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Review article

Black carbon emissions in Russia: A critical review

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HIGHLIGHTS

- The paper reviews studies on Russia's black carbon emissions.
- The study also adds organic carbon and uncertainty estimates.
- Russia's black carbon emissions are estimated at 688 Gg.
- Russian policies on flaring and on-road transport appear to have significantly reduced black carbon emissions recently.
- Using the new inventory, the study estimates Arctic forcing.

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ABSTRACT

This study presents a comprehensive review of estimated black carbon (BC) emissions in Russia from a range of studies. Russia has an important role regarding BC emissions given the extent of its territory above the Arctic Circle, where BC emissions have a particularly pronounced effect on the climate. We assess underlying methodologies and data sources for each major emissions source based on their level of detail, accuracy and extent to which they represent current conditions. We then present reference values for each major emissions source. In the case of flaring, the study presents new estimates drawing on data on Russia's associated petroleum gas and the most recent satellite data on flaring. We also present estimates of organic carbon (OC) for each source, either based on the reference studies or from our own calculations. In addition, the study provides uncertainty estimates for each source. Total BC emissions are estimated at 688 Gg in 2014, with an uncertainty range 401 Gg-1453 Gg, while OC emissions are 9224 Gg with uncertainty ranging between 5596 Gg and 14,736 Gg. Wildfires dominated and contributed about 83% of the total BC emissions: however, the effect on radiative forcing is mitigated in part by OC emissions. We also present an adjusted estimate of Arctic forcing from Russia's BC and OC emissions. In recent years, Russia has pursued policies to reduce flaring and limit particulate emissions from on-road transport, both of which appear to significantly contribute to the lower emissions and forcing values found in this study.

1. Introduction

Globally, BC is the second or third most important climate forcer (Bond et al., 2013; Collins et al., 2013; Stohl et al., 2015), though there remains significant uncertainty over BC emissions and their climate impact. Few countries have published national inventories of BC, and the scientific understanding of BC emission factors lags behind that of other major climate forcers, in part because the relative importance of BC as a climate forcer has only recently been understood.

BC has a net positive forcing effect on climate change through several mechanisms. These include directly absorbing solar radiation, reducing the albedo of snow and increasing snow melt (when BC deposits on snow), and changing the solar reflectance of clouds

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through a variety of interactions with atmospheric moisture and clouds (Bond et al., 2013; Collins et al., 2013; Stohl et al., 2015). Bond et al. (2013) estimate global emissions of BC to be 7500 Gg in 2000, with an uncertainty range of 2000 to 29,000 Gg.

BC is an aerosol comprised of fine particulate matter that is produced from the incomplete combustion of fossil fuels or organic matter. Different fuels and types of combustion can produce very different amounts of BC. For example, natural gas combustion produces very little BC, while diesel combustion can produce significant amounts. BC is co-emitted with organic carbon (OC), though the ratio changes depending on the type of fuel and efficiency of combustion. Unlike BC, OC has a net cooling effect as a climate forcer; thus, it is important where possible to consider both aerosols (Bond et al., 2013; Sand et al., 2016; Stohl et al., 2015).

Russia plays an important role regarding BC emissions and associated climate forcing, given its location and size. Russia covers the majority of the global land surface in the Arctic, and location of emissions is important because BC is very short-lived compared to CO_2. This is because BC has a pronounced impact on climate change near the Arctic, linked to BC's role in reducing snow albedo and its cloud interactions (Quinn et al., 2011). The closer emission sources are to the Arctic, the more likely there are to have stronger climate forcing impacts than if emitted at lower latitudes. Russia covers the majority of the global land surface in the Arctic, and hence emissions in Russia are critical for our understanding of BC as a climate forcer.

In addition, studies also indicate that $PM_{2.5}$ (of which BC is a major component) also causes significant health impacts (Fann et al., 2012; GBD, 2016; Janssen et al., 2012). It can enter the lungs and pass through human skin, causing respiratory illnesses, cardiovascular problems, and cancer. As a result, many countries have adopted policies to reduce the emissions of particulate matter, such as emission standards, and these policies typically also reduce BC emissions. The Russian Government has also adopted policies such as vehicle emission standards.

This study aims to present a comprehensive review of Russia's BC emissions, comparing methodologies and data behind existing estimates of these emissions. The studies to date have used methodologies with varying degrees of detail and accuracy, and the estimates that they produce vary significantly. For example, BC emissions in the transportation sector range from 7.7 Gg to 45.3 Gg (MNRE, 2015a) per year (Huang et al., 2015), while those on BC emissions from forest fires range from 81.9 Gg (Smirnov et al., 2015) to 519 Gg (Hao et al., 2016) per year. By directly comparing the existing studies referenced in this article and highlighting the estimates derived from the most detailed and/or current methodologies, this study aims to improve our understanding of Russia's BC emissions. In addition, this study adds an assessment of uncertainty to the existing literature, which is important given the wide range of estimates and the underlying uncertainty of emission factors and activity data. Uncertainty describes situations in which we have a limited understanding of emission factors or activity data; variability describes changes in activity or emission factor over time or based on different conditions. In the emissions inventory community, the term uncertainty is used to summarize both. We have attempted to reduce uncertainty by identifying the studies with the most detailed data and methodologies. For example, where some studies have assumed that Russian vehicles do not use control technologies, we relied on research that separated vehicles into emission classes, and hence showing this increased variability in activity data allowed for more precise application of emission factors, reducing uncertainty. This study also provides estimates of OC emissions from each source, which was not the case in all the studies reviewed. OC emissions are important for estimating net climate forcing.

Improved data on Russia's BC emissions are important for several reasons. Global climate models rely on such data, so data enhancements can provide a clearer picture of potential future climate change. Likewise, more accurate emissions data can help in developing priorities and plans to mitigate BC emissions.

2. Methodology

This review of BC emission estimates for Russia compares several estimates for emissions, emission factors, and underlying activity data for the major sources of BC emissions in Russia. We present a range of estimates published in peer-reviewed journals, reports, and presentations. Some emissions sources, such as transportation, have multiple estimates in the literature, each with a different level of detail, while others, such as flaring, have relatively few sources, reflecting limited historical information on emission factors and activity data. We also provide a detailed description of methodologies behind the emission estimates in describing each sector's emissions.

In general, emission inventories are calculated by multiplying activity data (such as volume of flaring) by an emission factor, and if needed, adjusting for control technology. While this seems simple, in most cases, determining the level of activity data can involve many data sets and/or modeling, and determining the appropriate emission factors to apply can also involve significant analysis. So if we extend the flaring example, the data we use comes from analysis of satellite images and the emission factors come from detailed field and laboratory research, as well as new data on the chemical content of Russian flare gas (also known as associated petroleum gas). Satellite data are useful for estimating emissions from large, open flames. For other emissions sources, it is significantly more accurate to use detailed economic and physical data, and to apply the most specific emission factors available. Modeling is useful in calculating BC emissions primarily in two circumstances: first in converting satellite flame data to emission estimates, and second in ensuring that bottom up transportation estimates of energy use matches top down energy statistics. In each case, we attempt to categorize the estimates based on several factors, including:

- The detail in activity data used for each study (some studies use more generalized fuel-based activity data, while others use detailed sectoral data, such as data on the vehicle fleet);
- The extent to which studies use the most current or comprehensive information possible, particularly with regard to emission factors;
- The applicability of the methodologies used (for example, a few studies used atmospheric modeling to assess emission levels).

