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OPTICS OF CLUSTERS, AEROSOLS, AND HYDROSOLES

Submicron Aerosol and Absorbing Substance in the Troposphere of the Russian Sector of the Arctic According to Measurements Onboard the Tu-134 *Optik* Aircraft Laboratory in 2020

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Abstract—A large-scale comprehensive study of the composition of the troposphere over the Russian sector of the Arctic was carried out in September 2020 onboard the Tu-134 *Optik* aircraft laboratory. We studied the spatiotemporal variations in aerosol and black carbon (BC) concentrations. The sensing data were used to analyze the general and particular features of the spatial variations in the vertical profiles of aerosol and BC concentrations. The columnar BC concentrations at the Arctic and subarctic latitudes were obtained.

Keywords: aerosol, black carbon, soot, vertical distribution, aircraft laboratory, the Arctic

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INTRODUCTION

The Arctic is an important component of the Northern Hemisphere climate system. It is the Arctic area where in recent decades there have been the considerable changes in sea ice, snow cover, permafrost, and atmospheric circulation [1, 2], heavily driven by the variations in the atmospheric radiation budget and snow-ice surface albedo [3–5].

At present, the supply of absorbing aerosol of anthropogenic origin to the atmosphere of the region is ranked by specialists as the second factor behind CO_2 that is responsible for the observed climate changes in the Arctic. Absorbing particles reduce the single scattering albedo in the atmosphere and, through deposition on the surface of ice and snow cover, decrease its reflective properties, thus leading to an additional increase in air temperature [6, 7]. Studies [8–11] showed that emissions of black carbon (BC) particles, released during incomplete combustion of fossil fuel and biomass at Northern Hemisphere midlatitudes, are one of the main pollution sources for the atmosphere. The continuing retreat of Arctic sea ice, making this area increasingly more accessible, leads to a potential increase of emissions from local industrial (shipping [12–14], oil and gas production [15]) sources. Based on measurements and modeling of the spatiotemporal variations in aerosol and BC concentrations, the authors of works [16–26] indicate enhanced pollution in the entire Arctic troposphere: the contribution from sources in northern Eurasia (North America and Asia) are predominant in lower layers (at high altitudes).

The aerosol radiative forcing is known to depend not only on concentrations, but also on microphysical properties of particles [27]. Model calculations [5, 28, 29] show that the surface temperature in the Arctic depends in a complex way on the vertical distribution of aerosol scattering and absorbing properties in the visible wavelength range.

In the recent decade, there have been markedly more works devoted to studying the aerosol properties in this area [10–15, 19–32]. In the Russian sector of the Arctic, in situ measurements have been performed regularly at polar stations in settlements Barentsburg (Svalbard Archipelago) [33, 34] and Tiksi [35, 36], at Ice Base Cape Baranov (Severnaya Zemlya Archipelago) [37, 38], and in yearly marine expeditions [39–43]. Rare studies onboard aircraft laboratories have also been carried out [44–46]. However, it should be noted that most publications are devoted to observing aerosol properties in the surface layer or optical characteristics integrated over the atmospheric column. At the same time, studies of the vertical distribution of

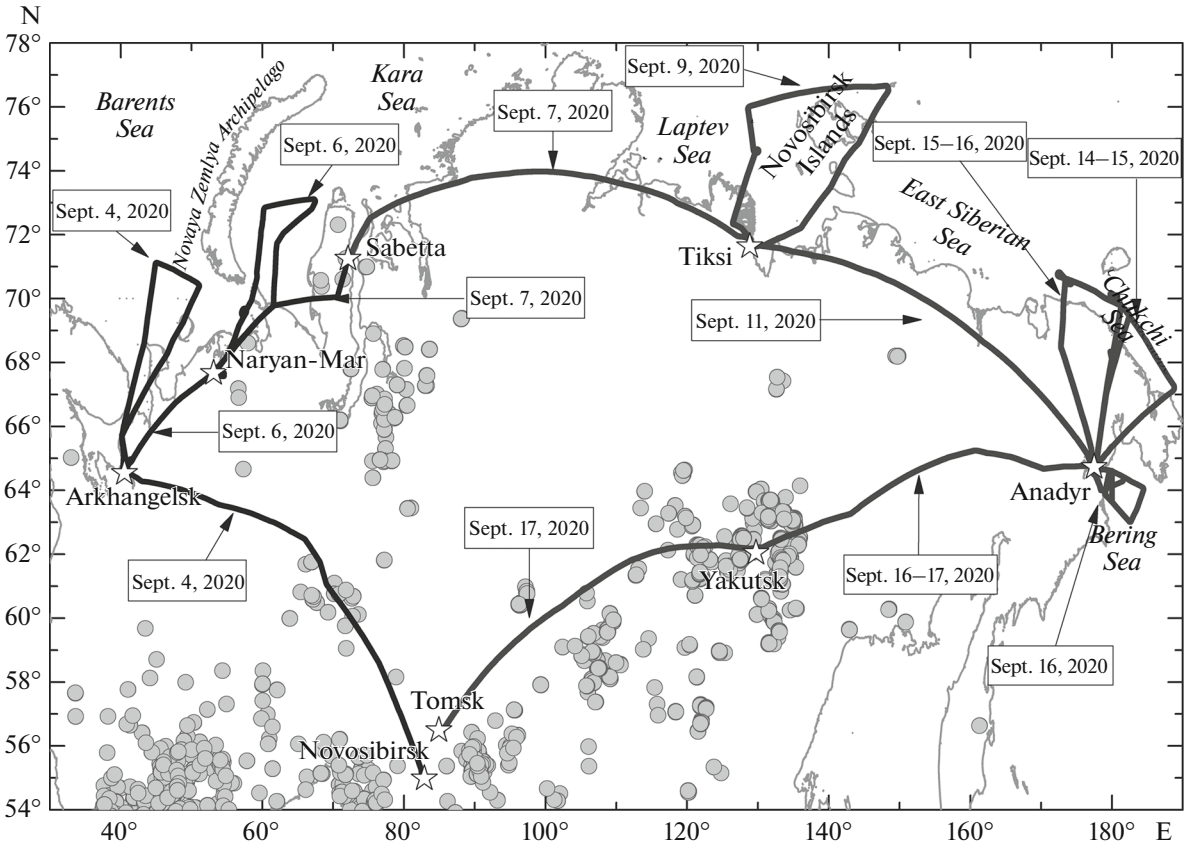

Fig. 1. Map of the flights of Tu-134 *Optik* aircraft laboratory in September 2020; circles indicate the centers of forest fires.

aerosol admixtures over the Arctic region are still fragmentary with respect to regions and periods of observations. We stress that, to the present, there is still a serious deficit of instrumental measurements, explaining the large uncertainty [7, 47, 48] of estimates of how different factors influence climate changes.

