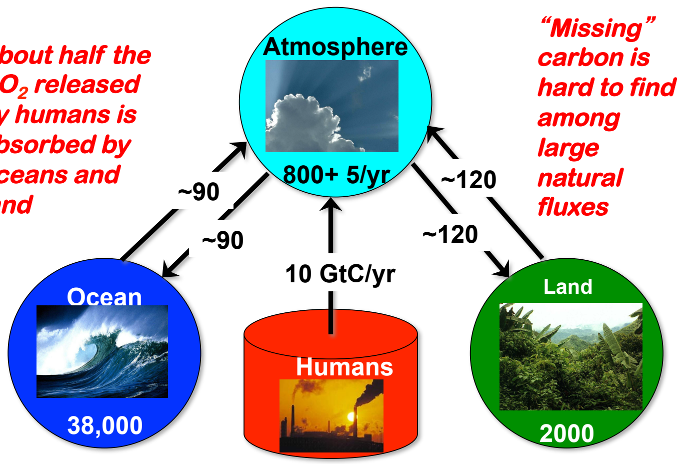
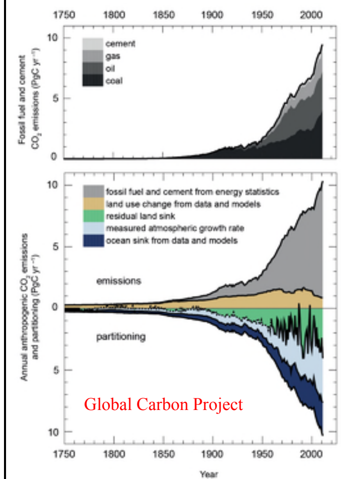
The Global Carbon Cycle

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



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

Carbon Sources and Sinks



- Half the carbon from fossil fuels remains in the atmosphere
- The other half goes into land and oceans
- Land sink was unexpected is very noisy, and remains unreliable in future
- Future of carbon sinks is much harder to predict than temperatures

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)

Carbonate Equilibria in Solution

Three equations (equilibria) in five unknowns

$$CO_2(\text{gas}) \longleftrightarrow CO_2(\text{dissolved}) \qquad [CO_2(aq)] = K_0 pCO_2$$

$$[CO_2(aq)] + H_2O \longleftrightarrow [H^+] + [HCO_3^-] \qquad K_1 = [H^+][HCO_3^-]/[CO_2(aq)]$$

$$[HCO_3^-] \longleftrightarrow [H^+] + [CO_3^{2-}] \qquad K_2 = [H^+][CO_3^{2-}]/[HCO_3^-]$$

Add two more constraints

$$TA = [HCO_3^-] + 2[CO_3^{2-}] + [B(OH)_4^-] + [NO_3^-] + [OH^-] - [H^+] \pm \text{minor species}$$

(Titration Alkalinity)

$$B(OH)_3 + H_2O \leftrightarrow H^+ + B(OH)_4^-, \qquad K_b = [H^+][B(OH)_4^-]/[B(OH)_3]$$

(Boric acid dissociation)

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

(Salinity)

The "Revelle Factor"

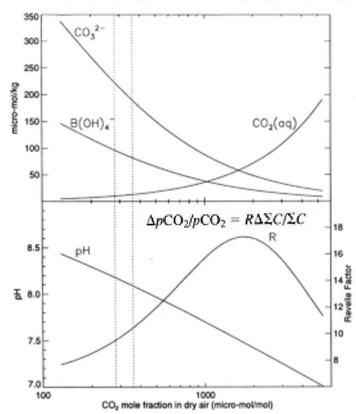
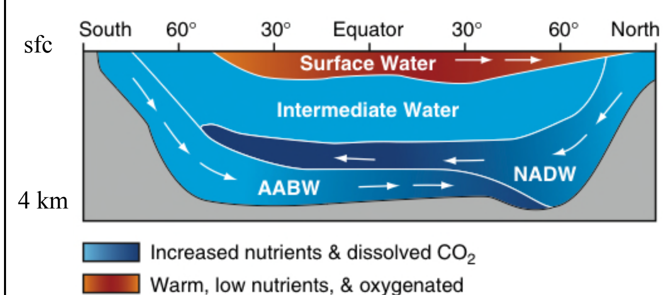


Figure 12.2. The response of surface ocean waters at 16°C to increasing atmospheric concentrations of CO_2, which is plotted on a logarithmic scale. The dissolved $CO_2(aq)$ increase is directly proportional to pCO_2 (Henry's Law). The decreases of CO_3^{2-} and $B(OH)_4^-$ have been calculated with the constants of Table 12.1. In the lower panel, pH is referred to the left axis, and the Revelle factor, R, (see main text) is referred to the right axis. The vertical dotted lines indicate the preindustrial (280 ppm) and the 1995 level of CO_2 (360 ppm).

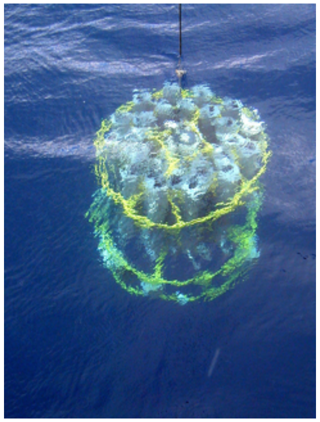
- As CO_2 is added to the atmosphere, CO_3^{2-} is consumed to form additional HCO_3^-
- As CO_3^{2-} becomes more scarce, Revelle factor increases, severely limiting capacity of ocean to absorb more CO_2
- At very high pCO_2, pH decreases enough that sedimentary $CaCO_3$ dissolves, providing CO_3^{2-} and decreasing *R* again

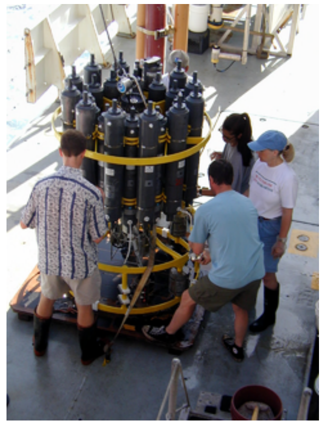
Vertical Structure of the Oceans



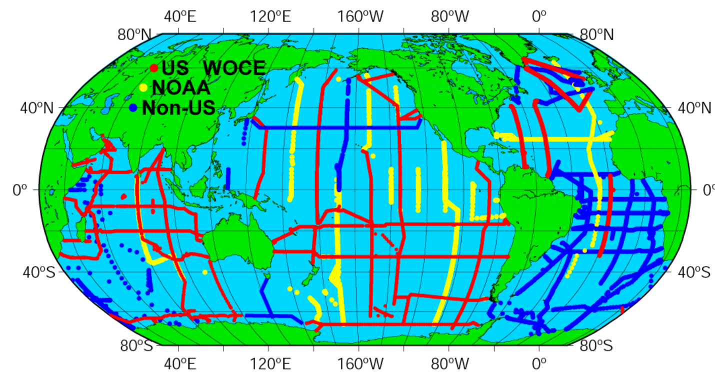
- Warm buoyant "raft" floats at surface
- Cold deep water is only "formed" at high latitudes
- Very stable, hard to mix, takes ~ 1000 years!
- Icy cold, inky black, most of the ocean doesn't know we're here yet!

