Simulation of Arctic Black Carbon using Hemispheric CMAQ: Role of Russia's BC Emissions, Transport, and Deposition

Kan Huang[1] and Joshua S. Fu[1,2]

[1]*Department of Civil & Environmental Engineering*
The University of Tennessee

[2]*UT-ORNL Center for Interdisciplinary Research and Graduate Education*

14th CMAS Conference

October 5 - 7, 2015

Outline

Introduction

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

Black carbon emissions reconstruction for Russia

- To fill information gaps

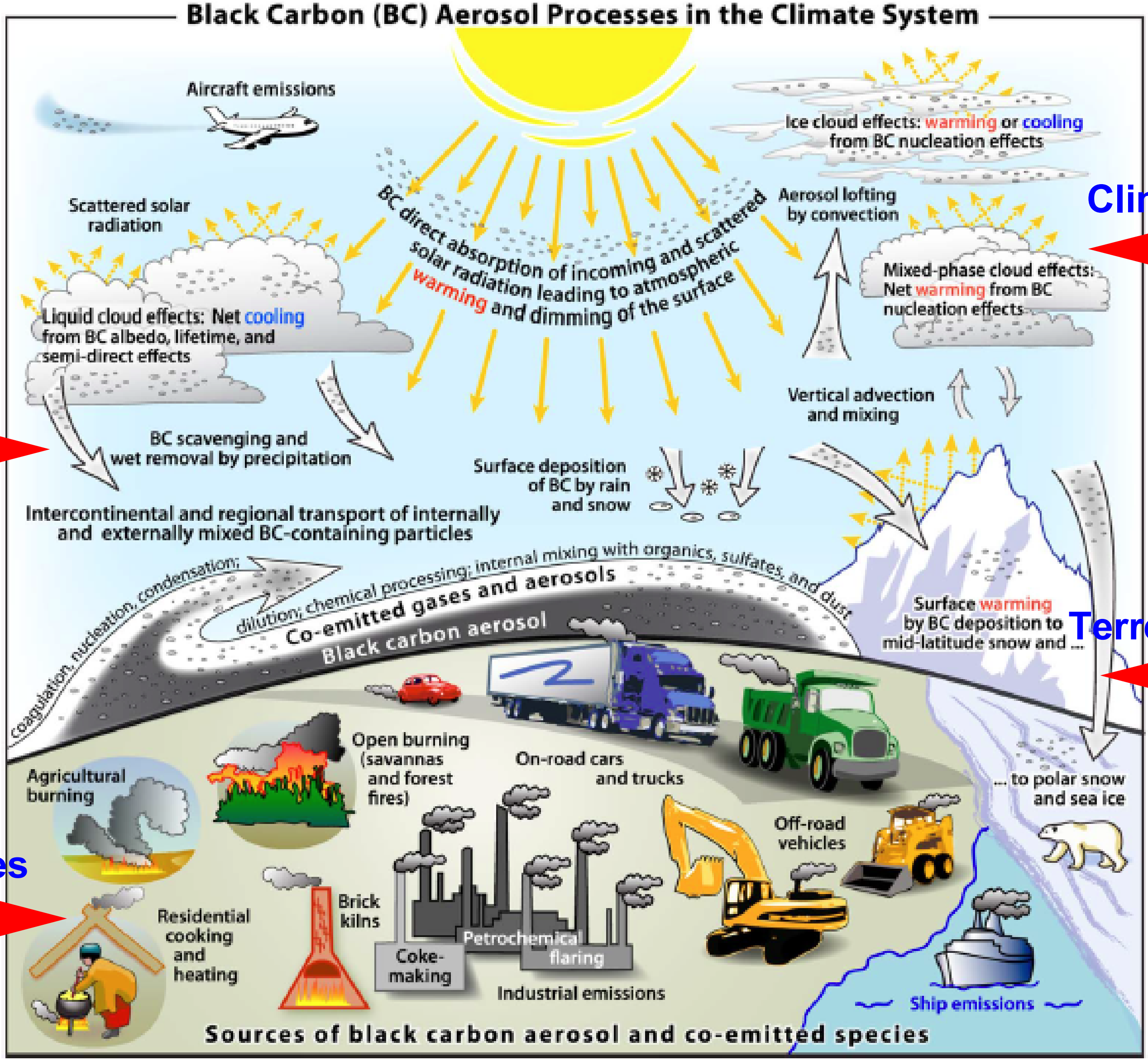
Numerical simulation and evaluation

- Hemispheric WRF/CMAQ modeling in the Arctic

Impact assessment

- Transport and deposition of black carbon in the Arctic

Background



Short lifetime

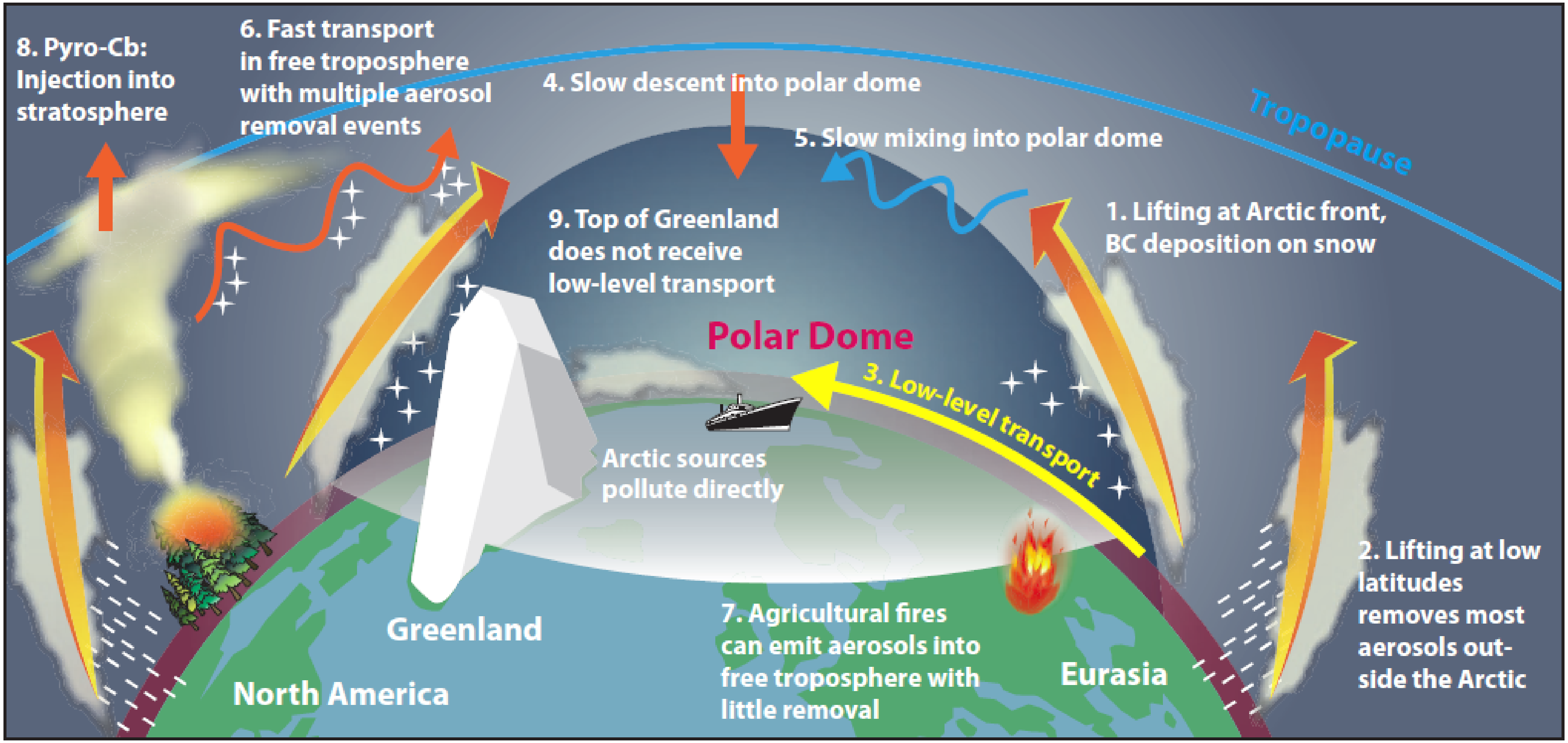
Climate response

Terrestrial impacts

Multiple sources

Bond et al., 2013, JGR

Background



(AMAP, 2011)

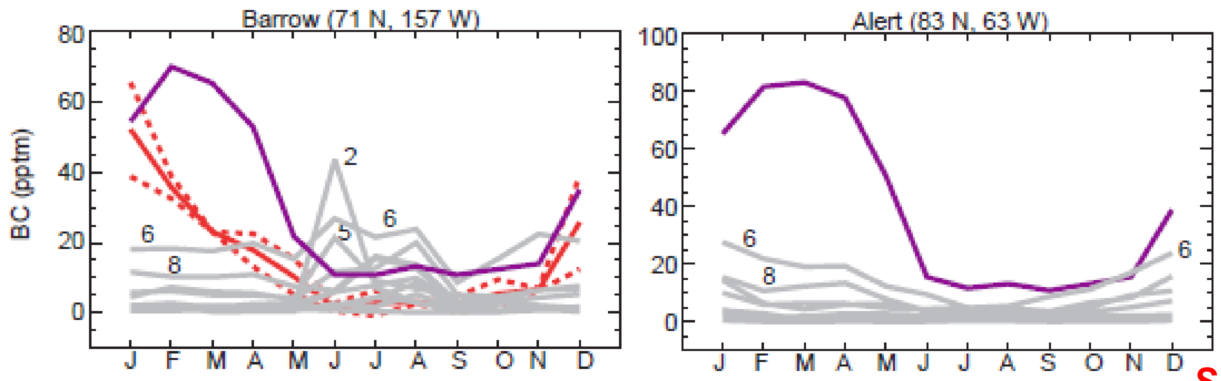
Main transport pathways of air pollutants to the Arctic

