ISSN 1024-8560, Atmospheric and Oceanic Optics, 2024, Vol. 37, No. 3, pp. 357–372. © The Author(s), 2024. This article is an open access publication.
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REMOTE SENSING OF ATMOSPHERE, HYDROSPHERE, AND UNDERLYING SURFACE

Air Composition over the Russian Arctic–4: Atmospheric Aerosols

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Received August 7, 2023; revised October 26, 2023; accepted November 17, 2023

Abstract—This work presents the analysis of the spatial distribution of number concentration, size distribution, and chemical composition of aerosol particles measured for the first time over the seas of the Russian Arctic. Various types of vertical distribution of the number concentration were recorded, characteristic of both coastal marine and continental areas. Most of them turned out to be of the continental type. Attention is also drawn to the almost complete absence of coarse particles above 2–3 km over all seas. The chemical composition of the Arctic aerosol at altitudes of both 200 m and 5000 m contains ions that can be referred to as both marine and continental. The identifiable carbon- and salt-free elemental part of the aerosol over the Arctic is 3–4 times larger than that of ions. Over all seas and at both altitudes, the Arctic aerosols mainly contain elements of terrigenous origin – Al, Cu, Fe, and Si. Over almost all seas, except the Barents Sea, Si is dominant in the elemental composition of the aerosol, its contribution over the Chukchi Sea reaching 85%. The analysis of backward trajectories showed that in all cases considered, whether the aerosol was formed over the continent or sea, air trajectories passed both over sea and over land. In this case, the formed particles could be enriched with additional ions and elements along their pathway. This work completes a cycle of the papers, devoted to studying air composition, which was carried out over the seas of the Russian Arctic in September 2020. Our results can be used to model the atmospheric processes occurring in the Arctic under the conditions of changing climate.

Keywords: Arctic, atmosphere, aerosol, air, vertical distribution, transport, impurity, number concentration, chemical composition

DOI: 10.1134/S102485602470057X

INTRODUCTION

Despite the efforts undertaken by the world community, global warming is still in progress, due mainly to changes in the air composition [1]. As early as very recently, the temperature in the Arctic was considered to grow 2–3 times faster than in other areas on the globe [2, 3]; however, recent analyses show that the temperature grows faster than a factor of 4 [4–6]. In this regard, a relevant question to ask is how the warming affects the air composition in the Arctic region; and, conversely, how changing composition affects the warming [7–9].

Aerosol is one of the air constituents, affecting appreciably radiation processes in the atmosphere [10]. Depending on its composition and altitude, aerosol may act to either cool or heat the air [11–13]. For instance, soot (black carbon), entering the particle composition, absorbs solar radiation and causes direct air heating [14]. Black carbon, formed during fires on continent and transported to the Arctic [15], after its deposition on ice or snow, reduces their albedo, which, on the one hand, causes their faster melting, and on the other hand, leads to additional absorption of radiation by underlying or water surface [16]. Residing in the upper troposphere, mineral dust causes air cooling [17]. Also, aerosol may influence the ecosystem productivity by increasing the scattered radiation, thus stimulating photosynthesis [18]. However, when aerosol loading increases strongly, the incoming direct solar radiation may decrease, so that photosynthesis may become less efficient [18].

Considering what uncertainty is introduced by (either positive or negative) aerosol radiative forcing to the total climate change [1], intense studies of spatio-temporal distribution of aerosols are carried out in foreign sector of the Arctic. This is done using all modern means of measurements: ground-based stations, ships, and aircraft laboratories. Based on data summarized in [19], as many as 119 field campaigns were conducted from 1990 to 2015 in the Arctic, aerosol parameters

Table 1. Technical characteristics of aerosol complex

Analyzer	D_p (intervals)	N, cm^{-3}, (error, %)	Frequency of measurements, s
DPS	3–200 nm (20)	0–500000 (±10)	80
GRIMM Model 1.109	0.25–32 μm (31)	0–2000 (±3)	6

D_p is the particle diameter, N is the number concentration.

were monitored at 350 ground-based observation sites, ship-based measurements amounted to 33000 h and aircraft observations to 11000 h. The achievements are markedly more modest in the Russian Arctic [20]. Quite regular aerosol studies are carried out in the near-water air layer onboard research vessels [21] in the absence of ice cover. We can also single out a few reference sites at which round-the-year observations in the surface air layer are carried out: Cape Baranov [22], Bely Island [23], Tiksi settlement [24], and Barentsburg settlement (Spitsbergen) [25]. The other studies represent short-term expeditions. No at all information on aerosol sensing in the Arctic onboard aircraft was found in the literature. Therefore, no information is available on the aerosol distribution and properties in the boundary layer and the free troposphere over the Russian Arctic.

To fill the gap in the data on vertical distribution of gas and aerosol admixtures in the troposphere over the Russian Arctic, an experiment, dealing with sensing of the atmosphere and water surface over water basins over all seas of the Arctic Ocean, was performed in September 2020 onboard the Tu-134 *Optik* aircraft laboratory. The authors of [26] described this experiment and the characteristics of the instrumentation used; also, they analyzed the average admixture concentrations in the atmosphere over all seas.

The purpose of this work is to study the specific features of the distribution of the number concentration and chemical composition of aerosol over all seas in the Russian Arctic.

1. METHODS AND MEANS OF MEASUREMENTS

To study the vertical structure of the size distribution of aerosol particles, the Tu-134 *Optik* aircraft laboratory was equipped by two types of instruments: the diffusional particle sizer (DPS) (Voevodsky Institute of Chemical Kinetics and Combustion, Siberian Branch, Russian Academy of Sciences), making it possible to retrieve the number distribution of nanoaerosols in the range from 3 to 200 nm in 20 size intervals; and the laser aerosol spectrometer Grimm Model 1.109 (Grimm Aerosol Technik GmbH & Co., Germany), designed for the measurements of the number concentration of aerosol particles in the size range from 0.25 to 32.0 μm. Both spectrometers are in a single aerosol complex, making it possible to cover the size range from 0.003 to 32 μm with a good resolution (51 intervals).

External air, composed of aerosol particles in the size range of 0.25–32 and 0.003–0.2 μm, was supplied to the instruments using the inlets with ∅ = 7.5 and 11 mm and the outlets with ∅ = 16 and 28 mm, respectively. The air inlet and outlet channels at instrument inputs and outputs were connected to each other by bypass shunt to avoid excessive pressure difference between input and output and minimize diffuse nanoparticle losses at the walls of inlet channels through increased total sample airflow, ensured by the shunt. Electroconductive silicone tubes were used as inlet channels to minimize the effect of electrostatic aerosol deposition. To reduce the inertial losses of large aerosol particles, the spectrometer Grimm Model 1.109 was placed as close as possible to inlet device on the aspiration rack. The technical characteristics of diffuse and laser spectrometers of aerosols are presented in Table 1.

In the period of the experiment, three types of aerosol sampling were carried out to determine aerosol chemical composition. Sampling installations differ by the number of filters and by the rate of air pumping through the filter. Two installations are designed for determining the inorganic and organic components in aerosol particle composition. Aerosol samples were collected in obedience to isokinetic conditions [26]. In essence, the sampling was through deposition of aerosol particles on filters by the aspiration method. The third installation was used to sample bioaerosols. The vertical distributions of the organic component and black carbon were considered previously in [27, 28].

