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
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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

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

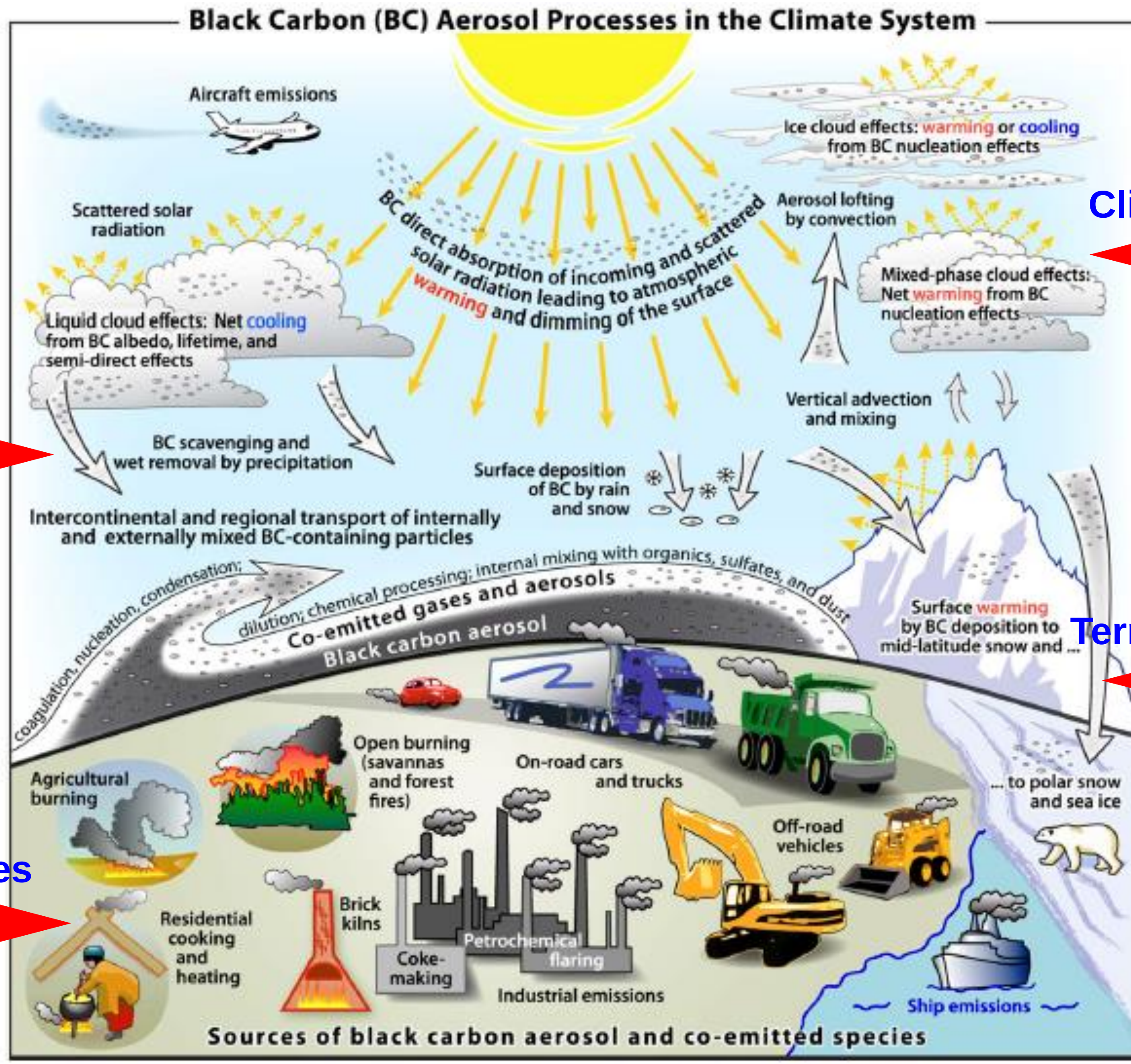
Background

Climate response

Short lifetime

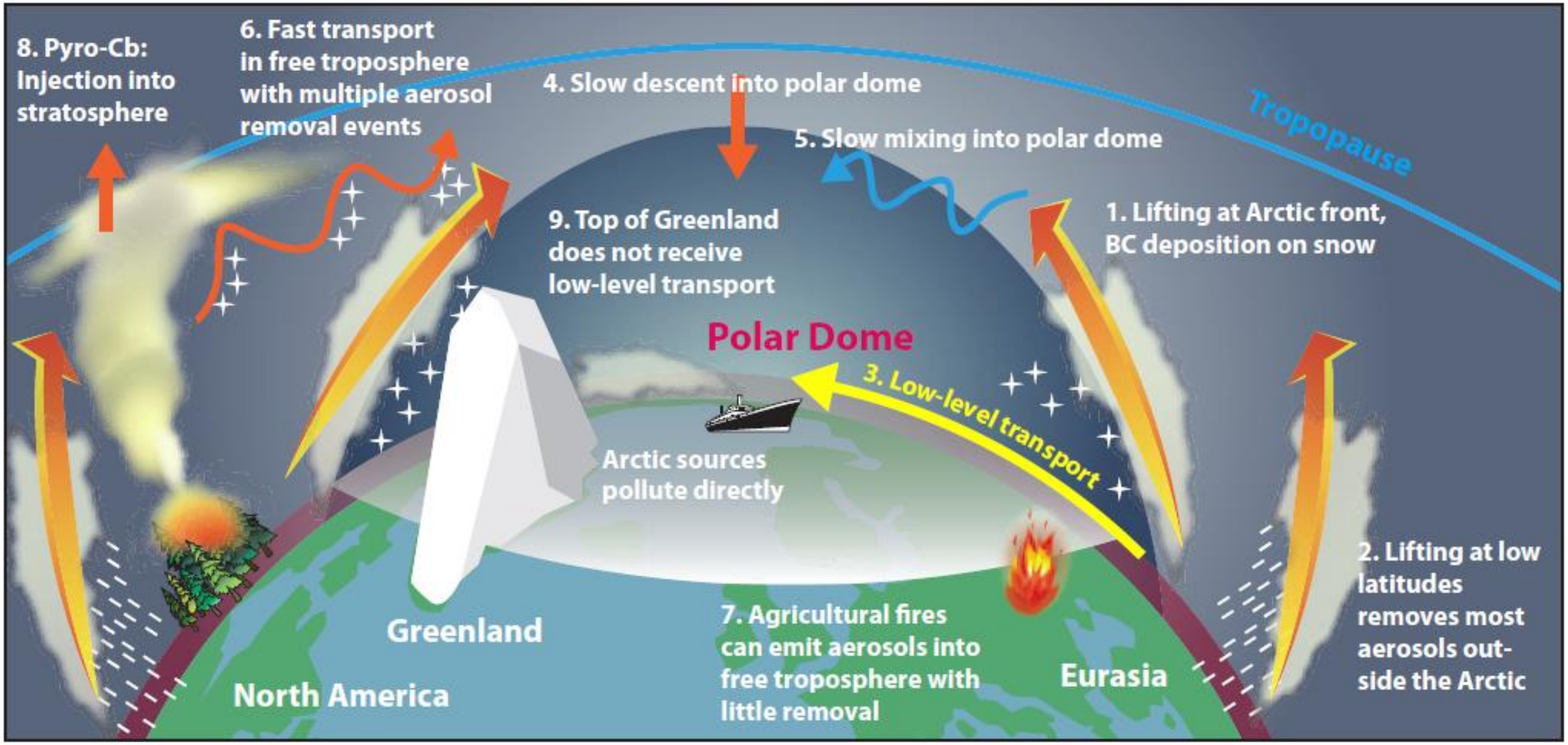
Multiple sources

Terrestrial impacts



Bond et al., 2013, JGR

Background



(AMAP, 2011)

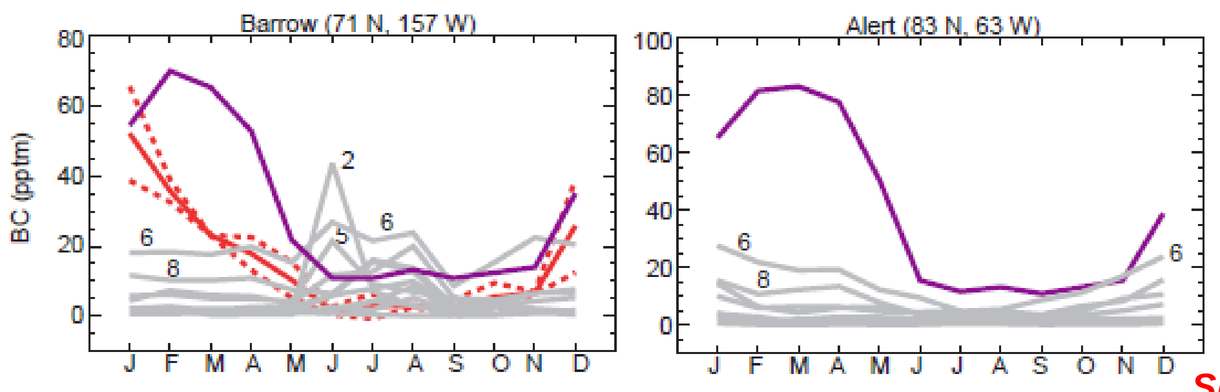
Main transport pathways of air pollutants to the Arctic

Background

Ensemble model simulations of Arctic black carbon

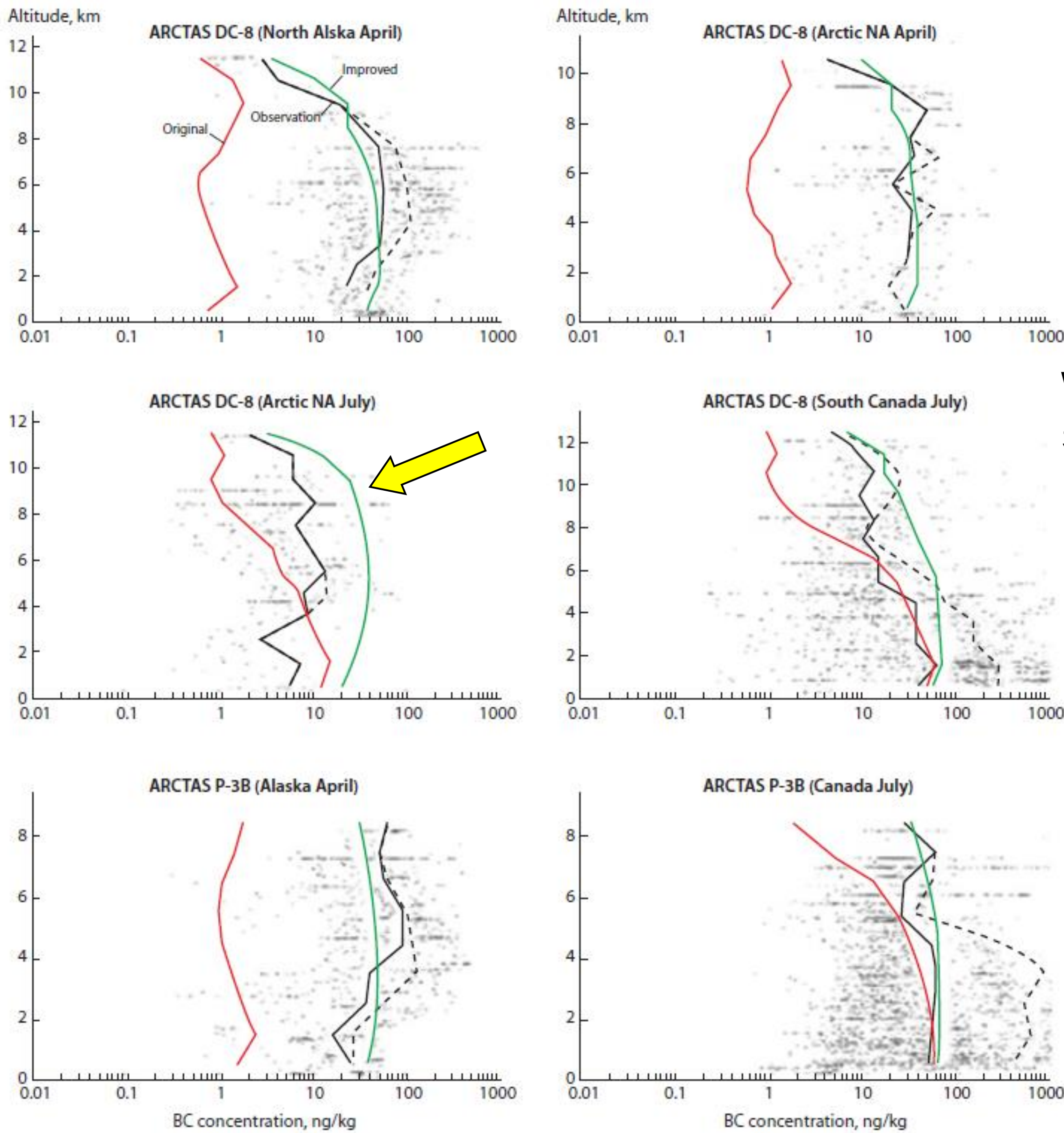
Model	Gas-phase	Aerosols	Prescribed lifetime	Horizontal Resolution
1. CAMCHEM	NO_x, CO	SO2, BC	Y	1.9
2. ECHAM5-HAMMOZ		SO2, BC		2.8
3. EMEP	NO_x, CO	SO2		1.0
4. FRSGC/UCI	NO_x, CO		Y	2.8
5. GEOSChem	NO_x	SO2, BC		2.0
6. GISS-PUCCINI	NO_x, CO	SO2, BC	Y	4.0
7. GMI	NO_x, CO	SO2, BC	Y	2.0
8. GOCART-2		SO2, 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 modified to improve model performance

