
REMOTE SENSING OF ATMOSPHERE, HYDROSPHERE,
AND UNDERLYING SURFACE

Complex Assessment of Air Composition over the Russian Arctic in September 2020

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Abstract—Climate warming in the Arctic is several times faster than in other regions of the globe. This can be the result of strengthening of feedbacks between climate and atmospheric composition. However, there are very few data on changes in the concentration of climatically active substances in this region. Therefore, to fill the gap in data on the vertical distribution of gas and aerosol composition of air over the Russian Arctic, an airborne survey of the atmosphere and water surface over all the Russian Arctic Ocean seas was performed with use of the Tu-134 Optik aircraft laboratory in September 2020. This paper analyzes the spatial distribution of gas and aerosol composition in the Arctic troposphere. It is shown that during the experiment, the CO₂ mixing ratio increased in the near-water and boundary layers and decreased in the free troposphere from west to east. The methane content in the near-water layer decreased in the same direction. Concentrations of CO, NO_x, and SO₂ in the Russian Arctic were very low, which was typical for remote background areas. All aerosol fractions also showed a decrease in their content from west to east.

Keywords: Arctic, atmosphere, aerosol, vertical distribution, sulfur dioxide, methane, ozone, nitrogen oxides, carbon oxides, transport, composition

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INTRODUCTION

According to the Intergovernmental Panel on Climate Change (IPCC), global warming, caused mainly by changes in air composition [1], continues, but unevenly across the globe. Air temperature increases most (four-time) rapidly in the Arctic compared to other regions [2–4]. This raises a number of questions: how does warming change the air composition in a region? how might actual variations in the composition affect the warming? [5–7] These questions can only be answered if we have information about the air composition [8]. However, such data for the Russian Arctic are lacking.

Measurements of air composition in this region were carried out only in the surface air layer in [9], in the near-water layer from drifting stations [10], or from ships [11]; mainly greenhouse gases were studied [12]. The concentrations of other trace atmospheric gases have been sporadically studied.

The processes of exchange of impurities between the water surface, which is increasingly free of ice, and the atmosphere remain beyond the scope of interest of scientists. The information about the vertical distribution of impurities is absent. Heating can occur not only in the surface air layer, but also in the middle tro-

posphere, as shown in [13, 14], which complicates modeling climate processes and environmental changes.

To date, there are no commercially available means for measuring the vertical distribution of gaseous and aerosol components of the atmosphere. The solution to the problem of air composition monitoring in the Arctic region, as in other remote points on the globe, was associated with the development of satellite sensing systems. According to [15], 15 spacecraft types were already in operation in 2007 and measured the aerosol and gas composition of the atmosphere. However, satellite measurement accuracy is insufficient [16]. Hence, it is necessary to improve both the hardware and technique of satellite sounding [17, 18].

Aircraft laboratories are widely used in many countries for studying the vertical distribution of gas and aerosol impurities in the Arctic. The aircraft method is recognized as standard for studying the air composition over vertical [19]. Therefore, to fill the gap in data on the vertical distribution of gas and aerosol compositions of the atmosphere over the Russian Arctic, we used the Tu-134 Optic aircraft laboratory.

The experiment on sounding the atmosphere and water surface over waters of all the Russian Arctic

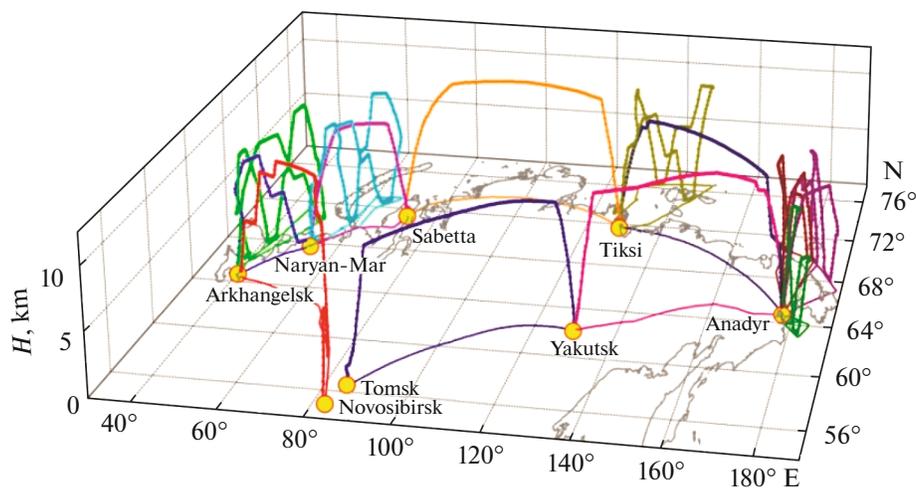


Fig. 1. Flight pattern during the campaign in September 2020.

