The use of airborne and ground based atmospheric observations in carbon cycle research

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Overview

- Introduction: Why Carbon Cycle Research

- Global Observations of atmospheric CO$_2$:
  - from remote islands to places nearby
  - from decades to seconds
  - Challenge: continental boundary layer, closeness to strong sources & sinks

- Airborne measurements of tracer distributions
  - Surface fluxes on regional scales (biosphere-atmosphere exchange, ...)
  - Transport processes (tropospheric mixing, convection, ...)

- Hypothesis: Airborne intensives provide paradigm datasets to
  - help design & test (falsify/validate) modeling frameworks
  - help integrate ground based data into data assimilation systems
The global mean radiative forcing of the climate system for the year 2000, relative to 1750

[IPCC Third Assessment Report - Climate Change 2001]
Greenhouse gases
(budgets, stability of pools)

Aerosols
(processes, sources)
Fundamental Carbon Cycle Questions

• Where and through which process is the excess anthropogenic carbon being taken up by land and ocean?

• What and how large are the key feedback links between the carbon cycle and the physical climate system?

• What is the carbon budget of a particular region (continent, country)?
First Scenarios Calculated with Coupled Carbon Cycle - Climate Models

Cox et al. 2001, Dufrene et al., 2001
IPCC 2001

CO₂ Concentration
Near Surface Temperature (global average)

Emissions [PgC a⁻¹]

Hadley
IPSL

1000ppm
750ppm
+5°C
+3°C

Cox et al. 2001, Dufrene et al., 2001
IPCC 2001
Estimating Regional Carbon Balances: Top-Down vs. Bottom-Up Approach

Atmospheric Observing System

Top-Down Inverse Modelling

Regional Experiment: Multiple Constraint at Very High Resolution

European Flux Estimates

Past

Future

Biomass, Soil Carbon Inventories

Bottom-Up Modelling

Remote Sensing

Process Studies

Ecosystem Flux Measurements
Carbon Cycle Observing Systems

**Plot/Site**
- Remote Sensing + GIS
- Flux Measurements
- Ecosystem Manipulation Experiments

**Eurogrid (~20-50km)^2**
- Forest/Soil Inventories

**World**
- Atmospheric CO₂ Concentration

**Countries**
- Scientific Carbon Cycle Target
- Political "Kyoto" Target
Carboeurope integrated approach to deliver multiple constraints on the C balance
Global network for atmospheric \( CO_2 \)
Global network for atmospheric CO$_2$
Global network for atmospheric $CO_2$
Global network for atmospheric CO₂
Continental boundary layer:
Harvard Forest Environmental Monitoring Site

Harvard Forest
Bermuda
Mauna Loa

Year

CO₂
320 360 400

hourly CO₂
midday CO₂
10 day medians
Bermuda CO₂
Mauna Loa CO₂
Continental boundary layer: diurnal cycle for different heights at a tall tower

WLEF Tall Tower

July average diurnal cycle (top level 24h mean subtracted)
Flux $\text{CO}_2 = w' \text{CO}_2'$
Flux towers give detailed information on atmosphere-biosphere exchange, for hours-decade, including annual sums...for ~ 100 ha.
2 AmeriFlux sites
400 km distance
Similar IAVs
(interannual variations)
- hourly CO$_2$, HF 30 m
- midday CO$_2$
- 10 day medians
- *Bermuda CO$_2$
- *Mauna Loa CO$_2$

Difference
Harvard Forest CO$_2$
– Bermuda CO$_2$

10-day median of the daily mean CO$_2$ flux at Harvard Forest (µmole m$^{-2}$s$^{-1}$)
**CO₂ Budget and Rectification Airborne Study**

“COBRA 2000”

Funding: NOAA, NASA, NSF, and DoE

[Gerbig et al., 2003a]
What models don’t need to resolve

Dry layer, high CO2, entrained from above CBL

Moist layer, low CO2, from surface

“unresolvable” eddies
⇒ “resolvable” mixed layer mean
What models don’t need to resolve

~ 100 profiles
(COBRA, summer 2000)

Uncertainty of mixed layer mean due to eddies:

0.2 ppm

(~ e.g. 25 layers, 1 ppm stddev. each)

[Gerbig et al., 2003a]


“Grain size”

of atmospheric CO$_2$

or

“how well-mixed is the atmosphere?”

