What have we learned about the global carbon cycle from GOSAT and OCO-2?

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Outline

• $CO_2$ from space – GOSAT and OCO-2
  – Benefit: spatial coverage, esp. over tropics
  – Drawback: systematic errors
  – Drawback & benefit: full-column vs. surface

• Tropical land biosphere:
  – Its role in the interannual variability of global $CO_2$
  – Is it a net source or sink?
    • Implications for impact of $CO_2$ fertilization
GOSAT & OCO-2 measurements

- Measure reflected solar rays to get sensitivity to surface
- Look at sun glint spot over ocean
- Throw out cloudy scenes
- Model full radiative transfer
  - Solve for aerosol amount, four types
  - Solve for surface pressure
  - Certain fixes to spectroscopy
- Solve for dry air $CO_2$ mixing ratio on 20 levels
- Report the pressure-weighted column integral, $X_{CO_2}$
- Bias correct this after the fact, vs. TCCON, etc.
Coverage from the *in situ* network

Tropical land areas mostly unobserved
Coverage from OCO-2

~25° spacing in longitude

~3.5° spacing in longitude
Number of measurements per season per 1°x1° box

<table>
<thead>
<tr>
<th>Season</th>
<th>GOSAT</th>
<th>OCO-2</th>
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<tbody>
<tr>
<td>Jan-Mar</td>
<td>5 years, 2009-2014</td>
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<td>Apr-June</td>
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<td>July-Sep</td>
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<td>Oct-Dec</td>
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30 60 90 120 150 180 210 240
Interannual Variability in the Global Carbon Budget

Fossil Fuel = Atmos + (Net Land + Ocean)

Net land + ocean uptake

Atmospheric storage:

OCEAN

LAND

Volcanoes

El Niños
TransCom3

- Less uptake by southern oceans
- Strong uptake by NH land bio ...
- ... balanced by outgassing from tropical land
- Most of IAV due to tropical land

(Gurney et al., 2002)
Increased $CO_2$ uptake due to higher $[CO_2]$ = "$CO_2$ effect" (Friedlingstein et al. 1995)

Mid-latitude sinks = -1.2 Pg y$^{-1}$

Tropical sinks = -3 Pg y$^{-1}$

See Schimel, Stephens, & Fisher, *PNAS*, 2015, for argument for significant tropical land sink

Satellite $CO_2$ data coverage could help pin down the magnitude of the effect

Stephens et al. (2007) say transport is to blame, these models are right
Details of my inversion setup

• PCTM off-line tracer transport model
• 4Dvar data assimilation scheme
• Weekly fluxes estimated across 2009-2016
• Forward runs at 2° x 2.5° (lat/lon)
• Inverse corrections at 6.7°x6.7° (lat/lon)
• Inversions starting from 4 different priors:
  – CASA + NOBM ocean + ODIAC FF
  – CASA + NOBM ocean + FFDAS FF
  – CASA + Takahashi ocean + ODIAC FF
  – CASA + Takahashi ocean + FFDAS FF
• GOSAT v7.3 data (2009-2016)
• OCO-2 v7b data: LN, LG, OG run separately
• Additional OCO-2 bias corrections applied:
  – LN: s31 (albedo) and .997/.9955 ratio
  – LG: s31
  – OG:
    • an airmass-based one
    • using only scenes with airmass ≤ 2.4
Phase plot of net tropical land flux from GOSAT inversion vs. global land+ocean uptake from in situ data

- GOSAT: tropical land regions the main driver of global CO$_2$ IAV since 2009
- Dense satellite data confirm the result obtained 15+ years ago from inversion of in situ CO$_2$ data but never really believed
**OCO-2** land glint data, when used in inversions, gives almost the same time history of flux for the tropical land as **GOSAT**.
OCO-2 land nadir data, gives a nearly identical time history of flux as the OCO-2 land glint data ... but with a ~ +1 Pg/yr offset

What about the ocean glint data? ...
**OCO-2** ocean glint data gives a different view than the other three...

Reason to believe that **OCO-2 OG** suffers more serious biases, though...
Positive bias on southern fringe in ocean glint mode

Also, an albedo-dependent bias over land (remove with “s31” correction)

(Slide from Chris O’Dell)
Factors influencing inverted fluxes

• Retrieval bias: LN / LG / OG
• Prior fluxes used
• Prior flux covariance assumed
  – Spatial/temporal pattern of errors
  – Overall tightness of land vs. ocean
• Differences in pure transport
  – Vertical mixing
  – Advection
• Other transport model differences
  – Resolution
• Inversion setup differences
  – Data span, data selection, data errors
  – Spin up period
• Inversion method differences
  – 4Dvar vs enKF
  – Control parameters: NEE vs NPP + RESP

→ Need to quantify these to understand what is causing the spread
→ Modeling errors seem to contribute at least as much as retrieval errors
**OCO-2 flux inversion MIP**

**Goal:** separate *OCO-2* retrieval errors from modeling errors/choices with controlled experiments:

Inversion results from:

- A. Schuh, GEOS-Chem, matrix
- J. Liu, GEOS-Chem, 4Dvar
- A. Jacobson, CT-NRT, EnKF
- L. Feng, GEOS-Chem, EnKF
- F. Deng, GEOS-Chem, 4Dvar
- S. Crowell, TM5, 4Dvar
- F. Chevallier, LSCE, 4Dvar
- S. Basu, TM5, 4Dvar
- D. Baker, PCTM, 4Dvar

<table>
<thead>
<tr>
<th>Data to invert</th>
<th>Science Experiments</th>
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<td>Sat</td>
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<td>Sat + in situ</td>
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<td>Ocean glint</td>
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<td>Land nadir</td>
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<td>Land glint</td>
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<td>TCCON</td>
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All groups use same data and data uncertainties; satellite data as 10-sec avgs
Across multiple models, the OCO-2 data points to the tropical/SH land being a source in 2015.
Conclusions

• GOSAT and OCO-2 land data confirm that the tropical land biosphere is the main driver of observed \( CO_2 \) inter-annual variability

• Systematic differences between OCO-2 viewing modes (retrieval biases?) make it difficult to estimate robust annual means, but...

• Tropical land biosphere does not seem to be a significant long-term net sink of \( CO_2 \)
  – Suggests \( CO_2 \) fertilization effect not the whole story

• Modeling assumptions also an issue
  – Prior flux distribution
  – Pattern and overall tightness of assumed prior flux uncertainties

• Team of inverse modelers working on understanding model and retrieval errors, in collaboration with OCO-2 retrieval team
Fluxes estimated using OCO-2 ocean glint data (only)

Some modeling groups place the impact of the SH ocean glint bias in the southern ocean ...

... some in the southern land

Tropical land regions mostly unobserved
Annual-mean flux estimates, Jan - Dec 2015
LAND + OCEAN, south vs. north of 23.4° S

Bias corrections bring LN, LG, OG results closer

Atmos - FF mass balance Jan-Dec 2015

Prior
In situ
GOSAT
OCO-2 land nadir
OCO-2 land nadir + s31
OCO-2 land nadir + s31r
OCO-2 land glint
OCO-2 land glint + s31
OCO-2 ocean glint
OCO-2 OG (+airmass BC)
OCO-2 OG (airmass < 2.4)

Tropical + NH carbon flux [PgC/yr]
Extratropical SH carbon flux [PgC/yr]