Atmospheric Transport Modeling and the Carbon Cycle

Read Peters et al 2007 PNAS

“CarbonTracker”

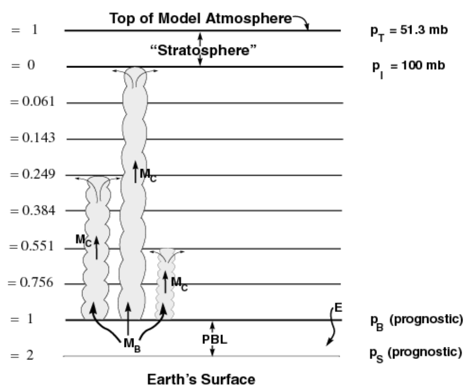
Transport

- Advection:
  - Stuff that was “upstream” moves here with the wind:

$$\frac{\partial q}{\partial t} = -u\frac{\partial q}{\partial x} - v\frac{\partial q}{\partial y} - w\frac{\partial q}{\partial z} + Source(q)$$

  - To predict the future amount of q, we simply need to keep track of gradients and wind speed in each direction
- What spatial scales are involved?
- Can we resolve advective transports by turbulent eddies and convective clouds (thunderstorms) in a global model?
  - (No)

Cumulus Transport (example)

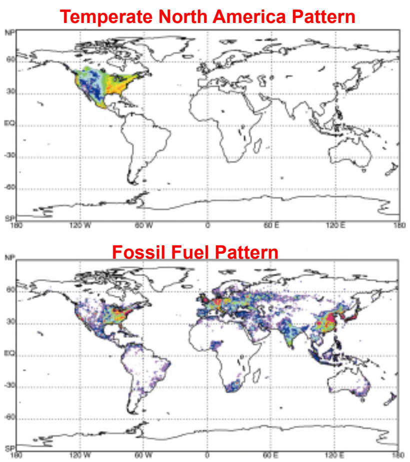


- Cloud “types” defined by lateral entrainment
- Separate in-cloud CO2 soundings for each type
- Detrainment back into environment at cloud top

Synthesis Inversion Procedure
(“Divide and Conquer”)

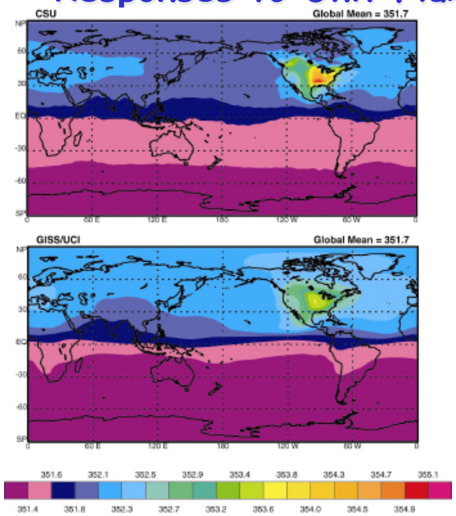
1. Divide carbon fluxes into subsets based on processes, geographic regions, or some combination
   1. Spatial patterns of fluxes within regions?
   2. Temporal phasing (e.g., seasonal, diurnal, interannual?)
2. Prescribe emissions of unit strength from each “basis function” as lower boundary forcing to a global tracer transport model
3. Integrate the model for three years (“spin-up”) from initially uniform conditions to obtain equilibrium with sources and sinks
4. Each resulting simulated concentration field shows the “influence” of the particular emissions pattern
5. Combine these fields to “synthesize” a concentration field that agrees with observations

Forward Transport Step



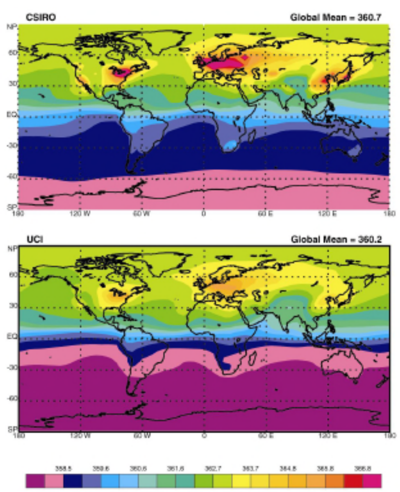
- Discretize emissions into spatial and seasonal "basis functions"
- Obtain archived winds from NWP reanalysis, or run a full GCM
- Advection by resolved winds
- Specify convective transports: HOW?