The inorganic component was analyzed in the Laboratory of Hydrochemistry and Atmosphere Chemistry at the Limnological Institute, Siberian Branch, Russian Academy of Sciences. The ions H^+, Li^+, Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, NO_2^-, Br^-, NO_3^-, SO_4^{2-}, $CH_3SO_3^-$, and F^- were determined after preliminary preparation of specimens, using the ICS-3000 ion chromatography system (Dionex Corporation, California, United States). A one-time measurement was accurate to within 2–6%. [25]. The 23 elements (Ag, Al, B, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe, Mg, Mn, Mo, Ni, Pb, Sb, Si, Sn, Sr, Ti, V, Zr) in the composition of aerosol samples were analyzed using the method of mass spectrometry with induc-

tively coupled plasma on an Agilent-7500 CE device (United States, Agilent Technologies Int) with an accuracy of 0.2%.

2. VERTICAL DISTRIBUTION

The aerosol complex measured the distribution of aerosols in a wide size range; therefore, the vertical distribution of the aerosol number concentration was analyzed by dividing the entire measured range into three fractions: Aitken nuclei (AN, 0.003–0.200 μm), accumulation mode (AM, 0.25–1.0 μm), and coarse mode (CM, > 1.0 μm). These fractions reflect the fundamental features of the aerosol particle formation and transformation processes in the atmosphere [29–31]. Figure 1 presents the vertical profiles of the number concentrations for the tree fractions.

Atmospheric sensing was carried out on September 4 over the Barents Sea, on September 6 over the Kara Sea, on September 9 over the Laptev Sea, on September 15–16 over the East Siberian Sea, and on September 14–15, 2020 over the Chukchi Sea. From here on, time is the Greenwich Mean Time (GMT), primarily because the entire experiment was carried out in nine time zones in a number of big administrative territories, on which the local and astronomical times do not coincide, such as in the region of Sakha Republic (Yakutia). In Fig. 1 the profile numbers correspond to times when these profiles were obtained: odd-numbered (even-numbered) profiles during ascent (descent). The corresponding times are indicated in the figure caption.

It should be noted that during the measurement campaign, this territory was dominated by a vast cyclone with developed clouds and precipitation; therefore, a part of the profiles, which were measured in clouds, is excluded from analysis.

From Fig. 1 it can be seen that different types of the vertical distribution of the aerosol number concentration were recorded, characteristic for both coastal marine and polar (and even remote continental) regions [32]. Certain concentration profiles (AN profiles over the Barents and Kara Seas, AM profiles over the Laptev and East Siberian Seas) showed a *Z*-shaped structure, explained by the formation processes of new particles (nucleation) in the upper troposphere [33]. At the same time, the most of the vertical distributions are characterized by the concentration maximal near the surface, then decreasing to a certain level at altitudes of 2–3 km, and showing minor variations in the free troposphere. Similar profiles were also observed during the Arctic campaigns, carried out by European and American researchers in the foreign sector of the Arctic [34–36]. From Fig. 1 we can see almost total absence of coarse particles above 2–3 km over all seas, possibly explained by the absence of convective flows over sea surface and rapid deposition of large particles from the atmosphere, as shown in [37].

The aerosol number concentrations may markedly differ over different parts of Arctic seas (Fig. 1); therefore, for a comparison, Fig. 2 presents number concentrations averaged for each water basin, obtained by averaging all the data obtained in tropospheric layers with the step of 500 m.

Figure 2a indicates that the AN mode is characterized by the concentration decreasing from west to east. The concentrations in the near-water layer (200 m) are maximal over the Barents and Kara Seas and minimal over the East Siberian and Chukchi Seas.

This regularity is partially distorted for AM (Fig. 2b). The concentration is the largest over the Kara Sea, and the Chukchi Sea is ranked second. In contrast, CM (Fig. 2c) shows the largest values, reaching 1.2 cm^{-3}, over the Chukchi Sea, and the Kara Sea is ranked second. Probably, this distribution of aerosol is due to its transport from coastal territories, because continental type of vertical profiles is recorded over most water basins (see Fig. 1).

A point in favor of this conclusion also follows from comparison of the number concentrations over coastal territories (Fig. 3). This tendency is especially evident for the AN mode (Fig. 3a). In the region of the Kara Sea, this regularity is distorted somewhat for the AM because this fraction is transported in the boundary layer near Naryan-Mar and Sabetta settlements at an altitude of about 1000 m (Fig. 3b). The tendency for the concentration to decrease from west to east is almost recovered for CM (Fig. 3c). An exception is region of Sabetta, where there is again a layer with increased concentration of large particles.

It should be noted that the tendency of aerosol concentration in the Russian Arctic decreasing from west to east was recorded previously during many marine expeditions [38, 39]. In this work this tendency is revealed in the period of short-term aircraft campaign.

3. SIZE DISTRIBUTION

Despite the existing gaps in the DPS and Grimm Model 1.109 detections of particles in the size interval 0.2–0.25 μm, the detected distributions agree well. This can be seen from Fig. 4, which shows the distribution of particles in the entire size range observed in the atmosphere.

As for the vertical profiles of the number concentration, regional differences are clearly manifested in this case (Fig. 4). The particle size distribution in the western part of the Russian Arctic varies more strongly with the altitude (the Barents and Kara Seas) in both the concentration and in the intensity and position of the main modes. The size spectra were markedly broader in the western than eastern part.

In the eastern part, the variations were strong only in the nucleation size range (D_p < 0.007 μm). The weather conditions during the flights in this region [26]

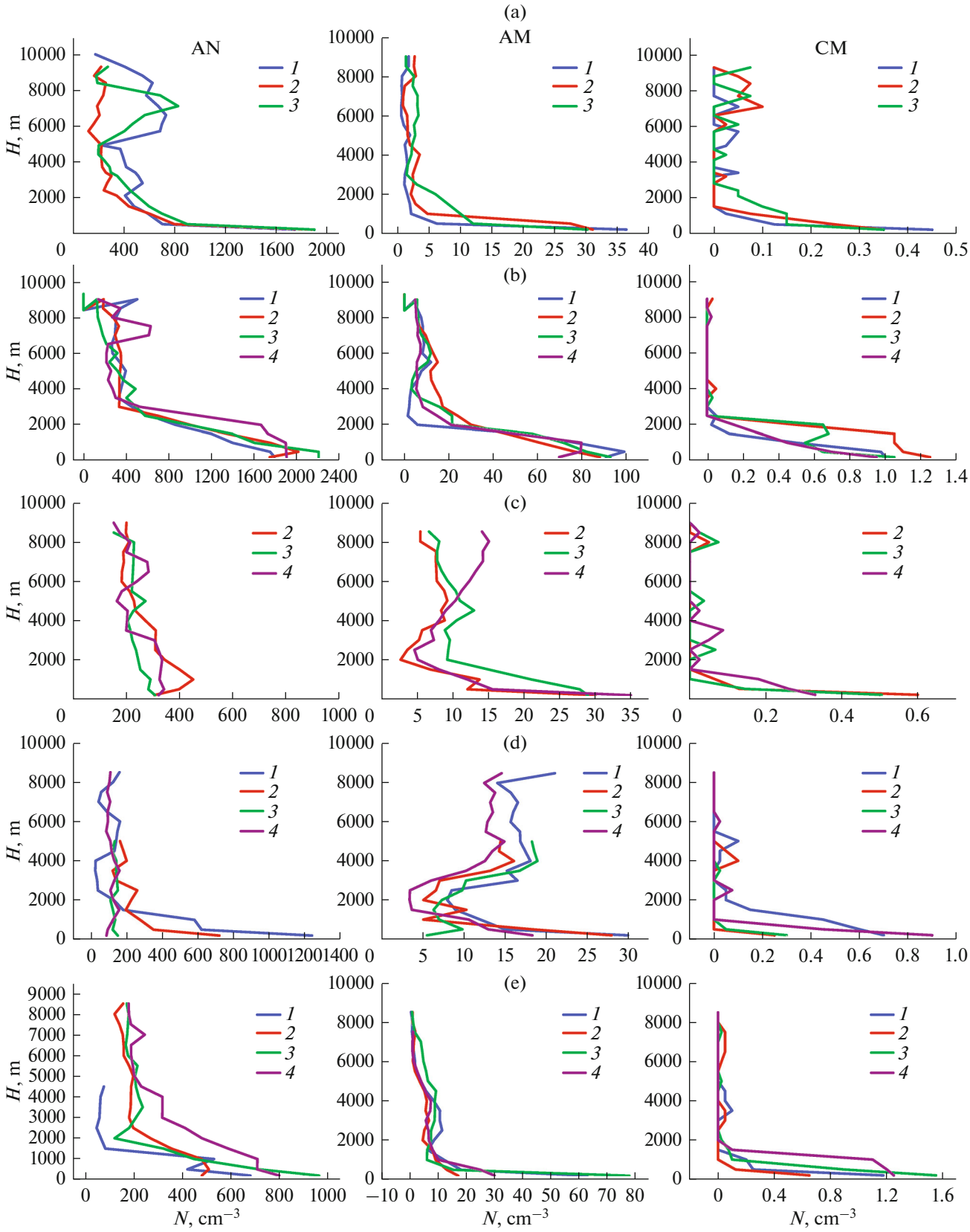
(a)
AN
AM
CM
(b)
(c)
(d)
(e)
H, m
N, cm−3
1
2
3
4

