Impacts of meteorological parameters and emissions on decadal and interannual variations of black carbon in China for 1980-2010

Yu-Hao Mao, Hong Liao*, Yongming Han, and Junji Cao
Outline

- Motivation
- Methods
- Simulated BC and Model Evaluation
- Simulated Decadal Trends of BC
- Simulated Interannual Variations of BC
- Direct Radiative Forcing of BC
- Summary and Conclusions
Environmental Effects of Black Carbon

Contribute 25% of the global total emissions [Cook et al., 1999; Bond et al., 2004]

The largest BC emitter: China

Absorb solar radiation

Cloud processes

Snow and ice albedo

Climate

Particulate matter

BC reduction may provide an efficient near-term solution to mitigate global warming and to improve air quality simultaneously.
Objectives of This work

- To quantify the decadal and interannual variations of surface concentrations and tropospheric column burdens of BC in China for 1980-2010.

- To quantify the roles of variations in meteorological parameters, anthropogenic and biomass burning emissions in the variations.
To identify the relative roles of variations in meteorological parameters and emissions in the decadal and interannual variations of BC in China for 1980-2010

**Methods**

**Assimilated MERRA meteorological fields**

**BC emissions**

**Global**
- Streets 2000+scaling factor for 2010

**Asia**
- The regional Emission inventory in Asia (REAS)

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Graph showing BC emissions from 1980 to 2010 with different emissions sources and regional data for Asia.
Compared to a recent top-down estimates of BC emissions in China [Fu et al., 2012], emissions in China from REAS (this study) are biased low by a factor of 2.

## Simulations

<table>
<thead>
<tr>
<th>Model Experiments</th>
<th>Meteorological Parameters</th>
<th>Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>VMET met</td>
<td>1980—2010</td>
<td>2010</td>
</tr>
<tr>
<td>VEMISAN Emission(an)</td>
<td>2010</td>
<td>1980—2010</td>
</tr>
<tr>
<td>VEMISBB Emission(bb)</td>
<td>2010</td>
<td>Not included</td>
</tr>
</tbody>
</table>

Turn off emissions in China

Doubled in Asia
Simulated Distribution of BC

- **High concentration regions:**
  - East China

- **Seasonal variation:**
  - JJA: 0.67 µg m\(^{-3}\)/DJF: 1.77 µg m\(^{-3}\)
    - (meteorological parameters and emissions from eg. heating)

- **Differences (2010-1980):**
  - Eastern China: 0.29 µg m\(^{-3}\) (24%)
  - Western China: 0.12 µg m\(^{-3}\) (66%)

>4 µg m\(^{-3}\)

>2.5 µg m\(^{-3}\)
Evaluation of Simulated BC Concentrations and AAOD

- Ground-base measurements of BC concentrations from literatures (20 sites)
- AERONET AAOD (12 sites)
- BC concentrations in ice cores and lake sediments

- Simulated BC concentrations show NMBs of $-37\%$ at remote sites, $-49\%$ at rural sites, and $-79\%$ at urban sites (VALL). Improved in VAN2X.
- Simulated annual mean BC AAOD in simulation VALL(VAN2X) show NMB values of $-77\%$ ($-57\%$) at urban sites and $-50\%$ ($-4\%$) at remote sites.
Comparisons With Measurements in Ice Cores

Observed annual BC concentrations (red) in ice cores in Tibetan Plateau [Xu et al., 2009] and simulated annual mean BC concentrations (black) in the atmosphere at 300 hPa and in surface air for 1980-2010.

The simulated BC concentrations in the atmosphere reasonably capture the interannual variations.

The evaluations of model results prove the ability of the GEOS-Chem model to reasonably capture the decadal and interannual variations of BC in China.
Simulated Decadal Trends of BC

<table>
<thead>
<tr>
<th>VALL</th>
<th>Concentrations (µg m⁻³)</th>
<th>Column burdens (mg m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>annual mean</td>
<td>0.7–1.0</td>
<td>0.8–1.1</td>
</tr>
<tr>
<td>2010—1980</td>
<td>0.21 (29%)</td>
<td>0.29 (37%)</td>
</tr>
</tbody>
</table>

The decadal trend

<table>
<thead>
<tr>
<th></th>
<th>Concentrations (µg m⁻³ decade⁻¹)</th>
<th>Column burdens (mg m⁻² decade⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980s</td>
<td>0.31</td>
<td>0.29</td>
</tr>
<tr>
<td>1990s</td>
<td>−0.20</td>
<td>−0.10</td>
</tr>
<tr>
<td>2000s</td>
<td>0.16</td>
<td>0.21</td>
</tr>
</tbody>
</table>

- **VALL VS. VEMIS**: emissions
- **VEMIS VS. VEMISAN**: anthropogenic emissions (98/95%)
- **VALL VS. VMET**
- **VNOC**: (8/21%) ~9% decade⁻¹
Simulated Decadal Trends of BC

The deviation from the mean (DM):

$$DM_i = \left( M_i - \frac{1}{n} \sum_{i=1}^{n} M_i \right) / \frac{1}{n} \sum_{i=1}^{n} M_i,$$

- $M_i$: the simulated annual mean BC in China for year $i$;
- $n$: the number of years examined ($n=31$ for years 1980–2010).

