Observational Constraints of Anthropogenic Combustion from Space: Opportunities for Monitoring Efficiency

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Combustion of hydrocarbon fuels produce not only CO$_2$, but several pollutants like CO and NO$_2$.

**Low Temperature Combustion:** High CO, Low NO$_2$, High OC

**High Temperature Combustion:** Low CO, High NO$_2$, High BC

**High Efficiency Combustion:** High CO$_2$, Low CO, High NO$_2$

**Enhancement Ratios**

- $C_{\text{fuel}} + \text{air and heat}$
  
  $C_{x_1}H_{x_2}O_{x_3}N_{x_4}S_{x_5} + n_1(1+e)(O_2 + 3.76N_2)$

  $\rightarrow n_2CO_2 + n_3H_2O + n_4O_2 + n_5N_2$

  $+ n_6CO + n_7NO + n_8NO_2 + n_9SO_2 + n_{10}C + \ldots$

**Emission Ratios**

- $E_{\text{city}}^{CO} = \sum A_{\text{sector}} \times EF_{\text{sector}}^{CO} \times (1 - CE_{\text{sector}}^{CO})$

- $E_{\text{city}}^{CO_2} = \sum A_{\text{sector}} \times EF_{\text{sector}}^{CO_2} \times (1 - CE_{\text{sector}}^{CO_2})$

- $\left(\frac{\Delta CO}{\Delta CO_2}\right)_{\text{city}} \sim \left(\frac{E_{\text{CO}}}{E_{\text{CO}_2}}\right)_{\text{city}} = \sum \left(\frac{E_{\text{CO}_2}}{E_{\text{total}}^{\text{CO}_2}}\right) \times \frac{EF_{\text{sector}}^{CO}}{EF_{\text{sector}}^{CO_2}}$
Previous Work (Silva et al. 2013 on MOPITT XCO and GOSAT XCO$_2$)

\[ \Delta \text{CO}_2/\Delta \text{CO} \] over Megacities

- Essen (28)
- London (37)
- Moscow (15)
- Seoul (32)
- Chicago (50)
- Tokyo (37)
- Hangzhou (36)
- Osaka/Kobe (32)
- Shanghai (21)
- Los Angeles (334)
- New York (37)
- Mumbai (36)
- Lagos (40)
- Changchun (25)
- Bangkok (46)
- Cairo (169)
- Lahore (137)
- Shenyang (20)
- Dhaka (93)
- Istanbul (127)
- Tehran (103)
- Guangzhou (54)
- Buenos Aires (63)
- New Delhi (69)
- Calcutta (135)

- Beijing/Tianjin (76)

\[ \text{ACOS v2.9} / \text{MOPITT v5} \Delta \text{CO}_2/\Delta \text{CO} \text{ (mol/mol)} \]

\[ \sim 7-9 \text{ ppbv/ppmv} \]

\[ \sim 25-50 \text{ ppbv/ppmv} \]

\[ y = 0.84x, \quad R^2 = 0.61 \]

\[ \text{ACOS v2.9} / \text{MOPITT v5} \Delta \text{CO}_2/\Delta \text{CO} \text{ (mol/mol)} \]

EDGAR 4.2 eCO$_2$/eCO (mol/mol)

United Kingdom

Germany

France

South Korea

USA

Japan

Russia

Pakistan

Turkey

Mexico

Indonesia

China

Australia
Tang et al., Evaluating High-Resolution Forecasts of Atmospheric CO and CO₂ from a Global Prediction System during KORUS-AQ Field Campaign, ACPD, 2017

<table>
<thead>
<tr>
<th></th>
<th>Region</th>
<th>DC-8</th>
<th>16-km Fx</th>
<th>Analysis</th>
<th>9-km Fx+An</th>
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<tbody>
<tr>
<td>ΔCO/ΔCO₂</td>
<td>Seoul</td>
<td>9.1±0.5</td>
<td>9.9±0.3</td>
<td>8.2±0.5</td>
<td>11.6±0.6</td>
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<td></td>
<td>West Sea</td>
<td>28.2±0.8</td>
<td>30.9±1.6</td>
<td>30.6±1.7</td>
<td>32.4±1.8</td>
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<th>Region</th>
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</thead>
<tbody>
<tr>
<td>R(CO,CO₂)</td>
<td>Seoul</td>
<td>0.78</td>
<td>0.94</td>
<td>0.77</td>
<td>0.78</td>
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<tr>
<td></td>
<td>West Sea</td>
<td>0.89</td>
<td>0.42</td>
<td>0.25</td>
<td>0.36</td>
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</tbody>
</table>

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<th>Region</th>
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</thead>
<tbody>
<tr>
<td>R(bCO,bCO₂)</td>
<td>Seoul</td>
<td>0.90</td>
<td>0.66</td>
<td>0.64</td>
<td></td>
</tr>
<tr>
<td></td>
<td>West Sea</td>
<td>0.80</td>
<td>0.82</td>
<td>0.82</td>
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|---------|-------------------------|--------|--------------------|

| Pasadena | 11 ppbv/ppmv (2008) |
| SoCAB    | 14 ppbv/ppmv (2010) |

| TRACE-P (2001) | 50-100 ppbv/ppmv (China) |
| SoCAB Peninsula | 12-17 ppbv/ppmv (Japan) |

| near Beijing | 22 ppbv/ppmv (2008) |
| Tae-Ahn Peninsula | 34-42 ppbv/ppmv (2005) |

Can satellite data of combustion products (CO, NOx, aerosols) provide constraints on trends in megacity combustion characteristics (complementary to ground-based & airborne measurements)?

