The black carbon content variations in the Arctic region during 2011 - 2018

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Abstract. Data on black carbon (BC) concentrations obtained from the board of research vessels (R/V) „Acad. Mstislav Keldysh“, „Acad. M.A. Lavrentyev“ and „Prof. Molchanov“ in 2011 – 2018. They were used to study the quantitative distribution of black carbon in the driving air layer over the seas of the Russian Arctic in the summer-autumn period and to determine its main source regions. Variations in the BC content in the near water layer of the atmosphere at the North Pole, in the Norwegian, Barents, Kara, East Siberian Seas and the Laptev Sea are obtained. As a result of 12 marine expeditions in the summer-autumn period of 2011 - 2018 the BC concentration in the atmospheric drive layer in the Arctic was mainly at the background level and averaged 47 ng/m³ (9-95 ng/m³). An increase in the BC concentration by several times, as shown by trajectory analysis, occurs occasionally upon receipt of air masses from the mainland, from areas of associated gas combustion. Low BC values were observed when air masses passed over the water surface from the northern regions of the Arctic. The BC concentration above the water surface depends on the state of the atmosphere in the region of soot sources on the mainland.

1. Introduction
Black carbon (soot), which is an important component of aerosols and insoluble particles that accumulate in the snow cover, has a significant impact on climate change and the degree of pollution in the Arctic [1]. Black carbon (BC) is formed as a result of incomplete combustion of fossil fuels (primarily coal, oil) and biomass or biofuels. It consists of submicron particles and their aggregates and can be transported to a large distance from their source, as well as a significant part of the scattered sedimentary matter of the atmosphere [2]. In addition to various effects on the radiation properties of the atmosphere, black carbon has a noticeable impact on the optical properties of an underlying surface: falling on snow and ice, it changes the albedo and radiation balance in the atmosphere – earth surface layer [2, 3]. Soot particles are air pollutants dangerous for human health. The fraction of aerosols with a diameter of less than 2.5 microns is the most toxic, because such particles cause and enhance respiratory, cardiovascular and allergic diseases [3].
There are few data on the BC concentration in the atmosphere and snow cover of the Russian Arctic, obtained by us together with colleagues [4,5] and Russian scientists [6,7], while in the American, Canadian, Norwegian, Danish and Finnish sectors of the Arctic more than 30 years, regular measurements.

The aim of this study was to ascertain the quantitative distribution of black carbon in the atmospheric surface layer over the Russian Arctic seas in the summer-autumn period and determine its primary source regions. We have carried out studies of the BC variations in the Arctic atmosphere by the optical method in 2011–2018.

2. Materials and research methods

Samples for determining the BC concentration in the drive air layer of the Arctic seas were taken in 12 expeditions in 2011 - 2018, by pumping air for 4-6 hours through quartz-fiber filters at an altitude of 10 m above sea level in headwind, so that to exclude smoke from the ship’s pipe. Subsequently, the content of black carbon (C_{BC} – BC concentration, ng/m\(^3\)), was determined in laboratory conditions by the aerometric method [4]. The periods of measuring the content BC over the seas of the Arctic are given in table 1.

The return trajectories of the transport of air masses and the aerosols transported by them, including black carbon, to the sampling points were calculated using the HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model [8].

3. Research Results and Discussion

Marine expeditions in the Arctic were carried out on ships: R / V „Acad. Mstislav Keldysh”, „Acad. M.A. Lavrentyev” and „Prof. Molchanov”. The average values of the BC concentration above the water surface of the Arctic seas in 2011 - 2018 are presented in table 1.

Table 1. The average values of the BC concentration above the water surface of the Arctic seas in 2011 – 2018, ng/m\(^3\)