Ocean seas was conducted in September 2020. The description of the experiment and equipment, as well as average concentrations of impurities over all the seas are given in [20]. In [21–24], the distribution of air composition over each of the seas was analyzed in detail.

The aim of this work is to summarize the results of the study of the spatial distribution of gas and aerosol components of the atmosphere in the Russian Arctic in September 2020. Unlike previous works, this article does not present individual vertical distributions, but profiles generalized for each of the seas and sections specially constructed by kriging [25]. This ensures a better visual presentation of measurement data and a more complete pattern of the spatial distribution of gases and aerosols.

1. MATERIALS AND METHODS

The Arctic campaign was performed from September 4 to 17, 2020. the flight pattern is shown in Fig. 1. During the experiment, concentration profiles of gaseous and aerosol components of the air were measured from the minimum permissible altitudes (200 m) to the upper troposphere (9000–10000 m). When climbing and descending over the seas, the aircraft was horizontally flying at three levels (200, 5000, and 9000 m) without changing the altitude or 5–15 min in order to sample aerosol on filters and study the spatial heterogeneity of the distributions of gas components and meteorological variables. Four vertical profiles were measured over each of the seas.

This work examines the concentrations of carbon dioxide and carbon monoxide (CO_2 and CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), methane (CH_4), ozone (O_3), nucleation aerosol particles (NUC), Aitken nuclei (AN), and accumulation (ACM) and coarse (CA) aerosol fractions. The char-

acteristics of the devices used in the measurements are given in Table 1.

2. RESULTS AND DISCUSSION

2.1. Gas Composition

Figure 2 shows the vertical distribution of the concentrations of trace atmospheric gases measured over the Arctic Ocean seas in the period from September 4 to 16, 2020. The longitude variations in CO_2 are significantly different in the free troposphere (FT) and the atmospheric boundary layer (ABL) (see Fig. 2a). Since Western Europe is a high-power anthropogenic source of various impurities, which are then usually transported from west to east, their content decreases in the same direction in the FT due to dispersion.

The pattern is different in the ABL. The ocean absorbs more than a third of excessive CO_2 in the atmosphere [26]. This is seen in Fig. 2a, where its concentration in the surface air layer is significantly lower than in the FT throughout the water area of the Russian Arctic. Inside the ABL, the CO_2 content increases from west to east in contrast to the lower layers (Table 2).

According to the data in Table 2, the CO_2 concentration was minimal over the Barents Sea (397.2 ± 0.5 ppm) and maximal over Chukchi Sea (410.3 ± 1.8 ppm). In our opinion, the decrease in CO_2 absorption by the ocean can be explained as follows. On the one hand, if the ocean assimilates CO_2 by dissolution, then its absorption should negatively depend on water temperature [27]. On the other hand, CO_2 is assimilated by plankton inhabiting in the upper ocean layer. The metabolic rate for many of plankton species positively and nonlinearly depends on water temperature [28]. According to Table 3, the higher the sea water temperature, the lower the CO_2 concentration in the air

Table 1. Specifications of gas analyzers and aerosol spectrometers

Device	Measured parameter	Measurement range	Uncertainty	Time constant, s
G2301-m	CO ₂	0–1000 ppm	<0.2 ppm	1
	CH ₄	0–20 ppm	<0.0015 ppm	1
	H ₂ O	0–70000 ppm	<150 ppm	1
Model 49C	O ₃	0–200 ppm	±0.001 ppm	1
Model 48C	CO	0–10000 ppm	±<1%	4
Model 42i-TL	NO/NO ₂ /NO _x	0–0.5 ppm	±0.0004 ppm	10
Model 43i-TLE	SO ₂	0–20 ppm	±0.0002 ppm	10
Diffusion aerosol spectrometer	<i>D_p</i> (20 channels)	3–200 nm	–	80
	<i>N</i>	0–500000 cm ⁻³	±10%	
GRIMM Model 1.109	<i>D_p</i> (31 channels)	0.25–32 μm	–	6
	<i>N</i>	0–2000 cm ⁻³	±3%	

D_p is the particle diameter; *N* is the number of particles per unit volume.