[Mu and Liao, 2014; Yang et al., 2015]

- **VALL VS. VEMIS VS. VMET**: emissions
- **VEMIS VS. VEMISAN**: anthropogenic emissions
- **Eastern China**: 1980(0.52), 1990(-0.38), 2000(0.25) μg m$^{-3}$ decade$^{-1}$
- **Western China**: 1980(0.07), 1990(-0.09), 2000(0.06) μg m$^{-3}$ decade$^{-1}$
Simulated Interannual Variations of BC

- The peaks and troughs in deviations in **VALL** simulation are consistent with those in either **VMET** or **VEMIS**.

- The DM values in **VMET** are larger in column burdens of BC than in surface concentrations.

- The interannual variations of BC in **VEMISAN** are similar to those in **VEMIS** (except in 2003).
Simulated Interannual Variations of BC

The APDM values of detrended simulated annual mean surface BC concentrations in China for 1980–2010

The mean absolute deviation (MAD):

\[
MAD = \frac{1}{n} \sum_{i=1}^{n} \left| M_i - \frac{1}{n} \sum_{i=1}^{n} M_i \right|
\]

The absolute percent departure from the mean (APDM):

\[
APDM = 100\% \times \frac{MAD}{\left(\frac{1}{n} \sum_{i=1}^{n} M_i \right)}
\]

\(M_i\): the detrended simulated annual mean BC in China for year \(i\);

\(n\): the number of years examined.

[Mu and Liao, 2014; Yang et al., 2015]

The **MAD** and **APDM** (or **DM**) represent the interannual variations of BC in terms of absolute value and percentage, respectively, averaged over the 31 years for 1980–2010 in the present study.
Simulated Interannual Variations of BC

- The MAD and APDM values in VMET and VEMIS are generally comparable.

- In DJF, both MAD and APDM values in VMET are 2 times of those in VEMIS.

- The MAD and APDM values of surface concentrations (column burdens) of BC in VEMISAN are 90% (70%) of those due to variations in VEMIS.

- The influences of biomass burning and non-China emissions on BC are largest in MAM.

<table>
<thead>
<tr>
<th>VALL</th>
<th>concentrations</th>
<th>column burden</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAD</td>
<td>0.013–0.034μg m⁻³</td>
<td>0.024–0.038mg m⁻²</td>
</tr>
<tr>
<td>APDM</td>
<td>2.5–4.2%</td>
<td>3.4–4.9%</td>
</tr>
</tbody>
</table>
Direct Radiative Forcing of BC

The annual mean all-sky TOA DRF of BC

- The variations of DRF are similar to the changes in tropospheric column burden.
- The increases of BC DRF in China from 1980 to 2010 (0.35 Wm\(^{-2}\)) are significant comparing to the global annual mean DRF values of BC (0.4 Wm\(^{-2}\)), tropospheric ozone (0.4 Wm\(^{-2}\)), and carbon dioxide (1.82 Wm\(^{-2}\)) reported by IPCC [2013].
Direct Radiative Forcing of BC

- The TOA DRF of BC (Wm$^{-2}$) in:
  - 1980: the lowest concentrations and tropospheric column burdens
  - 1990: the highest concentrations
  - 2010: the highest tropospheric column burdens

- From 1980 to 1990 (2010), the DRF shows a significant increase of $>0.3$ ($>0.5$) Wm$^{-2}$ in the most region of eastern China, with the largest value of 1.1 (1.4) Wm$^{-2}$ in the Sichuan Basin.
Direct Radiative Forcing of BC

- High column burdens lead to high DRF in 2010.
- The influence of meteorological parameters:
  - Column burdens of BC are higher in 2010 than in 1990 by 0.03 mgm\(^{-2}\) in VMET and by 0.01 mgm\(^{-2}\) in VEMIS.
Direct Radiative Forcing of BC

Contributions of non-China emissions to tropospheric column burdens of BC averaged over China for 1980–2010 from model simulation VNOC

The influence of non-China emissions:

- **Contributions to column burden:** 18–27% below 10 km and 25–36% at 1–6 km.
- **Account for** 0.32 Wm$^{-2}$ (31%) of simulated all-sky TOA DRF of BC averaged over China in 2010
- **From 1990 to 2010,** the contributions to column burden of increase by 0.04 mgm$^{-2}$ below 10 km and by 0.03 mgm$^{-2}$ at 1–6 km.
Summary and Conclusions

☐ The decadal variations:
  • The **decadal variations** of simulated annual mean surface concentrations (column burdens) of BC averaged over China were 0.31 μgm⁻³decade⁻¹ (0.29mgm⁻²decade⁻¹) in the 1980s, 0.20 (0.10) in the 1990s, and 0.16 (0.21) in the 2000s.