Fig. 1. Vertical distribution of the aerosol number concentration (N) over the Russian Arctic seas in September 2020: (a) Barents Sea, September 4, 2020, 13:30 GMT (*1*), 14:22 GMT (*2*), 14:52 GMT (*3*); (b) Kara Sea, September 6, 2020, 11:25 GMT (*1*), 12:13 GMT (*2*), 12:42 GMT (*3*), 13:29 GMT (*4*); (c) Laptev Sea, September 9, 2020, 04:21 GMT (*2*), 04:50 GMT (*3*), 05:31 GMT (*4*); (d) East Siberian Sea, September 15, 2020–September 16, 2020, 23:08 GMT (*1*); 23:40 GMT (*2*), 23:51 GMT (*3*), 00:22 GMT (*4*); and the Chukchi Sea, September 14, 2020–September 15, 2020, 00:13 GMT (*1*); 00:50 GMT (*2*), 01:18 GMT (*3*), and 01:50 GMT (*4*).

had led to a strong washout of aerosols and cleaning of the atmosphere, which can be clearly seen from the total absence of CM particles in the spectra. The intensities of the Aitken and accumulation modes, representing a major fraction of the total number concentration, did not change significantly with altitude, which affected the formation of a relatively uniform vertical distribution of the aerosol number concentration over the Chukchi and East Siberian basins.

4. CHEMICAL COMPOSITION

Samples for analysis of aerosol chemical composition were taken during horizontal flight at altitudes of 200, 5000, and 9000 m. The last two altitudes were determined from the reduced pressure, which corresponds to 760 mm Hg, or 1013 hPa. Our data at the level of 9000 m were already published in [40]; therefore, below, we will dwell only on results obtained at altitudes of 200 and 5000 m.

4.1. Ion Composition

The summed concentration of identified ions in the composition of aerosol particles is presented in Fig. 5.

From Fig. 5 it can be seen that the ion content in aerosol was maximal (0.96 μg/m^3) at an altitude of 200 m over the East Siberian Sea and minimal (0.63 μg/m^3) over the Laptev Sea. On the contrary, at an altitude of 5000 m the ion content was maximal (0.81 μg/m^3) over the Laptev Sea and minimal (0.13 μg/m^3) over the East Siberian Sea. No samples were taken over the Chukchi Sea due the presence of clouds. We can also note a weak tendency of decreasing ion content from west to east at an altitude of 5000 m (the confidence coefficient of the fit $R^2 = 0.075$).

Figure 6 shows the contribution of each ion to the total content of their summed concentration over Arctic seas.

From data in Fig. 6 it follows that ions of marine and continental origins are present in the composition of Arctic aerosol at altitudes of both 200 m and 5000 m,

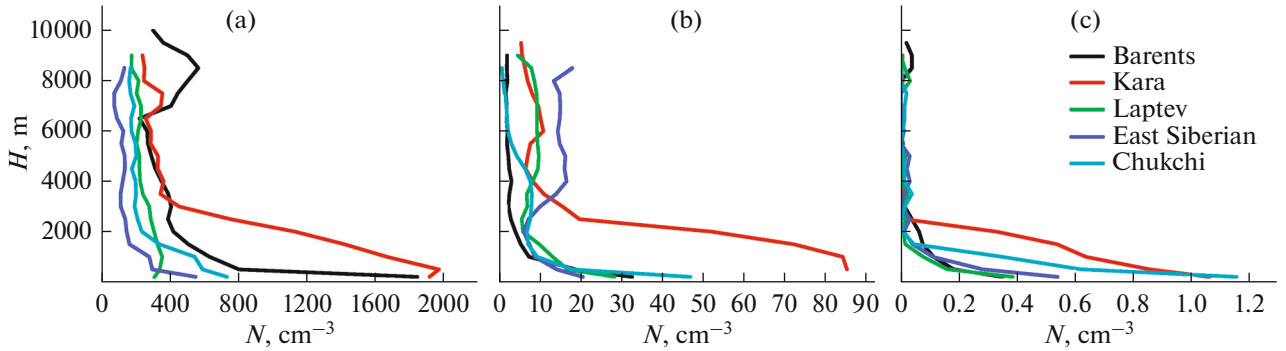

Fig. 2. Average aerosol number concentrations over seas of the Russian Arctic in September 2020: (a) AN; (b) AM; and (c) CM.

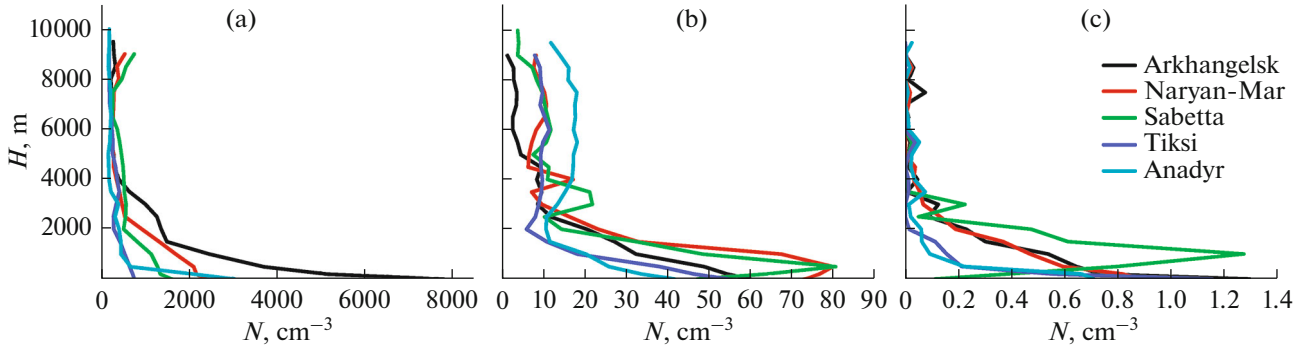

Fig. 3. Average aerosol number concentrations over coastal regions of the Russian Arctic in September 2020: (a) AN; (b) AM; and (c) CM.

