Authors' comments on Review #1

RC C676: 'Review comments on "Black carbon emissions from Russian diesel sources" by M. Evans', Anonymous Referee #1, 12 Mar 2015

Black carbon emissions from Russian diesel sources: case study of Murmansk

M. Evans, N. Kholod, V. Malyshev, S. Tretyakova, E. Gusev, S. Yu, and A. Barinov

MAJOR COMMENTS

Comment 1. For data such as emission factors and BC/PM ratios for different sources, the use of the data needs to be clearly justified. The source of the data also needs to be specified; some references were missing in the manuscript

Emission factors for on-road vehicles came from two sources:
a) Russian methodologies, developed by the Scientific Research Institute of Automobiles and Transportation (NIIAT):
- NIIAT: Calculation instruction (methodology) for emission inventory from vehicles into the air (in Russian). Scientific Research Institute of Automobiles and Transportation, Moscow, Russia, 2008a.
-NIIAT: Calculation instruction (methodology) for emission inventory from vehicles into the air (in Russian), Scientific Research Institute of Automobiles and Transportation, Moscow, Russia, 2008b.

b) European vehicular emissions model:
Emisia: COPERT 4 (Computer programme to calculate emissions from road transport), Prepared for the European Environment Agency (EEA), available at: http://www.emisia.com/content/copert-download (last access: 15 July 2014), 2011.

COPERT model is the source for BC ratios (speciation, fractions) of PM (f-BC) for on-road transport. The BC/PM ratios for on-road transport also can be found in

EEA, 2013. EMEP/EEA Air Pollutant Emission Inventory Guidebook — 2013. European Environment Agency, Copenhagen, Denmark. http://www.eea.europa.eu/publications/emep-eea-guidebook-2013/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-b-road-transport . (Table A4-2, Page 154).

Emission factors for other diesel sources are taken from: EEA, 2013. EMEP/EEA Air Pollutant Emission Inventory Guidebook — 2013. European Environment Agency, Copenhagen, Denmark.

Per reviewer's suggestion, we have used BC/PM ratios from EEA emissions guidebook to make the calculations consistent. As a result, we changed our BC and OC emission estimates (throughout the text).

Changes to the text

COPERT model is the source for BC/PM ratios for on-road transport. COPERT model includes data for EC fractions of PM (f-EC) as well as OM/EC ratios. Additional detail on our methodology can be found in (Evans et al., 2012).

For other sources, we used emission factors and speciation ratios from EMEP/EEA Air Pollutant Emission Inventory Guidebook (Table 1). We decided to use the European Monitoring and Evaluation Programme (EMEP) data for consistency. However, U.S. EPA has more rigorous procedure for determination of BC/PM ratios. EMEP is currently updating its emissions factors and speciation ratios.

Table 1. $PM_{2.5}$ emission factors and BC/PM ratios for diesel sources

Sector	*$PM_{2.5}$, gkg^{-1}*	*Source*	*BC/PM*	*Source*
Transport				
Rail	*1.44*	*EEA, 1.A.3.c, Table 3.1.*	*0.65*	*EEA, 1.A.3.c, Table 3.1.*
Other transport	*4.31*	*EEA, 1.A.4., Table 3-2*	*0.5*	*EEA, 1.A.4., Table D.1*
Industry				
Mining and quarrying	*3.551*	*EEA, 1.A. 4., Table 3-2*	*0.62*	*EEA, 1.A.4., Table D.2*
Construction	*4.308*	*EEA, 1.A. 4., Table 3-2*	*0.62*	*EEA, 1.A.4., Table D.2*
Other industry	*4.308*	*Same as construction*	*0.62*	*EEA, 1.A.4., Table D.2*
Other sectors				
Agriculture/forestry	*3.755*	*EEA, 1.A. 4., Table 3-2*	*0.57*	*EEA, 1.A.4., Table D.2*
Residential	*6.0*	*Data from (Bond, 2004)*	*0.66*	*Data from (Bond, 2004)*
Commercial and public services	*6.0*	*Data from (Bond, 2004)*	*0.66*	*Data from (Bond, 2004)*
Fishing	*1.4*	*EEA, 1.A.3.d, Table 3-2*	*0.31*	*EEA, 1.A.3.d, Table 3-2*
Fishing ($gkWh^{-1}$)	*0.3*	*EEA, 1.A.3.d, Table 3-10*	*0.31*	*EEA, 1.A.3.d, Table 3-1*

Comment 2. First paragraph in Section 2, I would suggest the authors use equations to explain how the emissions were calculated for each source with fuel consumption, activity and emission factor.

Calculations of black carbon emissions from all sources (except on-road transport) are very simple and can be expressed by the following equation

BC emissions = fuel (kg) x $PM_{2.5}$ emission factor (g/kg) x $BC/PM_{2.5}$ ratio

Source: EEA: EMEP/EEA Air Pollutant Emission Inventory Guidebook – 2009, European Environment Agency, Copenhagen, Denmark, 2009. http://www.eea.europa.eu/publications/emep-eea-emission-inventory-guidebook-2009/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1.a.3.b-road-transport-gb2009-update.pdf

The Supplement provides detailed calculation of BC emissions from on-road transport.

Changes to the text

"Calculations of black carbon emissions from all sources (except on-road transport can be expressed by Eq.1 (EEA, 2009):

BC emissions = fuel (kg) x $PM_{2.5}$ *emission factor* (gkg^{-1}) *x BC/*$PM_{2.5}$ *ratio (1)"*

Comment 3. Second paragraph in Section 2, the statements are vague. The authors need to clearly explain what the "Russian methodologies" are. What are the "other methodologies" used? Do "methodologies" mean "emission factors" or others?

The Russian Methodologies are (NIIAT, 2008a, b)

- NIIAT: Calculation instruction (methodology) for emission inventory from vehicles into the air (in Russian). Scientific Research Institute of Automobiles and Transportation, Moscow, Russia, 2008a.

-NIIAT: Calculation instruction (methodology) for emission inventory from vehicles into the air (in Russian), Scientific Research Institute of Automobiles and Transportation, Moscow, Russia, 2008b.

The "methodology" means not only emission factors but also how the emissions can be calculated. For example, there are different approaches to calculate cold start emissions in NIIAT and COPERT models.

Changes to the text

"Wherever possible, we used Russian methodologies or PM emission factors (NIIAT, 2008a, b)"

Please also see the changes to the Supplement described in Comment 5.

Comment 4. Second paragraph in Section 3, how was the "consolidated estimate" was performed as the data are different for summary data, detailed data and estimated consumption? What is the difference (exact numbers) among the three datasets?

A "consolidated estimate" is our assumption about diesel consumption in Murmansk region. We used information from different sources and data collection methodologies were not always clear. The "summary data" and "more detailed data" refer to official information from the Murmansk Statistical Office. The "summary data" is the total diesel consumption in the region while "more detailed data" reflect the consumption in various sectors.

Our consolidated estimate (in many cases using the bottom-up approach) of diesel consumption in Murmansk region is 242,500 tons in 2012. The Murmansk Statistical Office reports diesel consumption at 391,900 tons including 68,300 tons consumed by fishing ships. Our bottom-up calculations show that fishing ships consumed only 3,000 tons while in Russian territorial waters.

We have changed the text as follows:

"The summary data from the Murmansk Statistical Office and the more detailed data from various sectors appear to have some methodological differences. The summary data appear to include different categories across different years, causing major swings in the total reported fuel use. For example, the Murmansk Statistical Office reports diesel consumption at 391 900 t in 2012 while the total diesel consumption was 599 120 t in 2011. The official statistical data also includes bunker fuel for marine transport. The Murmansk Statistical Office reports that fishing ships consumed 68 300 t. Our bottom-up calculations show that these ships consumed only 3 000 t while in Russian territorial waters".

Comments 5. Third paragraph in Section 4.1, the paragraph is not well organized and difficult to follow. The authors really need to provide more details about NIIAT method and COPERT either in the main text or as supplemental materials (some of them are in Section 4.2 now). Full names of NIIAT and COPERT and the brief introduction need to be provided when they first appear. Moreover, the four methods in Table 3 need a clearer explanation.

We moved *Table 2. Main data sources on vehicle fleet and activity* to *Section 2. Methodology* and provided additional details about NIIAT and COPERT methodologies.

We have changed the text as follows:

"The Scientific Research Institute of Automobiles and Transportation (NIIAT) developed the Russian emission models. These models are based on COPERT 4 model with some simplifications. COPERT (COmputer Programme to calculate Emissions from Road Transport) is an emission calculator developed by EMISIA SA for the European Environment Agency (EEA)."

We added the following text to the Supplement.

"We used the COPERT model to calculate emissions from on-road transport. COPERT (COmputer Programme to calculate Emissions from Road Transport) is an emission calculator developed by EMISIA SA for the European Environment Agency (EEA). The COPERT 4 methodology is part of the EMEP/EEA air pollutant emission inventory guidebook for the calculation of air pollutant emissions and is consistent with the 2006 IPCC Guidelines for the calculation of greenhouse gas emissions.

COPERT has been developed for official road transport emission inventory preparation in EEA member countries. It can be downloaded for free at http://emisia.com/copert

The Russian emission model was developed by the Scientific Research Institute of Automobiles and Transportation (NIIAT). The model is based on the COPERT 4 model with some simplifications.

The NIIAT methodology is designed to calculate emissions from on-road transport in urban conditions. The main provisions are harmonized with the European methodology. NIIAT provided copies of the methodologies. There is no software developed for the NIIAT methodology. We developed an Excel spreadsheet for emission calculations.

Table R1-1 provides additional details about the models.

Table R1-1. Inputs for NIIAT and COPERT models

Input	*NIIAT*	*COPERT*
Temperature	*Time of warming up (cold starts) depends on temperature*	*Min/max, monthly*
	NIIAT	*COPERT*
Length of trip, km		+
Warming time, min	+	…
Number of cold starts per day	+	- (calculated based on trip length)
Fleet (number of registered vehicles), vehicle types	+ (and ecological classes)	+ (and ecological classes)
Average annual mileage, km	+	+
Speed, km/h	-	+
Average temperature, Celsius	+/+-	+
Slope effect	-	+ (advance option)
Load effect	-	+ (advance option)
RVP (pressure)	-	+
Humidity, %	-	+
Fuel quality	-	+

We calculated BC emissions from on-road transport using 4 different approaches to test for sensitivity. First, we used the COPERT model to calculate BC emissions using default European emission factors (EF) for various types and Euro class vehicles. Then we substituted the default emission factors with specific Russian EF to reflect the specifics of the Russian fleet. We also cross-checked the results using the NIIAT methodology with Russian emissions factors. Finally, instead of using the vehicle count from video surveys, we used COPERT to calculated emissions from the entire registered vehicle fleet. This allows us to show that using the registry data significantly overestimates the emissions in the city."

Section 8, Uncertainty analysis, needs be expanded with more information about uncertainty calculation (equations), values of uncertainty (at least added in Table 5). Can the authors separate the uncertainties for activity and emission factors and create another table to show the values?

We used a summary analysis of BC uncertainty ranges for the EF's from the Bond et al. inventory.

Bond, T. C., Streets, D. G., Yarber, K. F., Nelson, S. M., Woo, J.-H., and Klimont, Z.: A technology-based global inventory of black and organic carbon emissions from combustion, Journal of Geophysical Research: Atmospheres, 109, 10.1029/2003jd003697, 2004.

Table 2. Emission factor uncertainty (%)

Source Category	Low/Mid, %	High/Mid, %
Mining	50	230
On-road transport	50	180
Construction	50	230
Agriculture	50	230
Locomotives	50	230
Diesel generators	50	230
Fishing	50	230

The algorithm for uncertainty calculations was adopted from:

IPCC: IPCC good practice guidance and uncertainty management in national greenhouse gas inventories, Institute for Global Environmental Strategies, Hayama, Japan, 4-88788-000-6, 2000.

We made the following changes to the Supplement:

"Uncertainty estimates include uncertainty in activity data - uncertainty in fuel use and existence of emission controls. Activity data uncertainty is based on expert judgments.
We used a summary analysis of BC uncertainty ranges for the BC emission factors from the Bond inventory (Bond et al (2004).

Table S18. Emission factors uncertainty (%)

Source Category	*Low/Mid, %*	*High/Mid, %*
Mining	*50*	*230*
On-road transport	*50*	*180*
Construction	*50*	*230*
Agriculture	*50*	*230*
Locomotives	*50*	*230*
Diesel generators	*50*	*230*
Fishing	*50*	*230*

The algorithm for uncertainty calculations was adopted from:
IPCC: IPCC good practice guidance and uncertainty management in national greenhouse gas inventories, Institute for Global Environmental Strategies, Hayama, Japan, 4-88788-000-6, 2000.

Activity data uncertainty (U activity) is a combination of uncertainty on emission controls (U controls) and uncertainty in fuel consumption (U fuel).