Motivated by the urgency of the problem, a large-scale comprehensive study of the tropospheric composition over the Russian sector of the Arctic was undertaken in September 2020 onboard the Tu-134 *Optik* aircraft laboratory. In this work, we discuss the measurements of the vertical distribution of the contents of submicron aerosol and absorbing substance.

1. REGION OF SENSING AND INSTRUMENTATION

The route of the Tu-134 *Optik* aircraft laboratory is shown in Fig. 1. Most flights were carried out with a change in altitude. The aircraft climbed to an altitude of 9–10 km, and then descended to 200 m over the sea and to 500 m over the land. At altitudes of 200 m (500 m over the land), 5 and 9 km, the aircraft flew horizontally for ~10 min.

The Tu-134 *Optik* aircraft laboratory, instrumentation, and calibration and measurement techniques were described in [49].

The mass concentration of absorbing substance M_{BC} (μg/m^3) was measured using MDA-02 aethalometer developed at the Institute of Atmospheric Optics, Siberian Branch, Russian Academy of Sciences; and the angular scattering coefficient of "dry matter" of submicron particles μ_d ($\varphi = 45°$) (Mm^{-1} sr^{-1}) at a wavelength of 0.53 μm was recorded using a PhAN-M nephelometer. The mass concentration of submicron aerosol M_A (μg/m^3) was estimated empirically using the formula $M_A = 2.4\mu_d$ ($\varphi = 45°$) for the particle density of 1.5 g/cm^3.

2. ANALYSIS OF EXPERIMENTAL DATA

2.1. Altitude Distributions of Concentrations of Aerosol and Absorbing Substance

During the aircraft Arctic campaign we recorded different types of the vertical distribution of mass concentrations of aerosol M_A and absorbing substance M_{BC} (Fig. 2).

The vertical M_A and M_{BC} distributions over the Barents (Fig. 2a) and Kara (Fig. 2b) Seas are charac-

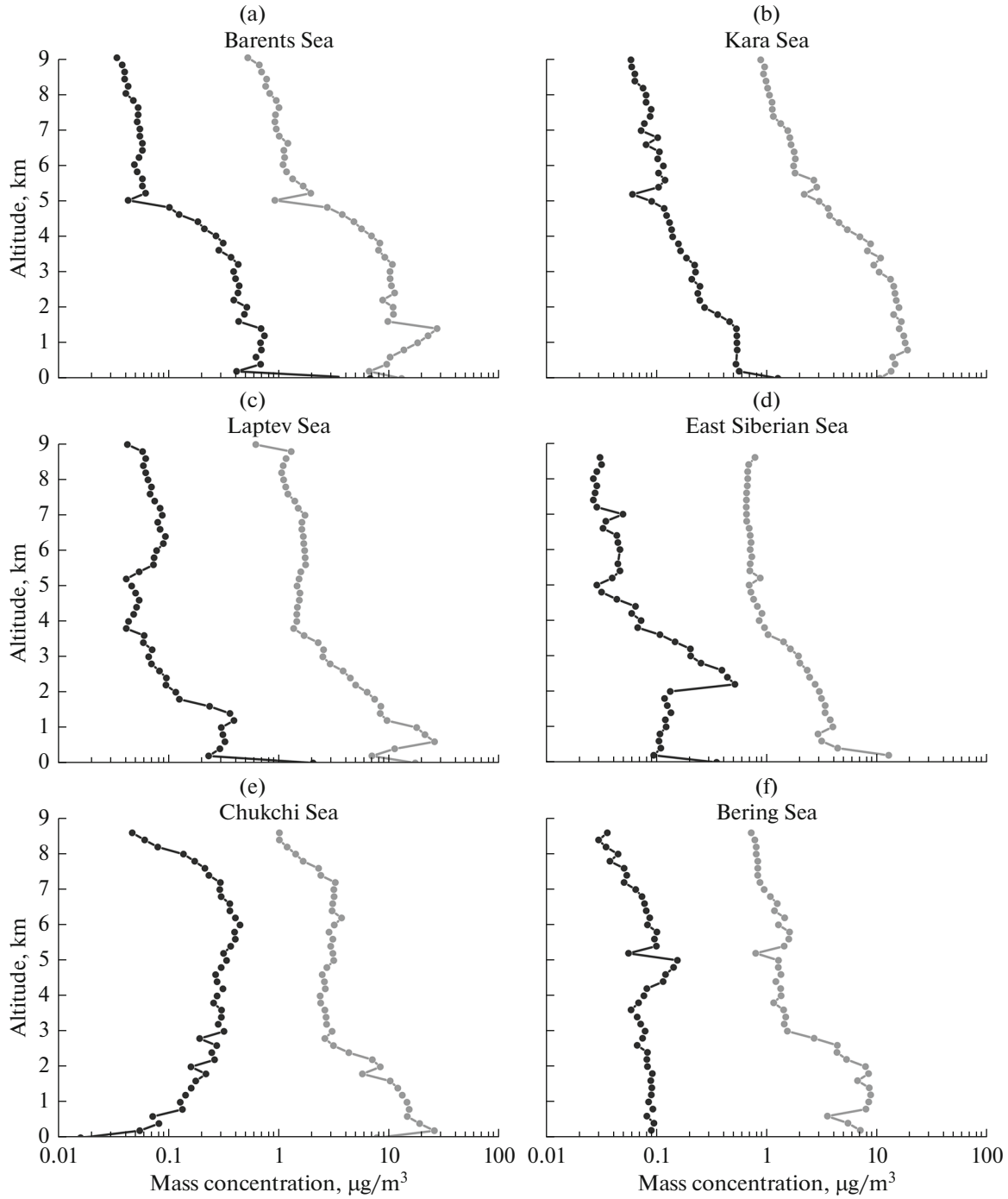

Fig. 2. Vertical profiles of the mass concentrations of submicron aerosol (gray line) and absorbing substance (black line) over: (a) Barents; (b) Kara; (c) Laptev; (d) East Siberian; (e) Chukchi; and (f) Bering Seas.

terized by values decreasing with altitude and a pronounced mixing layer up to 5 km. The correlation coefficient K between M_A and M_{BC} over the total dataset is 0.93 for the Barents Sea and 0.67 for the Kara Sea. Large mass concentrations in the lower atmospheric layers can be attributed to the sources of aerosol and absorbing substance existing on the Earth's surface. Analysis of back trajectories, obtained using the HYSPLIT model (https://www.ready.noaa.gov/HYSPLIT.php), showed that air masses during flights to this region came from the European part of the continent (Fig. 3a). High correlation coefficients seem to indicate that the measurements were carried out in a single air mass that was formed earlier and transported to the study region.

