Outstanding Issues in Satellite-based CO$_2$ (and CH$_4$) retrievals

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With contributions from the OCO-2/3 teams
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The XCO₂ Goal

We have a goal (my own interpretation):

To deduce accurate, science- and policy-relevant surface fluxes of CO2 at nation-state (or better) & monthly scales using top-down inversion systems driven by in-situ and satellite CO2 data.

To achieve this goal, we require:

• Extremely well-calibrated reflected sunlight spectra

• Highly accurate retrieved XCO2 from those spectra

• Robust top-down carbon source/sink inversion systems (with accurate transport and well-specified priors)

OCO-2 Has Largely Achieved this!
Gold standard for future sensors!

< 0.5 ppm (0.12%) (CO2M MRD)
< 0.2 ppm (0.05%) (Common Opinion)
The Current XCO$_2$ Situation

• Useful science with policy relevant information is starting.

LOCAL SCALES

Nassar et al., 2022
OCO 2/3 Measurements of Belchatow power plant

REGIONAL/GLOBAL SCALES

Byrne et al., 2022
OCO-2 contributions to Global Stock-Take

• Systematic errors in XCO2 are larger than 0.5 ppm.
  • Theory: Inst+Met+Spec+Aerosols, 1σ
    0.6 ppm Ocean, 0.8 ppm land  (Connor et al, 2016; McGarragh et al, 2023)
  • Actual (OCO-2 v11.1, 1σ):
    0.5 ppm Ocean, 0.7 ppm land

• What is dominating these systematic errors?
Surface Pressure Information

- Column gas columns are 1st-order sensitive to surface pressure.
- Retrieved surface pressure is not sufficiently accurate.
- Prior surface pressure accuracy depends on:
  - Accuracy of Meteorological Reanalysis (ERA-5, GEOS5, JRA, etc)
  - Accuracy of target surface altitude (DEM)
  - Geolocation Accuracy

\[ X_{CO2} = \frac{Column \ CO_2}{Column \ Dry \ Air} \propto \frac{Column \ CO_2}{P_{surf}} \]

March 2018 \( P_{surf} \) Differences

- OCO2 – GEOS5-FPIT [hPa]
  - -0.1 ± 2.2 hPa
  - 0.04 ± 0.9 ppm

- ERA5 – GEOS5-FPIT [hPa]
  - 0.1 ± 0.7 hPa
  - -0.04 ± 0.3 hPa

OCO-3 SAM over Sasan Ultra Mega power plant region, India, Feb 2022 [S. Pandey]

OCO2 XCO2 over Belchatow

NASDAQM – Copernicus [m]
Aerosol-induced errors

- Cloud-induced errors over land and water; even 3D-effects in otherwise clear pixels. (Massie et al., 2023)

- Simulations show that aerosols main cause of geometry- and albedo-correlated biases in OCO-3 SAMs (Bell et al., 2023). Also affects CH4 (Somkuti et al, 2023)!

- Can we find a 1-size-fits-all aerosol parameterization?

- Do we need accurate \textit{a priori} aerosols, such as from MAP on CO2M?

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<table>
<thead>
<tr>
<th>Retrieval</th>
<th>Aerosol Scheme</th>
<th>#Params</th>
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<tbody>
<tr>
<td>ACOS</td>
<td>5 fixed types, AODs+heights</td>
<td>9</td>
<td>O’Dell et al., 2018</td>
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<tr>
<td>UoL-FP</td>
<td>2 Aerosols + Cirrus: full profiles</td>
<td>60</td>
<td>Cogan et al., 2012</td>
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<td>RemoTeC</td>
<td>1 variable type: AOD, Height, Size</td>
<td>3</td>
<td>Butz et al., 2011</td>
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<tr>
<td>NIES</td>
<td>2 Aerosols: profiles; Cirrus: AOD+Height</td>
<td>14</td>
<td>Yoshida et al., 2013; Someya et al., 2023</td>
</tr>
<tr>
<td>FOCAL</td>
<td>1 type: AOD, Height, Angstrom Exponent</td>
<td>3</td>
<td>Reuter et al. (2017), Noel et al. (2021)</td>
</tr>
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OCO-retrieved AODs are poor

Cloud-induced low biases over water

Aerosol-induced land/water biases

Aerosol-induced biases correlated with geometry (left) and albedo (right)
We’ve greatly improved in ability to measure XCO$_2$ with satellites over the last ~15 years.

Systematic XCO$_2$ errors still limit both science and policy uses of our data.

Aerosol-induced errors are the largest contributor to systematic errors in ACOS retrievals, with only limited improvements over the last decade+. *Can we improve without dedicated aerosol sensors?*

The dry air column (= surface pressure) is also critical, but the current method of using the prior can be subject to important uncertainty sources. *Can we improve, and do we need to?*

These same types of errors affect XCH$_4$ retrievals as well!

Local/Urban systematic errors need less stringent requirements.

**Take-home messages**