U activity = (U fuel^2 +U controls^2)$^{1/2}$

The relative uncertainty in the emission for each activity and fuel combination is calculated as the square root of the sum of squares of the relative uncertainties in both activity data and the emission factors. The absolute uncertainty in the emission of each activity and fuel combination is derived by multiplying the relative uncertainty with the emission value.

We built two estimates which show possible minimum and maximum BC emissions in Murmansk region. The minimum emissions estimate reflects possible lower fuel consumption and higher use of emission controls. This estimate also accounts the lower level of uncertainty in emission factors. The maximum emissions scenario assumes a possible increase in emissions due to large diesel consumption and lack of controls. Tables S19 and S20 show calculations of low/middle and high/middle relative uncertainty of the inventory.

Table S19. BC emissions uncertainty, low /middle estimate

Source Category	BC emissions (t)	Fuel use,%	Assumptions on control,%	Activity data uncertainty (%)	Emission factor uncertainty (%)	Combined relative uncertainty (%)	Absolute uncertainty, (t)
Mining	279.3	5	50	50.2	50	70.9	198.0
On-road transport	53.7	10	10	14.1	50	52.0	27.9
Construction	12.0	50	30	58.3	50	76.8	9.2
Agriculture	3.9	10	20	22.4	50	54.8	2.1
Locomotives	22.3	10	20	22.4	50	54.8	12.2
Diesel generators	27.1	50	100	111.8	50	122.5	33.2
Fishing	5.3	5	30	30.4	50	58.5	3.0
Total	403.7					195.06	203.31

Table S20. BC emissions uncertainty, high /middle estimate

Source Category	BC emissions (t)	Fuel use (%)	Assumptions on control (%)	Activity data uncertainty (%)	Emission factor uncertainty (%)	Combined relative uncertainty (%)	Absolute uncertainty, (t)
Mining	279.3	20	5	20.6	230	230.9	645.0
On-road transport	53.7	200	30	202.2	180	270.7	145.4
Construction	12.0	30	5	30.4	230	232.0	27.8
Agriculture	3.9	10	0	10.0	230	230.2	8.9
Locomotives	22.3	30	0	30.0	230	231.9	51.7
Diesel generators	27.1	20	0	20.0	230	230.9	62.6

Fishing	*5.1*	*200*	*0*	*200.0*	*230*	*304.8*	*15.6*
Total	*403.42*					*658.37*	*667.00*

The relative uncertainty in BC emissions in Murmansk region is from -50% to +165%.

Section 9, I think this section needs either to be deleted or to be expanded to show the details on how the emissions are estimated for different sources for whole Russia, including activities and emission factors. I would rather suggest the authors to use the space for more discussions to interpret the emission data estimated with their method, possibly more graphs in addition to Table 5. How would the results be compared with BC emission in other parts of the world? Would it be possible for the authors to shown how the estimated emission can be applied in models to further understand its contribution to the Arctic BC concentration and BC climate impact?

We have added an explanation of the rationale for this section and additional details on the calculations. We believe that this simple estimation of Russia-wide black carbon emissions from diesel sources is important for future research. Emissions mitigation policies, especially emission standards, should be adopted at the national level. We showed that off-road vehicles are a significant source of BC emissions in the country. By adopting PM emission standards for these vehicles Russia can significantly reduce BC emissions in the future.

<u>We made the following changes to the text</u>

"Table 6. Diesel consumption in Russia, 2010

Sector	*Diesel, thousand t*
Transport	
Road transport	*12 508*
Rail	*1444*
Other transport	*1051*
Industry	
Mining and quarrying	*1152*
Construction	*631*
other industry	*765*
Other sectors	
Agriculture/forestry	*2829*
Residential	*1357*
Commercial and public services	*1165*
Fishing	*351*
Total	*23 253*

Source (IEA, 2012)

We decided to use the IEA data for consistency but used NIIAT estimates for the distribution of diesel consumption by types of vehicles.

PM emission factor is 4 gkg^{-1} fuel for Euro 0 vehicles, 1.1 for Euro 1 and Euro 2 vehicles and 0.8 gkg^{-1} fuel for higher ecological classes. We estimated total PM emissions from on-road diesel vehicles in Russia in 2010 at 33 404 t. We applied the BC/PM ratios to determine BC emissions (EEA, 2013)."

"NIIAT fuel based emission factors are low compared to international practice. For example, Bond et al (2004) used fuel-based emission factor for the former Soviet Union region at 4.4 gPM kgfuel^{-1}.

As a result, we cross-checked our calculations with the EEA methodology using bulk emissions factors (EEA, 2013). Suggested bulk emission factors (gkg-1 fuel) for former Soviet Union countries are the following: 4.95 for cars, 4.67 for LCV, 2.64 for heavy-duty trucks and 2.15 for buses. The total emissions from on-road transport were 33 404 t of PM, 19 892 t of BC and 5968 t of OC. The difference in BC calculations using NIIAT and EEA approaches is 16%.

We also calculated emissions using the NIIAT bottom-up estimate of diesel consumption by on-road vehicles in Russian (17.3 million t). The total emissions from on-road transport would be 44 252 t of PM, 27 544 t of BC and 8263 t of OC.

Table 8 shows the results of BC emission calculations from all sectors.

Table 8. PM2.5, BC and OC emissions from diesel sources in Russia, 2010 (t)

Sector	PM2.5	BC	OC
Transport			
On-road	33 404	19 892	5968
Rail	2 079	1352	270
Other transport	4 530	2265	680
Industry			
Mining and quarrying	4091	2536	761
Construction	2718	1685	506
Other industry	3296	2043	613
Other sectors			
Agriculture/forestry	10 623	6055	1817
Residential	8142	5374	1075
Commercial and public services	6990	4613	923
Fishing	491	152	30
Total	76 364	45 967	12 641

The largest sources of diesel BC emissions in Russia in 2010 were on-road transport (43%), agriculture/forestry (13%) and residential sources (12%)".

MINOR COMMENTS

(1)The manuscripts need to be proofread with professional English as there are some grammatical errors. Some of the paragraphs are very difficult to understand at the first time of reading.
Accepted

(2) Page 3259, Line 1, the sentence is verbose and needs to be rephrased. I think the authors only need to say that "BC is a major component of PM 2.5".
Accepted

We have changed the text as follows:
"BC is a major component of $PM_{2.5}$"

(3) Page 3259, Line 25, how much higher? What is "older estimates"?

We have adjusted the text as follows:

"In Murmansk, we found that 12% of light-duty passenger vehicles used diesel, which is somewhat higher than older estimates Russia wide".

We will add that "The Russian company Avtostat estimated that the share of diesel cars driving in Russia in 2012 was 4%. The share of newly-sold diesel cars was 6%".

(4) The authors should be consistent to use Euro 4, Euro 5 or Euro IV, Euro V.
In the European methodology, by convention, light duty vehicles are marked with Arabic numerals while Roman numbers are used for heavy-duty vehicles (trucks and buses).

(5) Page 3261, Line 16, "we used similar methods to estimate organic carbon (OC) emissions". I don't think this sentence is necessary because OC emission is not discussed in the manuscript.
We did not discuss OC calculations in the text but in Table 5, page 3282 (now table 9) and a new table 8 contain the results of all emission calculations, including OC.

We have adjusted the text as follows:

Table 8. $PM_{2.5}$, BC and OC emissions from diesel sources in Russia, 2010 (t)

Sector	*$PM_{2.5}$*	*BC*	*OC*
Transport			
On-road	*33 404*	*19 892*	*5968*
Rail	*2079*	*1352*	*270*
Other transport	*4530*	*2265*	*680*
Industry			
Mining and quarrying	*4091*	*2536*	*761*
Construction	*2718*	*1685*	*506*
Other industry	*3296*	*2043*	*613*

Other sectors			
Agriculture/forestry	*10 623*	*6055*	*1817*
Residential	*8142*	*5374*	*1075*
Commercial and public services	*6990*	*4613*	*923*
Fishing	*491*	*152*	*30*
Total	*76 364*	*45 967*	*12 641*

Table 9. $PM_{2.5}$, BC and OC emissions in Murmansk Region, 2012 (t).

Activity	*$PM_{2.5}$*	*BC*	*OC*
On-road transport in Murmansk Region	*98.9*	*53.7*	*36.2*
Mines	*450.5*	*279.3*	*83.8*
Locomotives	*30.5*	*19.8*	*4.0*
Construction	*15.6*	*9.7*	*2.9*
Agriculture	*5.0*	*2.9*	*0.9*
Diesel generators	*52.8*	*34.8*	*7.0*
Ships (in Russian waters)	*13.4*	*4.2*	*0.8*
Total	*666.7*	*404.4*	*135.5*

(6) Page 3268, Line 20, what is the "EPA speciation ratio"?
The "EPA speciation ratio" is the EPA defined BC/PM ratio (0.77)
Source: EPA: Report to Congress on Black Carbon, US Environmental Protection Agency, Washington DC EPA-450/R-12-001,2012.

However, per the reviewer's suggestion, we applied EEA emission factors and BC/PM ratios.

<u>We have adjusted the text as follows:</u>

"The BC/PM ratio is 0.57 (EEA, 2013)."

"We thus estimated total PM emissions from agricultural equipment in Murmansk Region at 5.0 t of $PM_{2.5}$, 2.9 t of BC and 0.9 t of OC."

(7) Table S1, what does "adjusted data" mean?
Table S1. shows bottom–up calculations of fuel consumption by on-road diesel vehicles in Murmansk Region. We corrected the registry in two ways: 1) We applied the distribution by Euro class that we found in our parking lot surveys. 2) We also apply the ratio between registered and observed vehicles in the city to the registry in the region. We reduced the number of vehicles in the region to factor out vehicles that are not in use.

(8) References missing
a. Page 3258, line 24

Bond, T. C., and Sun, H.: Can Reducing Black Carbon Emissions Counteract Global Warming?, Environ. Sci. Technol., 39 (16), 2005

b. Page 3266, Line 24
<u>We have adjusted the text as follows:</u>
"The BC/PM ratio is 0.62 (EEA, 2013)".

c. Page 3267, Line 10 – 12
<u>We have adjusted the text as follows:</u>
"The speciation ratio for BC/$PM_{2.5}$ for locomotives is 0.65 (EEA, 2013)."

Authors’ comments on Review #2

RC C676: 'Review comments on "Black carbon emissions from Russian diesel sources" by M. Evans', Anonymous Referee #1, 12 Mar 2015

Black carbon emissions from Russian diesel sources: case study of Murmansk

M. Evans, N. Kholod, V. Malyshev, S. Tretyakova, E. Gusev, S. Yu, and A. Barinov

MAJOR COMMENTS

Comment 1. The analysis does not include emissions associated to military and commercial ships saying that this is sensitive data. I can understand this for military ships but I do not believe that data of commercial and passenger ships are very sensitive. There are several emissions inventories for harbors in different parts of the world. Therefore, I believe that on this aspect something more could be actually done also for Murmansk region.

Based on consultations with Russian and Murmansk officials in the early stage of the project, we understood that there were sensitivities regarding commercial activity at the port and around the Kola Peninsula. As a result, we decided to not include the emissions from commercial ships in the inventory.

However, information about port calls is publicly available and not sensitive. Therefore, per the reviewer’s request, we analyzed information about five wide categories of ships called into the Murmansk port in 2012: 1) fishing; 2) cargo ships (general cargo, bulk and container ships), 3) tankers; 4) passenger ships and 5) support ships (tugs, research ships and other vessels).

We have changed the text as follows:

“The Murmansk Port is the largest Russian port in the Arctic. We analyzed emissions from fishing vessels, various cargo ships, tankers, passenger ships and support ships. The activity data for ships are based on the Russian Information System on State Port Control (Murmansk Port, 2014).”

Other categories of ships called into the Murmansk port include various cargo ships (general cargo, bulk and container ships), tankers, passenger ships and support ships (tugs, research ships and other vessels). We used the same methodology for emission calculations as for fishing ships.

We assumed that passenger and support ships use diesel. However, cargo ships and tankers use both heavy marine oil and diesel. We assumed that these ships use diesel only for one hour per call while in the port. Table 5 shows the number of port calls and emissions from different ship types.

Table 5. PM and BC emissions from ships

Type	Number of port calls	PM emissions, t	BC emissions, t	OC emissions t
Fishing	1713	3.7	1.1	0.2
Small fishing boats	n/a	0.7	0.2	0.0
Cargo, all	604	3.1	1.0	0.2
Tankers	420	2.7	0.8	0.2
Support	203	2.2	0.7	0.1
Passenger	83	1.0	0.3	0.1
Total	3 042	13.4	4.2	0.8

The Supplement provides additional details about the ships in Murmansk Region.