Liu, et al, 2011

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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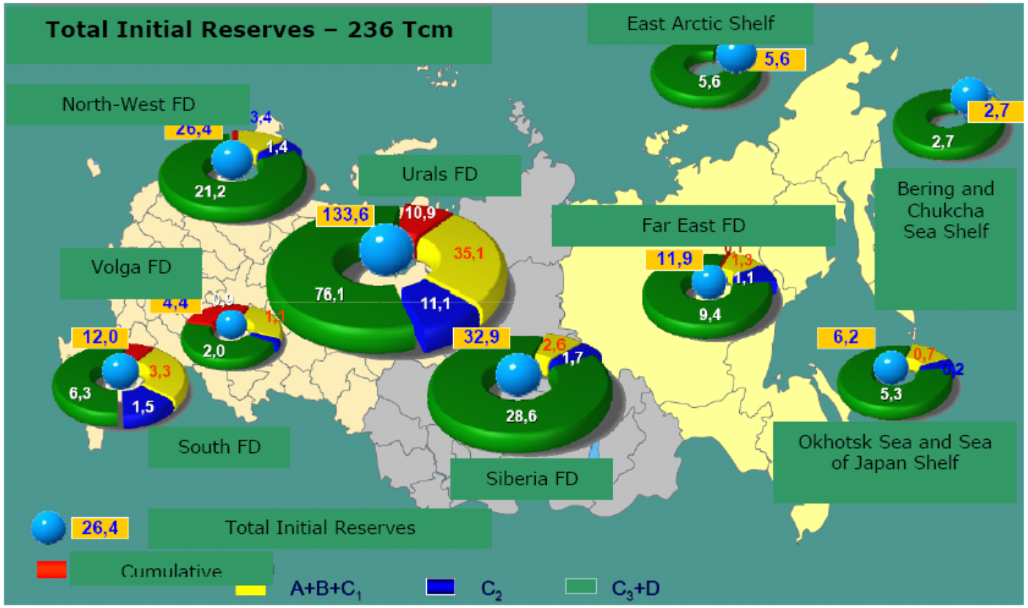
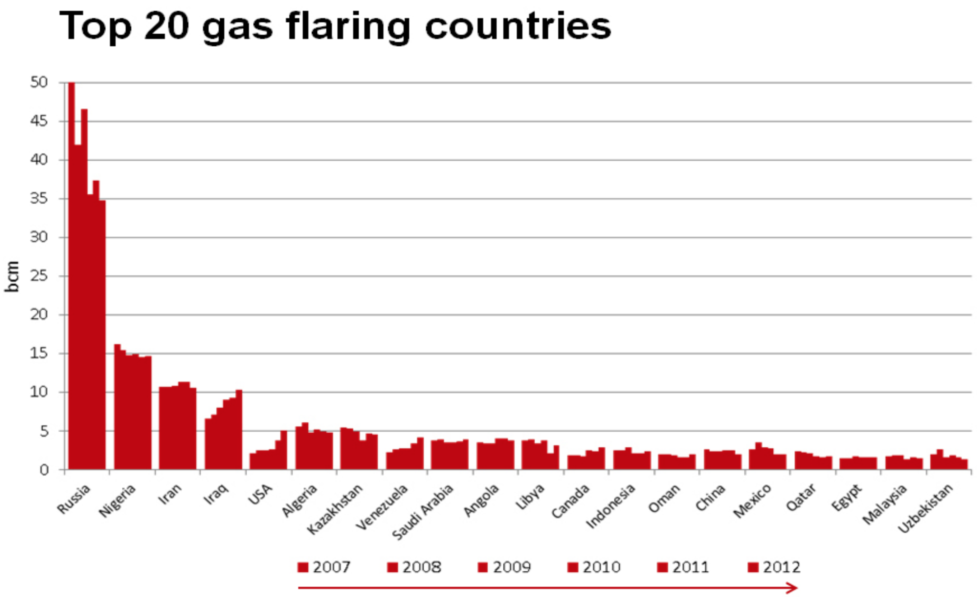
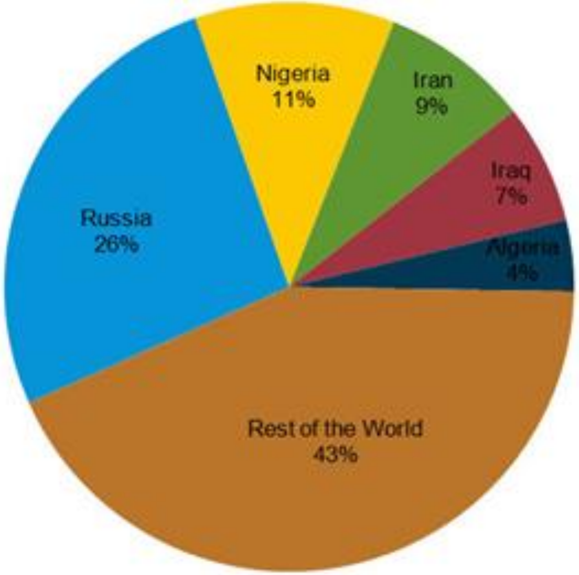
I. Gas flaring: a missing BC source



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

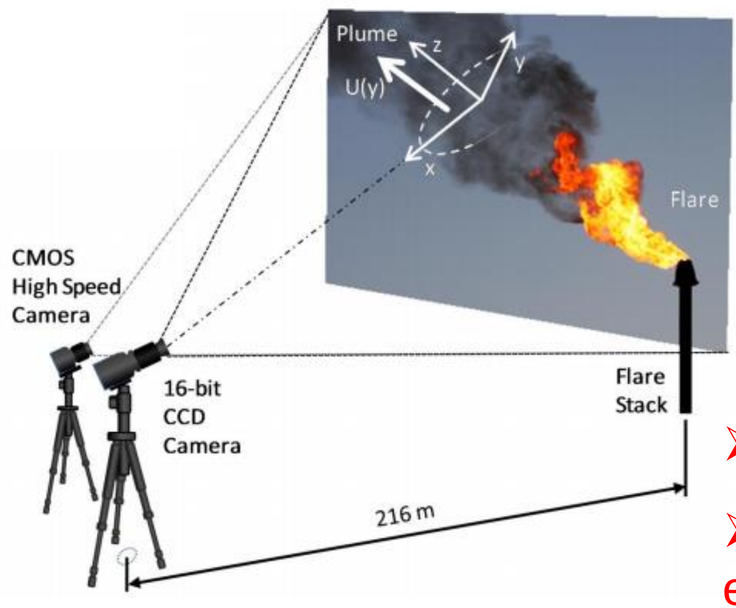




Gas flaring BC emission factor measurement

***In situ* measurement of gas flaring B 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 (τ≈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 (τ≈60%)
- Soot emission rate: 2.0 ± 0.66 g/s
- Roughly equivalent to emissions from **500** diesel buses continuously driving

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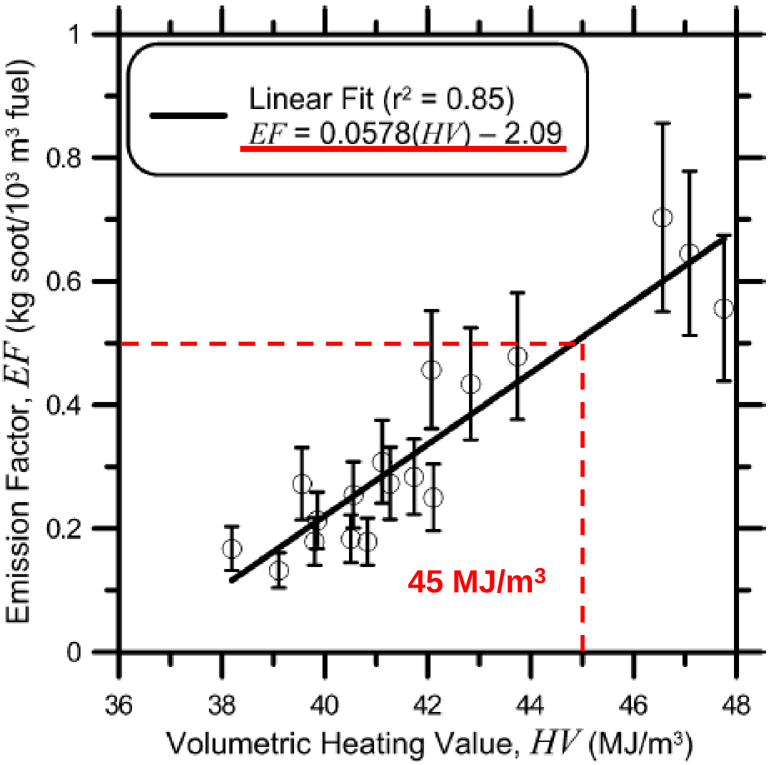
- ➢Significant difference of BC EF from different flares
- ➢EF measured by Sky-LOSA is not appropriate for emission estimation (i.e. unit in g/s)
- ➢Need mass of black carbon per mass of **fuel** burned

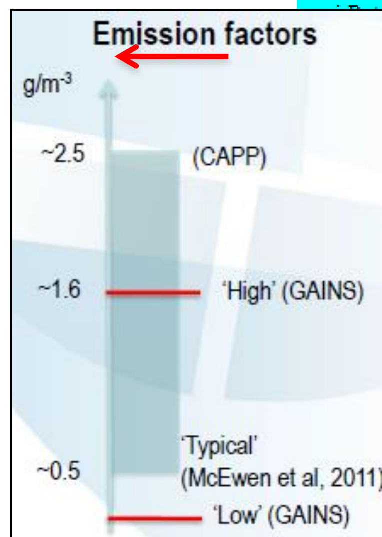
Courtesy:http://www.unep.org/ccac/Portals/50162/docs/ccac/initiatives/oil_and_gas/Sky%20-%20LOSA.PDF (taken from slides by Prof. Matthew Johnson from Carleton Univ.)

Estimation of gas flaring EF and emission in Russia

No field measurement available

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





Composition of the associated gas in Russia

Associated Gas Composition		Percentage (%)	Heating Value (MJ/m³)
Methane	CH_4	42.2661	39.9012
Ethane	C_2H_6	9.9207	69.9213
Propane	C_3H_8	14.4320	101.3231
[illegible]	$i\text{-}C_4H_{10}$	4.4313	133.1190
[illegible]ne	$n\text{-}C_4H_{10}$	7.2039	134.0610
[illegible]nes	$i\text{-}C_5H_{12}$	4.1191	148.4913
[illegible]ne	$n\text{-}C_5H_{12}$	4.8658	141.1918
[illegible]ne	$i\text{-}C_6H_{14}$	5.0317	176.8591
[illegible]ne	$n\text{-}C_6H_{14}$	1.4181	177.1907
[illegible]ne	$i\text{-}C_7H_{16}$	2.2952	205.0068
[illegible]ne	C_6H_6	0.0164	147.3980
[illegible]ne	$n\text{-}C_7H_{16}$	0.5915	205.0068
[illegible]ne	$i\text{-}C_8H_{18}$	1.4716	232.8155
[illegible]ne	C_7H_8	0.0756	373.0365
[illegible]ne	$n\text{-}C_8H_{18}$	0.1623	232.8155
[illegible]ne	$i\text{-}C_9H_{20}$	0.2905	260.6688
[illegible]ne	$n\text{-}C_9H_{20}$	0.2914	260.6688
[illegible]ne	$i\text{-}C_{10}H_{22}$	0.0694	288.4775
[illegible]ne	$n\text{-}C_{10}H_{22}$	0.0754	288.4775
Carbon dioxide	CO_2	0.3070	-
Nitrogen	N_2	0.6652	-
Hydrogen sulfide	H_2S	0.0000	

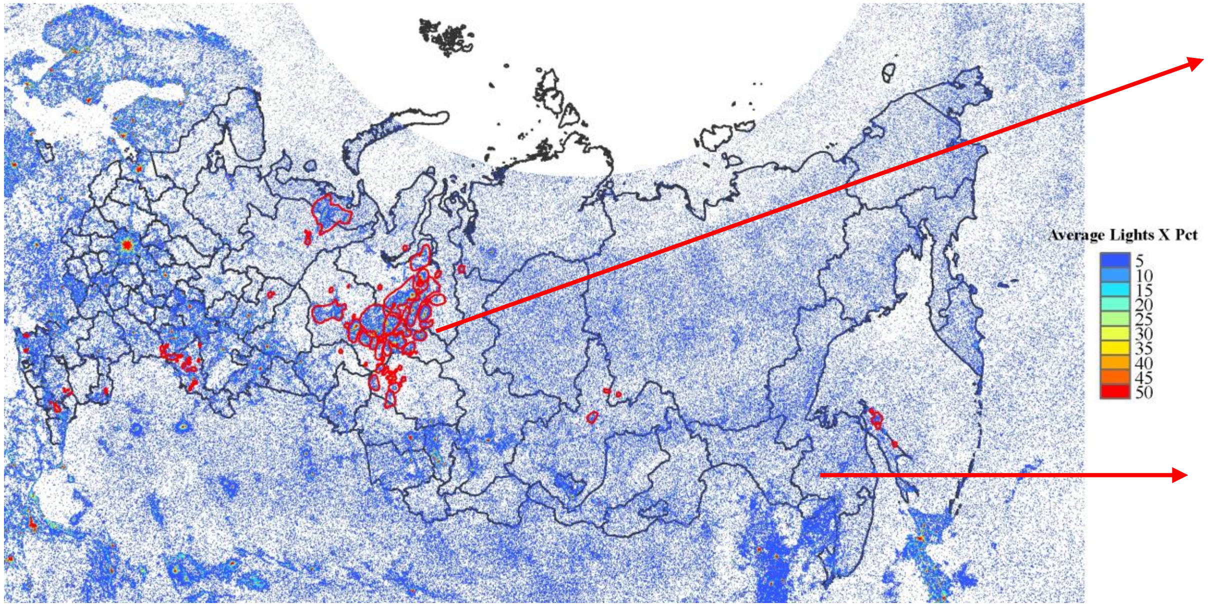
3.13 g/m³ ← **90.34 MJ/m³**

$BC_{flaring}$ = Volume * $Soot_{EF}$

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**.

