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OPTICAL MODELS AND DATABASES

Anthropogenic Black Carbon Emissions to the Atmosphere: Surface Distribution through Russian Territory

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Abstract—Official statistical data from the Ministry of Natural Resources and Ecology of the Russian Federation on anthropogenic pollutant emissions from Russian cities and regions for 2010 are analyzed, and the black carbon (BC) emission distribution through the Russian territory is estimated. The lack of this information makes it difficult to study the long-range atmospheric transport of BC and forecast the related climate and ecological effects. Calculations are based on available data on carbon monoxide (CO) and BC emissions from Russian cities and regions under the assumption of proportionality of the BC and CO emissions, independently of transport and stationary sources. The analysis includes 54 regions and almost 100 cities in an area within (50–72° N × 20–180° E), which covers about 94% of the Russian territory. The spatial distribution of the annual BC emission through the territory under study is modeled on a (1° × 1°) grid for the first time. The total annual BC emission from this area is estimated at (210 ± 30) Gg. The main anthropogenic BC sources are located in industrial regions of the central European part of Russia, Southern Ural, Western Siberia, and on the large sparsely populated territories of the Western Siberia with natural oil/gas extraction industry.

Keywords: atmospheric pollution, anthropogenic emissions, black carbon, Russian emissions

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INTRODUCTION

Black carbon (BC) is one of significant short-lived climate-relevant air components [1–3]. The role of atmospheric BC is especially significant in the climate of the polar regions [4, 5], which are key with respect to the global climate. Thus, in addition to different effects on the radiative properties of the atmosphere, BC noticeably affects the optical properties of the underlying surface: precipitating on snow and ice, it changes the albedo and radiative budget in the atmosphere–Earth's surface layer. Secondary climate effects also manifest themselves in upper tropospheric layers; they are connected with the effects of BC aerosol particles on processes of cloud and precipitation formation.

Anthropogenic admixtures can exist more than 10 days over the Arctic in a cold season, mixing within the Arctic front like in a huge reservoir [6]. About half the coast and 1/3 of the water area of the Arctic Ocean [7] belong to Russia; this makes the Russian Federation (and its air pollutant sources) one of key factors that form the composition and properties of the environment in polar latitudes of the Northern hemisphere.

Most model estimates of BC effect on the Arctic and midlatitude climate [4] are based on data on BC emissions received with the use of remote reverse modeling [8, 9] or from satellites (e.g., [10, 11]). Errors in these calculations can be quite high, since just the surface air layer, where the main anthropogenic BC and fire emissions occur, are analyzed worst of all with satellite instruments. Remote model estimate interpretation results strongly depend on the accuracy of accounting for weather conditions, clouds, properties of an underlying surface, vertical profiles of other atmospheric components throughout its depth, and other parameters. Therefore, ground-based estimates of the same parameters are important and interesting. Of course, they also have errors and disadvantages; in particular, data on anthropogenic emissions of different pollutants are strongly limited and often corrupted.

In this work, the spatial distribution of anthropogenic BC atmospheric emission sources over Russian territory is analyzed on the basis of the most complete and comparatively recent official statistical data from the Ministry of Natural Resources and Ecology of the Russian Federation [12, 13], and the data on the annual BC emission are represented in a form suitable for further ecological, climate, and economic estimations.

SOURCE DATA AND APPROACHES

Let us say a few words about the terminology. Black carbon was called soot, or graphite, in Russian literature until recent times. The name "elemental carbon" is more correct; it emphasizes that this matter is neither organic carbon nor diamond. The name "black carbon" (BC) reflects an important property of this component to absorb visible solar radiation. This property grounds the most common technique for measuring BC concentrations in air by absorption of filter aerosol samples. The term BC is used further in the analysis of emissions of matter called “soot” in ROSHYDROMET Annual Reports. Let us note that real soot can also include organic carbon and others materials.

Initial data for the estimates for 2010 were taken from [13]. Unfortunately, Russian official statistics do not report and, evidently, do not record, BC (soot) emissions from the territorial entities of the Russian Federation. There are data on BC emissions from cities, but only from stationary sources, and regional data on vehicle emissions. The use of data on urban BC emissions in estimation of its long-range atmospheric transport and pollution of distant Arctic regions provided evidently understated results [14]. In this case, small settlements and individual coal, oil, and gas extracting plants, which burn associated gas in the open air, are neglected, as well as emissions from natural and agricultural fires, which determine the atmospheric BC content in some regions in the warm season. On the other hand, the use of only vehicle BC emissions for regions is evidently insufficient as well. In addition, territories of some entities of the RF are larger in area than some European countries, which makes it difficult to use consolidated figures.