The vertical distributions of M_A and M_{BC} over the Laptev Sea (Fig. 2c) are characterized by values

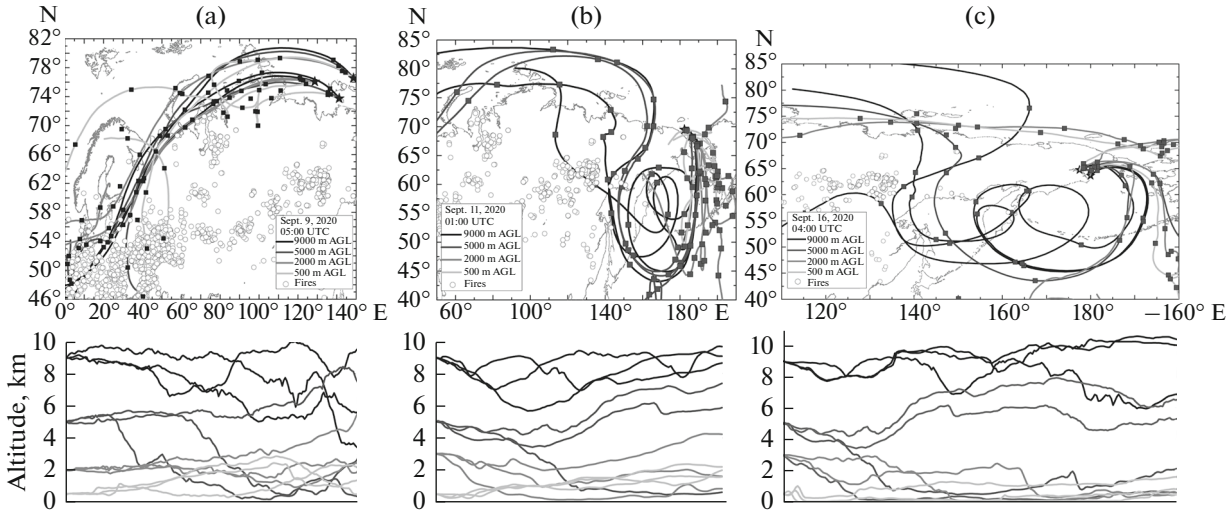

Fig. 3. 7-Day back trajectories of motion of air masses and the centers of temperature anomalies (circles), carried to the altitudes of 0.5; 2; 3; 5; and 9 km over the basins of: (a) Laptev; (b) Chukchi; and (c) Bering Seas.

decreasing with altitude, and a weak mixing layer up to 2 km; $K = 0.57$ over the total dataset for the Laptev Sea.

Over the East Siberian Sea (Fig. 2d), the vertical M_A distribution shows a poorly defined mixing layer up to 2 km with low concentrations of 13 μg/m^3 in the surface layer and a rapid decrease to 3 μg/m^3 at 2 km. The mass concentration of absorbing substance in low atmospheric layers (0.5–2 km) is characterized by small concentrations, ~0.1 μg/m^3; and M_{BC} increases to 0.5 μg/m^3 at altitudes from 2 to 3.5 km.

The recorded vertical distributions of submicron aerosol and "soot" are nonuniform and formed by different air masses at diverse altitudes. This is rather expected because, as an air mass moves over the territories where in the surface layer there are no permanently active intense soot sources, the general composition of submicron aerosol is driven by natural factors; and the main mass of absorbing particles comes to the region as a result of transport from remote industrial regions.

The M_{BC} value was found to increase with altitude over the Chukchi Sea (Fig. 2e); $M_{BC} = 0.2–0.5$ μg/m^3 at altitudes from 2 to 7 km. In its vertical profile over the Chukchi Sea, the M_A values decrease with altitude, and show a pronounced mixing layer up to 2.5 km. We note that at altitudes from 2.5 to 7.5 km over the Chukchi Sea, M_A ~2.9 ± 0.4 μg/m^3, which was a factor of 1.8 larger ($M_A = 1.6 \pm 0.1$ μg/m^3) than over the Laptev Sea, a factor of four larger ($M_A = 0.7 \pm 0.05$ μg/m^3) than over the East Siberian Sea, and a factor of 2.3 larger ($M_A = 1.3 \pm 0.2$ μg/m^3) than over the Bering Sea.

Analogous profiles of BC concentration were also obtained in 2008 during flights in the region of Barrow research station in Alaska in the framework of the POLARCAT program [50, 51], as well as along the coastal zone of the Laptev, East Siberian, and Chukchi Seas [46]. Probably, an inversion distribution of the concentrations of absorbing aerosol has been formed due to the absence of aerosol sources near the Earth's surface and to the effect of long-range pollutant transport. We note that the analysis of back trajectories and satellite maps of the centers of temperature anomalies (https://firms.modaps.eosdis.nasa.gov/) (see Fig. 1) shows that air masses were mainly transported from the European part of the continent and passed beyond the zones of wildfires; therefore, BC particles are mainly anthropogenic in origin.

The altitude distribution of M_A over the Bering Sea (Fig. 2f) is characterized by values decreasing with altitude and a well-defined mixing layer up to 3 km. On the other hand, there is no mixing layer for the vertical distribution of M_{BC}; and up to 3 km, M_{BC} varies in the range 0.08–0.1 μg/m^3. The correlation coefficient between M_A and M_{BC} is 0.27 over all dataset for the Bering Sea (Fig. 2f); and back trajectory analysis (Fig. 3c) showed that the vertical profiles of M_A and M_{BC} were formed at different altitudes by diverse air masses.

2.2. Spatial Distributions of Aerosol and Black Carbon Mass Concentrations

Long-term overflights between settlements (e.g. Tiksi – Anadyr, Yakutsk – Tomsk) have been carried out at altitudes of 9–10 km until approaching to landing (see Fig. 4).

We will consider the results from four flight paths: 1) Naryan-Mar – Sabetta; 2) Tiksi – Anadyr; 3) Novosibirsk – Arkhangelsk; and 4) Yakutsk – Tomsk.

