Using aircraft observations to evaluate satellite column CO$_2$ observation: OCO-2 B8 vs. B7

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Outline

• Direct comparison between aircraft observations and satellite column CO2 (XCO2) observations

• Compare aircraft observations to posterior CO2 concentrations constrained by satellite XCO2
  - Linkage between posterior CO2 errors and the accuracy of underlying fluxes
  - Linkage between posterior CO2 errors and the accuracy of the assimilated satellite observations
Directly comparison between aircraft and satellite $X_{CO2}$ observations

- Aircraft observations only observe partial column
  - Fill the rest of the column with simulated CO2 observations from transport model
  - Criteria: at least 10 vertical levels in the bottom 20 model levels have aircraft observations
- Colocations between aircraft profile and OCO2
  - Within 2.5 hours, and within 3° in both longitude and latitude
  - Apply OCO-2 averaging kernel to the (aircraft + model) profiles
Locations and the number of aircraft observations as a function of time
Amount of aircraft observations

(c) log(num) as a function of lat and height

(d) log(num) as a function of lon and height
Mean OCO-2 vs. $X_{CO2}(aircraft + model)$

- Limited spatial coverage
- B8 is relative low than "aircraft+model" over NA
- But much better performance over EU
Scatter plot between $X_{\text{CO2}}(\text{OCO-2})$ and $X_{\text{CO2}}(\text{aircraft + model})$

oco2-b8(land) vs. aircraft

RMS=1.19 ppm
Bias=-0.25 ppm

oco2-b7(land) vs. aircraft

RMS=1.84 ppm
Bias=0.61 ppm

Challenges

• Very few aircraft observations are underpass OCO-2 track
• Top and bottom levels are from model simulated values

Alternative method

• Constrain surface CO$_2$ fluxes with OCO-2 observations
• Compare posterior CO$_2$ concentrations with aircraft observations
  ▪ Can use all the available aircraft observations
Experimental design

- CMS-Flux inversion system with GEOS-Chem adjoint model
- Optimize monthly biosphere and ocean carbon fluxes at 4 x 5 resolution
- Assimilate OCO-2 B7 and B8 nadir observations separately
- Compare posterior CO2 with aircraft observations

- What does the comparison to aircraft observations indicate about the quality of underlying fluxes?
- Is the comparison between posterior CO$_2$ and aircraft sufficient to inform the quality of assimilated observations?
- What additional steps do we need to identify where and when B8 is more/less accurate than B7?
B8-B7 = -0.33 ppm
B8 $X_{CO2}$ are much lower than B7 over NH high latitudes
## B8 inversion has larger total sink than B7 inversion

<table>
<thead>
<tr>
<th></th>
<th>Total biosphere</th>
<th>Ocean</th>
<th>FF</th>
<th>Atmospheric Growth</th>
<th>NOAA CO2 derived growth rate</th>
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<td>2015</td>
<td></td>
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<tr>
<td>Land nadir b7</td>
<td>-1.00</td>
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<td>6.00+-0.53</td>
<td>6.30+-0.2</td>
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<td>2016</td>
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<td>Land nadir b7</td>
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<tr>
<td>Land nadir b8</td>
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<td>9.85</td>
<td>4.68</td>
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- B7 inversion results agree better with the observed atmospheric CO2 growth
The large differences are over the NH high latitudes
The flux differences respond to the B8 and B7 land nadir observation differences
Mean differences between posterior CO2 and aircraft obs averaged between equator and 30N in 2015

- Posterior CO2 concentrations are significantly improved relative to the prior.
- The mean differences are close to zero.
- B8 has slightly higher positive bias over US, and higher negative bias over Asia.
Mean differences between posterior CO2 and aircraft observations averaged over 30°N and 60°N in 2015

- Posterior CO2 concentrations are significantly improved relative to the prior
- B8-posterior CO2 errors are smaller than b7-posterior over NA.
Mean differences between posterior CO2 and aircraft observations averaged over 180W-120W in 2016

- Posterior CO2 concentrations are significantly improved relative to the prior
- B8 may have low biases over SH high latitudes
- The high biases over the NH high latitudes are much smaller in B8
Posterior CO2 concentrations are significantly improved relative to the prior.