The source data have not been differentiated with respect to months and seasons; therefore, the analysis of seasonal variations in the BC emissions in the atmosphere is impossible. However, these variations should be evident, since domestic heating, which is one of the main atmospheric BC sources, depends on season. Finally, our estimates concern only annual emissions.

A technique developed for estimation of atmospheric BC emissions from Russian regions on the basis of all data [13] on CO and BC emissions for Russian cities and regions is discussed in this work. The sum of CO emissions from cities (usually the largest region) is significantly lower than the total regional emission, which allows one to hope that this last parameter shows the emissions from territories outside cities.

Both CO and BC are emitted in the atmosphere during incomplete combustion of different carbonaceous fuels. The ratio of emissions of these pollutants depends on the fuel type and industrial and other processes typical for one or another city or region. Therefore, *proportional CO and BC emissions within a region become the main assumption.*

It is clear that CO and BC are emitted in the atmosphere by both stationary sources and vehicles both in cities and outside. Sums of these emissions compose regional emissions. No other CO and BC sources are considered in this approach.

The following data [13] were source for our estimates:

a) city CO emissions from stationary sources $(CO_c)^{st}$ and vehicles $(CO_c)^{v}$;

b) regional CO emissions from stationary sources $(CO_r)^{st}$ and vehicles $(CO_r)^{v}$;

c) BC (soot) emissions from stationary sources in cities $(BC_c)^{st}$ and from vehicles on the territory of regions $(BC_r)^{v}$.

The coefficients of proportionality of BC and CO emissions from vehicles k^{v} and stationary sources k^{st} are calculated separately for each region; further they are considered constant within a region:

$$k^{v} = (BC_r)^{v}/(CO_r)^{v}, \quad (1)$$

$$k^{st} = \left\langle \left\{ (BC_c)^{st}/(CO_c)^{st} \right\} \right\rangle, \quad (2)$$

where $\langle \quad \rangle$ mean averaging over regional cities, which are included in the analysis according to the presence of source data a)–c).

Then the total BC emission for each city included in the analysis

$$(BC_c) = (BC_c)^{st} + (CO_c)^{v} k^{v}.$$

For the region territory outside the cities, BC emission from stationary sources and vehicles and the total emissions (BC_) are calculated:

$$(BC\_)^{st} = \left((CO_r)^{st} - \Sigma\left\{ (CO_c)^{st} \right\} \right) k^{st},$$

$$(BC\_)^{v} = \left((CO_r)^{v} - \Sigma\left\{ (CO_c)^{v} \right\} \right) k^{v},$$

$$(BC\_) = (BC\_)^{st} + (BC\_)^{v}.$$

Finally, (BC_) values are uniformly distributed over the territory of the region and over (1° × 1°) grid cells accounting variation in the cell area with latitude (cell area almost halves when moving northward from the 50th to the 70th degrees of latitude).

The total BC emission from the territory of each region is calculated as the sum

$$(BC_r) = (BC\_) + \Sigma(BC_c).$$

It is clear that this technique (with averaging over cities) in regions with many cities, presented in an Annual Report, can ensure higher reliability of the resulting estimates. Vice versa, if a region is represented by only one city, the ratio between emissions of the pollutants under study cannot be confidently considered the same outside this city. This inhomogeneity of the source material significantly (along with uncertainties of numerical data in the Annual Reports) determines both absolute results of the estimates of spatial distribution of BC emissions and the dispersion of the estimate of total BC emissions from the Russian territory under study.

