Arctic Black Carbon: Role of Russia’s BC Emissions, Transport, and Deposition

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Workshop
Assessing the Impacts of Future Global Air Pollution Scenarios: Implications for HTAP2, AMAP, and Global IAMs
Potsdam, Germany
February 17-19, 2016
Main transport pathways of air pollutants to the Arctic

(AMAP, 2011)
Background

Ensemble model simulations of Arctic black carbon

<table>
<thead>
<tr>
<th>Model</th>
<th>Gas-phase</th>
<th>Aerosols</th>
<th>Prescribed lifetime</th>
<th>Horizontal Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. CAMCHEM</td>
<td>\text{NO}_x, CO</td>
<td>\text{SO}_2, BC</td>
<td>Y</td>
<td>1.9</td>
</tr>
<tr>
<td>2. ECHAM5-HAMMOZ</td>
<td>\text{NO}_x, CO</td>
<td>\text{SO}_2, BC</td>
<td>Y</td>
<td>2.8</td>
</tr>
<tr>
<td>3. EMEP</td>
<td>\text{NO}_x, CO</td>
<td>\text{SO}_2</td>
<td>Y</td>
<td>1.0</td>
</tr>
<tr>
<td>4. FRSGC/UCI</td>
<td>\text{NO}_x, CO</td>
<td>\text{SO}_2, BC</td>
<td>Y</td>
<td>2.8</td>
</tr>
<tr>
<td>5. GEOSChem</td>
<td>\text{NO}_x</td>
<td>\text{SO}_2, BC</td>
<td>Y</td>
<td>4.0</td>
</tr>
<tr>
<td>6. GISS-PUCCINI</td>
<td>\text{NO}_x, CO</td>
<td>\text{SO}_2, BC</td>
<td>Y</td>
<td>2.0</td>
</tr>
<tr>
<td>7. GMI</td>
<td>\text{NO}_x, CO</td>
<td>\text{SO}_2, BC</td>
<td>Y</td>
<td>2.0</td>
</tr>
<tr>
<td>8. GOCART-2</td>
<td>\text{SO}_2, BC</td>
<td>Y</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>9. LMDz4-INCA</td>
<td>\text{SO}_2, BC</td>
<td>Y</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>10. LLNL-IMPACT</td>
<td>\text{NO}_x, CO</td>
<td>\text{SO}_2, BC</td>
<td>Y</td>
<td>2.0</td>
</tr>
<tr>
<td>11. MOZARTGFDL</td>
<td>\text{NO}_x, CO</td>
<td>\text{SO}_2, BC</td>
<td>Y</td>
<td>1.9</td>
</tr>
<tr>
<td>12. MOZECHE</td>
<td>\text{NO}_x, CO</td>
<td>\text{SO}_2, BC</td>
<td>Y</td>
<td>2.8</td>
</tr>
<tr>
<td>13. SPRINTARS</td>
<td>\text{SO}_2, BC</td>
<td>Y</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>14. STOCHEM-HadGEM1</td>
<td>\text{NO}_x, CO</td>
<td>\text{SO}_2, BC</td>
<td>Y</td>
<td>3.8</td>
</tr>
<tr>
<td>15. STOCHEM-HadAM3</td>
<td>\text{NO}_x, CO</td>
<td>\text{SO}_2</td>
<td>Y</td>
<td>5.0</td>
</tr>
<tr>
<td>16. TM5-JRC</td>
<td>\text{NO}_x</td>
<td>\text{SO}_2, BC</td>
<td>Y</td>
<td>1.0</td>
</tr>
<tr>
<td>17. UM-CAM</td>
<td>\text{NO}_x, CO</td>
<td>\text{SO}_2, BC</td>
<td>Y</td>
<td>2.5</td>
</tr>
</tbody>
</table>

All models strongly underestimated BC concentrations in the Arctic

Arctic Haze

Shindell et al., 2008
Ensemble model simulations of Arctic black carbon during the ARCTAS-spring and ARCPAC campaigns in spring 2008 (Eckhardt et al., 2015)
Across-the-board adjustments such as altering wet scavenging rates may improve biases in one region but make them worse in another (Bond et al., 2013).
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
Gas flaring: an overlooked BC source

Russia possesses the largest natural gas reserves of 24% in the world as of 2009. (Dmitry Volkov, 2008)

Top 20 gas flaring countries

Russia is the top 1 and much more than gas flaring country

Source: World Bank
In situ measurement of gas flaring BC emission factor (Johnson et al., 2013)


Compressor station flare in Mexico, 2011
- 0.51-m dia., lightly sooting flare ($\tau \approx 90\%$)
- Soot emission rate: $0.067 \pm 0.02 \text{ g/s}$
- 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: $2.0 \pm 0.66 \text{ g/s}$
- 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-LOSAPDF (taken from slides by Prof. Matthew Johnson from Carleton Univ.)
Estimation of gas flaring EF and emission in Russia