Responses to Unit Flux from N.A.



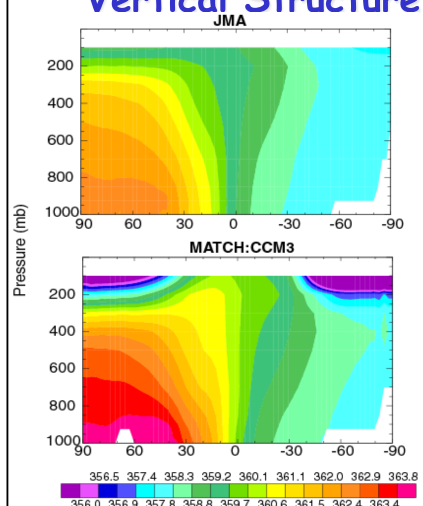
- Some models (e.g., CSU) show stronger gradients near source region
- Others (e.g., GISS) appear more thoroughly "mixed"

Fossil Fuel Response Functions



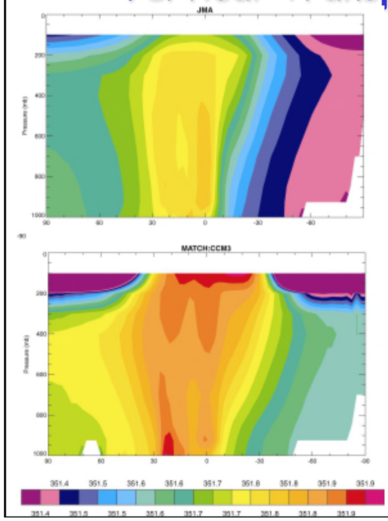
- Some models (e.g., CSIRO) show stronger gradients near source region
- Others (e.g., UCI) appear more thoroughly "mixed"

Vertical Structure: FF Response



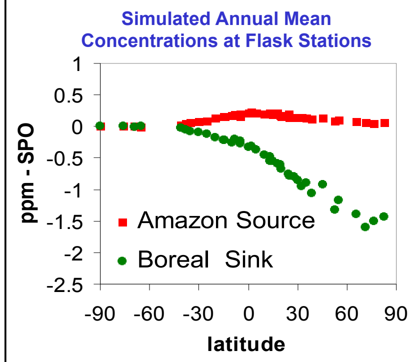
- Annual mean latitude-pressure cross sections show strong sensitivity to vertical mixing
- Strong vertical gradient in NH
- "Barrier" to cross-equator transport
- Reversed vertical gradient in SH
- Most of NS structure at surface in in NH subtropics

Vertical Transport is Crucial



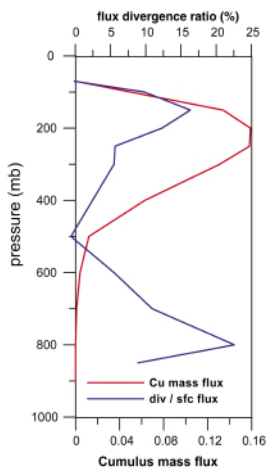
- Some models treat convection as "diffusive mixing" between adjacent layers
- Others treat convection as penetrative updrafts and downdrafts ("express elevators")
- Much of the surface structure actually related to vertical mixing

Poorly Constrained Tropical Fluxes



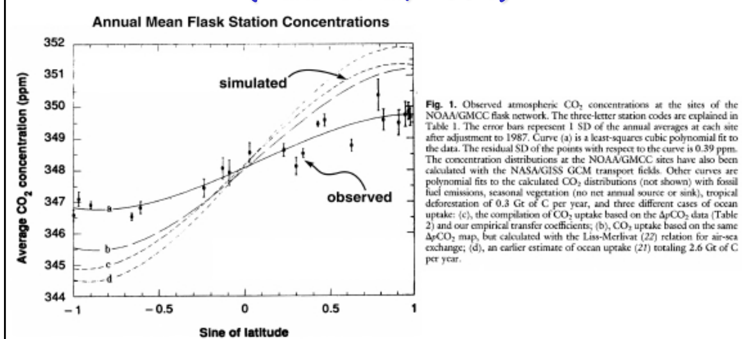
- Concentration response due to a 1 GtC/yr flux in the Amazon is much weaker than response due to a 1 GtC/yr flux in boreal forest
- This weak response is also poorly sampled in near the tropical continents

Convective Leakage



- Photosynthesis and cumulus convection are correlated in time and space in parts of the deep tropics
- Convective updrafts carry much of the "signal" of ecosystem flux aloft
- As much as 30% of the flux due to ecosystem metabolism leaves the atmospheric column in the upper troposphere, but nobody is looking there!