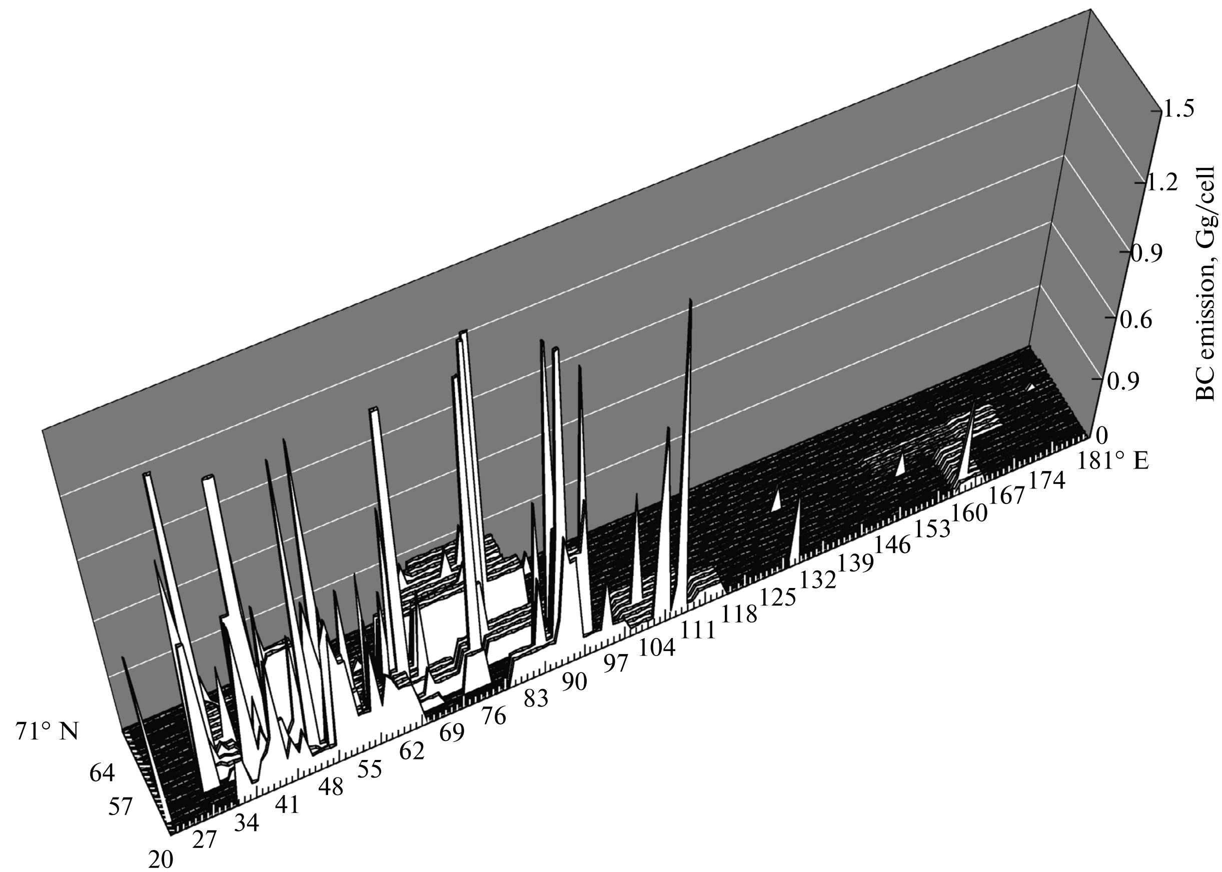

Fig. 1. Spatial distribution of anthropogenic BC emissions (Gg per cell area) on a (1° × 1°) grid through the Russian territory to the north of 50° N.

A territory within (50–72° N × 20–180° E) was studied; the analysis included 54 Russian regions and almost 100 cities, for which required data were available (see items a–c). This territory occupies about 16 millions km^2, with a population of more than 90 millions. Geographical coordinates of the cities and regions, as well as their areas and population were taken from data [13, 15–17] and on websites [18, 19]. The most southern territories of the RF (to the south of 50° N) remained beyond the scope of the analysis; their area is more than 1 million km^2, which is about 6% of the area of Russia.

SPATIAL DISTRIBUTION OF ANTHROPOGENIC BC EMISSIONS

Figure 1 shows the general distribution of anthropogenic BC emission through the Russian territory under study. Maxima of city emissions (up to 4000 t/year) are cropped by the limit of the selected scale.

Figure 2 shows the total meridional (summation over longitude for each meridian) and zonal (summation over latitude for each degree of longitude) distributions of these emissions. The areas of each "stripe" of 1° are equal in Fig. 2b, while they decrease from south to north in Fig. 2a. All the three diagrams show spatial features of population and economy on the Russian territory, which are caused by physical and economic conditions of regional development. The emissions are the highest in developed regions dense with population in the central European part of Russia, Southern Ural, Western Siberia, and in the sparsely populated territories of the Yamalo-Nenets and Khanty-Mansi Autonomous Areas, with the natural oil/gas extraction industry. The pronounced peaks in BC emissions from cities in Fig. 1 are similar to characteristic peaks of BC concentrations measured in TROICA expeditions, where traveling air masses transported pollutants from Russian cities to a sampler which moved throughout the Russian territory by train [20].