Observing the Deep Ocean





WOCE/JGOFS/OACES Global Survey Data



Anthropogenic DIC

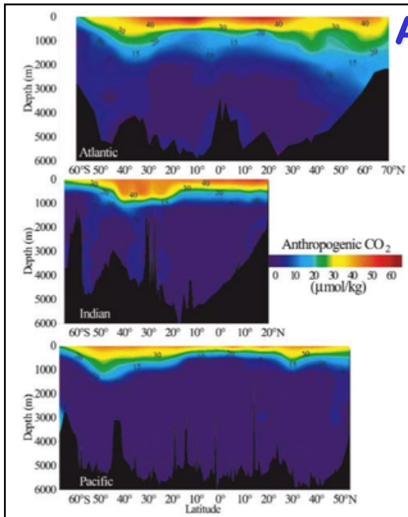
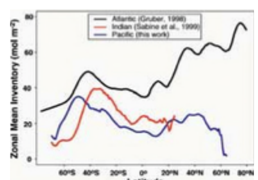


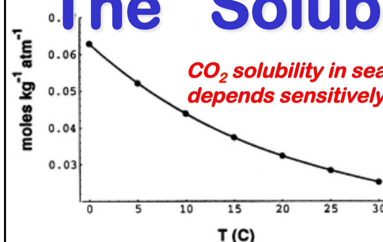
Figure 8. Zonal mean distributions of estimated anthropogenic CO_2 concentrations (in units of µmol kg⁻¹) along north-south transects in the Atlantic, Indian and Pacific oceans. The Pacific and Indian Ocean data are from the Global CO_2 Survey (this study), and the Atlantic Ocean data are from Gruber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

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

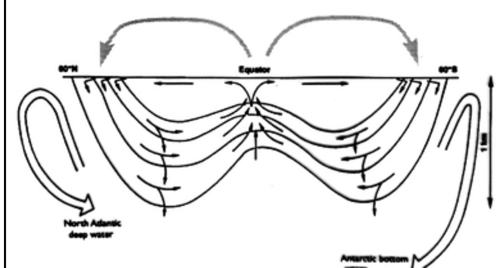


(Feeley et al, 2001)

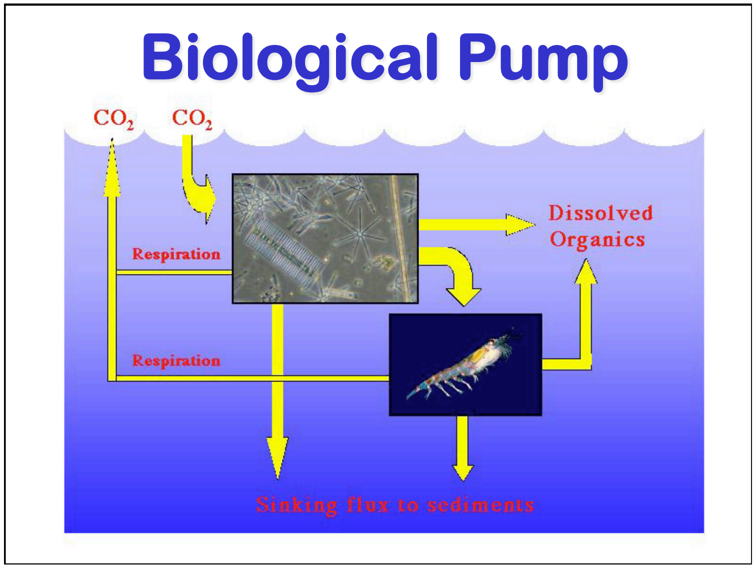
The "Solubility Pump"

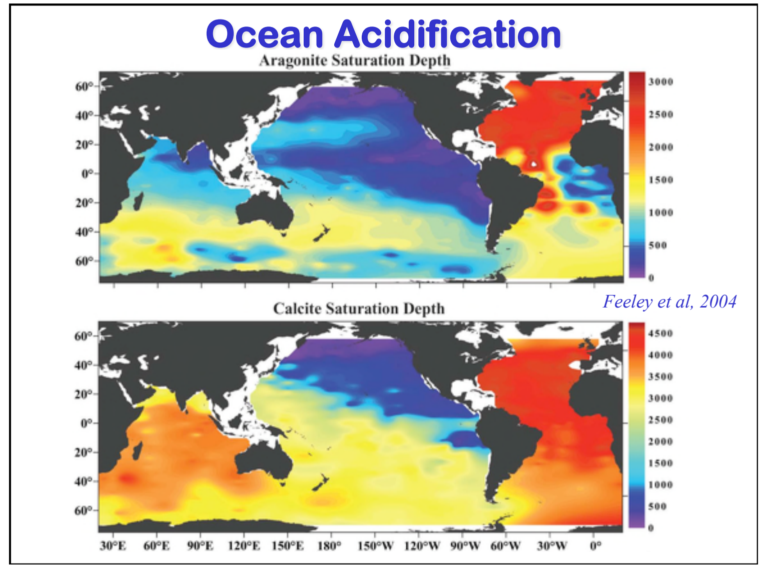


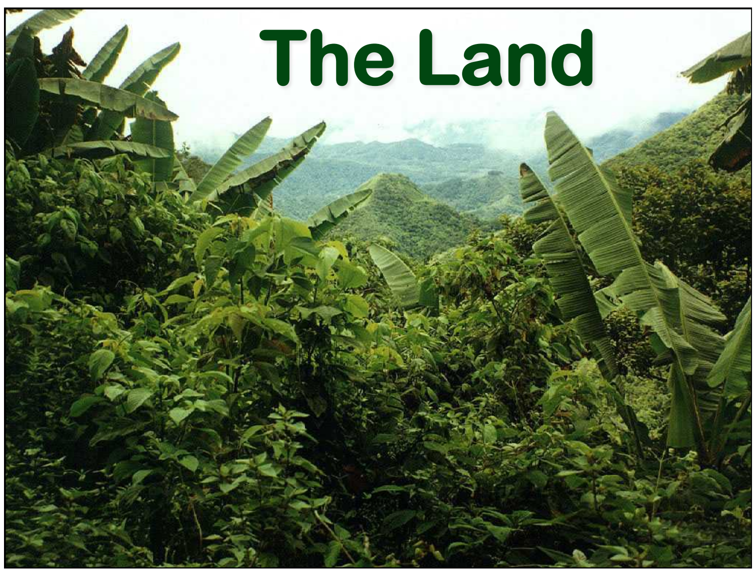
CO_2 solubility in seawater depends sensitively on SST