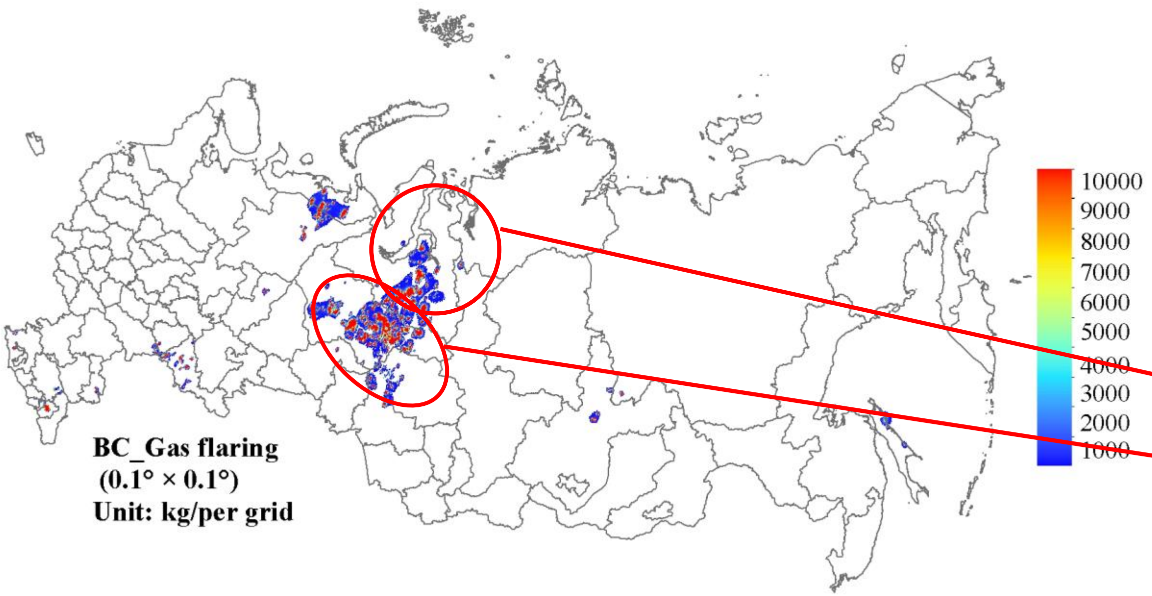
Spatial distribution of gas flaring BC emission



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



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

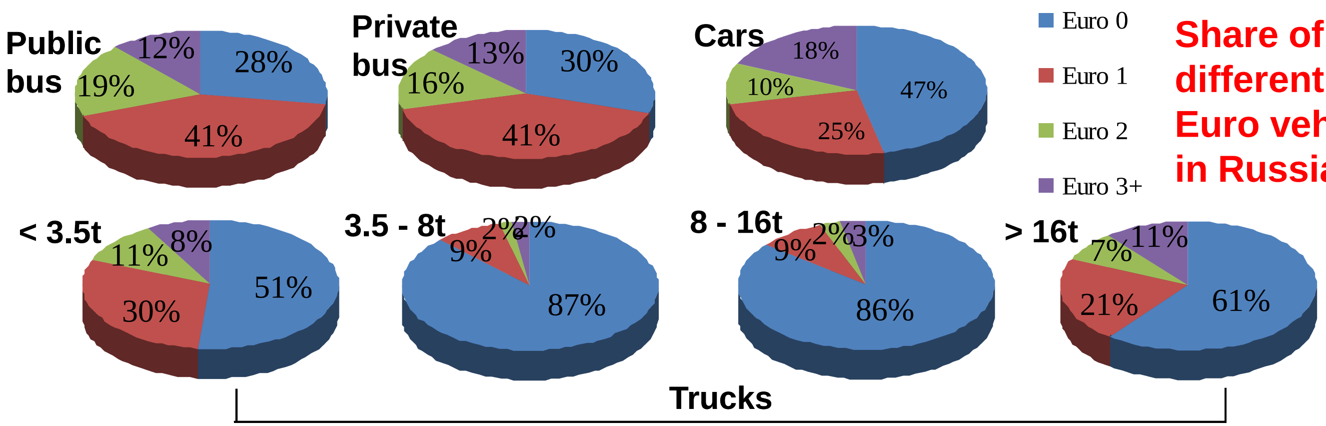
Major gas flaring regions:

Yamal-Nenets

Khanty-Mansiysk

II. Transportation BC emission

European Union		Russia	
Legislation	**Data**	**Legislation**	**Data**
Euro I	1/7/1992	Euro I	1/1/1999
Euro II	1/1/1996	Euro II	1/1/2006
Euro III	1/1/2000	Euro III	1/1/2008
Euro IV	1/10/2005	Euro IV	1/1/2010
Euro V	1/9/2009	Euro V	1/1/2014
Euro VI	1/9/2014	Euro VI	



Share of different Euro vehicles in Russia

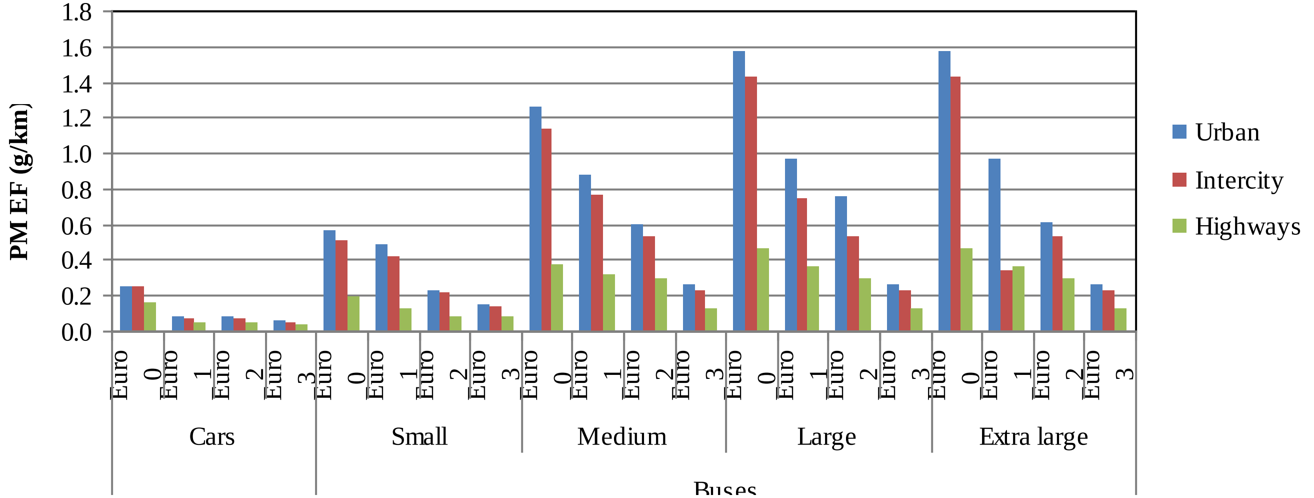
$$Emi_{hot} = \sum EF_{PM,\, ijk} \times (S_{ij} \times Eu_{ijk} \times R_{ij} \times VMT_{ijk}) \times (EC/PM_{2.5})_{ijk}$$

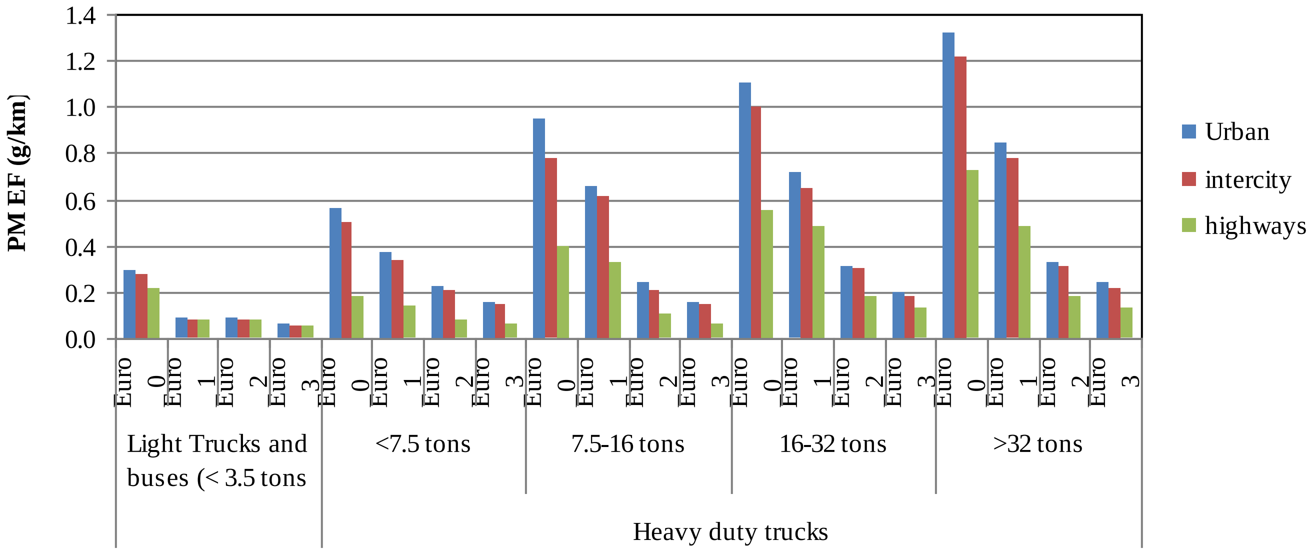
Where i, j, and k respresent the vehicle type, driving modes, and Euro standard, respectively. $EF_{PM,ijk}$ is the PM emission factors; S_{ij} is the vehicle stock number; Eu_{ijk} is the percentage share of vehicles with different Euro standards; R_{ij} is the anuual ratio of vehicle usage; VMT_{ijk} 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_{hot} is annual BC emission during the hot operation stage.

Data sources: Russian Federal State Statistics Service (2010), Russian Automotive Market Research (2011), and Stanley Root (2012).