Meridional Gradients
(Tans et al, 1990)



Simulated gradient way too steep for most emission scenarios

Ocean pCO2 Measurements

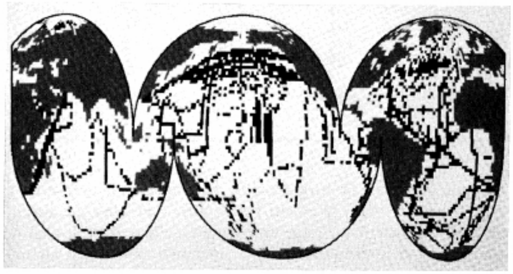


Fig. 2. The distribution of measurements of ΔpCO_2 since 1972. Where observations were made quasi-continuously, the values have been averaged over 2° intervals in longitude and latitude, and each of these intervals is represented by a single dot on the map.

- Reasonably well-constrained in NH and tropics
- Poor constraint in southern Ocean

"Permissible" Carbon Budgets

Table 3. Four modeled scenarios of the global atmospheric cycle. Fluxes are in units of gigatons of C per year and ΔpCO_2 is in microatmospheres. The terrestrial sources and sinks correspond to the basis functions: (i) tropical deforestation, (ii) carbon sequestering by temperate ecosystems, and (iii) CO_2 fertilization (see text). Fossil fuel combustion and the seasonality of the terrestrial biosphere is included in all cases. After fluxes to and from the terrestrial biosphere have been postulated, uptake by the oceans is adjusted to minimize the SD (in parts per million, last line) of the residual differences between the observed and calculated atmospheric CO_2 concentrations. The required annual average ΔpCO_2 is estimated for ocean basins with empirical air-sea gas transfer coefficients.

Source or sink	Scenario 1, flux	ΔpCO_2	Scenario 2, flux	ΔpCO_2	Scenario 3, flux	ΔpCO_2	Scenario 4, flux	ΔpCO_2
Tropical deforestation	0.3		0.3		2.0		2.0	
Temperate ecosystem uptake	0.0		0.0		0.0		−1.0	
CO_2 fertilization	0.0		−1.0		0.0		0.0	
Total terrestrial	0.3		−0.7		2.0		1.0	
North Atlantic (>50°N)	−0.7	−72	−0.5	−52	−0.7	−72	−0.5	−52
North Atlantic gyre (15° to 50°N)	−1.0	−52	−0.8	−42	−1.4	−73	−1.0	−52
North Pacific gyre (>15°N)	−1.0	−24	−0.7	−17	−1.4	−34	−1.0	−24
Equatorial (15°S to 15°N)	1.0	22	1.0	22	1.0	22	1.0	22
Combined southern gyres (15° to 50°S)	−1.4	−14	−1.1	−11	−2.3	−23	−2.3	−23
Antarctic (>50°S)	0.5	9	0.5	9	0.5	9	0.5	9
Total oceans	−2.6		−1.6		−4.3		−3.3	
SD of residuals	0.25		0.24		0.26		0.25	

"Permissible" Carbon Budgets (cont'd)

Table 4. Four modeled scenarios of the global atmospheric C cycle in which uptake by the northern and equatorial oceans is held fixed. Fluxes are in units of Gt of C per year. Equatorial ocean outgassing is lower than in Table 2 by 0.32 Gt of C per year to take into account El Niño episodes occurring about once every 4 years. After the rate of tropical deforestation has been postulated, CO_2 exchange with terrestrial ecosystems and the southern oceans is varied (indicated by asterisk) to produce agreement with the atmospheric observations. The estimates of uptake by the oceans are based on observed seasonal ΔpCO_2 values, monthly climatological winds and two sets of air-sea gas transfer coefficients, our empirical relation (Emp), and the Liss-Merlivat *(22)* relation (LM). In the latter case the equatorial oceanic source is smaller, so that less uptake is required at temperate latitudes in both hemispheres to balance the budget.