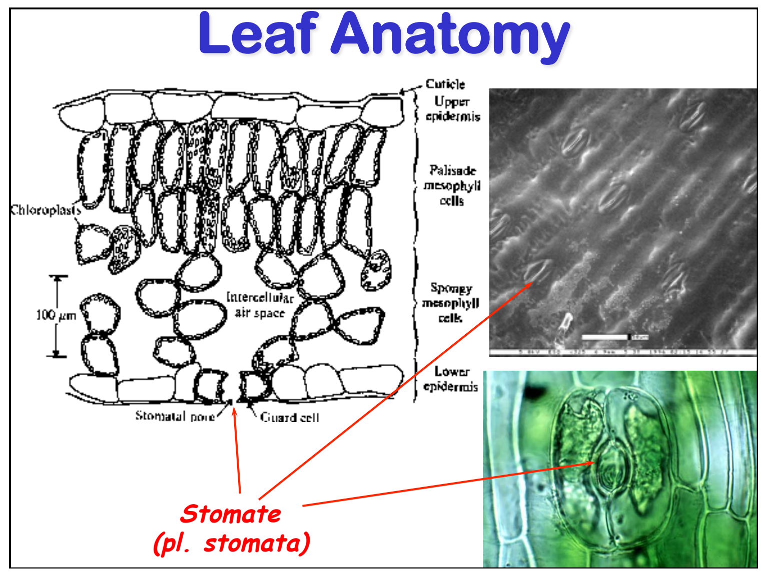


- CO_2 is highly soluble in cold high-lat waters
- Transported to deep ocean by convection and isopycnal mixing
- Dynamically-driven equatorial upwelling brings high-CO_2 water to surface
- Atmospheric transport closes the loop

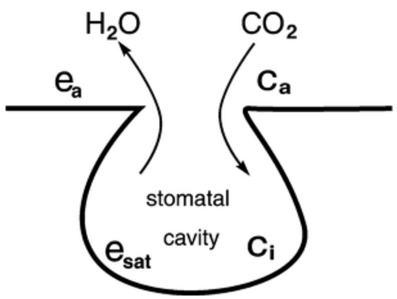

Biological Pump
CO_2
CO_2
Dissolved Organics
Respiration
Respiration
Sinking flux to sediments


Ocean Acidification
Aragonite Saturation Depth
Calcite Saturation Depth
Feeley et al, 2004

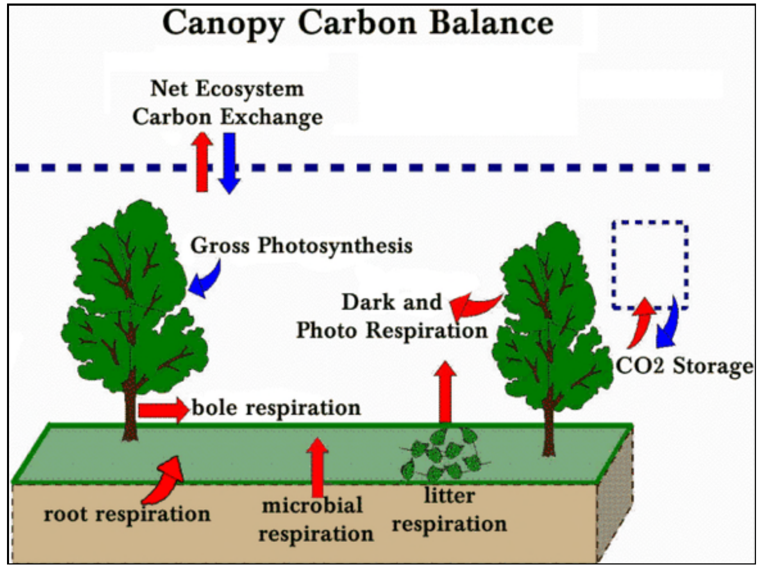

The Land


Leaf Anatomy
Cuticle
Upper epidermis
Palisade mesophyll cells
Chloroplasts
Intercellular air space
100 µm
Spongy mesophyll cells
Lower epidermis
Stomatal pore
Guard cell
Stomate
(pl. stomata)

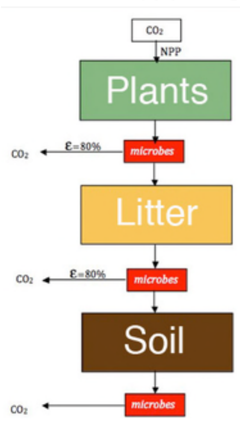
Carbon and Water



- 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

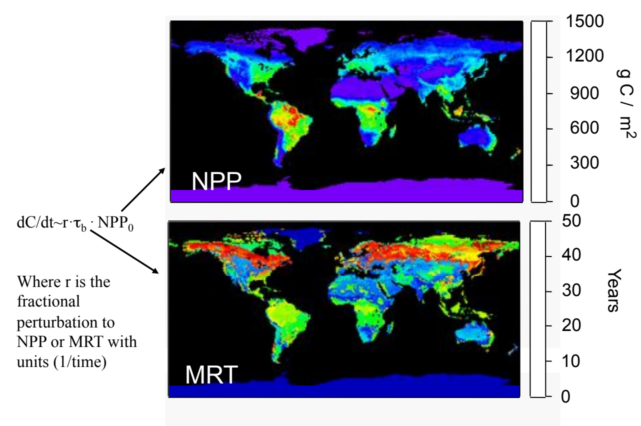


Carbon Storage & Turnover in Land Ecosystems

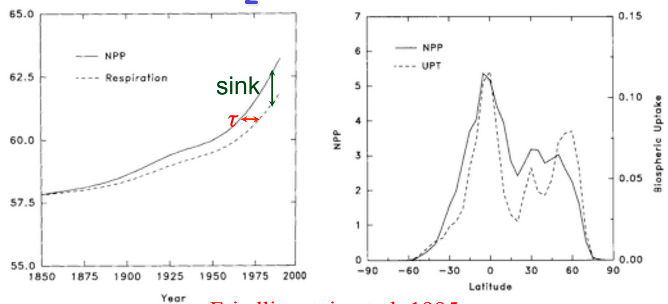


- Photosynthesis converts inorganic gas into living plants
- Plants die and become "litter"
- Microbes eat litter and poop soil carbon
- Soil carbon is eventually also eaten by microbes, but some lasts for many centuries