Background

Ensemble model simulations of Arctic black carbon

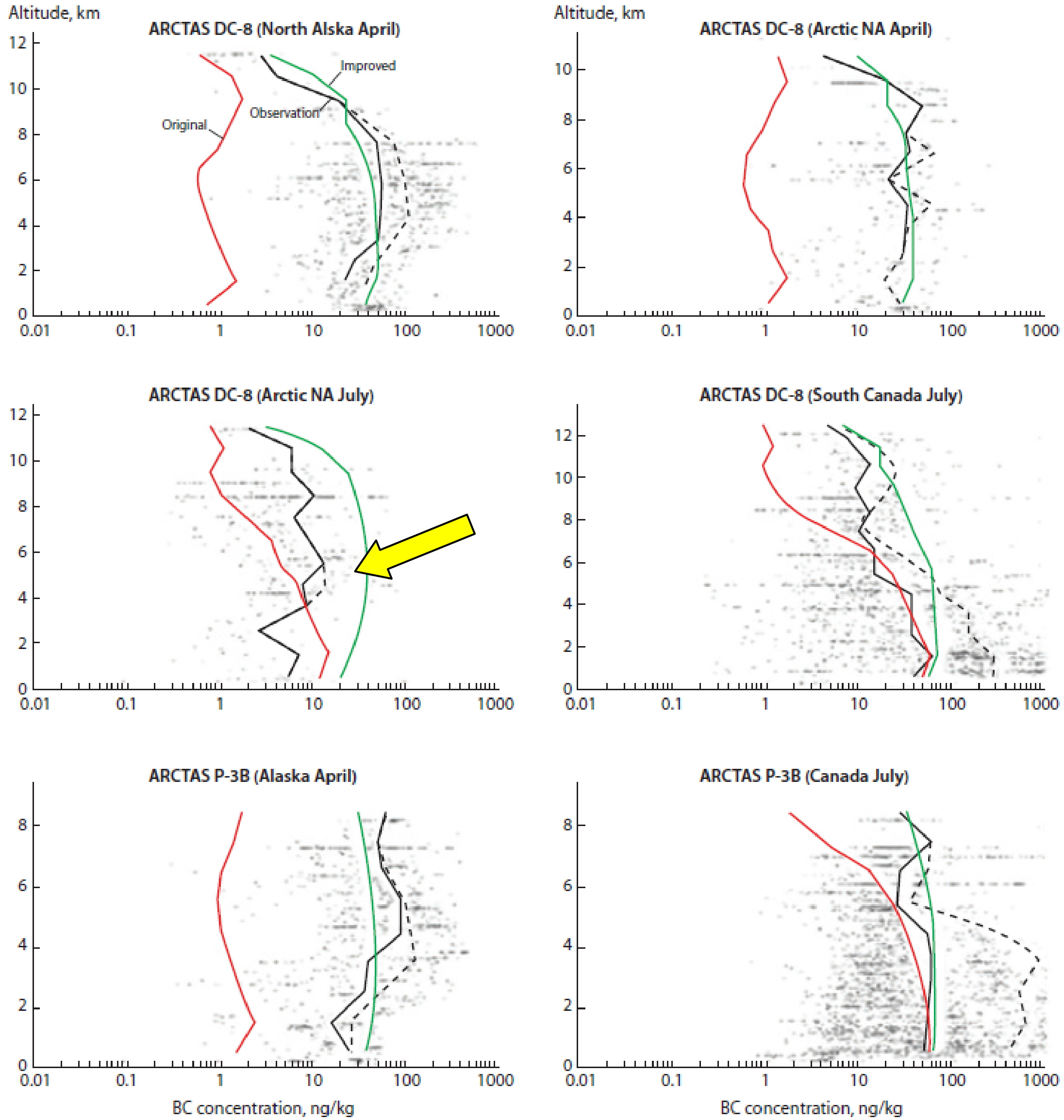
Model	Gas-phase	Aerosols	Prescribed lifetime	Horizontal Resolution
1. CAMCHEM	NO_x, CO	SO2, BC	Y	1.9
2. ECHAM5-HAMMOZ		SO2, BC		2.8
3. EMEP	NO_x, CO	SO2		1.0
4. FRSGC/UCI	NO_x, CO		Y	2.8
5. GEOSChem	NO_x	SO2, BC		2.0
6. GISS-PUCCINI	NO_x, CO	SO2, BC	Y	4.0
7. GMI	NO_x, CO	SO2, BC	Y	2.0
8. GOCART-2		SO2, BC		2.0
9. LMDz4-INCA		SO2, BC		2.5
10. LLNL-IMPACT	NO_x, CO	SO2, BC		2.0
11. MOZARTGFDL	NO_x, CO	SO2, BC	Y	1.9
12. MOZECH	NO_x, CO		Y	2.8
13. SPRINTARS		SO2, BC		1.1
14. STOCHEM-HadGEM1	NO_x, CO			3.8
15. STOCHEM-HadAM3	NO_x, CO	SO2	Y	5.0
16. TM5-JRC	NO_x	SO2, BC		1.0
17. UM-CAM	NO_x, CO		Y	2.5

All models strongly underestimated BC concentrations in the Arctic



Shindell et al., 2008

Background



wet scavenging schemes are revised to improve model performance

Liu, et al, 2011

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 among 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 ?

Outline

Introduction

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

Black carbon emissions reconstruction for Russia

- To fill information gaps

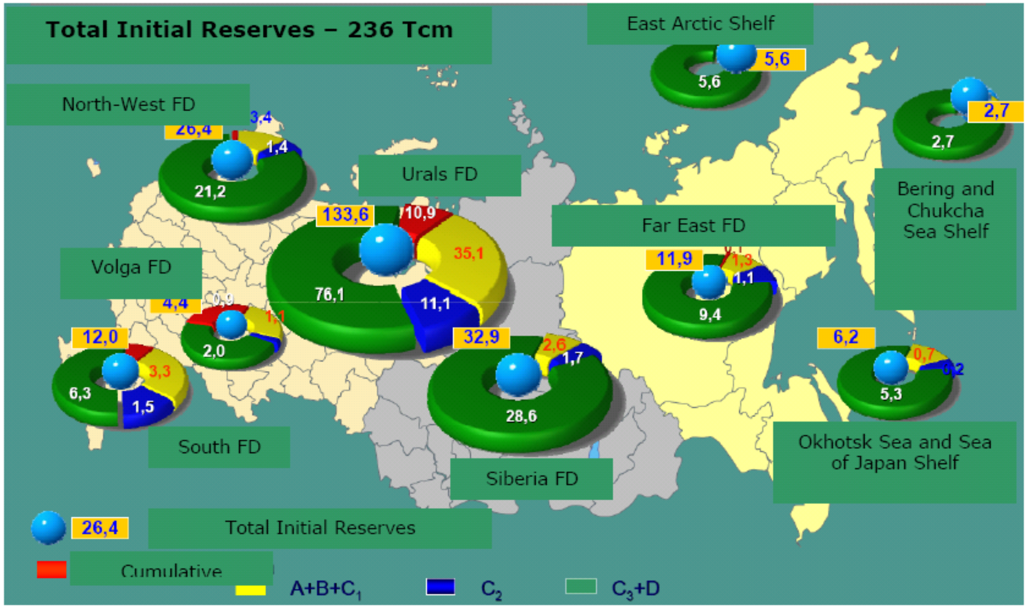
Numerical simulation and evaluation

- Hemispheric WRF/CMAQ modeling in the Arctic

Impact assessment

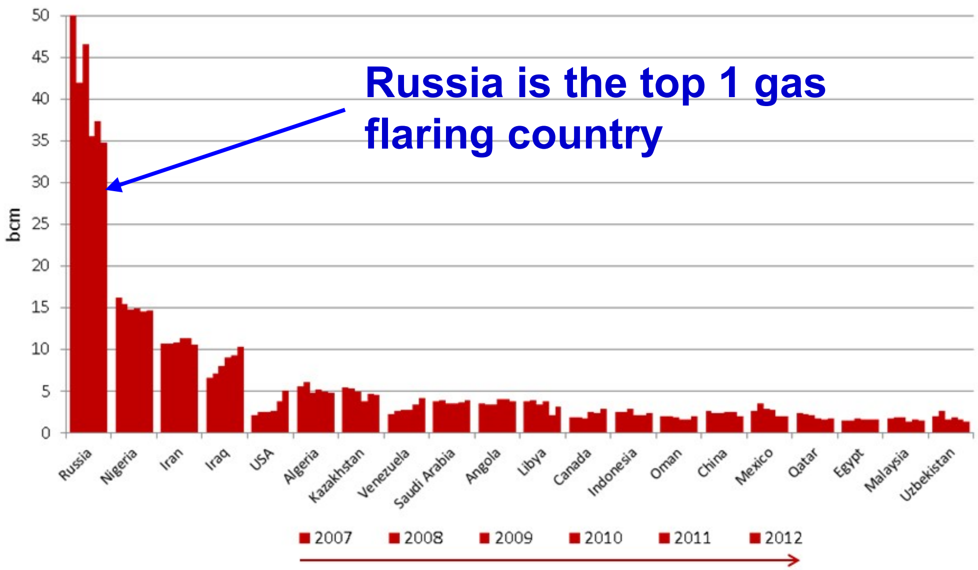
- Transport and deposition of black carbon in the Arctic

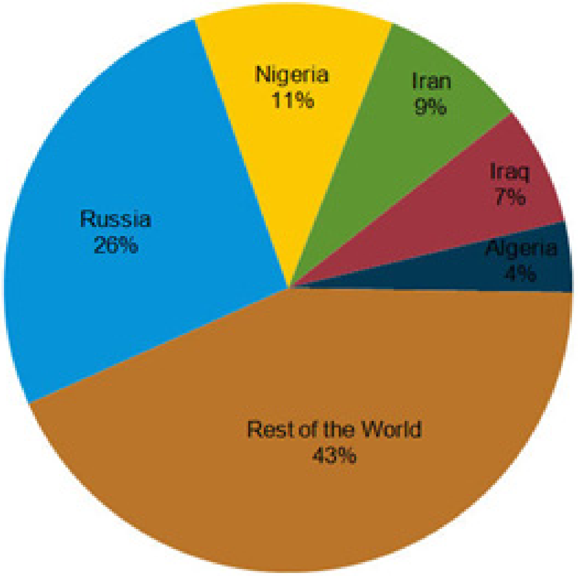
Gas flaring: a missing BC source



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

Top 20 gas flaring countries

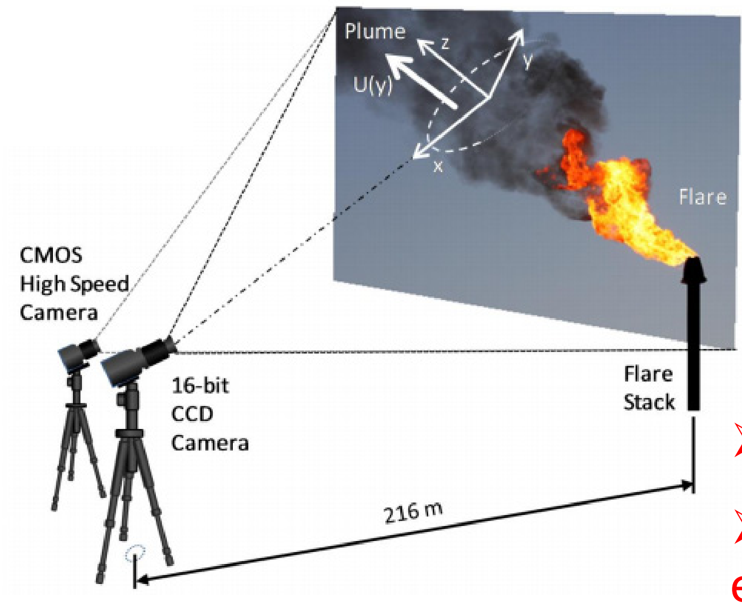




Gas flaring BC emission factor measurement

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

Sky-LOSA : <u>L</u>ine-<u>O</u>f-<u>S</u>ight <u>A</u>ttenuation of sky-light



Compressor station flare in Mexico, 2011

- 0.51-m dia., lightly sooting flare ($\tau \approx 90\%$)
- Soot emission rate: 0.067 ± 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 ± 0.66 g/s
- Roughly equivalent to emissions from **500** diesel buses continuously driving