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)

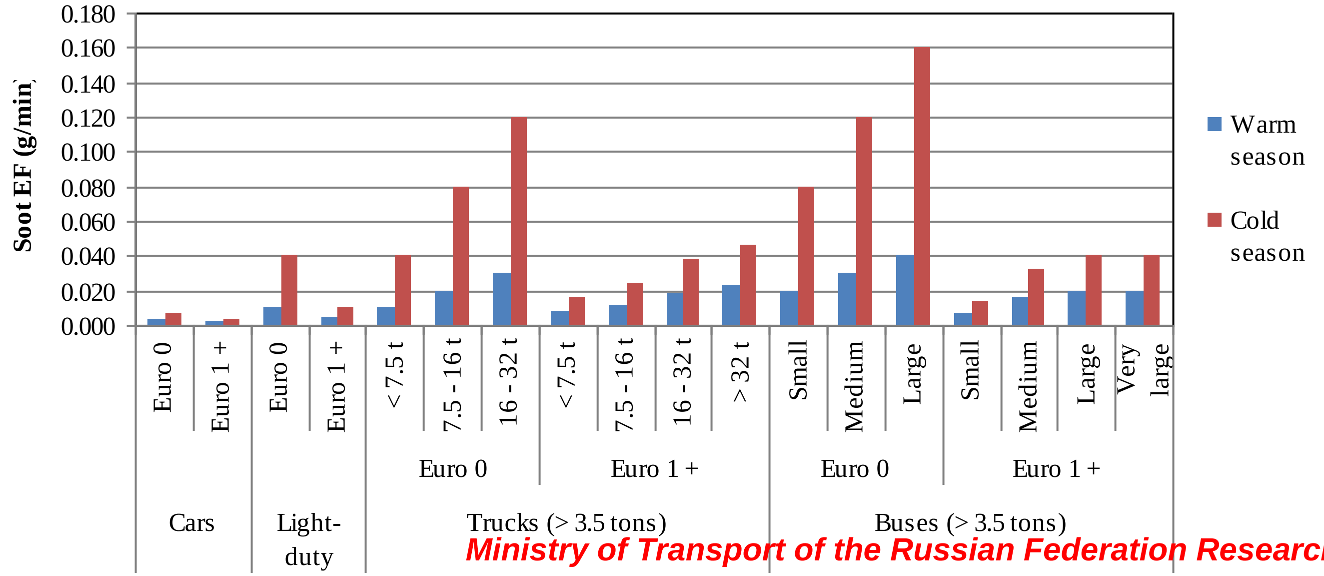




Ministry of Transport of the Russian Federation Research Institute, 2008

II. Transportation BC emission

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



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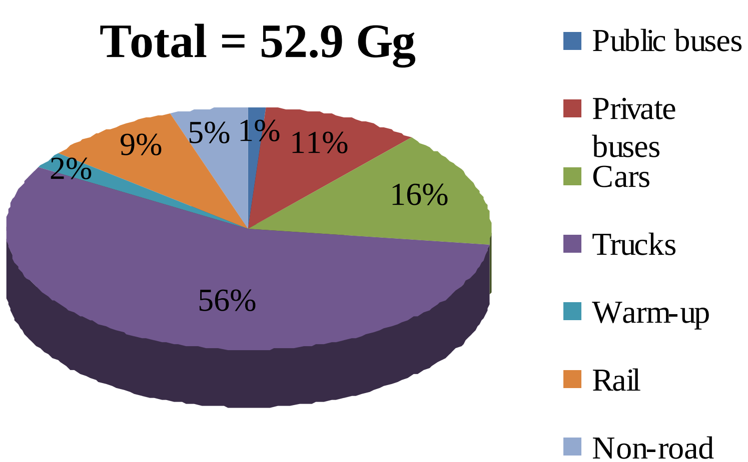
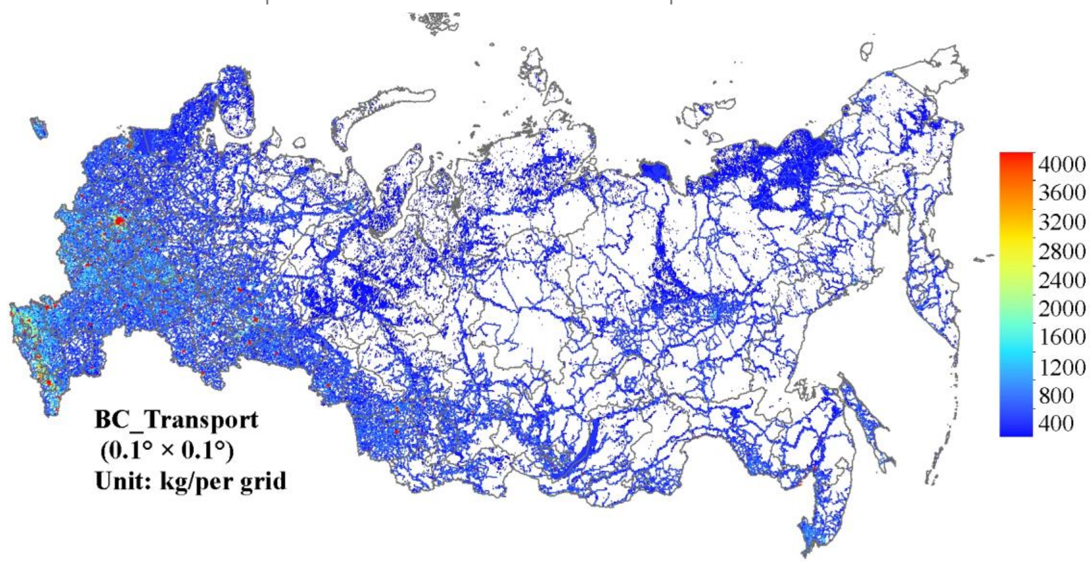
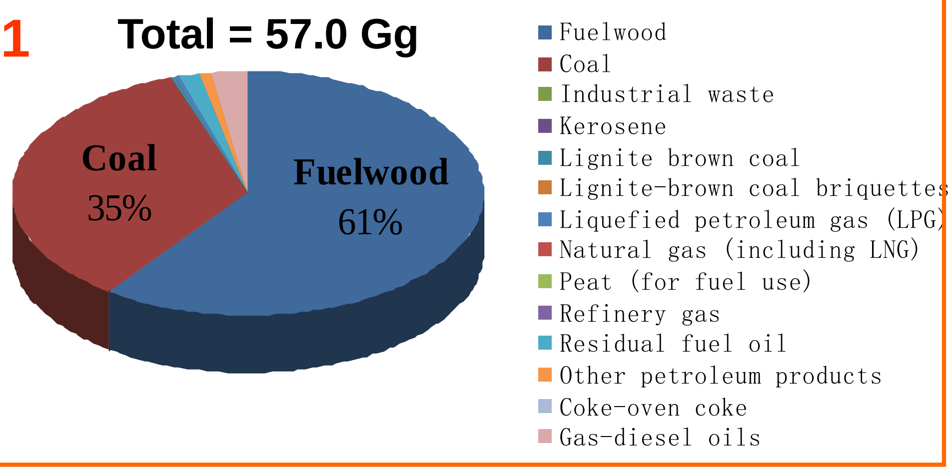




III. Residential BC emission

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

1



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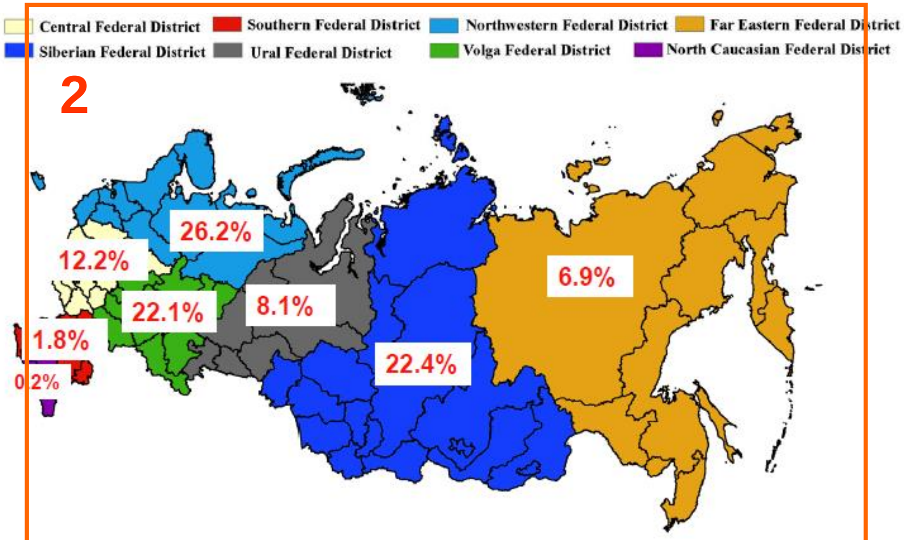

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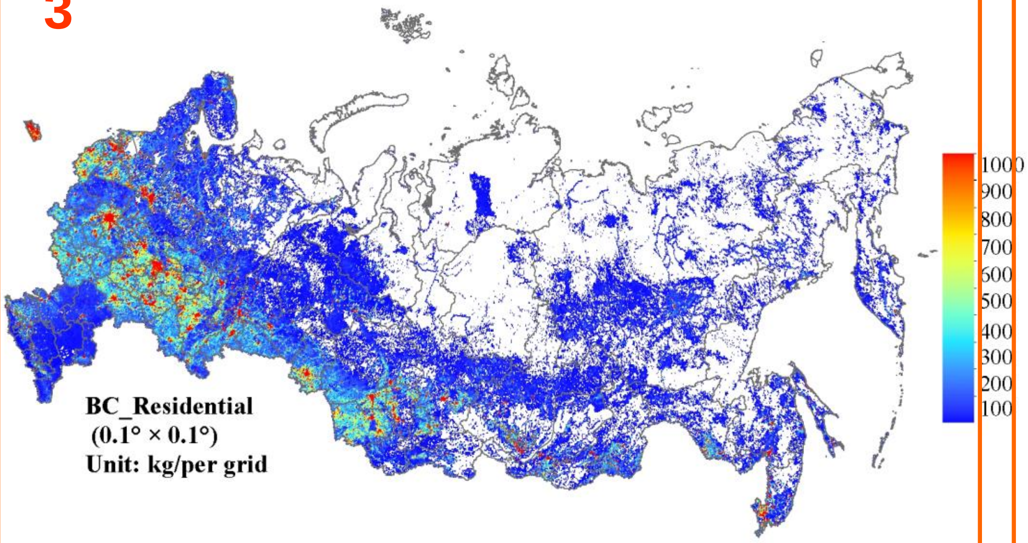


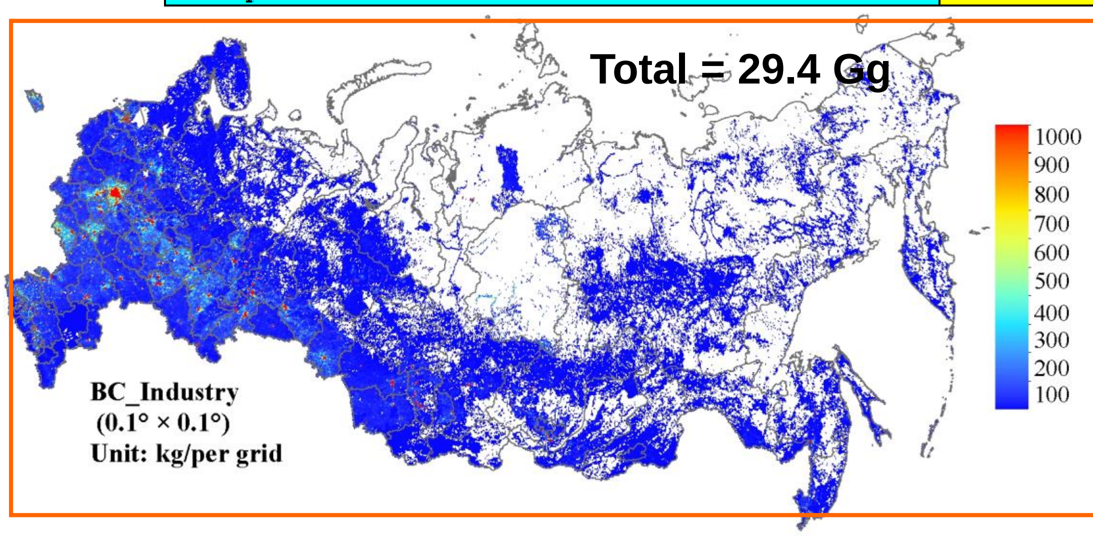
National BC -> Federal District level
based on residential firewood consumption from *Russia's FSSS* (*Federal State Statistics Service*)

District BC -> grid cell
population density within each district (*ORNL's LandScan dataset*)

IV. Industrial BC emission

$BC_{ind} = \sum PM_{raw,i} \times (1 - \eta_i) \times (BC/PM)_i$, where $PM_{raw,i}$ represents PM emission prior to technology controls, i and η represents the sub-sector and removal efficiency.