We highlight estimates that are based on more detailed and/or rigorous data, such that we can present both the range of estimates and the estimate that appears most likely. In the case of flaring, we also provide our own estimates using updated satellite data on flaring volumes as well as an estimate of the potential emission factor using new data on the heating value of Russia's flares (applied to the literature on flaring emission factors). To estimate emissions in the transportation sector, researchers use either fuel- or activity-based emission factors. For road transport, we use studies based on detailed activity data, while for all other modes of transportation we use fuel-based studies. We also added estimates of BC and OC emission from gasoline vehicles. For the heat and power, industrial, and domestic sectors, researchers use only fuel-based emission factors. BC emissions are the product of fuel use, unabated emission factor, and emission removal efficiency. Wherever possible, we also add additional information on the uncertainty of each of the sources. We estimate uncertainty based on the uncertainty associated with the underlying emission factors and activity data. Most of the previously published BC emission estimates for Russia do not include uncertainty estimates. Finally, we estimate emissions of both BC and OC, in many cases adding OC calculations to existing BC estimates using available speciation factors.

We provide qualitative information on the potential forcing of the different sources based on the range of existing studies. Because this study focuses on Russia, we primarily exclude global estimates that contain only regional breakdowns of emissions, without Russia-specific detail. However, in reviewing each sector, we did compare emission factors to those applied in global studies, such as Bond et al. (2013). Several research groups maintain databases with time series data on Russia's emissions. These include GAINS (Greenhouse Gas – Air Pollution Interactions and Synergies) and ECLIPSE (Evaluating the Climate and Air Quality Impacts of Short-lived Pollutants) at the International Institute for Applied Systems Analysis (IIASA) and EDGAR (Emission Database for Global Atmospheric Research) at the Joint Research Centre of the European Commission. These studies are important to note because they are typically based on globally consistent, detailed methodologies.

We recognize the importance of using Russia-specific emission factors wherever possible. Russian research institutes have developed numerous methodologies for calculating emissions; however, none of these specifically refers to BC, and only a few refer to clearly defined particles that can be readily compared to BC (e.g., PM_{10} or $PM_{2.5}$). Specifically, only the methodologies for emissions from road transportation, developed by the Russian Scientific Research Institute of Automobiles and Transportation (NIIAT) use PM_{10} as NIIAT derived them from European methodologies. Thus, it is important to use caution when considering Russia's emission factors (see the Supplementary Materials for additional details on Russian methodologies and terminology). We consider these terminological issues in our review of the literature.

For on-road transport, detailed activity data is available and robust emission inventories use activity-based emission factors. Due to large variety of combustion processes in the heat and power sector, industry and domestic sector, researchers can only use fuel-based emission factors. To estimate emissions from these sectors we use the results from the Community Emissions Data System (CEDS) project, currently being developed at the Pacific Northwest National Laboratory (PNNL) (Hoesly et al., 2017). They use data from the IEA and emission factors from the Speciated Emission Wizard (SPEW) database. SPEW is a relational database system that tabulates values of emission characteristics for each fuel/technology combination and activity data to produce emissions (Bond et al., 2004, 2007). The Supplementary Materials provides more information about the methodology of the CEDS project. We also considered numerous studies that provided a time-series or snapshot of specific emissions sources.

3. Emissions of black carbon and organic carbon in Russia

Below we present the comparative results for each sector along with a brief description of the emissions sources by sector. Thus, we cover flaring, transportation, wildfires and agricultural burning, the residential and domestic sectors, power generation and heating, and industry. Their order is based on the approximate net forcing from combined BC and OC emissions from each source. It is important to note that wildfires are by far the largest source of BC emissions, but they co-produce significant amounts of OC.

3.1. Flaring of associated petroleum gas

Russia is a major oil producer and has the largest volume of flared gas in the world. Flaring occurs because oil production results in the simultaneous production of associated petroleum gas (APG), which can vary in chemical and energy content. APG may be a valuable economic resource if captured and brought to markets (Carbon Limits, 2013; PFC Energy, 2007; Vazim et al., 2015). Typical uses include processing it into natural gas or liquefied petroleum gas, or burning it to produce power or heat. When APG is not used, it must either be vented or flared. Venting is harmful to the climate because it involves emissions of methane, with a global warming potential 28 times that of CO_2 (IPCC, 2013). Flaring involves emissions of not only CO_2 but also BC and other substances.

From 2003 to 2012, Russia adopted strong policies to encourage companies to utilize APG and to reduce flaring. Companies must now pay large fines for each ton of gas they flare. Market access is also easier now in many ways (Evans and Roshchanka, 2014; Røland, 2010). This may account for the significant drop in APG flaring shown in NOAA's satellite data as well as the reported increase in APG utilization (see Fig. 1).[1]

There are significant differences in estimates of Russia's volume of gas flared. Data based on satellite observations (Elvidge et al., 2016; NOAA, 2016a, b) show higher volumes of gas flared than Russian official statistics (including those published by the Ministry of Energy (Minenergo, 2015a) and those presented to the UNFCCC in Russia's greenhouse gas inventories (Government of Russian Federation, 2016)). Satellite estimates rely on satellite data on fires and calibrated algorithms that convert brightness and other factors into gas volumes. Fig. 1 below compares these different estimates as well as the reported changes in APG utilization. In this study, we rely on the satellite data as it has been tested through rigorous peer review. Map S1 in the Supplementary Materials shows the locations of the flaring sites in Russia.

Until recently, there were very few studies on BC emission factors from flaring. BC emissions from flaring depend on several factors including:

- The share of heavy hydrocarbons in the flare gas, as these heavier hydrocarbons can cause sooting;
- Impurities in the flare gas that can make combustion less efficient (this can also be represented as the heating value of the gas); and
- The velocity of APG as it crosses the flare tip (the lower the velocity, the greater the potential for BC emissions; typically larger flares have higher velocity).[2]

Because conditions can vary and few studies have involved actual measurement of APG flares, uncertainties in BC emission factors from flaring are high (Conrad and Johnson, 2017). The Canadian Association of Petroleum Producers has also published guidelines on estimating emissions associated with oil production (CAPP, 2014). Johnson et al. (2011, 2013) used optical techniques to estimate BC in flares in Uzbekistan and Mexico, respectively. However, because the gas content and flow rate in these studies were not known, they did not present an emission factor that can be easily applied to other sites (e.g., they share their results in grams per second not grams per unit of gas). McEwen and Johnson (2012) presented the first directly measured flaring emission factors. This study looked at laboratory-scale flares to test six different

[1] NOAA also changed the satellite it relies on for assessing flaring in 2011, switching from the Defense Meteorological Satellite to the Visual Infrared Imaging Radiometer Suite (VIIRS). However, this actually resulted in a slight increase in detected flares, not a decrease (Elvidge et al., 2016).

[2] Correspondence with Dr. David Picard, chemical and petroleum engineer, Clearstone Engineering, dated 7 June 2016.

