Atmospheric Inventories using OCO-2 Retrievals: Quantifying Uncertainty with an Ensemble of Opportunity

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Motivation

• There are many groups around the world using atmospheric data to glean source/sink information using different techniques and different models.

• The source/sink estimation problem is ill-posed – inherent uncertainty in the inference arising from:
  – Regularization constraints ("prior information")
  – Methods
  – Assumptions about data (precision, bias, error correlations)
  – Meteorological driving fields ("transport")

• We can use ensembles to try to get a handle on the trustworthiness of our estimates of sources/sinks.

• Past studies (i.e. Transcom) showed that in situ data constrain estimates that are highly sensitive to assumptions outside of North America and Europe.
The OCO-2 Flux Model Intercomparison Project

OCO-2 v7/v9 Standard
- 10s “Good” Data
- Standardized errors
- Separate by mode/surface type

Inversion Models
- Different transport
- Different initial conditions
- Different bio and ocean priors
- Different prior uncertainties
- Different DA Methods
- Standardized fossil fuel

Meaningful Spread
- Transport + Prior + Prior Uncert
- (Not from obs handling)

Baseline In Situ Results
- Ties to previous literature (Transcom, etc)
- Gives useful comparisons in well observed regions

Also, standardized ObsPack NRT in situ data from Andy Jacobson and Ken Schuldt at NOAA (Updated for Round 2)

https://www.esrl.noaa.gov/gmd/ccgg/OCO2_v9mip/index.php
<table>
<thead>
<tr>
<th>Inversion Models</th>
<th>Transport Models</th>
<th>Terrestrial Prior Models</th>
<th>Ocean Prior Models</th>
<th>DA Method Models</th>
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<tbody>
<tr>
<td>✓ Different transport</td>
<td>• GEOS-Chem</td>
<td>• CASA-GFED</td>
<td>• CT Clim</td>
<td>• 4DVar</td>
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<tr>
<td>✓ Different initial conditions</td>
<td>• PCTM</td>
<td>• BEAS</td>
<td>• CT Clim</td>
<td>• Ensemble Kalman Filter</td>
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<tr>
<td>✓ Different bio and ocean priors</td>
<td></td>
<td>• CT Clim</td>
<td>• Takahashi</td>
<td>• Ensemble Kalman</td>
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<tr>
<td>✓ Different prior uncertainties</td>
<td></td>
<td></td>
<td></td>
<td>Smoother</td>
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<tr>
<td>✓ Different DA Methods</td>
<td></td>
<td></td>
<td></td>
<td>• Bayesian Synthesis</td>
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<tr>
<td>✓ Standardized fossil fuel (ODIAC with Nassar temporal scaling)</td>
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<td>• Geostatistical Inverse Modeling</td>
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<th>Models Descriptions</th>
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<td>GEOS-Chem</td>
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All inverse estimates are constrained by the same dataset: OCO-2 land data.

“Typical” annual non-fossil flux:
- NH Sink
- Tropical source

Uncertainty = standard error of the mean:
- Generally follows the regions of largest flux
- Assumes no correlation between ensemble members
Different models (colors) respond differently to the OCO-2 data – particularly in data sparse time periods such as the NH winter.

Seasonal differences have a strong impact on annual differences, meaning that our annual uncertainty budget is controlled by what the models do when the data is sparse!
• There is no clear linkage between prior fluxes and the inferred fluxes
  – Example: OU is a relatively weak sink in the prior, but the largest sink in the inferred flux for North America, and vice versa for Baker in North Asia

• The uncertainty on the prior flux is another critical variable that is not specified in a common way different models (and so is hard to compare)
Atmospheric Transport Sensitivity

• Estimation of sources and sinks is highly sensitive to
  – How quickly the model moves air out of the atmospheric boundary layer
  – How quickly the model mixes the atmosphere in the latitudinal direction

• These time scales (together with the prior uncertainty) determine where the signal from the observations ultimately is used to update the fluxes

• The bottom right figure shows the persistent seasonal differences between TM5 and GEOS-Chem using the same fluxes and initial conditions. They seem to diverge at the equator and the NH “storm track”

Global Biogeochemical Cycles

Quantifying the Impact of Atmospheric Transport Uncertainty on CO₂ Surface Flux Estimates

Special Section: Climate and Weather: Modeling Atmospheric Circulation and Transport: American Meteorologist
• These results are separated by driving met reanalysis

• We see that the magnitude of the seasonal cycle depends strongly on the driving atmospheric fields – “standard error of the mean” may not be appropriate as uncertainty

• A key limiting factor for reducing uncertainty is improving atmospheric transport
Ensembles are necessary to quantify the trustworthiness of flux estimates that are driven by atmospheric data.

Former paradigm: sparse, high quality in situ data.

Modern paradigm: less precise satellite data with global coverage, likely with residual regional biases.

Perennial issues:
- Atmospheric transport (effects depend on the dataset used!)
- Prior fluxes and prior uncertainties
- Methods used (are we using the right techniques to handle these data?)

But with all of these challenges, we are still learning new things about the carbon cycle (e.g. Liu et al, 2017; Palmer et al, 2019; Crowell et al, 2019; Yin et al, 2020; ....)
Thanks!