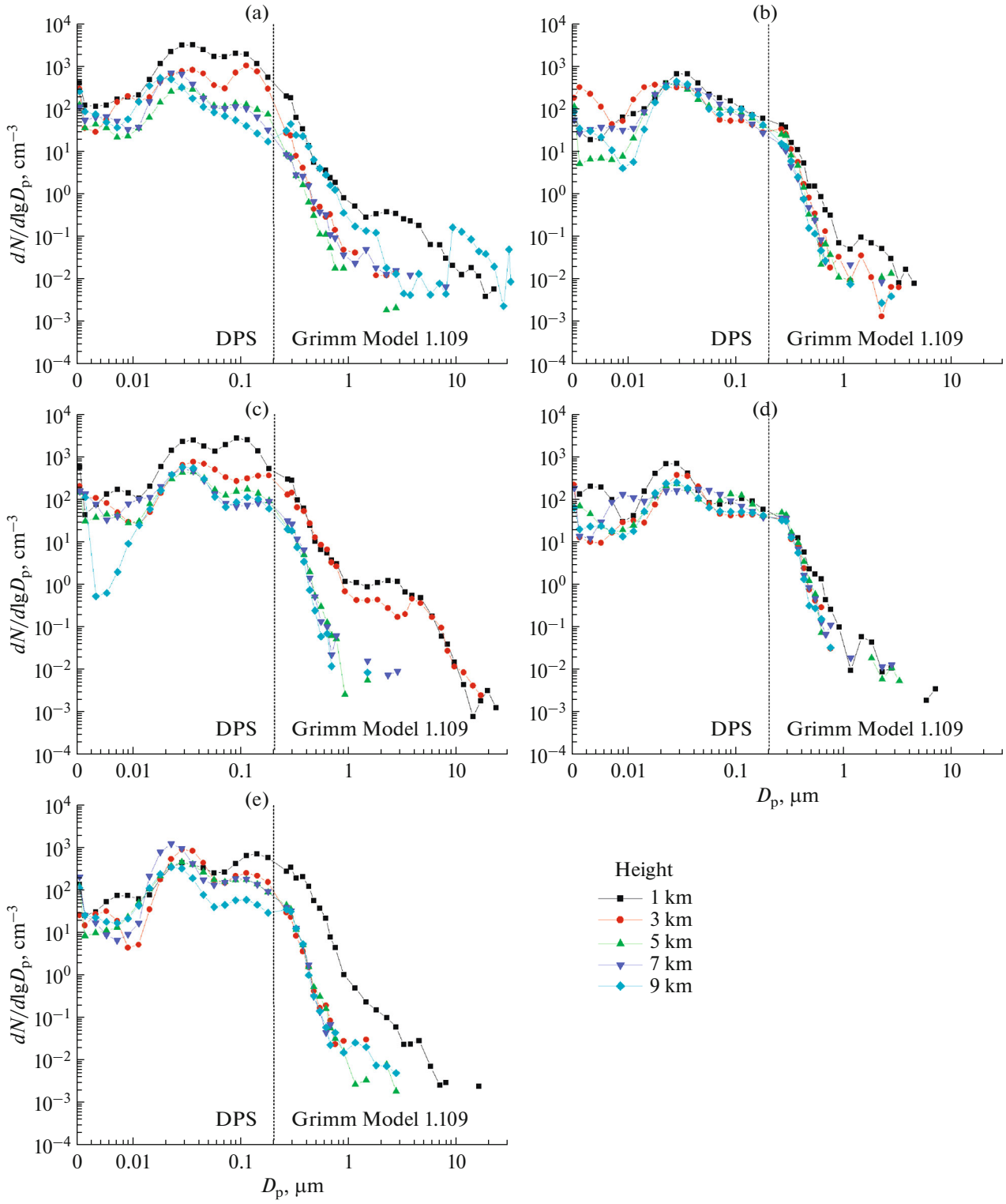

Fig. 4. Particle size distribution over seas of the Russian Arctic: (a) Barents Sea; (b) Chukchi Sea; (c) Kara Sea; (d) East Siberian Sea; and (e) Laptev Sea.

allowing us to conclude with a large confidence that tropospheric aerosols are mixed quite uniformly [41]. Samples were collected on the AFA-type (Petryanov) filters, trapping and effectively accumulating particles more than 0.1 μm in size [42]; therefore, this evidently reflects the multiday process of AM and CM forma-

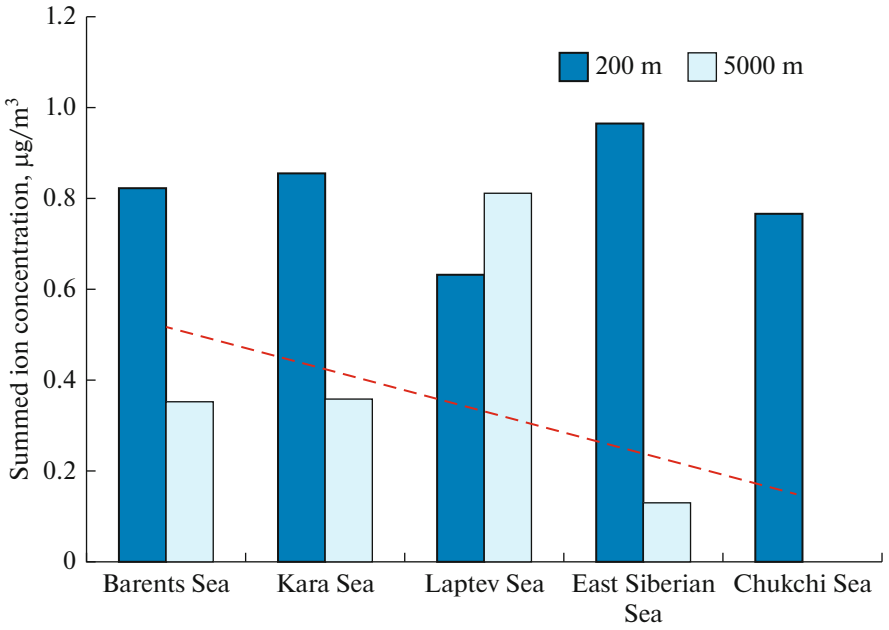

Fig. 5. Summed ion concentration in aerosol composition over Russian Arctic seas.

tion. The data, obtained previously [29–31], indicate that particles evolve from nucleation (2–3 nm) to accumulation (0.1–1.0 μm) mode in 4–5 days.

The main ions (up to 65%) of aerosol substance over the Barents Sea at an altitude of 200 m were Li^+, Na^+, and SO_4^{2-} ions. The Ca^{2+}, Mg^{2+}, Cl^-, and Br^- ions are present in marked (30%) amounts. At an altitude of 5000 m, the relationship of ions markedly changes; and up to 88% of ion composition is determined by ions of predominantly marine origin, i.e., Na^+, Mg^{2+}, Cl^-, and Br^-. Possibly, this is due the difference in the trajectories of air supply to this altitude during experiment.

For the Kara Sea at an altitude of 200 m, the particle composition is dominated by ions of continental origin: Li^+, NH_4^+, Ca^{2+}, NO_3^-, and SO_4^{2-}. These compounds are often thought to be anthropogenic [41]. At an altitude of 5000 m, the contribution of marine ions Na^+ and Cl^- increases up to 18%; nonetheless, the ions NH_4^+, Ca^{2+}, NO_3^-, and SO_4^{2-} are predominant. Thus, the ion composition over the Kara Sea strongly differs from the one recorded over the Barents Sea. Evidently, in addition to the effect of different situation-sensitive sources, to be discussed in the next section, there is also a permanent physicochemical prerequisite for these variations, namely, zonal separation of these seas by large chain of islands of Novaya Zemlya, acting to enhance the turbulence of airflows over the area under consideration.