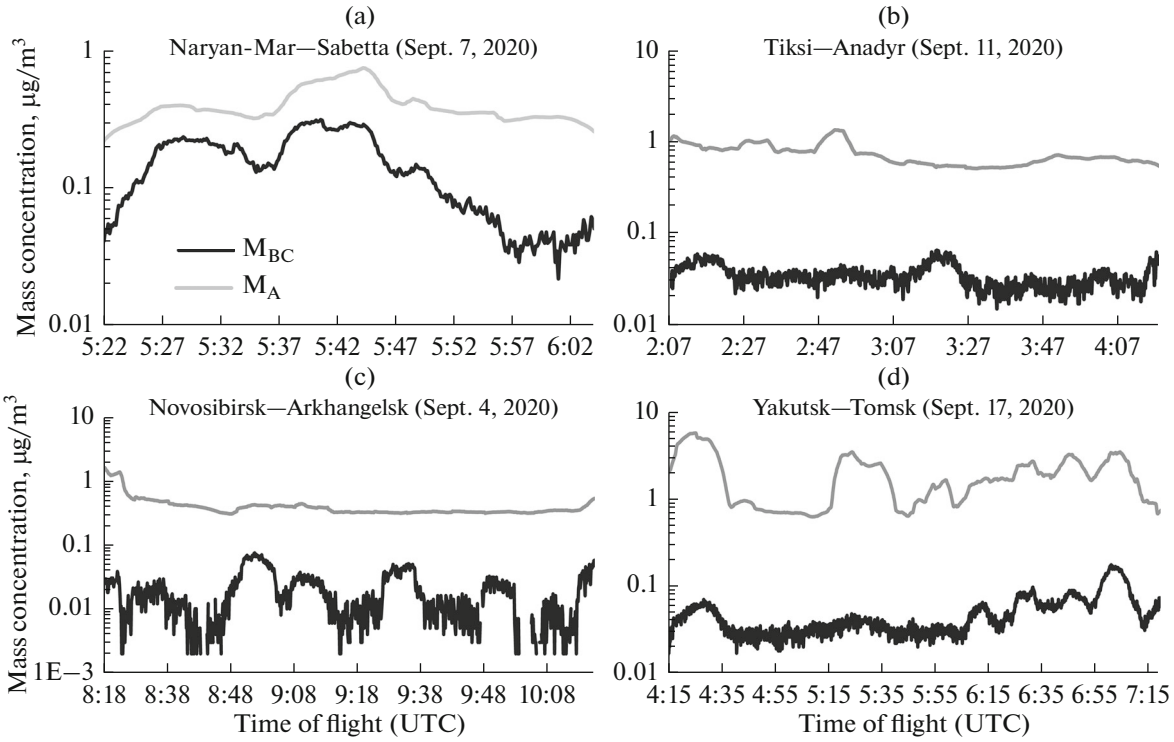

Fig. 4. Horizontal distributions of the mass concentrations of absorbing substance (black line) and aerosol (gray line) along: (a) Naryan-Mar – Sabetta; (b) Tiksi – Anadyr; (c) Novosibirsk – Arkhangelsk; and (d) Yakutsk – Tomsk flight paths.

The Naryan-Mar – Sabetta overflight (Fig. 4a) was on September 7, 2020. After climbing to an altitude of 8–10 km, the aircraft flew in a single air mass ($K = 0.8$) with increased content of absorbing submicron aerosol.

During the horizontal flight leg at an altitude above 8 km, $M_A = 0.4 \pm 0.12$ μg/m^3, and $M_{BC} = 0.14 \pm 0.09$ μg/m^3. As aircraft moved eastward, toward Sabetta, the "soot" and aerosol contents decreased. In our opinion, the Naryan-Mar – Sabetta segment is a striking example of the transport of substance from anthropogenic sources in the west.

On the Tiksi – Anadyr path (Fig. 4b) at the altitude above 8 km, $M_A = 0.72 \pm 0.19$ μg/m^3, and $M_{BC} = 0.03 \pm 0.01$ μg/m^3. On this segment, M_A and M_{BC} are almost uncorrelated ($K = 0.15$). Submicron aerosol content decreased when approaching Anadyr.

Despite the fact that the Tomsk – Arkhangelsk flight (Fig. 4c), which was on September 4, 2020, overpassed the industrial regions and fire centers (see Fig. 1), low mass concentrations $M_A = 0.4 \pm 0.19$ μg/m^3 and $M_{BC} = 0.02 \pm 0.02$ μg/m^3 were recorded in this area, with no correlation between them ($K = 0.1$).

The flight from Yakutsk to Tomsk (Fig. 4d) was over the centers of forest fires (see Fig. 1). On this segment, $M_A = 1.91 \pm 1.21$ μg/m^3, higher than along three other segments; $M_{BC} = 0.05 \pm 0.03$ μg/m^3. The contents of submicron aerosol and absorbing substance increased when approaching Tomsk.

2.3. Total BC Content in Atmospheric Column of 0.2–9 km

The spatial distribution of the total content of absorbing substance M_{BC}(col) in the atmospheric column up to 9 km is presented in Fig. 5. Over land, M_{BC}(col) was calculated from measurements performed during takeoffs and landings in settlements. We found that M_{BC}(col) = 0.6–6.9 mg/m^2 over Arkhangelsk, 0.4–6.5 mg/m^2 over Naryan-Mar, 1.4–2.5 mg/m^2 over Sabetta, 0.3–1.3 mg/m^2 over Tiksi, 0.5–1.3 mg/m^2 over Anadyr, and 0.9–1.0 mg/m^2 over Yakutsk. While moving from west to east, M_{BC}(col) over settlements decreases and becomes less dispersed.

Total columnar content of absorbing substance over sea water basins in the Russian Arctic was determined from data recorded when the aircraft descended from 9 km to 200 m and ascended from 200 m to 9 km. Observations showed that M_{BC}(col) varied from 0.36 to 1.75 mg/m^2 over the Barents Sea, from 1.12 to 2.54 mg/m^2 over the Kara Sea, from 0.41 to 1.5 mg/m^2 over the Laptev Sea, from 0.27 to 1.67 mg/m^2 over the East Siberian Sea, from 0.21 to 0.88 mg/m^2 over the Chukchi Sea, and from 0.52 to 0.6 mg/m^2 over the Bering Sea.

We note markedly spatially nonuniform distributions of soot and submicron aerosol over the Chukchi Sea. Let us compare the average values of M_{BC} and M_A measured on horizontal flight legs at the altitude of