We have added the following information t the Supplement:

The distribution of gross tonnage

Table S17. Tankers

Gross tonnage, t	Number of calls	Share, %
< 2000	27	6%
2000-4000	47	11%
4000-10000	7	2%
10000-20000	37	9%
20000-30000	108	26%
30000-40000	7	2%
40000-50000	171	41%
> 50000	16	4%
Total	420	100%

(Murmansk Port, 2014)

Table S18. Cargo ships

Gross tonnage, t	Number of calls	Share, %
< 2000	38	6.3%
2 000-4 000	128	21.2%
4 000-10 000	85	14.1%
10 000-20 000	120	19.9%
20 000-30 000	26	4.3%
30 000-40 000	87	14.4%
40 000-50 000	103	17.1%
> 50 000	17	2.8%
Total	604	100.0%

(Murmansk Port, 2014)

Table S19 Passenger ships

Gross tonnage, t	*Number of calls*	*Share, %*
< 3000	*7*	*8%*
4000-5000	*64*	*77%*
5000-10 000	*3*	*4%*
10 000 -15000	*3*	*4%*
15 000-20 000	*2*	*2%*
>20 000	*4*	*5%*
Total	*83*	*100%*

(Murmansk Port, 2014)

Comment 2. The emissions of road-transport calculated from the surveys are significantly different from those calculated by the registry of vehicles. It is reported that the registry has been somewhat corrected. Do you mean in terms of the total number of vehicles or in the fractions associated with the different categories (Cars, LDV, etc.) or in the emission quality (Euro 0, Euro 1 and so on). Probably it would be better to include this info in Table S5 (and/or S6) of the supplementary material.

We adjusted the registry in *two ways:*

1) *We applied the distribution by Euro class we found in the city to registered vehicles in the region.*
2) *We applied the ratio between registered and observed vehicles to estimate how much to adjust the total registry for actively emitting vehicles*

We have added the following text to the Supplement:

"The starting point in emission calculations is the analysis of the vehicle registry. Traffic police are responsible for registering all on-road vehicles in Russia. However, vehicle registries, particularly in countries where registries are out of date, are inadequate for emission calculations.

As a result, we decided to use a video survey method developed for IVE to study the traffic flows in Murmansk. The registry is outdated and shows many vehicles that are not in use anymore, mostly old, heavy-duty truck and buses. We compared data from the parking lot surveys with the vehicle registry and found that the differences are very significant. For example, the share of vehicles without emission controls (Euro 0) on the roads is much lower than is shown in the registry.

We adjusted the vehicles registry to correct the information about vehicle distribution by Euro class. For cars and LDV, we adjusted the information on Euro class distribution based on the parking lot surveys and data from a vehicle inspection station. For trucks and buses, we adjusted the numbers based on data from the largest bus company and other commercial vehicle companies."

Comment 3. It is not clear if these corrections were also applied to road-transport in Murmansk region (Table 5) because I believe that a similar overestimation will be present also at this level. Will it be possible to use the same correction factors for all the region?

We used the correction factors both in the city and the region.

We have added the following text to the Supplement 1.

"For emission calculations of vehicular emissions in Murmansk Region, we adjusted vehicle registry in two ways:

1) *We applied the distribution by Euro class that we found in the city to the registered vehicles in the region.*
2) *We applied the ratio between registered and observed vehicles to estimate how much to adjust the total registry for actively emitting vehicles."*

Comment 4. In table 3, the first three columns are from the surveys and the last one from the uncorrected registry. Is this right?

This is correct. We show the emission calculations using data from video surveys; they represent real emission in the city. We also show emissions calculations from uncorrected registry to show the discrepancy between emission estimates from different methods. Using unadjusted registry could significantly overestimate the emissions (by a factor of five). Researchers should be aware of this discrepancy to avoid overestimation of emissions from on-road vehicles.

To clarify in this in the text, we have adjusted the column headings:
added "based on surveys" to the first three columns and "uncorrected registry" to the last one.

5) Page 3274 (line 5 in Section 10). Please correct "form" with "from".

Thanks!

Black carbon emissions from Russian diesel sources: Case study of Murmansk

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Abstract

Black carbon (BC) is a potent pollutant because of its effects on climate change, ecosystems and human health. Black carbon has a particularly pronounced impact as a climate forcer in the Arctic because of its effect on snow albedo and cloud formation. We have estimated BC emissions from diesel sources in Murmansk Region and Murmansk City, the largest city in the world above the Arctic Circle. In this study we developed a detailed inventory of diesel sources including on-road vehicles, off-road transport (mining, locomotives, construction and agriculture), fishing and diesel generators. For on-road transport, we conducted several surveys to understand the vehicle fleet and driving patterns, and, for all sources, we also relied on publicly available local data sets and analysis. We calculated that BC emissions in Murmansk Region were 0.40 Gg in 2012. The mining industry is the largest source of BC emissions in the region, emitting ~~70~~69% of all BC emissions because of its large diesel consumption and absence of emissions controls. On-road vehicles are the second largest source emitting about 1~~2~~3% of emissions. Old heavy duty trucks are the major source of emissions. Emission controls on new vehicles limit total emissions from on-road transportation. Vehicle traffic and fleet surveys show that many of the older cars on the registry are lightly or never used. We also estimated that total BC emissions from diesel sources in Russia were ~~56.7~~50.8 Gg in 2010, and on-road transport contributed ~~55~~49% of diesel BC emissions. Agricultural machinery is also a significant source Russia-wide, in part because of the lack of controls on off-road vehicles.

1 Introduction

Black carbon (BC) is a potent pollutant, with a global warming potential 680 times that of CO_2 (on a 100 year basis) (Bond and Sun, 2005). It also contributes to adverse impacts on human health, ecosystems and air visibility. In particular, it is associated with respiratory and cardiovascular effects, as well as premature death. BC is the product of incomplete combustion, resulting in small, light-absorbing particles of 2.5 microns or less. ~~(or to state this in another way,~~ BC is a major component of $PM_{2.5}$~~)~~. Diesel and biomass combustion are both important global sources of BC and $PM_{2.5}$ emissions. Black carbon has a particularly pronounced impact as a climate forcer in the Arctic because of its effect on snow albedo and cloud formation (EPA, 2012).

This article provides a detailed inventory of BC emissions from diesel sources in Russia's Murmansk Region. Murmansk City is the largest city in the world above the Arctic Circle. Russian BC emissions are poorly understood in general (Stohl, 2013); this represents an important gap in our understanding of BC emissions and global BC forcing because Russia is by far the largest Arctic state in terms of territory. Bond et al (2004 and 2013) provide an overview of global emissions of black carbon and their forcing (Bond et al., 2004; Bond et al., 2013). The US Department of Agriculture estimates BC emissions from agricultural burning in Russia (USDA, 2012). McCarty et al (2012) estimate the range of average annual BC emissions from cropland burning in Russia at 8.90 Gg, based on agricultural statistics. Cheng (2014) estimates the likely geographic distribution of Russian black carbon emission sources.

Diesel is an important source of emissions globally, for example, the US EPA Report to Congress on Black Carbon indicates that nearly 50% of BC emissions in the United States came from mobile diesel engines in 2005 (EPA, 2012). Russia has several trends that affect its diesel consumption and emissions in the transport sector. Diesel is growing as a transportation fuel. Road traffic has grown rapidly in Russia in the past decade, linked to economic growth and growing demand for cars. The popularity of diesel light-duty vehicles has grown: many higher class or sports utility vehicles that perform well in snow rely on diesel. In Murmansk, we found that 12% of light-duty passenger vehicles used diesel, which is somewhat higher than older estimates Russia wide. The Russian company Avtostat estimated that the share of diesel cars driving in Russia in 2012 was 4%. The share of newly-sold diesel cars was 6%. Freight transport has also been growing in Russia. At the same time, Russia has European standards for limiting particulate emissions from on-road vehicles: currently, new or imported vehicles must be at least Euro 4. (In the European methodology, by convention, light duty vehicles are marked with Arabic numerals while Roman numbers are used for heavy-duty vehicles (trucks and buses). Euro 4 vehicle regulations require emissions that are 20–30 times lower than vehicles with no controls (e.g., Euro 0. In the past year, two of the largest bus companies in Murmansk Region began to upgrade their bus fleets, retiring old Euro 0 buses and replacing them with Euro IV and Euro V buses; our inventory base year (2012) predates this change.

Russia has also adopted European standards for fuel quality, which is important because emissions controls will not operate properly when diesel has high sulfur content. Russia has not introduced fuel quality standards as rapidly as its vehicle standards, so currently, three types of diesel are available on the market in Murmansk: Euro 3, 4 and 5. In 2013, Euro 5, with a maximum sulfur content of 10 ppm, accounted for 52% of Russian diesel production for the domestic market while the share of Euro 4 was 18% and Euro 3 was 26% (Novak, 2014).

Russia has no requirements for emission controls on off-road vehicles, so off-road vehicles, particularly in open-pit mines in Murmansk Region, represent a major source of black carbon emissions. While Russia has considered adopting European standards for off-road vehicles, it has not yet done so. At the same time, as with on-road transportation, we found evidence that some off-road vehicles in Russia exceed current requirements.

Regarding rail emissions, most Murmansk rail operates on electricity. Diesel locomotives operate in freight depots and within industrial facilities. Diesel locomotives in Murmansk do not appear to have controls. Likewise, we did not find evidence that diesel generators typically have controls, and there are no regulations requiring such controls.

We also assessed emissions from the large Murmansk fishing fleet. Despite the size of the fleet, it does not account for a large share of emissions in Murmansk Region. Most of the large fishing vessels registered in Murmansk rarely if ever call in to Murmansk Port, based on port registries.

By design and because of sensitivities and data availability, we did not include military consumption or consumption from commercial shipping in our analysis. The military likely represents an important source of consumption; commercial shipping, on the other hand, primarily relies on heavy fuel oil, not diesel, and most of the ships quickly leave Russian territorial waters.

The impact of regulations in reducing emissions is quite clear based on our analysis in Murmansk. Without regulation of vehicles and fuel, emissions would be substantially higher. Likewise, off-road vehicles and other sources would be significantly lower if emission controls were obligatory. For example, EPA calculates the effect of emission regulations of off-road vehicles in the US and estimates that BC emissions will decrease by 92% between 2005 and 2030 as a result of emission regulations (EPA, 2012).

2 Methodology

Our approach to estimating BC emissions involved combining fuel consumption and activity data with emission factors, which is consistent with the literature (Bond et al., 2004; Klimont et al., 2002; EPA, 2012; EEA, 2009, 2013; Streets et al., 2004). Since measured BC emission factors from Russian diesel sources are not available, we estimated BC emissions from PM emissions and then apply a speciation ratio to estimate BC emissions. We used similar methods to estimate organic carbon (OC) emissions.

Calculations of black carbon emissions from all sources (except on-road transport can be expressed by ~~the following~~ Eq.~~equation~~ 1 (EEA, 2009):

$$BC\ emisisons = fuel(kg) * PM\ emission\ factor\ (gkg^{-1}) * \frac{BC}{PM}\ ratio \qquad (1)$$

We applied different methodologies to different fuel combustion technologies.

The Scientific Research Institute of Automobiles and Transportation (NIIAT) developed the Russian emission models. These models are based on the COPERT 4 model with some simplifications. COPERT (COmputer Programme to calculate Emissions from Road Transport) is an emission calculator developed by EMISIA SA for the European Environment Agency (EEA).

Wherever possible, we used Russian methodologies or PM emission factors ~~for PM~~(NIIAT, 2008a, b); for example, we used both Russian and European emission factors to estimate emissions from on-road vehicles; the Russian methodologies included emission factors for the typical vehicle fleet on Russian roads.~~ (NIIAT, 2008a, b)~~, ~~though by international comparison,~~

~~some of the Russian cold start emission factors seemed quite low.~~ The COPERT model is the source for BC/PM ratios for on-road transport. COPERT model includes data for EC fractions of PM (f-EC) as well as OM/EC ratios. Additional detail on our methodology can be found in (Evans et al., 2012).

For ~~most~~ other sources, we used emission factors ~~from~~ and speciation ratios from EMEP/EEA Air Pollutant Emission Inventory Guidebook (Table 1). ~~the European Environment Agency (EEA, 2013).~~ We decided to use the European Monitoring and Evaluation Programme (EMEP) data for consistency. However, U.S. EPA has more rigorous procedure for determination of BC/PM ratios; EMEP is currently updating its emissions factors and speciation ratios.