16

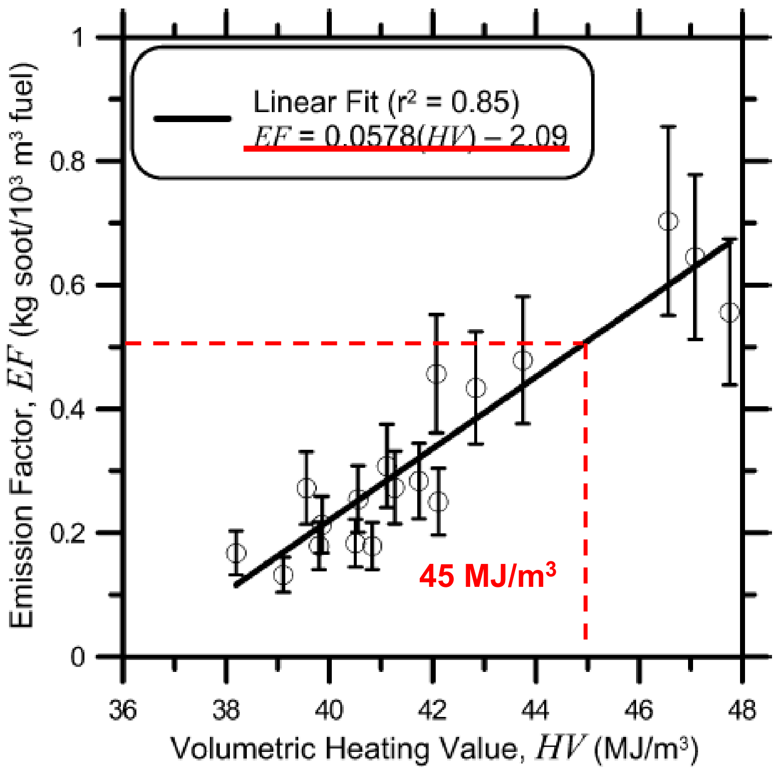
- ➢Significant difference of BC EF from different flares
- ➢EF measured by Sky-LOSA is not appropriate for emission estimation (i.e. unit in g/s)
- ➢Need mass of black carbon per mass of fuel burned

Courtesy:http://www.unep.org/ccac/Portals/50162/docs/ccac/initiatives/oil_and_gas/Sky%20-%20LOSA.PDF (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)



Composition of the associated gas in Russia

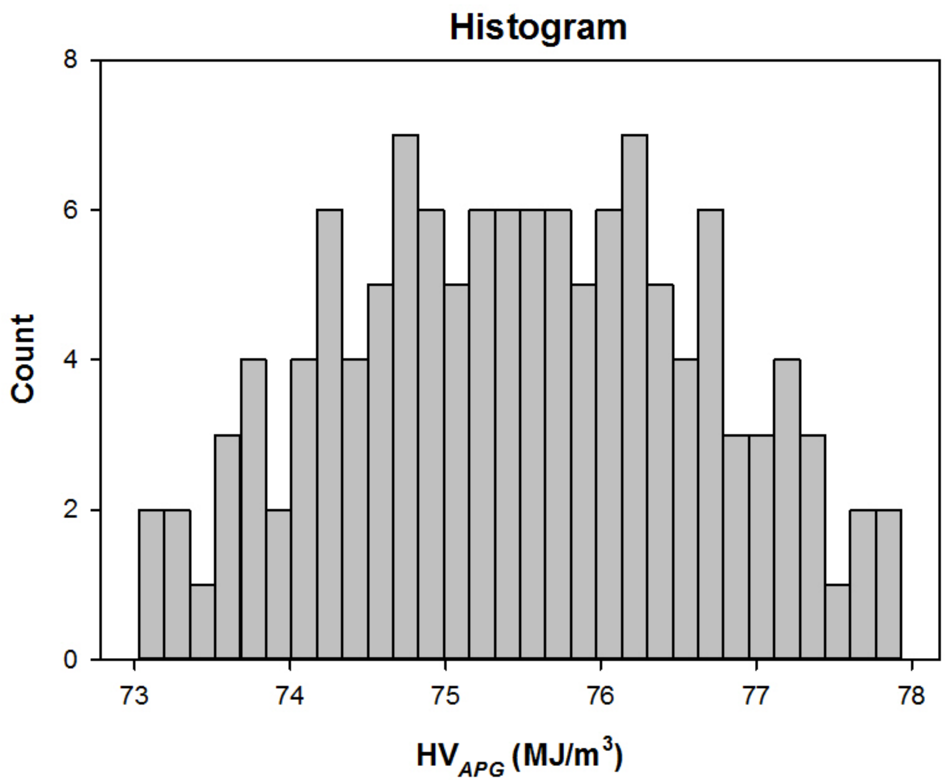
Associated Gas Composition		Heating Value (MJ/m^3)	Volume Percentage (%)		
			Stage 1	Stage 2	Stage 3
Methane	CH_4	39.9012	61.7452	45.6094	19.4437
Ethane	C_2H_6	69.9213	7.7166	16.314	5.7315
Propane	C_3H_8	101.3231	17.5915	21.1402	4.5642
i-Butane	$i\text{-}C_4H_{10}$	133.1190	3.7653	5.1382	4.3904
n-Butane	$n\text{-}C_4H_{10}$	134.0610	4.8729	7.0745	9.6642
i-Pentanes	$i\text{-}C_5H_{12}$	148.4913	0.9822	1.4431	9.9321
n-Pentane	$n\text{-}C_5H_{12}$	141.1918	0.9173	1.3521	12.3281
i-Hexane	$i\text{-}C_6H_{14}$	176.8591	0.5266	0.7539	13.8146
n-Hexane	$n\text{-}C_6H_{14}$	177.1907	0.2403	0.2825	3.7314
i-Heptane	$i\text{-}C_7H_{16}$	205.0068	0.0274	0.1321	6.726
Benzene	C_6H_6	147.3980	0.0017	0.0061	0.0414
n-Heptane	$n\text{-}C_7H_{16}$	205.0068	0.1014	0.0753	1.5978
i-Octane	$i\text{-}C_8H_{18}$	232.8155	0.0256	0.0193	4.3698
Toluene	C_7H_8	373.0365	0.0688	0.0679	0.0901
n-Octane	$n\text{-}C_8H_{18}$	232.8155	0.0017	0.0026	0.4826
i-Nonane	$i\text{-}C_9H_{20}$	260.6688	0.0006	0.0003	0.8705
n-Nonane	$n\text{-}C_9H_{20}$	260.6688	0.0015	0.0012	0.8714
i-Decane	$i\text{-}C_{10}H_{22}$	288.4775	0.0131	0.01	0.1852
n-Decane	$n\text{-}C_{10}H_{22}$	288.4775	0.0191	0.016	0.1912
Carbon dioxide	CO_2	-	0.0382	0.1084	0.7743
Nitrogen	N_2	-	1.343	0.453	0.1995
Hydrogen sulfide	H_2S	-	0	0	0

$$F_{HC} = \alpha_{HC,\,S1} * \beta_{S1} + \alpha_{HC,\,S2} * \beta_{S2} + \alpha_{HC,\,S3} * \beta_{S3},$$

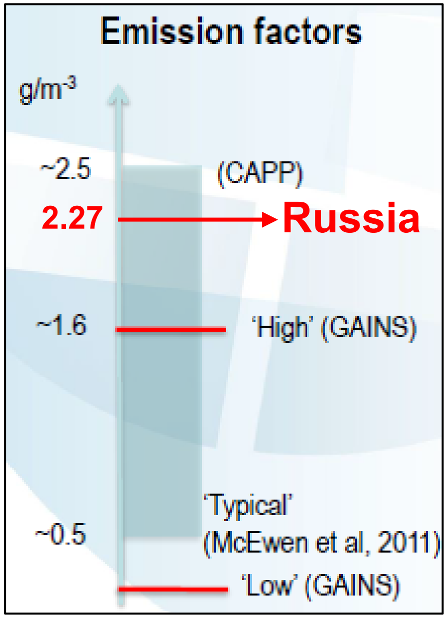
β_{S3}: [10%, …. 15%]; β_{S1}: [50%, …. 70%], and $\beta_{S2} = 1 - \beta_{S1} - \beta_{S3}$.

$$HV_{APG} = \sum HV_{HC} * F_{HC},$$

Estimation of gas flaring EF and emission in Russia (cont.)



$$EF_{flare} = 0.0578 \times HV_{APG} - 2.09$$

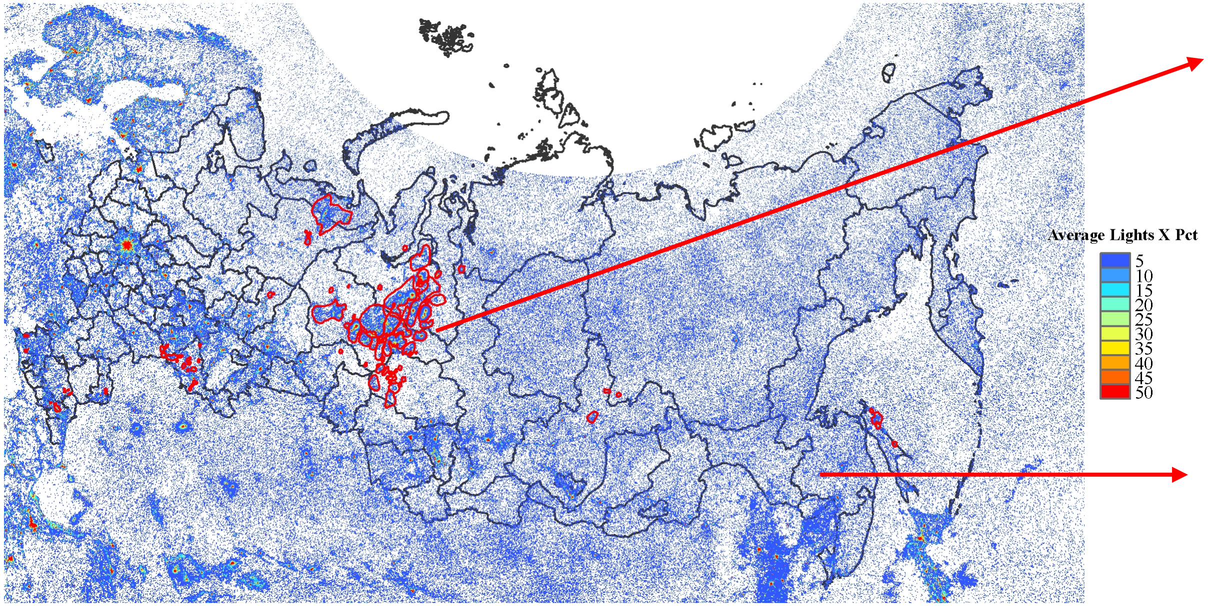


$BC_{flaring}$ = Volume * EF_{flare}

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**.

