Assessing the utility of ACOS v2.10 GOSAT column CO₂ retrievals by comparing to independent CO₂ measurements

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16 May 2012
Typical coverage for a sun-synchronous satellite

- **NADIR**
- **GLINT**

**1 day**

**4 days**

**7 days**

- ~25° spacing in longitude
- ~3.5° spacing in longitude
Outline

• Satellite data promise a new view: a move from the continental scale to the “regional” scale

• Things needed, first:
  – Efficient numerical methods for the flux inversion
  – Understanding of spatial and temporal correlations of fluxes and column concentrations along orbit
  – Way to remove systematic errors from the satellite retrievals

• Here: an attempt at removing systematic errors from satellite retrievals

Is it real or a bias in the satellite retrieval?
GOSAT comparison to CO$_2$ forward models

- **Compare satellite data to a suite of forward model runs:**
  - CT fluxes $\rightarrow$ TM5  
    Standard CT release
  - CT fluxes $\rightarrow$ PCTM  
    $\frac{1}{2}^\circ \times \frac{2}{3}^\circ$ resolution (lat/lon)
  - CSU fluxes $\rightarrow$ PCTM  
    SiB + Doney ocean
  - CSU fluxes $\rightarrow$ TM5  
    Just now being run

- Sample model at same time/place with same vertical weighting as the actual measurements
- Take the obs - model difference
- If the differences are all similar, blame it on retrieval errors
Obs versus model
(GOSAT vs. CT+PCTM)

Model versus model
(CT+TM5 vs. CT+PCTM)

Different forward model $X_{CO2}$ values are closer to each other than any are to the GOSAT-retrieved values

Blame GOSAT-model differences on GOSAT retrieval errors (mostly)
Some Filters (land H)

Figure courtesy of Chris O’Dell, CSU
## Filters Summary

<table>
<thead>
<tr>
<th>Variable</th>
<th>Allowed Range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Glint</td>
</tr>
<tr>
<td>outcome_flag</td>
<td>*</td>
</tr>
<tr>
<td>AOD Total</td>
<td>*</td>
</tr>
<tr>
<td>AOD Water Cloud</td>
<td>*</td>
</tr>
<tr>
<td>Diverging Steps</td>
<td>*</td>
</tr>
<tr>
<td>altitude_sd [m]</td>
<td>*</td>
</tr>
<tr>
<td>CO2_ratio</td>
<td>*</td>
</tr>
<tr>
<td>H2O_ratio</td>
<td>*</td>
</tr>
<tr>
<td>ΔP_s,clid [hPa]</td>
<td>*</td>
</tr>
<tr>
<td>AOD Ice Cloud</td>
<td>*</td>
</tr>
<tr>
<td>Reduced χ²</td>
<td>&lt; (1.5, 1.8, 2.0)</td>
</tr>
<tr>
<td>X_{CO2 Error} [ppm]</td>
<td>&lt; 1.5</td>
</tr>
<tr>
<td>Albedo Slope 3</td>
<td>&gt; 1.2e-5</td>
</tr>
<tr>
<td>ΔP_s [hPa]</td>
<td>-10 to 10</td>
</tr>
<tr>
<td>Albedo Slope 1</td>
<td>&lt; 4e-6</td>
</tr>
<tr>
<td>Albedo Slope 2</td>
<td>-7e-6 to -5e-7</td>
</tr>
<tr>
<td>ΔT offset [K]</td>
<td>&gt; -1</td>
</tr>
<tr>
<td>Band 1 Offset * 10^7</td>
<td>&lt; 5.0</td>
</tr>
<tr>
<td>Band 3 Albedo</td>
<td>&gt; 0.01</td>
</tr>
<tr>
<td>Blended Albedo</td>
<td></td>
</tr>
<tr>
<td>Signal_O2 * 10^7</td>
<td></td>
</tr>
</tbody>
</table>

* Same as Land H

Figure courtesy of Chris O’Dell, CSU
Fraction of GOSAT shots passing Chris’ filters

Number of shots remaining, 2009-2010:

- Ocean: 76 K
- M-Land: 48 K
- H-land: 73 K

Figures courtesy of Chris O’Dell, CSU
Post-hoc correction (land H)

Multi-Model Mean (bias = -1.25 ppm)

~15% of variance explained

Southern Hemisphere Approximation

Figure courtesy of Chris O’Dell, CSU
Proposed Corrections

Obs - model difference (1σ) after fit:

- Land, Gain H:
  \[ X'_{\text{CO}_2} = X_{\text{CO}_2} + 0.19 \cdot (\Delta P_s + 1.0 \text{ hPa}) + 7.0 \cdot (\text{Alb}_3 - 0.20) + 1.2 \text{ [ppm]} \]
  1.55 ppm

- Land, Gain M:
  \[ X'_{\text{CO}_2} = X_{\text{CO}_2} + 0.17 \cdot (\Delta P_s + 5.5 \text{ hPa}) + 7.0 \cdot (\text{Alb}_3 - 0.5) \text{ [ppm]} \]
  1.4 ppm

- Ocean Glint:
  \[ X'_{\text{CO}_2} = X_{\text{CO}_2} + 0.35 \cdot (\Delta P_s + 1 \text{ hPa}) + 6.8 \cdot (\text{AOD} - 0.2) \]
  \[ + 0.45 \cdot \min(\text{Offset}_{\text{Band}1} \cdot 10^7, 2.0) + 0.2 \text{ [ppm]} \]
  1.0 ppm

Slide courtesy of Chris O'Dell, CSU
Systematic differences (errors?) left after bias correction

- **Aerosol optical depth**
- **Latitude**
- **“Airmass” = atmospheric path length**
- **Signal in O2 band**
Time-dependence of concentrations on fluxes

\[
\begin{align*}
H_1^{-2} & \quad H_1^{-1} & \quad H_1^0 & \quad H_1^1 & \quad H_2^1 \\
H_2^{-1} & \quad H_2^0 & \quad H_2^1 & \quad H_3^1 & \quad H_3^2 \\
H_3^0 & \quad H_3^1 & \quad H_4^1 & \quad H_4^2 & \quad H_4^3 \\
H_4^1 & \quad H_4^2 & \quad H_4^3 & \quad H_5^4 & \quad H_5^5 \\
\vdots & \quad \vdots & \quad \vdots & \quad \vdots & \quad \vdots \\
H_\infty & & & & \\
\end{align*}
\]

Transport basis functions

\[
\begin{align*}
x_0 & \quad x_1 & \quad x_2 & \quad x_3 & \quad x_4 \\
z_0 & \quad z_1 & \quad z_2 & \quad z_3 & \quad z_4 \\
\vdots & \quad \vdots & \quad \vdots & \quad \vdots & \quad \vdots \\
x_M & \quad z_M \\
\end{align*}
\]

Transport basis functions

\[
\begin{align*}
x_{M-1} & \quad H_{M-1}^{M-3} & \quad H_{M-1}^{M-2} & \quad H_{M-1}^{M-1} & \quad H_{M-1}^M \\
x_M & \quad H_M^{M-3} & \quad H_M^{M-2} & \quad H_M^{M-1} & \quad H_M^M \\
\end{align*}
\]
4D-Var: NWP vs. carbon flux estimation

Solve for I.C.s over multiple short windows (6 hours): driven by the need to update predictions

Solve for B.C.s (fluxes) and I.C.s over long window (1 year +): retrospective

NWP

\[ x_0 \]
\[ x_0 \]
\[ x_0 \]
\[ x_0 \]
\[ \ldots \]
\[ \ldots \]
\[ \ldots \]
\[ x_0 \]
\[ x_0 \]

assimilation window

Carbon fluxes

\[ x_0 \]
\[ u_0 \]
\[ \ldots \]
\[ u_I \]
4-D Var Iterative Optimization Procedure

Minimum of cost function $J$

- Estimated Fluxes
- Forward Transport
  - Modeled Concentrations
  - Measurement Sampling
- "True" Concentrations
- Measurement Sampling
- "True" Measurements
- Assumed Measurement Errors
- Weighted Measurement Residuals
- $\Delta/(\text{Error})^2$
- Flux Update
  - Adjoint Fluxes = $\nabla$
- Adjoint Transport
- Forward Transport
- "True" Fluxes

Adjoint Transport
Measurement Sampling
Modeled Measurements
"True" Concentrations
"True" Measurements
Assumed Measurement Errors
Weighted Measurement Residuals
$\Delta/(\text{Error})^2$
Flux Update
- Estimated Fluxes
- Forward Transport
- "True" Fluxes
CO$_2$ flux estimation approach using GOSAT X$_{CO2}$