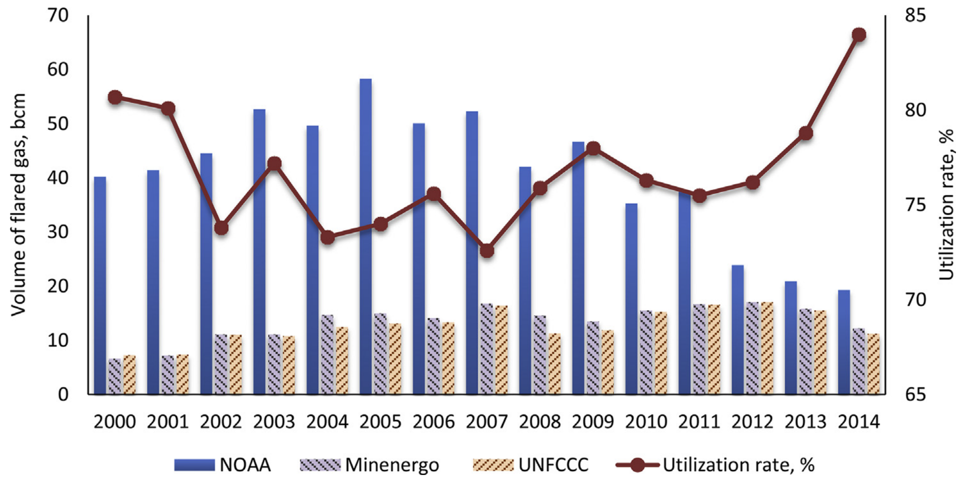

Fig. 1. Volumes and utilization rate of flared gas in Russia, 2000–2014.
Sources: (Elvidge et al., 2016; Government of Russian Federation, 2016; Minenergo, 2015a; NOAA, 2016a, b).

chemical compositions of gas selected to mimic APG compositions in Alberta, Canada. This study provided a formula based on the measured data that allows users to adjust the heating value of the gas within a given range. Schwarz et al. (2015) and Weyant et al. (2016) estimated the BC emissions factor from flares in North Dakota; however, U.S. flares tend to be significantly smaller than those in Russia (Elvidge et al., 2016). Russia's flares are also relatively inefficient,which means that they rarely completely combust APG (Evans and Roshchanka, 2014). Moreover, neither Schwarz et al. (2015) nor Weyant et al. (2016) assessed the impact of high heating value gases (such as ethane and propane) in their measurements and formulas. These denser, high heating value gases tend to produce higher BC emissions based on the results of McEwen and Johnson (2012). Gases denser than methane make up approximately 40% of Russia's APG (Fillipov, 2013). Table 1 summarizes these emission factors, as well as those of two inventory studies (Huang et al., 2015; Stohl et al., 2013a,b), described in more detail below.

The Greenhouse Gas – Air pollution Interactions and Synergies (GAINS) model derives its estimate of BC emission factors in Russia (1.6 g/m^3) from CAPP (2007), Johnson et al. (2011) and EPA (1995). According to Stohl et al. (2013a,b), GAINS uses these higher estimates because of concerns that median laboratory conditions in McEwen and Johnson (2012) may result in lower emissions levels not representative of industrial applications though Stohl et al. (2013a,b) did not conduct detailed calculations. Nonetheless, the emission factor Stohl et al. (2013a,b) selected closely matches an emission factor one can derive from McEwen and Johnson (2012) using an average heating value of APG at Russian production sites, drawing on APG composition data from Fillipov (2013) and Andreykina (2005).

Huang et al. (2015) provide a detailed methodology for developing their emission factor, drawing on McEwen and Johnson (2012) estimates from laboratory flares, adjusted upward for the Russia's APG heating value from the Alekhinskoe oil field. However, Huang et al. (2015) use expert judgement to assume that 30–50% of the gas is flared after some degree of processing, which increases the resulting heating value. Huang et al. (2015) also note that the heating value used is beyond the observed range from McEwen and Johnson (2012); Huang and Fu also use the same emission factor in their other publication (2016). Elvidge et al. (2016) provide satellite data indicating that over 99% of Russia's flaring takes place upstream, indicating that Huang et al. (2015) may have overestimated the share of downstream, high heating value flare gas. Klimont et al. (2016) also note that Huang et al. (2015) use an emission factor well beyond the range presented in the literature. Adjusting data from Huang et al. (2015) to reflect only APG from the first stage of processing (per the Fillipov (2013) data they use) would give a revised emission factor of 1.62 g/m^3 (similar to (Klimont et al., 2016) instead of 2.27 g/m^3. For this calculation, we used the approach described in Huang et al. (2015), but adjusted their inputs to the McEwen and Johnson (2012) formula to reflect the heat value of gas only at the first stage of gas processing from the single field that they present; the vast majority of Russian flaring involves gas that is at the first stage of processing.

Flare gas that is heavier and has a higher energy content than methane has a higher propensity to produce black carbon, according to the formula in McEwen and Johnson (2012). Additional work to establish Russia-specific emission factors would help in reducing uncertainty. However, in the interim, we have updated the emission factors from previous studies to consider the heating value of APG from a range of Russia's oil fields, drawing on both Fillipov (2013) and Andreykina (2005), focusing in particular on the heating value of APG before it has undergone processing. Table S1 in the Supplement summarizes the data on the chemical composition of APG at multiple fields in Western Siberia. Using these multi-site data on APG heating values and the formula from McEwen and Johnson (2012), we derive an average emission factor of 1.67 g/m^3. We then apply this new emission factor to the flaring data from NOAA (2016a, b).

We estimate uncertainty by taking the full range of emission factors shown in Table 1, such that Schwarz et al. (2015) is the lower end of the range and CAPP (2014) is the upper end. We multiply the uncertainty in emission factors by the uncertainty in volume of gas flared from the satellite data as described in Elvidge et al. (2016). Fig. 2 summarizes these results. As Russia's flaring has declined in recent years, so too have the associated BC emissions.

There are several sources of uncertainty regarding BC emissions from flaring in Russia. The largest source is the emission factor, which ranges in the different studies from 0.57 g/m^3 (Schwarz et al., 2015) to 2.56 g/m^3 (CAPP, 2014). The emission factor is closely linked to the heating value of the gas and the flow velocity. While there is some information on the heating value of Russia's APG, gas composition can vary over time and across different production sites. Thus, the heating value is an additional source of potential uncertainty that is difficult to quantify without additional data.

Table 1
BC emission factors from flaring in Russia.

	Units	Median	Maximum	Minimum	Method or location of the test
McEwen and Johnson (2012)	g/m^3	0.51	0.65	0.18	Laboratory
Stohl et al. (2013a,b)	g/m^3	1.60			Literature-based
CAPP (2014)	g/m^3	2.56			Canada
Schwarz et al. (2015)	g/m^3	0.57	0.71	0.43	North Dakota
Huang et al. (2015)	g/m^3	2.27			Literature-based
Huang and Fu (2016)	g/m^3	2.27			Literature-based
Weyant et al. (2016)	g/m^3	0.07	0.26	0.02	North Dakota
Klimont et al. (2016)	g/m^3	1.75			Literature-based
Johnson et al. (2011)	g/s	2.00	2.25	1.75	Uzbekistan
Johnson et al. (2013)	g/s	0.067	0.09	0.05	Mexico

However, one can consider the heating value to be one element of the emission factor uncertainty, within the range of 0.57–2.56 g/m^3. Finally, there is uncertainty in the volume of Russia's gas flared. Elvidge et al. (2016) estimate the global uncertainty in flared gas volumes is ± 13.6 bcm, or 9.5% of the volume, which would make the uncertainty in Russia's flaring ± 1.84 bcm. The potential range of BC emissions in 2014, taking the lowest and highest emission factors and flaring estimates when applying this method, is **32.2 Gg** with an uncertainty range of +21.9 to −22.2 Gg.

