Background determination for an urban domain

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Vulcan FFCO$_2$
(Gurney et al.)
## Northeast Corridor Partners

<table>
<thead>
<tr>
<th>NIST</th>
<th>University of Maryland</th>
<th>Earth Networks</th>
<th>...and more</th>
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<tr>
<td>David Allen</td>
<td>Russ Dickerson</td>
<td>Steve Prinzivalli</td>
<td>Northern Arizona University: Kevin Gurney</td>
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<td>Subhomoy Ghosh</td>
<td>Ross Salawitch</td>
<td>Clayton Fain</td>
<td>Boston University: Lucy Hutyra &amp; team</td>
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<td>Sharon Gourdji</td>
<td>Ning Zeng</td>
<td>Bryan Biggs</td>
<td>Bowdoin College: Barry Logan</td>
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<td>Israel Lopez Coto</td>
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<td>Michael Stock</td>
<td>CUNY: Andrew Reinmann</td>
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<td>Kimberly Mueller</td>
<td>Hao He</td>
<td>Charlie Draper</td>
<td>DOE/ORNL: Melanie Mayes &amp; Jeff Warren</td>
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<td>Kuldeep Prasad</td>
<td>Doyeon Ahn</td>
<td>William Callahan</td>
<td>Purdue University &amp; Stony Brook University:</td>
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<td>Tamae Wong</td>
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<td>Paul Shepson, Joe Pitt</td>
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<td>James Whetstone</td>
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<td>NOAA/ESRL:</td>
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<td>Peter Salameh, Kris</td>
<td>Colm Sweeney, John Miller, Isaac Vimont</td>
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<td>Verhulst, Jooil Kim,</td>
<td>U. Michigan: Eric Kort &amp; team</td>
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<td>&amp; LA Megacities team</td>
<td>U. Colorado/GNS Science:</td>
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<td>Jocelyn Turnbull</td>
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<td>Penn State: Ken Davis &amp; team</td>
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The Northeast Corridor: Washington/Baltimore

Karion et al., ESSD, 2020
Definition of Background

\[ y = y_{BG} + y_{enh} \]

The background is the mole fraction a tower would measure if fluxes inside the domain were zero.
Motivation

Observations

Background options
Washington/Baltimore analysis

• Use 1-yr inversion period: Nov 2016 - Oct 2017
• Hourly WRF-STILT footprints with particle back trajectories (500 particles per footprint)
• 6 urban sites (NEB, NWB, JES, HAL, ARL, NDC)
• 3 background sites (BUC, TMD, SFD)

Refer to this as “inner” or urban domain
Background methods (3 basic methods)

1. Sample global model at boundary edges using particle trajectories
3. Upwind observation-based
Method 1: Sampling Global Model

Sample Global model 4D CO$_2$ or CH$_4$ fields at the point when each particle exits the inner domain; average their concentrations.

CO$_2$: CT-v2019, CT-Europe (1x1, 3 hourly)
Method 2: Two-component background

\[ \gamma_{obs} = \gamma_{BG} + \gamma_{enh} \]

\[ \gamma_{obs} = \gamma_{BGfar} + \gamma_{BGnear} + \gamma_{enh} \]

\( \gamma_{BGfar} \) calculated same as Method 1:
Sample a Global model at the edge of the outer domain.

CMA is a NOAA aircraft site we use later in the analysis – shown here for reference.
Method 2: Two-component background

\[ \gamma_{obs} = \gamma_{BG\text{far}} + \gamma_{BG\text{near}} + \gamma_{enh} \]

- Use existing inventories with our WRF-STILT footprints to model \( \gamma_{BG\text{near}} \) in outer domain.
- Set fluxes to zero inside the inner domain
- \( \text{CO}_2 \):
  - Fossil: Vulcan 3.0 (2015)
  - Bio: VPRM, CASA
Method 3: Use upwind tower observations

A. Sample nearest background tower at the time of particle exit ("lagged observations") (not usually done)

B. Sample nearest background tower at the same time as the urban tower ("afternoon observations") (similar to Lauvaux et al.)

C. Sample a vertical column distribution above the nearest background tower at the time of particle exit (similar to Sargent et al.).
   • Investigated several ways to construct this column, used an OSSE to minimize bias.
Constructing vertical column at upwind sites: Afternoon hours

Z > PBL: free troposphere*

*Free troposphere value is derived from a “curtain” constructed using binned/smoothed NOAA aircraft observations at CMA.

Z < PBL: tower observation
Constructing vertical column at upwind sites: non-afternoon hours

\[ y(z = 1500) = y_{OBS}^{(prev. \ day \ aft)} \]
\[ y(z) = A + B(e^{-\frac{z}{\lambda}}) \]
\[ y(z = PBL) = y_{OBS} \]

*Choices for \( \lambda \) and FT altitude (1500) determined using OSSE.
Synthetic study for CO₂

\[ \gamma_{obs} = \gamma_{BGfar} + \gamma_{BGnear} + \gamma_{enh} \]

\( \gamma_{BG} = \text{“true background”} \)

- Create synthetic observations for urban and background sites.
- Create synthetic background columns.
- Evaluate background method by comparing with true background.
- Perfect meteorology, perfect fluxes - just look at how the upwind tower column (sampled by STILT particles) represents the true background for a given urban tower. *(method very similar as published in Mueller et al.)*
Synthetic study for CO₂

\[ y_{obs} = y_{BGfar} + y_{BGnear} + y_{enh} \]

\[ y_{BG} = \text{“true background”} \]

\[ y_{BGfar} = \text{CT-v2019} \]

\[ y_{BGnear} = \text{outer domain flux convolutions using VPRM + Vulcan, zeroed out in inner domain} \]

\[ y_{enh} = \text{enhancements from fluxes (VPRM+Vulcan) in inner domain.} \]
• Using Afternoon observations at the upwind tower causes low bias in the summer.