Figure 3a shows the estimates of annual BC emissions from Russian regions under study and CO emissions as results of summation of data [13] on atmospheric emissions from stationary sources and ground vehicles. The absence of a statistically significant correlation between these magnitudes is evidently absent (the correlation coefficient is 0.31).

Coefficients of proportionality of BC and CO emissions for vehicles k^v (1) differ insignificantly over regions; the standard deviation is 0.0024 at an average

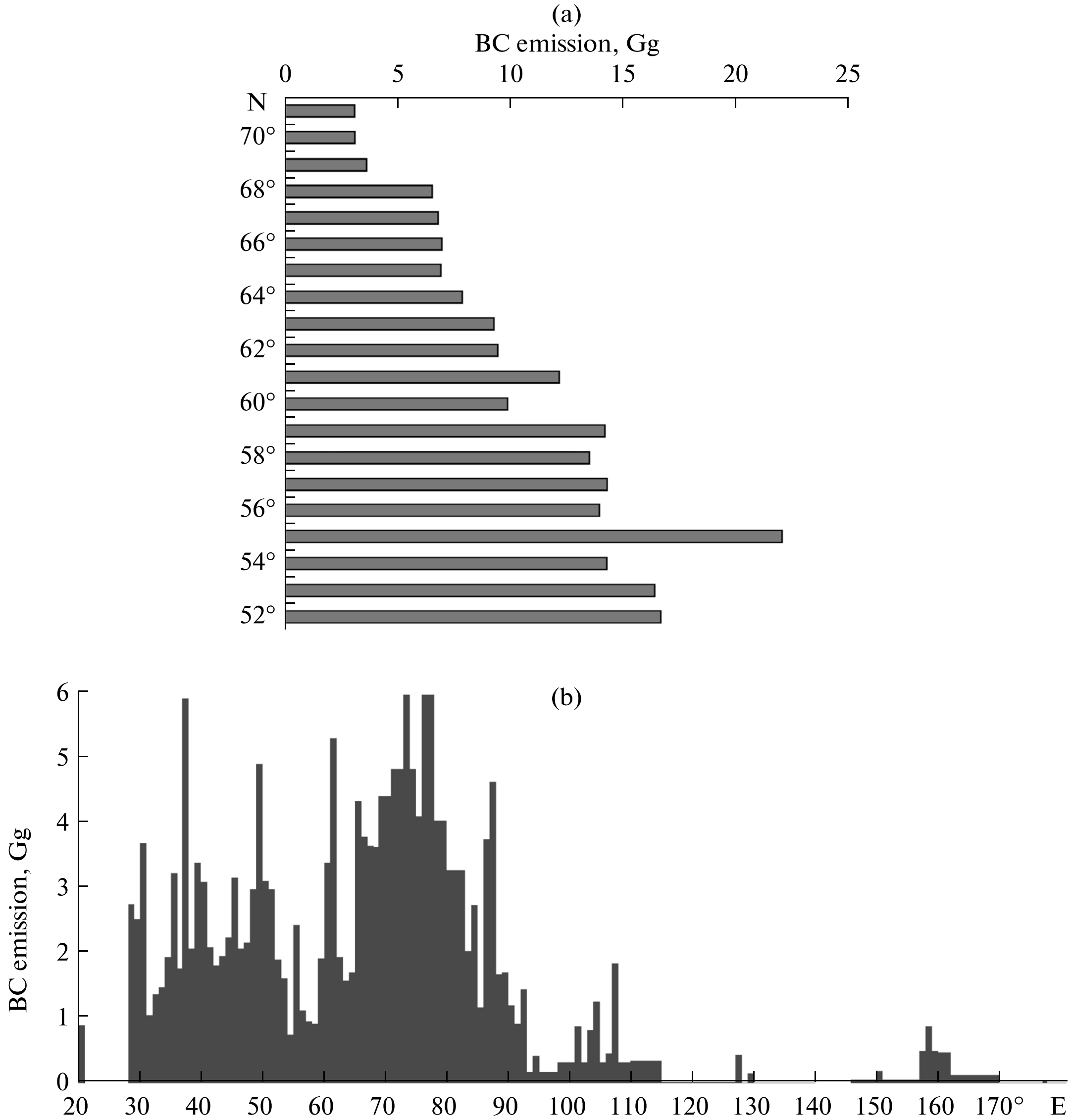

Fig. 2. Total (a) meridional and (b) zonal distributions of anthropogenic BC emissions from the Russian territory.

