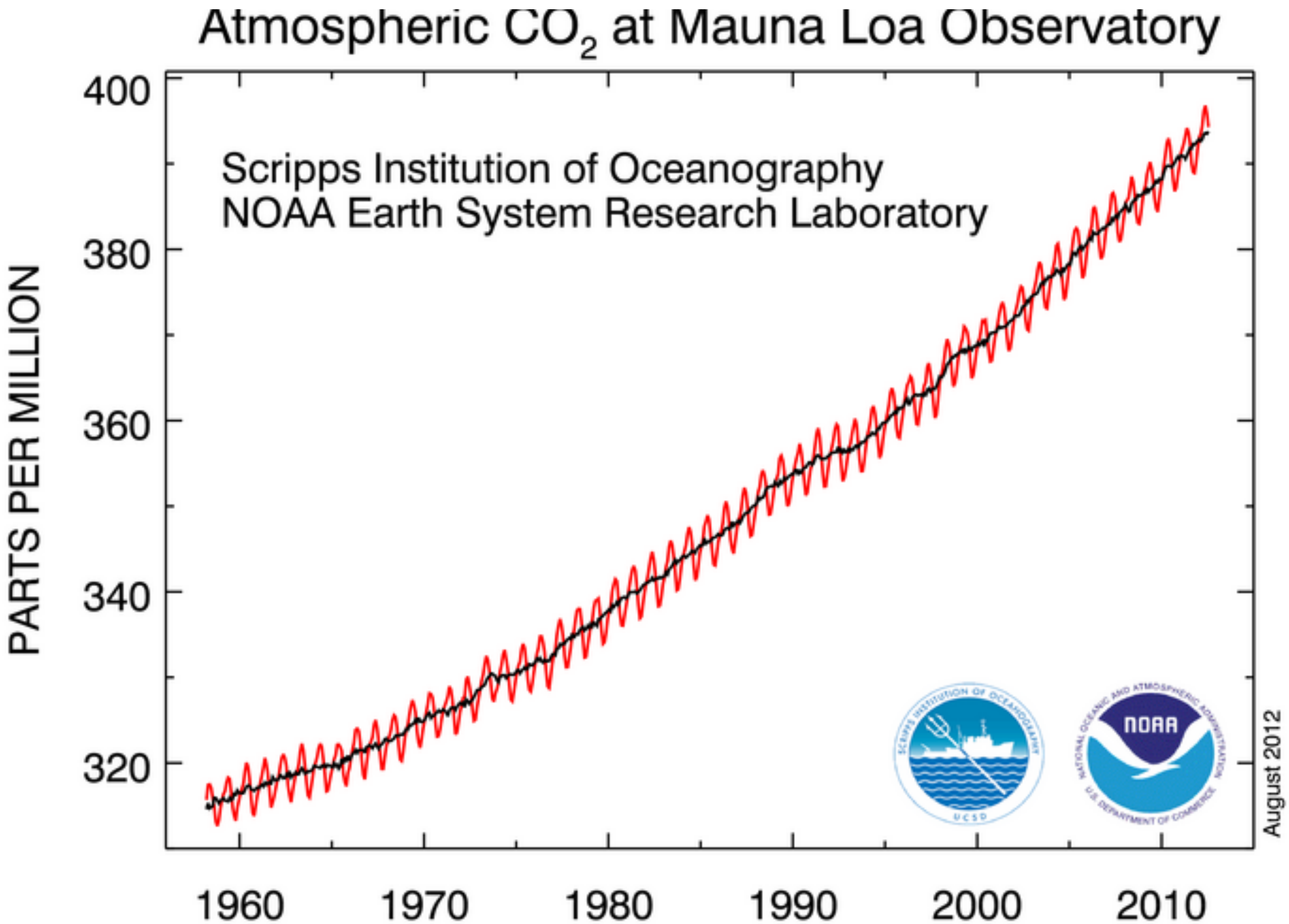
The Global Carbon Cycle

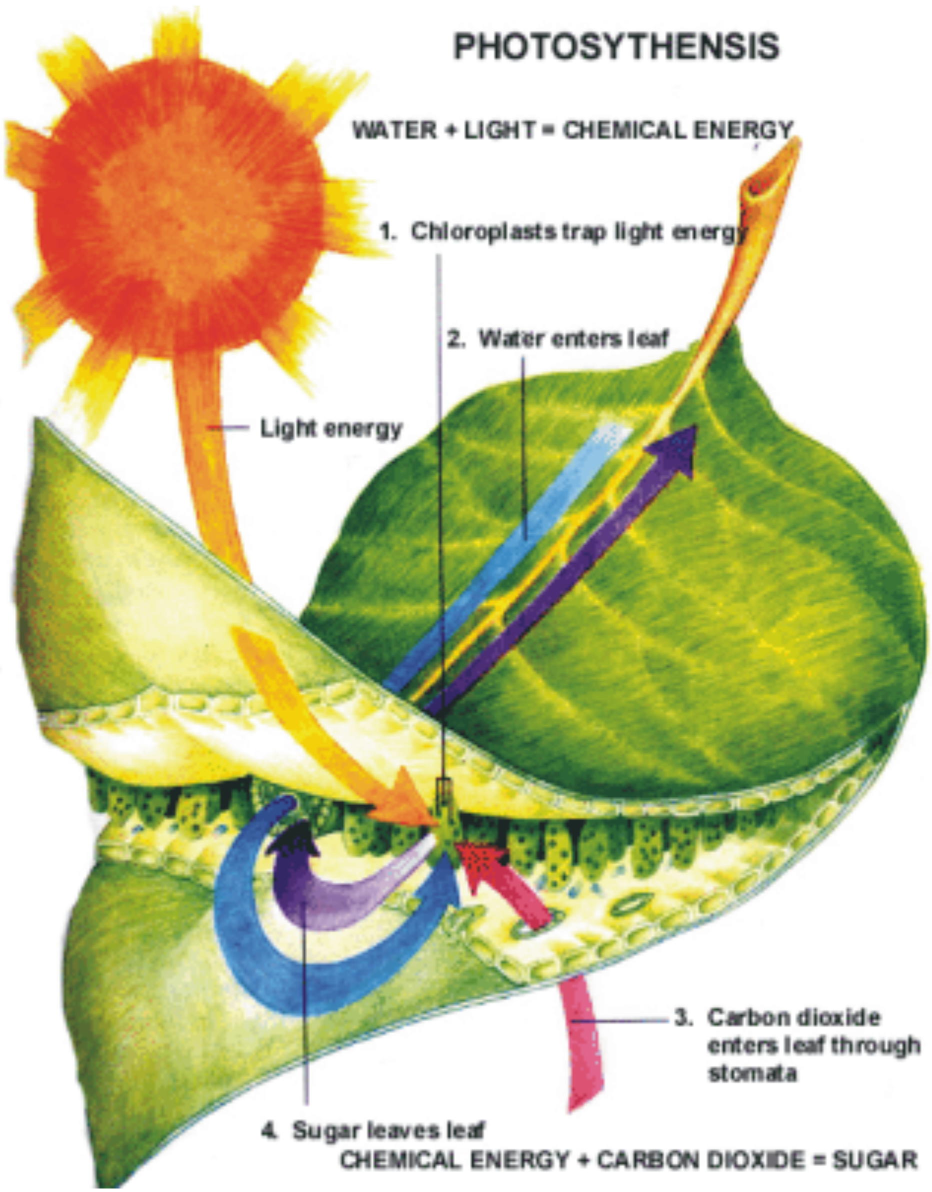
Atmospheric CO_2 levels



In a nutshell

- We are mining fossil CO_2 and titrating into the oceans, (buffered by acid-base chemistry)
- Much of the fossil CO_2 will remain in the atmosphere for 10's of thousands of years
- About half of fossil-fuel CO_2 is absorbed by poorly-quantified "sink" processes
- The strength and even the sign of potential carbon-climate feedback is among the most uncertain aspects of climate change in the 21st century

Carbon, Life, and Energy

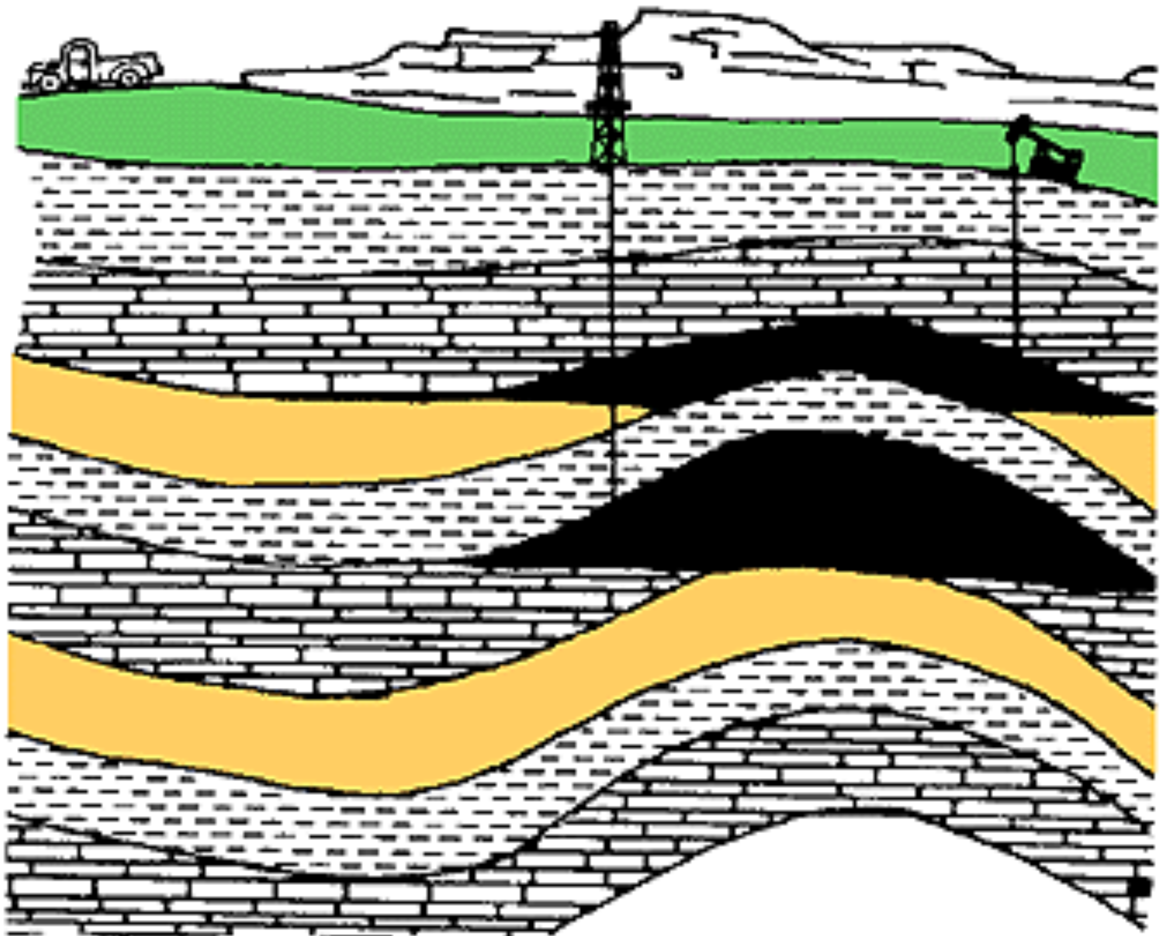


- Photosynthesis uses energy from the sun to **convert inorganic air (CO_2) to living biomass!**
- Most of this energy is released through respiration (back to CO_2) when plants are eaten by animals, bacteria, people

Breathing of the Earth

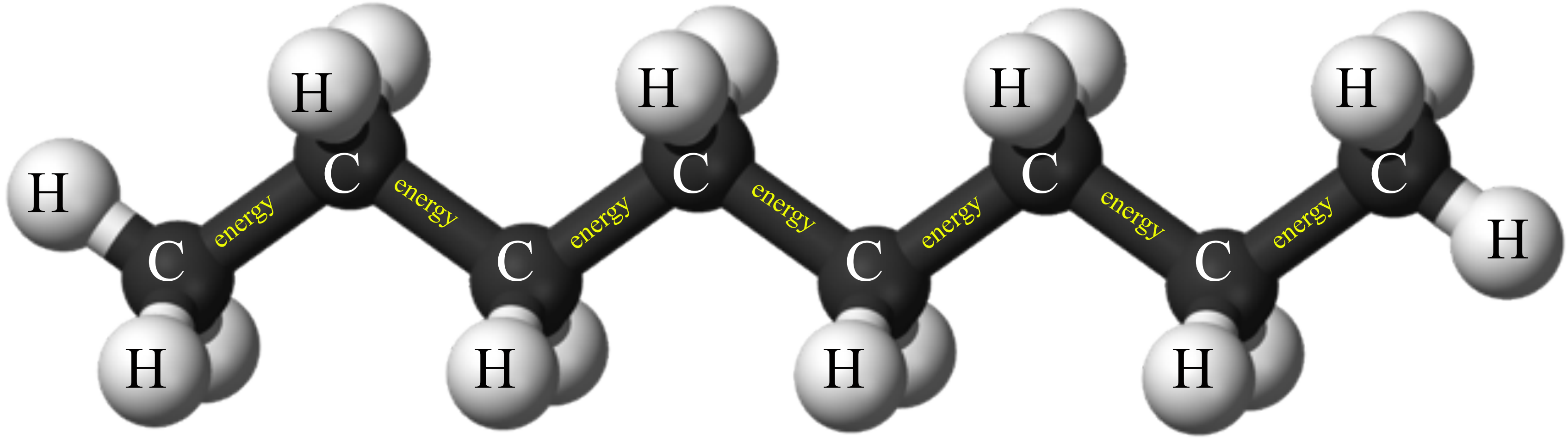
- Plants harvest solar energy to connect inorganic molecules of CO_2 into living organic biochemicals, like beads on a string
- Amazingly, about 1/7 of all the CO_2 molecules in the atmosphere are transformed into living biomass every year by photosynthesis!
- Nearly all of these molecules are replaced each year by respiration and decomposition of dead biomass
- A tiny residual accumulates over geologic time as coal, oil, and natural gas

Fossil Fuels

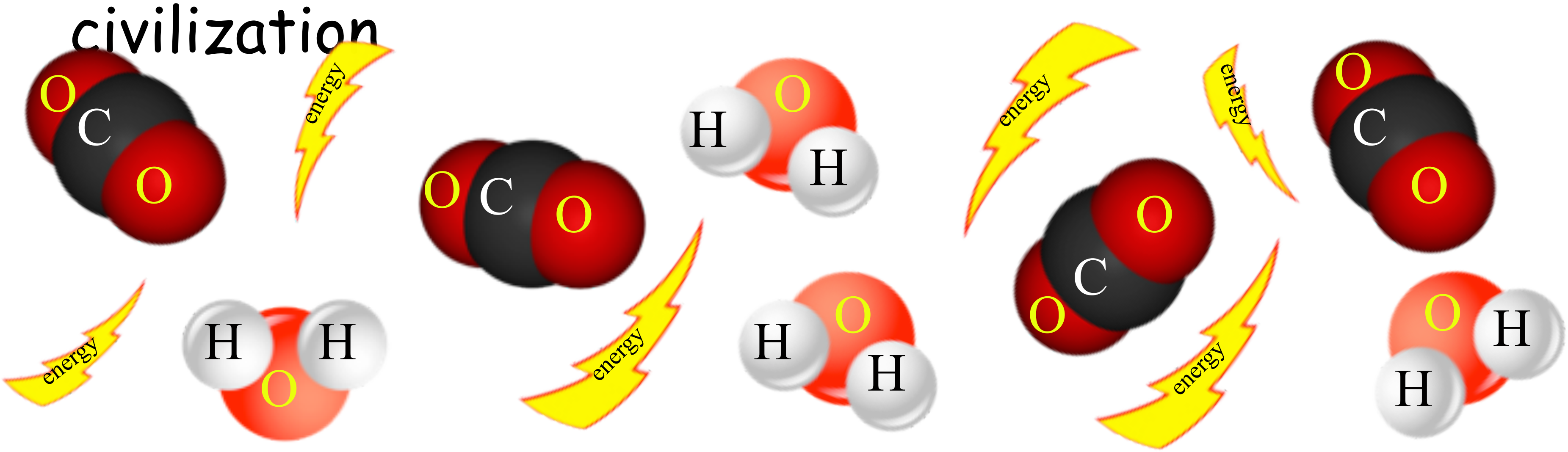


Some of the stored solar energy in biomass can be preserved in fossilized remains