| Measurement time | Norwegian sea | Barents sea | Kara sea | Laptev Sea | East-Siberian sea | North Pole |
|------------------|---------------|-------------|----------|------------|------------------|------------|
| Year             | Month         | sum         | aut      | sum         | aut              | Sum        | aut         | sum         | aut         | Spring       |
| 2011             | Sept          |             |          |             |                  | 68         |             |             |             | 29           |
| 2012             | Apr           |             |          |             |                  |            |             |             |             |              |
| 2013             | Aug           |             |          |             |                  | 80         |             |             |             |              |
| 2014             | June          | 35          |          | 76          |                  | 48         | 77          | 18          | 43          |              |
| 2015             | Aug           | 48          | 77       |             |                  | 37         | 37          | 18          | 46          |              |
|                  | Sept          |             |          |             |                  |            |             | 18          | 59          |              |
| 2016             | Sept          | 36          |          | 37          |                  | 36         | 36          | 18          | 61          | 59           |
|                  | Oct           |             |          |             |                  |            |             |             |             |              |
| 2017             | June          | 77          |          | 37          |                  | 39         | 46          | 24          |             |              |
|                  | July          |             |          |             |                  |            |             |             |             |              |
| 2018             | Aug           | 53          | 58       | 4           |                  | 11         | 23          |             |             |              |
|                  | Sept          |             |          |             |                  |            |             |             |             |              |
|                  | Oct           |             |          |             |                  |            |             |             |             |              |
| Average          |               | 77          | 37       | 42          | 64               | 29         | 4           | 43          | 32          | 59           |
| aut/sum          |               | 0,5         | 1,0      | 0,4         | 11,0             | 4          | 1,8         |              |              |              |
Variations in the BC content in the atmospheric layer at the North Pole, in the Norwegian, Barents, Kara, East Siberian Seas and the Laptev Sea are obtained. As a result of 12 marine expeditions in the summer-autumn period of 2011 - 2018 the black carbon concentration in the atmospheric drive layer in the Arctic was mainly at the background level and averaged 47 ng/m$^3$ (9 - 95 ng/m$^3$).

The longest BC concentration measurements were carried out in the Barents and Kara Seas, respectively during 9 and 8 months. The cruise 59 R/V „Acad. Mstislav Keldysh” in the White, Barents and Kara seas was implemented on September 12 - October 7, 2011 (Fig. 1). BC concentration was varied in the range of 10–940 ng/m$^3$. Low levels of black carbon in the atmosphere at 2 sections of the route (green lines) at a latitude of 73 - 75º N in the Kara Sea it averages 23 ng/m$^3$ (5.2 - 6.2) and 32 ng/m$^3$ (10.1 - 10.4) and an average of 108 ng/m$^3$ at higher latitudes of 76 -78º N (thin red line).

Figure 1. BC content variations in the atmosphere of the Barents and Kara Seas from September 12 to October 7, 2011 were carried out.

High C$_{BC}$ values, 100 - 900 ng/m$^3$, were obtained on September 14-21 and 470 ng/m$^3$ on October 5 (red line), when air masses came from the mainland from the places of associated petroleum gas (APG) burning from the Yamal-Nenets Autonomous Okrug (YaNAO) (1.4 - 4.1) and Komi Republic (12.1). A similar dependence of the BC content on the air masses path from the mainland was obtained in August 2014.

Figure 2. 3-day return trajectory of air masses transfer in the atmosphere on July 2017: a – 23, b – 24, and c - 29.
Low BC values were observed on August 5–15, 60 ng/m$^3$, when air masses passed over the water surface, and high, 70–1600 ng/m$^3$, were obtained August 4, 16 - 17, during the passage of air masses over the territory of Komi Republic, where APG is burned. In the Norwegian and Barents Seas on October 17–24, 2015, the average BC concentration was 37 ng/m$^3$.

The highest average BC concentrations, 77 ng/m$^3$, were obtained on July 21 - 28, 2017 in the Norwegian Sea, when air masses passed over the Scandinavian Peninsula, including over the places of APG burning. Figure 2 shows the 3-day return trajectories of air mass transfer on August 23, 24 and 29, 2017, and accordingly the concentration of air was obtained these days - 79, 114 and 62 ng/m$^3$. In the Barents Sea, from July 29 to August 9, 2017, when air masses came mainly from the clean regions of the Central Arctic, the average BC concentration was 38 ng/m$^3$.

The highest average BC concentrations, 77 ng/m$^3$, were obtained on July 21 - 28, 2017 in the Norwegian Sea, when air masses passed over the Scandinavian Peninsula and, possibly, over the places of APG burning. In the Barents Sea, from July 29 to August 9, 2017, when air masses came mainly from the clean regions of the Central Arctic, the average BC concentration was 38 ng/m$^3$.

From September 12 to October 7, 2011 the observations in the near-water atmosphere in the Barents and Kara Seas, the Laptev Sea, and the East Siberian Sea were carried out (Fig. 3).

For most of the ship’s route (in the Laptev Sea, Barents and East Siberian Seas), BC concentration of 20–40 ng/m$^3$ were obtained, with the exception of the 55–75°E (in Kara Sea), where the BC level varied between 40 - 170 ng/m$^3$. High values of the BC concentration were observed, as shown by trajectory analysis, when passing air masses over the territories of APG combustion in the YaNAO. We calculated the return trajectories of air mass transfer using the HYSPLIT model (Isobaric) [8].