The high bias over the NH high latitudes in 2016 are much smaller in B8.

B8 may have low bias over SH high latitudes.

Mean differences between posterior CO2 and aircraft obs averaged over 120W-60W in 2016.
Mean differences against aircraft observations averaged over 60W-0 in 2016

- Posterior CO2 concentrations are significantly improved relative to the prior
- The high bias over the NH high latitudes in 2016 are much smaller in B8
- B8 may have low bias over SH high latitudes
Linkage between the accuracy of posterior CO2 and the accuracy of underlying fluxes

We first define two functions that measure the RMS errors of posterior CO2 ($C_{\text{post}}$) relative to independent observations (O):

$$J_{B8} = (C_{B8} - O)^T (C_{B8} - O)$$

$$J_{B7} = (C_{B7} - O)^T (C_{B7} - O)$$
We then define the difference between these functions:

$$\Delta J = J_{B8} - J_{B7}$$

It can be rewritten as:

$$\Delta J = \left( (f_{B8} - f_{B7}) , M^T(C_{B8} - O + C_{B7} - O) \right)$$

where $f_{B8}$ and $f_{B7}$ are the posterior fluxes constrained by B8 and B7 observations respectively, and $M^T$ is the adjoint of the transport model. The above equation calculates changes of $\Delta J$ from the changes of fluxes (i.e., $(f_{B8} - f_{B7})$ ) at every grid point and time.

Liu and Bowman, 2016
Change of CO2 errors over SH due to flux differences at every grid point

Contributions of flux differences of CO2 errors over SH, total = 399.46 ppm^2

Positive: increase errors relative to
Change of CO2 errors over Asia due to flux differences at every grid point.

Contributions of flux differences changes of CO2 errors over Asia, total = 1156.33 ppm^2.
Change of CO2 errors over NA due to flux differences at every grid point

Contributions of flux diff to changes of CO2 errors over A US total = -142276 ppm²
Linkage between the accuracy of posterior CO$_2$ and the accuracy of the assimilated satellite observations

\[ \Delta J = \langle (f_{B8} - f_{B7}), M^T (C_{B8} - O + C_{B7} - O) \rangle \] (1)

The changes of posterior CO2 errors due to posterior flux differences at each grid point

\[ \Delta f = (f_{B8} - f_{B7}) \] (2)

Posterior flux differences

\[ \Delta C = F(\Delta f) \] (3)

Forward sensitivity experiments to pinpoint the satellite observations that cause the posterior flux differences.
Comparison to aircraft=>the quality of satellite $X_{CO2}$

$\text{CO2(B8)-aircraft}$

$\text{CO2(B7)-aircraft}$

$\Delta J = J_{B8} - J_{B7}$

$\Delta \tilde{J} = \langle (f_{post(B8)} - f_{post(B7)}) M^T (C_{post(B8)} - 0 + C_{post(B7)} - 0) \rangle$

Changes $\Delta \tilde{J}$ of from $f_{post(B8)}$ to $f_{post(B7)}$

$\Delta(X_{CO2})_{fpost(B8)-fpost(B7)}$

$\Delta X_{CO2(B8-B7)}$

Why

Forward model

Liu and Bowman, 2016
B8 $X_{CO2}$ might be too high over Central America in March-April

\[ \Delta J = J_{B8} - J_{B7} \]
An example: b8 improves CO2 accuracy

Posterior fluxes (B8 - B7) reduces $\Delta J$

$\Delta J = J_{B8} - J_{B7}$
Summary and Conclusions

• Methods:
  a) comparison to aircraft observations;
  b) compare posterior CO2 concentrations to aircraft observations;
  c) Project CO2 concentration errors to fluxes => sensitivity test => CO2 observations

• Directly comparing to aircraft observations shows that B8 has smaller random errors and biases than B7

• B7 inversion results agree better with the observed atmospheric CO2 growth

• The accuracy of posterior CO$_2$ concentrations relative to aircraft observations depends on region and season: e.g.,
  a) B8 is more accurate than B7 over NH high latitudes during summer;
  b) B8 is less accurate than B7 over central America during March-May 2015;
  c) B8 seems to have low bias over SH high latitudes in 2016