Hydrocarbons, Energy, and CO_2

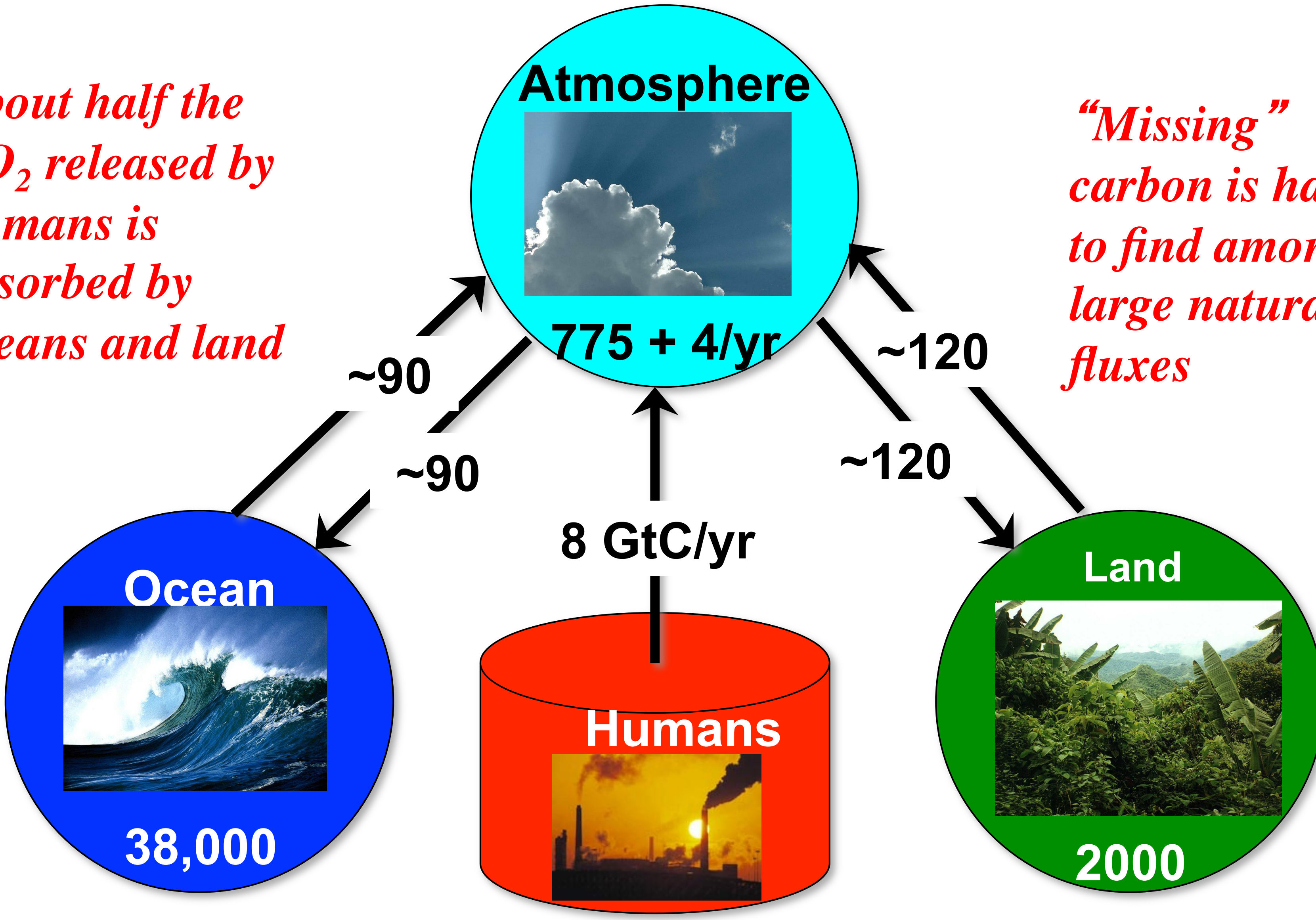


- We dig this stuff ("fossil fuels") up and **burn it**, **harvesting the stored energy** to power civilization



The Global Carbon Cycle

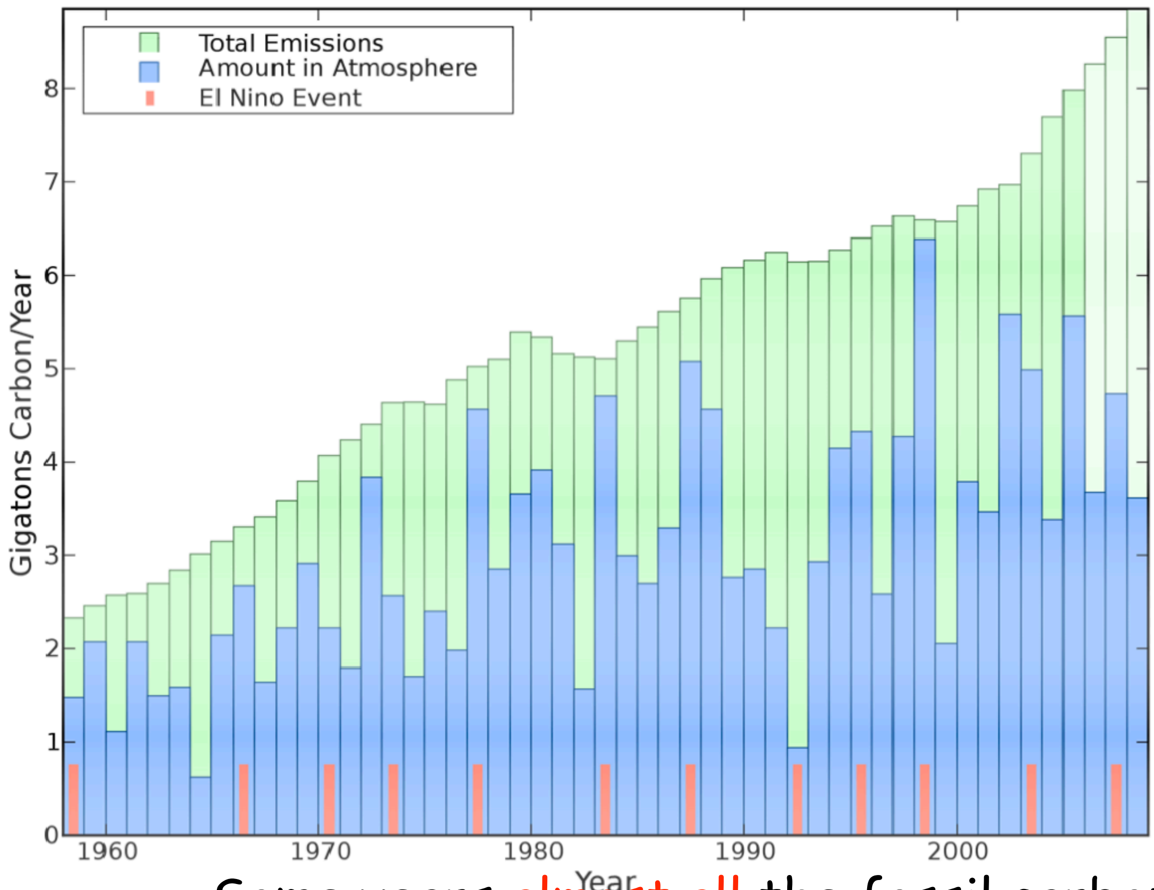
About half the CO_2 released by humans is absorbed by oceans and land

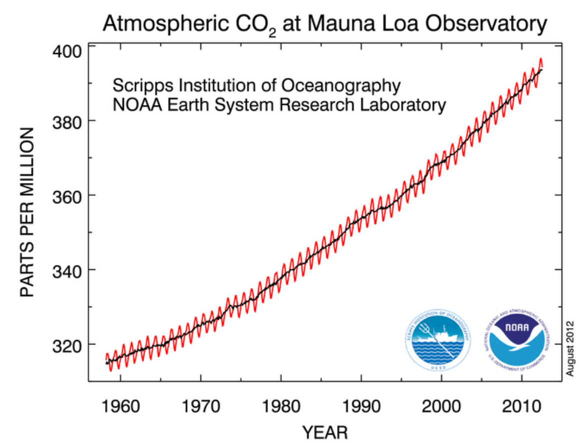


"Missing" carbon is hard to find among large natural fluxes

Sources and Sinks

Fossil Fuel Emissions of CO2 and Atmospheric Buildup, 1958-2008





Half the CO_2 "goes away!"

- Some years almost all the fossil carbon goes into the atmosphere, some years almost none
- Interannual variability in sink activity is much greater than in fossil fuel emissions
- Sink strength is related to El Niño. Why? How?

Where Has All the Carbon Gone?

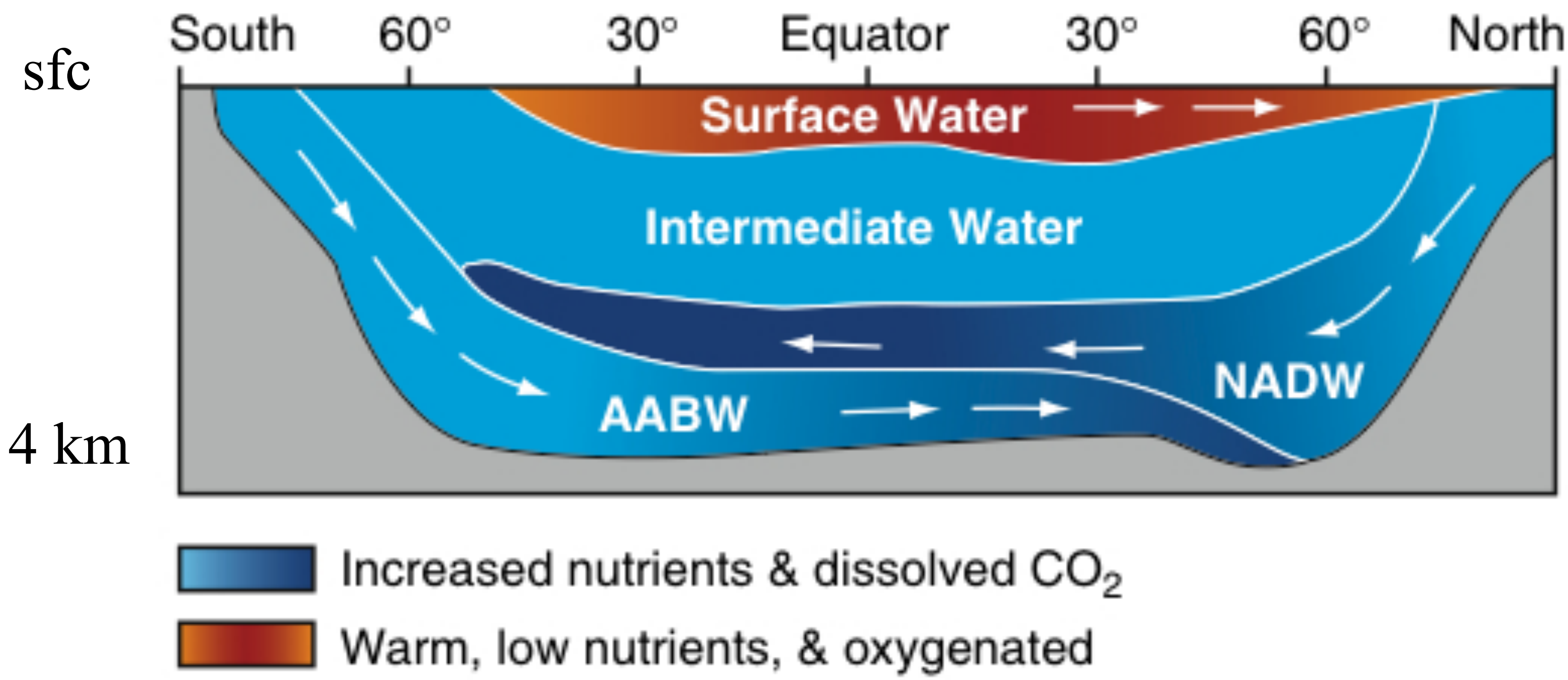
- Into the oceans
  - **Solubility pump** (CO_2 very soluble in cold water, but rates are limited by slow physical mixing)
  - **Biological pump** (slow "rain" of organic debris)

- Into the land
  - **CO_2 Fertilization**
    (plants eat CO2 … is more better?)
  - **Nutrient fertilization**
    (N-deposition and fertilizers)
  - **Land-use change**
    (forest regrowth, fire suppression, woody encroachment … but what about Wal-Marts?)
  - Response to **changing climate**
    (e.g., Boreal warming)


The
Oceans

Planetary Titration

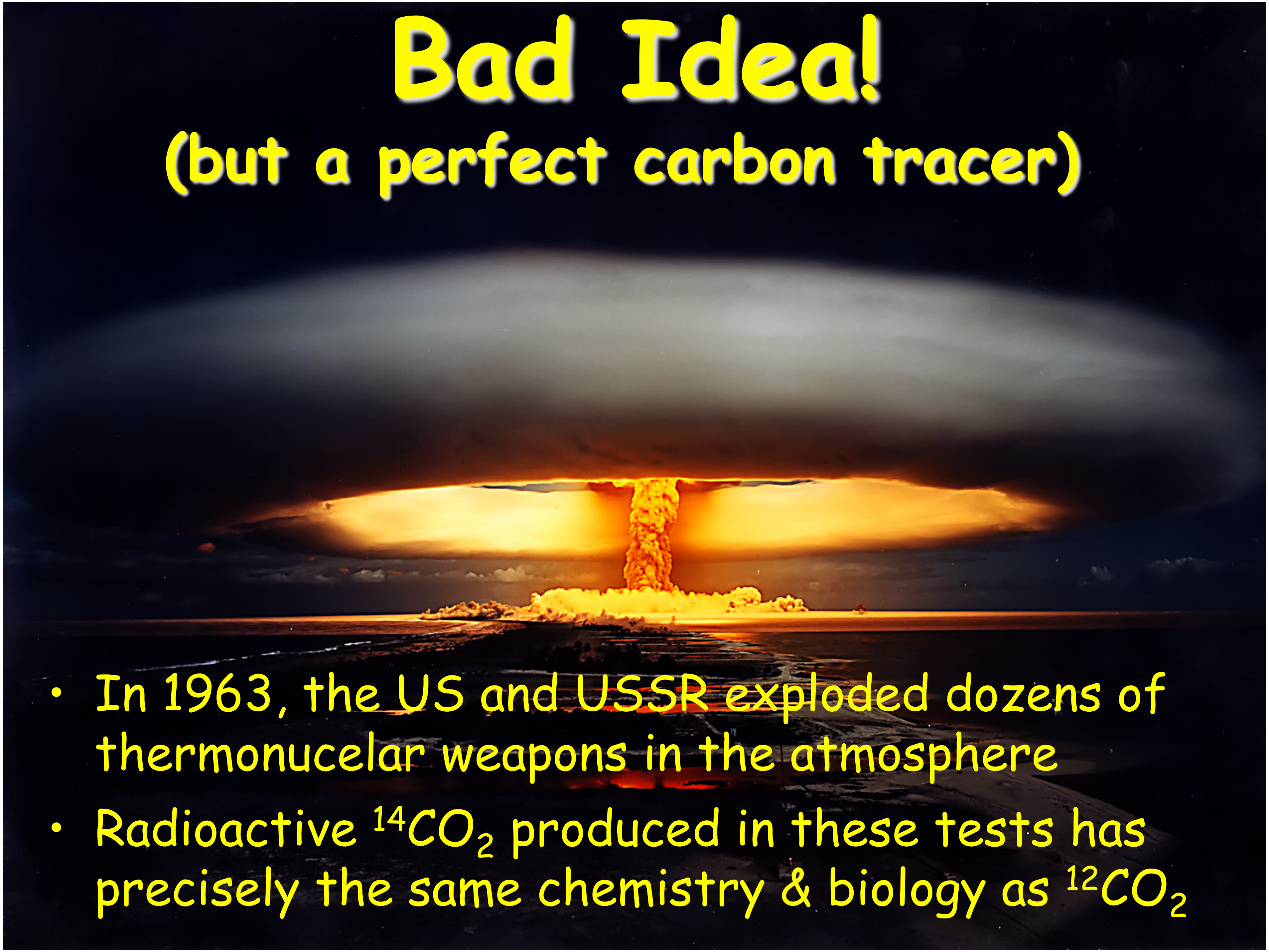
Vertical Structure of the Oceans



- Warm buoyant “raft” floats at surface
- Cold deep water is only “formed” at high latitudes
- Very stable, hard to mix, takes ~ 1000 years!
- Icy cold, inky black, most of the ocean doesn’t know we’re here yet!