**laboratory scale flare experiment**

*(McEwen and Johnson, 2012)*

- Linear Fit \((r^2 = 0.85)\)
- \(EF = 0.0578(HV) - 2.09\)
- \(45 \text{ MJ/m}^3\)

### Composition of the associated gas in Russia

<table>
<thead>
<tr>
<th>Associated Gas Composition</th>
<th>Heating Value ((\text{MJ/m}^3))</th>
<th>Volume Percentage (%)</th>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane (\text{CH}_4)</td>
<td>39.9012</td>
<td>61.7452</td>
<td>45.6094</td>
<td>19.4437</td>
<td></td>
</tr>
<tr>
<td>Ethane (\text{C}_2\text{H}_6)</td>
<td>69.9213</td>
<td>7.7166</td>
<td>16.3144</td>
<td>5.7315</td>
<td></td>
</tr>
<tr>
<td>Propane (\text{C}_3\text{H}_8)</td>
<td>101.3231</td>
<td>17.5915</td>
<td>21.1402</td>
<td>4.5642</td>
<td></td>
</tr>
<tr>
<td>i-Butane (\text{i-C}<em>4\text{H}</em>{10})</td>
<td>133.1190</td>
<td>3.7653</td>
<td>5.1382</td>
<td>4.3904</td>
<td></td>
</tr>
<tr>
<td>n-Butane (\text{n-C}<em>4\text{H}</em>{10})</td>
<td>134.0610</td>
<td>4.8729</td>
<td>7.0743</td>
<td>9.6642</td>
<td></td>
</tr>
<tr>
<td>i-Pentane (\text{i-C}<em>5\text{H}</em>{12})</td>
<td>148.4913</td>
<td>0.9822</td>
<td>1.4431</td>
<td>9.9321</td>
<td></td>
</tr>
<tr>
<td>n-Pentane (\text{n-C}<em>5\text{H}</em>{12})</td>
<td>141.1918</td>
<td>0.9173</td>
<td>1.3521</td>
<td>12.3281</td>
<td></td>
</tr>
<tr>
<td>i-Hexane (\text{i-C}<em>6\text{H}</em>{14})</td>
<td>176.8391</td>
<td>0.5266</td>
<td>0.7539</td>
<td>13.8146</td>
<td></td>
</tr>
<tr>
<td>n-Hexane (\text{n-C}<em>6\text{H}</em>{14})</td>
<td>177.1907</td>
<td>0.2403</td>
<td>0.2825</td>
<td>3.7314</td>
<td></td>
</tr>
<tr>
<td>i-Heptane (\text{i-C}<em>7\text{H}</em>{16})</td>
<td>205.0068</td>
<td>0.0274</td>
<td>0.1321</td>
<td>6.726</td>
<td></td>
</tr>
<tr>
<td>Benzene (\text{C}_6\text{H}_6)</td>
<td>147.3980</td>
<td>0.0017</td>
<td>0.0061</td>
<td>0.0414</td>
<td></td>
</tr>
<tr>
<td>n-Heptane (\text{n-C}<em>7\text{H}</em>{16})</td>
<td>205.0068</td>
<td>0.1014</td>
<td>0.0753</td>
<td>1.5978</td>
<td></td>
</tr>
<tr>
<td>i-Octane (\text{i-C}<em>8\text{H}</em>{18})</td>
<td>232.8155</td>
<td>0.0256</td>
<td>0.0193</td>
<td>4.3698</td>
<td></td>
</tr>
<tr>
<td>Toluene (\text{C}_8\text{H}_8)</td>
<td>373.0365</td>
<td>0.0688</td>
<td>0.0679</td>
<td>0.0901</td>
<td></td>
</tr>
<tr>
<td>n-Octane (\text{n-C}<em>8\text{H}</em>{18})</td>
<td>232.8155</td>
<td>0.0017</td>
<td>0.0026</td>
<td>0.4826</td>
<td></td>
</tr>
<tr>
<td>i-Nonane (\text{i-C}<em>9\text{H}</em>{20})</td>
<td>260.6688</td>
<td>0.0006</td>
<td>0.0003</td>
<td>0.8705</td>
<td></td>
</tr>
<tr>
<td>n-Nonane (\text{n-C}<em>9\text{H}</em>{20})</td>
<td>260.6688</td>
<td>0.0015</td>
<td>0.0012</td>
<td>0.8714</td>
<td></td>
</tr>
<tr>
<td>i-Decane (\text{i-C}<em>{10}\text{H}</em>{22})</td>
<td>288.4775</td>
<td>0.0131</td>
<td>0.01</td>
<td>0.1852</td>
<td></td>
</tr>
<tr>
<td>n-Decane (\text{n-C}<em>{10}\text{H}</em>{22})</td>
<td>288.4775</td>
<td>0.0191</td>
<td>0.016</td>
<td>0.1912</td>
<td></td>
</tr>
<tr>
<td>Carbon dioxide (\text{CO}_2)</td>
<td>-</td>
<td>0.0382</td>
<td>0.1084</td>
<td>0.7743</td>
<td></td>
</tr>
<tr>
<td>Nitrogen (\text{N}_2)</td>
<td>-</td>
<td>1.343</td>
<td>0.453</td>
<td>0.1995</td>
<td></td>
</tr>
<tr>
<td>Hydrogen sulfide (\text{H}_2\text{S})</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