Net Primary Production and mean residence times of carbon determines source/sink potential of ecosystems



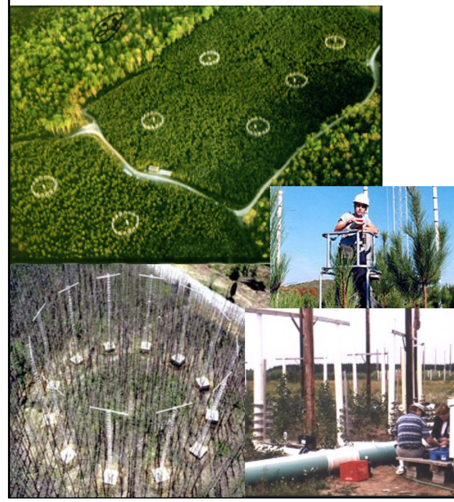
CO_2 Fertilization



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)



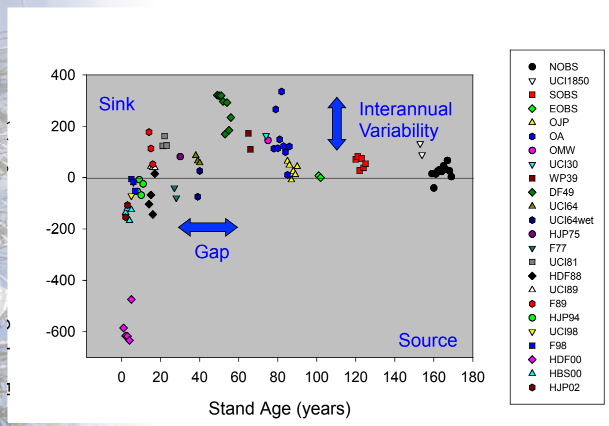
- Fumigation rings maintain steady levels of elevated CO_2 in canopies under changing weather conditions
- Control and replicated treatments test effects of CO_2, water, N, etc

Disturbance

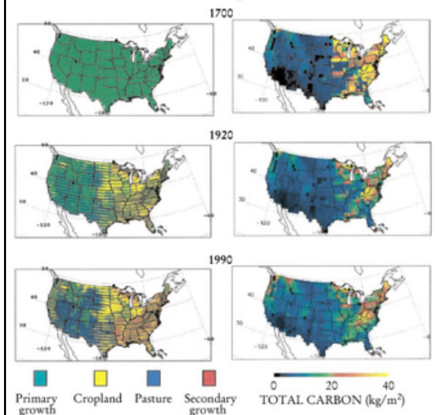
Disturbance and Recovery

Planted	2000	1988	1949
Height (m)	0.8	3-8	30-35

Fluxnet-Canada Annual Carbon Budgets



Agricultural Development & Abandonment



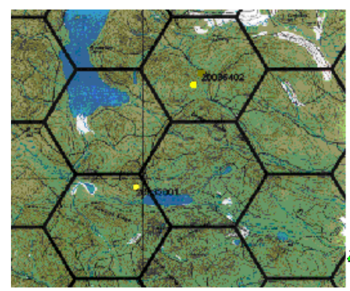
- Land clearing in 18th and 19th centuries released large amounts of CO_2 to atmosphere
- Shift of agriculture to Midwest and California in 20th century
- *Regrowing forests are a carbon sink*

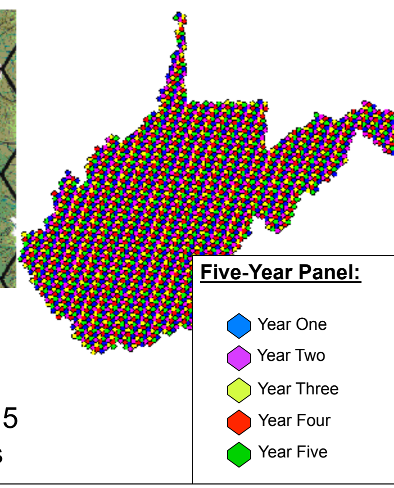
ED model result: Moorcroft *et al* (2001)

Forest Inventory Sampling

USDA Forest Service measures hundreds of thousands of plots!

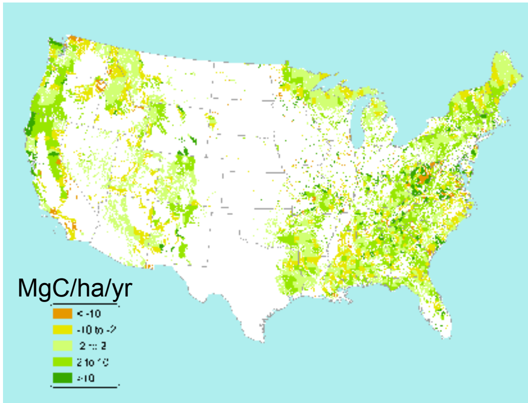
USDA Forest Service FIA Plots





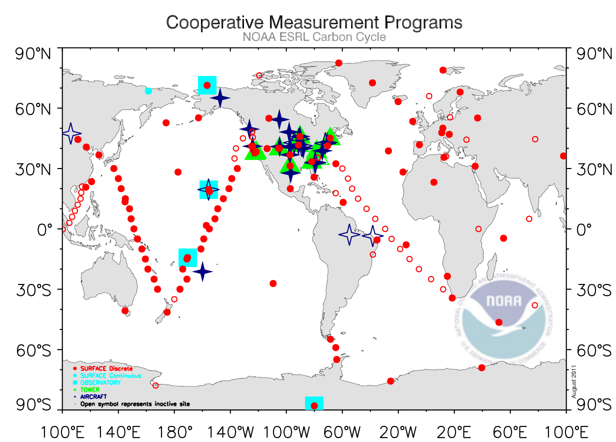
- 6000 acre grid cells
- 1 plot per grid cell
- >800K plots
- each plot visited every 5 (east) or 10 (west) years