Table 1. $PM_{2.5}$ emission factors and BC/PM ratios for diesel sources

Sector	$PM_{2.5}$, gkg^{-1}	Source	BC/PM	Source
Transport				
Rail	1.44	EEA, 1.A.3.c, Table 3.1.	0.65	EEA, 1.A.3.c, Table 3.1.
Other transport	4.31	EEA, 1.A.4., Table 3-2	0.5	EEA, 1.A.4., Table D.1
Industry				
Mining and quarrying	3.551	EEA, 1.A. 4., Table 3-2	0.62	EEA, 1.A.4., Table D.2
Construction	4.308	EEA, 1.A. 4., Table 3-2	0.62	EEA, 1.A.4., Table D.2
Other industry	4.308	Same as construction	0.62	EEA, 1.A.4., Table D.2
Other sectors				
Agriculture/forestry	3.755	EEA, 1.A. 4., Table 3-2	0.57	EEA, 1.A.4., Table D.2
Residential	6.0	Data from (Bond, 2004)	0.66	Data from (Bond, 2004)
Commercial and public services	6.0	Data from (Bond, 2004)	0.66	Data from (Bond, 2004)
Fishing	1.4	EEA, 1.A.3.d, Table 3-2	0.31	EEA, 1.A.3.d, Table 3-2
Fishing ($gkWh^{-1}$)	0.3	EEA, 1.A.3.d, Table 3-10	0.31	EEA, 1.A.3.d, Table 3-1

~~Additional detail on our methodology can be found in (Evans et al., 2012).~~

We collected detailed bottom up activity data from several sources, depending on the needs of the emission calculation methodology. We collected extensive primary data on road traffic in Murmansk (see Table 2 for details). The Supplement ~~1~~ provides additional details on several of these data sets.

Table 2. Main data sources on vehicle fleet and activity.

Type of Data	Description	Notes

Vehicle fleet	Basic registry information on each vehicle registered in Murmansk Region from Avtostat	We categorized the vehicles by make, model and age, and then assessed diesel use and ecological class based on manufacturer data of the models.
Passenger cars in use	Parking lot surveys at several locations throughout central and suburban Murmansk City	The surveys provided data on the vehicle models actually in use. We assessed the models for age and ecological class as we did with the Avtostat data.
Passenger cars in use and odometer readings	Database of vehicle inspection station on MSTU campus	This provided additional data on vehicles on the roads as well as their age and odometer readings (average km travelled per year).
Traffic intensity	Video surveys	MSTU conducted video surveys to count total traffic by vehicle type (cars, light-duty vehicles, buses and trucks) on different road categories in both central and suburban Murmansk City. Surveys covered different hours of the day.
Road categories and length	Municipal data on road categories and lengths	We used this data to help select road segments for the video surveys and to correlate the video survey data with the rest of the city roads by category.
Road speed and grade	GPS logger data	We used specialized GPS data loggers to track road speed by road type at different times of day. The loggers also provided data on road grade. In addition, we used data from the Yandex traffic service to assess road speed.

Regarding off-road vehicles, we used statistical data as well as public information from annual corporate reports and other public sources. For power generators, we received a detailed list of the largest off-grid diesel generators in Murmansk Region, and supplemented this with analysis comparing population centers with the power grid and statistics on fuel use. We also relied on regional statistical data about non-transport diesel consumption by different sectors of the economy. Regarding the ~~fishing~~ marine fleet, we used public data from Russian ship registries and port calls. We only counted the fraction of ~~fishing vessel~~ship emissions corresponding to the time the~~se vessels~~y spent in Russian territorial waters.

3 Analysis of fuel consumption in Murmansk Region

We reviewed the official statistical data on diesel consumption in Murmansk Region, which include annual summary data on consumption and stock changes by broad categories, and a breakdown of enterprise consumption for transport and non-transport needs organized by economic activity. The summary data from the Murmansk Statistical Office and the more detailed data from various sectors appear to have some methodological differences.~~, and t~~The summary data appear to include different categories across different years, causing major swings in the total reported fuel use. For example, the Murmansk Statistical Office reports diesel consumption at 391 900 t in 2012 while the total diesel consumption was 599 120 t in 2011. The official statistical data also includes bunker fuel for marine transport. The Murmansk Statistical Office reports that ~~marine transport~~fishing ships consumed 68 300 t. Our bottom-up calculations show that fishing ships consumed only 3 000 t while in Russian territorial waters.

Because of these factors, we also estimated consumption by sector using bottom up calculations where possible. Except in the case of mines, statistical data were significantly different from our bottom-up estimates.

In Table ~~1~~3 below, we provide ~~a~~our consolidated estimate of diesel use in Murmansk Region in 2012.

Table ~~1~~3. Estimated diesel consumption by sector in Murmansk Region, 2012.

Activity	Diesel use (t)
On-road transport *	65 100
Mines	139 000
Locomotives	21 200
Construction	4 100
Agriculture	1 300

Diesel generators, including:	8 800
Small generators for commerce and services *	7 100
Off-grid generators *	1 700
Fishing (in Russian territorial waters), including:	3 000
Large and medium vessels*	2 500
Small boats *	500
Total	**242 500**

* - bottom up calculations. The other numbers come from regional statistics. This table does not consider marine shipping and military fuel use.

The Supplement provides more details: Table S.1 provides additional details on our bottom-up fuel calculation for on-road transport; Table S.9 highlights these calculations for mines, and tables S.16 and S.~~17~~20 estimate fuel use for fishing and diesel generators, respectively.

4 On-road transport in Murmansk

4.1 Activity data

On-road transportation is one of the largest sources of black carbon emissions in the region; it also appears to be the largest diesel source in Russia as a whole. We conducted detailed surveys and data collection related to the vehicle fleet, traffic and vehicle use in assessing on-road transport emissions. Russia does not have detailed, published data on road traffic by vehicle type and class, and most Russian transportation experts believe that vehicle registries include some vehicles that are not used or used only lightly. As a result, we used multiple sources to study on-road transport in Murmansk and the region. Table ~~2~~3 highlights our surveys and data sources.

Table 2. Main data sources on vehicle fleet and activity.

Type of Data	Description	Notes
Vehicle fleet	Basic registry information on each vehicle registered in Murmansk Region from Avtostat	We categorized the vehicles by make, model and age, and then assessed diesel use and ecological class based on manufacturer data of the models.
Passenger cars in use	Parking lot surveys at several locations throughout central and suburban Murmansk City	The surveys provided data on the vehicle models actually in use. We assessed the models for age and ecological class as we did with the Avtostat data.
Passenger cars in use and odometer readings	Database of vehicle inspection station on MSTU campus	This provided additional data on vehicles on the roads as well as their age and odometer readings (average km travelled per year).
Traffic intensity	Video surveys	MSTU conducted video surveys to count total traffic by vehicle type (cars, light-duty vehicles, buses and trucks) on different road categories in both central and suburban Murmansk City. Surveys covered different hours of the day.
Road categories and length	Municipal data on road categories and lengths	We used this data to help select road segments for the video surveys and to correlate the video survey data with the rest of the city roads by category.
Road speed and grade	GPS logger data	We used specialized GPS data loggers to track road speed by road type at different times of day. The loggers also provided data on road grade. In addition, we used data from the Yandex traffic service to assess road speed.

The Supplement provides additional details on several of these data sets.

Murmansk City had 16 400 diesel vehicles registered in 2012, while in Murmansk Region, there are 45 600 diesel vehicles registered. The registry showed that 45% of all cars and other light duty vehicles (LDVs), 62% of trucks and 75% of buses are likely Euro 0, based on their age. Passenger cars in general are much newer and cleaner than buses or trucks. Based on parking lot surveys of 2235 cars, we found that on average, 12% of the passenger cars in Murmansk run on diesel, which is higher than the Russian average. The average age of diesel passenger cars in Murmansk City is 5.6 years.

We relied on several data sources to assess average annual mileage for passenger cars; NIIAT provided estimates for average annual mileage of other vehicle types. We used our video survey data to estimate average annual daily traffic (AADT), and then multiplied this by the kilometers of road by road category to estimate vehicle-kilometers traveled (VKT) in the city.

~~We used these calculated metrics along with our other data in estimating emissions in the NIIAT methodology for large cities. In COPERT, we compared VKT to average kilometers traveled by different vehicle classes to estimate the total fleet appearing on the roads.~~ We also adjusted the regional registry using the ratio between registered and observed vehicles obtained in Murmansk City. We estimated there were 14 500 diesel cars, 2 600 LDVs, 3 900 trucks and 260 buses used in the region.

4.2 Emissions Estimates

We used several methodologies to estimate emissions in the city and the region. We reviewed several Russian methodologies, including two prepared by the Scientific Research Institute for Automobile Transport (NIIAT, 2008a, b), as well as the European Environmental Agency methodology, COPERT (Emisia, 2011). The NIIAT methodologies use Russian-specific emission factors for $PM_{2.5}$ based on the average fleet of vehicles of each ecological class on Russian roads. At the same time, the Russian methodologies have much lower emission factors for cold starts in small vehicles than other international methodologies. While some Russian drivers warm their cars before they begin driving, which reduces emissions from cold starts, without survey data measuring cold start emissions more precisely, we decided it would be more consistent with inventories elsewhere to use European emission factors for cold starts, particularly given the cold Russian climate.

First, we used the COPERT model to calculate BC emissions using default European emission factors for various types and Euro class vehicles. Then we substituted the default emission factors with specific Russian emission factors to reflect the specifics of the Russian fleet.

~~Thus, we used COPERT with Russian emission factors for the hot operation stage to reflect the Russian vehicle fleet~~. Figure 1 summarizes our emission estimates by vehicle type using COPERT with Russian emission factors.

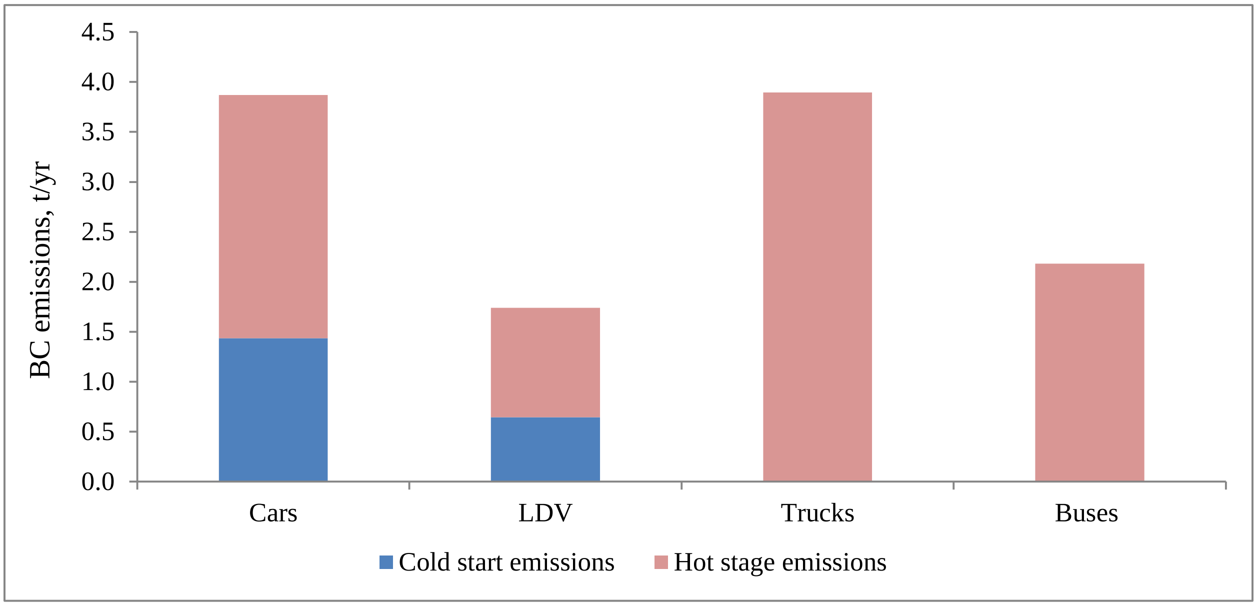

Fig. 1**.** Cold start and hot stage BC emissions in Murmansk City by vehicle type (~~in~~ t).

Figure 2 shows the percentage split of emissions between Euro classes for each vehicle type. The majority of emissions come from Euro 0 vehicles, in particular Euro 0 trucks. Cold starts also play an important role. Among passenger cars and other light-duty vehicles, 37% of total black carbon emissions come from cold starts.