The divergences are even stronger over the Laptev Sea, where at an altitude of 200 m the aerosol composition is dominated by Na^+, Cl^- (45%) and Ca^{2+}, SO_4^{2-} (35%). At a level of 5000 m, the main (67%) contribution is due to Na^+, Ca^{2+}, Br^-, and Cl^-; also, the role of the ions H^+ increases to 18%, indicating the dearth of cations in aerosol composition.

As over the Laptev Sea, as over the East Siberian Sea, the main contribution to aerosol composition at the altitude of 200 m was due to Na^+, Cl^- (46%) and Ca^{2+}, SO_4^{2-} (33%) ions. At an altitude of 5000 m, the absolute concentrations of ions Na^+ and SO_4^{2-} were below the detection limit, so that the predominant contributions were due to Ca^{2+} (41%) and Cl^- (37%); also, against this background, the relative content of the ion F^- increases to 13%.

In aerosol over the Chukchi Sea at an altitude of 200 m, predominant were the marine ions Na^+ (30%) and Cl^- (37%); also, the percentage was large for the K^+ ion, usually serving an indicator of forest fires [41].

Thus, when going from western to eastern seas, in the aerosol composition there were decreased contributions of continental and, possibly, anthropogenic aerosol, and an increased percentage of marine aerosol.

In contrast to the number concentration, the aerosol chemical composition was repeatedly measured in the Russian Arctic onboard research vessels. Comparison of our data from an altitude of 200 m with near-water data [38, 43, 44] shows that they are a factor of 2–3 smaller in absolute value. This is quite naturally because the aerosol concentration was shown in Section 2 to decrease with altitude.

Our data are close to results obtained at remote island station Cape Baranov, in both concentration and composition [45].

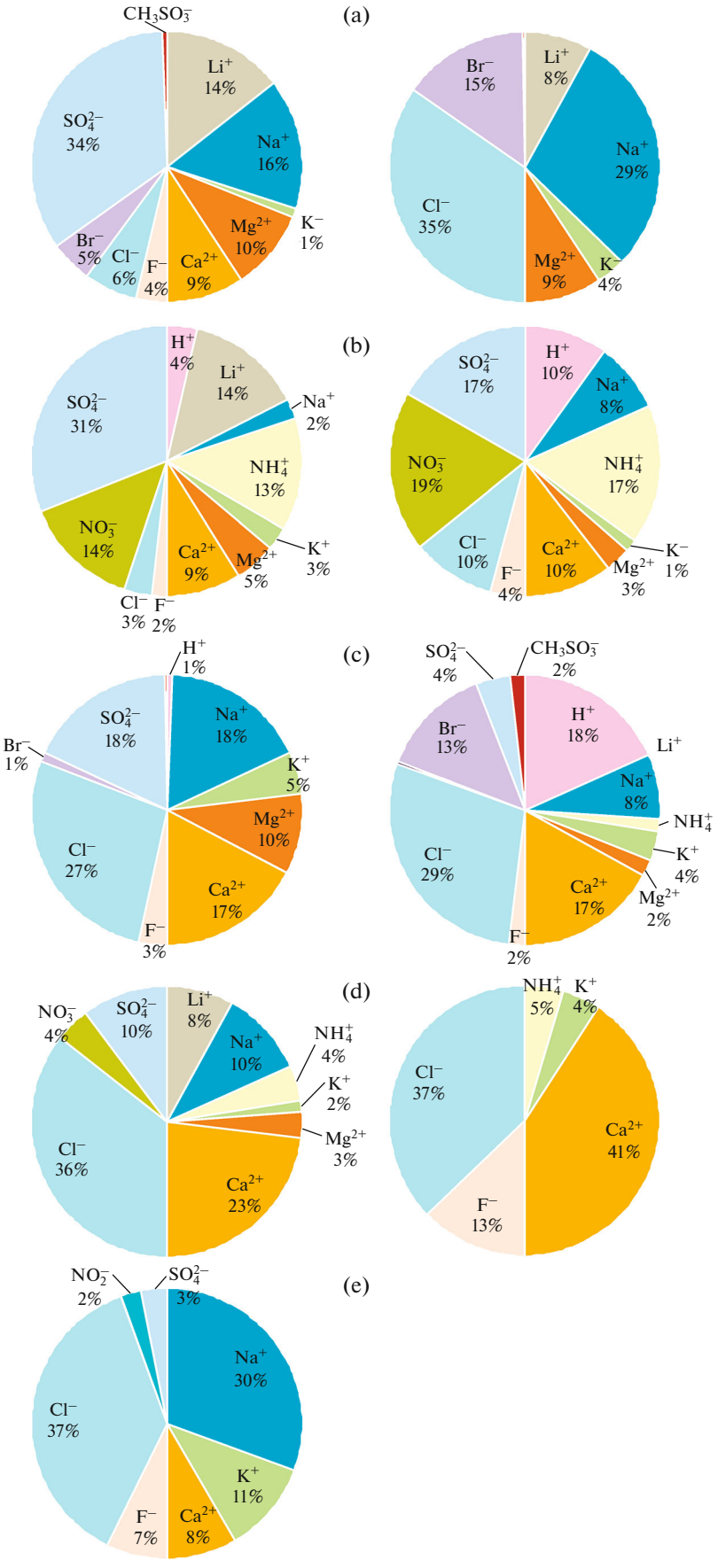
(a)
$CH_3SO_3^-$
Li+ 14%
Na+ 16%
K− 1%
Mg2+ 10%
Ca2+ 9%
F− 4%
Cl− 6%
Br− 5%
SO_4^{2-} 34%
Br− 15%
Li+ 8%
Na+ 29%
Cl− 35%
Mg2+ 9%
K− 4%
(b)
H+ 4%
Li+ 14%
Na+ 2%
SO_4^{2-} 31%
NH_4^+ 13%
NO_3^- 14%
Ca2+ 9%
Mg2+ 5%
K+ 3%
Cl− 3%
F− 2%
SO_4^{2-} 17%
H+ 10%
Na+ 8%
NO_3^- 19%
NH_4^+ 17%
Cl− 10%
F− 4%
Ca2+ 10%
Mg2+ 3%
K− 1%
(c)
H+ 1%
SO_4^{2-} 18%
Na+ 18%
Br− 1%
K+ 5%
Mg2+ 10%
Cl− 27%
Ca2+ 17%
F− 3%
SO_4^{2-} 4%
$CH_3SO_3^-$ 2%
Br− 13%
H+ 18%
Li+
Na+ 8%
NH_4^+
Cl− 29%
K+ 4%
Ca2+ 17%
Mg2+ 2%
F− 2%
(d)
NO_3^- 4%
SO_4^{2-} 10%
Li+ 8%
Na+ 10%
NH_4^+ 4%
K+ 2%
Mg2+ 3%
Cl− 36%
Ca2+ 23%
NH_4^+ 5%
K+ 4%
Cl− 37%
Ca2+ 41%
F− 13%
(e)
NO_2^- 2%
SO_4^{2-} 3%
Na+ 30%
Cl− 37%
K+ 11%
F− 7%
Ca2+ 8%

Fig. 6. Ion composition of aerosol over Russian Arctic seas, %-equiv, at an altitude of 200 (left) and 5000 m (right): (a) Barents sea; (b) Kara sea; (c) Laptev Sea; (d) East Siberian Sea; and (e) Chukchi Sea.