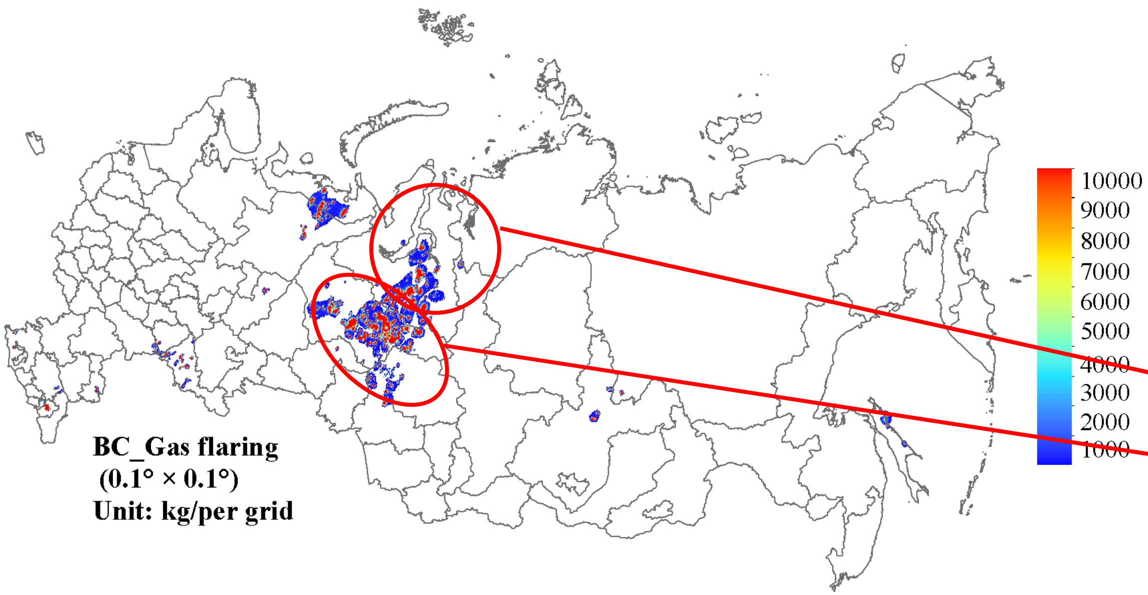
Spatial distribution of gas flaring BC emission



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



Spatial distribution of gas flaring BC emission (0.1*0.1 degree)

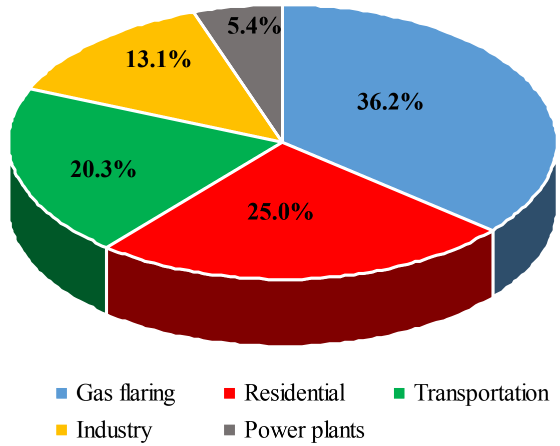
Major gas flaring regions:

Yamal-Nenets

Khanty-Mansiysk

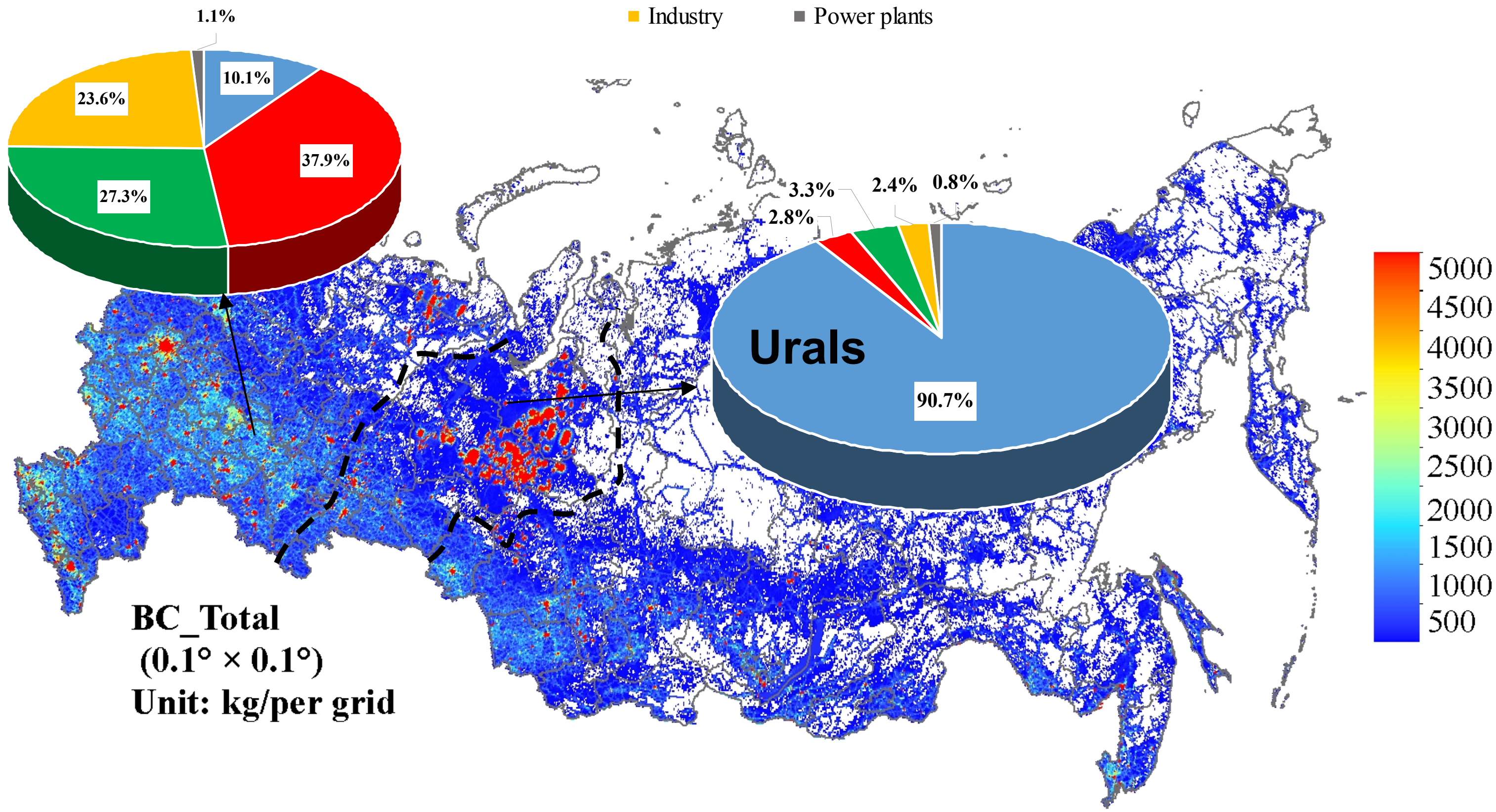
Russian anthropogenic BC emissions by sectors

- Residential
- Transportation
- Industry
- Power plants



Year 2010:

Russian anthropogenic BC = 224 Gg/yr



Outline

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

- Transport and deposition of black carbon in the Arctic

Arctic black carbon modeling domain

Hemispheric CMAQ（H-CMAQ）

CMAQ v5.0.1

Meteorological Input:
WRF V3.5.1

Projection:
Polar

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

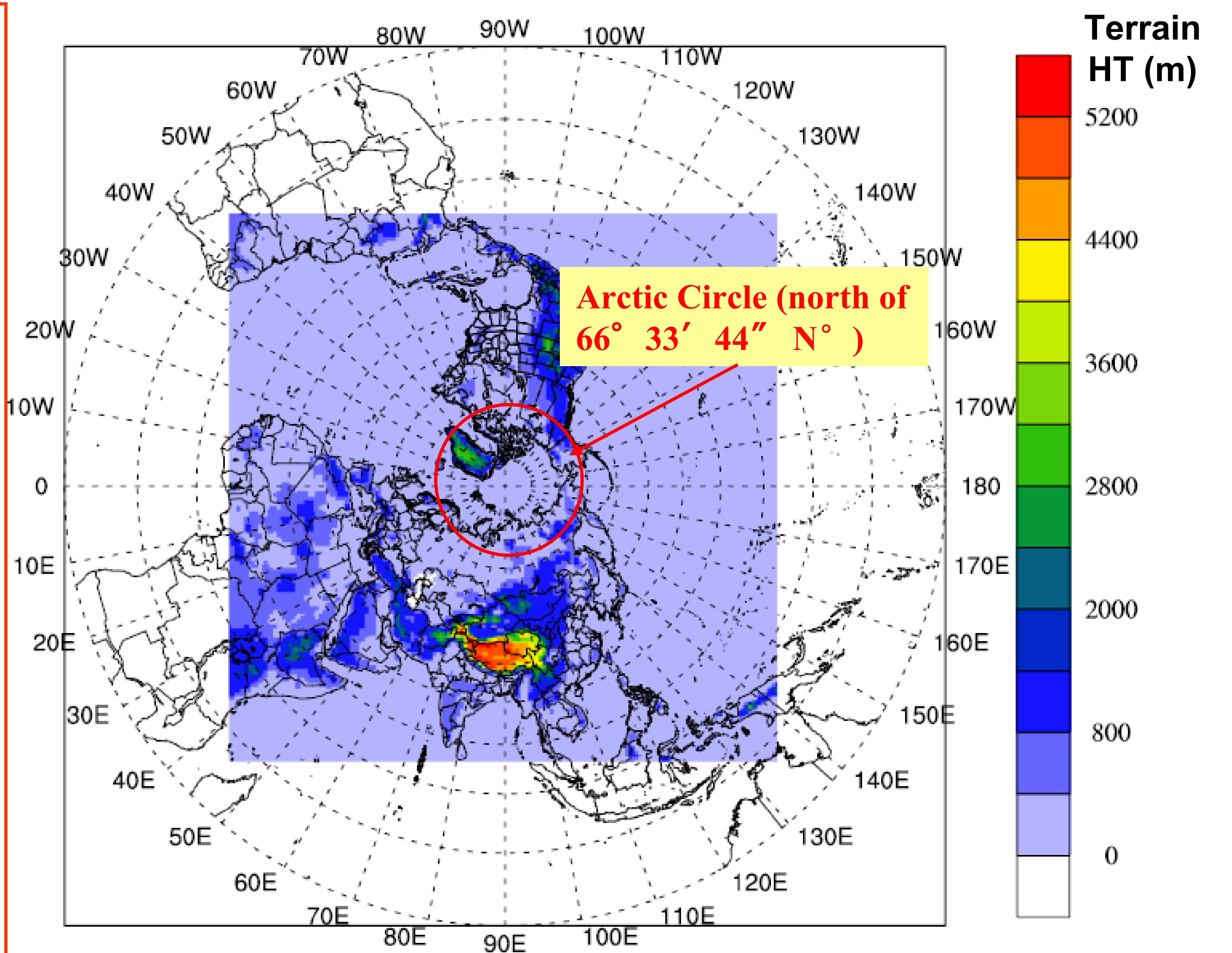
Vertical Spacing:
44 layers

Gas chemistry:
CB05

Aerosol mechanism:
AERO5

Simulation year:
2010

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



Black carbon emissions inputs

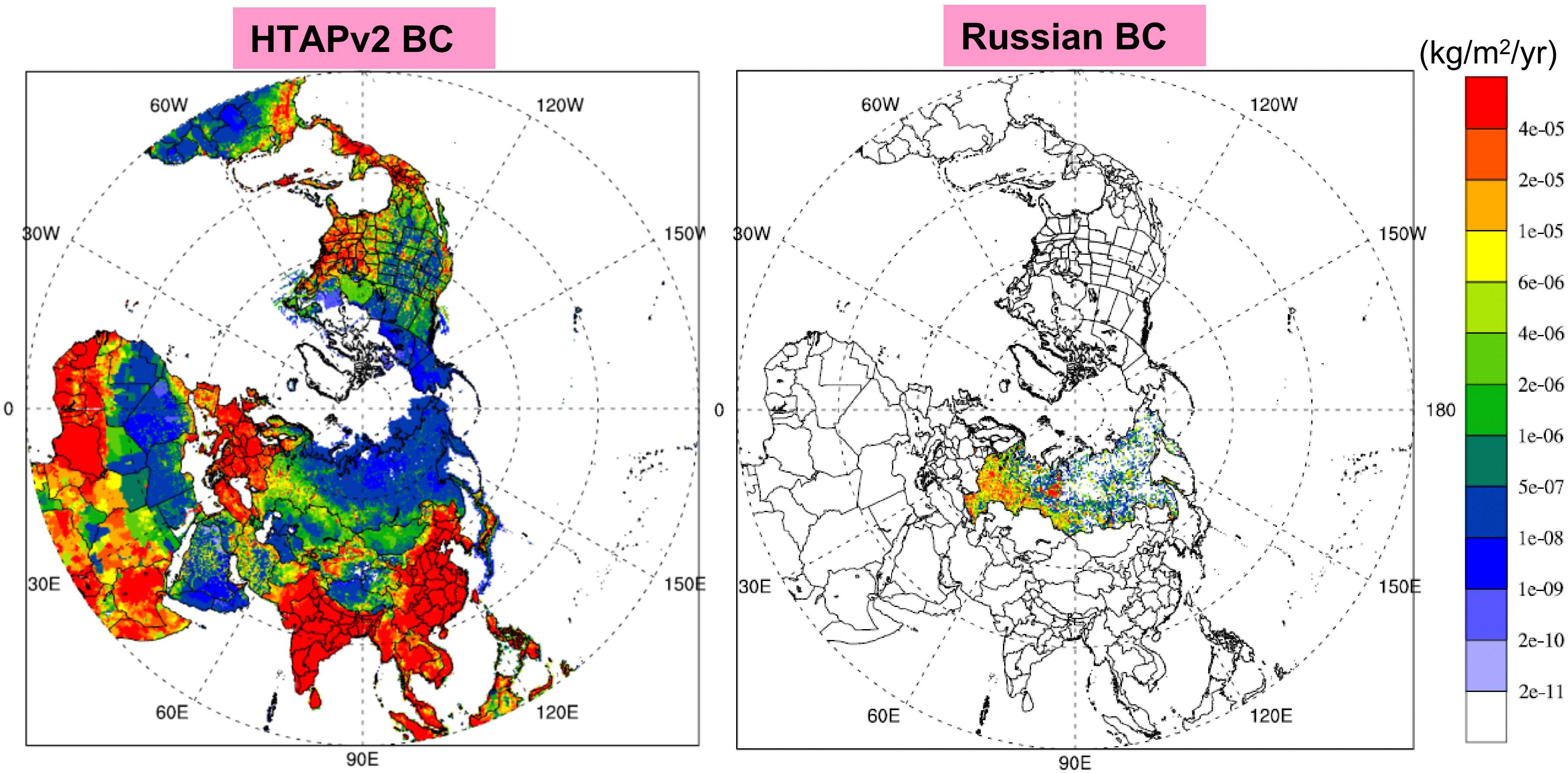
Default global anthropogenic BC emission inventory:

EDGAR (Emission Database for Global Atmospheric Research) HTAPv2 (Hemispheric Transport of Air Pollution) 2010 [0.1° × 0.1°]

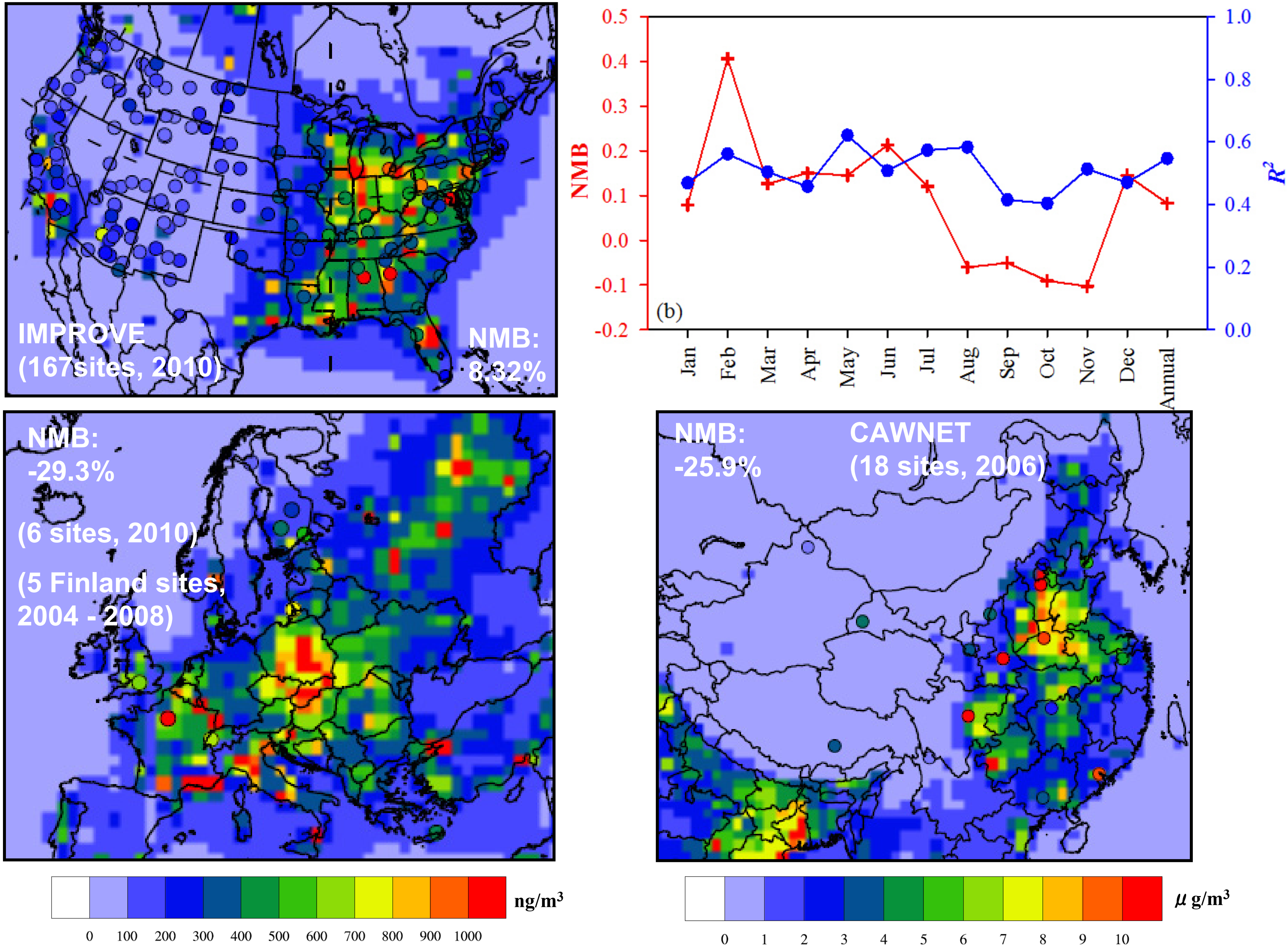
Industry + power plant + traffic + residential + shipping + air

Biomass burning emission:

GFEDv4s (Global Fire Emission Database) [0.25° × 0.25°]



Model performances in US, W. Europe and China



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

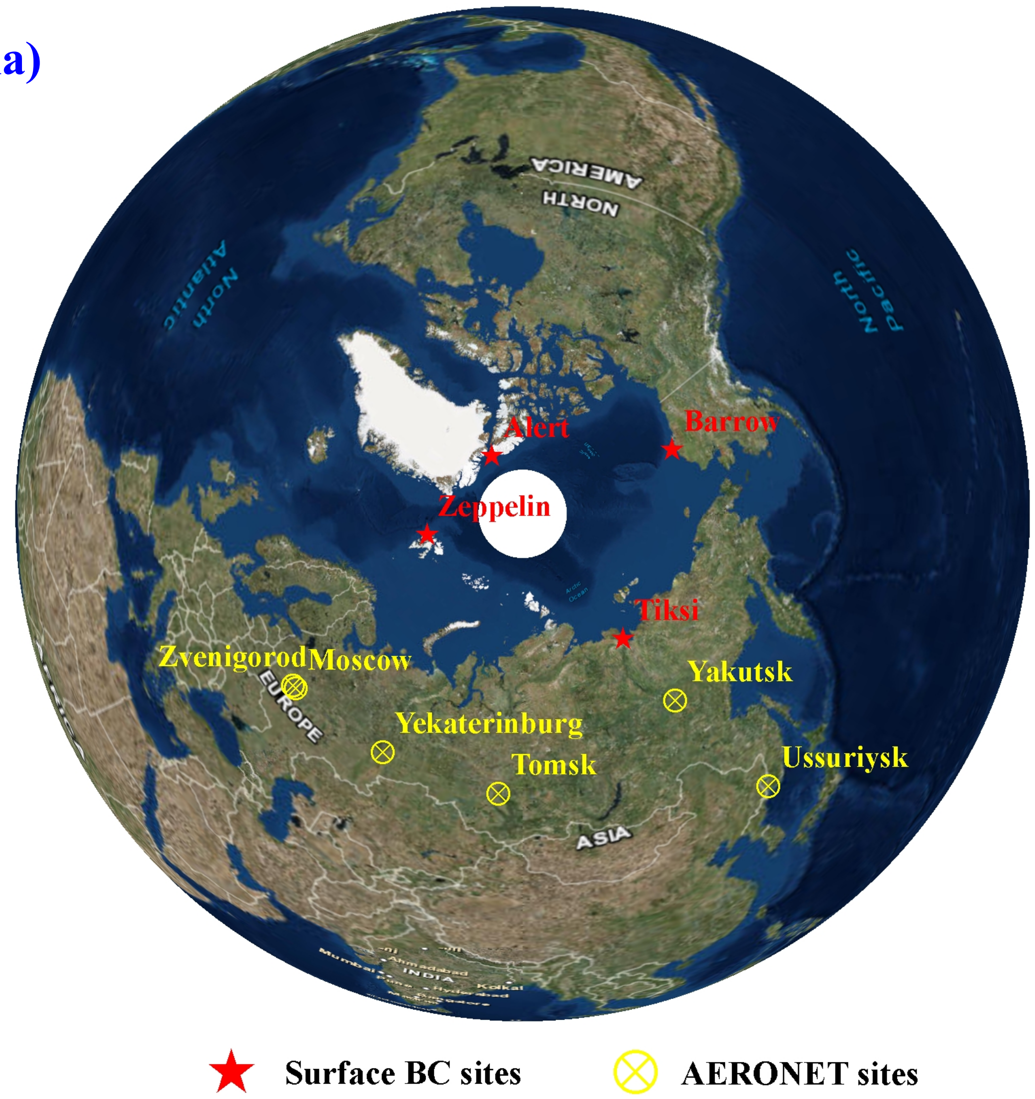
(56.5 ° N, 85.0 ° E)

