Arctic Black Carbon (ABC) : Emission, Origin, and Transport Modeling In Arctic Region

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Workshop
Improving Black Carbon Emission Estimates and Abatement
Milan, Italy
May 13-14, 2015
Introduction

- Background: climate effects from black carbon
- Motivation: mitigate warming in the Arctic

Black carbon emissions reconstruction for Russia

- To fill information gaps

Numerical simulation and evaluation

- Hemispheric WRF/CMAQ modeling in the Arctic

Impact assessment

- Revisit origin, transport and deposition of black carbon in the Arctic
Background

Multiple sources

Short lifetime

Climate response

Terrestrial impacts

Bond et al., 2013, JGR
Main transport pathways of air pollutants to the Arctic

(AMAP, 2011)
Background

Ensemble model simulations of Arctic black carbon

All models strongly underestimated BC concentrations in the Arctic

Shindell et al., 2008
Background

Wet scavenging schemes are modified to improve model performance.
Motivations

Arctic black carbon simulation problems:
- Large diversity of modeling BC from different models (Shindell et al., 2008)
- Strong underestimation of BC in Arctic (Shindell et al., 2008; Koch et al., 2009)
- Improper wet scavenging parameterizations (Bourgeois et al., 2011; Liu et al., 2011)

Major emission source regions for Arctic black carbon:
- Europe (EMEP)
- United States (USEPA NEI)
- Canada (NPRI)
- Russia

Uncertainty on raw emission factors, control technologies for a range of sources.
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I. Gas flaring: a missing BC source

Russia possess the largest natural gas reserves of 24% in the world as of 2009. (Dmitry Volkov, 2008)
Gas flaring BC emission factor measurement

*In situ* measurement of gas flaring BC emission factor (Johnson et al., 2013)

**Sky-LOSA**: Line-Of-Sight Attenuation of sky-light

- Compressor station flare in Mexico, 2011
  - 0.51-m dia., lightly sooting flare ($\tau \approx 90\%$)
  - Soot emission rate: $0.067 \pm 0.02$ g/s
  - Roughly equivalent to emissions from 16 diesel buses continuously driving

- Gas Plant Flare in Uzbekistan, 2008
  - 1.05-m dia., visibly sooting flare ($\tau \approx 60\%$)
  - Soot emission rate: $2.0 \pm 0.66$ g/s
  - Roughly equivalent to emissions from 500 diesel buses continuously driving

- Significant difference of BC EF from different flares
- EF measured by Sky-LOSA is not appropriate for emission estimation (i.e. unit in g/s)
- Need mass of black carbon per mass of fuel burned

Courtesy: http://www.unep.org/ccac/Portals/50162/docs/ccac/initiatives/oil_and_gas/Sky-LOSA.PDF (taken from slides by Prof. Matthew Johnson from Carleton Univ.)
Estimation of gas flaring EF and emission in Russia