  • The changes in **emissions** were the major driver of the decadal trends of BC.

☐ The interannual variations:
  • The **interannual variations** were 20% to 15% (20% to 11%) for DM, 0.068 μgm⁻³ (0.069 mgm⁻²) for MAD, and 7.7% (7.1%) for APDM.

  • The interannual variations were dependent on variations of both **emissions and the meteorological parameters** such as the transport.
More details about this work:
Thanks very much for your attention!
# Evaluation of Simulated BC concentrations and AAOD

## Table 2. Observed and Simulated Annual Mean Surface BC Concentrations (µg m\(^{-3}\)) at 20 Sites in China\(^a\)

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude °N</th>
<th>Longitude °E</th>
<th>Altitude (m)</th>
<th>Observation Period</th>
<th>BC Concentrations</th>
<th>Reference(^d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Akdala</td>
<td>47.1</td>
<td>88.0</td>
<td>562</td>
<td>2004.8–2005.3</td>
<td>0.35</td>
<td>[1]</td>
</tr>
<tr>
<td>Zhuzhang</td>
<td>28.0</td>
<td>99.7</td>
<td>3583</td>
<td>2004.8–2005.2</td>
<td>0.34</td>
<td>[1]</td>
</tr>
<tr>
<td>Muztagh Ata</td>
<td>38.3</td>
<td>75.0</td>
<td>4500</td>
<td>2005</td>
<td>0.055</td>
<td>[2]</td>
</tr>
<tr>
<td>Nam Co</td>
<td>30.8</td>
<td>91.0</td>
<td>4730</td>
<td>2006.7–2007.1</td>
<td>0.082</td>
<td>[3]</td>
</tr>
<tr>
<td>Waliguan</td>
<td>36.3</td>
<td>100.9</td>
<td>3616</td>
<td>2000–2010</td>
<td>0.30</td>
<td>[4]</td>
</tr>
<tr>
<td>Wusumu</td>
<td>40.6</td>
<td>112.6</td>
<td>1221</td>
<td>2005.9; 2006.12006.7; 2007.5</td>
<td>3.10</td>
<td>[5]</td>
</tr>
<tr>
<td>Gaolanshan</td>
<td>36.0</td>
<td>105.9</td>
<td>2075</td>
<td>2006–2007</td>
<td>3.77</td>
<td>[6]</td>
</tr>
<tr>
<td>Longfengshan</td>
<td>44.7</td>
<td>127.6</td>
<td>337</td>
<td>2006–2007</td>
<td>2.25</td>
<td>[6]</td>
</tr>
<tr>
<td>Taiyangshan</td>
<td>29.2</td>
<td>111.7</td>
<td>571</td>
<td>2006–2007</td>
<td>2.61</td>
<td>[6]</td>
</tr>
<tr>
<td>Lanzhou</td>
<td>35.6</td>
<td>104.1</td>
<td>1966</td>
<td>2007.1–2009.8</td>
<td>1.59</td>
<td>[7]</td>
</tr>
<tr>
<td>Maofengshan</td>
<td>23.3</td>
<td>113.5</td>
<td>550</td>
<td>2009</td>
<td>2.43</td>
<td>[8]</td>
</tr>
<tr>
<td>Chengdu</td>
<td>30.7</td>
<td>104.0</td>
<td>496</td>
<td>2006–2007</td>
<td>10.8</td>
<td>[6]</td>
</tr>
<tr>
<td>Dalian</td>
<td>38.9</td>
<td>121.6</td>
<td>92</td>
<td>2006–2007</td>
<td>5.3</td>
<td>[6]</td>
</tr>
<tr>
<td>Panyu</td>
<td>22.9</td>
<td>113.3</td>
<td>5</td>
<td>2006–2007</td>
<td>7.5</td>
<td>[6]</td>
</tr>
<tr>
<td>Zhengzhou</td>
<td>34.8</td>
<td>113.7</td>
<td>99</td>
<td>2006–2007</td>
<td>9.4</td>
<td>[6]</td>
</tr>
<tr>
<td>Xian</td>
<td>34.4</td>
<td>109.0</td>
<td>363</td>
<td>2006–2007</td>
<td>12.1</td>
<td>[6]</td>
</tr>
<tr>
<td>Dongguan</td>
<td>23.0</td>
<td>113.5</td>
<td>30</td>
<td>2009</td>
<td>5.3</td>
<td>[7]</td>
</tr>
</tbody>
</table>

\(^a\) Model results are from simulations VALL and VAN2X. See text and Table 1 for the definitions of model simulations.