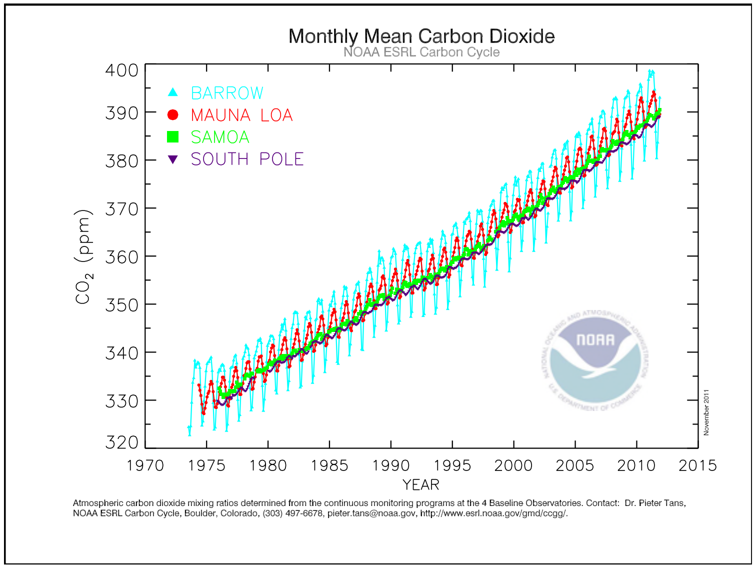
Average annual live tree C stock change by county, estimated from FIA data

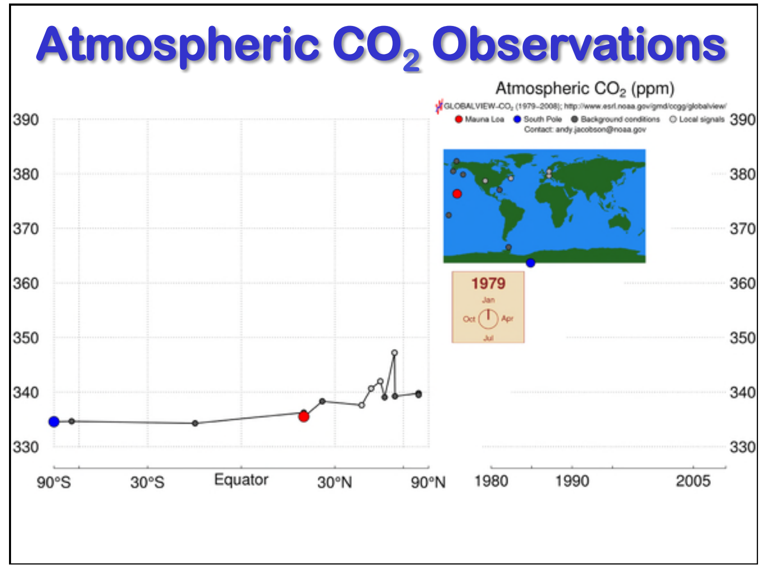


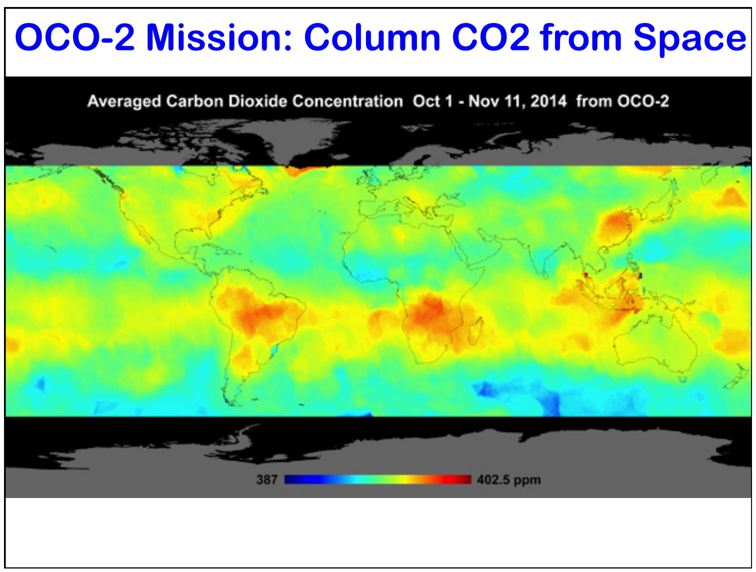
Courtesy of Linda Heath, USFS

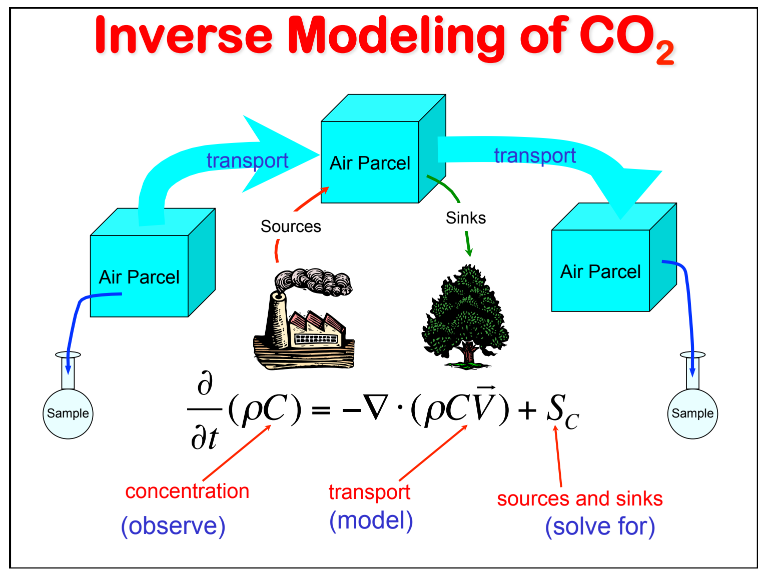
Atmospheric CO_2 Observations (in-situ)