The European project ECLIPSE (Evaluating the CLimate and Air Quality ImPacts of Short-livEd Pollutants) (ECLIPSE, n/d), created to develop and assess effective emission abatement strategies for short-lived climate forcers, provides an emission inventory that contains estimates of BC and OC emissions. The ECLIPSE data estimates that OC emissions from flaring are 20% as large as those of BC (Klimont et al., 2013; Sand et al., 2016). Applying this estimate to our BC calculations, we calculate OC emissions from flaring in Russia in 2014 to be **6.4 Gg**, with an uncertainty range of +4.37 to −4.46 Gg.

3.2. Transportation

Transportation includes on-road transport (passenger cars, light-commercial vehicles, buses and heavy-duty trucks), rail, ships (domestic navigation) and aircraft. Off-road vehicles (e.g. used in agriculture or construction) are not included in this section.

The transportation sector in Russia has grown dramatically in recent years. Between 2000 and 2013 the number of registered passenger cars doubled and the number of trucks increased by 40%. The on-road fleet will likely continue to grow as there are about 300 cars per 1000 people in Russia compared to 500–700 cars in OECD countries (Kholod and Evans, 2016). Diesel vehicles are by far the largest source of BC emissions from transport because gasoline and natural gas -powered vehicles emit practically no BC.

Russia adopted its first emission standard limiting PM emissions from on-road vehicles in 2006. Since then Russia has introduced more stringent vehicle standards (often referred to as Euro standards), and the current emission standard for new on-road vehicles is Euro 5 (Eurasian Commission, 2011). The introduction of emission standards has led to significant emission reductions from new vehicles. For example, the emission factors for new Euro 5 vehicles are about 20 times less than for Euro 1. Thus, the base year of the emission inventories from on-road vehicles is an important factor to consider given that the vehicle fleet upgrades have a significant impact on overall emissions.

There are two main approaches for calculating BC emissions from transport. The first method of emission calculations is based on fuel consumption. BC emissions are the product of fuel consumed by type of vehicle and emissions factors for these types of vehicles. In most cases, only two types of vehicles are considered: light-duty (cars) and heavy-duty (trucks and buses). This method yields large uncertainty, especially when there are rapid changes in the vehicle fleet. However, researchers use this method if detailed activity data are not available. This is especially true about estimating emissions from off-road transport such as locomotives and ships.

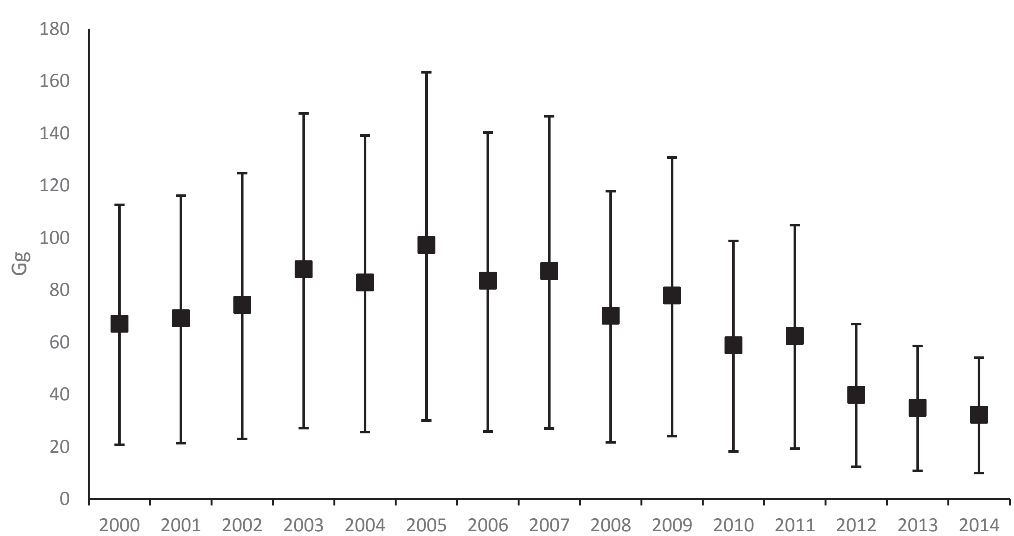

Fig. 2. BC emissions from APG flaring in Russia, Gg.

The second method is based on detailed vehicle activity data. BC emissions depend on several factors, including the number of vehicles by type and emission standard, the average annual distance traveled by type of vehicle, $PM_{2.5}$ emission factors, and $BC/PM_{2.5}$ speciation ratios. Other factors include the distribution of traffic by road type, ambient temperature (for cold starts), speed, and the presence of superemitters (vehicles that have very high emissions compared to regular ones).

There are a few studies of BC (or $PM_{2.5}$) emissions from on-road transport in Russia (Table 2). Based on (Bond et al., 2007) Lamarque et al. (2010) combine fuel consumption data with information on combustion technologies and emission controls. Evans et al. (2015) estimate BC emissions combining energy data from the International Energy Agency (IEA) with fuel-based emission factors from the European Environment Agency (EEA guidebook). The Ministry of Environment and Natural Resources uses fuel-based emission factors to estimate emissions from transport, but this study lacks methodological explanations (MNRE, 2015a). Donchenko (2007, 2013) calculates $PM_{2.5}$ emissions from road transport using data about the number of vehicles by type and emission standard, and Russia-specific PM emission factors developed by NIIAT (for PM emission studies, we apply the $BC/PM_{2.5}$ speciation ratio from the EEA emission guidebook (EEA, 2013) to calculate comparable BC emissions). The Global Transportation Roadmap model, developed by the International Council on Clean Transportation (ICCT), projects emissions from transport through 2050. The Roadmap model uses assumptions about the number of registered vehicles, the average annual distance traveled, and the distribution of the vehicle fleet by type and fuel (ICCT, 2015). However, the model estimates emissions from all registered vehicles and does not factor in superemitters (Hoesly et al., 2017). estimate BC and OC emissions using fuel-based emission factors. Huang et al. (2015) use data about all registered vehicles and factor in the stock use. They use Russia-specific emission factors developed by NIIAT and assume that all heavy-duty trucks and buses use diesel. For all cars, both gasoline and diesel, they use diesel $PM_{2.5}$ emission factors and lower $BC/PM_{2.5}$ ratios. Table 2 summarizes BC estimates from these studies.

Kholod et al. (2016) published a comprehensive study on BC emissions from on-road transport in Russia. Using data from a complete Russia's vehicle registry, they disaggregate the number of registered vehicles by type, fuel, and emission standard, estimate the share of active vehicles, apply NIIAT emission factors, and factor in the superemitters. Kholod et al. (2016) use the European COPERT (COmputer Programme to calculate Emissions from Road Transport) model which many countries use to prepare their emission inventories (Ntziachristos et al., 2009) to calculate BC and OC emissions from on-road transport. We use this study as a baseline reference for BC emissions from on-road transport in Russia.

Kholod et al. (2016) estimate that on-road diesel vehicles emitted 20.7 Gg of BC and of 10.5 Gg OC in 2014. Heavy-duty trucks account for 60% of the on-road BC emissions, while cars represent only 5%. Vehicles without emission controls emitted 22% of all BC while superemitters accounted for 43% of emissions. Kholod et al. (2016) estimate that the range of uncertainty is from 13.9 Gg to 26.6 Gg for BC and from 4.5 Gg to 12.9 Gg for OC. BC/OC coefficients were derived from the COPERT model.