![Figure 3](image_url)

**Figure 3.** BC concentration variations in the atmosphere of the Barents, Kara and East Siberian Seas and Laptev Sea: 1 – August 22 – September 9, 2017, 2 – September 10 – 30, 2017.

In Figure 4 shows the 3-day return trajectory of the air mass transfer in the atmosphere on August 27, 2017 (10:00 UTC) and the dedicated area of the APG combustion locality (70 - 80 east longitude and 65 - 70 north latitude). The trajectories of August 26, 2017 (17:00 UTC) and August 27, 2017 (16:00 UTC) have a similar view. In Table 2 shows the periods when the air masses were over the places of APG burning and the moments when radio sounding readings data were obtained about the altitude profile of temperature of the atmosphere [9].
Figure 4. a - 3-day return trajectory of air masses transfer in the atmosphere on August 27, 2017 (10:00 UTC) and the dedicated area of the APG combustion locality, b - trajectories above the APG combustion locality: 1 - August 26, 2017 (17:00 UTC), 2 - August 27, 2017 (9:00 UTC) and 3 – August 27, 2017 (16:00 UTC).

Table 2. Periods of air masses above the places of APG burning and moments of receiving radio sounding readings data about the altitude temperature profile of atmosphere

| Carbon black sampling Date (Time) | Smoke APG Date (Time) | Radiosonde Measurement time | Smoke under inversion dT, hour |
|-----------------------------------|-----------------------|-----------------------------|-----------------------------|
| 26(17)                            | 24(11)-25(11)         | 24(12)-25(12)               | 52                          |
| 27(9)                             | 25(9)-26(9)           | 25(12)-26(12)               | 40                          |
| 27(16)                            | 25(22)-26(16)         | 26(00)-26(12)               | 27                          |
| 28(10)                            | 26(10)-27(10)         | 26(12)-27(12)               | 12                          |

24 (12) – 1050-1400 m, 25 (00) – 700-1300 m, 25 (12) - 600-1100 m, 26 (00) - 300-900 m, 27(12) – 120 m, 26 (12), 27(12) - no inversions

From the type of temperature profile variability, we determined the inversion heights and periods of neutral situations of the state of the atmosphere. A high BC concentration on August 26, 2017 (17:00 UTC), 174 ng/m$^3$, was obtained with passing air mass within 52 hours lower inversion over the territory of APG combustion. On August 27, 2017 (9:00 a.m. and 4:00 p.m. UTC), the BC dropped to 79 and 58 ng/m$^3$ when air masses passed above the places of APG burning for 40 and 27 hours, respectively. On August 28, 2017 (10:00 UTC), when the air mass moved outside the territory of APG combustion, the BC concentration decreased to 20 ng/m$^3$.

Using the HYSPLIT model (model vertical velocity), the following was obtained: At a high BC concentrations, 174 ng/m$^3$, on August 26, the air mass of air existed most of its time above the APG combustion area in its central part (74 - 77°E) and at low, 79 and 58 ng/m$^3$, - on its edge (77 – 79°E). Thus, the level of air pollution along the route above the water surface significantly depended on the state of the atmosphere above the places of APG burning.
The lowest average concentration, 4 ng/m$^3$, was recorded in the Laptev Sea in August 2018. As the trajectory analysis showed, in this case the air masses came from the north.

On April 5 – 20, 2012, air samples were taken daily at „Barneo” Station (North Pole, 89.14–89.75°N and 4.14°W – 47.83°E) at a distance of 1 km from her. At wind speeds of more than 3 m/s, the average concentration of aircraft was 29 ng/m$^3$. With a weak wind, less than 3 m/s, the BC concentration increased to 100 - 270 ng/m$^3$. This is due to the fact that 1-2 planes and helicopters flew into the station per day, tractors cleared the runway and the territory of the station from snow, and heat guns worked in the diesel fuel around the clock to heat the premises. As a result, a polluted air layer over ice floe was formed.

4. Conclusions
Variations of the black carbon content in the near water layer of the atmosphere at the North Pole, in the Norwegian, Barents, Kara, East Siberian Seas and the Laptev Sea are obtained. As a result of 12 marine expeditions in the summer-autumn period of 2011 - 2018 the BC concentration in the atmospheric layer in the Arctic was mainly at the background level and averaged 47 ng/m$^3$ (9 - 95 ng/m$^3$). Increase of the BC concentration by several times occurred occasionally when the air masses from the mainland came, from APG combustion areas and the BC concentration above the water surface depended on the state of the atmosphere in the region of soot sources on the mainland.

5. References
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