Top-down Estimate of Black Carbon Emissions for City Cluster Using Ground Observations: A Case Study in Southern Jiangsu, China

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Outlines

• **Motivation**
  Evaluation of local emission inventory
  Black carbon: sources and uncertainty

• **Methods: Model description**

• **Results and discussions**
  Result of the constrained top-down emissions
  Impacts of sites, prior emissions and precipitation

• **Conclusion**
Motivation - Discrepancy between obs. and sim.

China

City

Nanjing

Ma et al., 2006; Han et al., 2015; Zhao et al., 2015
**Motivation** - Simulations from different inventories

### Maps
- **National**
- **Regional**
- **Local**

### Table

<table>
<thead>
<tr>
<th>Pollutants</th>
<th>National (MEIC)</th>
<th>Regional (Fu et al., 2013)</th>
<th>Provincial (this work)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NMB %</td>
<td>NME %</td>
<td>NMB %</td>
</tr>
<tr>
<td>SO₂</td>
<td>48.45 %</td>
<td>76.53 %</td>
<td>74.08 %</td>
</tr>
<tr>
<td>NO₂</td>
<td>21.02 %</td>
<td>35.99 %</td>
<td>29.84 %</td>
</tr>
<tr>
<td>O₃</td>
<td>-65.55 %</td>
<td>68.57 %</td>
<td>-53.93 %</td>
</tr>
<tr>
<td>PM₂.₅</td>
<td>-51.63 %</td>
<td>55.32 %</td>
<td>-49.16 %</td>
</tr>
</tbody>
</table>

*Zhou et al., ACP, 2017*
Black carbon/elemental carbon

- Complicated sources (Industry, transportation, household)
- Significant climate (and health) impacts
Emissions of black carbon

- Contained combustion (~4600 Gg)
- Open burning (~3400 Gg)

Bond et al., JGR, 2004

Lu et al., ACP, 2011
Inter-annual trends and uncertainty

Inter-annual trends in China’s BC emissions  Cui et al., ACP, 2015
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Method  Linear regression + transport model

**Whole country**  Fu et al., ACP, 2012

- Bottom-up emissions
- Top-down emissions

**Pearl river delta**  Li et al., ACP, 2015

- Bottom-up emissions($\times10^{-3}$GgC $y^{-1}$)
- Top-down emissions($\times10^{-3}$GgC $y^{-1}$)

For **Bottom-up emissions**,

\[ c_{obs} - c_{background} = \beta_1 c_{residential} + \beta_2 c_{non-residential} + \beta_3 c_{biomass} + \epsilon \]

For **Top-down emissions**,

\[ c_{obs} - c_{background} = \beta_1 c_{transportation} + \beta_2 c_{non-transportation} + \beta_3 c_{biomass} + \epsilon \]

**Application in southern Jiangsu city cluster**

- Constraining emissions from hourly on-line ground measurements
- Revising emissions by sector from detailed categories of emissions

\[ c_{obs} = \beta_1 c_{industry} + \beta_2 c_{residential} + \beta_3 c_{transportation} + \beta_4 c_{power} + \epsilon \]

\[ E_{top-down} = \beta_1 E_{industry} + \beta_2 E_{residential} + \beta_3 E_{transportation} + \beta_4 E_{power} + \epsilon \]
**Method – Modeling domain and site location**

**WRF-CMAQ modeling domain**

**City cluster**
SU-XI-CHANG-ZHEN-NAN

**Observation sites**
- **NJU** Suburban site (upwind)
- **PAES** Urban (downwind)

**NJU Suburban site (upwind)**
**PAES Urban (downwind)**
Method – Ground measurements

\[ c_{\text{obs}} = \beta_1 c_{\text{industry}} + \beta_2 c_{\text{residential}} + \beta_3 c_{\text{transportation}} + \beta_4 c_{\text{power}} + \varepsilon \]

\[ E_{\text{top-down}} = \beta_1 E_{\text{industry}} + \beta_2 E_{\text{residential}} + \beta_3 E_{\text{transportation}} + \beta_4 E_{\text{power}} + \varepsilon \]

NJU: Suburban site (upwind); PAES Urban (downwind)

Chen et al., AR, 2017
Method - Emission data

\[ E_{\text{top-down}} = \beta_1 E_{\text{industry}} + \beta_2 E_{\text{residential}} + \beta_3 E_{\text{transportation}} + \beta_4 E_{\text{power}} + \epsilon \]

- **Local inventory 2012**
  - Industry
    - Energy use
    - Production
  - Household
    - Energy use
    - Straw yield
  - Transport
    - Vehicle numbers
    - Energy use
  - Power
    - Electricity