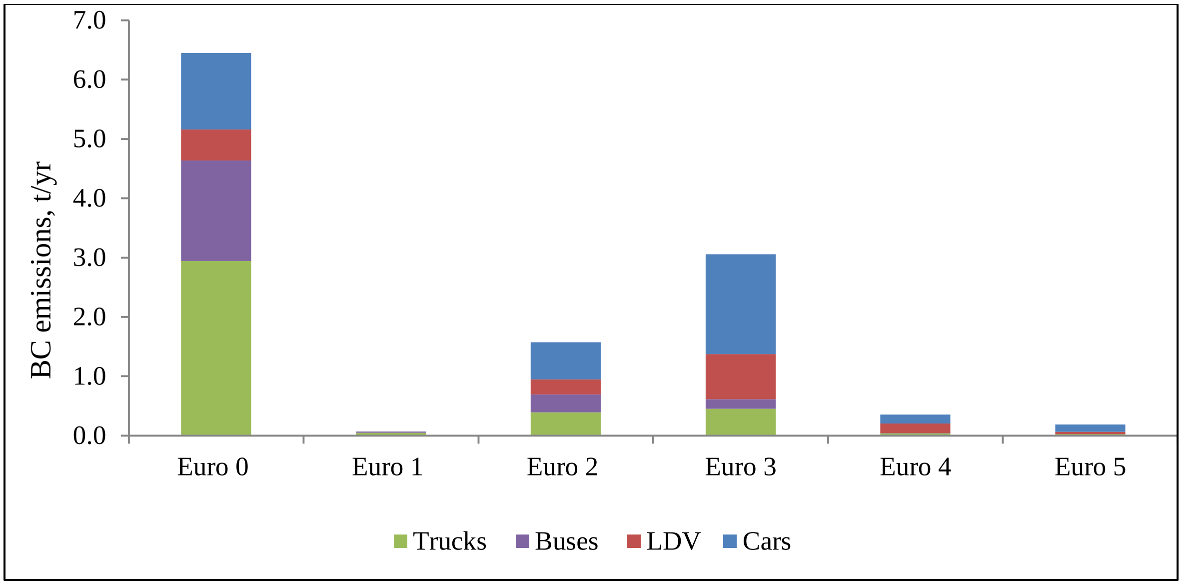

Fig. 2. BC emissions in Murmansk City by ecological class and vehicle type (t).

As a cross-check, we also calculated emissions with the Russian methodologies. We used the NIIAT methodology for large cities. We also used the NIIAT universal methodology, which factors in low usage of registered vehicles in Russia in its formulas. We also cross-checked the results using the NIIAT methodology with Russian emissions factors. Finally, instead of using the vehicle count from video surveys, we used COPERT to calculated emissions from the entire registered vehicle fleet in Murmansk City. This allows us to show that using the registry data significantly overestimates the emissions in the city.

Table 43 presents a summary of total vehicle emissions in the city using each of the methodologies Supplement Table S5 provides aAdditional details on the emissions calculations are available in Supplement Table S5.

Table ~~3~~4. BC emissions in Murmansk City from on-road transport, different methodologies, t yr^{-1}.

	COPERT with NIIAT EFs (based on surveys)	NIIAT universal (based on surveys)	NIIAT for large cities (based on surveys)	COPERT with NIIAT EFs (~~full~~ uncorrected registry)
Cars	3.9	2.5	3.0	6.1
LDV	1.7	1.1	1.1	14.4
Trucks	3.9	3.9	2.7	28.7
Buses	2.2	2.2	1.0	5.7
Total	**11.7**	**9.7**	**7.8**	**54.9**

The results in Table ~~3~~4 clearly show that one should be very careful in using registry data for emission estimates. The difference between estimated emissions from the observed fleet is 4.7 times smaller than the potential emissions from the fleet of all registered vehicles, as the Russian vehicle registries likely contain many vehicles not actually in use.

We also calculated total road transport emissions in Murmansk Region using the NIIAT universal methodology (NIIAT, 2008). This methodology is simpler and designed for use with limited vehicle activity data; estimating emissions at the regional level provides a snapshot of the relative weight of different black carbon emission sources in the region. At the same time, we recognize that this is an approximate estimate and may, for example, underestimate emissions from cold starts and overestimate driving by older, Euro 0 vehicles. We found total road transport emissions in the region to be 98.9 t of $PM_{2.5}$ and 53.7 t of BC (Supplement Table S6).

5 Off-road transport

5.1 Mines

The mining industry is an economic backbone in Murmansk Region. It accounts for about 40% of the region’s industrial output. The region produces 100% of Russian apatite, nepheline and brazilite, 45% of nickel and 11% of iron ore.

The mining industry is by far the largest industrial consumer of diesel in Murmansk Region. According to official statistical data, mining companies in the region consumed 139 000 t of diesel in 2012. The largest mines in Murmansk Region are Apatite Joint Stock Company, Kovdorskiy GOK, Olenegorskiy GOK and Kolskaya GMK (Supplement Table S9).

Most of the companies operate open-pit mines; large, haul trucks and mining equipment are the major diesel consumers. The Belarusian automaker BELAZ supplies the majority of the largest trucks, i.e., those with a payload capacity over 100 t. Most BELAZ trucks are equipped with Cummins and MTU engines. Table S.10 shows the technical characteristics of BELAZ trucks. Recently, mining enterprises have been purchasing more foreign-made trucks, and mines have been gradually replacing the older BELAZ models with Caterpillar and Komatsu trucks. Nevertheless, BELAZ trucks still constitute 70% of the Russian mining fleet (Petrovich et al., 2013).

Mining operations continue nonstop and on average each truck operates well over 6300 h per year (Mining Magazine, 2007). There is no official data on the number of mining trucks in Murmansk Region. Using information from individual mines, we estimated that there are no less than 250 mining trucks. In addition to dump trucks, mines operate a wide range of machinery, including excavators, bulldozers, loaders, drilling equipment and other machinery. On average, excavators and bulldozers operate 7 270 and 6660 hours per year, respectively. The mines also use supplementary, smaller on-road trucks with payloads from 13 to 45 t.

Statistical data in the region indicate that mining companies consumed 139 013 t of diesel fuel in 2012. We also cross-checked this data through bottom-up estimates of fuel use in the largest mines. The results of cross-checking showed that the statistical data and bottom-up calculations match closely (with a difference of less than 1%).

Russia does not have emission regulations for off-road vehicles but often uses foreign-made, off-road vehicles and equipment. Thus, we have used both US EPA and European Environment Agency information about emission requirements for off-road vehicles. Table S 7 shows PM emission requirements in the US and Europe.

The extent of controls is one of the important uncertainties regarding emission estimates from the mining sector. Since there are no emission control requirements, the mining vehicles may not meet even Tier 1 requirements. Based on information from Cummins, 88% of the large, Cummins-powered, BELAZ mining trucks have no controls on their engine exhaust and the remaining 12% meet EPA Tier 1 requirements (Mueller, 2014). A smaller population of Caterpillar and Komatsu trucks meets Tier 1 or Tier 2 requirements. (Supplement Table S11).

The $PM_{2.5}$ emission factor for off-road, industrial mobile sources and machinery without emission controls is 3.551 gkg^{-1} fuel and the emission factor for equipment with some controls is 0.967 gkg^{-1} fuel. The BC/PM ratio is 0.62 (EEA, 2013).

We estimated that $PM_{2.5}$ emissions in the mining industry in Murmansk Region are 450.5 t per year. ~~The speciation BC/PM ratio is 0.62.~~ Total BC and OC emissions in the mining industry in Murmansk Region estimated to be 279.3 t and 83.8 t per year, respectively.

5.2 Locomotives

Diesel locomotives are only in limited use in Murmansk Region because all the main railroads are electrified. According to data from the Murmansk statistical office, diesel locomotives at the Murmansk branch of Russian Railways consumed 21 200 t of diesel in 2012 (GSK, 2012).

Diesel locomotives in Russia do not have any emission controls. Some of the locomotives in Murmansk Region are more than 30 years old. Since we have limited information on the activity of the small line haul and switch locomotives, the only way to estimate BC emissions is to use the fuel consumption method.

The emission factor for $PM_{2.5}$ of switch locomotives is 1.44 gkg^{-1} of fuel. The speciation ratio for $BC/PM_{2.5}$ for locomotives is 0.~~73~~65 (EEA, 2013). Thus, locomotives in Murmansk Region emitted 30.5 t of $PM_{2.5}$, including ~~22.3~~ 19.8 t of BC and 4.~~5~~0 t of OC.

5.3 Construction and road management

This sector includes building construction and road management. According to official statistics, the building construction industry used 3 205 t of diesel. ~~and r~~Road management companies used 865 t of diesel fuel for off-road vehicles, machinery and equipment~~ in 2012~~.

Building construction is stagnant in Murmansk Region. The region's population is declining and the formerly powerful construction industry is deteriorating. The vast majority of equipment in the construction industry is very old. There are over 1800 pieces of equipment and more than 50% of equipment and machinery need replacement (see Supplement Table S12 for details). We assume that 90% of equipment has no emission controls and 10% has some controls.

We used EMEP-EEA emission factors (EEA, 2013) for off-road vehicles in the construction industry, e.g. 4.038 $gPM_{2.5}kg^{-1}$ fuel for vehicles without controls and 0.967 gkg^{-1} fuel for equipment with some controls. The BC/PM ratio for construction is 0.62. Hence, off-road building construction vehicles in Murmansk Region emitted 12.7 t of $PM_{2.5}$, ~~9.8~~7.9 t of BC and ~~2.0~~1.6 t of OC.

The road management sector includes minor road reconstruction and snow removal. Murmansk City is located on the shore of the Barents Sea and the level of precipitation is quite high. On average, there is snow on the ground 180–200 days per year. The snow removal fleet was significantly updated recently with Russian-made, multifunctional vehicles and off-road vehicles, including new tractors and graders, do not have any emission controls.

Similarly to construction, we have to exclude on-road vehicles from the emission calculations. The emission factor for off-road machinery without emission controls in this sector is 3.551 $gPM_{2.5}kg^{-1}$ fuel and the BC/PM ratio is 0.62 (EEA, 2013). Off-road vehicles in this sector in Murmansk Region emitted 2.8 t of $PM_{2.5}$, ~~2.2~~1.7 t BC and 0.4 t OC.

Total emissions from off-road vehicles and equipment in building construction and road management sector were 15.6 t of $PM_{2.5}$, ~~12.0~~9.7 t BC and 2.~~4~~09 t OC.

5.4 Agriculture

Over 90% of Murmansk Region lies above the Arctic Circle and agriculture is not well developed. The agricultural machinery in the region is Russian-made with a small fraction of foreign-made equipment; 62% of agricultural machinery is older than 10 years.

According to regional statistics agricultural enterprises in Murmansk Region consumed 1344 t of diesel in 2012. The emission factor for agricultural equipment without emission controls is 3.755 $gPM_{2.5}kg^{-1}$ fuel assuming no controls and -the BC/PM ~~speciation~~ ratio is 0.57 (EEA, 2013). We thus estimated total PM emissions from agricultural equipment in Murmansk Region at 5.~~1~~0 t of $PM_{2.5}$, 2.9 t of BC and 0.~~6~~9 t of OC. ~~Using EPA speciation ratio (EPA, 2012), emissions from agricultural equipment in Murmansk region in 2012 estimated to be 3.9 t of BC and 0.8 t of OC.~~

6 Fishing and marine transport

The Murmansk Port is the largest Russian port in the Arctic. We analyzed emissions from fishing vessels, various cargo ships, tankers, passenger ships and support ships.

The activity data for ships are based on the Russian Information System on State Port Control (Murmansk Port, 2014). We obtained information about diesel engine capacity from the Russian Maritime Register of Shipping (The Russian Maritime Register of Shipping, 2014). The Murmansk ~~Fishing~~ Port is located 22 nautical miles from the open sea and we analyzed emissions from the port to the edge of ~~the~~ Russian territorial waters (~~a~~ further 12 miles out to sea). We assume that it takes 7 hours to get from the port to the edge of the territorial waters.

Fishing is an important part of Murmansk's economy. The fishing industry in Murmansk Region provides 16% of Russia's total fish catch. Fishing companies in Murmansk Region operate mainly in nearby international waters (62% of the catch). Only a quarter of the catch occurs in Russian 12 mile territorial waters (Committee for the Fishery Complex of Murmansk Region, 2013).

The fishing fleet in Murmansk Region consists of 226 sea vessels (2012) or 76% of all civilian vessels in the Russian Arctic. The average age of the vessels is 26 years old. (See Supplement Tables S13-S14 for details).

In addition to large and medium ocean-going vessels, there are around 100 small vessels for off-shore fishing. All this fish catch from these small vessels was brought into ports in Murmansk Region.

It is very difficult to estimate the fuel consumption in the fishing industry. The official statistics shows that fishing companies consumed 68 289 t of diesel in 2012. However, there are several challenges with this data. First, Russian fishing vessels buy and consume the majority of their fuel outside of Russia and Russian territorial waters. Second, companies may have an incentive to overreport fuel consumption, possibly to increase their reported costs. As a result, we provide a bottom up estimate of fuel consumption in the Russian waters for fishing.

We calculated fuel use and BC emissions in Murmansk based on the port calls for large and medium fishing vessels and, for small vessels, our estimates draw on the reported number of small fishing boats and local expert judgment on their operations.

Large and medium fishing vessels called into the Murmansk Fishing Port 1713 times in 2012, according to the Russian Information System on State Port Control (Murmansk Fishing Port, 2014).