Source or sink	Scenario 5		Scenario 6		Scenario 7		Scenario 8	
	Emp	LM	Emp	LM	Emp	LM	Emp	LM
Tropical deforestation	0.0	0.0	1.0	1.0	1.0	1.0	2.5	2.5
CO_2 fertilization*	0.0	0.0	0.0	0.0	−1.0	−1.0	−3.0	−3.0
Temperate uptake*	−2.0	−2.0	−3.0	−2.9	−2.3	−2.0	−1.9	−1.9
Boreal source*	0.0	0.0	0.4	0.4	0.4	0.2	0.7	0.7
Total terrestrial	−2.0	−2.0	−1.6	−1.5	−1.9	−1.8	−1.7	−1.7
Arctic and sub-arctic (>50°N)	−0.23	−0.12	−0.23	−0.12	−0.23	−0.12	−0.23	−0.12
Combined northern gyres (15°N to 50°N)	−0.36	−0.18	−0.36	−0.18	−0.36	−0.18	−0.36	−0.18
Equatorial (15°S to 15°N)	1.30	0.65	1.30	0.65	1.30	0.65	1.30	0.65
Combined southern gyres* (50°S to 50°S)	−1.5	−1.1	−1.9	−1.6	−1.6	−1.3	−1.8	−1.4
Antarctic (>50°S)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Total oceans	−0.3	−0.3	−0.7	−0.8	−0.4	−0.5	−0.6	−0.6
SD of residuals (ppm)	0.26	0.28	0.27	0.29	0.27	0.28	0.28	0.29

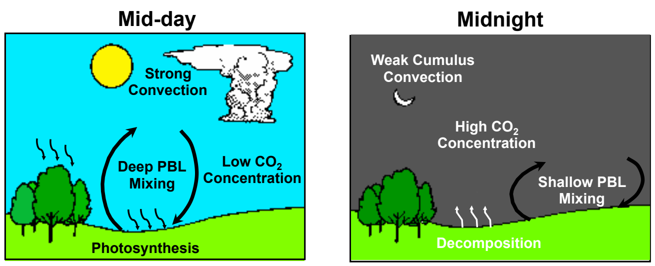
- "Postulate" a rate of tropical deforestation
- Set NH and tropical oceans to agree with pCO2 data
- Adjust NH lands and Southern Ocean to match observed atmospheric [CO2] gradient

Rectifier Analogy

Covariance between surface fluxes and atmospheric transport of CO_2 produces near-surface concentration timeseries with truncated minima

The effect is analogous to an electronic rectifier produced by a diode.

Diurnal Rectifier Forcing



Dilution of photosynthesis signal through deep mixing

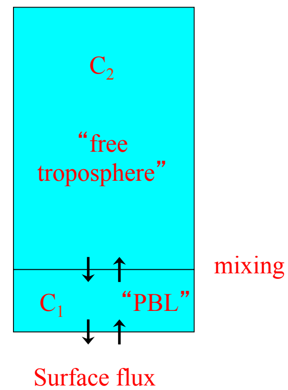
Transport of low-CO_2 air into upper troposphere

Accumulation of respiration signal near the surface

Elevated CO_2 in lower troposphere

Daily mean: Accumulation of CO_2 near the ground, depletion aloft

Conceptual Rectifier Model



$$\frac{\partial C_1}{\partial t} = F - \frac{(C_1 - C_2)}{\tau}$$

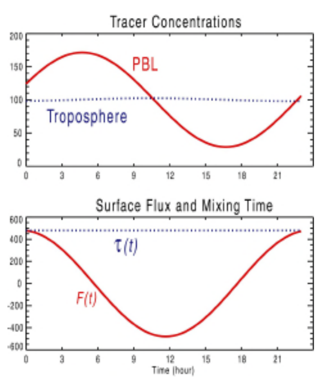
$$\frac{\partial C_2}{\partial t} = \quad + \frac{(C_1 - C_2)}{\tau}$$

where

F is the surface flux

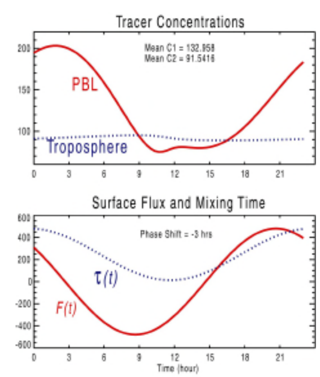
τ is the "mixing time scale"