There were about 42 million gasoline light-duty vehicles (passenger cars and light commercial vehicles) in Russia in 2014, but there are no studies on the BC emissions from these vehicles. To estimate BC and OC emissions from gasoline vehicles, we use the COPERT model and apply the same methods as described in Kholod et al. (2016) to estimate the number of active gasoline vehicles. Because there are no Russia-specific emission factors for gasoline vehicles in the NIIAT methodology, we use $PM_{2.5}$ emission factors and OC/BC speciation ratios from the EEA emission guidebook (EEA, 2013). We also apply the same uncertainty approach used above for gasoline vehicles. BC emissions from all gasoline vehicles are ranged from 0.1 to 0.3 Gg with a central value of 0.2 Gg. OC emissions are in the range of 0.3 Gg–0.5 Gg with a central value of 0.4 Gg. The Supplementary Materials provide additional details on the spatial distribution of BC emissions from on-road vehicles in Russia.

In addition to on-road vehicles, other sources of BC emissions in the transportation sector include locomotives and domestic navigation (ships). To estimate emission from these sources, most studies combine data on fuel consumption and fuel-based emission factors.

There are very limited data on BC emissions from rail and shipping. Kholod et al. (2016) estimate emissions from locomotives to be 8.4 Gg of BC and 1.7 Gg of OC in 2014. For comparison, BC emissions from locomotives in the ICCT roadmap model were estimated at 8 Gg in 2010 and 9 Gg in 2015 (ICCT, 2015). Hoesly et al. (2017) estimate emissions from rail at 3.9 Gg of BC and 1.3 Gg of OC in 2014.

Domestic navigation is not a significant source of BC emissions in Russia. Ships emitted about 0.5 Gg of BC and 0.1 Gg of OC in 2014 (Kholod et al., 2016). Hoesly et al. (2017) estimate emissions from domestic navigation to be 0.6 Gg of BC and 0.4 Gg of OC in 2014.

Table 2
BC emissions from on-road transport (sorted by base year).

Study	Base year	BC emissions (Gg)	Covered sources
Lamarque et al. (2010)	2000	32	Transport, including aircraft and ships
Donchenko (2007)	2006	54 Gg $PM_{2.5}$ (29 Gg BC)[a]	On-road transport
Global transportation roadmap model (ICCT, 2015)	2010	12	On-road transport
Evans et al. (2015)	2010	20	On-road diesel transport
Huang et al. (2015)	2010	45	On-road transport
Donchenko (2013)	2011	39 Gg $PM_{2.5}$ (20 Gg BC)[a]	On-road transport
MNRE (2015a)	2013	8	Transport
Kholod et al. (2016)	2014	30	On-road transport, rail and ships
		21	On-road diesel transport
Hoesly et al. (2017)	2014	35	On-road transport, rail and ships
		31	On-road transport
Global transportation roadmap model (ICCT, 2015)	2015	8	On-road transport

[a] Assuming that the BC/PM speciation ratio for on-road transport is 0.53 (EEA, 2013).

Total BC emissions from the transportation sector (diesel and gasoline vehicles, locomotives and ships) are estimated to be in the range from 16.3 Gg to 41.2 Gg with a central value of **29.8 Gg**. Total OC emissions from transportation are estimated to be in the range from 7.8 Gg to 16.9 Gg with a central value of **12.7 Gg** in 2014.

3.3. Wildfires and agricultural burning

BC emissions from wildfires and agricultural burning play an important role in Russia because of its large area. Russia is the largest country in the world by land area, and forests cover 1.2 billion hectares of its territory (Fedstat, 2016b). Russia is also a large agricultural producer with the third largest area of arable land in the world (after the U.S. and India). Russia contributes 13% to global BC emissions from forest fires, 5% to global BC emissions from agricultural burning, and 2% to global BC emissions from grassland fires (EPA, 2012).

According to official statistics, about 2 million hectares of forest burned annually from 2008 to 2012 (Fedstat, 2016a). Humans cause most agricultural fires in Russia (Hao et al., 2016; Mollicone et al., 2006). The Russian Statistical Service reports that people caused up to 60% of Russian forest fires instances (Fedstat, 2016c), while Russia's climate change assessment report estimates this number to be as high as 90% (Roshydromet, 2014). However, the Intergovernmental Panel on Climate Change (IPCC) considers wildfires as non-anthropogenic in its Fifth Assessment Report (IPCC, 2013). Annual weather patterns also have a large influence over annual wildfire activity, as indicated by the large fluctuations in Russia's emissions from wildfires.

Emissions from forest fires and agricultural burning have had a significant effect on air quality in Russian cities and densely populated regions (Chubarova et al., 2008; Damoah et al., 2004; Konovalov et al., 2011; Zvyagintsev et al., 2011). Spring fires can more than double the Arctic haze (Warneke et al., 2008, 2010).

BC from fires can be transported and deposited on ice and snow in the Arctic (Stohl et al., 2007; Treffeisen et al., 2007). Severe forest fires in 2003 resulted in very high emissions, which significantly contributed to the BC deposited in the Arctic (Evangeliou et al., 2016; Generoso et al., 2007; Hao et al., 2016). Because fire activity can fluctuate significantly across years, we provide ranges as well as averages as opposed to data for a single base year as with other emission sources.

In the literature on Russia's emissions from both forest fires and agricultural burning, BC emissions are calculated as the product of the burned area, fuel load, combustion completeness, and the emission factors for the plant species burned.

There are two main approaches to estimating the burned area. The first approach is based on satellite data. The National Aeronautics and Space Administration (NASA) maintains two sun-synchronous polar-orbiting satellites, Terra and Aqua, that provide active fire locations, burned areas, and fire radiative power from three MODIS (MODerate Resolution Imaging Spectroradiometer) instruments (NASA, 2016). BC studies also use the Global Fire Emissions Database (GFED), which combines satellite information on fire activity and vegetation productivity to estimate area burned and emissions (GFED4, 2016).

The second approach is a bottom-up calculation based on data from official government statistics. Data on forest area burned forest fires and annual mass straw burned can be gathered from several sources. For forest fires, Russia's Forest Protection Service provides information on forest area burned, which in turn is based on reported fires. However, these estimates are several times lower than the data on area burned from satellites (Shvidenko and Schepaschenko, 2013). For agricultural fires, researchers analyze the agricultural statistics to estimate the amount of annual straw surplus burned. Straw surplus is calculated as the difference between the agricultural residuals and straw utilization. The straw usage approach that is based on official statistics yields results close to those from the satellite data (McCarty et al., 2012; Romanenkov et al., 2014).

Because official statistics may overlook remote areas where there is no direct land-based observation (Roth, 2016), most researchers prefer using satellite data from NASA (Hao et al., 2016; McCarty et al., 2012; Romanenkov et al., 2014). Some studies rely on statistics, either because they pre-date robust satellite data (for inventories for mid 1990s (Bond et al., 2004) or because researchers used data from the Russian Forest Service (Smirnov et al., 2015).

Data on two other elements of the emission calculation formula – fuel load and combustion completeness – are limited for Russia, and direct use of data from other countries is not always appropriate (Conard and Ivanova, 1997). For example, Rogers et al. (2015) found that Russia's fires are less intense, destroy less live vegetation, and kill fewer trees than fires in the U.S. For their recent study of forest fires in Northern Eurasia, Hao et al. (2016) have developed a fuel loading dataset for forested and non-forested areas using land cover maps and a dominant forest species map.