No field measurement available

Only laboratory test  *(McEwen and Johnson, 2012)*

<table>
<thead>
<tr>
<th>Associated Gas Composition Percentage (%)</th>
<th>Heating Value (MJ/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane (CH₄)</td>
<td>42.2661</td>
</tr>
<tr>
<td>Ethane (C₂H₆)</td>
<td>9.9207</td>
</tr>
<tr>
<td>Propane (C₃H₈)</td>
<td>14.4320</td>
</tr>
<tr>
<td>Butane i-C₄H₁₀</td>
<td>4.4313</td>
</tr>
<tr>
<td>Butane n-C₄H₁₀</td>
<td>7.2039</td>
</tr>
<tr>
<td>Pentane i-C₅H₁₂</td>
<td>4.1191</td>
</tr>
<tr>
<td>Pentane n-C₅H₁₂</td>
<td>4.8658</td>
</tr>
<tr>
<td>Hexane i-C₆H₁₄</td>
<td>5.0317</td>
</tr>
<tr>
<td>Hexane n-C₆H₁₄</td>
<td>1.4181</td>
</tr>
<tr>
<td>Heptane i-C₇H₁₅</td>
<td>2.2952</td>
</tr>
<tr>
<td>Heptane n-C₇H₁₅</td>
<td>0.0184</td>
</tr>
<tr>
<td>Octane i-C₈H₁₈</td>
<td>0.5915</td>
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<tr>
<td>Octane n-C₈H₁₈</td>
<td>0.1623</td>
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<td>Nonane i-C₉H₂₀</td>
<td>1.4716</td>
</tr>
<tr>
<td>Nonane n-C₉H₂₀</td>
<td>0.0756</td>
</tr>
<tr>
<td>Decane i-C₁₀H₂₂</td>
<td>0.2905</td>
</tr>
<tr>
<td>Decane n-C₁₀H₂₂</td>
<td>0.0694</td>
</tr>
<tr>
<td>Carbon dioxide (CO₂)</td>
<td>0.3070</td>
</tr>
<tr>
<td>Nitrogen (N₂)</td>
<td>0.6652</td>
</tr>
<tr>
<td>Hydrogen sulfide (H₂S)</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

$\text{BC}_{\text{flaring}} = \text{Volume} \times \text{Soot}_{\text{EF}}$

Volume: Gas flaring volume of Russia in 2010 was **35.6 BCM** (billion cubic meters)

The BC emission from Russia’s gas flaring in 2010 is estimated to be **111.5 Gg**.
Spatial distribution of gas flaring BC emission

Gas flare areas (red polygon) retrieved from satellite (U.S. Air Force Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS))

Spatial allocation proxy (contour) nighttime lights product

Data source: NOAA NGDC

Major gas flaring regions:
- Yamal-Nenets
- Khanty-Mansiysk
II. Transportation BC emission

<table>
<thead>
<tr>
<th>Legislation</th>
<th>Data</th>
<th>Legislation</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Euro I</td>
<td>1/7/1992</td>
<td>Euro I</td>
<td>1/1/1999</td>
</tr>
<tr>
<td>Euro II</td>
<td>1/1/1996</td>
<td>Euro II</td>
<td>1/1/2006</td>
</tr>
<tr>
<td>Euro III</td>
<td>1/1/2000</td>
<td>Euro III</td>
<td>1/1/2008</td>
</tr>
<tr>
<td>Euro IV</td>
<td>1/10/2005</td>
<td>Euro IV</td>
<td>1/1/2010</td>
</tr>
<tr>
<td>Euro V</td>
<td>1/9/2009</td>
<td>Euro V</td>
<td>1/1/2014</td>
</tr>
<tr>
<td>Euro VI</td>
<td>1/9/2014</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Share of different Euro vehicles in Russia**

- **Public bus**: 19% (Euro 0), 28% (Euro 1), 41% (Euro 2), 12% (Euro 3+)
- **Private bus**: 16% (Euro 0), 13% (Euro 1), 30% (Euro 2), 41% (Euro 3+)
- **Cars**: 10% (Euro 0), 47% (Euro 1), 25% (Euro 2), 18% (Euro 3+)
- **Trucks**: 30% (Euro 0), 13% (Euro 1), 8% (Euro 2), 19% (Euro 3+)


\[
E_{\text{hot}} = \sum E_{\text{PM,ijk}} \times (S_{ij} \times E_{ij} \times R_{ij} \times VMT_{ijk}) \times (EC/PM_{2.5})_{ijk}
\]

Where \(i, j,\) and \(k\) represent the vehicle type, driving modes, and Euro standard, respectively. \(E_{\text{PM,ijk}}\) is the PM emission factors; \(S_{ij}\) is the vehicle stock number; \(E_{ij}\) is the percentage share of vehicles with different Euro standards; \(R_{ij}\) is the annual ratio of vehicle usage; \(VMT_{ijk}\) is the annual driving mileage per vehicle; \((EC/PM_{2.5})_{ijk}\) is the emission mass ratio of EC in PM_{2.5}; And \(E_{\text{hot}}\) is annual BC emission during the hot operation stage.
II. Transportation BC emission