\(^b\) Results are from model simulation VALL.

\(^c\) Results are from model simulation VAN2X.


\(^e\) Normalized mean biases (NMB) = 100% × (Model − Observation)/Observation, where Model and Observation are the simulated and observed BC concentrations, respectively.
## Evaluation of Simulated BC concentrations and AAOD

### Table 3. AERONET-Derived and GEOS-Chem-Simulated Annual Mean BC Absorption Aerosol Optical Depth (AAOD) at 12 AERONET Sites in China

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude(°N)</th>
<th>Longitude(°E)</th>
<th>Altitude(m)</th>
<th>Time</th>
<th>Observation</th>
<th>Model</th>
<th>NMB^d (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Rural</td>
<td>Urban</td>
<td></td>
</tr>
<tr>
<td>Taihu</td>
<td>31.2</td>
<td>120.2</td>
<td>20</td>
<td>2006–2010</td>
<td>0.054</td>
<td>0.021^b</td>
<td>−61 (−24)</td>
</tr>
<tr>
<td>SACOL</td>
<td>35.9</td>
<td>104.1</td>
<td>1965</td>
<td>2006–2010</td>
<td>0.031</td>
<td>0.010 (0.019)</td>
<td>−68 (−39)</td>
</tr>
<tr>
<td>Xinglong</td>
<td>40.4</td>
<td>117.6</td>
<td>970</td>
<td>2006–2010</td>
<td>0.037</td>
<td>0.027 (0.053)</td>
<td>−27 (43)</td>
</tr>
<tr>
<td>Shouxian</td>
<td>32.6</td>
<td>116.8</td>
<td>22</td>
<td>2008</td>
<td>0.038</td>
<td>0.021 (0.040)</td>
<td>−45 (5)</td>
</tr>
<tr>
<td>Hefei</td>
<td>31.9</td>
<td>117.2</td>
<td>36</td>
<td>2008</td>
<td>0.047</td>
<td>0.026 (0.050)</td>
<td>−45 (6)</td>
</tr>
<tr>
<td>Xianghe</td>
<td>39.8</td>
<td>117.0</td>
<td>36</td>
<td>2005–2010</td>
<td>0.058</td>
<td>0.027 (0.052)</td>
<td>−53 (−10)</td>
</tr>
<tr>
<td>Beijing</td>
<td>40.0</td>
<td>116.4</td>
<td>92</td>
<td>2002–2010</td>
<td>0.065</td>
<td>0.026 (0.050)</td>
<td>−60 (−23)</td>
</tr>
<tr>
<td>Yulin</td>
<td>38.3</td>
<td>109.7</td>
<td>1080</td>
<td>2002</td>
<td>0.061</td>
<td>0.010 (0.019)</td>
<td>−84 (−69)</td>
</tr>
<tr>
<td>HK_PolyU</td>
<td>22.3</td>
<td>114.2</td>
<td>30</td>
<td>2006–2010</td>
<td>0.062</td>
<td>0.008 (0.017)</td>
<td>−87 (−73)</td>
</tr>
<tr>
<td>HK_Hok_Tsui</td>
<td>22.2</td>
<td>114.3</td>
<td>80</td>
<td>2008–2010</td>
<td>0.045</td>
<td>0.010 (0.018)</td>
<td>−78 (−60)</td>
</tr>
<tr>
<td>Chen-kung</td>
<td>23.0</td>
<td>120.2</td>
<td>50</td>
<td>2004–2010</td>
<td>0.025</td>
<td>0.006 (0.010)</td>
<td>−76 (−60)</td>
</tr>
<tr>
<td>NCU</td>
<td>25.0</td>
<td>121.2</td>
<td>171</td>
<td>2002–2010</td>
<td>0.030</td>
<td>0.005 (0.009)</td>
<td>−83 (−70)</td>
</tr>
</tbody>
</table>

^aModel results are from simulations VALL and VAN2X. See text and Table 1 for the definitions of model simulations.
^bResults are from model simulation VALL.
^cResults are from model simulation VAN2X.
^dNormalized mean biases (NMB) = 100% × (Model − Observation)/Observation, where Model and Observation are the simulated and derived BC AAOD, respectively.