value of 0.007, which can be used for estimates throughout Russia. Vice versa, the ratio of BC and CO emissions from stationary sources (2) varies strongly from region to region (average k^{st} is about 0.073 at a standard deviation of 0.114), which witnesses a variety of industrial and domestic processes that produce these emissions.

The table includes statistical parameters of the regional distribution of BC and CO emissions, and some economic and statistical parameters calculated. The BC/CO emission ratio is about 0.017 from the consolidated figures. In this case, the absolute magnitudes of the emissions and their ratios vary significantly over the regions. As for the total CO and BC emissions from the Russian territory under study, CO^v is about 1.5 times higher than CO^{st}, while BC^v is about 1/4 of BC^{st}.

Note that CO and BC emissions are not proportional to areas or population of the regions (Figs. 3b and 3c). Only CO emission to the atmosphere from ground vehicles is proportional to the population of a region (the correlation coefficient is 0.82). The distributions of total CO emissions (from stationary sources and vehicles), shown in Fig. 3, are not given implicitly in [13], though they can be used for different economic and other estimates.

In general, the annual anthropogenic CO emission from the Russian territory under study in 2010 was about 12.16 Tg [13]; the BC (soot) emission has been estimated at (210 ± 30) Gg, which corresponds well to estimates from other works: 11 Tg of CO in 2010 [11] and 230 Gg of BC in 2008 [5]. In view of differences in the principal approaches to the estimation and proba-