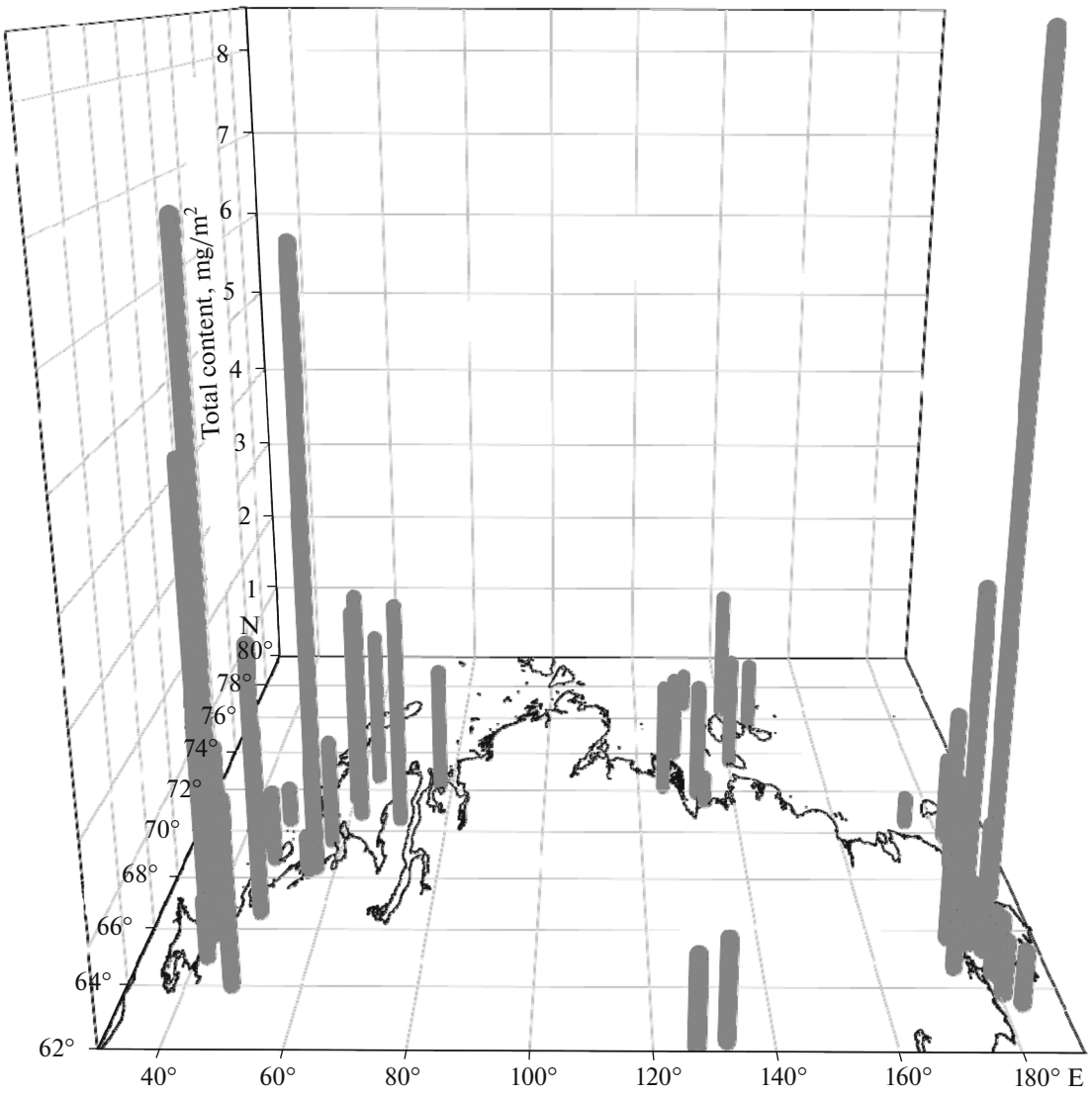

Fig. 5. Spatial distribution of the total content of absorbing substance in atmospheric column up to 9 km.

200 m in two different regions. On the first leg 83 km in length (173.43° W, 68.04° N – 174.85° W, 68.57° N) $M_{BC} = 0.14 \pm 0.18$ μg/m^3, $M_A = 11.04 \pm 5.6$ μg/m^3, and $K = 0.84$. On the second leg 91 km in length (178.96° W, 69.85° N – 177.62° W, 69.52° N) $M_{BC} = 0.07 \pm 0.07$ μg/m^3, $M_A = 46.64 \pm 33.57$ μg/m^3, and $K = -0.2$.

A single anomalously high value M_{BC}(col) = 8.48 mg/m^2 was recorded in the Chukchi Sea near Kolyuchin Island (174.38° W, 67.4° N). It is just over this water basin where we noted the inversion-character vertical profile of M_{BC} (Fig. 2e) and concluded that it was formed by different air masses that came from the northeastern part of the Pacific Ocean, Alaska, and Yakutia (Fig. 3b).

We summarize the results of our measurements by noting that the total columnar content of absorbing substance in the Asian part of the Arctic compare well with the data obtained during POLARCAT-2008 flight campaign on the route Novosibirsk – Salekhard – Khatanga – Chokurdakh – Pevek – Chokurdakh – Yakutsk – Mirny – Novosibirsk [46].

CONCLUSIONS

Based on data of aircraft sensing of the troposphere, obtained during a complex experiment for studying the composition of the troposphere in the Russian sector of the Arctic in September 2020 over the Barents, Kara, Laptev, East Siberian, Chukchi, and Bering Seas, we determined the vertical profiles of the mass concentration of submicron aerosol and absorbing substance.

It is shown that the altitude distributions of the contents of aerosol and absorbing substance over the Bar-

ents and Kara Seas are similar in character: the values are maximal near surface and decrease with altitude.

Again, over the Chukchi Sea we recorded an inversion distribution of "soot" over the altitude. We found that in the observation period over this water basin, the vertical distribution of aerosol characteristics was formed by different air masses coming from the northeastern part of the Pacific Ocean, Alaska, and Yakutia, the northwestern part of the continent.

We note that the analysis of the correlations between the concentrations of submicron aerosol and soot in the atmosphere over different water basins revealed significant differences. It is shown that the variations of these quantities demonstrated close correlations over the Barents and Kara Seas. Back trajectory analysis showed that the measurements in this area were conducted in relatively stable air masses. On the contrary, in the eastern sector of the Arctic flights the correlations between M_{BC} and M_A were weak over the entire vertical profile. This fact indicates that in the observation period the structure of the vertical distribution of aerosol composition was formed by airflows, coming from different territories, in a good agreement with the data from trajectory analysis.

The conjecture that BC particles, recorded in almost all flights in September 2020 in the atmosphere over the Arctic seas, are mainly anthropogenic in origin was based on the estimate of the relationship between M_A and M_{BC}. Our analysis of satellite images and migration of air masses, the trajectories of which passed mainly outside wildfire zones, suggests that smoke plumes from fires could hardly influence strongly the increase of the concentrations of absorbing substance in the entire altitude range up to 9 km.

These arguments make it possible to justifiably conclude that the particles of absorbing substance are supplied to the troposphere of the Arctic sea basins as part of long-range transport of industrial pollutants from the continent.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