Spatial differences of pairs of mixed layer profiles measured within 3 hours of each other
Grain size of atmospheric CO$_2$: Variogram

Variogram for a given "distance bin" ($h$=average distance):

$$2\gamma(h) = \text{var} \left( CO_2(s_i) - CO_2(s_j) \right) \text{ with } h = |s_i - s_j|$$

classical Variogram:

$$2\hat{\gamma}(h) = \frac{1}{N(h)} \sum_{N(h)} \left( CO_2(s_i) - CO_2(s_j) \right)^2$$

with $N(h)$: Number of pairs

robust Variogram:

$$2\overline{\gamma}(h) = \left\{ \frac{1}{N(h)} \sum_{N(h)} \left| CO_2(s_i) - CO_2(s_j) \right|^{1/2} \right\}^4$$

$$= \frac{0.457 + 0.494 / N(h)}{N(h)}$$
Fitting of power variogram model

Variogram:
Variance of differences of pairs of mixed layer profiles measured within 3 hours of each other

Power variogram fit:

\[ 2\gamma(h) = 2 \left( c_0 + c_1 \cdot h^\lambda \right) \]

\[ \lambda = 1.44 \]
\[ c_1 = 5 \times 10^{-3} \text{ ppm km}^{-1.44} \]
\[ c_0 = 0.19 \text{ ppm} \]
Spatial simulation for CO$_2$
Spatial simulation for $CO_2$

$Stdev(CO_2)$ within each subgrid of size $\Delta x \Delta y$
“Grain size” of atmospheric $CO_2$: Representation error

<table>
<thead>
<tr>
<th>Grid size [km]</th>
<th>Representation error [ppm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>100</td>
<td>0.5</td>
</tr>
<tr>
<td>200</td>
<td>1.0</td>
</tr>
<tr>
<td>300</td>
<td>1.5</td>
</tr>
<tr>
<td>400</td>
<td>2.0</td>
</tr>
<tr>
<td>500</td>
<td>2.5</td>
</tr>
</tbody>
</table>

0.2 ppm
Precision of mixed layer mean $CO_2$ (turbulence)

[Gerbig et al., 2003a]
"Grain size" of atmospheric CO$_2$: Representation error

![Graph showing COBRA 2000 data with grid size on the x-axis and representation error on the y-axis.]

- At 30 km: additional 0.2 ppm representation error
- 0.2 ppm Precision of mixed layer mean CO$_2$ (turbulence)

[Gerbig et al., 2003a]
"Grain size" of atmospheric CO$_2$:
Representation error

at 200 km: additional 1.1 ppm representation error

0.2 ppm Precision of mixed layer mean CO$_2$ (turbulence)

[Gerbig et al., 2003a]
**Receptor Oriented Atmospheric Model “ROAM”**

**DATA**
- COBRA CO$_2$ data
- Fossil fuel flux
- Lateral CO$_2$ boundary condition from Pacific observations
- EDAS assimilated meteorological fields
- AmeriFlux data
- IGBP vegetation grid

**PRODUCT**
- advedted CO$_2$
- “measured” vegetation ΔCO$_2$
- modeled vegetation ΔCO$_2$
- Optimization ($\lambda_i$)
- Influence (Footprints)

**Regional fluxes + functional response to meteorological conditions**

**Surface influence**

**Northern Transect**

[Gerbig et al., 2003b]
Receptor Oriented Atmospheric Model “ROAM”

Stochastic Time Inverted Lagrangian Transport Model
- driven by assimilated or forecasted winds (NCEP, ECMWF)

Particle location at different times before arriving at aircraft

[Lin et al., 2003], [Gerbig et al., 2003b]
What does a (tall) tower “see”?  

STILT  
Stochastic Time Inverted Lagrangian Transport Model  
[Gerbig et al., 2003b]  
[Lin et al., 2003]

Footprint  
\[ \int I(x_r,t_r | x,t) \, dt \]

Harvard Forest

CO_MEAS  
CO_STILT  
CO_backgnd

[ppb]
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$$\int I(x_r, t_r | x, t) \, dt$$

[Harvard Forest]

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[ppb]

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![Map of Harvard Forest with data plots showing CO_MEAS, CO_STILT, and CO_backgnd over time.](Image)
What does a (tall) tower “see”?  