Two-Box Model: No Rectification



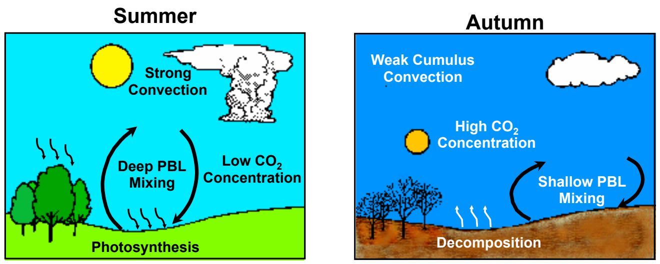
- Sinusoidal surface fluxes
- Mixing time scale is constant
- Result is a sinusoidal diurnal cycle of PBL concentration
- Damped sinusoidal variations in the troposphere are out of phase with PBL

Two-Box Rectifier Forcing



- Diurnal cycles of flux and mixing are correlated
- Classic "rectified" signal
- Phase lag maximizes rectification … reflects tracer "capacity" of PBL
- Diurnal mean in lower box is 133% of global mean

Seasonal Rectifier Forcing



Dilution of photosynthesis signal through deep mixing

Transport of low-CO_2 air into upper troposphere

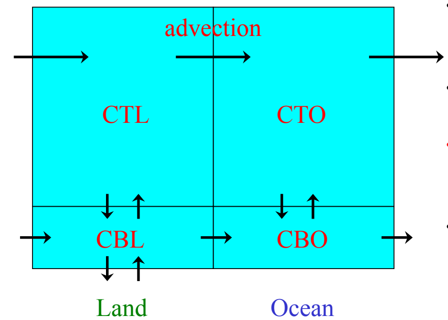
Accumulation of respiration signal near the surface

Elevated CO_2 in lower troposphere

Annual mean: Accumulation of CO_2 near the ground, depletion aloft

Four-Box Model

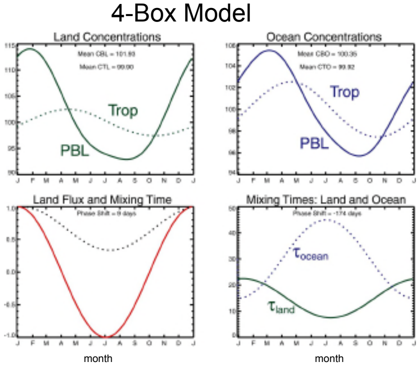
(analogous to flask network?)



- Forcing over land is identical to two-box model
- No surface flux over ocean
- Advection between land and ocean … cyclical boundaries
- Wind speed is 5x faster in troposphere than PBL

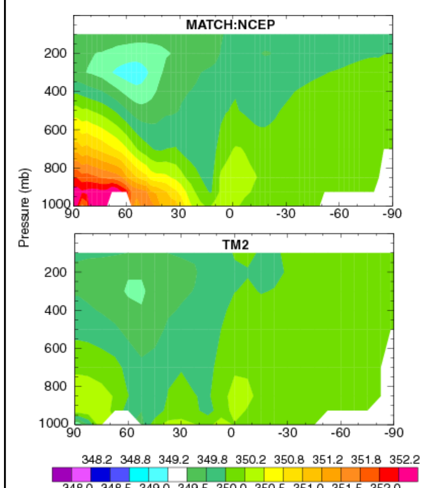
Seasonal Rectifier

4-Box Model



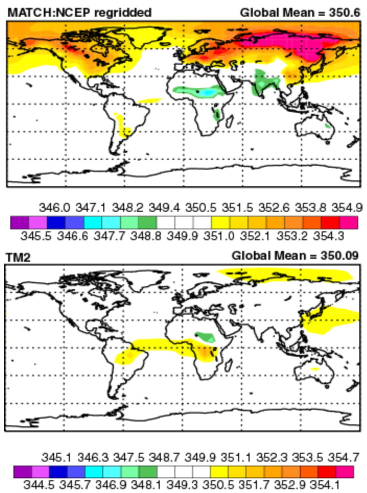
- Rectifier forcing on land is diluted by mixing over ocean (where $F = 0$)
- Vertical mixing over ocean has opposite seasonality relative to land
- Depending on parameter choices, free tropospheric advection and marine mixing can obliterate signal in MBL