Geophysical Research Letters

Analysis of long-term observations of NOx and CO in megacities and application to constraining emissions inventories

Bingli Hao1,2, Brian C. McNider3, Gregory J. Frost3, Agnes Barbeau4, David G. Carslaw5, Kevin Civerolo6, Claire Granier7,1, Paul S. Monks8, Sarah Monks9,10, David D. Parrish11,12, Itzela B. Pollack11,12, Karen H. Rosenlof10, Thomas B. Ryerson10, Erika von Schneidemesser12, and Michael Trainer12

Fig. 9, Ch. 8, D. Parrish (lead)
WMO/IGAC Impacts of Megacities on Air Pollution and Climate, (2012)
Opportunity to Monitor From Space Anthropogenic Combustion Pathways

### SATELLITE DATA (2005-2016)
- MOPITT v6 TIR/NIR total CO column
- OMI Domino v2 trop NO\(_2\) column
- OMI NASA PCA v3 PBL SO\(_2\) column

### REGRESSION & TIME SERIES ANALYSIS
- Reduced Major Axis Regression
- Seasonal Trend decomposition with LOESS
- Robust Regression Using Iteratively Reweighted Least-Squares

Regressions were conducted with respect to NO\(_2\) across 2x2 degree spatial extent centered within each megacity. Only positive correlations are included in the analysis.

Tang et al. (2018), in revision
Opportunities to confront models and analysis

Assess consistency:
\[ x^a = x^f + P_f H_T (H P_f H_T^T + R)^{-1} (y - H x^f) \]
\[ x^a - x^f = P_f H_T (H P_f H_T^T + R)^{-1} (\Delta y) \]
\[ \Delta x = \left( \frac{\Delta x}{\Delta y} \right) (H P_f H_T^T) (H P_f H_T^T + R)^{-1} (\Delta y) \]

Some inconsistencies exist between model or analysis-derived versus observed trends
These findings are consistent in terms of pattern across cities with IASI products...

... with patterns driven by differences in the rate of change of NO$_2$ and CO across the decade
Opportunity to Distinguish Flaming and Smoldering Fire Phases

Smoke Index

Analogous Smoke Index


Tang and Arellano, JGR,
Can we verify this modeled chemical response of CH$_4$ to changes in CO by observed $\Delta$CH$_4$/\$\Delta$CO from current/future retrievals?

\[
\frac{d[CH_4]}{dt} = S_{CH_4} - R1; \quad R1 = k_1[CH_4][OH]
\]

\[
\frac{d[CO]}{dt} = S_{CO} + R1 - R2; \quad R2 = k_2[CO][OH]
\]

\[
\frac{d[OH]}{dt} = S_{OH} - R1 - R2 - R3; \quad R3 = k_3[X][OH]
\]
Spatial and Temporal Variations in Characteristic Ratios of Elemental Carbon to Carbon Monoxide and Nitrogen Oxides across the United States

Aishwarya Raman* and Avelino F. Arellano, Jr.

Emerging Patterns of O₃ Sensitivity to CO over Megacities
Derived from IASI Retrievals
(in preparation)

9-year Linear Trend (% per year)

<table>
<thead>
<tr>
<th></th>
<th>Beijing</th>
<th>Shanghai</th>
<th>Shenzhen</th>
<th>Los Angeles</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔO₃</td>
<td>-2.63±1.18</td>
<td>-0.72±0.17</td>
<td>1.14±1.89</td>
<td>-0.47±0.17</td>
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<tr>
<td>ΔCO</td>
<td>-4.85±4.45</td>
<td>-0.60±0.90</td>
<td>-0.98±0.58</td>
<td>-2.68±6.27</td>
</tr>
<tr>
<td>ΔO₃/ΔCO</td>
<td>0.58±2.15</td>
<td>-0.62±0.67</td>
<td>0.38±0.42</td>
<td>2.69±4.46</td>
</tr>
</tbody>
</table>

### Some Thoughts

1) There is utility in multi-species analysis of satellite retrievals on atmospheric composition, especially from combustion-related constituents over megacities and fire regions (information on sectoral spatiotemporal distribution of emissions and consistency).

2) As these are obviously proof-of-concepts, the value has yet to be quantified through multi-species assimilation/inversions.

3) An OSSE activity towards bringing these pieces together would be an important first step to further demonstrate its value. Issues with regards to collocation, representativeness, retrieval sensitivities & errors can be addressed along with newer satellite retrievals.

4) In conjunction, validation with airborne and ground-based measurements is absolutely needed.

5) Confronting model simulations, forecast, and analysis with multi-species constraints may be the way to go in ensuring consistency in our estimates.

6) Such proposed OSSE activity has synergies with WMO/Integrated Global Greenhouse Gas Information System (IG3IS) and IGAC/Analysis of eMissions using Observations (AMIGO).