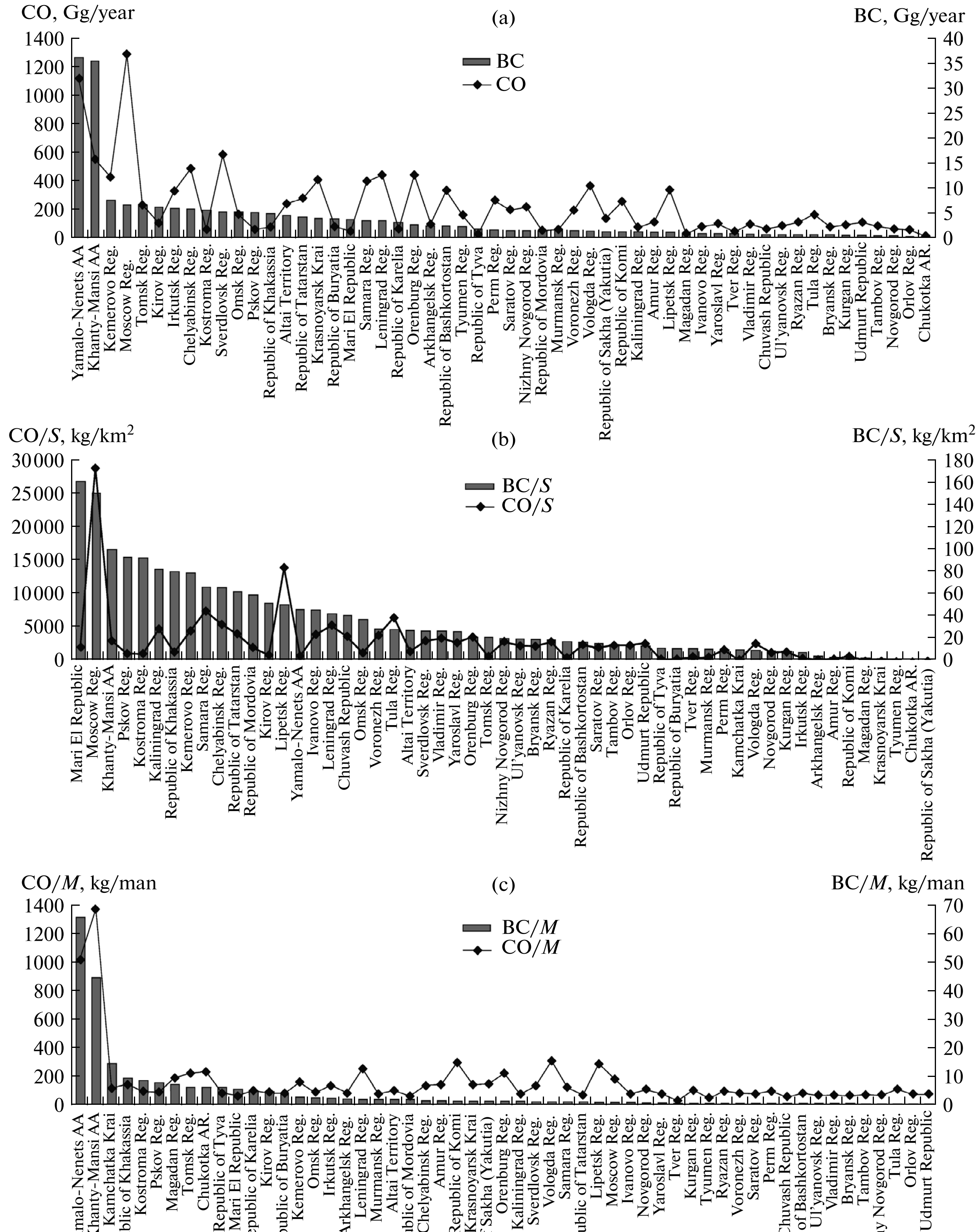

Fig. 3. Anthropogenic BC and CO emissions (a) from the territory of regions, (b) per unit area (S is the region area), and (c) per inhabitant (M is the population of a region).

Statistics of CO and BS emissions in the atmosphere on regions considering the areas (S) and population (M). Regions with maximal and minimal values of the parameters are given in parentheses

Statistical parameter	CO^v, Gg/year	CO^{st}, Gg	BC, Gg	BC/S, kg/km^2	BC/M, kg/man	BC/CO
Average	132	90.1	3.86	34.6	4.4	0.022
Standard deviation	174	156	6.6	36.0	10.5	0.023
Median	79.5	25.15	1.6	20.2	1.3	0.011
Maximum	1242 (Moscow Reg.)	950 (Yamalo-Nenets AA)	36.3 (Yamalo-Nenets AA)	161.5 (Mari El Republic)	65.6 (Khanty-Mansi AA)	0.088 (Kostroma Reg.)
Minimum	3.5 (Chukotka AR)	3.9 (Orlov Reg.)	0.31 (Chukotka AR)	0.43 (Republic of Sakha (Yakutia))	0.37 (Udmurt Republic)	0.0036 (Lipetsk Reg.)

ble interannual variations in the emissions, the values can be considered satisfactorily close.

The resulting distributions of anthropogenic BC emissions into the atmosphere through the Russian territory (Fig. 1) were used for estimation of the BC concentration in the atmosphere and flows to the Arctic coast of the Arctic Ocean near the Nenets, Gydanskii, and Lena Delta Wildlife Reserves [21]. In contrast to previous calculations [14], where only BC emission from cities were considered and indicators for pollution for the region of the Nenets Nature Reserve were underestimated, new results agree satisfactorily with results in the Russian Arctic [22–26]. In addition to absolute values of the emissions, discrimination of the Gydanskii Nature Reserve region as the most BC polluted among other regions considered is one of the most important results of the estimation [21]. This is due to anthropogenic BC emission sources on the territories of Yamalo-Nenets and Khanty-Mansi Autonomous Areas, which is typical for territories with developed and growing oil and gas infrastructure.

CONCLUSIONS

Atmospheric emissions of anthropogenic BC from the Russian territory (spatial distribution on a 1° × 1° grid) have been estimated for the first time on the basis of official statistical data from the Ministry of Natural Resources and Ecology of the Russian Federation for 2010. The analysis has been carried out for 95% of the Russian territory to the north of 50° N with a population of 90 million.

The total annual BC emission from this area is estimated at (210 ± 30) Gg. The highest emissions are typical for industrial regions with the dense populations of the central European part of Russia, Southern Ural, Western Siberia, and for large sparsely populated territories of Yamalo-Nenets and Khanty-Mansi Autonomous Areas with a natural oil/gas extraction industry.

The resulting estimates are represented in the form of diagrams and tables and can be further used for model calculations, analysis and forecast of climate, ecological, and economical effects caused by anthropogenic BC emissions and propagation in the atmosphere.

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