• Using observations at upwind tower lagged by travel time causes high bias.

• Column background less biased and has a smaller standard deviation, but still noisy.

These conclusions are specific to our network design, location of our towers.
CO₂ (OSSE result) error/bias (Estimate - Truth)
Can we evaluate against observations?

Sure!

• Compare modeled to real observations at urban sites for different backgrounds.

• Limit analysis to hours where the background dominates mole fraction at urban sites: i.e. when footprints are below the 10th percentile, (e.g. during high-wind events &/or high PBL)
Summary of background methods compared and evaluated

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Type of background</th>
<th>$Y_{BGfar}$</th>
<th>$Y_{BGnear}$</th>
<th>$Y_{BG}$</th>
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</thead>
<tbody>
<tr>
<td>CTd03 Global-CT</td>
<td>Global model sampling at inner domain boundary</td>
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<td></td>
<td>CarbonTracker v2019 (Jacobson, et al., 2020)</td>
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<tr>
<td>CTEd03 Global-CTE</td>
<td>Global model sampling at inner domain boundary</td>
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<td>CarbonTracker Europe (Peters et al., 2010)</td>
</tr>
<tr>
<td>CT+Vulcan+CASA</td>
<td>2-component background</td>
<td>CarbonTracker v2019</td>
<td>Vulcan 3.0* (Gurney) + CASA (Zhou/Williams)</td>
<td>$Y_{BGfar} + Y_{BGnear}$</td>
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<tr>
<td>OBScol Upwind column</td>
<td>Upwind observations</td>
<td></td>
<td></td>
<td>Sampled from a vertical column</td>
</tr>
<tr>
<td>OBSaftbg Upwind aft</td>
<td>Upwind observations</td>
<td></td>
<td></td>
<td>Mean afternoon average from same day minus $y_{enh}$</td>
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</tbody>
</table>

*FFDAS is used in portion of domain in Canada (outside Vulcan range)
Column-based upwind background performs well in general, but shows low bias in summer. Some of this could be due to fluxes inside domain being incorrect in summer – even though we limit to time periods where they are small.

Note: this comparison is now of the full modeled concentration \( y = y_{bg} + y_{enh} \) against observations.

We filter for hours when \( y_{enh} \) is small to minimize errors due to incorrect fluxes inside the domain.
Two ways to look at the results: Bias (left) and Variability (right)

Taylor diagram indicates that the model using the column-based background is closest to the observations and has the highest correlation over the year.
Uncertainty: use spread of backgrounds?

HAL daily afternoon mean

CO₂ (ppm)

Jan Feb Mar Apr

HAL

Signal-to-Noise Ratio

SNR (Δ CO₂ / 1⁻ᵃ)


5-day smoothing window

Mean: 2.9
Median: 1.6

35% of days have SNR < 1
What did we learn?

• In the Washington/Baltimore area the background is variable in space and time.

• We must be careful in using upwind observations, especially for CO$_2$ in the growing season.

• Sampling vertical column above an upwind site performs well without requiring knowledge of any fluxes.

• Even in the best-case scenario, there is a lot of uncertainty/error in the background.

• Best choice may be to use an ensemble of independent background options when we can, because that gives us an idea of the uncertainty.
Uncertainty: use spread of backgrounds?
Where do particles exit? (altitude)
CO₂ (OSSE result) error/bias (Estimate - Truth)

- Using Afternoon observations at the upwind tower causes low bias in the summer.
- Using observations at upwind tower lagged by travel time causes high bias.
- Column background less biased and has a smaller standard deviation, but still noisy.
CO$_2$ (OSSE result) error/bias (Estimate - Truth)
Comparison w/ flights

• 12 flights in 2017
• Isolate individual vertical profiles, compare with the constructed vertical profile at the BG site closest to the profile.
• Averaged all vertical profiles into altitude bins (100 m)
• Average the differences over multiple profiles and then multiple flight days.
• Figure shows mean difference +/- 1-sigma
• Profiles may not have been close to the site, so values within the PBL are expected to have higher residuals.
Same analysis for CH4

Observational background greatly outperforms models - because upwind fluxes are not well-known!
Examples of constructed background (BUC)

winter

summer

morning

afternoon
Impact

Model-obs comparison: Model is column-obs background + d03 fluxes.

Modeled enhancement for different d03 flux combinations.
Impact

Choice of BG makes a much bigger impact than choice of d03 fluxes!!

Model-obs comparison: Model is various BG options + VPRM+VULCAN in d03.
NOAA Aircraft Flask Samples @ Cape May, NJ

Ccgcrv with 3 polynomials, 4 harmonics

\[
cma_{\text{lon}} = -74.320 \\
cma_{\text{lat}} = 38.830
\]