Global Rectifier Response



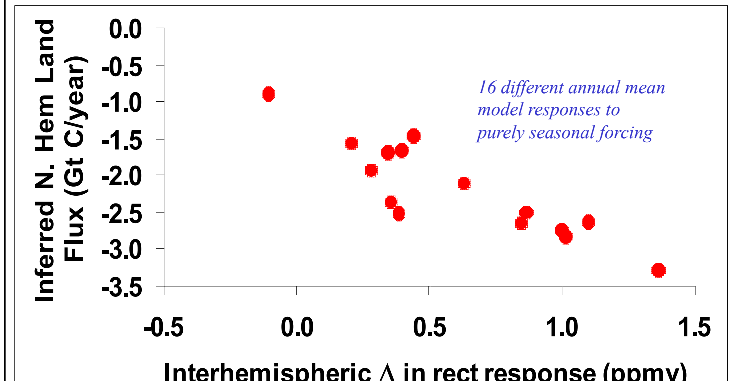
- Very strong model dependence!
- Elevated CO2 near surface over seasonal land
- Depleted CO2 aloft over land
- Not much going on in SH (mostly ocean)

Surface Rectifier Response

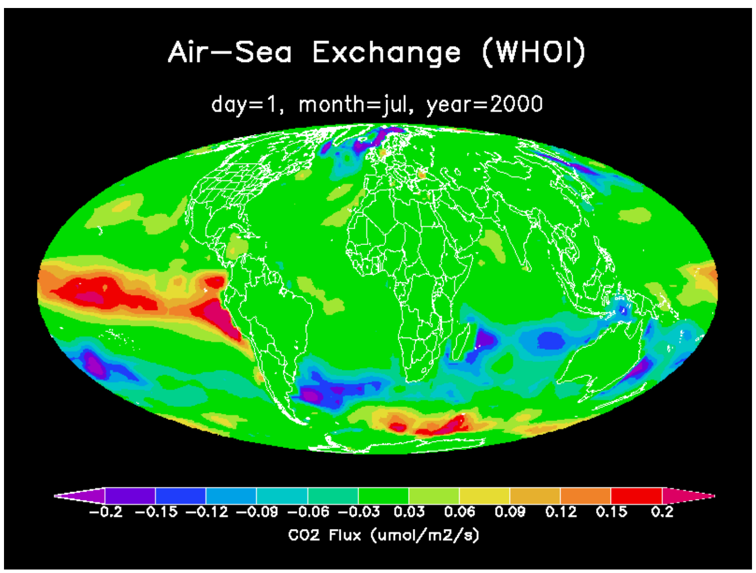


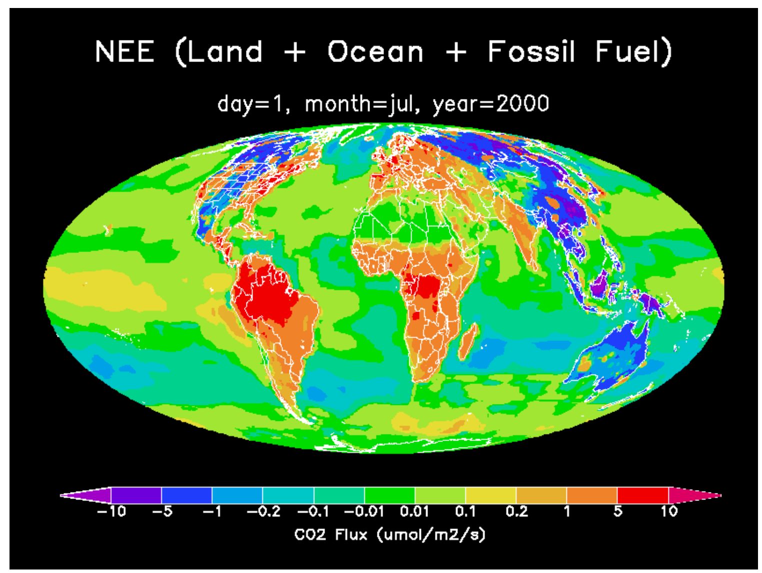
- Differences in vertical structure among models produce huge differences in annual mean surface [CO_2]
- These differences are interpreted by the inversion as differences in surface fluxes
- Remember, they were produced by a flux field that integrates to zero at every grid cell in the annual mean!