1. R. W. Lindsay, J. Zhang, A. Schweiger, M. Steele, and H. Stern, "Arctic sea ice retreat in 2007 follows thinning trend," J. Clim. **22**, 165–176 (2009).
2. *Climate Change 2013—The Physical Science Basis.* Chapter 7. *Clouds and Aerosols,* Ed. by O. Boucher, D. Randall, P. Artaxo, C. Bretherton, G. Feingold, P. Forster, V.-M. Kerminen, Y. Kondo, H. Liao, U. Lohmann, P. Rasch, S. K. Satheesh, S. Sherwood, B. Stevens, and X. Y. Zhang (Cambridge University Press, 2013), p. 571–657. https://doi.org/10.1017/CBO9781107415324.016
3. J. A. Screen and I. Simmonds, "The central role of diminishing sea ice in recent Arctic temperature amplification," Nature **464**, 1334–1337 (2010).
4. F. Pithan and T. Mauritsen, "Arctic amplification dominated by temperature feedbacks in contemporary climate models," Nat. Geosci. **7**, 181–184 (2014).
5. A. A. Vinogradova and T. B. Titkova, "Atmospheric black carbon and surface albedo in the Russian Arctic during spring," Atmos. Ocean. Opt. **33** (3), 260–266 (2020).
6. D. Shindell and G. Faluvegi, "Climate response to regional radiative forcing during the twentieth century," Nat. Geosci. **2**, 294–300 (2009).
7. *AMAP Assessment 2015: Black Carbon and Ozone as Arctic Climate Forcers* (AMAP, Oslo, 2015).
8. D. Koch and J. Hansen, "Distant origins of Arctic black carbon: A Goddard institute for space studies ModelE experiment," J. Geophys. Res. **110**, D04204 (2005).
9. A. Stohl, "Characteristics of atmospheric transport into the Arctic troposphere," J. Geophys. Res. **111**, D11306 (2006).
10. S. Sharma, M. Ishizawa, D. Chan, D. Lavoue, E. Andrews, K. Eleftheriadis, and S. Maksyutov, "16-year simulation of Arctic black carbon: Transport, source contribution, and sensitivity analysis on deposition," J. Geophys. Res. Atmos. **118**, 943–964 (2013).
11. S. Arnold, K. Law, C. Brock, J. Thomas, S. Starkweather, K. von Salzen, A. Stohl, S. Sharma, M. Lund, M. Flanner, T. Petaja, H. Tanimoto, J. Gamble, J. Dibb, M. Melamed, N. Johnson, M. Fidel, V.-P. Tynkkynen, A. Baklanov, S. Eckhardt, S. Monks, J. Browse, and H. Bozem, "Arctic air pollution: Challenges and opportunities for the next decade," Elementa: Sci. Anthropocene **4**, 000104 (2016).
12. S. Eckhardt, O. Hermansen, H. Grythe, M. Fiebig, K. Stebel, M. Cassiani, A. Baecklund, and A. Stohl, "The influence of 25 cruise ship emissions on air pollution in Svalbard—a harbinger of a more polluted Arctic?," Atmos. Chem. Phys. **13**, 8401–8409 (2013).
13. J. J. Corbett, D. A. Lack, J. J. Winebrake, S. Harder, J. A. Silberman, and M. Gold, "Arctic shipping emissions inventories and future scenarios," Atmos. Chem. Phys. **10**, 9689–9704 (2010).
14. N. Melia, K. Haines, and E. Hawkins, "Sea ice decline and 21st century trans-Arctic shipping routes," Geophys. Rev. Lett. **43**, 9720–9728 (2016).
15. G. P. Peters, T. B. Nilssen, L. Lindholt, M. S. Eide, S. Glomsrod, L. I. Eide, and J. S. Fuglestvedt, "Future emissions from shipping and petroleum activities in the Arctic," Atmos. Chem. Phys. **11**, 5305–5320 (2011).
16. S. Sharma, E. Andrews, L. A. Barrie, J. A. Ogren, and D. Lavoue, "Variations and sources of the equivalent black carbon in the High Arctic revealed by long-term observations at Alert and Barrow: 1989–2003," J. Geophys. Res. **111**, D14208 (2006).
17. D. T. Shindell, M. Chin, F. Dentener, R. M. Doherty, G. Faluvegi, A. M. Fiore, P. Hess, D. M. Koch,

I. A. MacKenzie, M. G. Sanderson, M. G. Schultz, M. Schulz, D. S. Stevenson, H. Teich, C. Textor, O. Wild, D. J. Bergmann, I. Bey, H. Bian, C. Cuvelier, B. N. Duncan, G. Folberth, L. W. Horowitz, J. Jonson, J. W. Kaminski, E. Marmer, R. Park, K. J. Pringle, S. Schroeder, S. Szopa, T. Takemura, G. Zeng, T. J. Keating, and A. Zuber, "A multi-model assessment of pollution transport to the Arctic," Atmos. Chem. Phys. **8**, 5353–5372 (2008).

