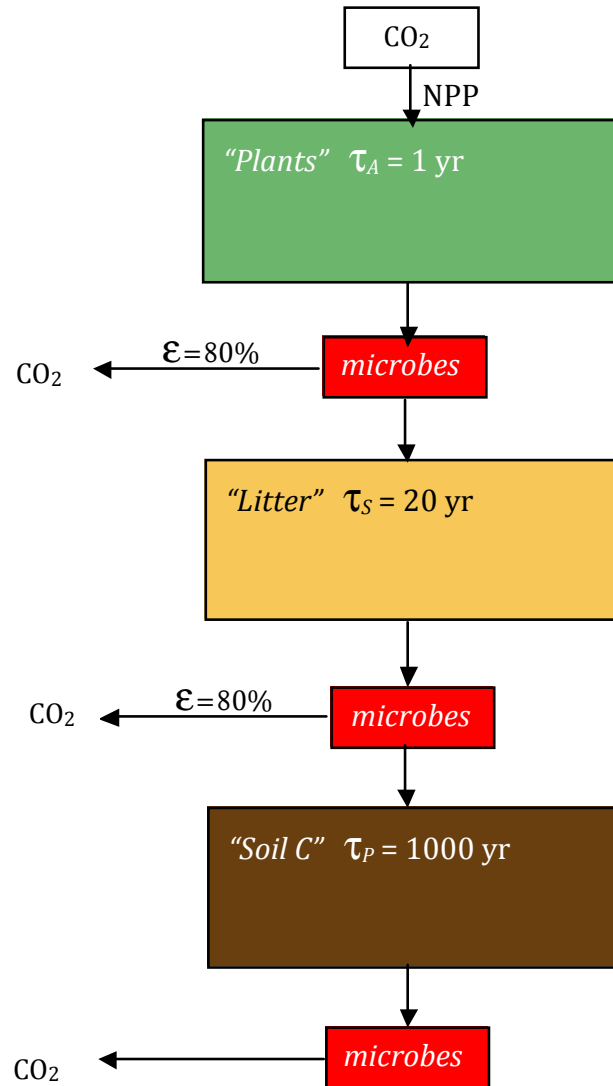
**Stomate**  
(pl. stomata)

# Eddy Covariance

- Calibration
  - IRGA - WMO gas stds.
  - Temperature
  - Net Radiation
  - PPFD
- Intercomparisons
  - Fluxes: H, LE, CO<sub>2</sub>
  - Met: T, Rn, PPFD
  - 30 sites, 8 countries



# Land Box Model



- Three boxes
- Plants convert CO<sub>2</sub> to organic matter
- Microbes convert organic matter to slower and slower stuff
- Adjustable CO<sub>2</sub> fertilization
- Temperature dependent decomposition

# The Atmosphere

A “mixing reservoir”  
for CO<sub>2</sub>

Adjustable climate  
sensitivity  $dT/d[CO_2]$

Adjustable time scale  
(~ “heat capacity”)

# Learning Objectives

- Comprehensible and **predictable**
- Observations limit choice of **parameters**
- Future climate determined by CO<sub>2</sub> (**integral**) rather than emissions (**derivative**)
- Very **long time scale** response!
- Modeling can be **fun!**



# Experiments

- **Calibration** (predict the past)
  - Prescribe initial CO<sub>2</sub> and emissions(t)
  - Adjust land-use to get CO<sub>2</sub> history (compared to firn and flasks)
  - Adjust climate sensitivity & heat capacity (compare to proxy & GISStemp)
- **21<sup>st</sup> Century** (AR4 Scenarios)
- The **“long tail”** (*uh oh!*)