The last element in the calculation formula is BC emission factors. Since information on Russia-specific emission factors is limited, Hao et al. (2016) used emission factors for forest fires determined from aircraft measurements in the United States. The BC emission factors were assumed to be 0.93 g/kg and 1.36 g/kg for forest and non-forest fires, respectively (Hao et al., 2016). For agricultural burning, McCarty et al. (2012) use an emission factor of 0.69 g/kg for agricultural residue, which was calculated as the average from four different studies.

Table 3 shows BC emisisons from wildfires and agriculturals burning. Hao et al. (2016) and McCarty et al. (2012) provide the most comprehensive estimates of BC emissions from wildfires and agriculturals burning, respectively. Moreover, these studies provide estimates for a range of years, which is important as fire activity can vary significantly across years. We use the results from these two studies as references estimates for BC emissions from wildfires and agriculturals burning.

Using Hao et al. (2016) and McCarty et al. (2012) as reference values, the total annual BC emissions from wildfires in forests, grasslands, and other natural areas were estimated to be **569 Gg** during the 14-year period from 2002 to 2015 (Hao et al., 2016), while the annual BC emissions from agricultural fires were estimated to be **9 Gg** (McCarty et al., 2012).

With regard to OC emissions from wildfires, there are only two studies for Russia. Lamarque et al. (2010) estimate OC emissions from forest fires, grassland fires, and agricultural burning to total 2954 Gg in 2000. Sand et al. (2016) estimate OC emissions from agricultural burning to be 77 Gg in 2010. To estimate OC emissions from forest fires in recent years, we calculate OC/BC conversion ratios from Lamarque et al.'s study on forest fires (17.8:1) and grassland fires (9.7:1) and apply them to Hao et al.'s estimates of BC emissions in 2002–2015. Using this approach, we estimate OC emissions from wildfires to be **8954 Gg**. For agricultural burning, we use an OC/BC conversion ratio of 7:1 as reported by McCarty et al. (2012). Thus, we estimate OC emissions from agricultural burning to be in the range from 14 Gg to 154 Gg with a central value of **63 Gg**.

To estimate uncertainty in BC emissions from wildfires, we assume based on expert judgment that the uncertainty is 30% for burned areas, 20% for fuel loading, 5% for combustion completeness and 15% for emission factors. (For the discussion about uncertainty in emissions from fires see for example May et al. (2014)). The range of BC estimates is from 345 Gg to 793 Gg. The range of OC emissions from wildfires is from 5429 Gg to 12,479 Gg.

Table 3
BC emissions from wildfires and agricultural burning.

Study	Period	Emissions, Gg	Data sources
Lamarque et al. (2010) as used in EPA (2012)	2000	BC emissions, including forest 145 grassland 35 agricultural burning 7 OC emissions, including forest 2582 grassland 338 agricultural burning 34	UNFCCC Secretariat, Global Fire Monitoring Center publications, and FAO statistics
McCarty et al. (2012)	Average 2003–2009	Agricultural burning 9 (2–22) of BC	Satellite data
Smirnov et al. (2015)	2007–2012	Forest 82 (45–119) of BC	Data from the Russian Forest Service
Hao et al. (2016)	Average 2002–2015	BC emissions: forest 424 grassland 41 shrubland 45 savanna 59	Satellite data
Sand et al. (2016)	2010	Agricultural burning: 24 of BC 77 of OC	Satellite data

3.4. Residential/domestic sector

The residential sector includes homes owned by households while the domestic sector includes residential buildings, institutional and commercial buildings, as well as agricultural, forestry, fishing, and other unspecified sectors. In this section, we compare the estimates of BC emissions from both residential and domestic sectors (Table 4).

Russia has a well-developed system of natural gas supply for heating and cooking in the residential sector and extensive district heating. However, given the size of the country, not all homes are connected to these centralized energy supply systems. About 84% of apartments are connected to district heating systems, and 68% of all households have access to natural gas supply (centralized or compressed natural gas tanks) (GKS, 2013). In rural areas, more than 5 million households (about 10% of all households) rely on wood for heating and cooking (Government of Russian Federation, 2003); additional households rely on coal or oil products, though there are no specific estimates on the share. According to the Russian Energy Strategy through 2020, published in 2003, annual wood consumption in Russia is 50 million cubic meters and only 6 million cubic meters were commercially sold. According to Russian statistics, commercial production of wood for heating was 15.6 million cubic meters in 2010 and 14.9 million cubic meters in 2014 (Fedstat, 2015). Thus, the real consumption of firewood is possibly higher than officially reported, given the discrepancy in commercial fuel data.

Huang et al. (2015) estimate BC emissions from the residential sector using data on both fossil fuel combustion from the UN Statistic Division and fuelwood from Russian statistics. They do not cite the source for wood consumption, which makes it difficult to assess the data quality.

In addition to the residential sector, several studies present results of BC emission estimates for the domestic sector. Lamarque et al. (2010) present the highest estimate of BC emissions from the domestic sector. The results from Sand et al. (2016) and GAINS (Amann et al., 2013) are similar, while the Russian government presents the lowest estimate of BC emissions from the domestic sector.

Hoesly et al. (2017) estimate emissions from the residential sector specifically and from the domestic sector more broadly. Biomass combustion is responsible for about one third of BC emissions from the domestic sector. Specifically, they estimate BC emissions to be 14.1 Gg from the residential sector and **27.0 Gg** from the domestic sector in 2014. OC emissions were estimated at 10.8 Gg from the residential sector and **122.7 Gg** from the domestic sector. The uncertainty range in the domestic sector is from 20 Gg to 428 Gg for BC and 91 Gg and 1944 Gg for OC. We present these estimates as the reference for the domestic sector.

3.5. Energy sector

Russia has a well-developed energy industry, which is the backbone of Russia's economy providing 27% of GDP, 43% of budget revenues and 63% of the value of exports (Minenergo, 2015b). BC emissions from the energy sector include emissions during the extraction of fossil fuels (energy sector own energy use) and emissions from generation and distribution of electricity and heat.

According to the IEA, total installed capacity of electricity generation facilities is 223 GW with a peak demand of 157 GW. Natural gas dominates the energy mix for electricity production (49%). Coal and oil products produce 17% and 3% of electricity, respectively, and nuclear and hydro produce the rest (IEA, 2014).

Russia has the largest district heating industry in the world. Natural gas is also the predominant fuel for district heating (60%), while coal and oil products provide, respectively, 20% and 5% of district heating (IEA, 2014). Most of Russia's large thermal power plants produce both heat and electricity. Though natural gas dominates the energy mix in electricity and heat generation, gas is a clean fuel with respect to BC emissions. As a result, coal-fired and heavy-oil power plants are the largest sources of BC emissions in the power and heat sectors in Russia.

There are a limited number of studies on BC emissions from the heat and power sector (Table 5). Since there are a wide variety of combustion technologies in this sector (as well as in industrial and the residential sectors), all studies use fuel-based emissions factors.

Lamarque et al. (2010) estimate BC emissions from 1850 to 2000 for the "Russia +" region, which includes Russia and three Caucasus countries (the estimate for Russia alone is available from EPA (2012)). Similarly, the GAINS model, developed by IIASA, estimates BC and OC emissions from this sector for the "Russia +" region from 2000 to 2050.

Russia submitted its first report on BC and methane emissions to the Arctic Council in 2015 (MNRE, 2015a). The Ministry of Natural Resources and Environment produced the report but provided few methodological explanations.