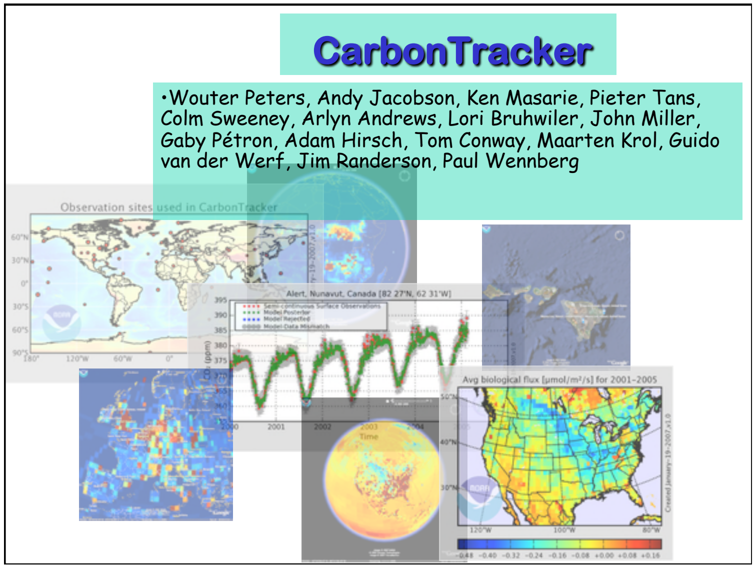


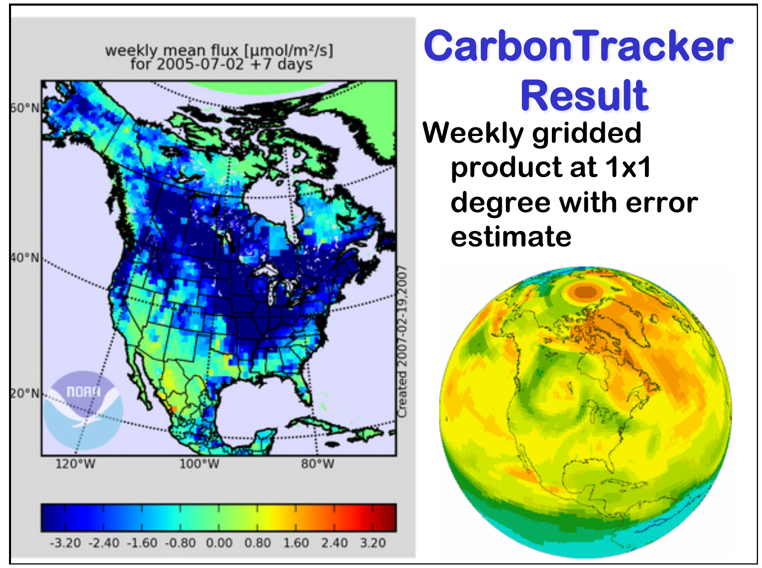

Monthly Mean Carbon Dioxide
NOAA ESRL Carbon Cycle
BARROW
MAUNA LOA
SAMOA
SOUTH POLE
CO_2 (ppm)
YEAR
Atmospheric carbon dioxide mixing ratios determined from the continuous monitoring programs at the 4 Baseline Observatories. Contact: Dr. Pieter Tans, NOAA ESRL Carbon Cycle, Boulder, Colorado, (303) 497-6678, pieter.tans@noaa.gov, http://www.esrl.noaa.gov/gmd/ccgg/.

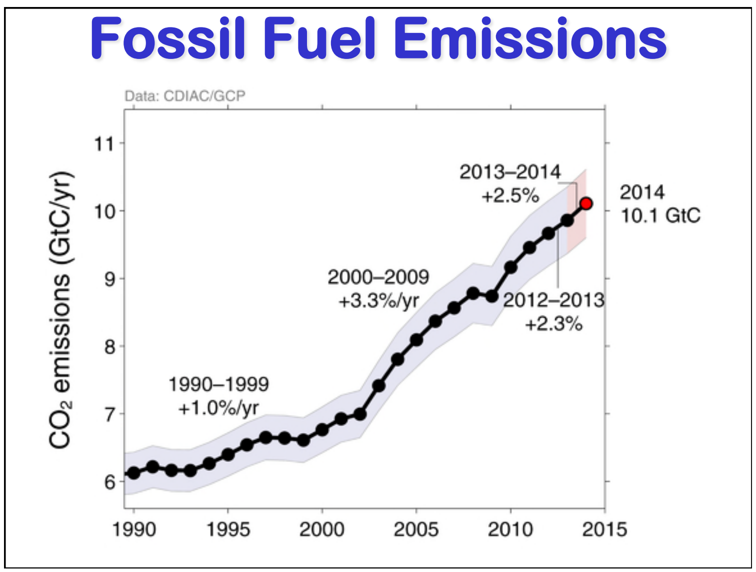

Atmospheric CO_2 Observations
Atmospheric CO_2 (ppm)
1979
90°S
30°S
Equator
30°N
90°N
1980
1990
2005

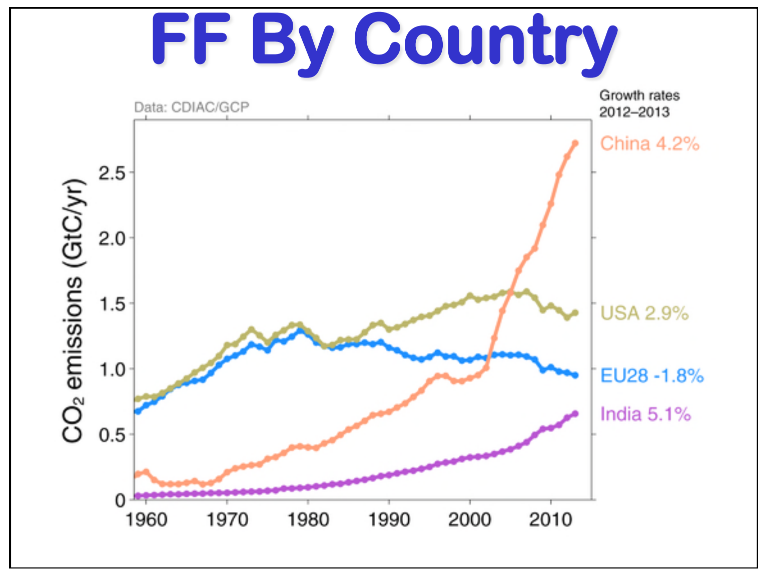

OCO-2 Mission: Column CO2 from Space
Averaged Carbon Dioxide Concentration Oct 1 - Nov 11, 2014 from OCO-2
387
402.5 ppm