STILT: Stochastic Time Inverted Lagrangian Transport Model  

[Gerbig et al., 2003b]  
[Lin et al., 2003]

Footprint  

\[ \int I(x_r, t_r | x, t) \, dt \]

Harvard Forest
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  - [Gerbig et al., 2003b]
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- regional fluxes + functional response to meteorological conditions

**Northern Transect**
- 24h NEE [μmol/(m² s)]
  - 8/19/2000

**Surface influence**
- Scaling factor
- a priori a posteriori
- GEE forest R GEE crop R GEE shrub R

[Gerbig et al., 2003b]
Receptor Oriented Atmospheric Model “ROAM”

The GSB (Greatly Simplified Biosphere)

+ Radiation and Temperature Sensitivity at ~ 15 eddy flux sites (AmeriFlux)
The GSB (Greatly Simplified Biosphere)

IGBP Terrestrial Vegetation Map: 17 classes

Minimal Terrestrial Vegetation Map: 3 classes

\[ \text{~10-15 useful eddy flux sites (AmeriFlux)} \]
(mostly NE and SE forests)

\[ \text{NEE} = \lambda_i \ b_i \ T + \lambda_{ip} \ A_i \ SWR / (\Gamma_i + SWR) \]

(b, A, \Gamma) from eddy flux data, T and SWR from EDAS
\[ \lambda \text{ factors for upscaling, with a priori uncertainty. [Gerbig et al., 2003b]} \]
The GSB (Greatly Simplified Biosphere)

+ captures dominant patterns of variability in space (vegetation cover) and time (light sensitive)

- Not very detailed, only diagnostic
Receptor Oriented Atmospheric Model “ROAM”

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Influence (Footprints)

Biosphere flux model

Optimal scaling of regional fluxes with functional response to meteorological conditions

24h NEE [µmol/(m² s)]
8/19/2000

Northern Transect

Scaling factor

[Gerbig et al., 2003b]
“Grain size” of atmospheric CO$_2$: Representation error

![Graph showing simulated representation error vs. grid size]

- Simulated representation error: grid degradation in surface fluxes

⇒ “Grain size” caused by patterns in surface flux

[Gerbig et al., 2003b]
Receptor Oriented Atmospheric Model “ROAM”

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Northern Transect

24h NEE [µmol/(m² s)]
8/19/2000

[Gerbig et al., 2003b]
Receptor Oriented Atmospheric Model “ROAM”

- Does it work? Is this realistic?
  - Compare spatial tracer distribution with observations to validate (or falsify)

[Gerbig et al., 2003b]
Large-scale “biospheric” $\text{CO}_2$ distribution

COBRA 2000 northern survey

Meas.  Model  Model

$\text{CO}_2$ [ppm]  $\text{CO}_2$ [ppm]

no subgr. conv.  excessive convection
Large-scale “biospheric” CO$_2$ distribution

COBRA 2000 northern survey

vertical mixing, convection...

Meas.

Model no subgr. conv.

CO$_2$ [ppm]

Model excessive convection

CO$_2$ [ppm]
Large-scale “biospheric” CO$_2$ distribution

COBRA 2000 northern survey

Meas.

vertical mixing, “$z_i$”...

Model

no subgr. conv.

excessive convection
Constraints on Convective Fluxes

COBRA-2003, June 2003

CO₂ Measurements over the U.S.

ΔCO₂ \sim 10 \text{ ppm}
STILT-BRAMS: convection

Stochastic Time Inverted Lagrangian Transport Model coupled to Brazilian Regional Atmospheric Modeling System

Backward particle motion, receptor at top of COBRA profile 6/28/03, ~18:00

+ fluxes, + boundary condition ...
Forecasting of airmass history: Lagrange Experiment

ETA12 061120
file used: 061018; receptor xsec length: 200 km; winderr: 3.81 m/s
COBRA Maine (June 11, 2004)

upstream (morning)

CO2

downstream (afternoon)
Concluding Remarks

Future observational network:
- More continental sites that are closer to processes
- Vertical distribution:
  - CMDL: rental aircraft
  - IAGOS: Integration of routine Aircraft measurements into a Global Observing System
  - remote sensing (ground based and satellite based)

Airborne intensive data can provide
- Constraints on fluxes / terrestrial processes
  - Tight constraint on regional scale: Lagrangian experiments
- “Testbed” for a modeling framework
  - we can only learn from discrepancies models vs. measurements (mixing, convective redistribution)

How we can learn: Interplay between modeling and experiment
- Model => Measurement: utilize the little flexibility we have in the experiments (many constraints by sensors/physics, platforms)
- Measurement => Model (example: grain size): models are more flexible than we often think, need to design models to match measurements (thus they become falsifiable)