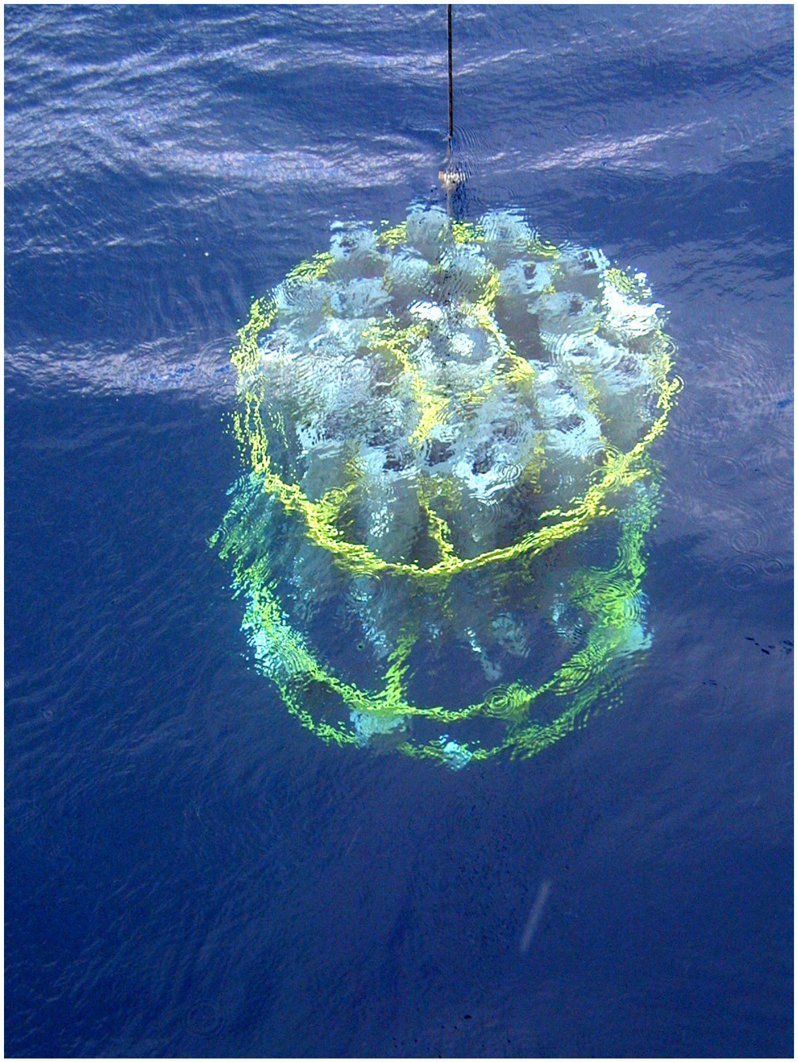
Bad Idea!

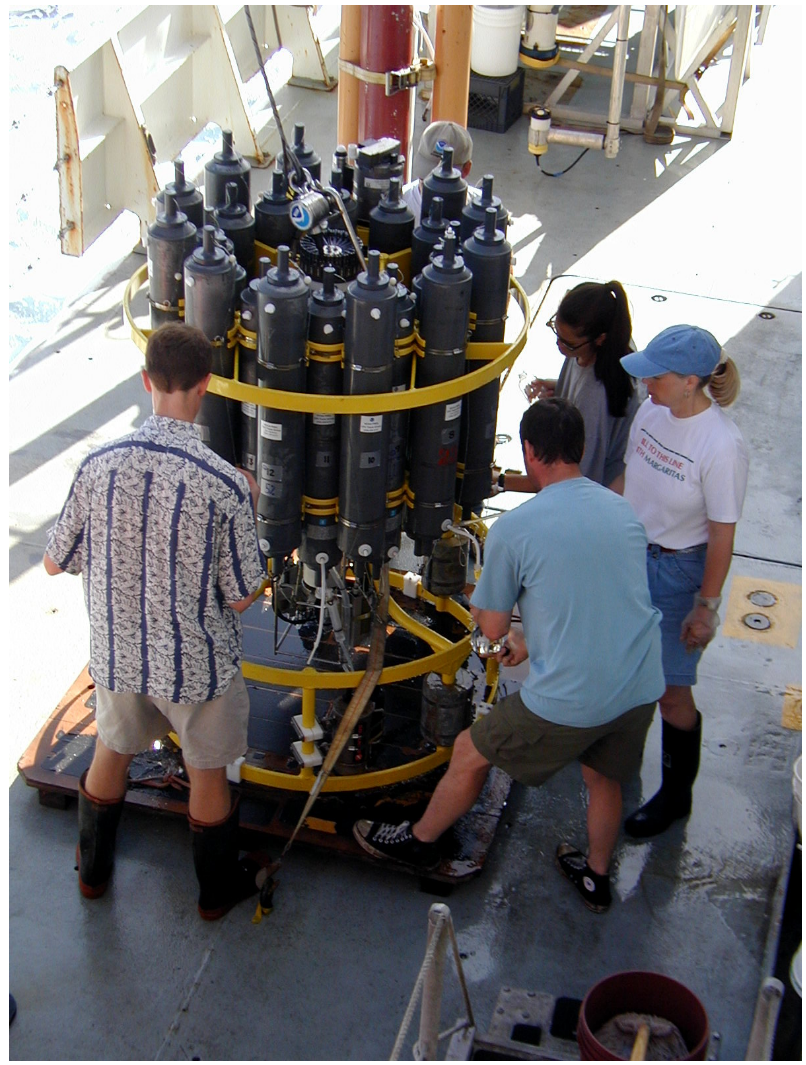
(but a perfect carbon tracer)



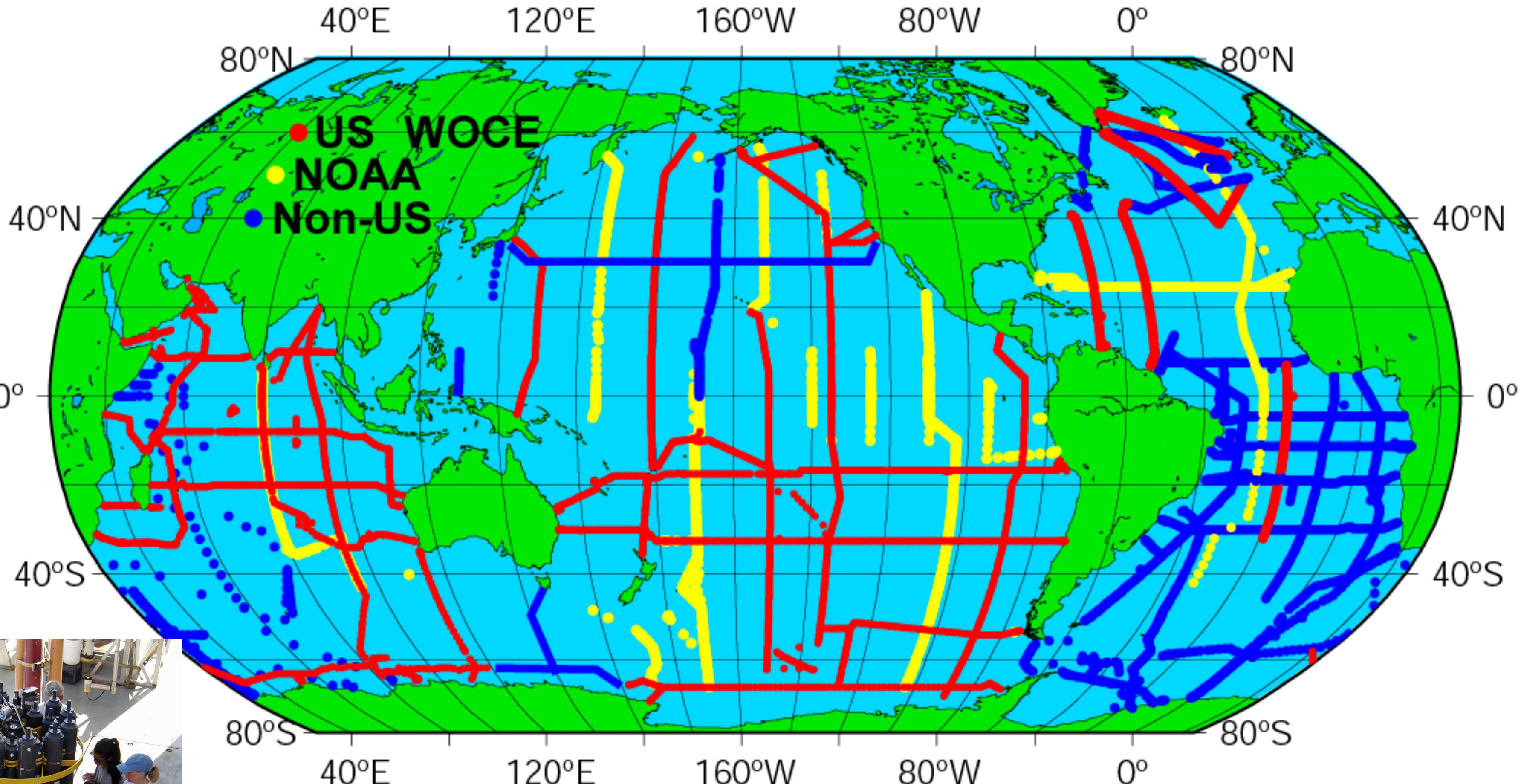
- In 1963, the US and USSR exploded dozens of thermonucelar weapons in the atmosphere
- Radioactive $^{14}CO_2$ produced in these tests has precisely the same chemistry & biology as $^{12}CO_2$

Observing the Deep Ocean





Observing the Deep Ocean



WOCE/JGOFS/OACES Global Survey Data

Anthropogenic DIC

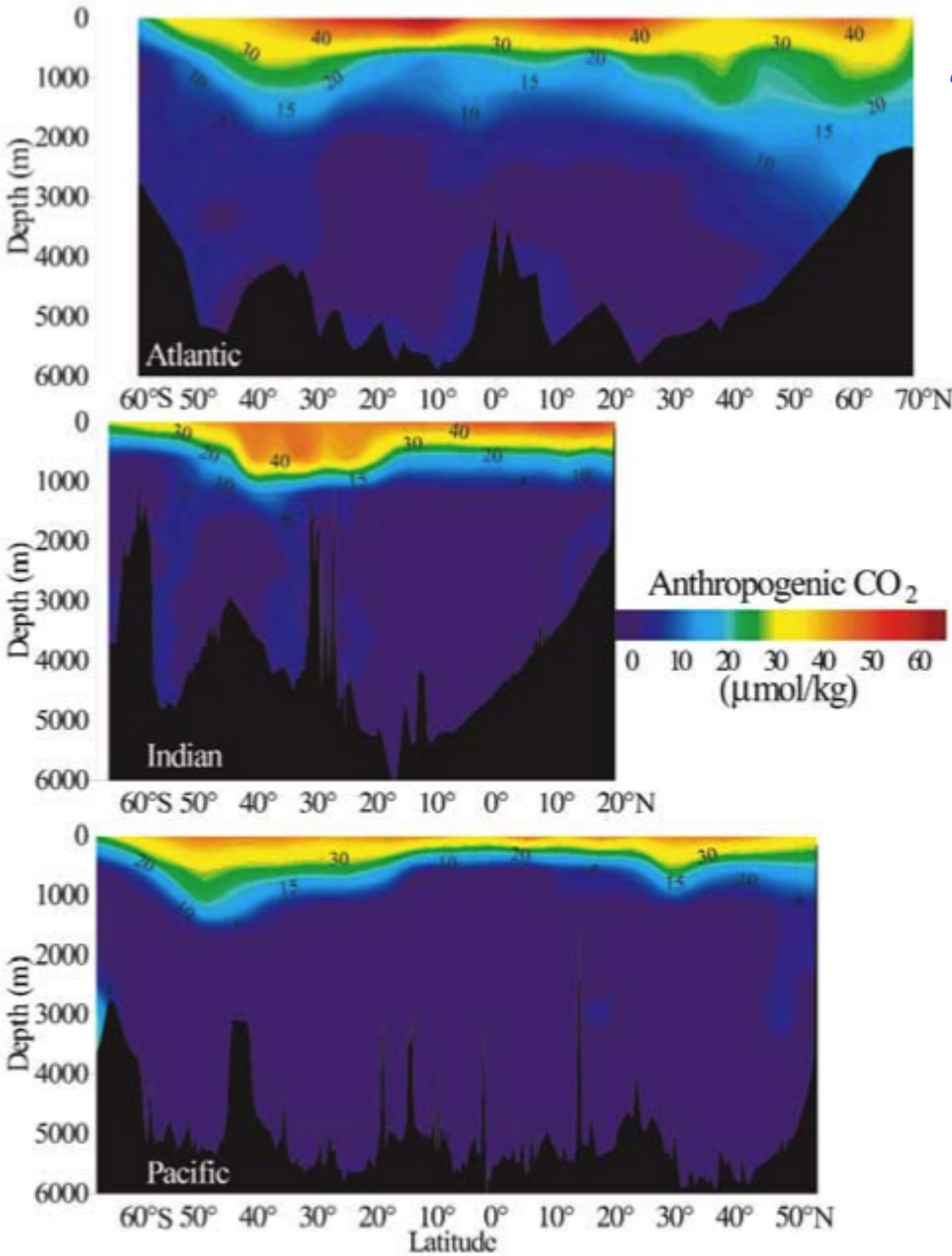
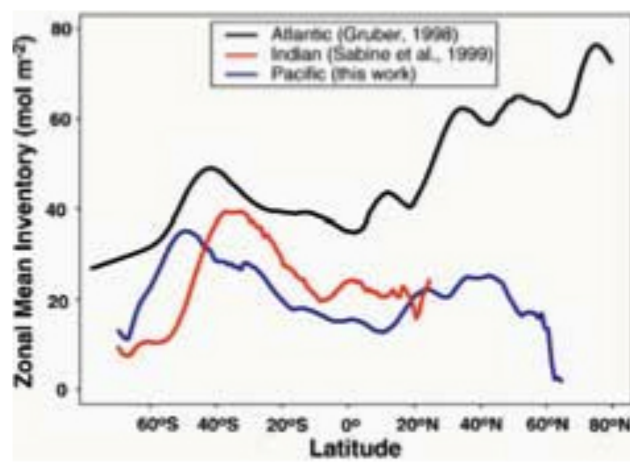


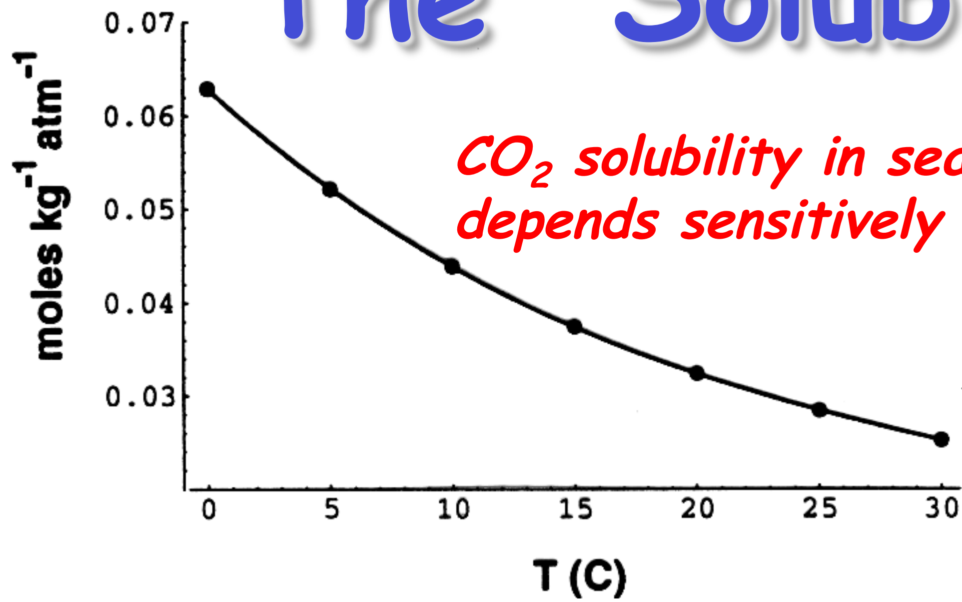
Figure 8. Zonal mean distributions of estimated anthropogenic CO_2 concentrations (in units of µmol kg^{-1}) along north-south transects in the Atlantic, Indian and Pacific oceans. The Pacific and Indian Ocean data are from the Global CO_2 Survey (this study), and the Atlantic Ocean data are from Gruber (1998).