• Variational carbon data assimilation system
• Optimize weekly CO$_2$ fluxes for 2010 at 4½°x6° (lat/lon)
• Prior fluxes, a CarbonTracker “projection” (Jacobson):
  – fossil fuel from preliminary 2010 statistics (CDIAC)
  – “climatological” fluxes for land biosphere and ocean
    (average of 2000-2009 values from CT 2010)
  – NOT optimized against in situ data for 2010
• PCTM off-line atmospheric transport model, driven by
  GEOS5 analyzed meteorology fields
  – CT fluxes run thru at ½°x⅔° (lat/lon) to get prior [CO2]
  – Flux corrections estimated at 4½°x6° (lat/lon)
4DVar flux inversion cases

Seven flux inversions cases for 2010 using:

- **NOAA in situ**: 62 weekly flask sites, 4 continuous sites, 8 tall towers (daily)
- **TCCON columns**, 14 sites
- **Screened ACOS ver. 2.9 GOSAT $X_{CO2}$**:
  - No bias correction
  - a separate 3-parameter bias correction for ocean and high- and medium-gain land data
4DVar CO₂ Flux Estimates w/ ACOS v.2.9  GOSAT Xₜ\textsubscript{CO₂}

- Projected CT Prior
- Post. w/ GOSAT data
- Δ = Post. - Prior

April-June 2010

July-September 2010

Full year 2010

10⁻⁸ [kgCO₂ m⁻² s⁻¹]

[Map of global CO₂ flux estimates with color gradients showing changes from April-June to Full year 2010 with and without GOSAT data.]
$CO_2$ flux corrections to the CT-PCTM prior [10^{-8} \text{ kgCO}_2 \text{ m}^{-2} \text{ s}^{-1}]$ when assimilating only:

**ACOS v2.9 GOSAT**

<table>
<thead>
<tr>
<th>H-Land, M-Land, &amp; Ocean</th>
<th>H-Land &amp; Ocean</th>
<th>NOAA in situ</th>
<th>TCCON</th>
</tr>
</thead>
<tbody>
<tr>
<td>No bias correction</td>
<td>3-param. bias corr.</td>
<td>Wunch bias corr., H-L only</td>
<td></td>
</tr>
</tbody>
</table>

JFM

AMJ

JAS

OND

Ann
Evaluation of a posteriori $CO_2$ fields against independent data

1σ error [ppm] between optimized model and TCCON (in 2-hr bins)

<table>
<thead>
<tr>
<th>Prior</th>
<th>[ppm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prior</td>
<td>1.307</td>
</tr>
<tr>
<td>GOSAT, H+M+Ocn, no bias corr.</td>
<td>1.204</td>
</tr>
<tr>
<td>GOSAT, H+M+Ocn, 3-param.</td>
<td>1.172</td>
</tr>
<tr>
<td>GOSAT, H+Ocn, Wunch #1</td>
<td>1.219</td>
</tr>
<tr>
<td>GOSAT, H+Ocn, Wunch #2</td>
<td>1.219</td>
</tr>
<tr>
<td>GOSAT, H+Ocn, Wunch #3</td>
<td>1.213</td>
</tr>
<tr>
<td>NOAA <em>in situ</em></td>
<td>1.268</td>
</tr>
<tr>
<td>TCCON</td>
<td>1.054</td>
</tr>
</tbody>
</table>
Next: make a similar plot for inversions / data comparisons using:

- **ACOS GOSAT XCO2**
- NOAA surface *in situ* data
- NOAA routine aircraft profiles
- **TCCON XCO2**
- HIPPO, AIRS, TES, AirCore, etc
**EnKF & 4DVar**

KF sliding flux window with $N_{\text{times}}$ fluxes in it

- **EnKF**
  - Large ensemble ($N_{\text{ens}}$) of **FWD** runs done simultaneously
  - No adjoint needed!

- **4DVar**
  - **FWD** and **ADJ** runs pass through full span $N_{\text{iter}}$ times, serially

**Computational work:**
- $N_{\text{times}} \times N_{\text{ens}}$ for EnKF (in parallel)
- $4 \times N_{\text{iter}}$ for 4DVar (serial)

**Columns in C, where $P=CC^T$:**
- $N_{\text{ens}}$ for EnKF
- $2 \times N_{\text{iter}}$ for 4DVar

**Backward propagation of information:**
- For EnKF, depends on time width of window - shorter spans give poorer constraints at larger time/space scales