4.2. Elemental Composition

Elemental (and not only ion) composition was analyzed in samples collected. In particular, we determined the following elements: Ag, Al, B, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe, Mg, Mn, Mo, Ni, Pb, Sb, Si, Sn, Sr, Ti, V, and Zr. The total sum of carbon- and salt-free identified part of aerosol elemental composition is presented in Fig. 7.

Figure 7 demonstrates that at an altitude of 200 m, the concentrations of elements are maximal over the Kara and Laptev Sea; and at 5000 m, over the Kara Sea. We can also note that the concentrations of elements tend to decrease from west to east (from the Barents Sea to the Chukchi Sea).

From Fig. 8 it can be seen that over all seas, the aerosol elemental composition is dominated by Si, the contribution of which reaches 85%. Also of note is that the number of identified microelements in aerosol decreases when moving from west to east. For instance, the number of microelements at different altitudes varies from 15 to 21 over the Barents and Kara Seas and from 10 to 12 over the East Siberian and Chukchi Seas. Over the Barents and Kara Seas the aerosol composition is dominated by predominantly terrogenically derived Al, Cu, Fe, Si at an altitude of 200 m and by Ti, Ca, Fe, Si, Al, and Cu at an altitude of 5000 m. The predominant elements over the eastern seas at both altitudes were mainly Fe, Si, Cu, and Al. In the aerosol composition over seas in the eastern part of the Arctic, we detected no Pb, Co, Sn, Ni, Cd, and V (especially at an altitude of 5000 m) that could indicate that technogenic aerosol is predominant over seas in the Russian Arctic.

Comparison of our data with previous research [21, 46, 47] shows a good agreement, in both the set of identified elements and in their concentrations.

5. RESULTS AND DISCUSSION

Table 2 lists the predominant ions and elements, which we recorded during experiment in September 2020.

Data in Table 2 indicate that both continental and marine sources influenced the formation of the Arctic aerosols. The presence of the ions NH_4^+ and SO_4^{2-}, possibly, reflects the contribution of an anthropogenic source, especially over the western seas; the presence of Na^+ and Cl^- indicates that the marine source is strong.

The transport of aerosol to the Arctic was predicted theoretically quite long ago [48, 49]. The transport efficiency for the sector under study was calculated in [50, 51]. In a large cycle of their works [52–59], Vinogradova et al. showed the efficiency of aerosol transport to the Arctic from the continental part of Russia, and used measurements to show the transport pathways. The transport of particles and black carbon from

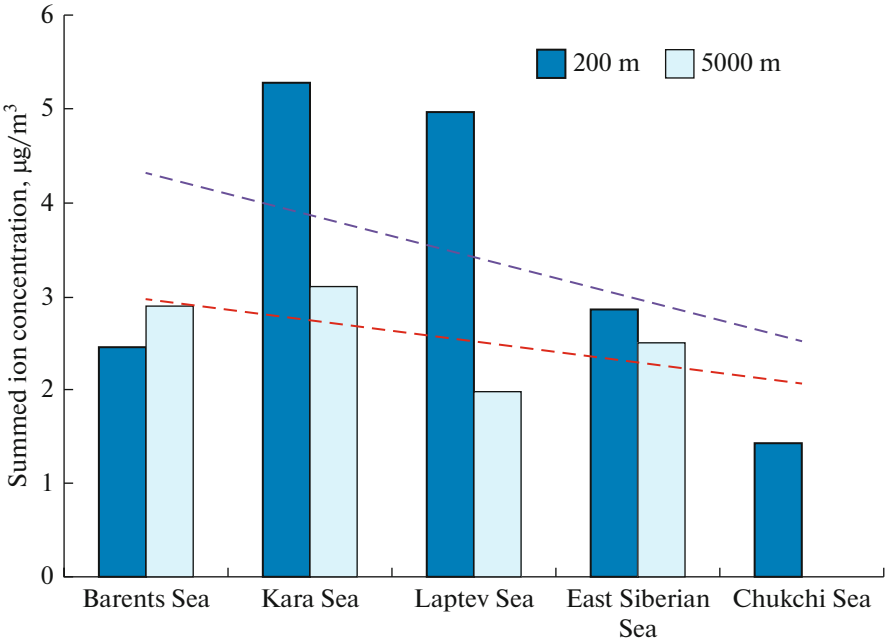

Fig. 7. Summed elemental composition of carbon- and salt-free part of atmospheric aerosol over the Russian Arctic seas.

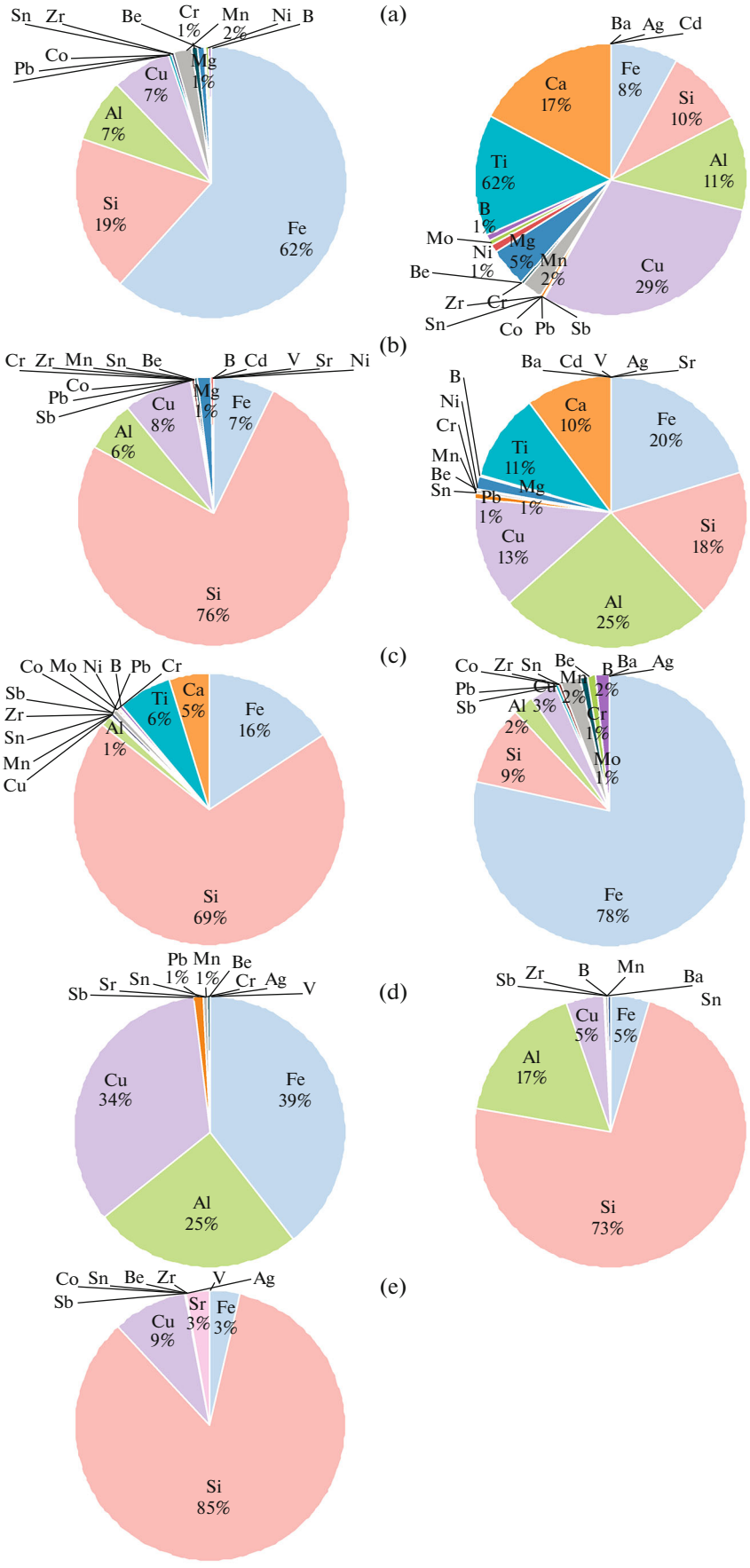
(a)
Sn Zr Be Cr 1% Mn 2% Ni B
Co
Pb
Cu 7%
Mg 1%
Al 7%
Si 19%
Fe 62%
Ba Ag Cd
Fe 8%
Si 10%
Ca 17%
Ti 62%
Al 11%
B 1%
Mo
Ni 1%
Mg 5%
Mn 2%
Cu 29%
Be
Zr
Cr
Sn
Co Pb Sb
(b)
Cr Zr Mn Sn Be B Cd V Sr Ni
Co
Pb
Sb
Mg 1%
Cu 8%
Fe 7%
Al 6%
Si 76%
Ba Cd V Ag Sr
B
Ni
Cr
Mn
Be
Sn
Ca 10%
Fe 20%
Ti 11%
Mg 1%
Pb 1%
Si 18%
Cu 13%
Al 25%
(c)
Co Mo Ni B Pb Cr
Sb
Zr
Sn
Mn
Cu
Ti 6%
Ca 5%
Fe 16%
Al 1%
Si 69%
Co Zr Sn Be Mn 2% B Ba Ag
Pb
Sb
Cu 3%
Al 2%
Cr 1%
Si 9%
Mo 1%
Fe 78%
(d)
Pb 1% Mn 1% Be
Sb
Sr
Sn
Cr Ag
V
Cu 34%
Fe 39%
Al 25%
Sb Zr B Mn Ba
Sn
Cu 5%
Fe 5%
Al 17%
Si 73%
(e)
Co Sn Be Zr V Ag
Sb
Sr 3%
Cu 9%
Fe 3%
Si 85%