- Estimated from total observed DIC using stoichiometry
- Most anthropogenic CO2 confined to top few 100 m
- "Shoaling" in tropics, convection at higher latitudes
- Some "contamination" of bottom water in Atlantic (both hemispheres)

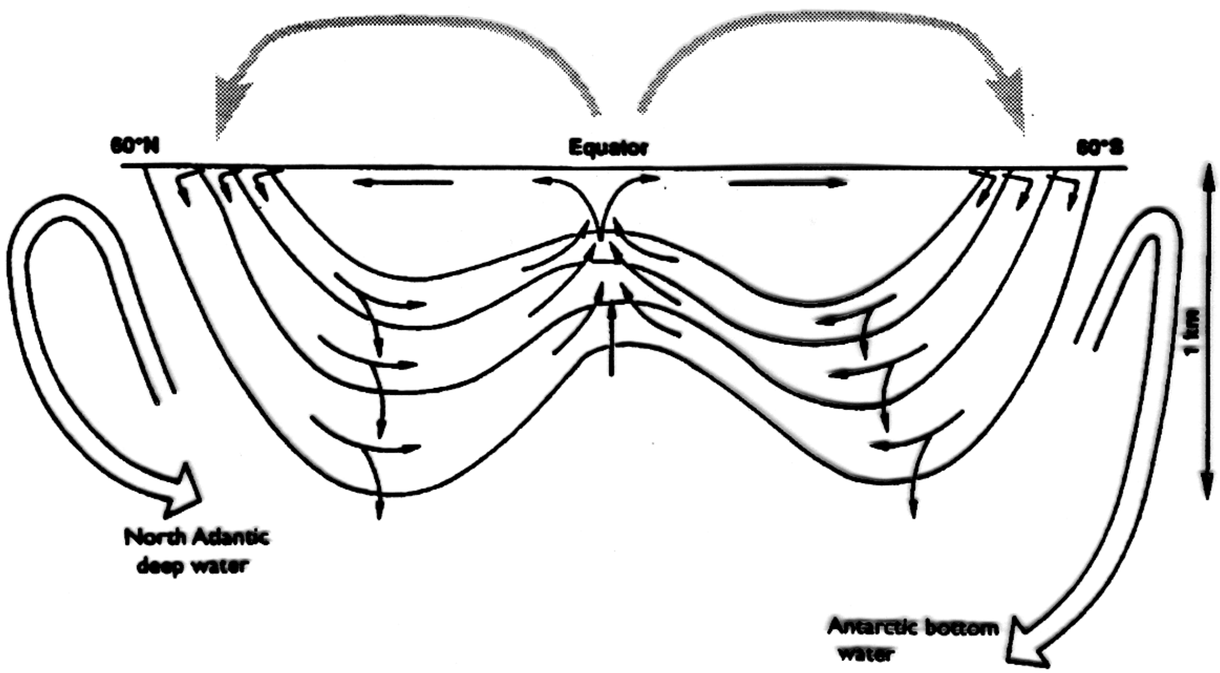


(Feeley et al, 2001)

The "Solubility Pump"

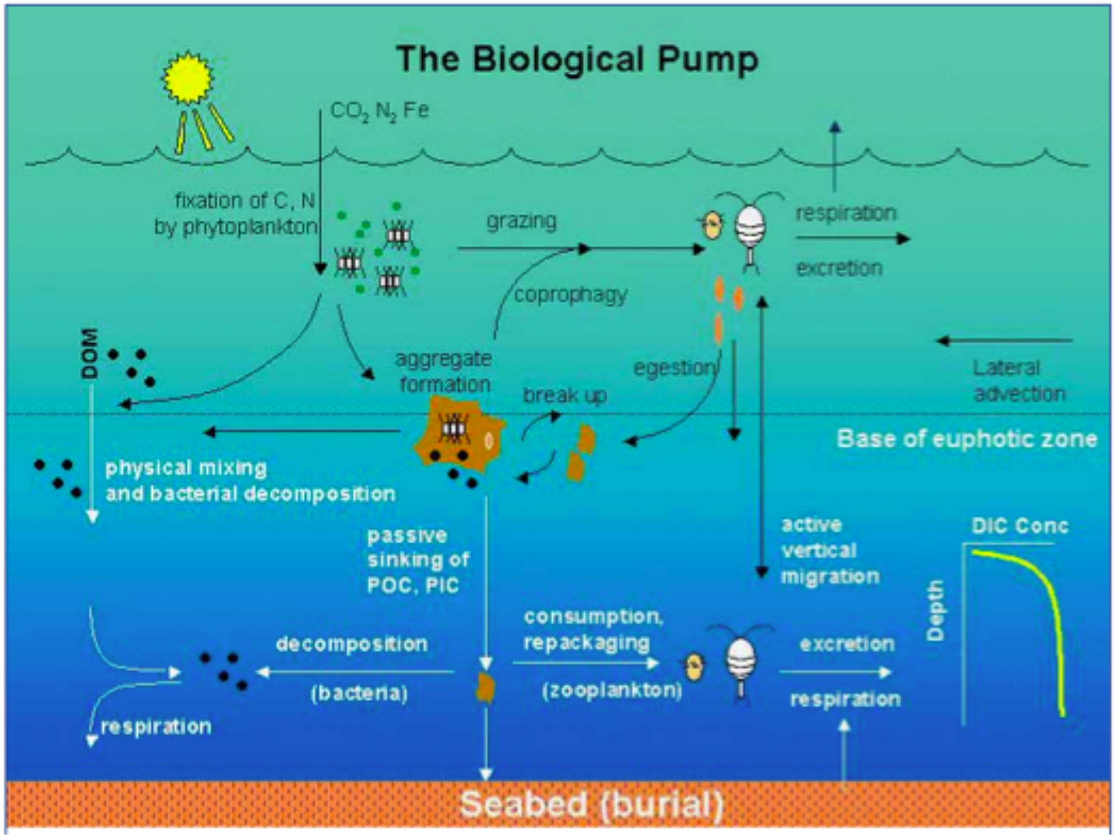


CO_2 solubility in seawater depends sensitively on SST



- CO_2 is highly soluble in cold high-lat waters
- Transported to deep ocean by convection and isopycnal mixing
- Dynamically-driven equatorial upwelling brings high-CO_2 water to surface
- Atmospheric transport closes the loop

"Biological Pump"

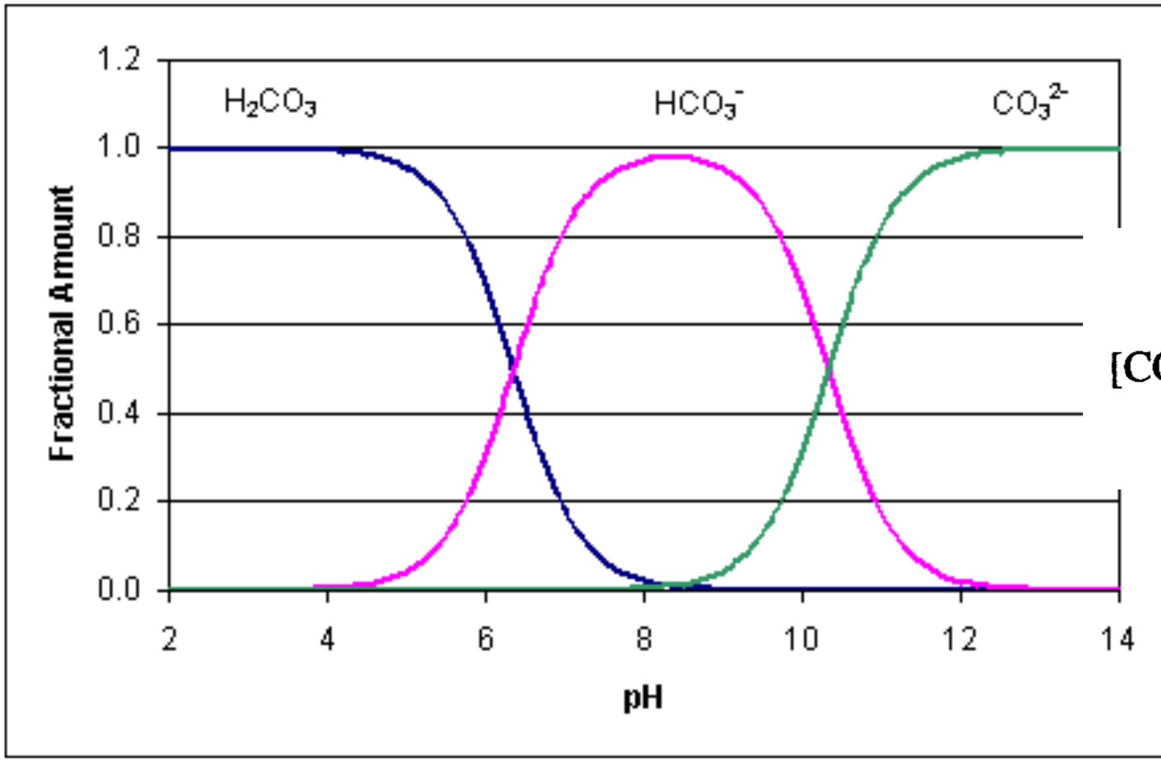


Ducklow et al (2001)

- Primary production limited by availability of nutrients and light
- Loss of nutrients from light by sinking must equal delivery of nutrients by upwelling

- "Primary production" generates communities of phytoplankton from DIC and nutrients in the presence of light
- Zooplankton "graze" on phytoplankton
- Bacterial decomposition and heterotrophic respiration recycle DIC and nutrients to the water column
- Detrital particles from dead phytoplankton and zooplankton waste coagulate into progressively larger particles
- Larger particles sink faster than turbulence can resuspend them, so fall below euphotic zone

Dissolved CO_2 in Seawater



$$CO_2(\text{gas}) \longleftrightarrow CO_2(\text{dissolved})$$

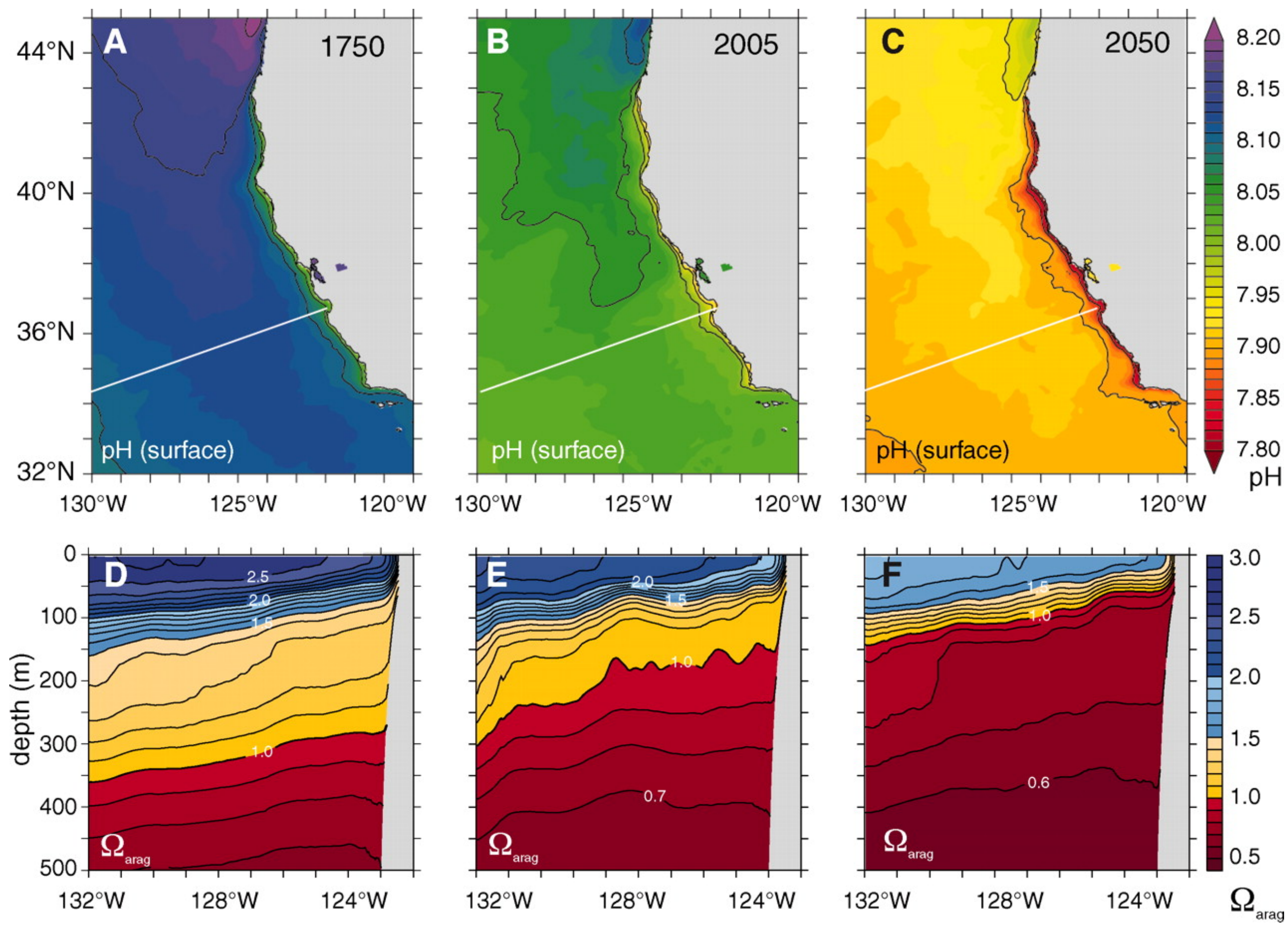
$$[CO_2(aq)] + H_2O \longleftrightarrow [H^+] + [HCO_3^-]$$

$$[HCO_3^-] \longleftrightarrow [H^+] + [CO_3^{2-}]$$

- CO_2 dissolves (weakly) in seawater, forming a buffered system w/ bicarbonate and carbonate
- Strongly interacts with pH and alkalinity

Ocean Acidification

Fig. 1 Temporal evolution of ocean acidification in the California CS from 1750 until 2050 for the A2 scenario.