PM emission factors (g/km) of various vehicle types dependent on different Euro standards (Euro 0 – Euro 3) and driving conditions (urban, intercity and highways)

Ministry of Transport of the Russian Federation Research Institute, 2008
II. Transportation BC emission

Total = 52.9 Gg

Soot emission factors (g/min) during warm-up (cold start)

Ministry of Transport of the Russian Federation Research Institute, 2008
III. Residential BC emission

Residential BC emissions in Russia are based on fuel consumption data and EFs.

1. Total = 57.0 Gg

   - Fuelwood: 61%
   - Coal: 35%

2. National BC -> Federal District level based on residential firewood consumption from Russia’s FSSS (Federal State Statistics Service)

3. District BC -> grid cell population density within each district (ORNL’s LandScan dataset)
IV. Industrial BC emission

\[ BC_{\text{ind}} = \sum PM_{\text{raw}, i} \times (1 - \eta_i) \times (BC/PM) \]

where \( PM_{\text{raw}, i} \) represents PM emission prior to technology controls, \( \eta_i \) and \( \eta \) represents the sub-sector and removal efficiency.

<table>
<thead>
<tr>
<th>Industry sector</th>
<th>PM emission (Gg)</th>
<th>Removal efficiency (%)</th>
<th>BC/PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacture of food products, including beverages and tobacco</td>
<td>445.68</td>
<td>94.1</td>
<td>0.16</td>
</tr>
<tr>
<td>Textile and clothing manufacture</td>
<td>9.81</td>
<td>81.7</td>
<td>0.26</td>
</tr>
<tr>
<td>Manufacture of leather, Leather goods and footwear</td>
<td>1.23</td>
<td>70.0</td>
<td>0.33</td>
</tr>
<tr>
<td>Manufacture of wood and wood products</td>
<td>730.90</td>
<td>97.7</td>
<td>0.32</td>
</tr>
<tr>
<td>Pulp and paper production, publishing and printing</td>
<td>744.95</td>
<td>94.8</td>
<td>0.01</td>
</tr>
<tr>
<td>Manufacture of coke and refined petroleum</td>
<td>132.79</td>
<td>89.0</td>
<td>0.41</td>
</tr>
<tr>
<td>Chemical production</td>
<td>2426.41</td>
<td>98.7</td>
<td>0.05</td>
</tr>
<tr>
<td>Manufacture of rubber and plastic products</td>
<td>8.84</td>
<td>87.1</td>
<td>0.16</td>
</tr>
<tr>
<td>Manufacture of other nonmetallic mineral products</td>
<td>7878.74</td>
<td>98.1</td>
<td>0.01</td>
</tr>
<tr>
<td>Basic metals and fabricated metal products</td>
<td>12061.32</td>
<td>97.8</td>
<td>0.02</td>
</tr>
<tr>
<td>Manufacture of machinery</td>
<td>65.95</td>
<td>76.0</td>
<td>0.11</td>
</tr>
<tr>
<td>Manufacture of electrical, electronic and optical equipment</td>
<td>28.50</td>
<td>83.4</td>
<td>0.06</td>
</tr>
<tr>
<td>Vehicles and equipment production</td>
<td>66.81</td>
<td>75.8</td>
<td>0.08</td>
</tr>
<tr>
<td>Other production</td>
<td>60.82</td>
<td>92.3</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Total = 29.4 Gg

National BC -> Provincial level based on provincial industrial revenues from Russia’s FSSS (Federal State Statistics Service)

Provincial BC -> grid cell population density within each district (ORNL’s LandScan dataset)