**Scaling from activity levels without emission control progress**

Zhou et al., 2017
Method - Contribution by sector

\[
c_{\text{obs}} = \beta_1 c_{\text{industry}} + \beta_2 c_{\text{residential}} + \beta_3 c_{\text{transportation}} + \beta_4 c_{\text{power}} + \epsilon
\]

Brute Force Method □ WRF-CMAQ □

<table>
<thead>
<tr>
<th></th>
<th>industry</th>
<th>residential</th>
<th>transportation</th>
<th>power</th>
</tr>
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<tbody>
<tr>
<td>Base</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Case1</td>
<td></td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Case2</td>
<td>√</td>
<td></td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Case3</td>
<td>√</td>
<td>√</td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>Case4</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td></td>
</tr>
</tbody>
</table>

NJU

PAES
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```
c_{obs} = \beta_1 c_{industry} + \beta_2 c_{residential} + \beta_3 c_{transportation} + \beta_4 c_{power} + \epsilon
```

<table>
<thead>
<tr>
<th></th>
<th>factor</th>
<th>t</th>
<th>Sig.</th>
<th>VIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan.</td>
<td>\beta_1</td>
<td>0.421</td>
<td>2.649</td>
<td>0.008</td>
</tr>
<tr>
<td></td>
<td>\beta_2</td>
<td>1.313</td>
<td>3.667</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>\beta_3</td>
<td>0.790</td>
<td>2.226</td>
<td>0.026</td>
</tr>
<tr>
<td>Apr.</td>
<td>\beta_1</td>
<td>0.221</td>
<td>0.960</td>
<td>0.338</td>
</tr>
<tr>
<td></td>
<td>\beta_2</td>
<td>0.582</td>
<td>1.625</td>
<td>0.105</td>
</tr>
<tr>
<td></td>
<td>\beta_3</td>
<td>0.673</td>
<td>2.205</td>
<td>0.028</td>
</tr>
<tr>
<td>Jul.</td>
<td>\beta_1</td>
<td>0.346</td>
<td>3.092</td>
<td>0.002</td>
</tr>
<tr>
<td></td>
<td>\beta_2</td>
<td>0.393</td>
<td>0.948</td>
<td>0.344</td>
</tr>
<tr>
<td></td>
<td>\beta_3</td>
<td>0.550</td>
<td>2.201</td>
<td>0.028</td>
</tr>
<tr>
<td>Oct.</td>
<td>\beta_1</td>
<td>0.335</td>
<td>1.924</td>
<td>0.055</td>
</tr>
<tr>
<td></td>
<td>\beta_2</td>
<td>1.516</td>
<td>4.123</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>\beta_3</td>
<td>0.744</td>
<td>2.801</td>
<td>0.005</td>
</tr>
</tbody>
</table>

Criteria: \(t>2\)  \(b: \text{Sig.<0.05}\)  \(c: \text{VIF<10}\)
Results and discussion – Emission levels

Emissions largely reduced from Top-down constraining

Total emissions reduced by 50.6%

- Industry: 66.6%
- Residential: 2.9%
- Transportation: 31.9%

Nanjing emissions (bottom-up method)
Results and discussion – Model performance

Top-down emissions reduced overestimation

**Jan.**  
NME: 1.555  
NME: 1.395

**Apr.**  
NME: 0.732  
NME: 0.429

**Jul.**  
NME: 0.927  
NME: 0.424

**Oct.**  
NME: 0.431  
NME: 0.408

**PAES**

\[
NME = \frac{\sum_{i=1}^{n} |P_i - O_i|}{\sum_{i=1}^{n} O_i} \times 100\% \quad (P: \text{prediction}; \ O: \text{observation})
\]
Results and discussion – Impacts of sites

Contribution from Nanjing (NAN)

PAES > NJU □ 81.8%

Contribution from other cities

NJU > PAES □ 81.3%

Chen et al., AR, 2017
### Results and discussion – Impacts of sites

Consideration of different spatial representativeness of the two sites

\[
\begin{align*}
c_{\text{obs-NJU}} &= \beta_1 c_{\text{industry}} + \beta_2 c_{\text{residential}} + \beta_3 c_{\text{transportation}} + \beta_4 c_{\text{power}} + \varepsilon \\
c_{\text{obs-PAES}} &= \alpha_1 c'_{\text{industry}} + \alpha_2 c'_{\text{residential}} + \alpha_3 c'_{\text{transportation}} + \alpha_4 c'_{\text{power}} + \varepsilon
\end{align*}
\]

<table>
<thead>
<tr>
<th>sector</th>
<th>factor</th>
<th>( t^a )</th>
<th>Sig. ( b )</th>
<th>VIF ( c )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NJU (other cities)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \beta_1 )</td>
<td>0.416</td>
<td>1.711</td>
<td>0.088</td>
<td>2.025</td>
</tr>
<tr>
<td>( \beta_2 )</td>
<td>0.947</td>
<td>2.498</td>
<td>0.013</td>
<td>2.520</td>
</tr>
<tr>
<td>( \beta_3 )</td>
<td>0.651</td>
<td>2.134</td>
<td>0.034</td>
<td>2.655</td>
</tr>
<tr>
<td><strong>PAES (Nanjing)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \alpha_1 )</td>
<td>0.193</td>
<td>3.464</td>
<td>0.001</td>
<td>1.436</td>
</tr>
<tr>