18. D. Hirdman, H. Sodemann, S. Eckhardt, J. F. Burkhart, A. Jefferson, T. Mefford, P. K. Quinn, S. Sharma, J. Strom, and A. Stohl, "Source identification of short-lived air pollutants in the Arctic using statistical analysis of measurement data and particle dispersion model output," Atmos. Chem. Phys. **10**, 669–693 (2010).
19. A. Hecobian, Z. Liu, C. J. Hennigan, L. G. Huey, J. L. Jimenez, M. J. Cubison, S. Vay, G. S. Diskin, G. W. Sachse, A. Wisthaler, T. Mikoviny, A. J. Weinheimer, J. Liao, D. J. Knapp, P. O. Wennberg, A. Kurten, J. D. Crounse, J. St. Clair, Y. Wang, and R. J. Weber, "Comparison of chemical characteristics of 495 biomass burning plumes intercepted by the NASA DC-8 aircraft during the ARCTAS/CARB-2008 field campaign," Atmos. Chem. Phys. **11**, 13325–13337 (2011).
20. C. A. Brock, J. Cozic, R. Bahreini, K. D. Froyd, A. M. Middlebrook, A. McComiskey, J. Brioude, O. R. Cooper, A. Stohl, K. C. Aikin, J. A. de Gouw, D. W. Fahey, R. A. Ferrare, R. -S. Gao, W. Gore, J. S. Holloway, G. Hubler, A. Jefferson, D. A. Lack, S. Lance, R. H. Moore, D. M. Murphy, A. Nenes, P. C. Novelli, J. B. Nowak, J. A. Ogren, J. Peischl, R. B. Pierce, P. Pilewskie, P. K. Quinn, T. B. Ryerson, K. S. Schmidt, J. P. Schwarz, H. Sodemann, J. R. Spackman, H. Stark, D. S. Thomson, T. Thornberry, P. Veres, L. A. Watts, C. Warneke, and A. G. Wollny, "Characteristics, sources, and transport of aerosols measured in spring 2008 during the Aerosol, Radiation, and Cloud Processes Affecting Arctic Climate (ARCPAC) project," Atmos. Chem. Phys. **11**, 2423–2453 (2011).
21. J. Cohen, J. A. Screen, J. C. Furtado, M. Barlow, D. Whittleston, D. Coumou, J. Francis, K. Dethloff, D. Entekhabi, J. Overland, and J. Jones, "Recent Arctic amplification and extreme mid-latitude weather," Nat. Geosci. **7**, 627–637 (2014).
22. J. Schmale, J. Schneider, G. Ancellet, B. Quennehen, A. Stohl, H. Sodemann, J. F. Burkhart, T. Hamburger, S. R. Arnold, A. Schwarzenboeck, S. Borrmann, and K. S. Law, "Source identification and airborne chemical characterisation of aerosol pollution from long-range transport over Greenland during POLARCAT summer campaign 2008," Atmos. Chem. Phys. **11**, 10097–10123 (2011).
23. H. Sodemann, M. Pommier, S. R. Arnold, S. A. Monks, K. Stebel, J. F. Burkhart, J. W. Hair, G. S. Diskin, C. Clerbaux, P.-F. Coheur, D. Hurtmans, H. Schlager, A.-M. Blechschmidt, J. E. Kristjansson, and A. Stohl, "Episodes of cross-polar transport in the Arctic troposphere during July 2008 as seen from models, satellite, and aircraft observations," Atmos. Chem. Phys. **11**, 3631–3651 (2011).
24. S. A. Monks, S. R. Arnold, L. K. Emmons, K. S. Law, S. Turquety, B. N. Duncan, J. Flemming, V. Huijnen, S. Tilmes, J. Langner, J. Mao, Y. Long, J. L. Thomas, S. D. Steenrod, J. C. Raut, C. Wilson, M. P. Chipperfield, G. S. Diskin, A. Weinheimer, H. Schlager, and G. Ancellet, "Multi-model study of chemical and physical controls on transport of anthropogenic and biomass burning pollution to the Arctic," Atmos. Chem. Phys. **15**, 3575–3603 (2015).
25. K. S. Law, A. Stohl, P. K. Quinn, C. A. Brock, J. F. Burkhart, J.-D. Paris, G. Ancellet, H. B. Singh, A. Roiger, H. Schlager, J. Dibb, D. J. Jacob, S. R. Arnold, J. Pelon, and J. L. Thomas, "Arctic air pollution: New insights from POLARCAT-IPY," Bull. Am. Meteorol. Soc. **95**, 1873–1895 (2014).
26. A. Stohl, Z. Klimont, S. Eckhardt, K. Kupiainen, V. P. Shevchenko, V. M. Kopeikin, and A. N. Novigatsky, "Black carbon in the Arctic: The underestimated role of gas flaring and residential combustion emissions," Atmos. Chem. Phys. **13**, 8833–8855 (2013).
27. J. K. Kodros, S. J. Hanna, A. K. Bertram, W. R. Leaitch, H. Schulz, A. B. Herber, M. Zanatta, J. Burkart, M. D. Willis, J. P. D. Abbatt, and J. R. Pierc, "Size-resolved mixing state of black carbon in the Canadian High Arctic and implications for simulated direct radiative effect," Atmos. Chem. Phys. **18**, 11345–11361 (2018).
28. B. H. Samse, G. Myhr, M. Schul, Y. Balkanski, S. Bauer, T. K. Berntsen, H. Bian, N. Bellouin, T. Diehl, R. C. Easter, S. J. Ghan, T. Iversen, S. Kinne, A. Kirkevag, J.-F. Lamarque, G. Lin, X. Liu, J. E. Penner, O. Seland, R. B. Skeie, P. Stier, T. Takemura, K. Tsigaridis, and K. Zhang, "Black carbon vertical profiles strongly affect its radiative forcing uncertainty," Atmos. Chem. Phys. **13**, 2423–2434 (2013).
29. M. G. Flanner, "Arctic climate sensitivity to local black carbon," J. Geophys. Res. Atmos. **118**, 1840–1851 (2013).
30. C. Tomasi, A. A. Kokhanovsky, A. Lupi, C. Ritter, A. Smirnov, M. Mazzola, R. S. Stone, C. Lanconelli, V. Vitale, B. N. Holben, S. Nyeki, C. Wehrli, V. Altonen, G. de Leeuw, E. Rodriguez, A. B. Herber, K. Stebel, A. Stohl, N. T. O'Neill, V. F. Radionov, T. Zielinski, T. Petelski, S. M. Sakerin, D. M. Kabanov, Y. Xue, L. Mei, L. Istomina, R. Wagener, B. McArthur, P. S. Sobolewski, J. Butler, R. Kivi, Y. Courcoux, P. Larouche, S. Broccardo, and S. J. Piketh, "Aerosol remote sensing in polar regions," Earth-Sci. Rev. **140**, 108–157 (2015).
31. J. P. D. Abbatt, W. R. Leaitch, A. A. Aliabadi, A. K. Bertram, J.-P. Blanchet, A. Boivin-Rioux, H. Bozem, J. Burkart, R. Y. W. Chang, J. Charette, J. P. Chaubey, R. J. Christensen, A. Cirisan, D. B. Collins, B. Croft, J. Dionne, G. J. Evans, C. G. Fletcher, M. Gali, R. Ghahremaninezhad, E. Girard, W. Gong, M. Gosselin, M. Gourdal, S. J. Hanna, H. Hayashida, A. B. Herber, S. Hesaraki, P. Hoor, L. Huang, R. Hussherr, V. E. Irish, S. A. Keita, J. K. Kodros, F. Kollner, F. Kolonjari, D. Kunkel, L. A. Ladino, K. Law, M. Levasseur, Q. Libois, J. Liggio, M. Lizotte, K. M. Macdonald, R. Mahmood, R. V. Martin, R. H. Mason, L. A. Miller, A. Moravek, E. Mortenson, E. L. Mungall, J. G. Murphy, M. Namazi, A.-L. Norman, N. T. O'Neill, J. R. Pierce, L. M. Russell, J. Schneider, H. Schulz, S. Sharma, M. Si, R. M. Staebler, N. S. Steiner, J. L. Thomas, K. von Salzen, J. J. B. Wentzell, M. D. Willis, G. R. Wentworth, J.-W. Xu, and J. D. Yakobi-Hancock, "Overview paper: New insights into aerosol and climate in the Arctic," Atmos. Chem. Phys. **19**, 2527–2560 (2019).