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



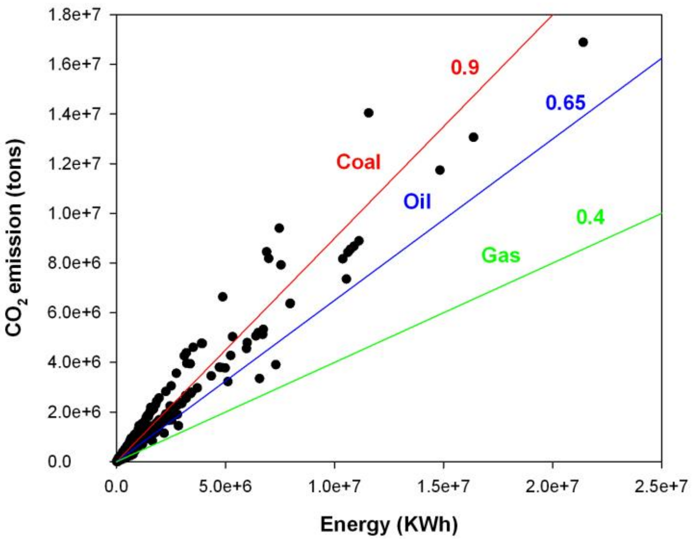
National BC -> Provincial level based on provincial industrial revenues from *Russia's FSSS* (*Federal State Statistics Service*)
Provincial BC -> grid cell population density within each district (*ORNL's LandScan dataset*)

Data from SRI-Atmosphere

V. Power plants BC emission

Sector	Particulate matter emission (Gg)	Removal efficiency (%)	PM into atmosphere (Gg)
Energy Industry	26294.212		1186.671
Electricity production	24292.676	96.5	840.986
Transmission and distriction of steam and hot water	1903.862	82.9	326.044
Collection, purification and distribution of water	86.41	90.2	8.455
Production and distribution of gaseous fuels	11.265	0.7	11.185

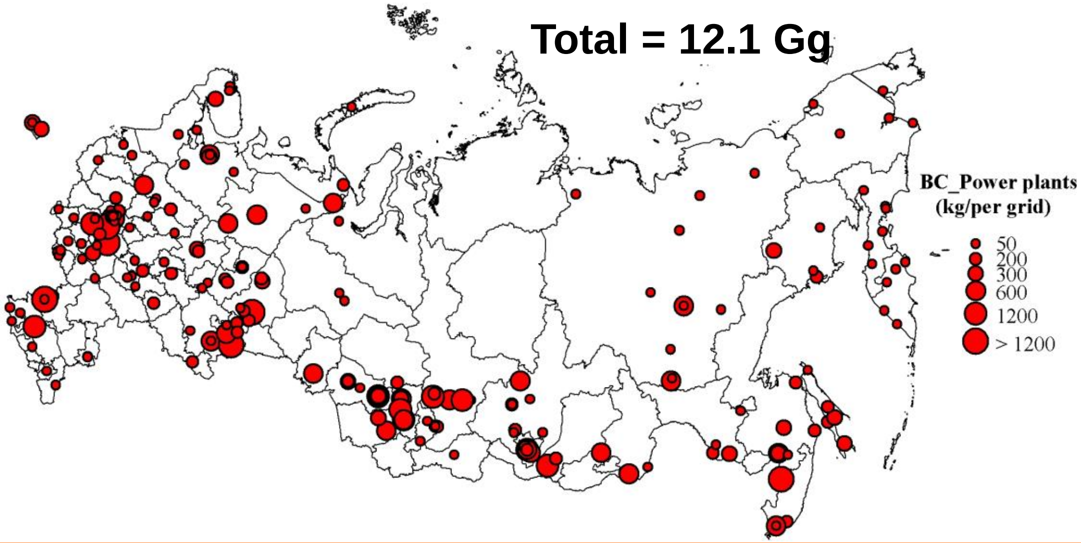
Categorize fuel types of thermal power plants in Russia by using the energy intensity (tons of CO_2 emitted per MWh)



Coal: Intensity > 0.9 tons CO_2/MWh

Oil: Intensity 0.65 - 0.9 tons CO_2/MWh

Gas: Intensity 0.4 - 0.65 tons CO_2/MWh

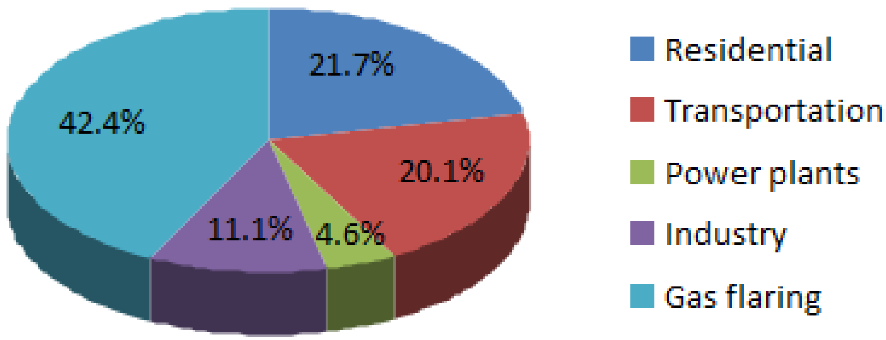


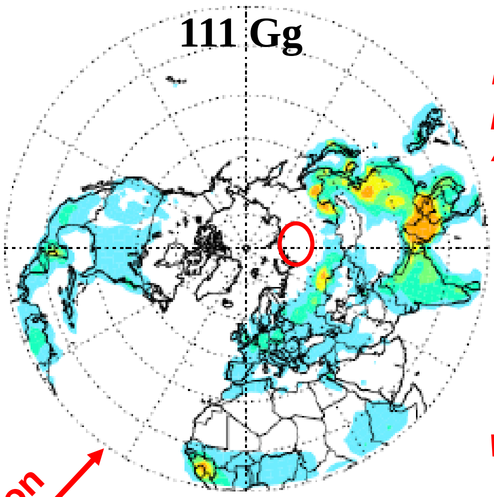
National BC -> grid level

CARMA (Carbon Monitoring for Action): power plant location, energy capacity and CO_2 emission.