~~We obtained information about diesel engine capacity from the Russian Maritime Register of Shipping (The Russian Maritime Register of Shipping, 2014).~~ Using the information about the installed power capacity, engine load and time travelled, we calculated PM emissions within Russian territorial waters from fishing vessels. ~~applied~~ PM emission factor is ~~of~~ ~~1.4~~0.3 $gkWh^{-1}$

and the BC/PM ratio is 0.31 (EEA, 2013) to ~~calculate PM emissions within Russian territorial waters from fishing vessels.~~ We assumed that all fishing vessels use diesel (According to the EEA emissions inventory guidebook, only 3.8% of fishing vessels use both diesel and bunker fuel oil). We estimate that these large and medium fishing vessels emitted 3.7 t of PM and ~~4.3~~1.1 t of BC. ~~and 0.9 t of OC in 2012~~.

In addition, there are about 100 small fishing ships. Detailed registries and other data about installed engine capacity and hours of operation are not available. ~~, so i~~In consultation with local fishing and marine experts, we assumed that the average engine capacity is 50 kW, engine load is 60%, the boats sail 800 hours per year. The total BC emissions by small fishing boats were 0.88~~40~~ ~~kg~~ t per year.

Total ~~BC~~ emissions from all types of fishing vessels in Murmansk Region ~~territorial waters~~ were 6.4 ~~5117~~ ~~kg~~t of PM and 2.0 t of BC.

We also prepared bottom-up estimates of fuel use, based on information about rated engine power, hours of operation and specific fuel consumption (g fuel kWh^{-1}). The specific fuel consumption is 203 g diesel kWh^{-1} (EEA, 2013). The fuel consumption by large and medium ships during their travel within Russian territorial waters is 2481 t per year (Supplement table S16 ~~shows~~provides additional details). The fuel consumption by small boats is 487 t yr^{-1}.

Other categories of ships calling into the Murmansk port include various cargo ships (general cargo, bulk and container ships), tankers, passenger ships and support ships (tugs, research ships and other vessels). We used the same methodology for emission calculations as for fishing ships.

We assumed that passenger and support ships use diesel. However, cargo ships and tankers use heavy marine oil and diesel. We assumed that these ships use diesel only for one hour per call while in the port. Table 5 shows the number of port calls and emissions from ships in Russian territorial waters.

Table 5. Number of port calls and emissions from ships

Type	Number of port calls	PM emissions, t	BC emissions, t	OC emissions t
Fishing	1713	3.7	1.1	0.2
Small fishing boats	n/a	0.7	0.2	0.0
Cargo, all	604	3.1	1.0	0.2
Tankers	420	2.7	0.8	0.2

Support	203	2.2	0.7	0.1
Passenger	83	1.0	0.3	0.1
Total	3 042	13.4	4.2	0.8

Source: (Murmansk Port, 2014)

The Supplement ~~2~~ provides additional details about the ships in the Murmansk Port.

7 Diesel generators

We found several types of diesel generators and heaters in Murmansk Region. The largest category in terms of fuel use and emissions is generators and heaters that small market shops and service providers operate in settled areas. The next largest category includes off-grid generators that operate for a large portion of the year, typically up to 12 h a day.

We found the least data for the very small generators and heaters used in commerce and services – the government does not appear to regulate or keep statistics on these small generators. The data quality regarding diesel generators is very low and the uncertainty is very high. In total, government statistics show that non-transport diesel use from these sectors was 7100 t in 2012. We also verified the existence of such generators by looking at the number of dealers selling diesel generators in Murmansk. With ~~an~~ the emission factor for diesel generators of ~~4~~6.0 g PM kg^{-1} fuel ~~use~~ and ~~a~~ BC/PM ratio of 0.~~74~~66 for this category (Bond et al, 2004), we assumed that such small generators and heaters emitted 42.6 t of PM, ~~21.0~~ 28.1 t of BC and ~~4.2~~ 5.6 t OC in 2012.

Regarding off-grid generators, it is important to note that the majority of Murmansk Region's urban and rural energy consumers receive their power from the Kola Power Grid. Several dozen settlements in the region lack access to centralized electricity supply, due to their remote locations; instead they rely on diesel generators (Minin, 2012). The largest villages without centralized electricity supply receive diesel subsidies. Supplement Table S~~17~~20 shows the capacity of these subsidized diesel generators and their annual fuel consumption. In total, according to the Development Strategy for Energy Savings in Murmansk Region, there were 80 settlements without centralized electricity supply in 2009. About 150 village diesel generators with a total capacity of 3.8 MW provided electricity to these settlements (Government of Murmansk Region, 2009). We used information about fuel consumption and power capacity of generators with subsidized fuel and proportionally calculated the possible total fuel consumption by this category of generators. Using bottom-up calculations, we estimated that off-grid generators consume 1700 t of diesel per year. We further estimate that off-grid generators in Murmansk Region emitted 10.2 t of PM, ~~5.2~~6.7 t of BC and 1.~~0~~3 t of OC.~~ in 2012.~~

The total ~~BC~~ emissions from diesel generators in the region estimated to be ~~26.3~~52.8 t of PM, 34.8 t of BC and 7.0 t of OC ~~emissions were 5.3 t~~.

8 Uncertainty analysis

Uncertainties exist in emission factors, activity data and emission controls; we used multiple approaches to estimate and reduce uncertainties of the BC emissions inventory. This could help us validate the inventory estimates, choose appropriate methodological approaches and improve the accuracy of the results (IPCC, 2006). This could also help peer reviewers understand the reliability of our inventory estimates. We used five methods to assess and minimize uncertainties (EEA, 2013; IPCC, 2006, 2000), including:

- Multiple approaches to collecting and validating activity data;
- Literature and other documented data for cross-checks;
- Cross-checks of bottom-up activity data and fuel allocation;
- Error propagation; and
- Expert judgment.

We derived aggregate uncertainties of the emissions inventory based on the error propagation method. We combined uncertainties of emission factor and activity data by source category, and then combined uncertainties by source category to estimate overall uncertainty of the inventory (IPCC, 2006). For emission factors, we use uncertainties from Bond inventory (Bond, 2004) (Supplement Table S18)~~and confidence intervals reported by previous studies (e.g. emission factors from EPA, EEA, Russian methodologies and journal articles)~~. Uncertainties in activity data are primarily assessed based on expert judgment.

The relative uncertainty in the emission for each activity and fuel combination is calculated as the square root of the sum of squares of the relative uncertainties in both activity data and the emission factors. The absolute uncertainty in the emission of each activity and fuel combination is derived by multiplying the relative uncertainty with the emission value. The relative uncertainty in BC emissions in Murmansk region is from -50% to +165%.

For major sources of BC emissions, we also used cross-checks to assess sectoral uncertainties. For on-road emissions~~, we checked our results against multiple methodologies, and~~we found ~~there~~that there is a 19% difference between estimated emissions from COPERT with NIIAT emission factors and COPERT with COPERT emission factors.

The largest uncertainty in mining lies in assumptions on emission controls and fuel use (Supplement Table S19 and S20). ~~Uncertainty in emissions from mining vehicles appears to be the greatest.~~ Uncertainty about Tier distribution could significantly change the results of our emissions calculation given the significant fuel consumption in the mining industry.

9 Simple estimate of Russian diesel emissions

According to IEA data, Russia consumed 23.3 million t of diesel in 2010 (IEA, 2012). On-road transport accounted for 12.~~7~~5 million t of diesel, while agriculture and forestry consumed an additional 2.8 million t and industry 2.6 million t of diesel. All other sectors combined consumed an additional 2.9 million t of fuel (Table 6).

Table 6. Diesel consumption in Russia, 2010

Sector	Diesel, thousand t
Transport	
Road transport	12 508
Rail	1444
Other transport	1051
Industry	
Mining and quarrying	1152
Construction	631
other industry	765
Other sectors	
Agriculture/forestry	2829
Residential	1357
Commercial and public services	1165
Fishing	351
Total	23 253

Source (IEA, 2012)

Since on-road transport is the largest consumer of diesel, we conducted a more detailed analysis of BC emissions by on-road vehicles. We simply applied fuel-based emission factors to all other sectors.

According to the Federal State Statistics Service of the Russian Federation, there were 5 181 200 diesel vehicles in Russia in 2010. NIIAT conducted bottom-up calculations of fuel consumption by on-road vehicles in Russia and estimated it at 17.3 million t per year. We decided to use the IEA data for consistency but used NIIAT estimates for the distribution of diesel consumption by types of vehicles. Supplement Table ~~S20~~ S21 shows fuels consumption by different types of vehicles and Supplement Table S22~~1~~5 shows diesel fleet distribution by ecological class based on NIIAT estimates. ~~We used these estimates to calculate BC emissions from on-road transport; for all other sectors we used IEA data~~.

We calculated PM emissions by using NIIAT fuel-based emissions factors (NIIAT, 2008). The PM emission factor is 4 gkg^{-1} fuel for Euro 0 vehicles, 1.1 for Euro 1 and Euro 2 vehicles and 0.8 gkg^{-1} fuel for higher ecological classes. We estimated total PM emissions from on-road diesel vehicles in Russia in 2010 at 31 001 t. We applied the BC/PM ratios to determine BC emissions (EEA, 2013). Table 7 shows the results of the BC emissions calculations from on-road diesel vehicles in Russia in 2010.

~~and applied the BC/PM speciation ratio (EPA, 2012) to determine BC emissions. Table 4 shows the results of the BC emissions calculations from on-road diesel vehicles in Russia in 2012.~~

Table ~~4~~7. BC emissions from on-road diesel vehicles in Russia in 2010, t.

~~Ecological class / Vehicle type~~	~~Euro 0~~	~~Euro 1~~	~~Euro 2~~	~~Euro 3 and higher~~
~~Cars~~	~~203~~	~~0~~	~~62~~	~~365~~
~~Trucks~~	~~21,203~~	~~1,029~~	~~2,287~~	~~1,871~~
~~Buses~~	~~2,973~~	~~245~~	~~511~~	~~368~~

	Euro 0	Euro 1	Euro 2	Euro 3+	Total
Cars	533	8	82	138	762

Trucks	10 347	653	1 451	1 278	13 728
Buses	1 451	156	324	251	2 182
Total	12 331	817	1 857	1 668	16 672

We estimated total BC emissions from on-road diesel vehicles in Russia ~~in 2010~~ at ~~31 117~~ 16 670 t ~~-~~in 2010. ~~and total OC emissions at 4,588 t.~~ The vast majority of BC emissions (6~~8~~2%) came from Euro 0 trucks.

NIIAT fuel based emission factors are low comparing to international practice. For example, Bond et al (2004) used fuel-based emission factor for the former Soviet Union region at 4.4 gPM $kgfuel^{-1}$.

As a result, we ~~We~~ cross-checked ~~this result~~our calculations with the EEA methodology using bulk emissions factors (EEA, 2013). ~~The total BC emissions are 34 226 t (the difference is 9%).~~ ~~Suggested~~EEA bulk emission factors (gkg^{-1} fuel) for former Soviet Union countries are ~~the following~~as follows: 4.95 for cars, 4.67 for LCV, 2.64 for heavy-duty trucks and 2.15 for buses. The total emissions from on-road transport were 33 404 t of PM, 19 892 t of BC and 5 968 t of OC. The difference in BC calculations using NIIAT and EEA approaches is 16%.

As we mentioned above, the choice of BC/PM ratios can change the results of emission calculations. For example, if we use the EPA speciation ratio (0.74) for on-road transport, BC emissions in Russia would be 24 719 t, or 24% higher.

These results are similar to those presented in the EPA Report to Congress on Black Carbon (EPA, 2012). According to EPA estimates, BC emissions from transport (including aircrafts and marine shipping) in Russia were 32 Gg in 2000.

Table 8 shows the results of emission calculations from other diesel sources.

Table 8. $PM_{2.5}$, BC and OC emissions from diesel sources in Russia, 2010 (t)

Sector	$PM_{2.5}$	BC	OC
Transport			
On-road	33 404	19 892	5968
Rail	2079	1352	270
Other transport	4530	2265	680
Industry			
Mining and quarrying	4091	2536	761
Construction	2718	1685	506

Other industry	3296	2043	613
Other sectors			
Agriculture/forestry	10623	6055	1817
Residential	8142	5374	1075
Commercial and public services	6990	4613	923
Fishing	491	152	30
Total	76 364	45 967	12 641

The largest sources of diesel BC emissions in Russia in 2010 were on-road transport (43%), agriculture/forestry (13%) and residential sources (12%).