Fig. 8. Elemental composition of carbon- and salt-free part of atmospheric aerosol over the Russian Arctic seas, mass.%, at an altitude of 200 (left) and 5000 m (right): (a) Barents Sea; (b) Kara Sea; (c) Laptev Sea; (d) East Siberian Sea; and (e) Chukchi Sea.

the continent to the ocean basin was also shown in works of Popovicheva [60, 61].

In regard to the aforesaid, we will consider the pathways along which air was supplied to the regions of aerosol sampling at an altitudes of 200 and 5000 m, presented in Fig. 9. Taking into account the above-mentioned period of aerosol formation in the atmosphere of 4–5 days, the back trajectories were constructed for a period of 6 days. For each sampling case we specified three points: start, middle, and end of the sampling site.

From Fig. 9, it can be seen that in all cases considered here (no matter where, whether over continent or sea, the aerosol was born), the air trajectories passed both over sea and land. In this case, the formed particles could be enriched by additional ions and elements along the transport pathway.

For instance, air, from which aerosol was sampled over the Barents Sea at an altitude of 200 m, originated over different regions of the continent; however, it passed over sea in the final phase. This can be clearly seen from the profiles of trajectories in the lower part of Fig. 9. Naturally, components of continental and marine aerosol were identified. Air, which came to an altitude of 5000 m over this same sea, is of oceanic origin. However, it then traveled a long pathway over Scandinavia, and so could be enriched by elements of continental origin.

For the collected air samples over the Kara Sea at an altitude of 200 m there is a similar trajectory: the origin over the Scandinavian coast, followed by the loop over the European territory of Russia (ETR). It is noteworthy that air descended deep below, where industrial regions are located. And only the concluding part of the trajectory passed again over the sea surface. The pathways of aerosol at an altitude of 5000 m for the Kara Sea passed over the continent, with two lying over industrial regions of Western Europe and the ETR. Therefore, for both seas the chemical composition of aerosol comprises ions and elements which can be considered to be anthropogenic.

Table 2. Dominant ions and elements at an altitude of 200 m

Sea	Ion	Elements
Barents	Na^+, SO_4^{2-}	Fe, Si
Kara	NH_4^+, SO_4^{2-}	Si
Laptev	Na^+, Ca^{2+}, Cl^-, SO_4^{2-}	Fe, Si
East Siberian	Ca^{2+}, Cl^-	Fe, Cu, Al
Chukchi	Na^+, Cl^-	Si

Air, supplied in the Laptev, East Siberian, and Chukchi basins, originated over the sea surface. However, trajectories in all cases passed, at least partially, over the continent, which could favor enrichment of aerosol by terrogenic ions and elements.

In regard to the processes of enriching the aerosol along its pathway, it is appropriate to mention the clearly underestimated work [62], in which it was shown that with mechanical processes aerosols from 5 to 20 nm may form in large quantities (up to 10^{10} particles from the area of 1 cm^2). These particles are readily and long transported in the atmosphere and may serve the basis for formation of AM aerosols.

We noted above the low concentrations of atmospheric aerosol in the Russian Arctic, especially CM. This is easily explained by the period of experiment. Based on the data from a number of researchers [63–66], in September in the Arctic the aerosol concentration is minimal.

CONCLUSIONS

Our quite a short aircraft experiment made it possible to compare the aerosol microphysical characteristics over all seas of the Russian Arctic.

We recorded different types of the vertical distribution of the aerosol particle number concentration, characteristic for coastal marine and polar, and even remote continental regions. Certain concentration profiles showed a *Z*-shaped structure. At the same time, most vertical distributions were of continental type, when the concentration maximum was near the surface and then decreased with altitude. Also of note is an almost total absence of coarse particles above 2–3 km over all seas. The mode of Aitken nuclei is characterized by a rapid decrease in concentration from west to east: the largest values in the near-water layer (200 m) are observed over western (Barents and Kara) seas, and the smallest values, over the East Siberian and Chukchi Seas. Probably, this distribution of aerosol is due to its transport from coastal territories, because its shape over most basins corresponded to the concentration profiles observed over continents.

We also noted the regional differences in particle size distribution. Both the total aerosol concentration and concentrations and modal sizes of the fractions vary most strongly in the western part of the Russian Arctic. The size spectra are markedly wider in this part than in the eastern part, where variations were significant only in the nucleation size range ($D_p < 0.007$ μm). The concentrations of the Aitken and accumulation mode, which were the main fractions of the total number concentration, did not show strong variations with altitude. The data, obtained during the Arctic cam-