Data from SRI-Atmosphere
V. Power plants BC emission

Categorize fuel types of thermal power plants in Russia by using the energy intensity (tons of CO₂ emitted per MWh)

- **Coal**: Intensity > 0.9 tons CO₂/MWh
- **Oil**: Intensity 0.65 - 0.9 tons CO₂/MWh
- **Gas**: Intensity 0.4 - 0.65 tons CO₂/MWh

<table>
<thead>
<tr>
<th>Sector</th>
<th>Particulate matter emission (Gg)</th>
<th>Removal efficiency (%)</th>
<th>PM into atmosphere (Gg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Industry</td>
<td>26294.212</td>
<td></td>
<td>1186.671</td>
</tr>
<tr>
<td>Electricity production</td>
<td>24292.676</td>
<td>96.5</td>
<td>840.986</td>
</tr>
<tr>
<td>Transmission and districion of steam and hot water</td>
<td>1903 862</td>
<td>82.9</td>
<td>326.044</td>
</tr>
<tr>
<td>Collection, purification and distribution of water</td>
<td>86.41</td>
<td>90.2</td>
<td>8.455</td>
</tr>
<tr>
<td>Production and distribution of gaseous fuels</td>
<td>11.265</td>
<td>0.7</td>
<td>11.185</td>
</tr>
</tbody>
</table>

Total = 12.1 Gg

National BC -> grid level
CARMA (Carbon Monitoring for Action): power plant location, energy capacity and CO₂ emission.
Sectoral contributions to Russian anthropogenic BC emissions

Russian anthro BC = 263 Gg

BC emission prepared for ARCTAS

Wang et al., 2011

BC Total
(0.1° × 0.1°)
Unit: kg/per grid
Comparison to other emission inventories

(AMAP, 2011)
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WRF/CMAQ modeling system

- NCEP Reanalysis
- Boundary
- Initial
- JPROC
- WRF
- MCIP
- HTAP BC
- Russian BC
- Biomass GFED
- Base Sim.
- New Sim.
- CMAQ Chemistry-Transport Model
  - Gas-phase Chemistry
  - Advection
  - Diffusion
  - Aerosol Chemistry
  - Aerosol Deposition
  - Aqueous Chemistry
- Outputs
  - Conc.
  - Depo.
  - Radiation
  - Health
- Nested Simulation
ABC modeling domain setup

CMAQ extended to Hemispheric Scales (H-CMAQ)

**CMAQ v5.0.1**
Meteorological Input: WRF V3.5.1

Projection: Polar

Horizontal Spacing: 180*180 (108 km * 108 km)

Vertical Spacing: 44 layers

Gas chemistry: CB05

Aerosol mechanism: AERO5

Simulation year: 2010

IC/BC: GEOS-Chem v9-01-03

Arctic Circle (north of 66° 33'44" N°)
Default global anthropogenic BC emission inventory:
EDGAR (Emission Database for Global Atmospheric Research) HTAPv2
(Hemispheric Transport of Air Pollution) 2010 [ 0.1 ° × 0.1 ° ]
Industry + power plant + traffic + residential + shipping + air

Biomass burning emission:
GFEDv3 (Global Fire Emission Database) [ 0.5 ° × 0.5 ° ]

Black carbon emissions input

HTAPv2 BC

Russian BC

(kg/m²/yr)
Model performances in US, W. Europe and China

**IMPROVE**
(167 sites, 2010)
NMB: 8.32%

NMB: -25.9%
(6 sites, 2010)

NMB: -29.3%
(5 Finland sites, 2004 - 2008)
Observational sites in Russia and the Arctic