~~BC emissions from diesel sources in agriculture and forestry were 8180 t, industrial emissions were 5610 t (including 2536 t from mining) and while emissions from other sectors combined were 11 818 t. We estimated total BC emissions in Russia from diesel combustion at 56 726 t (56.7 Gg) in 2010.~~

10 Conclusions

We conducted a detailed, bottom-up assessment of emissions from diesel combustion in Murmansk Region, based on surveys of vehicles, traffic and data collection regarding other significant sources (see Table ~~5~~9).

Table ~~5~~9. $PM_{2.5}$, BC and OC emissions in Murmansk Region, 2012 (t).

Activity	$PM_{2.5}$	BC	OC
On-road transport in Murmansk Region	98.9	53.7	36.2
Mines	450.5	279.3	83.8
Locomotives	30.5	~~22.3~~19.8	~~4.5~~4.0
Construction	15.6	~~12.0~~9.7	~~2.4~~2.9
Agriculture	5.0	~~3.9~~2.9	~~0.8~~0.9
Diesel generators	~~35.2~~52.8	~~27.1~~34.8	~~5.4~~7.0
~~Fishing~~ Ships (in Russian waters)	13.4~~16.5~~	4.2~~5.1~~	~~1.0~~0.8
Total	~~652.3~~666.7	~~403.4~~404.4	~~134.1~~135.5

We also conducted an initial estimate of Russian emissions form diesel combustion. In both Murmansk and Russia, on-road transportation is a large source of BC emissions. Within this category, Euro 0 trucks make up the vast majority of emissions. This reflects the fact that Russia now has requirements for emission controls on new vehicles, resulting in comparatively low emissions f~~o~~rom cars and most new trucks and buses. We also found that many registered vehicles~~, particularly~~ older vehicles, are driven infrequently based on parking lot and traffic video surveys, which is consistent with the literature. Surprisingly, we found that regional statistic on fuel use for on-road transportation indicate significantly lower consumption than our bottom-up estimates of fuel use in this category. In Murmansk Region, the largest category of emissions is off-road vehicles, in particular mining (69%). In Russia as a whole, agriculture represents the second largest diesel BC source. In both these cases, the high emissions are linked to the absence of control technologies and the lack of emission standards for off-road vehicles. Off-road vehicles represent an important opportunity for reducing emissions, for example, with emission standards for new vehicles and engines.

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Supplement of

Black carbon emissions from Russian diesel sources: Case study of Murmansk

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On-road transport in Murmansk City and Murmansk Region.

Table S1. Bottom–up calculation of fuel consumption by on-road diesel vehicles in Murmansk Region.

	Quantity	Fuel consumption, t
Passenger cars	14,500	19,700
Light duty vehicles	2,600	11,100
Heavy duty trucks	3,900	31,300
Buses	260	3,000
Total	21,260	65,100

Based on adjusted data.

Table S2. Number and total length of roads in Murmansk City.

	Number of roads	Total length, km	Share, %
Category I – Arterial	22	37	27%
Category II – Highways	53	58	42%
Category III – Local	106	43	31%
Total	181	138	100%

(Murmansk City Administration, 2009)

Table S3. Average annual kilometers traveled per vehicle, different sources.

	NIIAT[a]	Avtostat[b]	MSTU inspection station[c]
Cars	15,000	16,700	17,000
LDVs	35,000	NA	NA
Trucks	35,000	NA	NA
Buses	45,000	NA	NA

[a]NIIAT, 2008;
[b]Avtostat, 2010;
[c]MSTU, 2012.

Table S4. Number of on-road vehicles by category in Murmansk City (based on video surveys).

	Cars	LDVs	Trucks	Buses
Euro 0	491	74	228	76
Euro 1	0	0	0	2
Euro 2	545	82	90	12
Euro 3	2,072	322	133	27
Euro 4	600	112	41	6
Euro 5	1,745	339	50	1
Total	5,453	929	546	124

Table S5. BC emissions from on-road vehicles in Murmansk City based on COPERT with NIIAT emission factors (t per year).

Vehicle class	Number of vehicles, based on video surveys	PM cold start, t/year	PM hot emissions, t/year	Total PM emissions, t/year	BC/PM ratio	BC emissions, t/year
Cars						
Euro 0	491	0.87	1.47	2.34	0.55	1.29
Euro 1	0	0	0	0	0.70	0.00
Euro 2	545	0.29	0.49	0.78	0.80	0.62
Euro 3	2,072	0.73	1.24	1.98	0.85	1.68
Euro 4	600	0.06	0.11	0.17	0.87	0.15
Euro 5	1,745	0.05	0.08	0.13	1	0.13
Total cars	**5,452**	**2.00**	**3.39**	**5.40**		**3.89**
Light duty vehicles						
Euro 0	74	0.35	0.60	0.95	0.55	0.52
Euro 1	0	0.00	0.00	0.00	0.70	0.00
Euro 2	82	0.12	0.20	0.32	0.80	0.26
Euro 3	322	0.33	0.56	0.90	0.85	0.76
Euro 4	112	0.07	0.12	0.19	0.87	0.16
Euro 5	339	0.01	0.02	0.04	1	0.04
Total light duty vehicles	**929**	**0.89**	**1.50**	**2.39**		**1.74**
Trucks						
Euro 0	228	-	5.89	5.89	0.50	2.94
Euro I	0	-	0.07	0.07	0.65	0.05
Euro II	90	-	0.60	0.60	0.65	0.39
Euro III	133	-	0.64	0.64	0.70	0.45
Euro IV	41	-	0.05	0.05	0.75	0.04
Euro V	50	-	0.04	0.04	0.75	0.03
Total trucks	**546**	**-**	**5.89**	**5.89**		**3.90**
Buses						
Euro 0	76	-	3.39	3.39	0.50	1.69
Euro I	1	-	0.03	0.03	0.65	0.02
Euro II	12	-	0.46	0.46	0.65	0.30
Euro III	27	-	0.23	0.23	0.70	0.16
Euro IV	7	-	0.01	0.01	0.75	0.01
Euro V	1	-	0.00	0.00	0.75	0.00
Total buses	**124**	**-**	**3.39**	**3.39**		**2.18**
Total Murmansk	**7,051**	**2.89**	**16.31**	**19.20**		**11.7**

The starting point in emission calculations is the analysis of the vehicle registry. Traffic police is responsible for registering all on-road vehicles in Russia. However, vehicle registries, particularly in countries where registries are out of date, are inadequate for emission calculations.

As a result, we decided to use a video survey method developed for IVE to study the traffic flows in Murmansk. We compared data from video survey with vehicle registry and found that the differences are very significant. The registry is outdated and shows many vehicles that are not in use anymore, mostly old heavy duty truck and buses. For example, the share of vehicles without emission controls (Euro 0) on the roads is much lower than is shown in the registry. As a result we rely on video survey to estimate the number of vehicles in use in the city.

We adjusted the vehicles registry to correct the information about the vehicle distribution by Euro class. For cars and LDV, we adjusted the information on Euro class distribution based on the parking lot surveys and data from a vehicle inspection station. For trucks and buses, we adjusted the numbers based on data from the largest bus company and other commercial vehicle companies.

We used COPERT model to calculate emissions from on-road transport. COPERT is a free software program developed by Emisia SA. The development of COPERT is coordinated by EEA, in the framework of the activities of the European Topic Centre for Air Pollution and Climate Change Mitigation. COPERT has been developed for official road transport emission inventory preparation in EEA member countries. COPERT can be downloaded for free at http://emisia.com/copert

NIIAT methodology is designed to calculate emissions from on-road transport in urban conditions. Main provisions are harmonized with the international methodology inventory of emissions EMEP /CORINAIR. NIIAT provided copies of the methodologies. There is no software developed for NIIAT methodology. We developed an Excel spreadsheet for emission calculations.

For emission calculations of vehicular emissions in Murmansk Region, we adjusted vehicle registry in two ways:

1) We apply the distribution by Euro class we found in the city to registered vehicles in the region.
2) We apply the ratio between registered and observed vehicles to eliminate from the registry vehicles that are not is use.

Table S6. BC emissions from on-road vehicles in Murmansk Region, (based on universal NIIAT methodology) (t per year).

Vehicle class	Number of vehicles	PM cold start, t/year	PM hot emissions, t/year	Total PM emissions, t/year	BC/PM ratio	BC emissions, t/year
Cars						
Euro 0	1,309	0.01	3.93	3.94	0.55	2.17
Euro 1	0	0.00	0.00	0.00	0.70	0.00
Euro 2	1,454	0.01	1.31	1.31	0.80	1.05
Euro 3	5,526	0.02	3.32	3.33	0.85	2.83
Euro 4	1,600	0.00	0.29	0.29	0.87	0.25
Euro 5	4,653	0.01	0.21	0.22	1.00	0.22
Total cars	**14,542**	0.05	9.05	9.10		6.53
Light duty vehicles						
Euro 0	238	0.02	1.92	1.94	0.55	1.07
Euro 1	0	0.00	0.00	0.00	0.70	0.00
Euro 2	264	0.01	0.65	0.65	0.80	0.52
Euro 3	1,005	0.02	1.76	1.77	0.85	1.51
Euro 4	291	0.00	0.31	0.31	0.87	0.27
Euro 5	846	0.01	0.06	0.07	1.00	0.07
Total light duty vehicles	**2,645**	0.06	4.69	4.75		3.44
Trucks						
Euro 0	1,628	0.68	71.77	72.45	0.50	36.22
Euro I	29	0.00	0.20	0.21	0.65	0.13
Euro II	638	0.02	1.93	1.95	0.65	1.27
Euro III	961	0.05	2.56	2.60	0.70	1.82
Euro IV	395	0.02	0.21	0.23	0.75	0.17
Euro V	251	0.01	0.12	0.14	0.75	0.10
Total trucks	**3,902**	0.78	76.80	77.58		39.72
Buses						
Euro 0	139	0.03	5.90	5.93	0.50	2.97
Euro I	4	0.00	0.02	0.02	0.65	0.01
Euro II	48	0.00	0.71	0.71	0.65	0.46
Euro III	57	0.01	0.78	0.79	0.70	0.55
Euro IV	13	0.00	0.02	0.02	0.75	0.01
Euro V	2	0.00	0.00	0.00	0.75	0.00
Total buses	**262**	0.04	7.43	7.47		4.01
Total Murmansk Region	**21,351**	**0.94**	**97.96**	**98.90**		**53.70**

Off-road mining vehicles and equipment

Table S7. PM emission standards for off-road diesel vehicles in the U.S. and EU (g/kWh).

Rated Power (kW)	EPA (U.S.)			EEA (Europe)		
	EPA(U.S.) Tier	Model Year	PM (g/kWh)	Stage	Year (transient load)	PM (g/kWh)
				Pre stage		
kW<8	Tier 1	2000	1.0	Stage 1	-	-
	Tier 2	2005	0.80	Stage 2	-	-
8<kW<19	Tier 1	2000	0.80	Stage 1	-	-
	Tier 2	2005	0.80	Stage 2	-	-
19<kW<37	Tier 1	1999	0.80	Stage 1	-	-
	Tier 2	2004	0.60	Stage 2	2001	0.80
	-	-	-	Stage 3A	2007	0.60
37<kW<75	Tier 1	1998	-	Stage 1	1999	0.85
	Tier 2	2004	0.40	Stage 2	2004	0.40
	Tier 3	2008		Stage 3 A	2008	
75<kW<130	Tier 1	1997	-	Stage 1	-	-
	Tier 2	2003	0.30	Stage 2	2003	0.30
	Tier 3	2007		Stage 3 A	2007	
130<kW<560	Tier 1	1996	0.54	Stage 1	-	-
	Tier 2	2003	0.20	Stage 2	2002	0.20
	Tier 3	2006		Stage 3 A	2007	
kW>560	Tier 1	2000	0.54	Stage 1	-	-
	Tier 2	2006	0.20	Stage 2	-	-
	Tier 3	-	-	Stage 3 A	-	-

Table S8. $PM_{2.5}$ emission factors for off-road machinery, g/kg of diesel fuel.

Sector	<1981	1981-1990	1991-Stage I	Stage I	Stage II
Mobile combustion in manufacturing industries and construction land-based mobile machinery; Commercial and institutional land-based mobile machinery	6.207	4.308	3.551	0.967	1.031

(EEA, 2013)

Table S9. Diesel fuel consumption by the largest mines in Murmansk Region, tons.

Company	2010	2011	2012
Apatity	65,954	67,509	64,469
Kovdorskiy GOK	35,277	42,262	47,395
Olenegorskiy GOK	16,635	18,661	21,233
Kolskaya GMK	5,766	9,786	5,457

Sources: Apatity - http://www.e-disclosure.ru/portal/company.aspx?id=645,
Kovdorskiy GOK - http://www.e-disclosure.ru/portal/company.aspx?id=3406,
Olenegorskiy GOK - http://www.e-disclosure.ru/portal/company.aspx?id=5740,
Kolskaya GMK - http://www.e-disclosure.ru/portal/company.aspx?id=7833,

Table S10. Technical characteristics of BELAZ trucks.