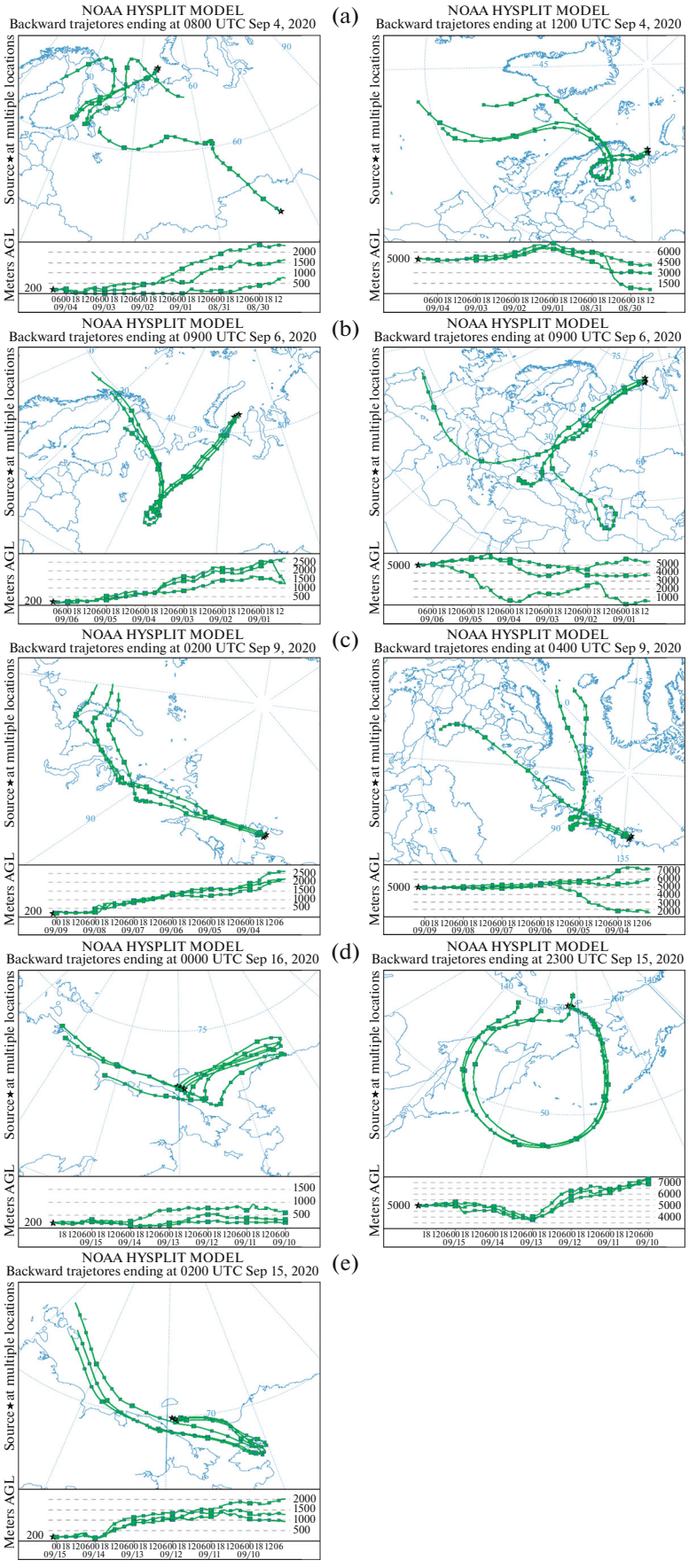
NOAA HYSPLIT MODEL
Backward trajetores ending at 0800 UTC Sep 4, 2020
(a)
NOAA HYSPLIT MODEL
Backward trajetores ending at 1200 UTC Sep 4, 2020
NOAA HYSPLIT MODEL
Backward trajetores ending at 0900 UTC Sep 6, 2020
(b)
NOAA HYSPLIT MODEL
Backward trajetores ending at 0900 UTC Sep 6, 2020
NOAA HYSPLIT MODEL
Backward trajetores ending at 0200 UTC Sep 9, 2020
(c)
NOAA HYSPLIT MODEL
Backward trajetores ending at 0400 UTC Sep 9, 2020
NOAA HYSPLIT MODEL
Backward trajetores ending at 0000 UTC Sep 16, 2020
(d)
NOAA HYSPLIT MODEL
Backward trajetores ending at 2300 UTC Sep 15, 2020
NOAA HYSPLIT MODEL
Backward trajetores ending at 0200 UTC Sep 15, 2020
(e)
Source★at multiple locations
Meters AGL

Fig. 9. Back trajectories of air masses supplied to the aerosol sampling region in the Russian Arctic at an altitude of 200 (left) and 5000 m (right): (a) Barents Sea; (b) Kara Sea; (c) Laptev Sea; (d) East Siberian Sea; and (e) Chukchi Sea.

paign, can be thought to be unique, because throughout the globe in most aircraft studies the measurements of aerosol particles with $D_p < 0.1$ μm are carried out with much worse resolution; while in the Russian Arctic, this study was carried out for the first time.

Ions of marine and continental origins are present in the chemical composition of the Arctic aerosol at altitudes of 200 and 5000 m. Over the Barents Sea, Li^+, Na^+ and SO_4^{2-}, accounted for the most part (almost 65%) of ions in aerosols at an altitude of 200 m; and the ions Na^+, Mg^{2+}, Cl^-, and Br^- were predominant (up to 88%) at the level of 5000 m. Possibly, this was because of the difference in trajectories of supply of air into the region of the experiment to these altitudes. The ions Li^+, NH_4^+, Ca^{2+}, NO_3^-, and SO_4^{2-}. were predominant in particle composition at both altitudes for the Kara Sea. Over the Laptev Sea at an altitude of 200 m these were ions Na^+, Cl^- (45%) and Ca^{2+}, SO_4^{2-} (35%). At 5000 m, the main contribution (67%) is due to ions of marine origin: Na^+, Ca^{2+}, Br^-, and Cl^-; and due to the dearth of cations, the role of H^+ ions increases to 18%. Over the East Siberian Sea, the aerosol composition was dominated by Na^+, Cl^- (46%) and Ca^{2+}, SO_4^{2-} (33%) at an altitude of 200 m, and by Ca^{2+} (41%) and Cl^- (37%) at an altitude of 5000 m, against the background of extremely low concentrations of Na^+ and SO_4^{2-}. Aerosol over the Chukchi Sea at an altitude of 200 m was dominated by the marine ions Na^+ (30%) and Cl^- (37%).

Thus, as we moved from western to eastern seas, the contribution to aerosol composition of continental aerosol and, possibly, anthropogenic aerosol decreased and the contribution of marine aerosol increased.

As we moved from west to east, the number of identified microelements decreased in the composition of the salt-free, carbon-free part of the atmospheric aerosol. Elements of terrogeous origin in the aerosol composition were predominant mainly at an altitude of 200 m over the Barents and Kara Seas (Al, Cu, Fe, Si), and at an altitude of 5000 m over the eastern seas (Ti, Ca, Fe, Si, Al, Cu, Fe, Si, Cu, Al). Silicon (Si) was predominant (contribution of 69–85%) over the Kara, Laptev, East Siberian, and Chukchi Seas. The contribution of the continental factor decreased against the background of the west–east increasing marine factor in the formation of ion and elemental composition. It should also be noted that there were not elements of clearly anthropogenic origin, i.e., Pb, Co, Sn, Ni, Cd, and V, in the aerosol composition over the Russian Arctic seas, especially at an altitude of 5000 m.

Analysis of back trajectories showed that in all cases, considered here, the trajectories of the air mass passed over sea and land. It is also important to stress that, in the period of the experiment, the concentrations of all ions and elements analyzed were low, characteristic for background, remote regions.

FUNDING

Atmospheric sensing was carried out on unique scientific installation Tu-134 *Optik* aircraft laboratory supported by the Ministry of Science and Higher Education of the Russian Federation (V.E. Zuev Institute of Atmospheric Optics, Siberian Branch, Russian Academy of Sciences). Data were processed and results analyzed under the support from the Ministry of Science and Higher Education of the Russian Federation under the project "Studying the anthropogenic and natural factors of variations in the air composition and environmental entities in Siberia and the Russian Arctic under the conditions of rapid climate changes using the unique scientific installation Tu-134 *Optik* aircraft laboratory (agreement no. 075-15-2021-934).

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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Translated by O. Bazhenov