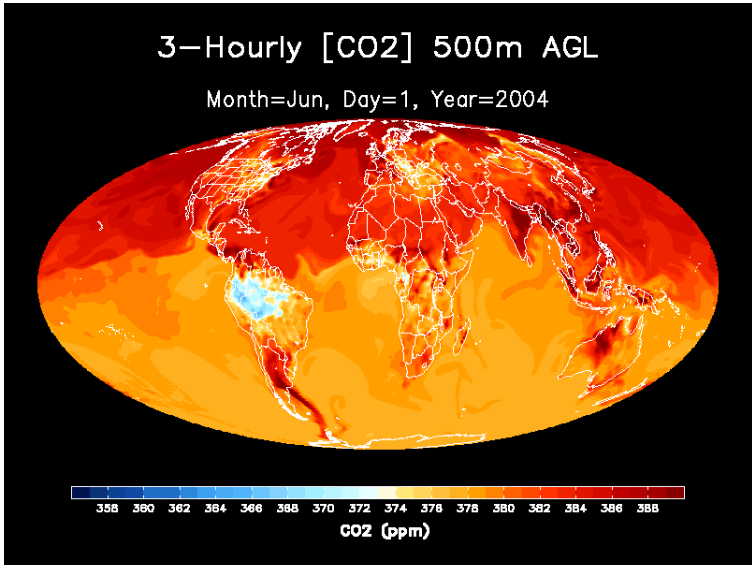
Rectifier Controls Inversion Result



Rectifier response is the major source of uncertainty in NH sink structure, but can't observe directly in atmosphere

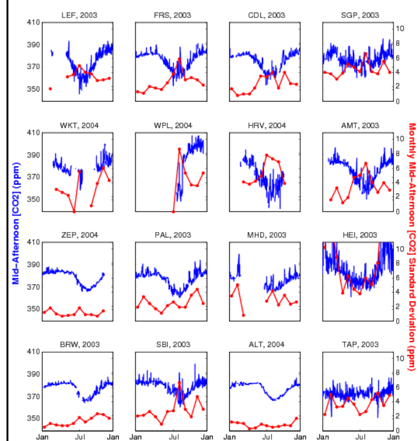


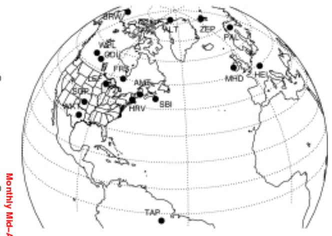




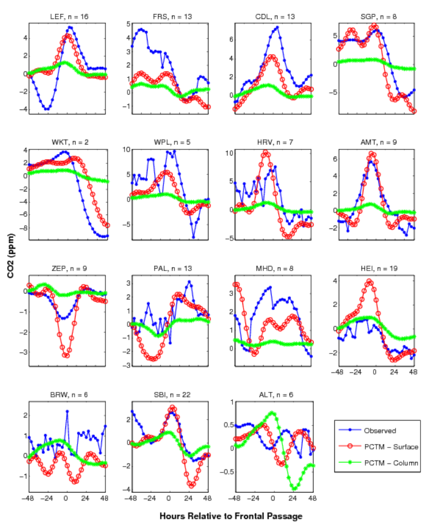
Strong Synoptic Variations

Mid-Afternoon [CO_2], 2003





- Monthly σ of 5-10 ppm, strongest in summer
- Day-to-day variations at some sites comparable to seasonal cycle
- Some events can be traced across multiple sites
- "Toto, I don't think we're in Hawaii anymore!"

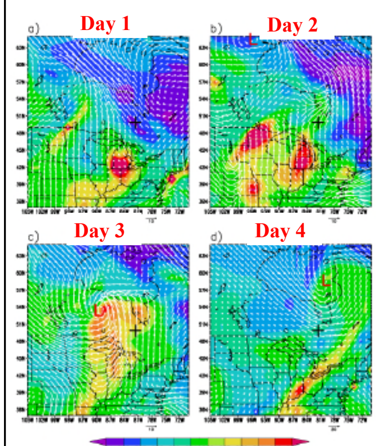


Frontal CO_2 "Climatology"

- Multiple cold fronts averaged together (diurnal & seasonal cycle removed)
- Some sites show frontal drop in CO_2, some show frontal rise … controls?
- Simulated shape and phase similar to observations
- What causes these?