32. D. Watson-Parris, N. Schutgens, C. Reddington, K. J. Pringle, D. Liu, J. D. Allan, H. Coe, K. S. Carslaw, and P. Stier, "In situ constraints on the vertical distribution of global aerosol," Atmos. Chem. Phys. **19**, 11765–11790 (2019).
33. S. M. Sakerin, D. M. Kabanov, V. F. Radionov, D. G. Chernov, Yu. S. Turchinovich, K. E. Lubo-Lesnichenko, and A. N. Prakhov, "Generalization of results of atmospheric aerosol optical depth measurements on Spitsbergen Archipelago in 2011–2016," Atmos. Ocean. Opt. **31** (2), 163–170 (2018).
34. *The Current State of the Natural Environment on Spitzbergen Archipelago,* Ed. by L.M. Savatyugin (Arctic and Antarctic Research Institute, St. Petersburg, Russia, 2021). https://doi.org/10.30758/978-5-98364-101-3
35. A. P. Makshtas and T. Uttal, "Start of joint Russian-American atmospheric observations in Tiksi," Ros. Polyar. Issled., No. 2, 35–38 (2010).
36. E. Asmi, V. Kondratyev, D. Brus, T. Laurila, H. Lihavainen, J. Backman, V. Vakkari, M. Aurela, J. Hatakka, Y. Viisanen, T. Uttal, V. Ivakhov, and A. Makshtas, "Aerosol size distribution seasonal characteristics measured in Tiksi, Russian Arctic," Atmos. Chem. Phys. **16**, 1271–1287 (2016).
37. S. M. Sakerin, L. P. Golobokova, D. M. Kabanov, D. A. Kalashnikova, V. S. Kozlov, I. A. Kruglinskii, V. I. Makarov, A. P. Makshtas, S. A. Popova, V. F. Radionov, G. V. Simonova, Yu. S. Turchinovich, T. V. Khodzher, O. I. Khuriganova, O. V. Chankina, and D. G. Chernov, "Measurements of physicochemical characteristics of atmospheric aerosol at research station "Ice Base Cape Baranov" in 2018," Atmos. Ocean. Opt. **32** (5), 511–520 (2019).
38. A. P. Makshtas and V. T. Sokolov, "Scientific-research station "Ice Base Cape Baranov"—field summer season 2014," Ros. Polyar. Issled. **17** (3), 10–12 (2014).
39. O. B. Popovicheva, N. Evangeliou, K. Eleftheriadis, A. C. Kalogridis, N. Sitnikov, S. Eckhard, and A. Stohl, "Black carbon sources constrained by observations in the Russian High Arctic," Environ. Sci. Technol. **51** (7), 3871–3879 (2017).
40. S. M. Sakerin, A. A. Bobrikov, O. A. Bukin, L. P. Golobokova, Vas. V. Pol'kin, Vik. V. Pol'kin, K. A. Shmirko, D. M. Kabanov, T. V. Khodzher, N. A. Onischuk, A. N. Pavlov, V. L. Potemkin, and V. F. Radionov, "On measurements of aerosol-gas composition of the atmosphere during two expeditions in 2013 along the Northern Sea Route," Atmos. Chem. Phys. **15**, 12413–12443 (2015).
41. S. A. Terpugova, P. N. Zenkova, D. M. Kabanov, V. V. Pol'kin, L. P. Golobokova, M. V. Panchenko, S. M. Sakerin, A. P. Lisitzin, V. P. Shevchenko, N. V. Politova, V. S. Kozlov, T. V. Khodzher, V. P. Shmargunov, and D. G. Chernov, "Results of the study of aerosol characteristics in the atmosphere of the Kara and Barents Seas in summer and autumn 2016," Atmos. Ocean. Opt. **31** (5), 507–518 (2018).
42. L. P. Golobokova, T. V. Khodzher, O. N. Izosimova, P. N. Zenkova, A. O. Pochyufarov, O. I. Khuriganowa, N. A. Onishyuk, I. I. Marinayte, V. V. Polkin, V. F. Radionov, S. M. Sakerin, A. P. Lisitzin, and V. P. Shevchenko, "Chemical composition of atmospheric aerosol in the Arctic region and adjoining seas along the routes of marine expeditions in 2018–2019," Atmos. Ocean. Opt. **33** (5), 480–489 (2020).
43. S. M. Sakerin, D. M. Kabanov, V. I. Makarov, V. V. Polkin, S. A. Popova, O. V. Chankina, A. O. Pochufarov, V. F. Radionov, and D. D. Rize, "Spatial distribution of atmospheric aerosol physicochemical characteristics in Russian sector of the Arctic ocean," Atmosphere **11**, 1170 (2020).
44. O. Yu. Antokhina, P. N. Antokhin, V. G. Arshinova, M. Yu. Arshinov, B. D. Belan, S. B. Belan, D. K. Davydov, G. A. Ivlev, A. V. Kozlov, P. Nédélec, J.-D. Paris, T. M. Rasskazchikova, D. E. Savkin, D. V. Simonenkov, T. K. Sklyadneva, G. N. Tolmachev, and A. V. Fofonov, "Vertical distributions of gaseous and aerosol admixtures in air over the Russian Arctic," Atmos. Ocean. Opt. **31** (3), 300–310 (2018).
45. A. S. Kuz'michev, T. I. Babukhina, A. V. Gan'shin, A. N. Luk'yanov, R. M. Markov, A. M. Romanovskii, V. U. Khattatov, D. V. Kirin, and E. P. Malinina, "Remote and in situ measurements of aerosol concentration in the Arctic troposphere from the YAK-42D "Roshydromet" research aircraft," Rus. Meteorol. Hydrol. **41** (5), 365–372 (2016).
46. V. S. Kozlov, M. V. Panchenko, V. P. Shmargunov, D. G. Chernov, E. P. Yausheva, V. V. Pol'kin, and S. A. Terpugova, "Long-term investigations of the spatiotemporal variability of black carbon and aerosol concentrations in the troposphere of West Siberia and Russian Subarctic," Chem. Sustainable Dev. **24** (4), 423–440 (2016).
47. Q. Yang, C. M. Bitz, and S. J. Doherty, "Offsetting effects of aerosols on Arctic and global climate in the late 20th century," Atmos. Chem. Phys. **14**, 3969–3975 (2014).
48. M. Sand, T. K. Berntsen, K. von Salzen, M. G. Flanner, J. Langner, and D. G. Victor, "Response of Arctic temperature to changes in emissions of short-lived climate forcers," Nat. Clim. Change **6**, 1–5 (2015).
49. G. G. Anokhin, P. N. Antokhin, M. Yu. Arshinov, V. E. Barsuk, B. D. Belan, S. B. Belan, D. K. Davydov, G. A. Ivlev, A. V. Kozlov, V. S. Kozlov, M. V. Morozov, M. V. Panchenko, I. E. Penner, D. A. Pestunov, G. P. Sikov, D. V. Simonenkov, D. S. Sinitsyn, G. N. Tolmachev, D. V. Filippov, A. V. Fofonov, D. G. Chernov, V. S. Shamanaev, and V. P. Shmargunov, "OPTIK Tu-134 aicraft laboratory," Opt. Atmos. Okeana. **24** (9), 805–816 (2011).
50. J. R. Spackman, R. S. Gao, W. D. Neff, J. P. Schwarz, L. A. Watts, D. W. Fahey, J. S. Holloway, T. B. Ryerson, J. Peischl, and C. A. Brock, "Aircraft observations of enhancement and depletion of black carbon mass in the springtime Arctic," Atmos. Chem. Phys. **10**, 9667–9680 (2010).
51. J. Liu, S. Fan, L. W. Horowitz, and H. Levy Ii, "Evaluation of factors controlling long-range transport of black carbon to the Arctic," J. Geophys. Res. **116**, D04307 (2011).

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