Surface pH

Aragonite Saturation depth

Gruber et al., 2012

Ocean Acidification

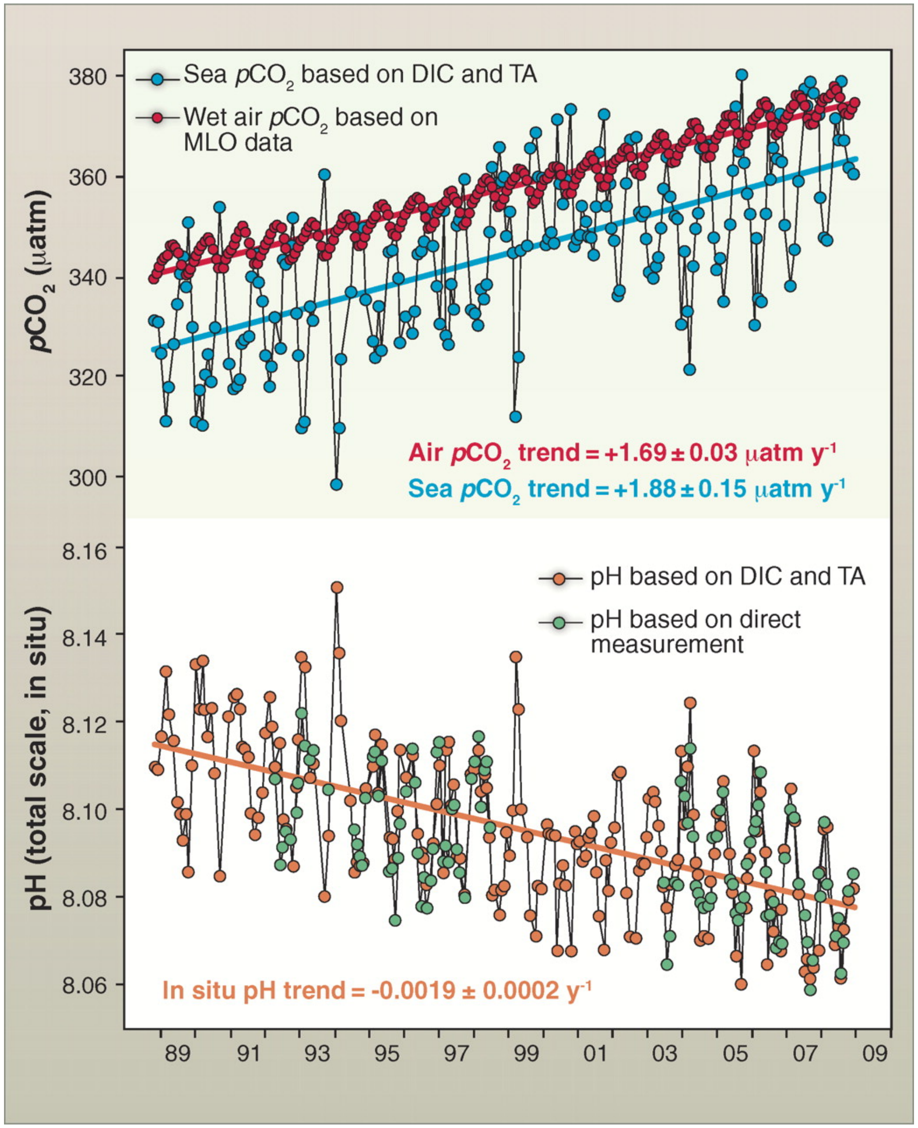


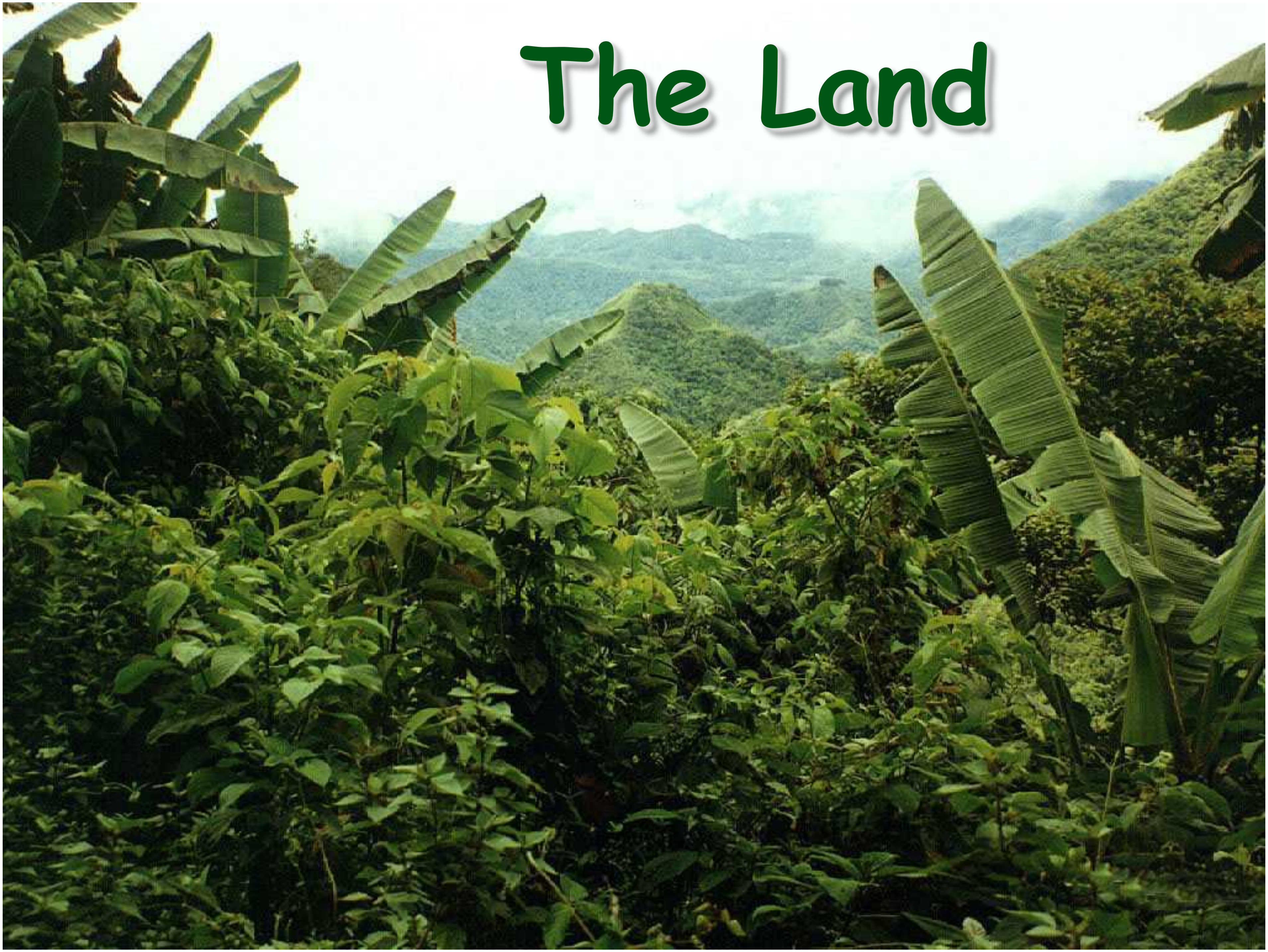
Fig. 2 Time series of (top) atmospheric CO2 and surface ocean pCO2 and (bottom) surface ocean pH at the atmospheric Mauna Loa Observatory (MLO) on the island of Hawai‘i and Station ALOHA in the subtropical North Pacific north of Hawai‘i, 1988–2008. [Adapted from (26)].

Doney et al., 2010

OCEAN: SUMMARY

- Ocean is thermally stratified; mixing is slow, transport to depth confined to NADW and AABW
- Carbon isotopes (^{14}C) from nuclear tests provide a 'marker' for us to record mixing of anthropogenic CO_2
- Computer models agree with observations; Oceans take up ~2.3 GT carbon/year
- As atmospheric CO_2 rises, ocean uptake will increase
- BUT; more CO2 => more acidic ocean

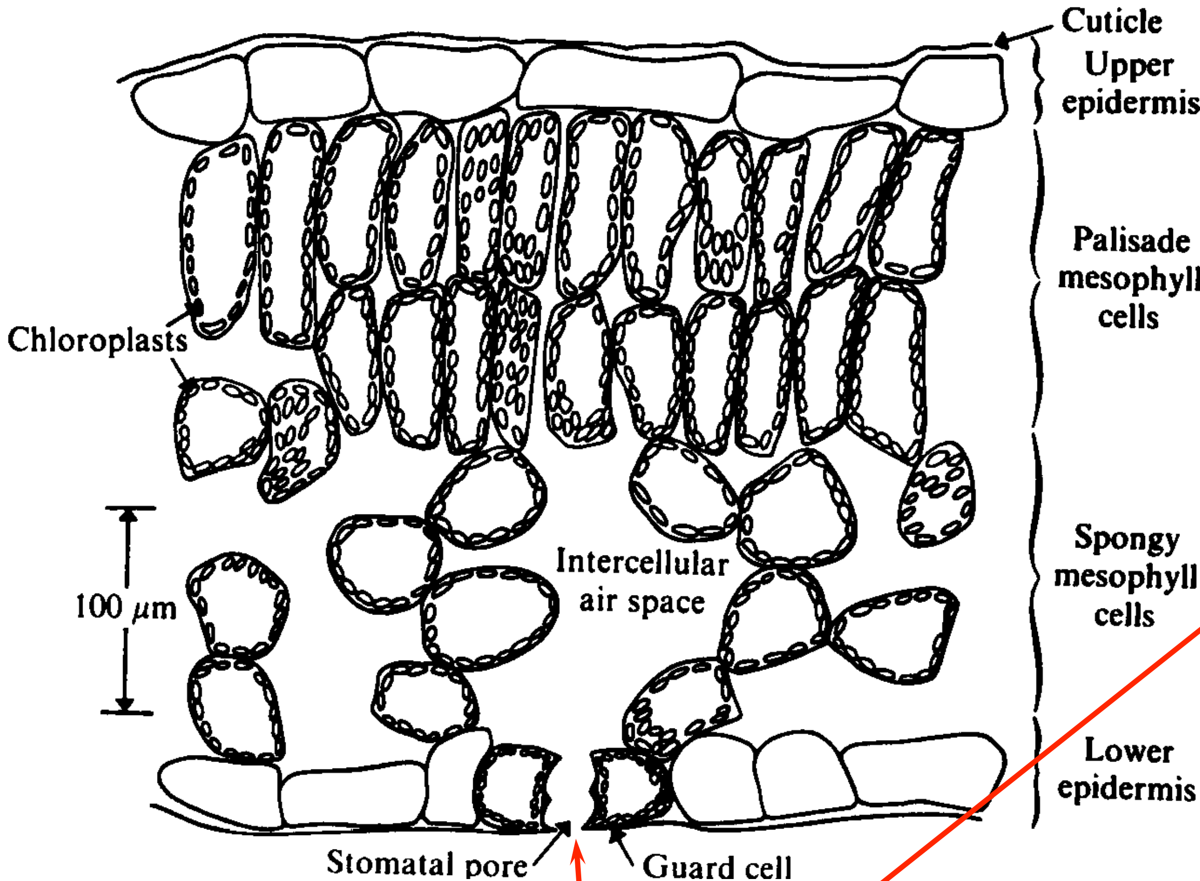
The Land

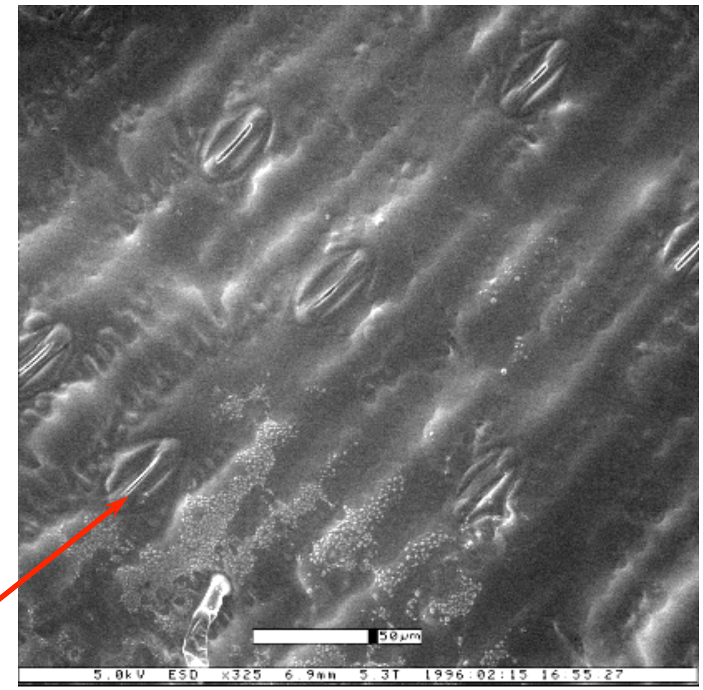


Carbon Balance; Things we know

1. Atmospheric CO_2 increases annually, in response to Fossil Fuel consumption
2. Only about ½ of the CO_2 we release stays in the atmosphere
3. About ¼ of the CO_2 we release ('half of the half') goes into the ocean; this is fairly well understood
4. The other ¼ MUST go into the land; what is going on?

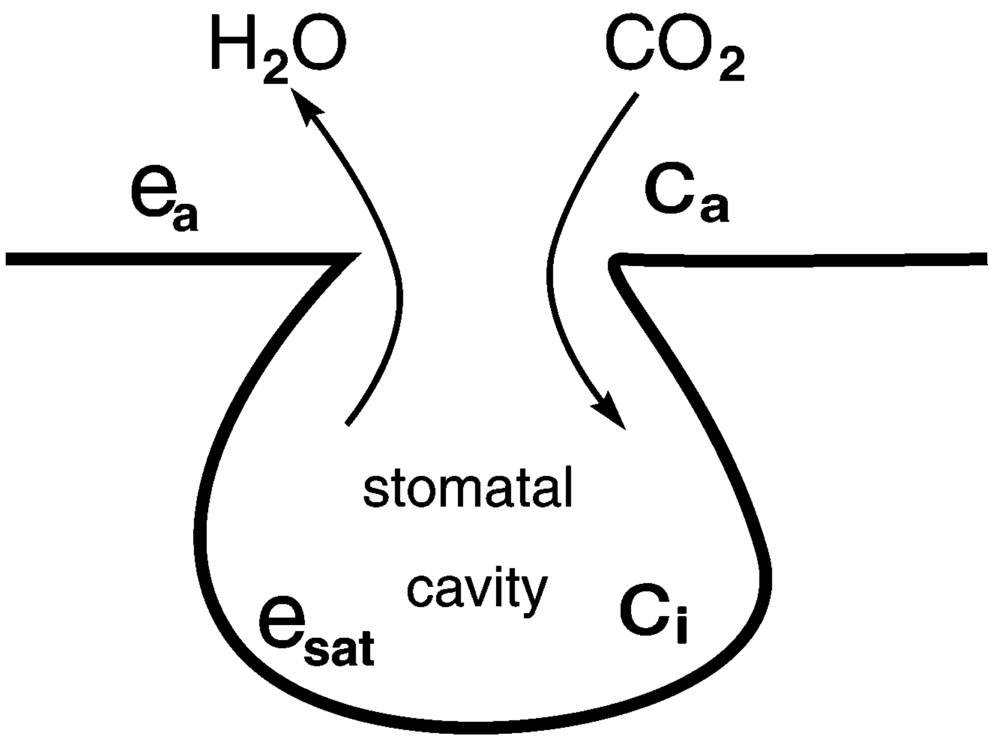
Leaf Anatomy





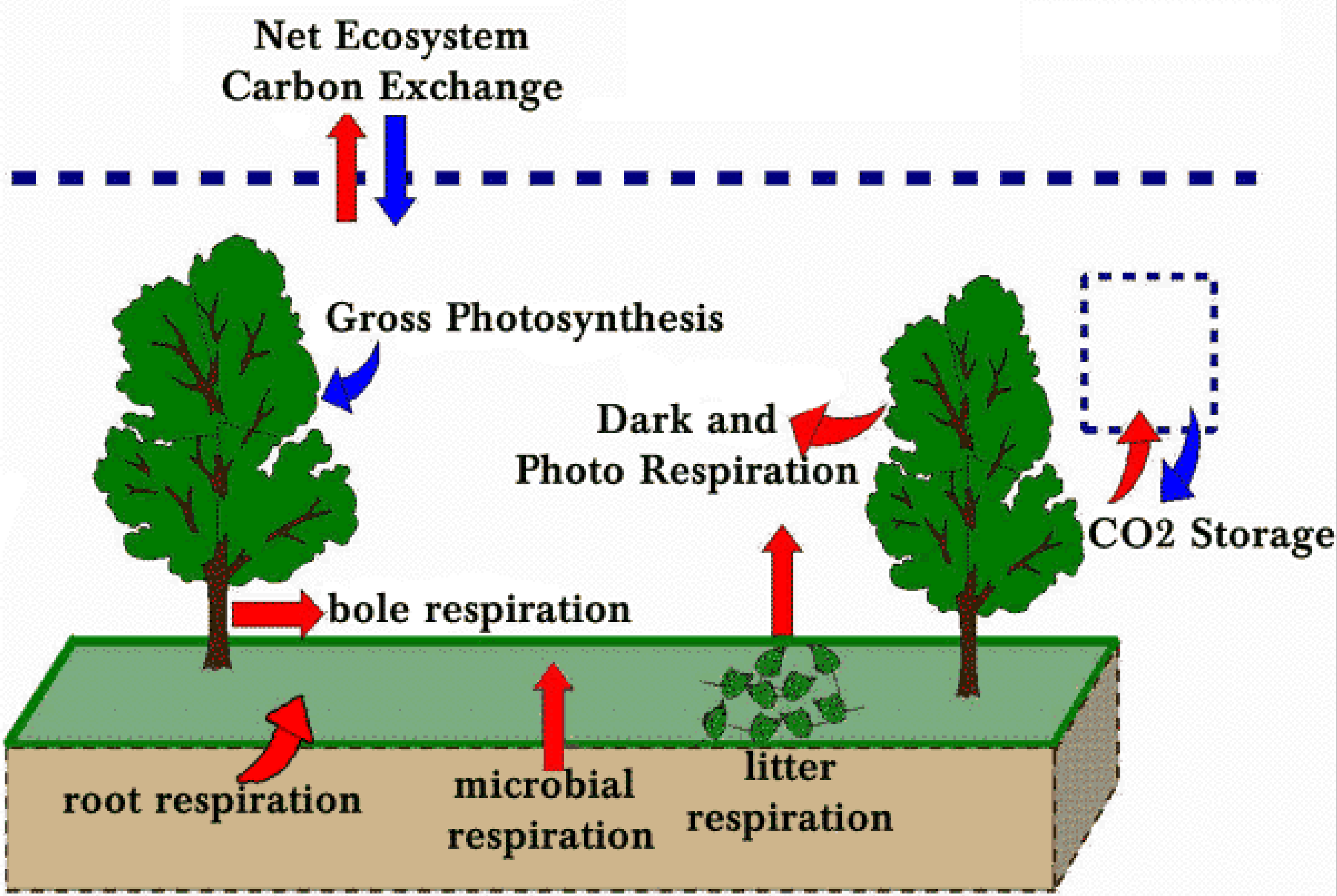
Stomate
(pl. stomata)

Carbon and Water



- Plants eat CO_2 for a living
- They open their stomata to let CO_2 in
- Water gets out as an (unfortunate?) consequence
- For every CO_2 molecule fixed about 400 H_2O molecules are lost