Sectoral contributions to Russian anthropogenic BC emissions

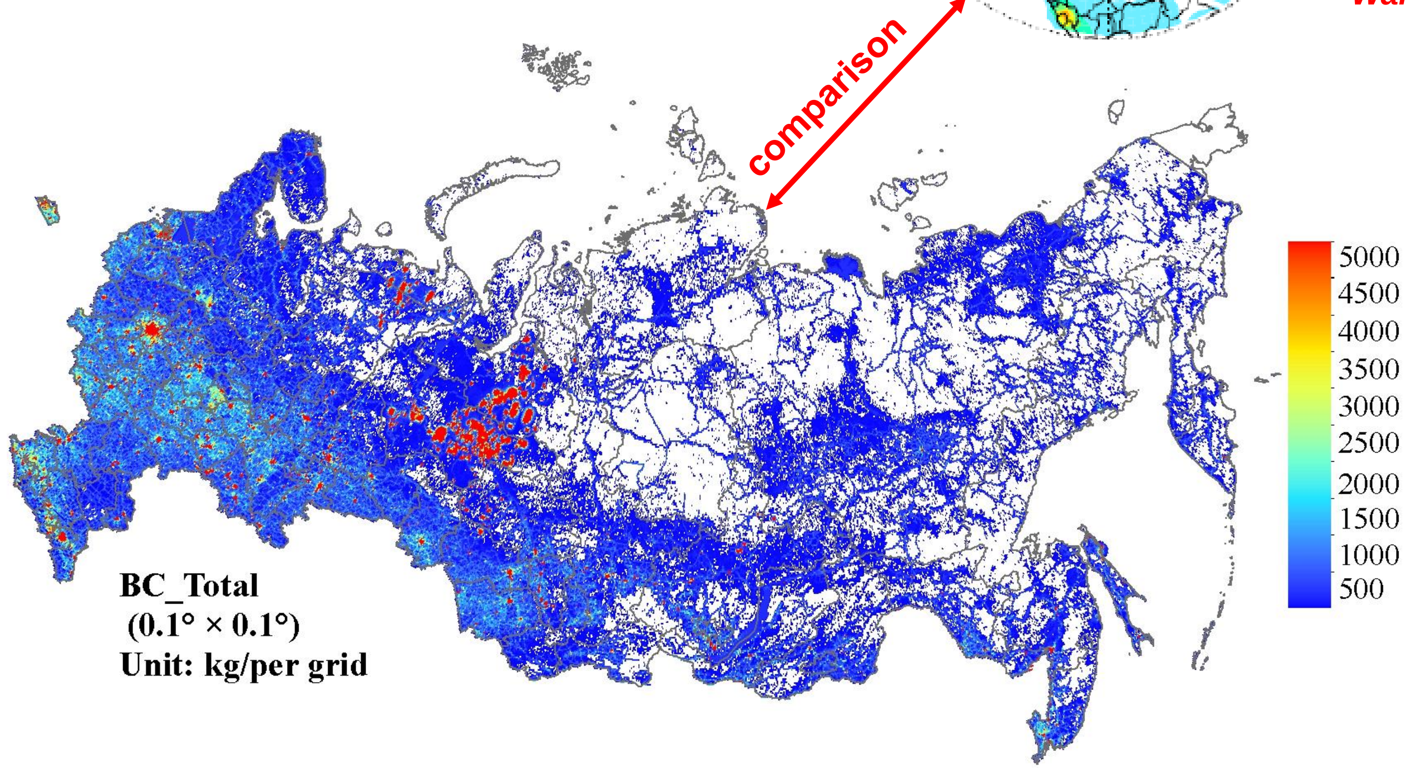
Russian anthro BC = 263 Gg



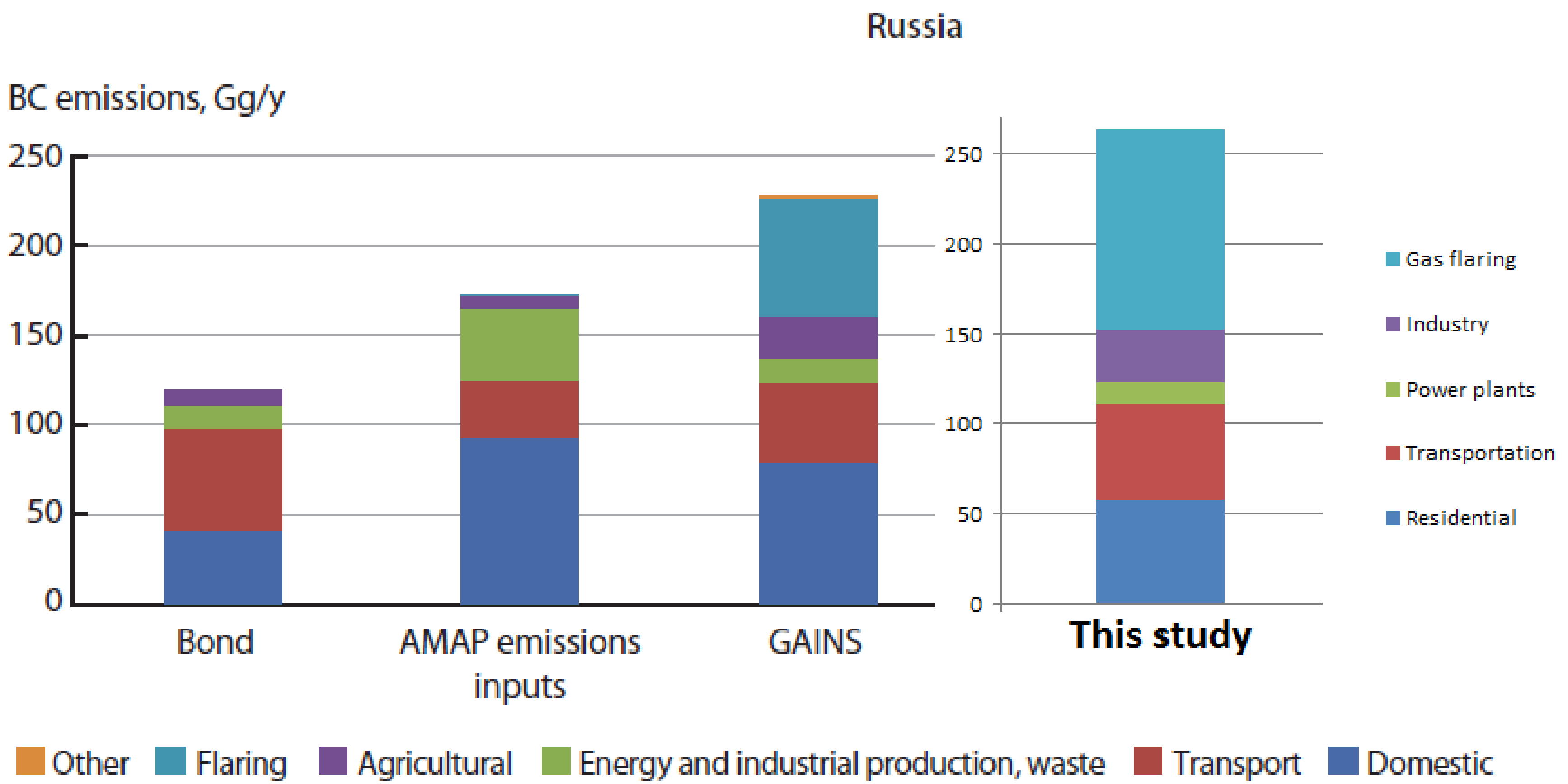


BC emission prepared for ARCTAS

Wang et al ., 2011



Comparison to other emission inventories



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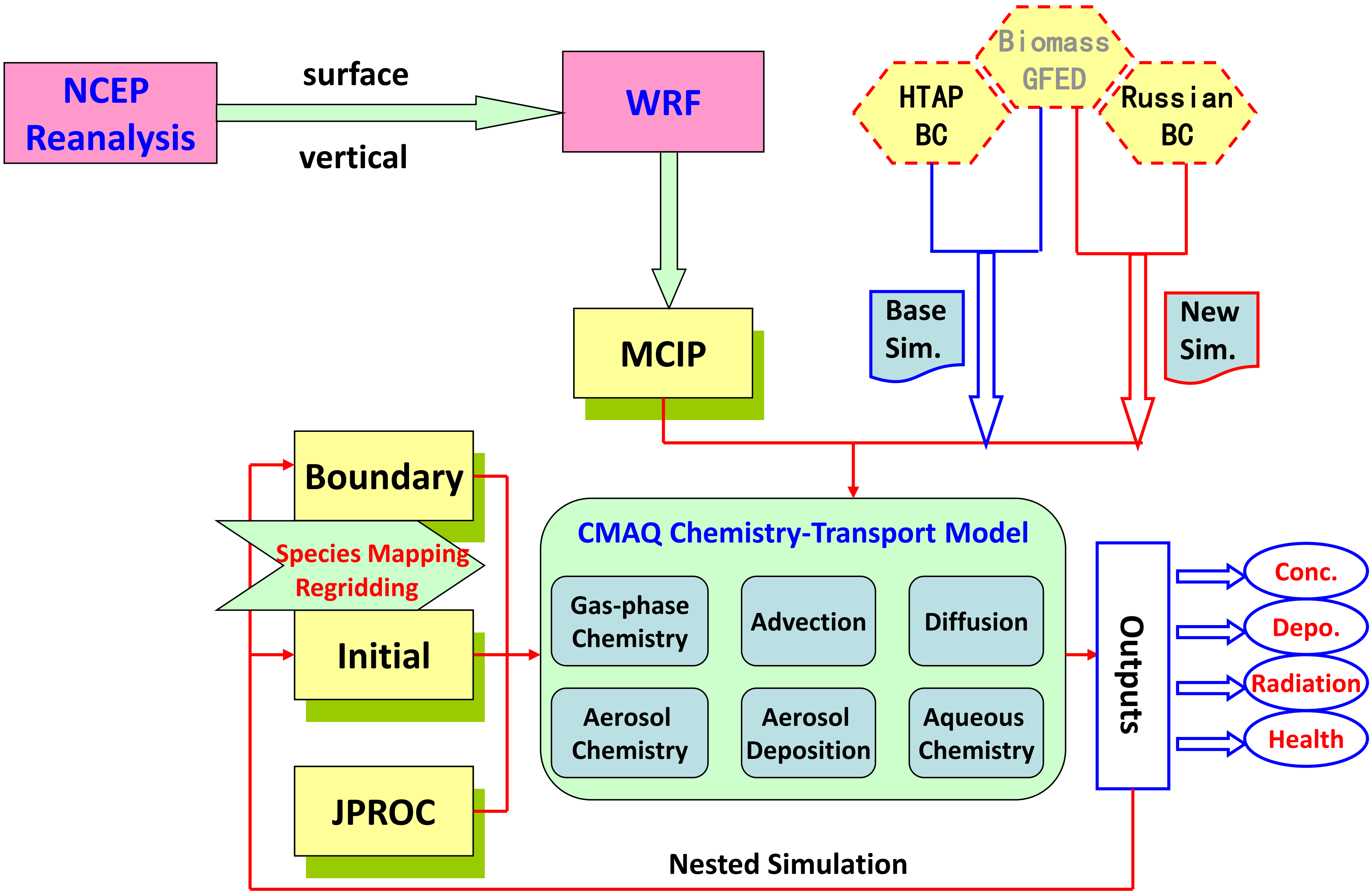
WRF/CMAQ modeling system



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)

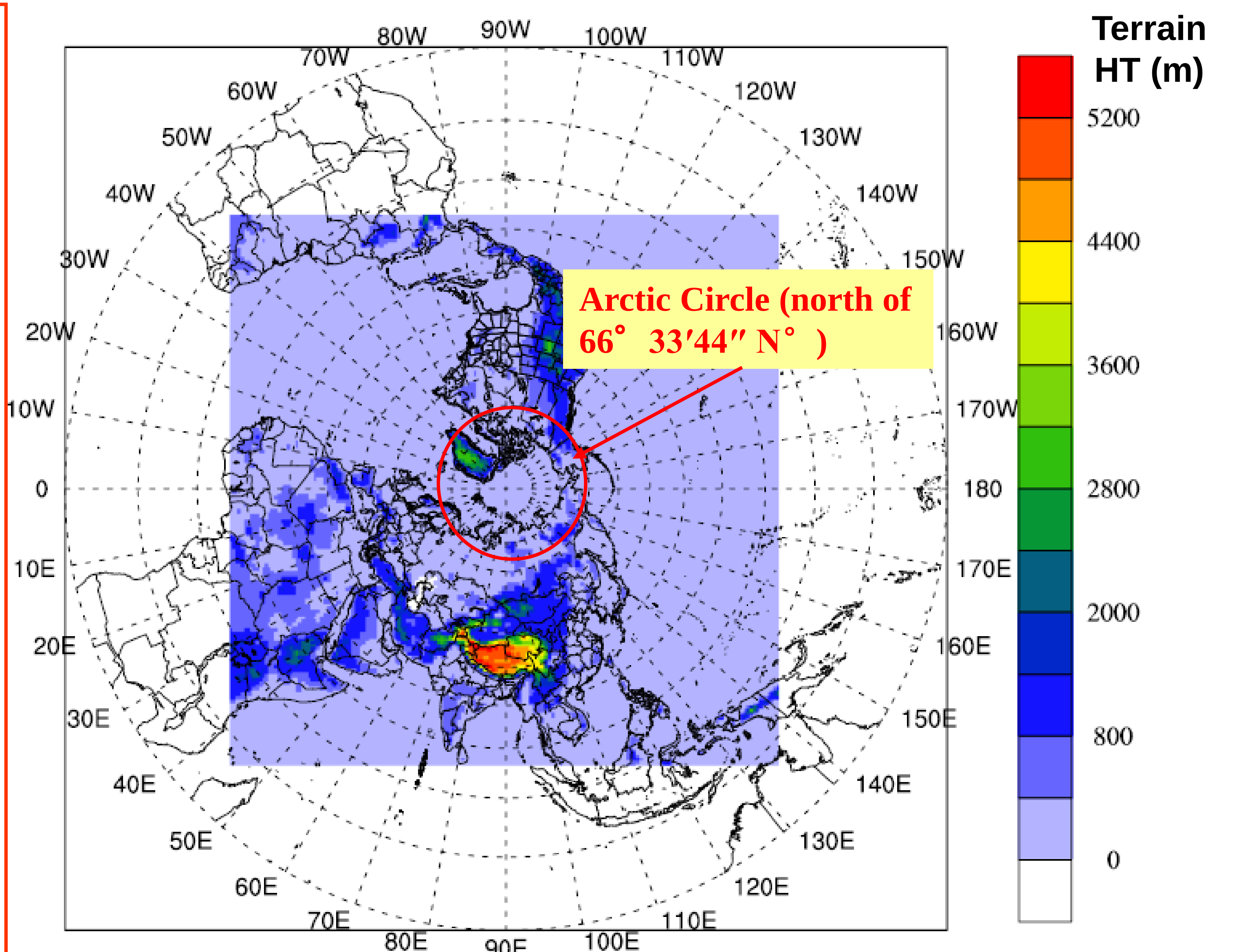
Vertical Spacing:
44 layers

Gas chemistry:
CB05

Aerosol mechanism:
AERO5

Simulation year:
2010

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



Black carbon emissions input

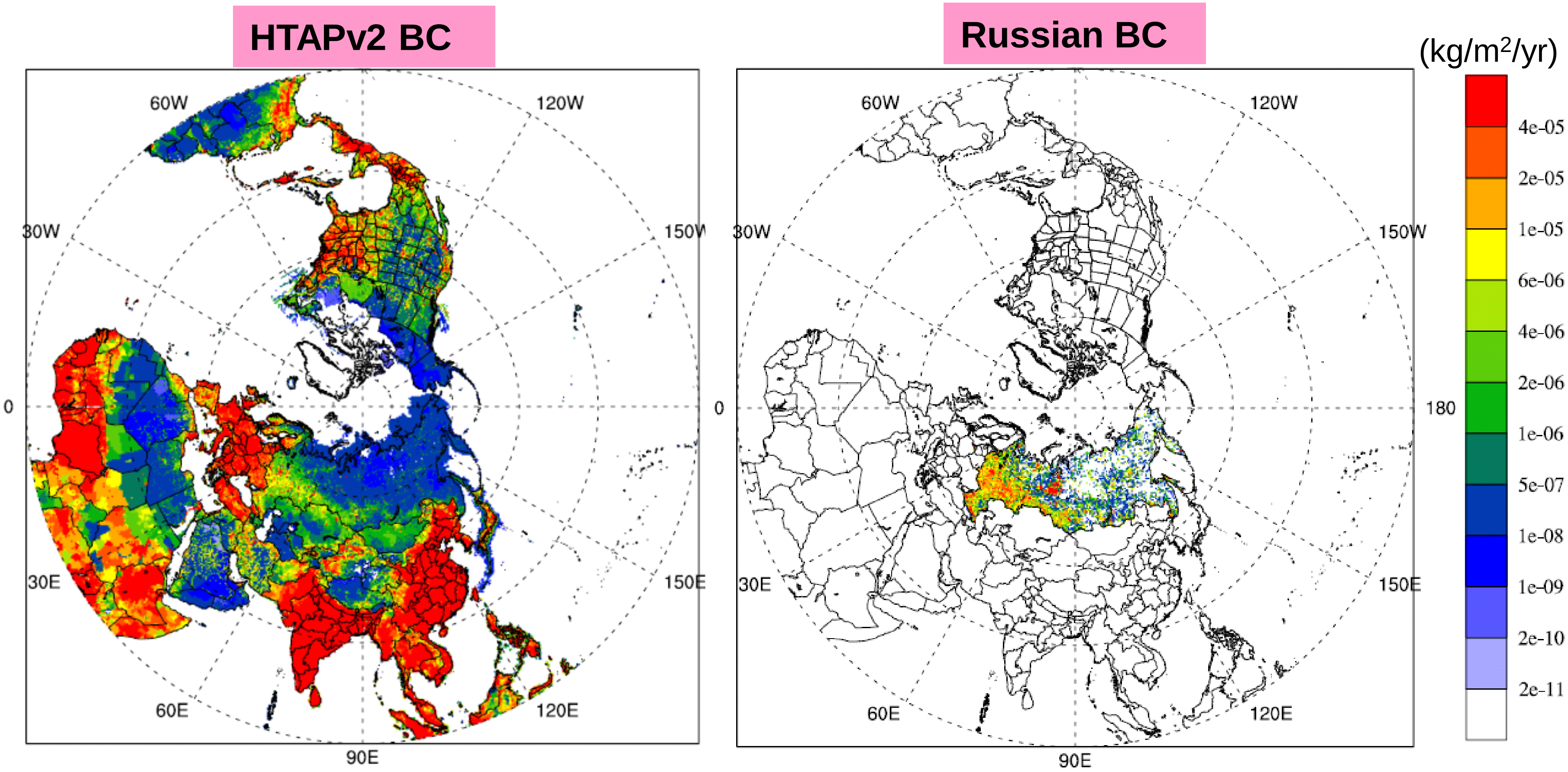
Default global anthropogenic BC emission inventory:

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

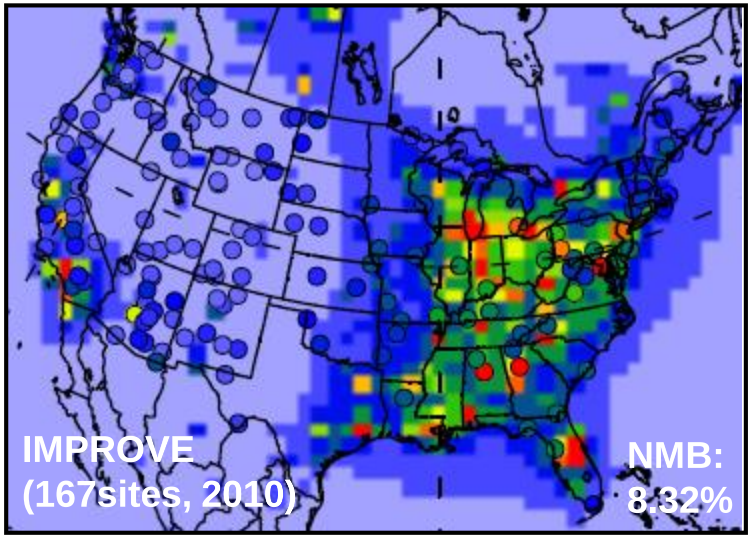
Industry + power plant + traffic + residential + shipping + air

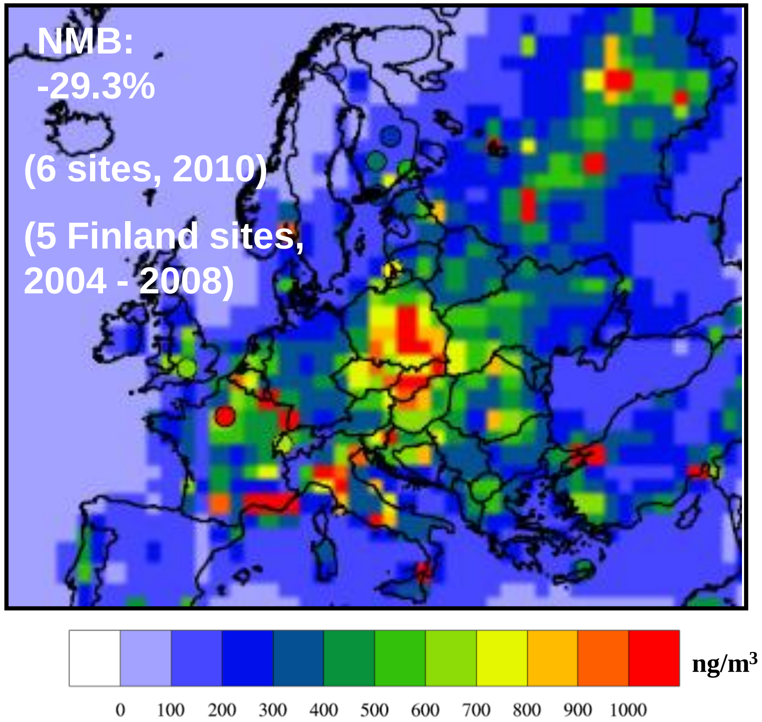
Biomass burning emission:

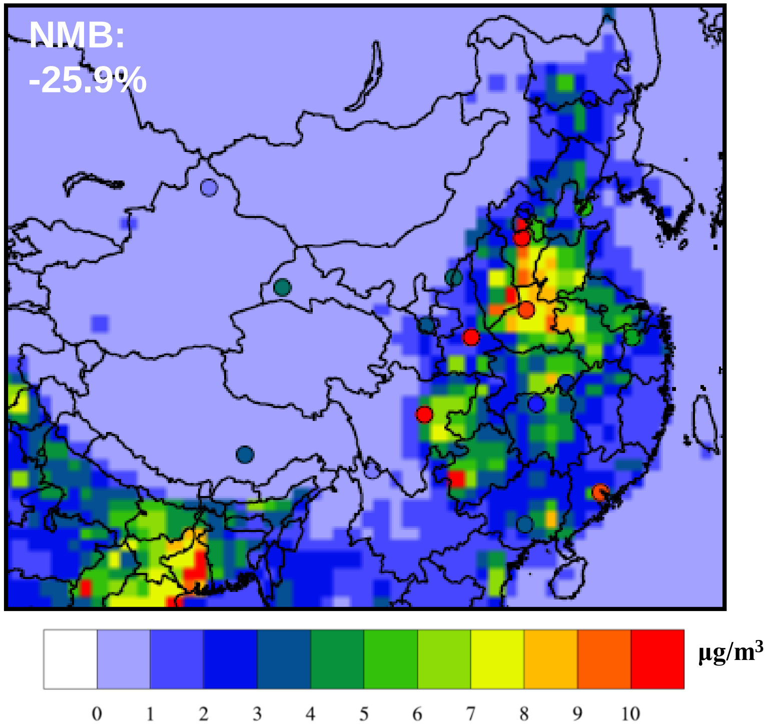
GFEDv3 (Global Fire Emission Database) [0.5° × 0.5°]



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

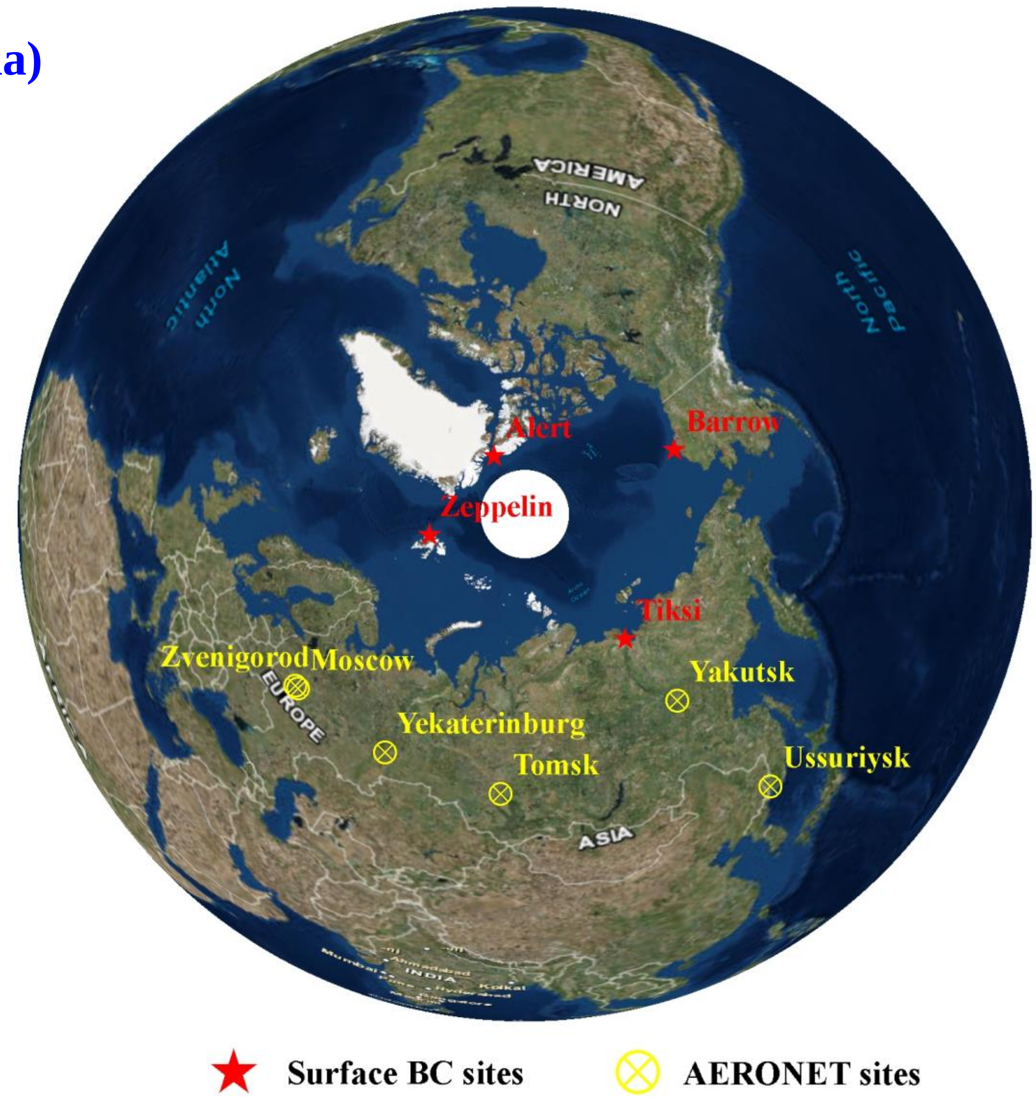
(56.5° N, 85.0° E)

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

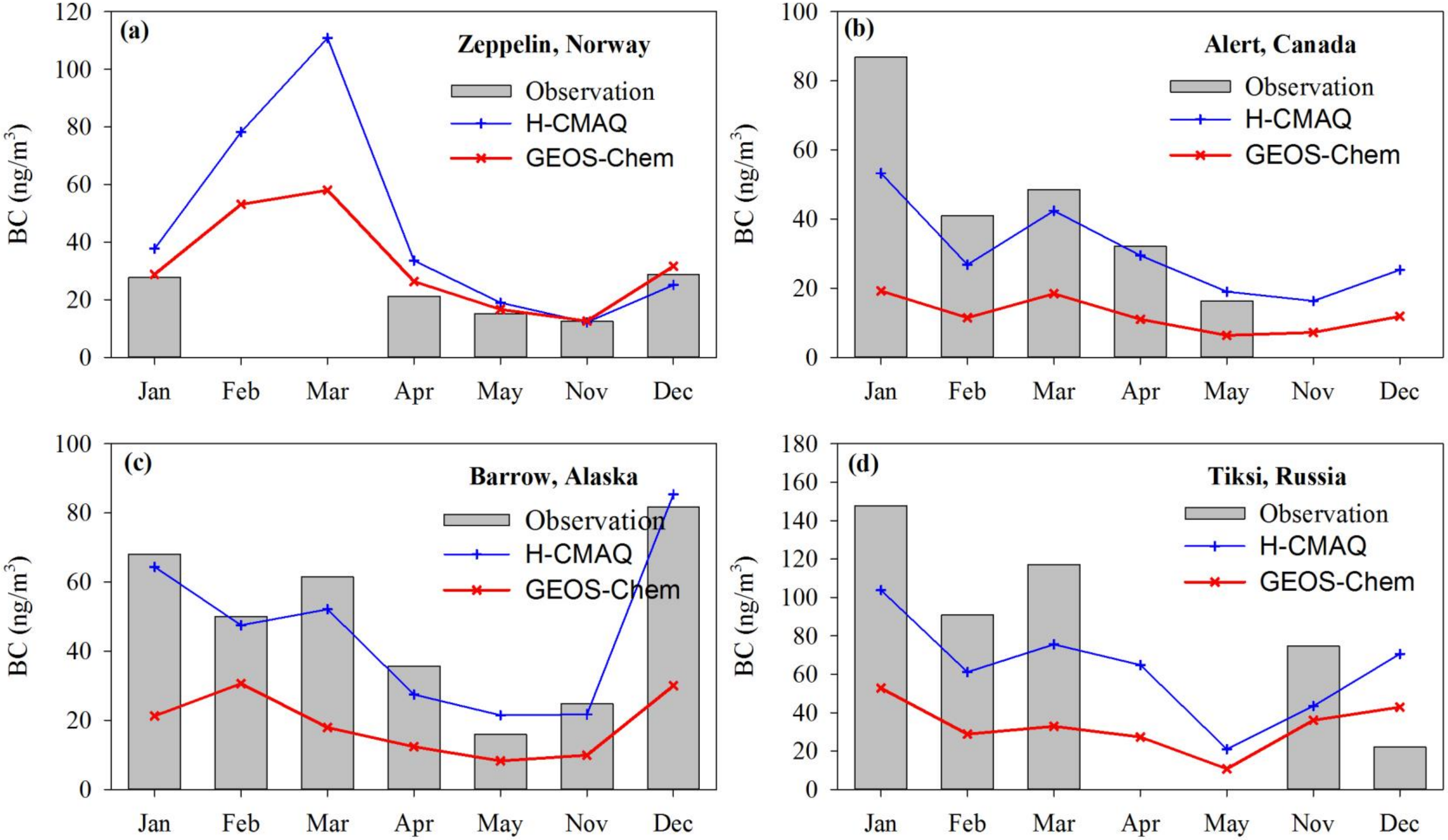
(78.9° N, 11.9° E)

Tiksi, Russia

(71.6° N, 128.9° E)

H-CMAQ vs. GEOS-Chem Simulation in the Arctic

Lower BC prediction by GEOS-Chem than H-CMAQ

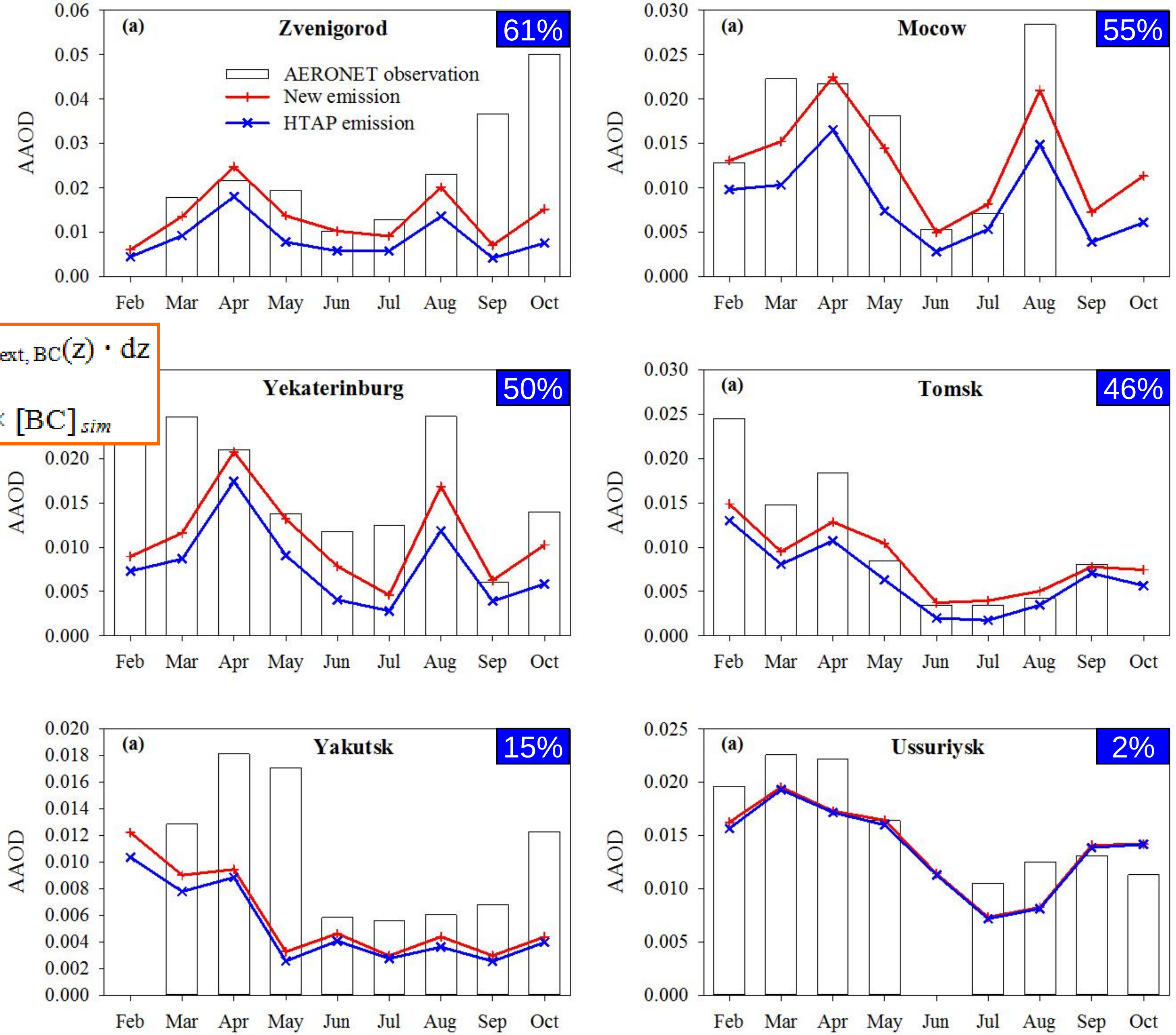


Compared to the conventional global chemical transport model (e.g. GEOS-Chem) with cylindrical projection, H-CMAQ with a polar projection seens to better resolve the cross-pole atmospheric transport.