Nick Parazoo et al, in prep

Deformational Flow



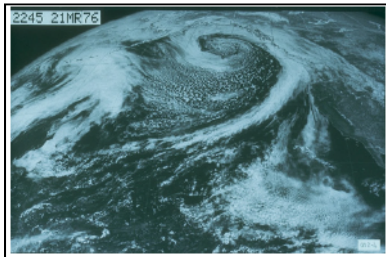
$$\frac{D_g}{Dt}\left(\frac{\partial C}{\partial x}+\frac{\partial C}{\partial y}\right)=-\left(\frac{\partial u_g}{\partial x}\frac{\partial C}{\partial x}+\frac{\partial v_g}{\partial x}\frac{\partial C}{\partial y}\right)-\left(\frac{\partial u_g}{\partial y}\frac{\partial C}{\partial x}+\frac{\partial v_g}{\partial y}\frac{\partial C}{\partial y}\right)$$

gradient strength

shear deformation
- tracer field rotated by shear vorticity

stretching deformation
- tracer field deformed by stretching

- Large-scale gradients produced by flux differences
- CO_2 anomalies organized along cold front
- dC/dx ~ 15ppm/300 km!



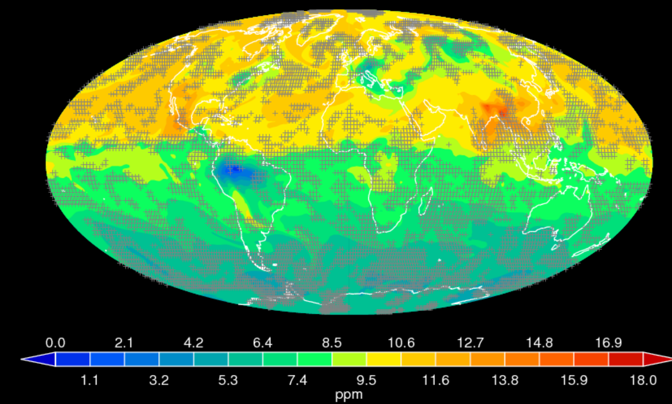
Midlatitude CO_2 Fronts

- Weather anomalies (clouds, rain, heat, drought, etc) produce regional NEE anomalies
- Persistent NEE anomalies produce regional CO_2 anomalies
- Deformation flow compresses CO_2 gradient along boundary, then stretches zone of high gradient along frontal zone
- But frontal zones are often cloudy …

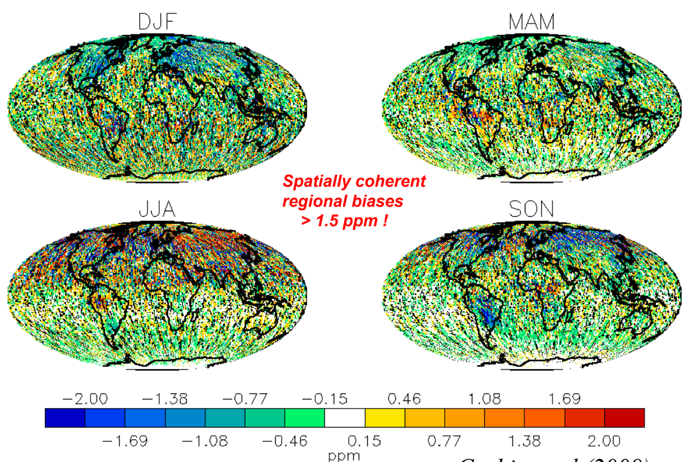
Global Clearsky Sampling Errors

Column CO2 with Cloud Mask

Day= 1, Month=Jun, Year=2003

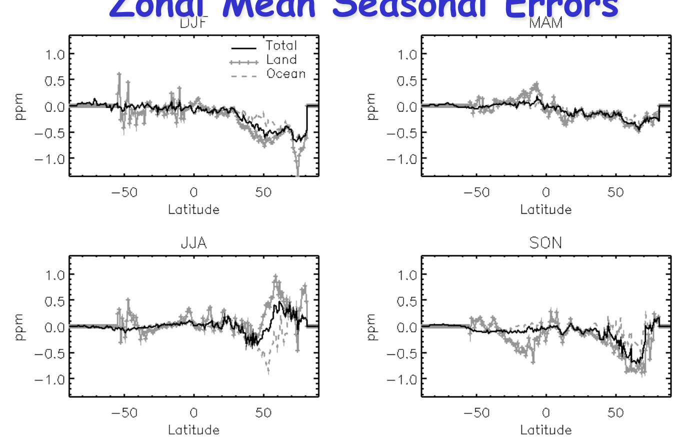


Seasonal Clearsky Sampling Error



Corbin et al (2008)

Zonal Mean Seasonal Errors



Errors in mean meridional gradients > 1 ppm!

Corbin et al (2008)