\[
F_{HC} = \alpha_{HC, s1} \cdot \beta_{s1} + \alpha_{HC, s2} \cdot \beta_{s2} + \alpha_{HC, s3} \cdot \beta_{s3},
\]
\[
\beta_{s3} : [10\%, \ldots, 15\%]; \beta_{s1} : [50\%, \ldots, 70\%], \text{and } \beta_{s2} = 1 - \beta_{s1} - \beta_{s3},
\]
\[
HV_{APG} = \sum HV_{HC} \cdot F_{HC},
\]
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 81.0 Gg.

$BC_{flaring} = \text{Volume} \times EF_{flare}$

$EF_{flare} = 0.0578 \times HV_{APG} - 2.09$
Spatial distribution of gas flaring BC emission in Russia

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

Gas flares are identified as “lights index” values of 8.0 or greater for all the one km² grid cells (Elvidge et al., 2009).
## II. Transportation BC emission

### Share of different Euro standards vehicles in Russia

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

### PM Emission Factor Calculation

\[ E_{m,ij,k} = \sum EF_{PM,ij,k} \times \left(S_{ij} \times Eu_{ijk} \times R_{ij} \times VMT_{ijk}\right) \times \left(EC/PM_{2.5}\right)_{ijk} \]

Where \(i, j, \text{and } k\) represent the vehicle type, driving modes, and Euro standard, respectively. \(EF_{PM,ij,k}\) is the PM emission factors; \(S_{ij}\) is the vehicle stock number; \(Eu_{ijk}\) 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 \(E_{m,ij,k}\) is annual BC emission during the hot operation stage.

*Ministry of Transport of the Russian Federation Research Institute (by Russian), 2008*
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

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

Ministry of Transport of the Russian Federation Research Institute, 2008

Total = 52.9 Gg

BC_Transport (0.1° x 0.1°)
Unit: kg/per grid
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
   - Federal State Statistics Service (FSSS) dataset

3. District BC -> grid cell
   - LandScan dataset

Total BC = 57.0 Gg

National BC distribution:
- 22.4% in Sberian Federal District
- 26.2% in Volga Federal District
- 8.1% in Ural Federal District
- 6.9% in North Caucasian Federal District
- 12.2% in Far Eastern Federal District
- 0.2% in Southern Federal District
- 1.8% in Northwestern Federal District

BC_Residential (0.1° × 0.1°)
Unit: kg/per grid

Russia’s Federal Districts

LandScan dataset

Population density within each district.

(ORNL’s LandScan dataset)
IV. Industrial BC emission

\[ BC_{ind} = \sum PM_{raw, i} \times (1 - \eta) \times (BC/PM)_i \], where \( PM_{raw, i} \) represents PM emission prior to technology controls, \( i \) 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)
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)

<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>96.5</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 districution 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

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

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

Year 2010:
Russian anthropogenic BC = 224 Gg/yr

BC emission prepared for ARCTAS [Wang et al., 2011]
Arctic 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:
GFEDv4s (Global Fire Emission Database) [0.25° × 0.25°]
Model performances in US, W. Europe and China

IMPROVE (167 sites, 2010)
NMB: 8.32%

CAWNET (18 sites, 2006)
NMB: -25.9%

NMB: -29.3%
(6 sites, 2010)
(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)
Role of Russian BC emissions in the Arctic

Improvement of modeled BC levels are mainly found during the Arctic Haze periods, i.e. December – March.
Role of gas flaring in triggering the high BC episodes
1-week backward trajectories (March 17 -19, 2010)
Gas flaring from Russia contributes an increasing fraction as the measured BC concentrations at the Arctic increase. (higher BC, flaring contributes more)

\[ Y = 0.63X + 28.5 \]

\[ R^2 = 0.50 \]
Monthly BC dry deposition perturbations

BC dry deposition (new – base)  

ratio:  (new – base)/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.

- Enhanced BC loadings over the Arctic based on simulation may predict acceleration of warming and ice melting in the future.
Relevant Publications:


Thank you for your attention!!
EF uncertainties: 1. gas compositions are varied for a specific region (~30 liter review-ranges)

2. Flaring experiment: ~20% (McEwen and Johnson, 2012)

Around 37% of the regions have gas flaring BC EFs of 0.2 – 0.5 g/m3.

Around 56% of the regions have gas flaring BC EFs higher than 0.6 g/m3.
Global gas flaring BC emission rates (2008 - 2010) (0.1° x 0.1°)

BC: 157 Gg/yr
(2008-2010 mean)

- Russia: 15%
- Middle East: 11%
- Niger: 14%
- Others: 60%

Unit: kg/m²/s
High: 1.2649e-010
Low: 7.6134e-015
Spatial distribution of emissions from gas flaring

Location of flares: Source: NASA, World Bank, GAINS model