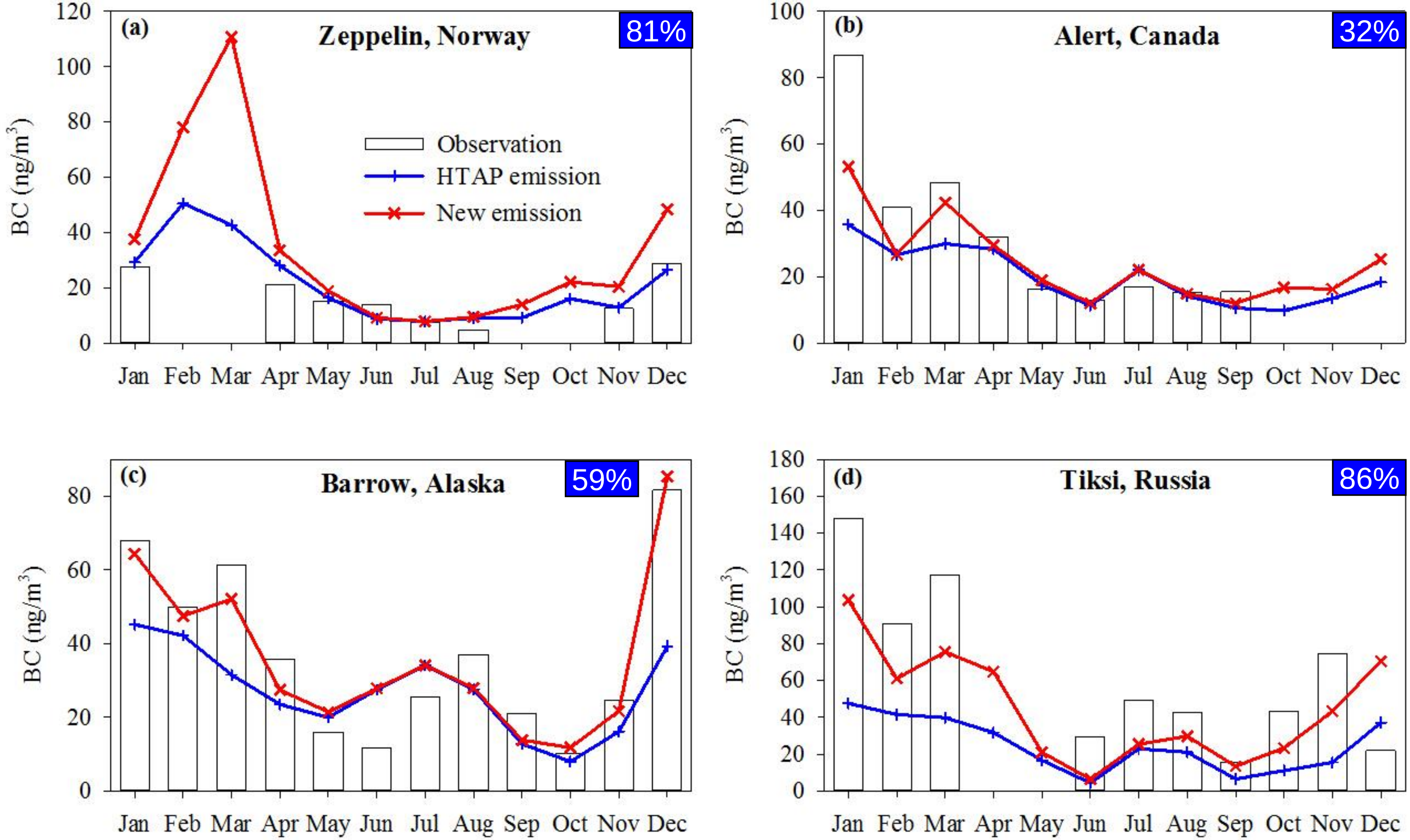
Model performances in Russia

$$AAOD_{sim} = \int \sigma_{ext,\,BC}(z) \cdot dz$$

$$\sigma_{ext,\,BC} = 10.0 \times [BC]_{sim}$$



Model performances in the Arctic



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

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

Monthly BC dry deposition perturbations

BC dry deposition (new – base) **ratio: (new – base)/new**

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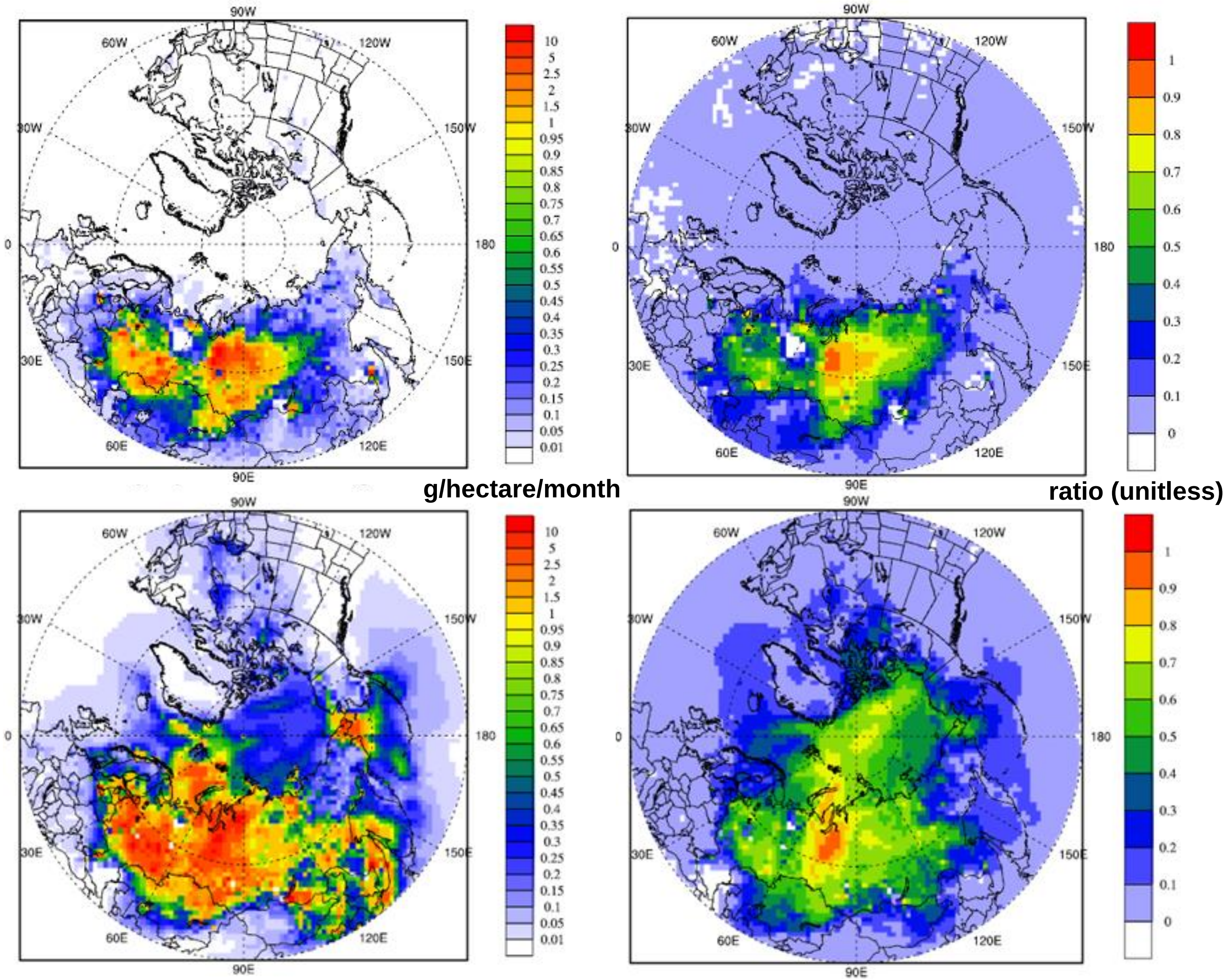
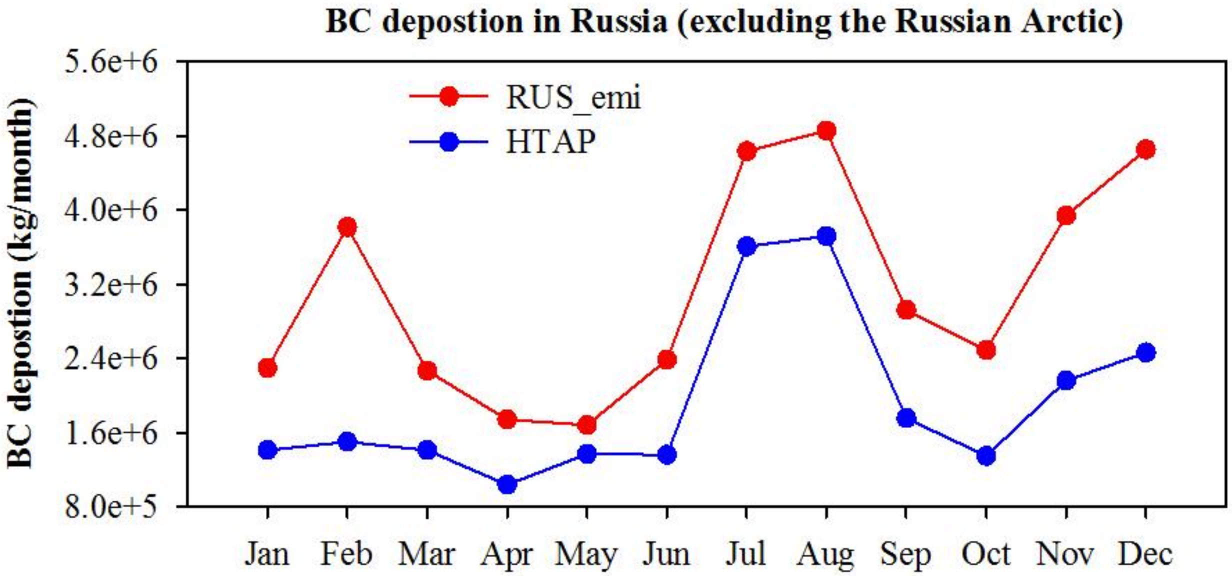
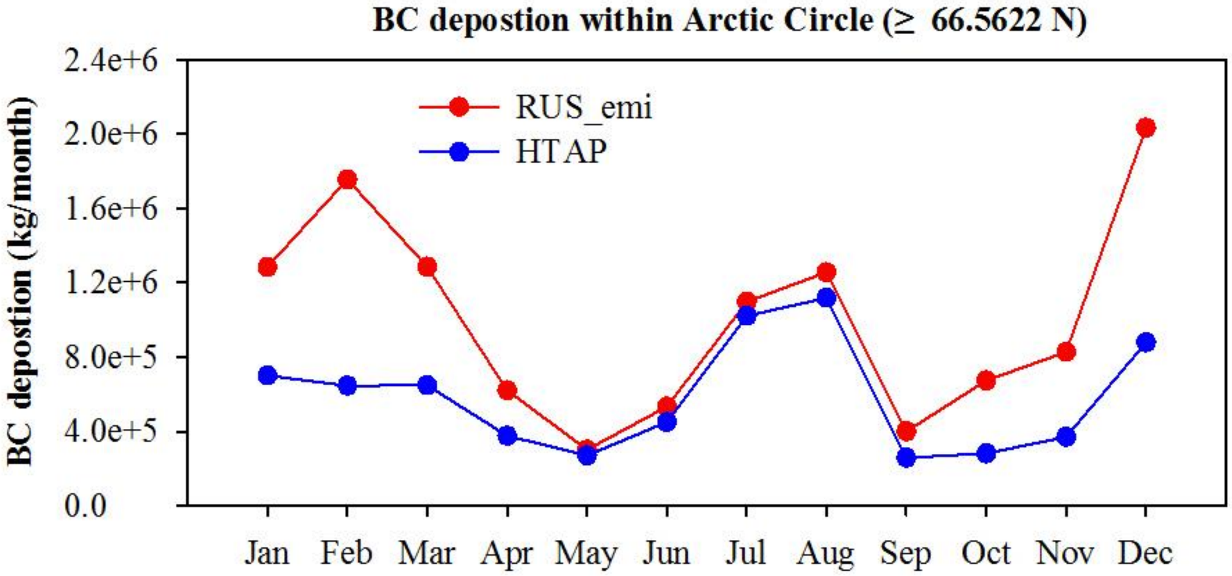


Monthly BC dry deposition perturbations





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 vey 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.

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Thank you for your attention!