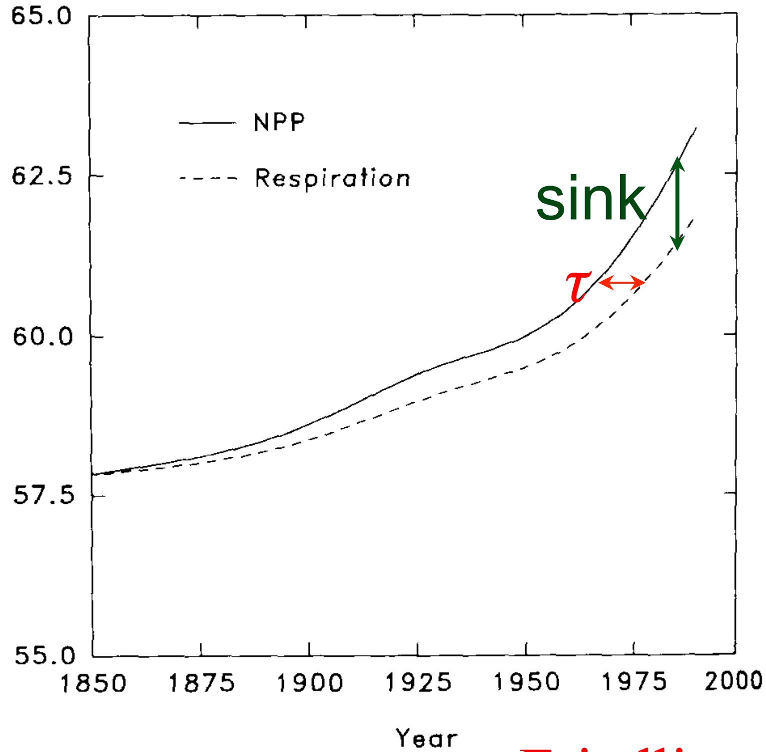
Canopy Carbon Balance

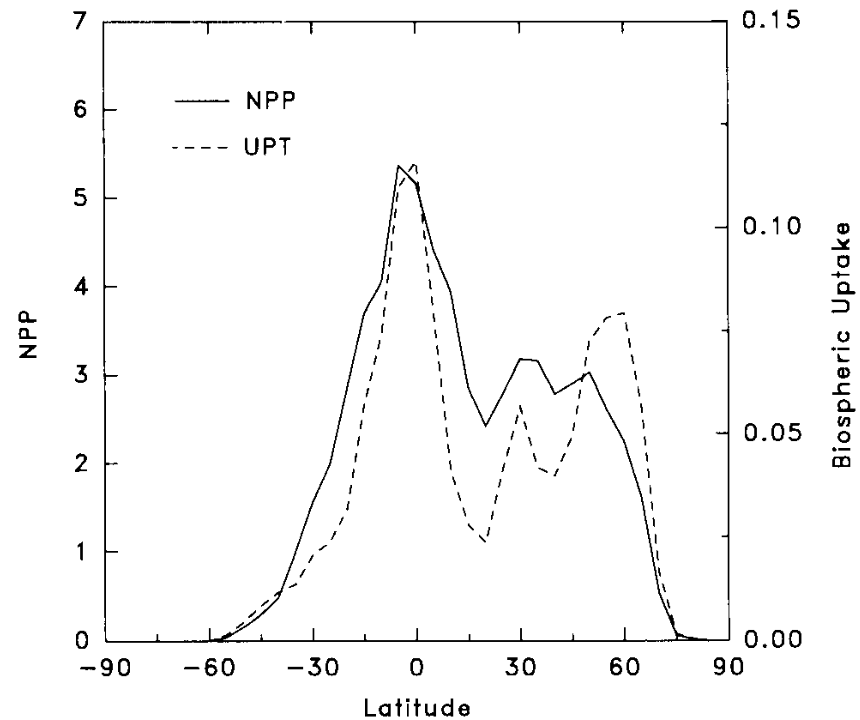


Land Carbon Sink

- If the land is taking up ¼ of the released fossil fuel CO_2, then the plants are growing faster than they are decomposing!
- What are some mechanisms?
  - CO_2 fertilization
  - Nitrogen fertilization
  - Season broadening

CO_2 Fertilization





Friedlingstein et al, 1995

- Increasing plant growth (NPP) due to enhanced atmospheric CO_2
- Delayed increased respiration (residence time)
- Spatial pattern follows both NPP and residence τ

Free Air Carbon Enrichment (FACE)

- Fumigation rings maintain steady levels of elevated CO_2 in canopies under changing weather conditions
- Control and replicated treatments test effects of CO_2, water, N, etc

Duke FACE Results

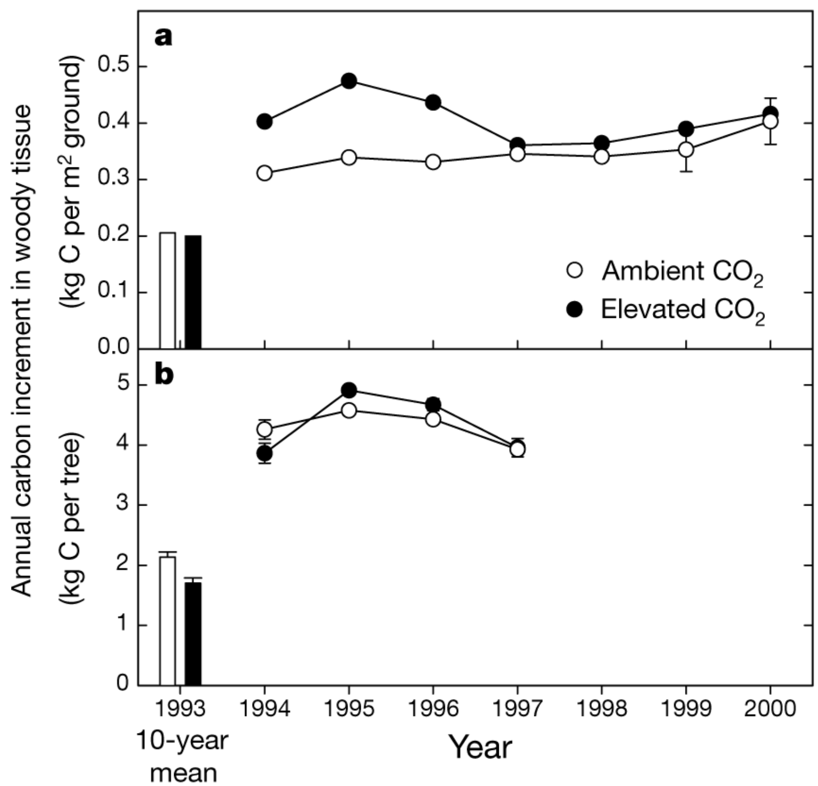
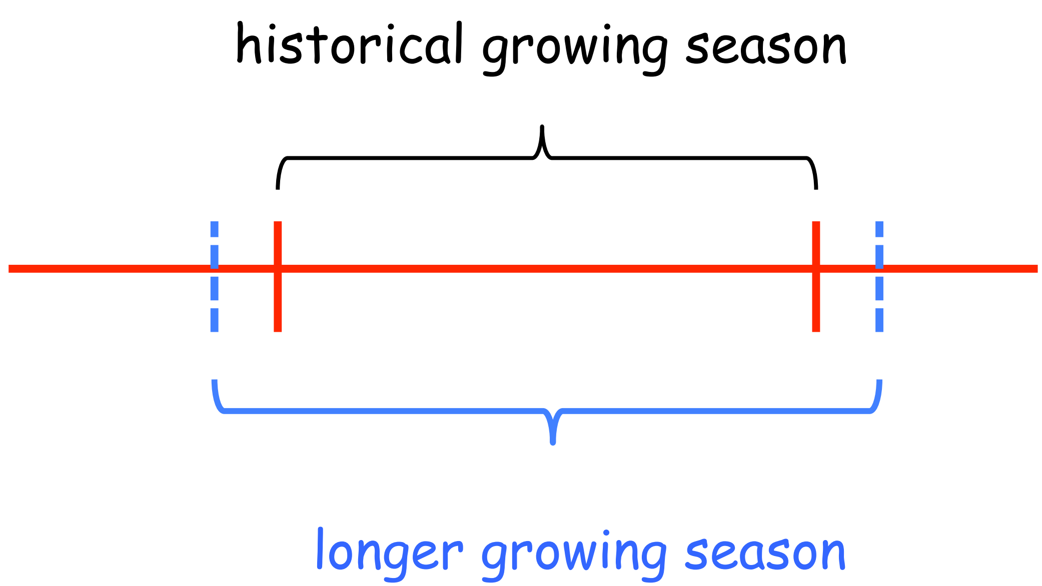


Figure 1 A comparison of annual carbon increment under elevated atmospheric CO_2 concentration (initiated in 1994) and ambient concentration without nutrient addition. **a**, Plot-level comparison between the free-air CO_2 enrichment prototype ($FACE_P$) and a nearby untreated, ambient CO_2 plot (in the past 2 yr, the number of untreated plots was increased to five). **b**, Individual tree comparison between trees in $FACE_P$ and trees selected at random from the entire stand. Data for 1993 are shown as means for the first 10 yr of the stand's life.

Oren et al (2001)

- Enhanced growth in elevated CO_2
- "Acclimitization" after a few years

Season Broadening



More carbon taken up during longer growing season, respiration hasn't 'caught up' yet...

Other Mechanisms

- Woody encroachment
  - Arctic
  - savanna
- Fire suppression

But…(there's always a 'but')

- Woody Encroachment
  - Warming may result in permafrost thaw
  - Release of stored carbon

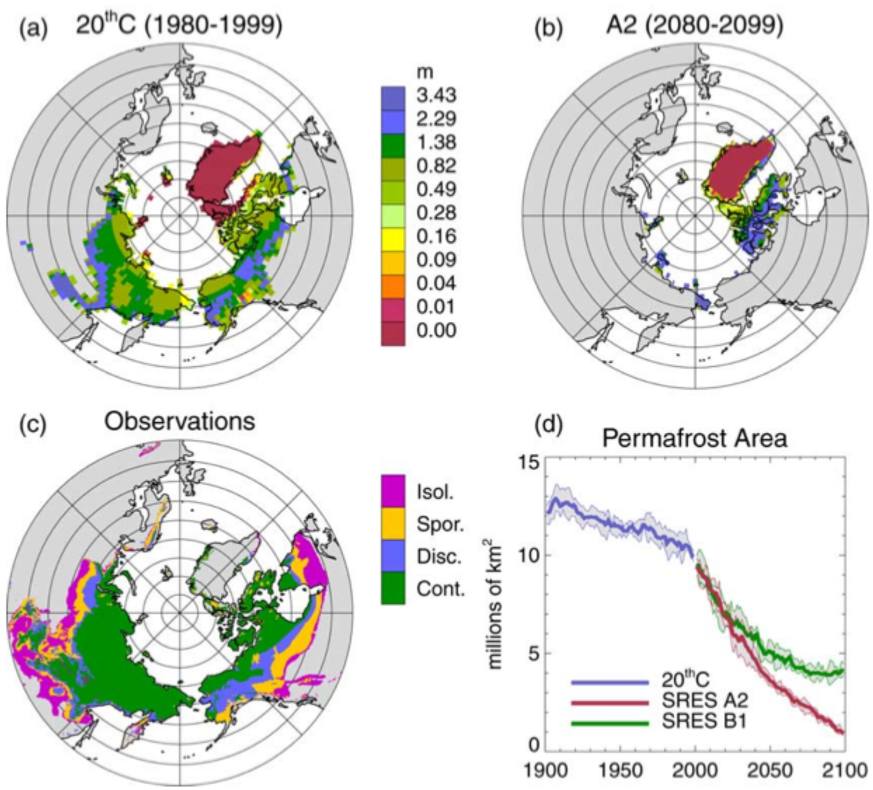


Figure 1. Ensemble mean permafrost area and active layer thickness as simulated in CCSM3 at the end of the (a) 20th and (b) 21st centuries. (c) Observational estimates of permafrost (continuous, discontinuous, sporadic, and isolated). (d) Time series of simulated global permafrost area (excluding glacial Greenland and Antarctica). The gray shaded area represents the ensemble spread.

Lawrence et al., 2005

But…(there's always a 'but')

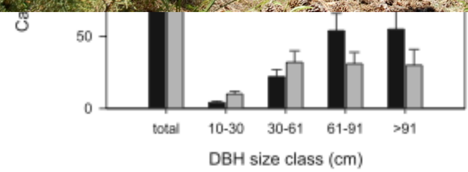


Figure 1. Mean and 95% confidence intervals for (a) tree density and (b) carbon stored in live aboveground biomass for conifer forests receiving ≥114 cm mean annual precipitation.

- Fire Suppression
  - Some studies show a release of CO_2 in the last century
  - Higher intensity of fires that do occur

But…(there's always a 'but')

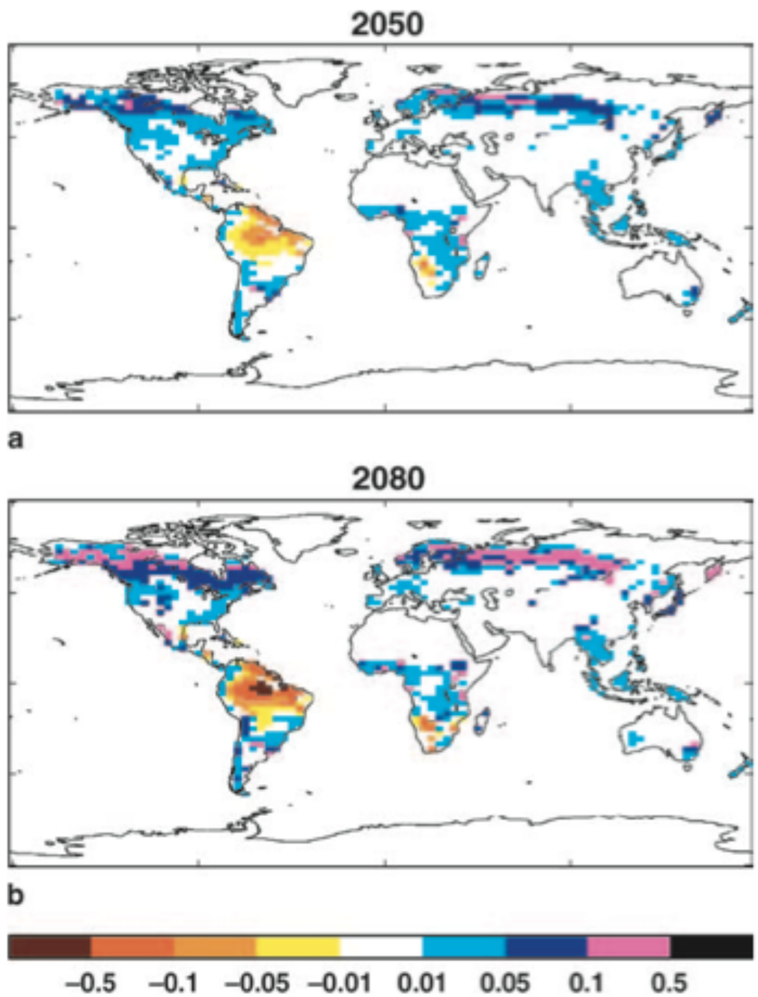
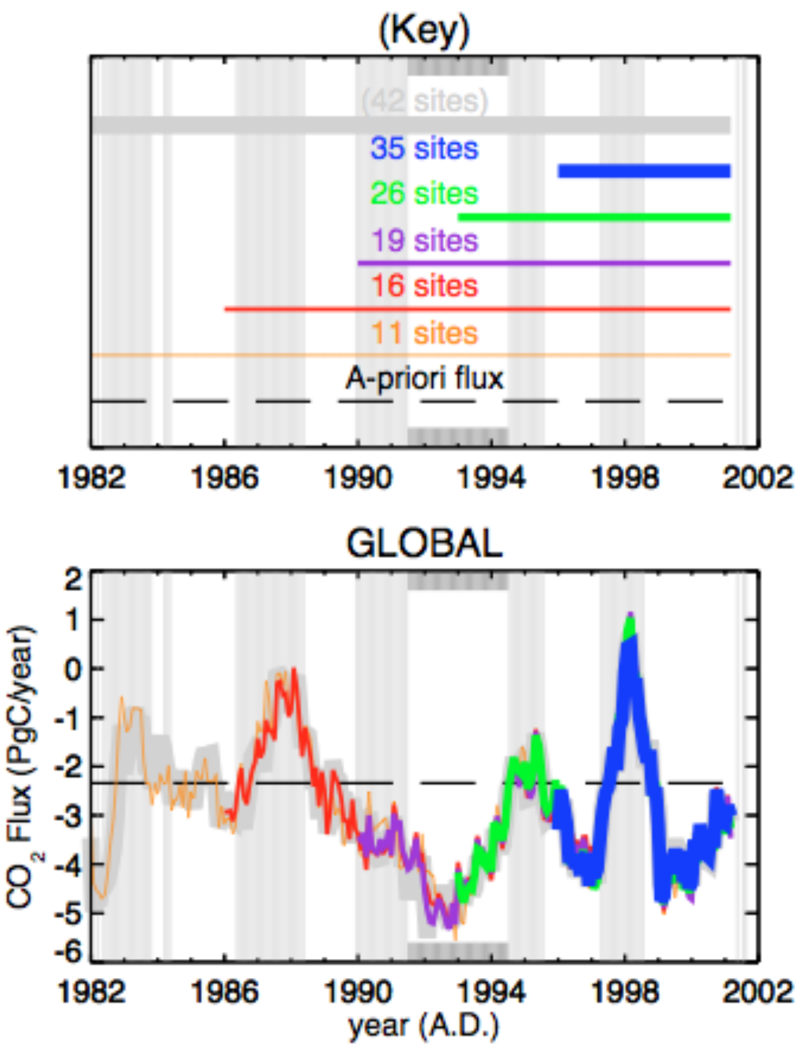