**AERONET (Russia)**

**Moscow**
(55.7 ° N, 37.5 ° E)

**Zvenigorod**
(55.7 ° N, 36.8 ° E)

**Yekaterinburg**
(57.0 ° N, 59.5 ° E)

**Tomsk**
(56.5 ° N, 85.0 ° E)

**Yakutsk**
(61.7 ° N, 129.4 ° E)

**Ussuriysk**
(43.7 ° N, 132.2 ° E)

**Arctic sites**

**Barrow, USA**
(71.3 ° N, 156.6 ° W)

**Alert, Canada**
(82.5 ° N, 62.3 ° W)

**Zeppelin, Norway**
(78.9 ° N, 11.9 ° E)

**Tiksi, Russia**
(71.6 ° N, 128.9 ° E)

🌟 Surface BC sites 🆓 AERONET sites
Compared to the conventional global chemical transport model (e.g. GEOS-Chem) with cylindrical projection, H-CMAQ with a polar projection seems to better resolve the cross-pole atmospheric transport.
Model performances in Russia

\[ \text{AAOD}_{\text{sim}} = \int \sigma_{\text{ext, BC}}(z) \cdot dz \]

\[ \sigma_{\text{ext, BC}} = 10.0 \times [\text{BC}]_{\text{sim}} \]
Model performances in the Arctic

(a) **Zeppelin, Norway**

- Observation
- HTAP emission
- New emission

(b) **Alert, Canada**

- Observation
- HTAP emission
- New emission

(c) **Barrow, Alaska**

- Observation
- HTAP emission
- New emission

(d) **Tiksi, Russia**

- Observation
- HTAP emission
- New emission

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Percentages:
- Zeppelin, Norway: 81%
- Alert, Canada: 32%
- Barrow, Alaska: 59%
- Tiksi, Russia: 86%
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Monthly BC dry deposition perturbations

BC dry deposition (new – base)  
ratio:  \((\text{new} - \text{base})/\text{new}\)

JUN

DEC
Monthly BC dry deposition perturbations

BC deposition in Russia (excluding the Russian Arctic)

BC deposition within Arctic Circle (≥ 66.5622 N)
Conclusions

- Russian black carbon emissions are strongly underestimated, e.g. gas flaring and transportation emissions.
- By using the new Russian BC emission as model input, the model performance could be significantly improved against observations. Previous studies on adjusting the physical processes in the model could be misleading.
- The role of Russian emission on the BC surface level and deposition in the Arctic has been significantly underestimated and even overlooked in some regions.
Outlook

Our result is expected to advance the research in the following areas:

- Warming partly caused by the black carbon emissions could induce sea ice melting in the Arctic. On one hand, it increases more opportunities for the oil and gas industries in the Arctic region. On the other hand, more challenges are to be met, e.g. requirements on the drilling technology, risks of contamination such as oil spill.

- Sea ice melting in the Arctic may also cause other increased activities such as cargo shipping, which is also source for BC emission. Hence, sea ice melting — increased BC emissions — warming could be a positive loop for even faster warming in the Arctic region.

- Warming of the Arctic is threatening the ecology there, e.g. thawing of the frozen ground (permafrost), redistribution of soil, organics, and nutrients, and change of the bacteria communities.
Next steps

There are a few aspects that we propose to further advance the understanding of Russian BC emissions:

◼ **Data Gaps**: Local Russian BC emission factors are very rare. Bottom-up emission estimation is impossible based on the current available activity data.

◼ **Technical Cooperation**: International cooperation with Russia’s local authorities is needed, especially on the quantification of emission factors for various emissions sources with different control technologies.

◼ **Policy Decision**: Priority emission sources that impact the Arctic should be identified. Cost-effective tools on abating BC emissions should be designed and applied.
Acknowledgment

This work is supported by Interagency Acquisition Agreement S-OES-11_IAA-0027 from the U.S. Department of State to the U.S. Department of Energy. We sincerely thank our Russian counterparts Alexander Romanov, Irina Morozova, and Yulia Ignatieva and Vitaly Y. Prikhodko’s coordination with SRI - Atmosphere to obtain part of the emission source data used in this study. This work does not reflect the official views or policies of the United States Government or any agency thereof, including the funding entities.
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Thank you for your attention!