<td>( \alpha_2 )</td>
<td>0.360</td>
<td>1.889</td>
<td>0.061</td>
<td>1.436</td>
</tr>
<tr>
<td>( \alpha_3 )</td>
<td>0.651(^d)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

More stringent emission control policies in Nanjing were implied compared to other southern Jiangsu cities.
### Results and discussion – Impacts of sites

More improvement when spatial representativeness considered

\[
NME = \frac{\sum_{i=1}^{n} |P_i - O_i|}{\sum_{i=1}^{n} O_i} \times 100\% \quad (P: \text{prediction}; \ O: \text{observation})
\]

<table>
<thead>
<tr>
<th>Location</th>
<th>Result1</th>
<th>Result2</th>
<th>Result3</th>
<th>Result4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NJU</strong></td>
<td>NME</td>
<td>0.423</td>
<td>0.386</td>
<td>0.326</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>0.341</td>
<td>0.427</td>
<td>0.489</td>
</tr>
<tr>
<td><strong>PAES</strong></td>
<td>NME</td>
<td>0.732</td>
<td>0.429</td>
<td>0.396</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>0.637</td>
<td>0.530</td>
<td>0.658</td>
</tr>
</tbody>
</table>

Result1  Original bottom-up inventory
Result2  Emissions constrained with two sites (representativeness not considered)
Result3  Emissions constrained with two sites (representativeness considered)
Result4  Emissions constrained with only one site (NJU)
Results and discussion – Impacts of emissions

The a prior emission data:

Local inventory
Zhou et al., 2017 □ Nanjing Univ. □

National inventory
MEIC □ Tsinghua Univ. □

Discrepancies largely decreased with emission constraining

Discrepancies in prior emissions

Discrepancies in posterior emissions
Results and discussion – Impacts of emissions

The impacts of prior emissions were limited

Modelling results of posterior inventories were closer than those of prior ones
Precipitation with a temporal resolution of 3 h

48 h back trajectories at NJU and PAES

Hourly accumulative precipitation along the 48 h back trajectories
Results and discussion - Impacts of precipitation

The $\Delta$BC/$\Delta$CO ratio at the two sites separated by different accumulated precipitation along the back trajectories during 48 h

Data screening: We exclude BC-CO data pairs receiving more than 3 mm (NJU) and 5 mm (PAES) to minimize the effect of wet deposition and to retain sufficient data points for statistical significance.
### Results and discussion - Impacts of precipitation

The impact of precipitation was moderate;

More effects on emission sources of relatively large uncertainty

\( c_{\text{obs}} = \beta_1 c_{\text{industry}} + \beta_2 c_{\text{residential}} + \beta_3 c_{\text{transportation}} + \beta_4 c_{\text{power}} + \varepsilon \)

\( E_{\text{top-down}} = \beta_1 E_{\text{industry}} + \beta_2 E_{\text{residential}} + \beta_3 E_{\text{transportation}} + \beta_4 E_{\text{power}} + \varepsilon \)

<table>
<thead>
<tr>
<th>Factor</th>
<th>( \beta )</th>
<th>t</th>
<th>RD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td></td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>Industry</td>
<td>0.38</td>
<td>2.38</td>
<td>9.5</td>
</tr>
<tr>
<td>Residential</td>
<td>0.31</td>
<td>0.31</td>
<td>-20.6</td>
</tr>
<tr>
<td>Transportation</td>
<td>0.75</td>
<td>1.8</td>
<td>36.4</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td></td>
<td></td>
<td><strong>13.4</strong></td>
</tr>
</tbody>
</table>

RD: relative difference from the estimates without data screening
Conclusions

- Black carbon emissions in southern Jiangsu city cluster were constrained combining chemistry transport model and available ground measurements with a multiple regression model.

- The modeling performance was improved with the constrained emissions. Reduced emissions from constraint implied the effectiveness of emission control in recent years.

- Uncertainty from the a prior inventory and non-linearity between emissions and concentrations was limited. Emissions could be better constrained if more available measurements are included.
Thanks for attention!

For More Information:

http://www.airqualitynju.com/

Zhao et al., Atmos Chem Phys, 19, 2095, 2019

Zhou et al., Atmos Chem Phys, 17, 211, 2017

Cui et al., Atmos Chem Phys, 15, 8657, 2015

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