Transport Modeling and the Carbon Cycle

Read Peters et al 2007 PNAS "CarbonTracker"

Transport

- Advection:
  - Stuff that was "upstream" moves here with the wind:
    \[
    \frac{\partial q}{\partial t} = -u \frac{\partial q}{\partial x} - v \frac{\partial q}{\partial y} - w \frac{\partial q}{\partial z} + \text{Source}(q)
    \]
  - 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 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 $\Delta$CO$_2$ 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 CO$_2$ cycle in which $\delta$CO$_2$ is matched with the rate of assimilation by the oceans and atmospheric CO$_2$ is held fixed. Values are in terms of 10$^{-8}$ CO$_2$/yr. Emission rates are calculated to be less than $3.9 \times 10^9$ Mg C/yr, to make the steady state possible. CO$_2$ mass balance is calculated to be less than $-0.5 \times 10^7$ Mg C/yr.

<table>
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<th>Scenario</th>
<th>CO$_2$ uptake (10$^{-8}$ Mg C/yr)</th>
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<td>Scenario 4</td>
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</tbody>
</table>

"Permissible" Carbon Budgets (cont’d)

- 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

**Mid-day**
- Strong Convection
- Deep PBL Mixing
- Low CO₂ Concentration
- Photosynthesis
- Accumulation of respiration signal near the surface
- Elevated CO₂ in lower troposphere
- Transport of low-CO₂ air into upper troposphere
- Dilution of photosynthesis signal through deep mixing
- Mid-day: Accumulation of CO₂ near the ground, depletion aloft

**Midnight**
- Weak Cumulus Convection
- Shallow PBL Mixing
- High CO₂ Concentration
- Decomposition
- Accumulation of CO₂ near the surface
- Mixing time scale
- Deep PBL

Conceptual Rectifier Model

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

where

- \( F \) is the surface flux
- \( t \) 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

**Summer**
- **Strong Convection**
- **Deep PBL Mixing**
- **Low CO₂ Concentration**
- **Dilution** of photosynthesis signal through deep mixing
- **Transport** of low-CO₂ air into upper troposphere

**Autumn**
- **Weak Cumulus Convection**
- **Shallow PBL Mixing**
- **High CO₂ Concentration**
- **Accumulation** of respiration signal near the surface
- **Elevated CO₂ in lower troposphere**

*Annual mean: Accumulation of CO₂ near the ground, depletion aloft*

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### Four-Box Model
(analogous to flask network?)

- **Advection**
- **CTL** → **CTO**
- **CBL** → **CBO**

- 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

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### 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

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### 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 [CO₂].
- 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.

Air–Sea Exchange (WHOI)

day=1, month=jul, year=2000

NEE (Land + Ocean + Fossil Fuel)

day=1, month=jul, year=2000
**Strong Synoptic Variations**

- Monthly $\sigma$ 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 CO₂ “Climatology”**

- Multiple cold fronts averaged together (diurnal & seasonal cycle removed)
- Some sites show frontal drop in CO₂, some show frontal rise … controls?
- Simulated shape and phase similar to observations
- What causes these?
  
  *Nick Parazoo et al, in prep*

**Deformational Flow**

- Large-scale gradients produced by flux differences
- CO₂ anomalies organized along cold front
- $\frac{dC}{dx} \sim 15$ ppm/300 km!

**Mid-Afternoon [CO₂], 2003**

- [Graph showing atmospheric CO₂ transport with various plots and maps illustrating synoptic variations and deformational flow.]

** ATS 760 Global Carbon Cycle**

**Atmospheric CO₂ Transport**

[Graph showing 3-Hourly [CO₂] 500m AGL with data for Month=Jun, Day=1, Year=2004.]
• Weather anomalies (clouds, rain, heat, drought, etc) produce regional NEE anomalies
• Persistent NEE anomalies produce regional CO\textsubscript{2} anomalies
• Deformation flow compresses CO\textsubscript{2} gradient along boundary, then stretches zone of high gradient along frontal zone
• But frontal zones are often cloudy …

Spatially coherent regional biases > 1.5 ppm!

Errors in mean meridional gradients > 1 ppm!