Huang et al. (2015) estimate BC emissions from the energy sector in Russia assuming that all BC emissions are fully attributed

Table 4
BC emissions from residential/domestic sector (sorted by base year).

Study	Base year	BC emissions, Gg	Notes
Lamarque et al. (2010)	2000	102	Domestic
Huang et al. (2015)	2010	56	Residential, including wood combustion 34.2 Gg coal combustion 17.3 Gg
GAINS (Amann et al., 2013)	2010	18	Domestic
Sand et al. (2016)	2010	22	Domestic; Gg of carbon (ECLIPSE emission data set V4.0a)
MNRE (2015a)	2012	13	Domestic
Hoesly et al. (2017)	2014	27	Domestic, including residential 14.1 Gg agriculture, forestry, fishing 7.3 Gg commercial-institutional 5.6 Gg

to coal-fired power plants. Russian power plants are required to report calculated estimates of emissions. Assuming that emissions reported by the Russian Statistical Service (reported as solid matter) equal emissions of total suspended particulates (TSP), Huang et al. (2015) developed conversion factors to downscale reported emissions to $PM_{2.5}$ and then to BC emissions. (Additional information on the Russian terminology for soot and BC is available in the Supplementary Materials.) The researchers assume that the $PM_{2.5}$/TSP ratio is 0.286 and the BC/$PM_{2.5}$ ratio is 0.0357. However, we argue that it is more accurate to break out emissions by source of fuel, rather than assume that all BC emissions are from coal-fired power plants. Though coal-powered plants generated 19.3% of heat, and heavy-fuel oil (mazut) produced only 3.7% in 2013 (IEA, 2015), the $PM_{2.5}$ emission factor for coal is 3.4 g/GJ while the emission factor for heavy-fuel oil is 19.3 g/GJ (EEA, 2013). As a result, the emissions from coal-fired and heavy fuel oil power plants are equally important.

Hoesly et al. (2017) use IEA data for all fuels used for electricity and heat generation, including coal, heavy fuel oil, and diesel. Natural gas dominates the emery mix in this sector (63%). Coal is the second largest fuel (32%) and biomass fuels account for only 3% of power and heat production in Russia. The BC emission factor for biomass is much higher than the emissions factor for hard coal and, as a result, BC emissions from combustion of biomass are about three times higher than the emissions from coal and heavy oil. This study also estimates BC emissions from refinery process emissions.

Hoesly et al. (2017) estimate emissions from the heat and power sectors to be **16.4 Gg** of BC and **66.9 Gg** of OC. Using the uncertainty in SPEW emission factors and uncertainty in energy consumption, we estimate that the uncertainty range is from 11.9 Gg to 26.7 Gg for BC and 48.4 Gg and 108.7 Gg of OC. We use these estimates as reference values for emissions in the heat and power sector.

3.6. Industry

BC emissions from industry include emissions from the combustion of coal, oil, diesel, and other fuels in metallurgy, the chemical industry, mining, construction, manufacturing, and other industries. Table 6 shows the available BC estimates for industry.

The estimates of BC emissions by Lamarque et al. (2010) and the Russian government (MNRE, 2015a) are similar and based on fuel balances, while Kholod et al. (2016) estimate BC emissions from diesel sources only.

Huang et al. (2015) use the method they developed for the power sector to estimate BC emissions from industry. They use Russian estimates of raw particulate emissions and BC/PM ratios from industry. However, Russian statistics do not use the terms "particulate matter" and "black carbon" (see the Supplement), making it difficult to compare Russian data with international data and international speciation factors. This estimate is based on a typographical error, stating that raw particulate emissions from industry were about 24,663 Gg in 2010, but Russian statistics provide estimates for emissions of "solid matter" from stationary sources at 2400 Gg in 2010 and 2000 Gg in 2014. The Russian Ministry of Natural Resources and Environment reported that stationary sources emitted 2381 Gg of solid matter in 2010 and 1922 Gg in 2014 (MNRE, 2015b). The amount of all pollutants from stationary sources was 19,116 Gg in 2010 (MNRE, 2013, 2015b), which is less than the amount reported in Huang et al. (2015).

Hoesly et al. (2017) use IEA energy data and apply BC and OC emission factors from the SPEW tool. Natural gas accounts for about 80% of the energy used in industry, but the largest emissions are from diesel combustion (85%). The mining industry alone is the largest source of BC emissions (about 40% of industrial BC emissions). Hoesly et al. (2017) estimate emissions from industry to be **5.2 Gg** of BC and **2.0 Gg** of OC.

The uncertainty in BC emissions from industry in Russia is very large. There are no Russia-specific emission factors for BC, and emission factors from other countries may not be comparable to those in Russia. We estimate the uncertainty in the range from 1.0 Gg to 51.3 Gg of BC with a central value of 5.1 Gg. OC emissions are estimated at 2.0 Gg with an uncertainty range of 0.4–19.7 Gg. We use these results as reference values for emissions from industry.

3.7. Summary of BC and OC emissions in Russia

Based on the studies we reviewed, we estimate Russia's BC

Table 5
BC emissions from the energy sector (sorted by base year).

Study	Base year	BC emissions (Gg)	Notes
Lamarque et al. (2010)	2000	5	Cited from (EPA, 2012)
GAINS (Amann et al., 2013)	2010	12	"Russia +" region (Russia, Armenia, Azerbaijan, and Georgia)
Huang et al. (2015)	2010	12	Coal only
MNRE (2015a)	2013	94	Production and distribution of power, gas, and water
Hoesly et al. (2017)	2014	16	Electricity and heat

Table 6
BC emissions from industry (sorted by base year).

Study	Base year	BC emissions (Gg)	Notes
Lamarque et al. (2010)	2000	33	As presented in (EPA, 2012)
Huang et al. (2015)	2010	29.3	manufacture of coke/refined petroleum 20.6%, metals 18.5%, wood products 18.4%, food products 14.6%
MNRE (2015a)	2013	31.1	Manufacturing
Kholod et al. (2016)	2014	6.3	Diesel only
Hoesly et al. (2017)	2010	5.5	Industry, including
	2014	5.2	mining 2.1 Gg construction 0.5 Gg food-tobacco 0.5 Gg wood products 0.4 Gg chemicals 0.3 Gg non-metallic minerals 0.3 Gg transport equipment 0.3 Gg

emissions in 2014 at 688 Gg, and OC emissions at 9224 Gg. Table 7 presents our summary of BC and OC estimates for Russia. While this study seeks to improve our understanding of BC emissions in Russia, there is still significant uncertainty associated with BC emissions. This is due to a large extent from our relatively limited understanding of emission factors under different conditions. Flaring, wildfires, and industry in particular have wide uncertainty ranges. Overall, the uncertainty ranges from 401 Gg to 1453 Gg in BC emissions and from 5596 Gg to 14,736 Gg in OC emissions.

The reference BC estimates for emissions from flaring and transportation presented in this study are, in most cases, significantly lower than in some recent studies. Russian policies to reduce flaring and vehicle emission control regulations have likely played a large role in decreasing Russia's BC emissions in recent years, which is one reason that studies vary. Wildfires are the important exception, where the reference values from Hao et al. (2016) are higher than some studies, including those in the ECLIPSE database, resulting in a net increase in estimated emissions from wildfires.

4. Radiative forcing in the Arctic

BC is well known to have a strong radiative forcing effect. However, because the combustion processes that emit BC also emit OC (and sulfate aerosols), which has a radiative cooling effect, the full forcing effect of the combustion process is more difficult to determine. As the relative emission amounts determine the degree of radiative warming or cooling, it is important to consider the BC/OC emission ratio when looking at climate effects.