Fig. 4. Simulated changes in fractional cover of the broad-leaf tree functional type relative to 2000. 30-year means centred around (**a**) 2050 and (**b**) 2080

- Amazon Conversion
  - Future climate will be drier in Amazonia
  - Tropical Forests may be converted to grassland or savanna
  - Large release of CO_2

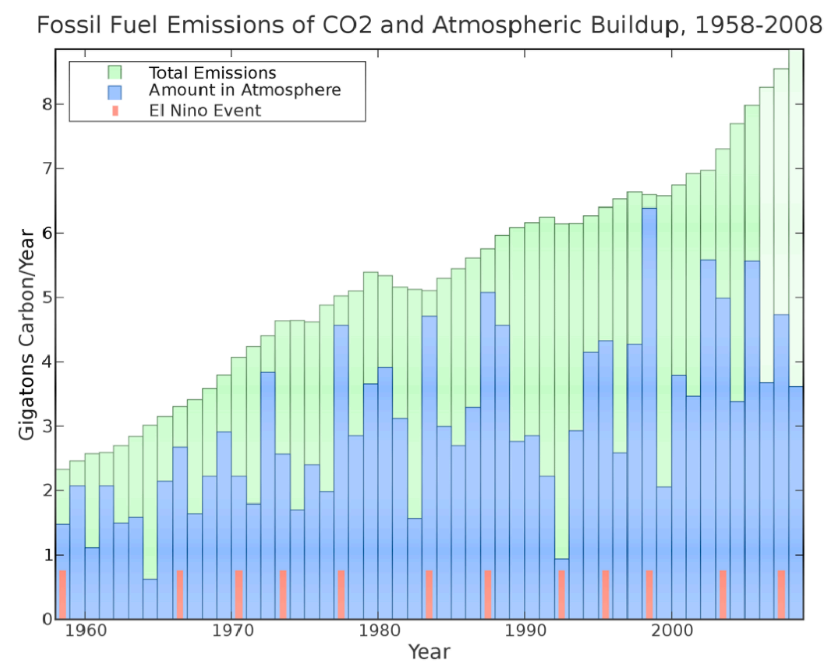
Betts et al., 2004

Sink Variability



Rödenbeck et al., 2003

- Total 'sink' varies with time



Sink Variability

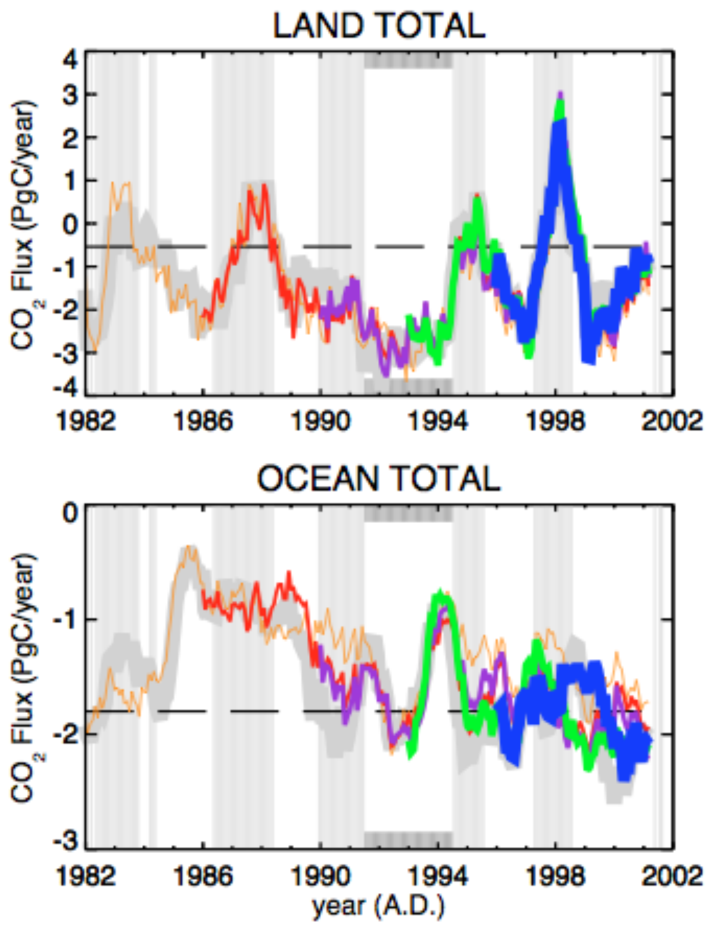
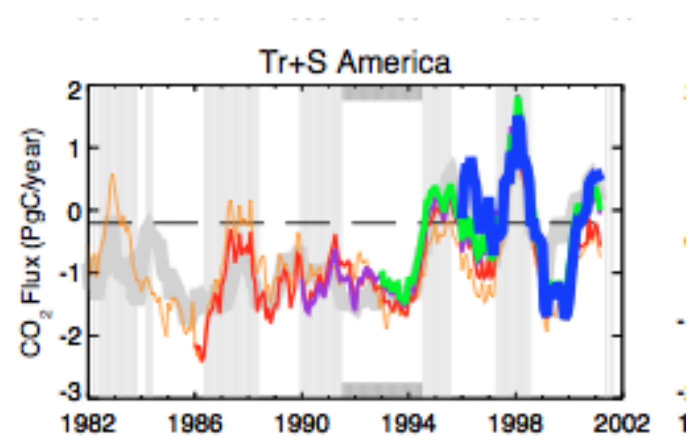


Fig. 5. Part II: Breakup of the standard estimates into land-atmosphere and ocean-atmosphere fluxes.

- Land Sink is more variable than ocean sink
- Land sink can change sign!
- Tropics



Rödenbeck et al., 2003

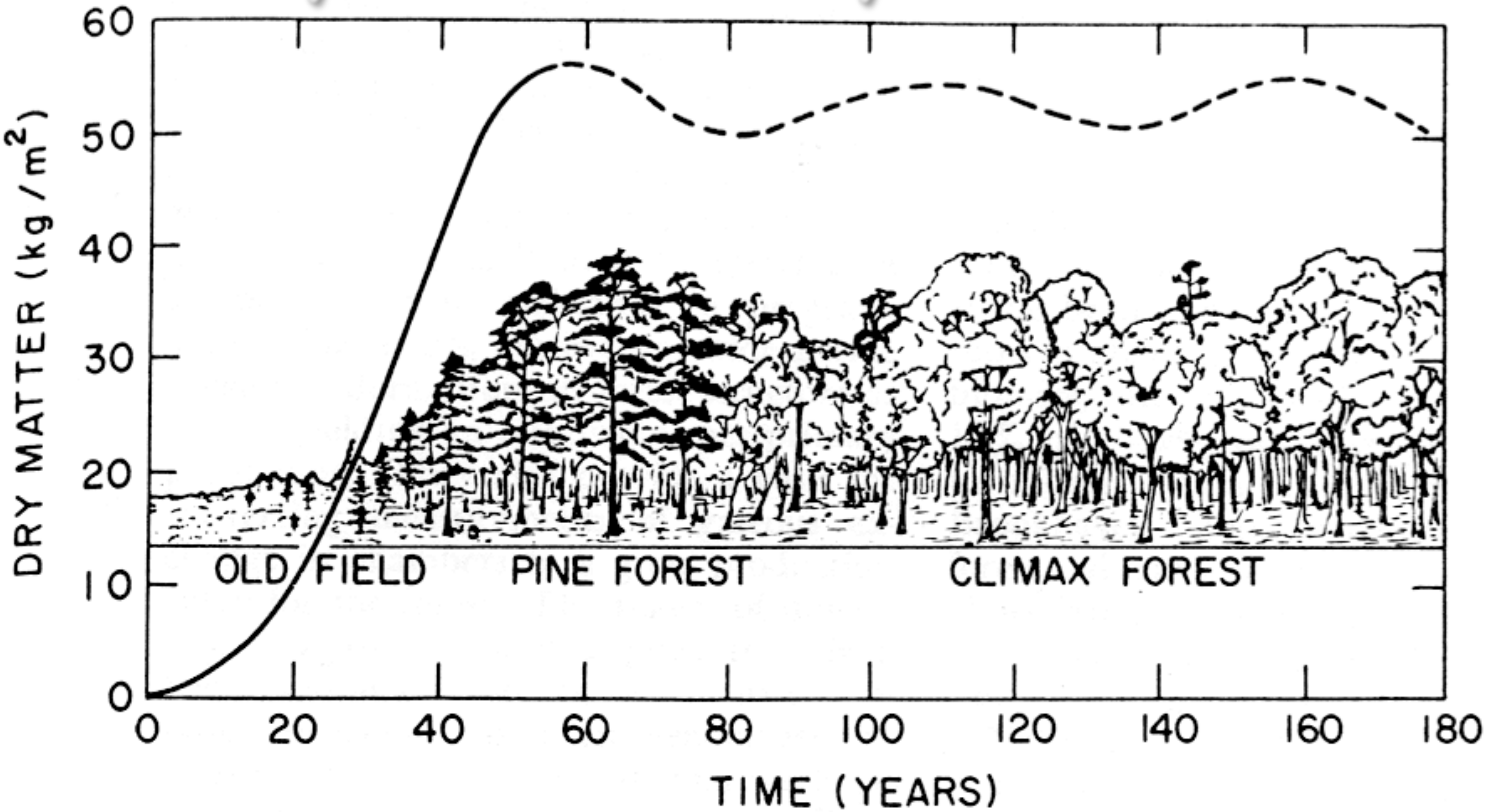
Let's Review:

- What we KNOW:
  - Atmospheric CO_2 levels are rising
  - Human caused
  - There is a natural 'sink' of ~half of emitted CO_2
    - Ocean
    - Land
  - Land sink is more variable than oceanic
  - In general terms, plants are growing more than they are dying

Let's Review:

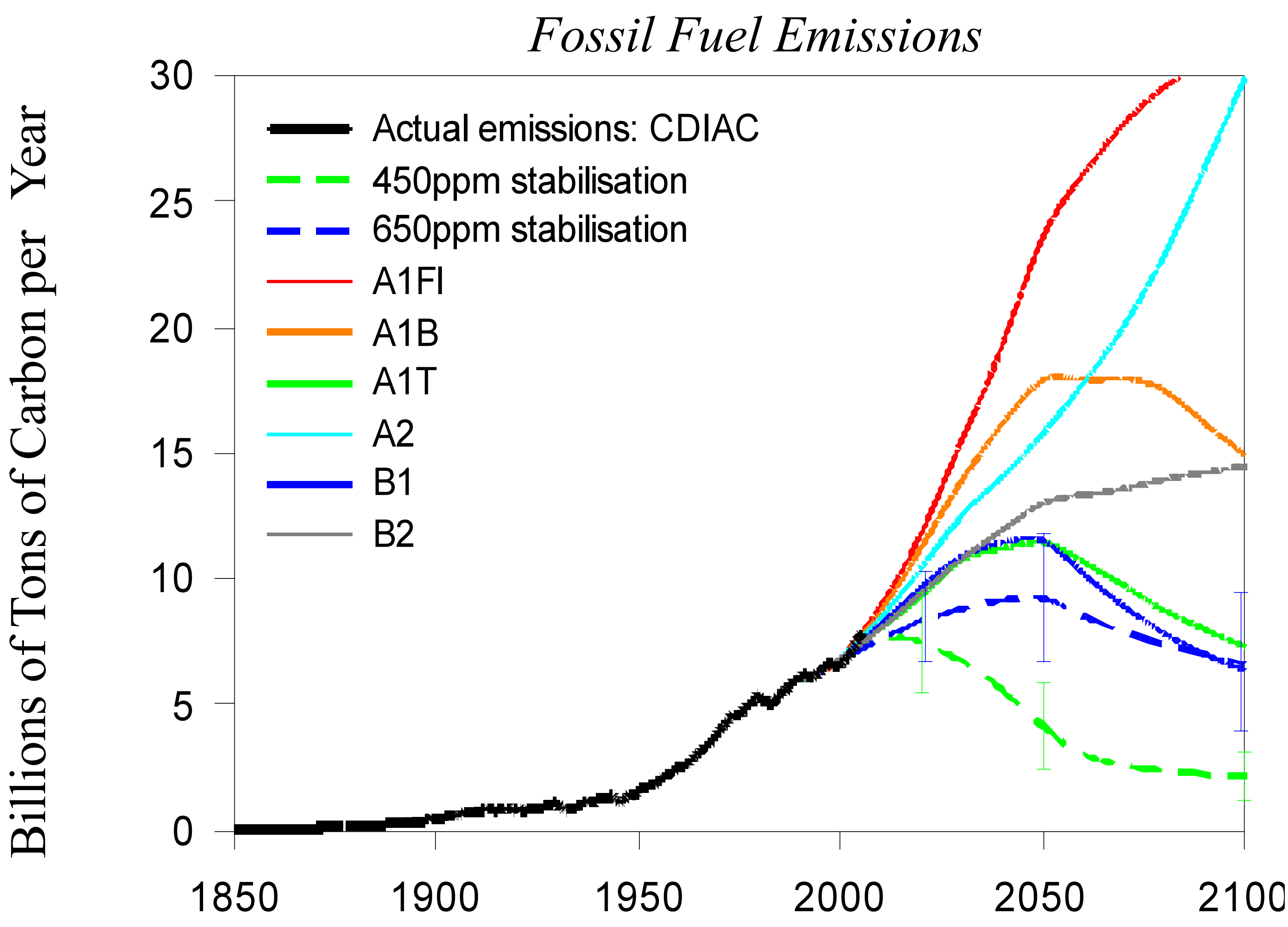
- What we DON'T KNOW:
  - What are the exact physical mechanisms responsible for the land sink, and their relative magnitude
  - What is the spatial organization of the land sink?
  - How will the land sink behave in the future?
  - What action, if any, will humans take?