Inverse Modeling of CO_2
transport
Air Parcel
transport
Air Parcel
Sources
Sinks
Air Parcel
Sample
Sample
$\frac{\partial}{\partial t}(\rho C) = -\nabla \cdot (\rho C \vec{V}) + S_C$
concentration
(observe)
transport
(model)
sources and sinks
(solve for)

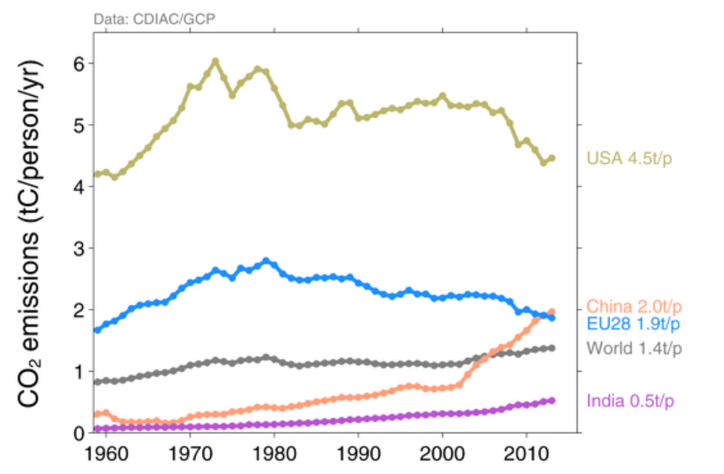

CarbonTracker
•Wouter Peters, Andy Jacobson, Ken Masarie, Pieter Tans, Colm Sweeney, Arlyn Andrews, Lori Bruhwiler, John Miller, Gaby Pétron, Adam Hirsch, Tom Conway, Maarten Krol, Guido van der Werf, Jim Randerson, Paul Wennberg
Observation sites used in CarbonTracker
Alert, Nunavut, Canada [82 27'N, 62 31'W]
Avg biological flux [μmol/m²/s] for 2001–2005


weekly mean flux [μmol/m²/s]
for 2005-07-02 +7 days
60°N
40°N
20°N
120°W
100°W
80°W
Created 2007-02-19,2007
-3.20 -2.40 -1.60 -0.80 0.00 0.80 1.60 2.40 3.20
CarbonTracker Result
Weekly gridded product at 1x1 degree with error estimate


Fossil Fuel Emissions
Data: CDIAC/GCP
CO₂ emissions (GtC/yr)
11
10
9
8
7
6
1990 1995 2000 2005 2010 2015
1990–1999
+1.0%/yr
2000–2009
+3.3%/yr
2012–2013
+2.3%
2013–2014
+2.5%
2014
10.1 GtC

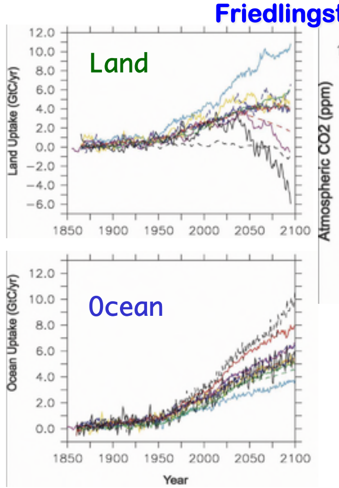

FF By Country
Data: CDIAC/GCP
Growth rates
2012–2013
CO₂ emissions (GtC/yr)
2.5
2.0
1.5
1.0
0.5
0
1960 1970 1980 1990 2000 2010
China 4.2%
USA 2.9%
EU28 -1.8%
India 5.1%

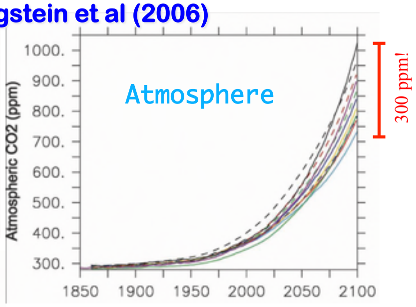
FF per Capita



Carbon-Climate Futures

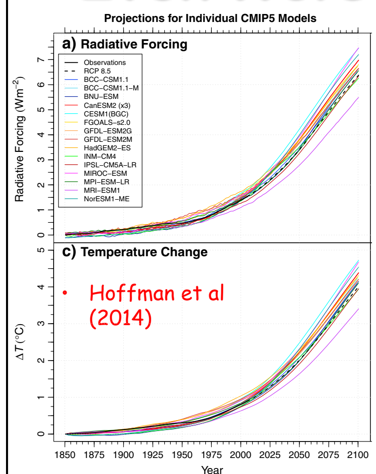
Friedlingstein et al (2006)





- Coupled simulations of climate and the carbon cycle (CMIP3, C4MIP)
- Given nearly identical human emissions, different models project dramatically different futures!
- Mostly depends on CO_2 fert & temp

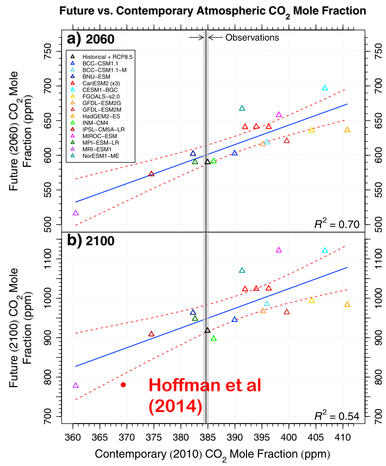
Even Worse in CMIP5 !



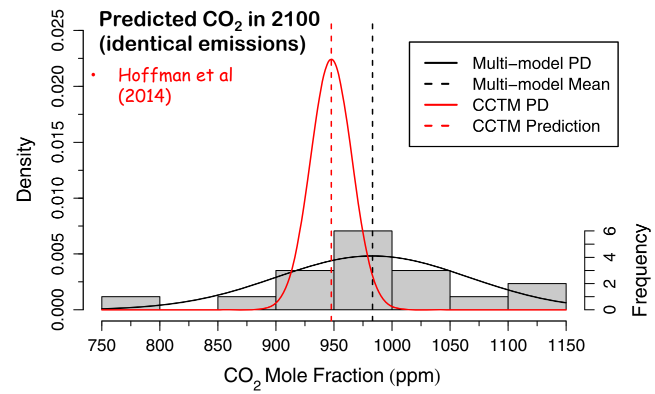
- More processes (land use, regrowth, nitrogen, fire)
- Now more than 350 ppm spread in CO_2!
- For identical emissions, radiative forcing varies by almost 2 W m^{-2} (more than RCP 4.5 vs RCP 6)
- Warming varies by 1.5 °C (comparable to spread in physical climate)
- Carbon cycle impacts climate uncertainty as much as clouds or people!