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)

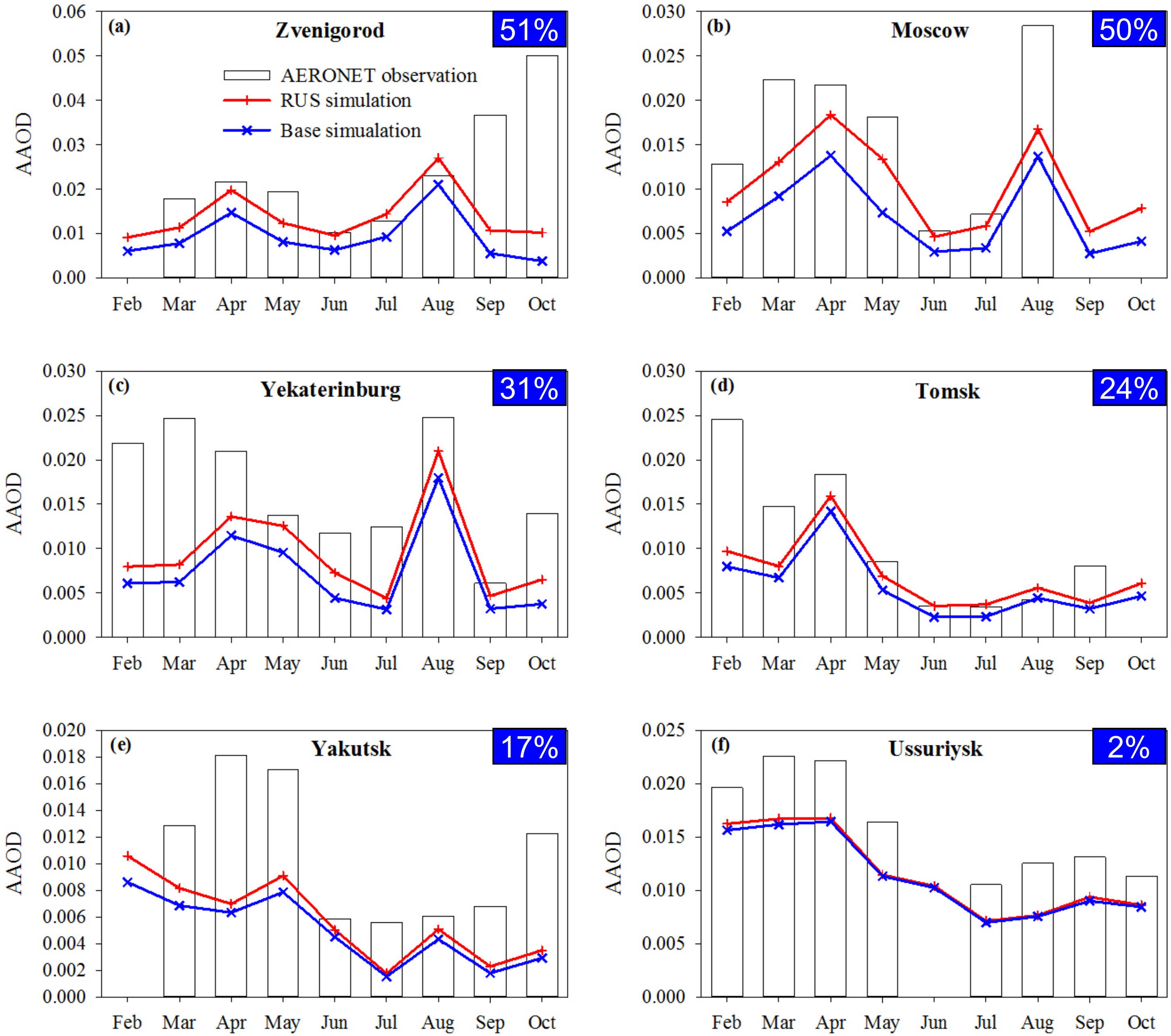
Zeppelin, Norway

(78.9 ° N, 11.9 ° E)

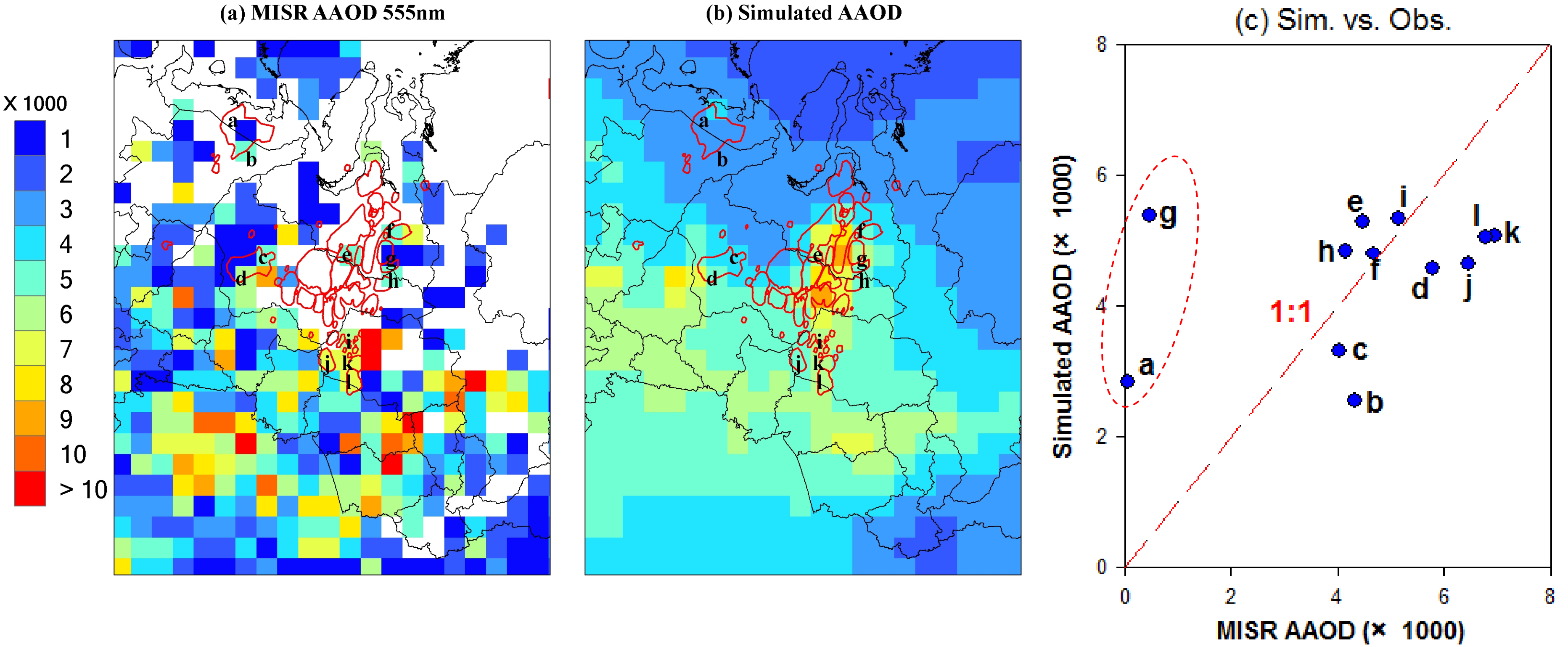
Tiksi, Russia

(71.6 ° N, 128.9 ° E)

Model performance in Russia



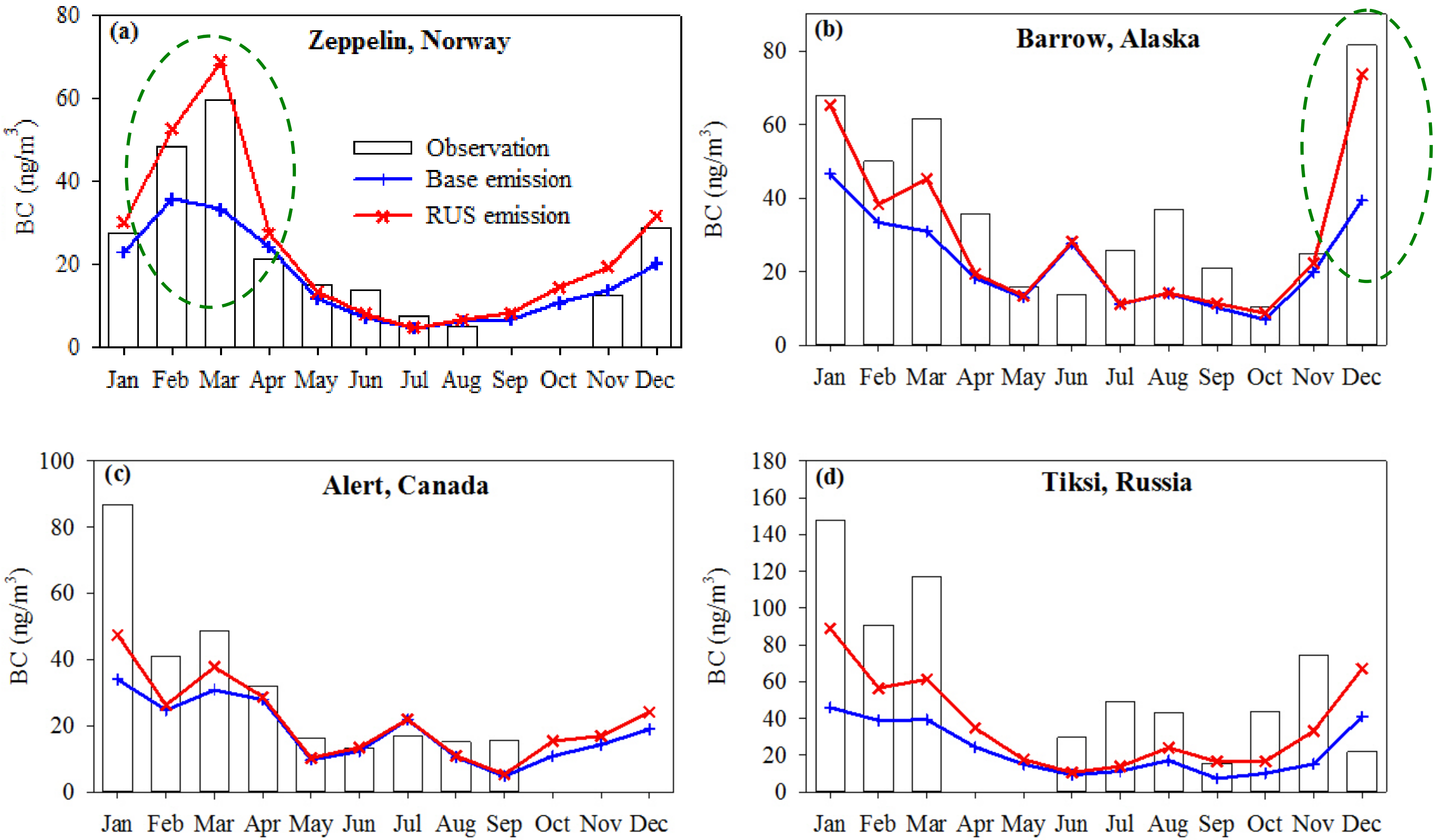
Model performance in Russian flaring source regions