Model	Payload, tons	Engine	Rated power capacity, kW
7547	45	YaMZ-240NM2	368
75473	45	Cummins KTA 19-C	448
7555B	55	Cummins KTTA 19-C	522
7555D	55	Cummins KTTA 19-C	522
7555E	60	Cummins QSK 19-C	560
7555F	55	Cummins QSK 19-C	522
75570	90	Cummins QST 30-C	783
75571	90	Cummins QST 30-C	783
75121	120	Pielstick 8PA4-185	882
7513	130-136	Cummins QSK 45-C	1193
7513A	130-136	MTU DD 12V4000	1194
75131	130-136	Cummins KTA 50-C	1194
75137	130-136	MTU DD 12V4000	1193
75135	110-130	Cummins KTA 38-C	895
75139	130-136	Cummins KTA 50-C	1194
7514	120	Cummins KTA 38-C	895
75170	154-160	Cummins QSK 45-C	1491
75172	154-160	MTU DD 12V4000 (Detroit Diesel)	1400 (1875)
75174	154-160	MTU DD 12V4000 (Detroit Diesel)	1400 (1875)

(BELAZ, 2014)

Table S11. Technical characteristics of foreign-made mining trucks.

Model	Payload, tons	Engine	Rated power capacity, kW
CAT 777D	90	Caterpillar 3508B EUI Tier I emissions standard	746
CAT 777F	90	Cat® C32 ACERT™ Tier 2	758
CAT 785C	136	Caterpillar 3512B-EUI Tier I emissions standard	1082
Komatsu HD-1200-1	136	KTTA 38C-1350 Cummins KTA-38-C1200	1007/895
Komatsu HD785	91	SAA12V140E-3 EPA Tier 2	895
Terex Mining Unit Rig MT 3300 AC	136	MTU/DDC 12 V 4000 / Cummins QSK45	1286/1193
HD-1200	120	Cummins KTA-2300C	895

We assumed that 88% of mining equipment has no emission controls. If we increase the share of equipment which meets Tier 1 standard from 12 to 18%, BC emissions from mining would decrease by 13 tons per year, or more than from all on-road transport in Murmansk City.

Construction equipment

Table S12. Construction equipment and machinery in Murmansk Region.

	2007	2008	2009	2010	2011	2012	2013
Excavators	221	206	228	218	192	213	217
Cranes	39	28	25	19	18	14	21
Graders	65	70	71	82	70	80	74
Bulldozers	195	185	218	216	200	249	244
Special cranes	11	15	19	12	13	13	9
Tower cranes	24	14	11	5	5	4	3
Mobile cranes	128	125	152	131	114	113	138
Lifts	46	42	52	45	41	47	54
Loaders	113	173	152	129	142	221	227
Tractors	97	80	130	122	128	143	126
Drills	4	3	5	2	7	7	9
Rollers	67	58	56	55	46	43	37
Cement mixers	26	32	18	11	8	10	8
Construction and finishing equipment	160	140	252	263	545	551	376
Hydro hummers	28	30	32	27	27	43	32

(MBS, 2012)

There are many uncompleted construction sites that have remained in this state for many years. Only 32,600 square meters of residential buildings and 34,100 square meters of non-residential buildings were built in 2012. Industrial construction is growing, but diesel consumption in this sector appears under industrial consumption, so we did not consider it separately here. There are 16 major building construction companies, and 3.8% of the labor force or 12,000 people work in the construction industry. Currently, construction creates 3.4% of the gross regional product.

Fishing and marine transport in Murmansk Region

Table S13. Number of fishing vessels registered in Murmansk Region.

	2000	2006	2007	2008	2009	2010	2011	2012
Fishing vessels	279	270	270	265	247	225	219	214
Super trawler	20	12	11	11	11	12	12	12
Large	37	26	20	17	15	14	14	12
Medium	203	169	164	156	145	133	125	122
Small	19	63	75	81	76	66	68	68
Fish transport vessels	24	25	33	21	18	16	13	12
All	303	295	303	286	265	241	232	226

(Zabolotsky, 2012)

Table S14. Age structure of the fishing fleet, 2012 (years).

	Up to 20 years		20 years or more		Average age, years
	number	%	number	%	
Fishing vessels	30	14.0	184	86.0	26.2
Extra-large	2	16.7	10	83.3	23.1
Large	2	16.7	10	83.3	25.8
Medium	16	13.1	106	86.3	26.8
Small	10	14.7	58	85.3	25.9
Fish transport vessels	1	8.3	11	91.7	30.7
All	31	13.7	195	86.3	26.5

(Committee for the Fishery Complex of Murmansk Region, 2013)

Table S15. Distribution of fishing vessels by engine power (based on the Murmansk Fishing Port calls).

Engine power, kW	Share of port calls
< 240	34%
240-300	5%
300-400	1%
400-500	4%
500-600	12%
600-700	2%
700-800	2%
800-900	16%
900-1000	4%
1000-1100	11%
2000-3000	4%
3000-4000	2%
4000-5000	2%
Total	100%

(Murmansk Port, 2014)

Table S16. Bottom-up calculation of fuel consumption by medium and small fishing vessels (based on the Murmansk Fishing Port calls).

Engine power, kW	Number of port calls	Engine load %	Time, hours	Fuel eficiency, kg diesel /kWh	Fuel consumption, kg
220	542	0.6	7	0.203	100,351
232	7	0.6	7	0.203	1,385
272	73	0.6	7	0.203	16,929
294	48	0.6	7	0.203	12,032
331	20	0.6	7	0.203	5,644
368	36	0.6	7	0.203	11,295
241	15	0.6	7	0.203	3,082
265	25	0.6	7	0.203	5,648
590	143	0.6	7	0.203	71,934
596	9	0.6	7	0.203	4,573
618	19	0.6	7	0.203	10,011
626	7	0.6	7	0.203	3,736
736	44	0.6	7	0.203	27,611
860	302	0.6	7	0.203	221,437
970	74	0.6	7	0.203	61,200
1120	30	0.6	7	0.203	28,647
1325	12	0.6	7	0.203	13,556
1470	9	0.6	7	0.203	11,280
1500	32	0.6	7	0.203	40,925
1620	46	0.6	7	0.203	63,536
1650	22	0.6	7	0.203	30,949
1760	9	0.6	7	0.203	13,505
1800	17	0.6	7	0.203	26,090
1950	24	0.6	7	0.203	39,902
2005	7	0.6	7	0.203	11,966
2040	15	0.6	7	0.203	26,090
2160	21	0.6	7	0.203	38,674
2200	6	0.6	7	0.203	11,254
2800	7	0.6	7	0.203	16,711
3000	10	0.6	7	0.203	25,578
3080	28	0.6	7	0.203	73,528
4350	9	0.6	7	0.203	33,379
5300	39	0.6	7	0.203	176,232
Total	1707				1,238,672

(Murmansk Port, 2014)

The distribution of gross tonnage of the ships calling into the Murmansk Port

Table S17. Tankers

Gross tonnage, t	Number of calls	Share, %
< 2000	27	6%
2000-4000	47	11%
4000-10000	7	2%
10000-20000	37	9%
20000-30000	108	26%
30000-40000	7	2%
40000-50000	171	41%
> 50000	16	4%
Total	420	100%

(Murmansk Port, 2014)

Table S18. **Cargo ships**

Gross tonnage, t	Number of calls	Share, %
< 2000	38	6.3%
2 000-4 000	128	21.2%
4 000-10 000	85	14.1%
10 000-20 000	120	19.9%
20 000-30 000	26	4.3%
30 000-40 000	87	14.4%
40 000-50 000	103	17.1%
> 50 000	17	2.8%
Total	604	100.0%

(Murmansk Port, 2014)

Table S19 **Passenger ships**

Gross tonnage, t	Number of calls	Share, %
< 3000	7	8%
4000-5000	64	77%
5000-10 000	3	4%
10 000 -15000	3	4%
15 000-20 000	2	2%
>20 000	4	5%
Total	83	100%

(Murmansk Port, 2014)

Diesel generators in Murmansk Region

Table S20. Diesel generators using subsidized fuel in remote areas of Murmansk Region.

Settlement	Quantity	Capacity, kW	Fuel consumption, tons per year
Krasnoschele	2	400	341
	1	500	
Kanevka	2	90	30
Sosnovka	1	90	30
Varzuga	1	60	
Kashkarantsy	1	30	62
Tetrino	1	30	13
Pyalitsa	1	30	7
Chavanga	1	100	117
Chapoma	1	100	42
TOTAL	12	1430	642

(Ministry of Energy of Murmansk Region, 2012)

We also obtained a registry of back-up diesel generators from the Murmansk Ministry of Energy. According to the registry, there are 540 diesel generators in the region, which are used as back-up sources of electrical power. We assumed that this is a very small source of emissions because power supply on the Kola Peninsula is very stable, so each back-up generator appears to operate at most a few hours per year. As a result, we did not calculate fuel use or emissions from these generators.

Uncertainty estimates of BC emissions in Murmansk Region

Uncertainty estimates include uncertainty in activity data - uncertainty in fuel use and existence of emission controls. Activity data uncertainty is based on expert judgments.

We used a summary analysis of BC uncertainty ranges for the BC emission factors from the Bond inventory (Bond et al (2004).

Table S21. Emission factors uncertainty (%)

Source Category	Low/Mid, %	High/Mid, %
Mining	50	230
On-road transport	50	180
Construction	50	230
Agriculture	50	230
Locomotives	50	230
Diesel generators	50	230
Fishing	50	230

The algorithm for uncertainty calculations was adopted from:

IPCC: IPCC good practice guidance and uncertainty management in national greenhouse gas inventories, Institute for Global Environmental Strategies, Hayama, Japan, 4-88788-000-6, 2000.

Activity data uncertainty (U activity) is a combination of uncertainty on emission controls (U controls) and uncertainty in fuel consumption (U fuel).

U activity = $(\text{U fuel}^2 + \text{U controls}^2)^{1/2}$

The relative uncertainty in the emission for each activity and fuel combination is calculated as the square root of the sum of squares of the relative uncertainties in both activity data and the emission factors. The absolute uncertainty in the emission of each activity and fuel combination is derived by multiplying the relative uncertainty with the emission value.

We built two scenarios which reflect possible minimum and maximum BC emission in the region. Minimal emissions scenario reflects possible decrease in fuel consumption in the sectors and higher use of emission controls. Maximum emissions scenario show possible increase in emissions due to large diesel consumption and lack of controls. Tables S22 and S23 show calculations of low/middle and high/middle relative uncertainty of the inventory.

Table S22. BC emissions uncertainty, low /middle estimate

Source Category	BC Emissions (t)	Fuel use, %	Assumptions on control,%	Activity data uncertainty (%)	Emission factor uncertainty (%)	Combined relative uncertainty (%)	Absolute uncertainty, (t)
Mining	279.3	5	50	50.2	50	70.9	198.0
On-road transport	53.7	10	10	14.1	50	52.0	27.9
Construction	12.0	50	30	58.3	50	76.8	9.2
Agriculture	3.9	10	20	22.4	50	54.8	2.1
Locomotives	22.3	10	20	22.4	50	54.8	12.2

Diesel generators	27.1	50	100	111.8	50	122.5	33.2
Fishing	5.3	5	30	30.4	50	58.5	3.0
Total	403.7					195.06	203.31

Table S23. BC emissions uncertainty, high /middle estimate

Source Category	BC Emissions (t)	Fuel use (%)	Assumptions on control (%)	Activity data uncertainty (%)	Emission factor uncertainty (%)	Combined relative uncertainty (%)	Absolute uncertainty, (t)
Mining	279.3	20	5	20.6	230	230.9	645.0
On-road transport	53.7	200	30	202.2	180	270.7	145.4
Construction	12.0	30	5	30.4	230	232.0	27.8
Agriculture	3.9	10	0	10.0	230	230.2	8.9
Locomotives	22.3	30	0	30.0	230	231.9	51.7
Diesel generators	27.1	20	0	20.0	230	230.9	62.6
Fishing	5.1	200	0	200.0	230	304.8	15.6
Total	403.42					658.37	667.00

The relative uncertainty in BC emissions in Murmansk region is from -50% to +165%.

On-road diesel fleet in Russia

Table S24. Diesel consumption by on-road vehicles in Russia in 2010.

Fuel consumption	Share, %	Diesel, million tons
Cars	4.4	0.550
Trucks	81.1	10,144
Buses	14.5	1,814

Source: (Donchenko, 2013)

Table S25. Diesel fleet distribution by environmental class in Russia in 2010 (%).

Ecological class/Vehicle type	Euro 0	Euro 1	Euro 2	Euro 3 and higher
Cars	44	2	17	37
Trucks	51	9	20	20
Buses	40	12	25	22

Source: (Donchenko, 2013)

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