Past as Prelude

- Models that underpredict contemporary CO_2 also predict low CO_2 in the future, and vice versa
- Evaluation of past carbon cycle simulations constrain future feedback



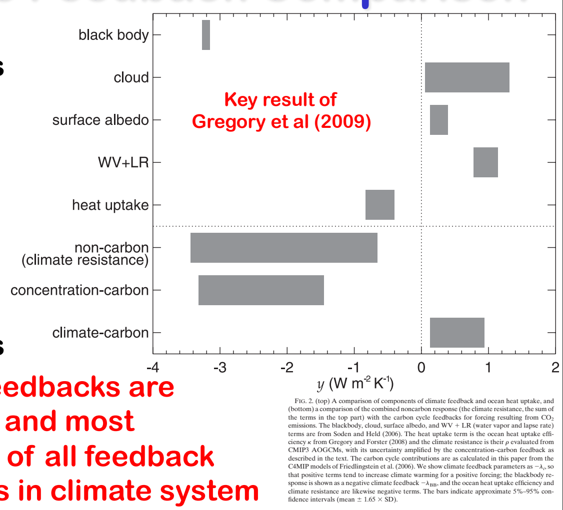
Carbon Constraint



- Fivefold reduction in model spread in 2100
- No mechanism … simple scalar multiplication of sinks

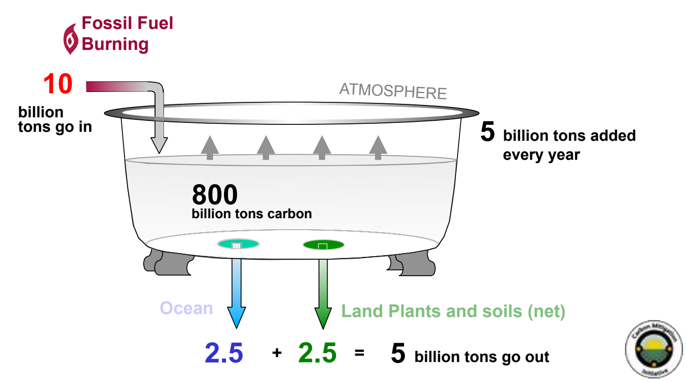
Climate Feedback Comparison

- Carbon feedbacks are compared "apples-and-apples" to other climate feedbacks



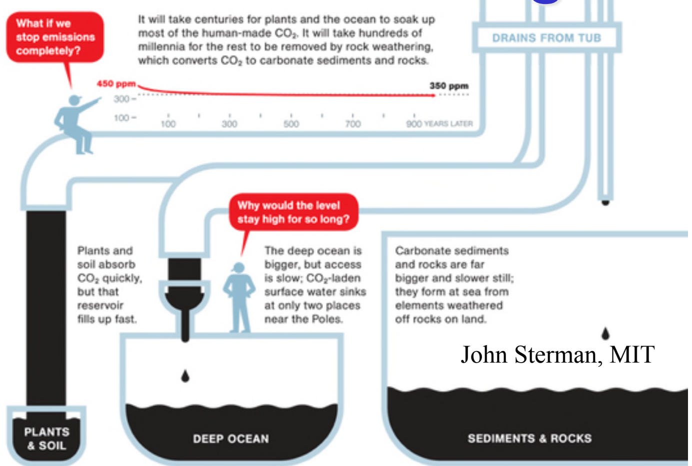
- Carbon feedbacks are strongest and most uncertain of all feedback processes in climate system

CO_2 "Budget" of the World



Climate forcing comes from the water, not from the faucet!

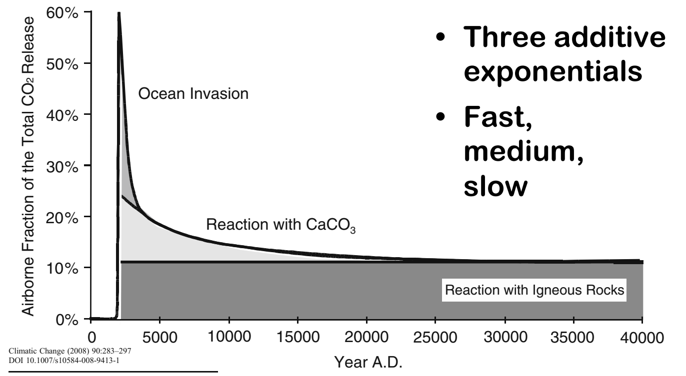
Bathtub Drainage



John Sterman, MIT

http://ngm.nationalgeographic.com/big-idea/05/carbon-bath

The Long Tail



- Three additive exponentials
- Fast, medium, slow

Climatic Change (2008) 90:283–297
DOI 10.1007/s10584-008-9413-1

The millennial atmospheric lifetime of anthropogenic CO_2

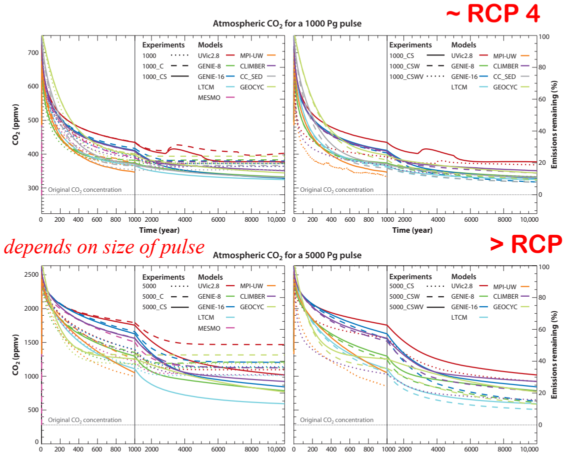
David Archer · Victor Brovkin

Can't fit sum of exponentials with a single "atmospheric lifetime"

Long Tail Intercomparison

Annu. Rev. Earth Planet. Sci. 2009.37:117-134. Downloaded from arjournals.annualreviews.org by UNIVERSITY OF CHICAGO LIBRARIES on 04/28/09. For personal use only.

~ RCP 4



Duration depends on size of pulse

> RCP 8

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 perturbations 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
- Some anthropogenic CO_2 lasts for millennia

Consider taking
ATS 760 next fall!

ats760.atmos.colostate.edu

10:00 – 10:50 T & Th