MISR AAOD: 0.0053; **CMAQ AAOD**: 0.0045; **NMB**: - 14.0%

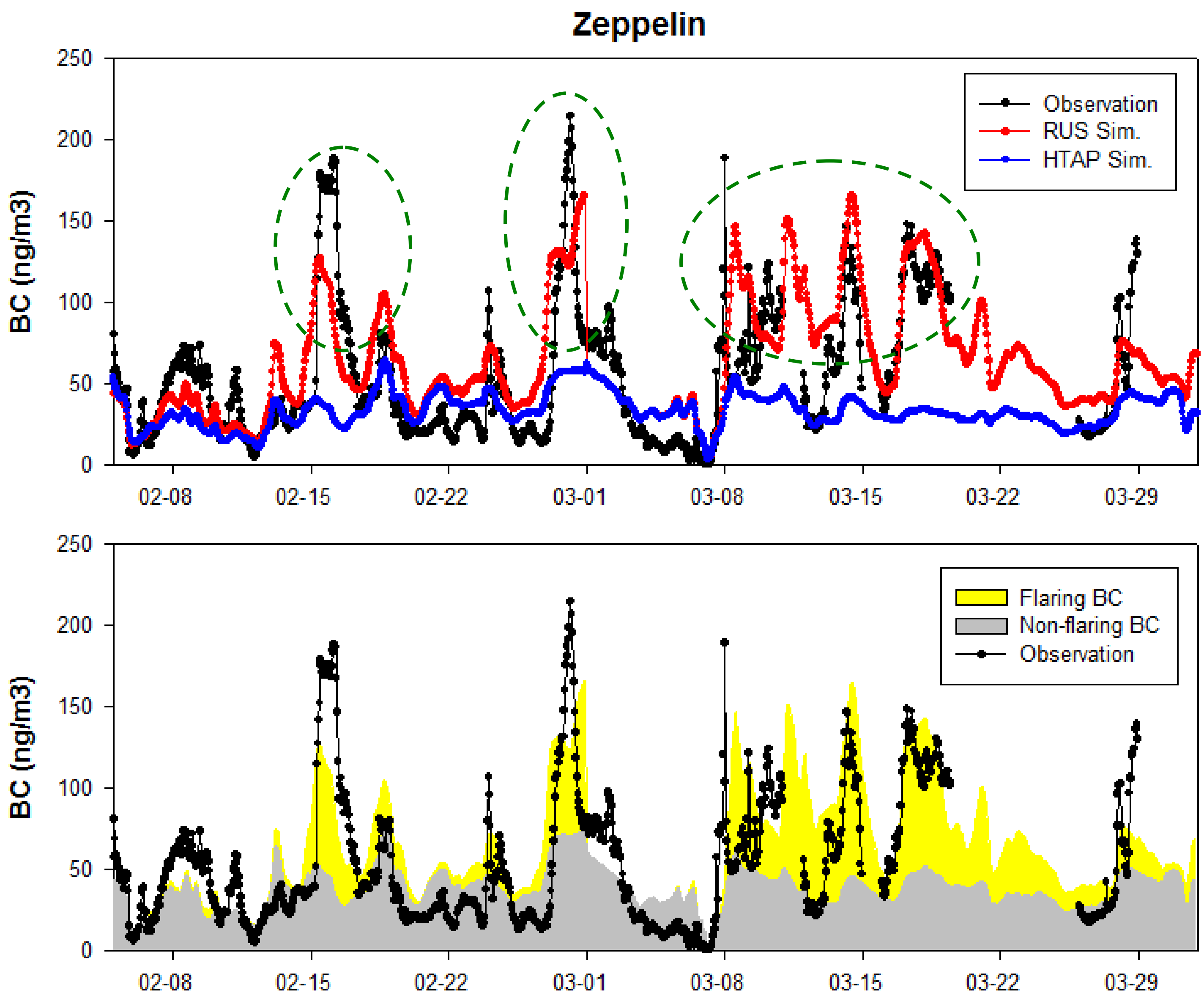
MISR: *The Multi-angle Imaging SpectroRadiometer*

Role of Russian BC emissions in the Arctic

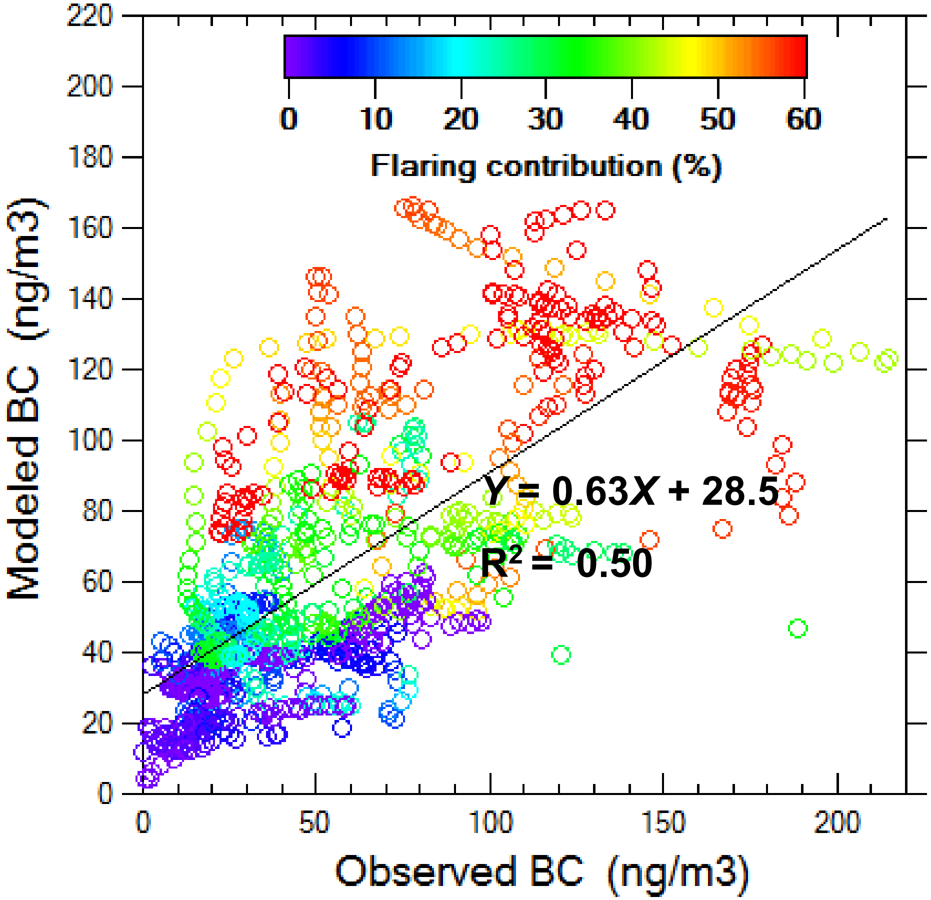


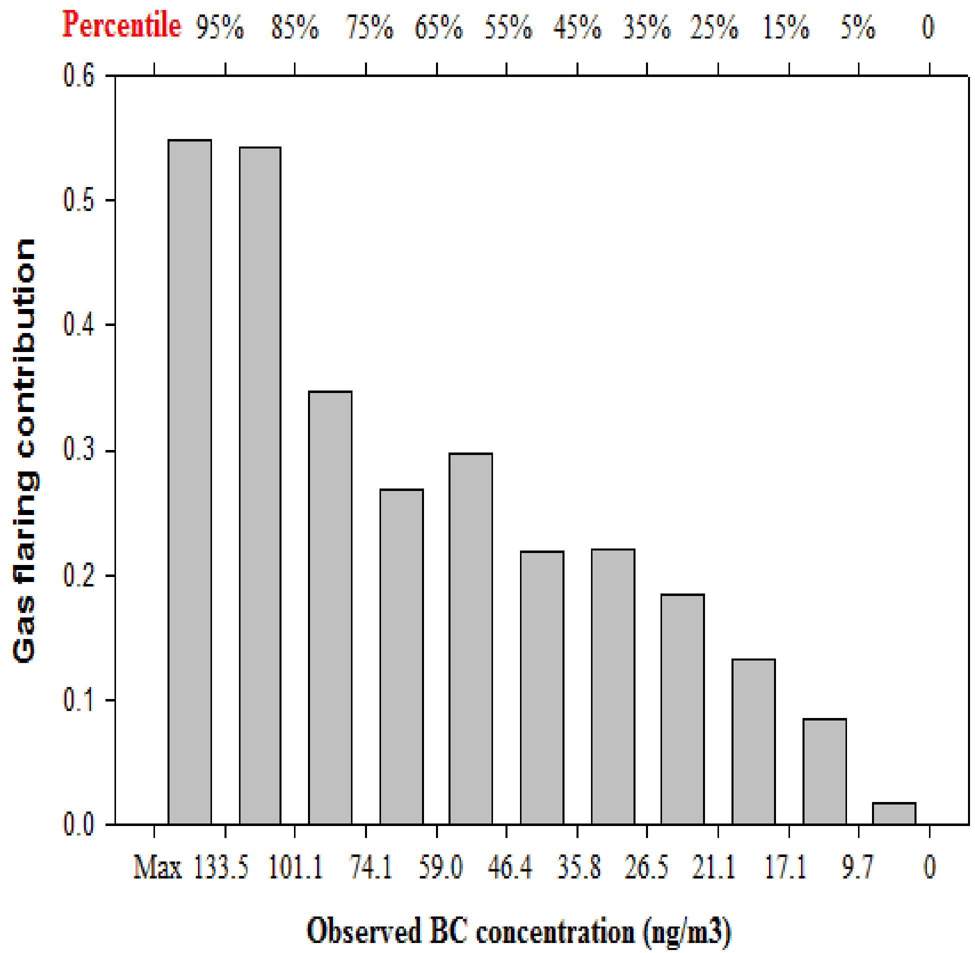
Improvement of modeled BC levels are mainly found during the Arctic Haze periods, i.e. December – March.

Role of gas flaring in triggering the high BC episodes



Gas flaring contribution as a function of measured BC





Gas flaring from Russia contributes an increasing fraction as the measured BC concentrations at the Arctic increase.