Sand et al. differentiate between the radiative forcing effects of BC and OC emissions in Russia by sector (Sand et al., 2016). The researchers report that even though grass and forest fires result in the highest BC emissions of the sectors analyzed, the net radiative forcing effect was small (1.3 mWm^{-2}) because of the even higher emissions of OC. BC emissions from gas flaring resulted in the highest radiative forcing of any sector (64 mWm^{-2}). Different sectors and fuels have large differences in their ratio of BC and OC emissions, which in turn has a significant impact on overall radiative forcing. Other factors that affect the BC/OC ratio are the efficiency of combustion and the extent of emissions controls.

Table 8 compares the reference results from this study with those from Sand et al. (2016). Our forcing o estimates were calculated by scaling back the estimates from Sand et al. (2016).

The adjusted emission estimates presented in this paper, thus, show a net increase in both BC and OC emissions compared to the numbers presented in Sand et al. (2016). For reference, Sand et al. (2016) also considers the impact of SO_2 and O_3 in their forcing calculations, which we have not considered given the focus of this paper is on BC.

Location also plays a large role in radiative forcing in part because of differences in surface albedo. Sand et al. compares the direct radiative forcing of BC in three latitude zones: the Arctic, 28° N - 60° N, and 28° S-28° N (Sand et al., 2016). For each sector analyzed, the direct radiative forcing from BC was highest in the Arctic and lowest between 28° S and 28° N. This result highlights the exceptional sensitivity of the Artic to BC emissions. Because the surface albedo of regions covered in snow and ice is so high, large swings in albedo are possible, especially from the accumulation of a strong light absorber like BC. Stronger light absorption raises the local air temperature and melts snow and ice, amplifying the effect (Bond et al., 2013; Hansen and Nazarenko, 2003; Koch and Del Genio, 2010; Quinn et al., 2008; Quinn et al., 2011; Warren and Wiscombe, 1980).

Where BC/OC emissions occur has a profound impact on the Arctic, with emissions in and near the Arctic being the most influential (Bond et al., 2013; Quinn et al., 2011; Wobus et al., 2016). Because Russia covers the majority of the global land surface in and near the Arctic, emissions in the country play an outsized role in Arctic warming, and, conversely, emission reductions in the region can reap large mitigation rewards. Wobus et al. report the effects of BC and OC (and SO_2) emissions by sector on temperature change in the Russian Arctic (Wobus et al., 2016). BC and OC emissions in the domestic and transport sectors resulted in the highest temperature increase while emissions from the energy, industry, and waste sectors and fires showed cooling effects (Wobus et al., 2016).

Overall, comparing our data on BC and OC emissions in Russia with those from Sand et al. (2016), we find a decrease in Arctic forcing by 39%, which is significant. While some of this decrease is due to more detailed methodologies or data, the majority of it is because of policies that Russia has undertaken in the past decade, particularly regarding flaring and transportation. Russia significantly raised the fines it charges for flared methane emissions beginning in 2012, and began preparing the industry for this change several years earlier through policy announcements and efforts to ease market access for APG (Evans and Roshchanka, 2014). BC emissions from flaring dropped by 48.5% from 2011 (the year before the fines were raised) to 2014. Likewise, Russia began requiring emission controls on new and imported vehicles in 2006, such that today, 95% of the active diesel passenger fleet and 75% of trucks have some degree of controls (Kholod and Evans, 2016; Kholod et al., 2016). Using the dataset from Kholod et al. (2016) we estimate that without emission controls BC emissions from active diesel vehicles would be 34.2 Gg or 40% higher. Combined, the policy changes from vehicle emission controls and flaring fines likely decreased emissions in 2014 by approximately

Table 7
BC and OC emissions in Russia.

Sector	BC, Gg (uncertainty range, Gg)	OC, Gg (uncertainty range, Gg)	Base year(s)	Study cited
Flaring	32 (10–54)	6 (2–11)	2014	Own estimates
Transportation	30 (16–41)	13 (8–17)	2014	Kholod et al. (2016)
Wildfires*	569 (345–790)	8950 (5430–12,480)	Average of 2002–2015	Hao et al. (2016); Own estimates for uncertainty
Agricultural burning	9 (2–22)	63 (17–155)	Average of 2003–2009	McCarty et al. (2012)
Domestic sector	27 (15–468)	123 (90–1944)	2014	Hoesly et al. (2017)**
Power generation and heating	16 (12–27)	67 (48–109)	2014	Hoesly et al. (2017)**
Industry	5 (1–51)	2 (1–20)	2014	Hoesly et al. (2017)**
Total	688 (401–1453)	9224 (5596–14,736)		

Note: * we take an average of the fire activity in recent years as the reference value because fire activity can fluctuate significantly from year to year based on weather patterns and other factors.
**- Uncertainty estimates are calculated using low and high SPEW emission factors and various estimates for energy consumption (mostly from the IEA and Russian estimates).

Table 8
BC and OC emissions in Russia and their radiative forcing in the Arctic.

Sector	Reference values		ECLIPSE and Sand et al. (2016)			Our estimates based on reference values	
	Emissions	Emissions	Emissions	Emissions	Forcing in the Artic	Forcing in the Arctic	Difference in forcing from Sand et al. (2016)
	BC	OC	BC	OC	BC + OC	BC + OC	BC + OC
	Gg	Gg	Gg	Gg	mWm^{-2}	mWm^{-2}	mWm^{-2}
Flaring	32	6	65	13	64.0	31.8	−32.2
Transportation	30	13	52	57	22.7	14.6	−8.1
Wildfires	569	8950	155	2455	1.3	7.3	6.0
Agricultural burning	9	63	25	78	4.8	0.5	−4.3
Domestic sector	27	123	22	45	8.8	6.5	−2.3
Power generation, heating and industry	21	69	19	33	7.6	6.4	−1.2
Total	**688**	**9224**	**337**	**2680**	**109.2**	**67.1**	**−42.1**

44 Gg (30.3 Gg for flaring and 13.5 Gg for transport), which represents 37% of total Russia's anthropogenic BC emissions in 2014 (assuming wildfires are non-anthropogenic). This provides a powerful lesson for other countries seeking to reduce their climate-related emissions in the near term through policies. At the same time, Russia still has very large opportunities to further mitigate its BC emissions from flaring, transportation and other sectors. For example, the largest volume of flaring globally still takes place in Russia, large numbers of older vehicles have high emissions, and off-road vehicles only rarely employ control technologies.

5. Conclusions

This paper presents consolidated estimates of BC and OC emissions in Russia, using detailed analysis of the methodologies and data from multiple studies. We highlight the study or studies for each sector that appears to have the most detailed, robust methodologies and data, which we share as reference estimates. Many studies of Russia's emissions present only estimates of BC, not OC as well, and they also, in many cases, lack uncertainty estimates. We have added both OC estimates and uncertainty to each of the reference sectoral estimates. We estimate Russia's BC emissions at 688 Gg and OC emissions at 9224 Gg in 2014. We found that Arctic forcing from Russia's BC and OC emissions is 39% lower than was previously estimated, to a large extent because of policy interventions that have reduced emissions from flaring and transportation. The results of this review can be used by policy makers to prioritize emission reduction mitigation measures. Climate modelers can use the updated data for better representation of Russia's BC and OC emissions in global climate models.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2017.05.026.

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