Ecosystem Recovery & Succession



Woodwell and Whittaker, 1968

Emission Scenarios



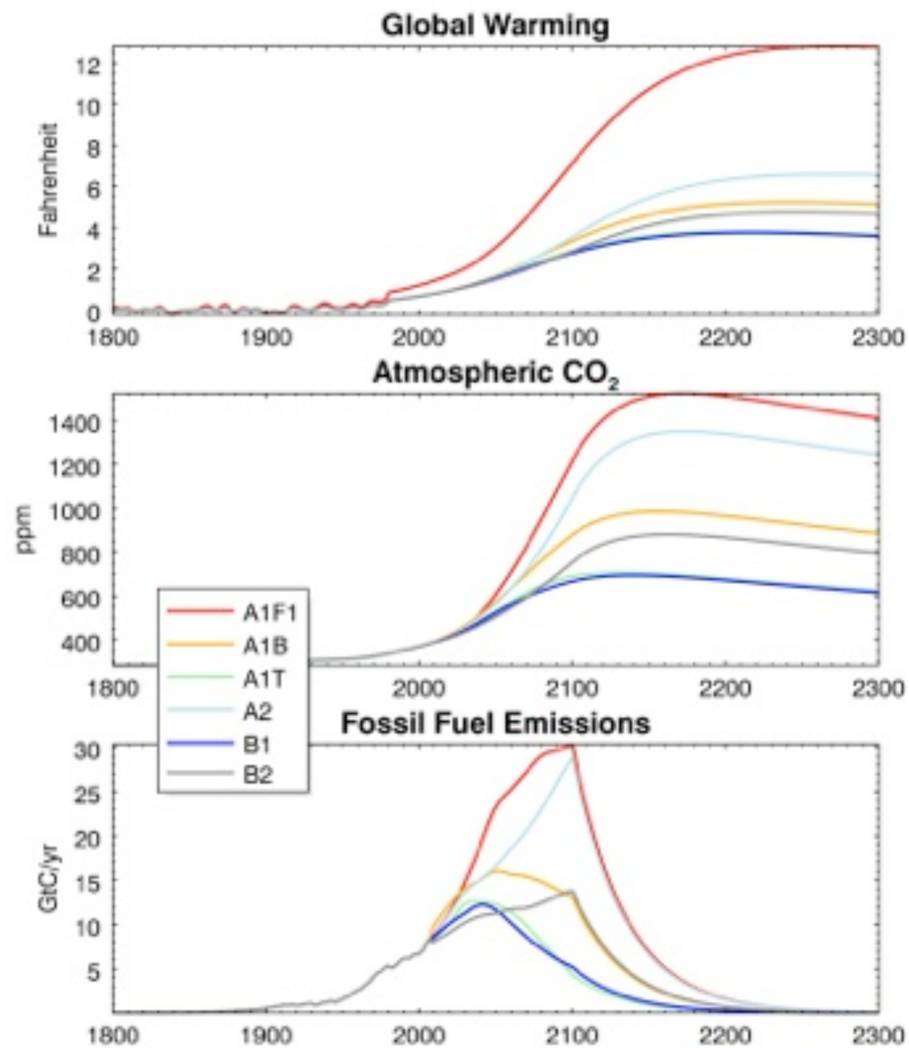
Common Myth

- "When we reduce or stop the burning of fossil fuel, the CO_2 will go away and things will go back to normal"

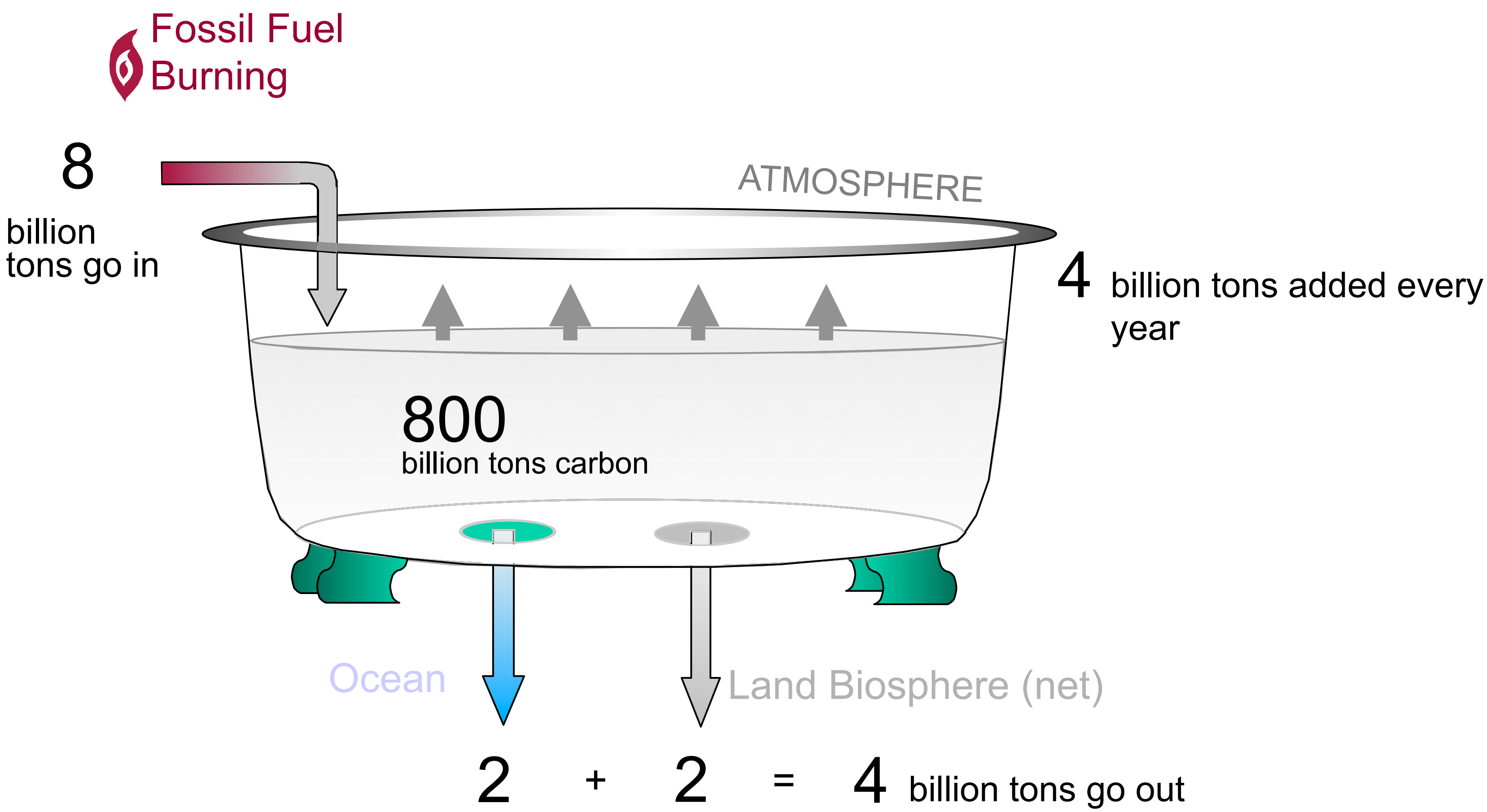
CO_2 from fossil fuel will react with oceans, but only as fast as they "mix"

Eventually, fossil CO_2 will react with rocks

About 1/3 of today's emissions will stay
in the air 'permanently'!

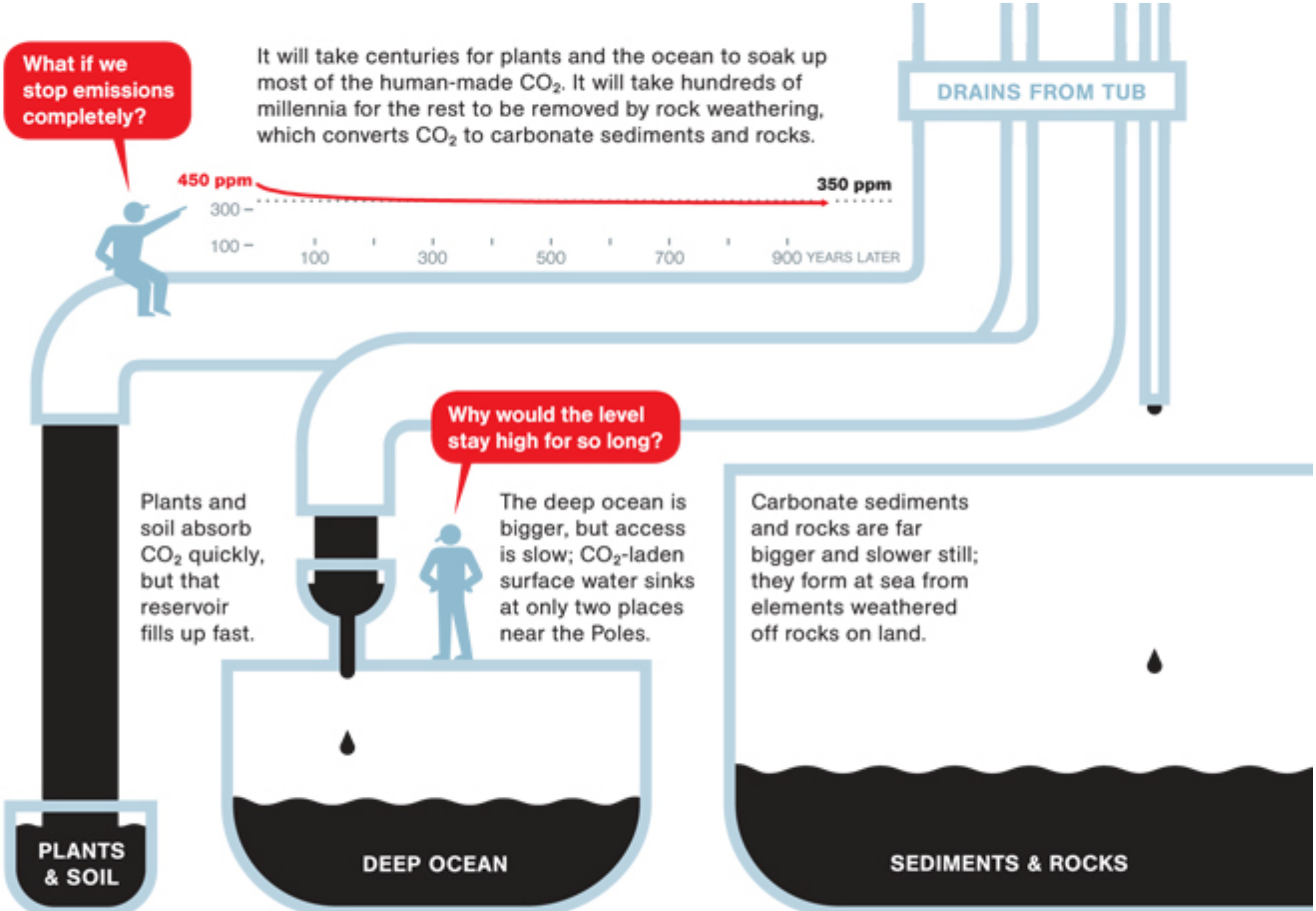


CO_2 "Budget" of the Atmosphere



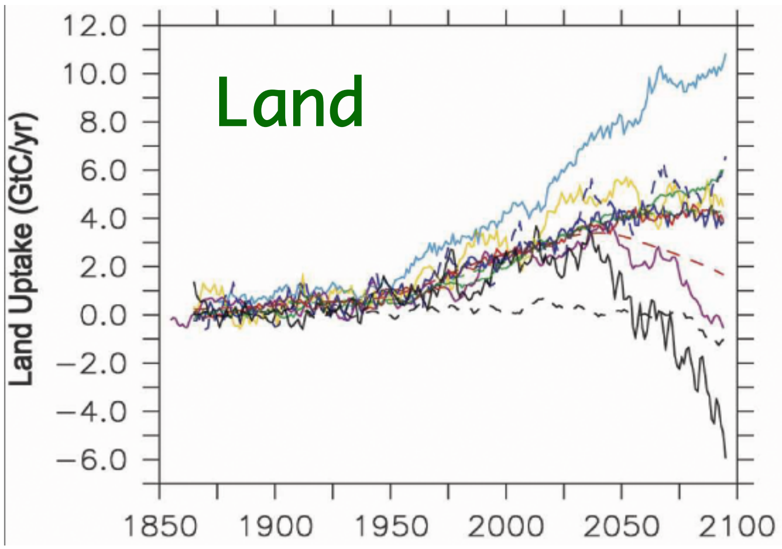
Rob Socolow and Steve Pacala http://www.princeton.edu/wedges/
Climate Mitigation Initiative, Princeton University

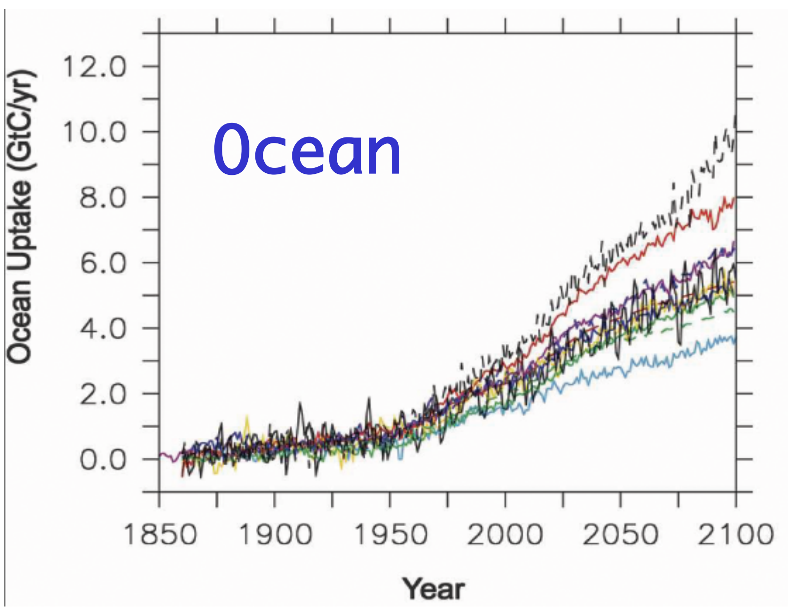
Bathtub Drainage

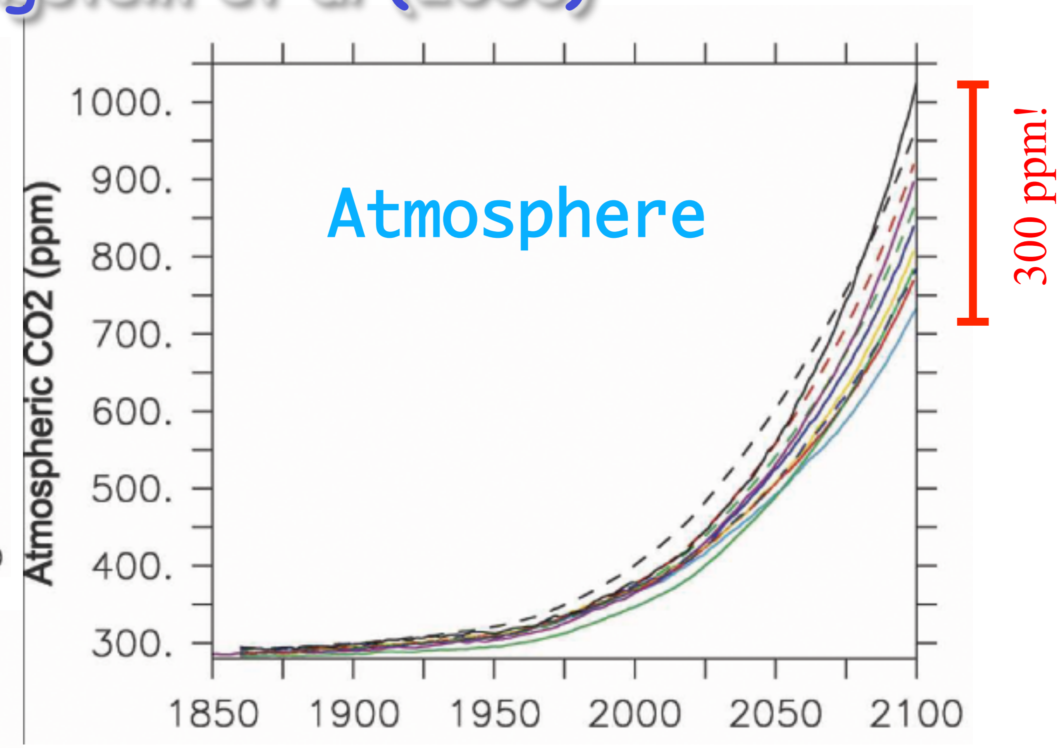


Carbon-Climate Futures

Friedlingstein et al (2006)







- Coupled simulations of climate and the carbon cycle
- Given nearly identical human emissions, different models project dramatically different futures!

Summary

- Emissions of CO_2 by global industry are part of a much bigger biogeochemical cycle of carbon
- About half of anthropogenic CO_2 emissions are removed from the atmosphere by pertubations to natural biogeochemistry that are not completely understood
- Uncertainties in future human emissions and in the response of global biogeochemistry to changing climate are among the leading sources of uncertainty in predictions of 21st century climate

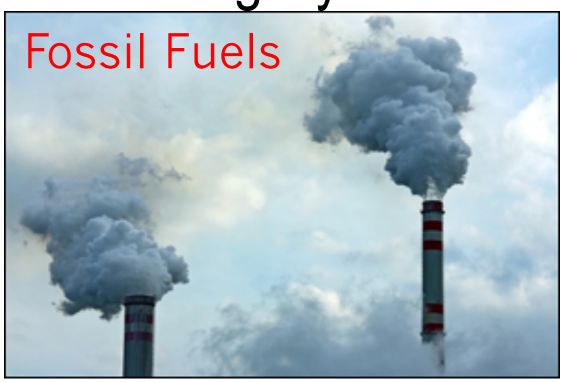
Emerging Technology!

- Land 'sink' is small residual from large uptake (photosynthesis) and respiration terms
- Global observation of these terms have not been available
- New observations of fluorescence from plants may provide a window into global photosynthesis processes
- This, in turn, may help us to be able to describe the land sink more completely for both present and future climate!

Fate of Anthropogenic CO_2 Emissions (2000-2009)

1.1±0.7 PgC y^{-1}

7.7±0.5 PgC y^{-1} +



4.1±0.1 PgC y^{-1}

47%

2.4 PgC y^{-1}

27%

Calculated as the residual of all other flux components

26%

2.3±0.4 PgC y^{-1}

Average of 5 models

Global Carbon Project 2010

Slide courtesy of C. O'Dell, CSU