Outline

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

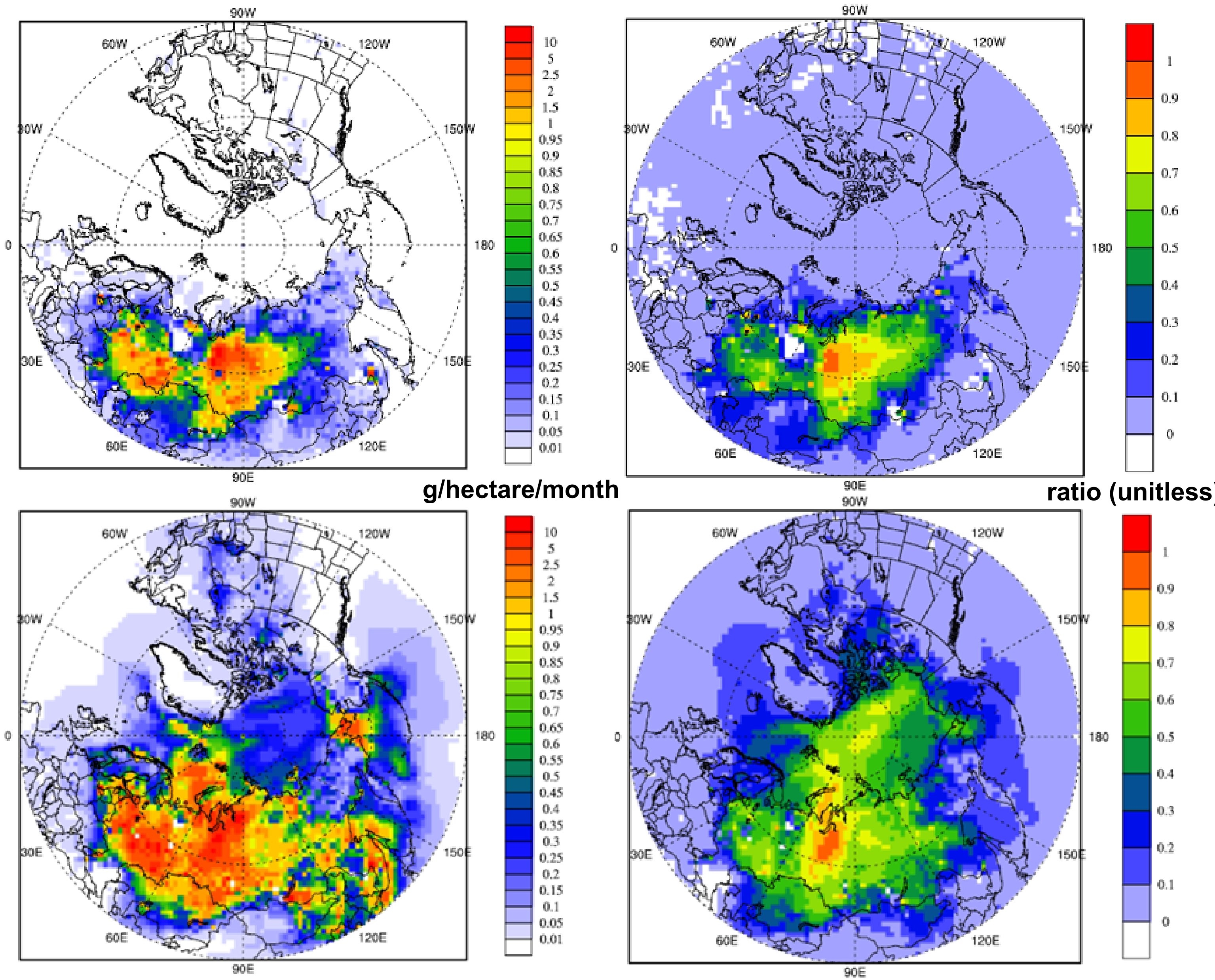
- Transport and deposition of black carbon in the Arctic

Monthly BC dry deposition perturbations

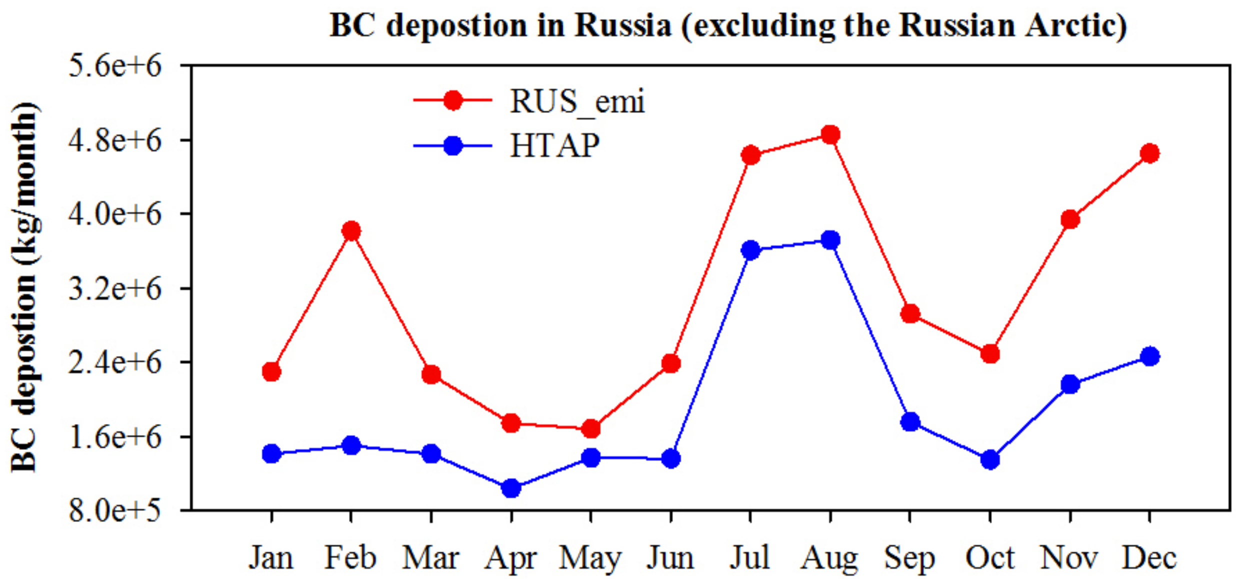
BC dry deposition (RUS – HTAP) ratio: (RUS – HTAP)/RUS

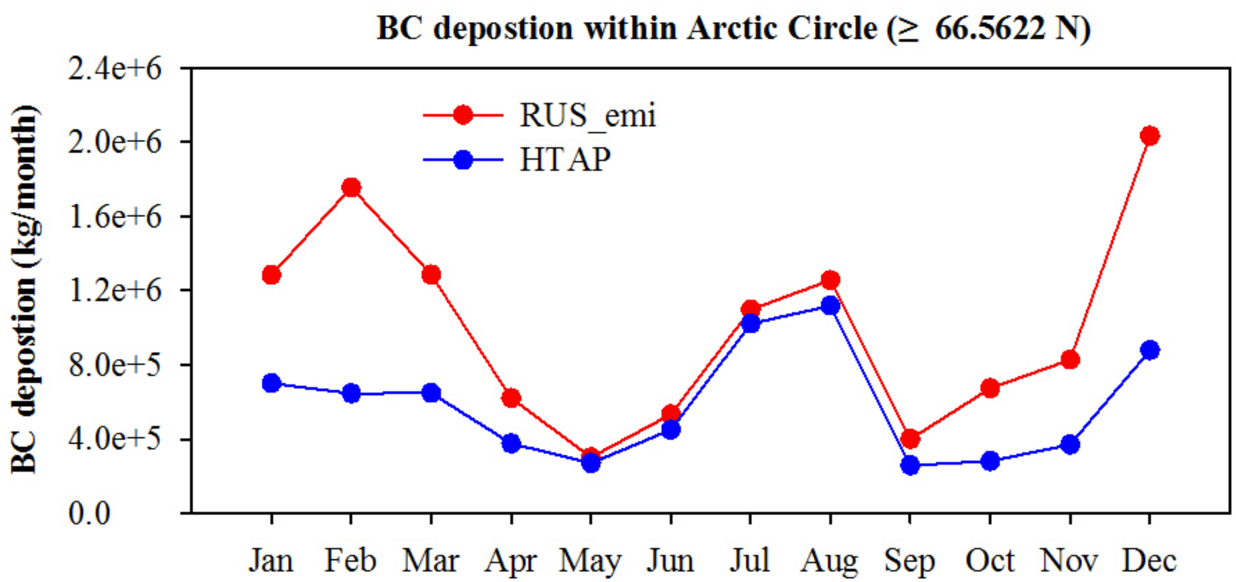
JUN

DEC



Monthly BC dry deposition perturbations





Conclusions

- Russian black carbon emissions are strongly underestimated, e.g. gas flaring.

- By using the new Russian BC emission as model input, the model performance could be significantly improved against observations. Previous studies by revising the physical processes in the model could be misleading.

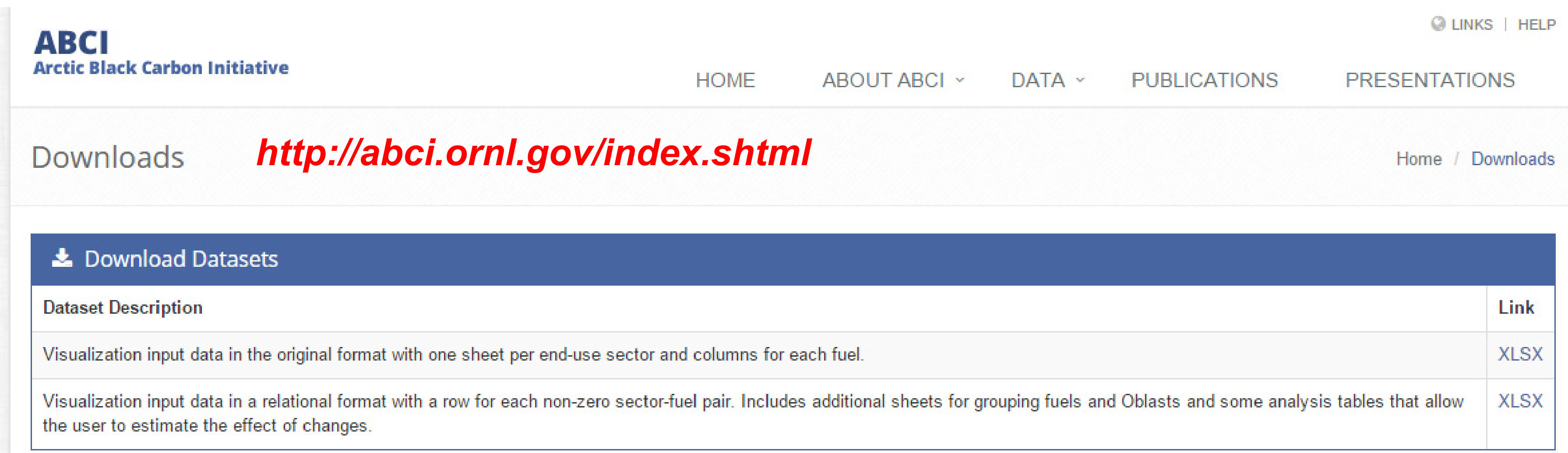
- Gas flaring is a crucial emission source contributing to the high BC episodes in the Arctic although its source area is limited within a small region.

- 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.

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.

Data Repository



Reference: Huang, K., Fu, J. S., V. Y. Prikhodko, J. M. Storey, A. Romanov, E. L. Hodson, J. Cresko, I. Morozova, Y. Ignatieva, J. Cabaniss (2015), Russian anthropogenic black carbon: Emission reconstruction and Arctic black carbon simulation, ***Journal of Geophysical Research-Atmospheres***, doi:10.1002/2015JD023358.