Table 2. Average and median concentrations of trace atmospheric gases over the Russian Arctic seas

Sea	Layer, km	CO ₂ , ppm	CH ₄ , ppb	CO, ppb	NO _x , ppb	SO ₂ , ppb	O ₃ , ppb
<i>Average ± SD</i>							
Barents	ABL < 1.9	400.1 ± 4.7	2009.1 ± 31.2	89 ± 18	0.68 ± 0.22	0.55 ± 0.22	32 ± 13
	FT > 1.9	411.4 ± 1.4	1932.7 ± 10.7	95 ± 20	0.42 ± 0.12	0.39 ± 0.13	54 ± 6
Karskoe	ABL < 1.8	405.6 ± 2.9	2065.4 ± 35.5	112 ± 17	0.56 ± 0.18	0.43 ± 0.10	28 ± 10
	FT > 1.8	411.8 ± 1.2	1937.8 ± 24.2	94 ± 19	0.34 ± 0.13	0.35 ± 0.08	53 ± 6
Laptev	ABL < 1.6	407.8 ± 1.6	2003.7 ± 21.1	106 ± 18	0.27 ± 0.07	0.36 ± 0.08	33 ± 9
	FT > 1.6	410.6 ± 1.6	1942.4 ± 15.3	90 ± 18	0.28 ± 0.08	0.37 ± 0.07	53 ± 7
East Siberian	ABL < 1.8	409.2 ± 0.8	2006.7 ± 13.5	104 ± 16	0.29 ± 0.07	0.42 ± 0.07	31 ± 5
	FT > 1.8	408.3 ± 1.0	1950.0 ± 13.8	87 ± 16	0.24 ± 0.05	0.41 ± 0.08	43 ± 6
Chukchi	ABL < 1.3	409.6 ± 2.1	1998.4 ± 17.5	96 ± 14	0.26 ± 0.04	0.39 ± 0.08	31 ± 4
	FT > 1.3	409.5 ± 2.1	1947.8 ± 9.90	88 ± 17	0.26 ± 0.09	0.38 ± 0.08	46 ± 8
<i>Median (IQR)</i>							
Barents	ABL < 1.9	397.4 (7.4)	2018.2 (51.2)	89 (24)	0.60 (0.39)	0.50 (0.18)	26 (18)
	FT > 1.9	411.5 (1.7)	1930.1 (10.6)	95 (24)	0.42 (0.14)	0.38 (0.11)	54 (7)
Karskoe	ABL < 1.8	406.2 (3.4)	2084.6 (36.3)	111 (23)	0.48 (0.21)	0.44 (0.13)	23 (12)
	FT > 1.8	411.9 (1.5)	1934.0 (31.8)	94 (25)	0.34 (0.16)	0.35 (0.10)	53 (8)
Laptev	ABL < 1.6	407.5 (2.8)	2006.4 (34.2)	106 (25)	0.26 (0.05)	0.36 (0.11)	32 (13)
	FT > 1.6	410.7 (2.3)	1943.1 (21.1)	89 (24)	0.28 (0.11)	0.37 (0.09)	54 (10)
East Siberian	ABL < 1.8	409.2 (0.6)	2012.1 (6.6)	105 (23)	0.27 (0.11)	0.41 (0.10)	29 (2)
	FT > 1.8	408.7 (1.4)	1952.1 (18.3)	87 (22)	0.25 (0.07)	0.41 (0.11)	45 (10)
Chukchi	ABL < 1.3	409.3 (4.0)	2002.7 (28.4)	97 (19)	0.26 (0.05)	0.38 (0.13)	31 (7)
	FT > 1.3	409.4 (3.7)	1943.5 (14.6)	87 (19)	0.26 (0.13)	0.38 (0.11)	49 (11)

IQR is the interquartile range.

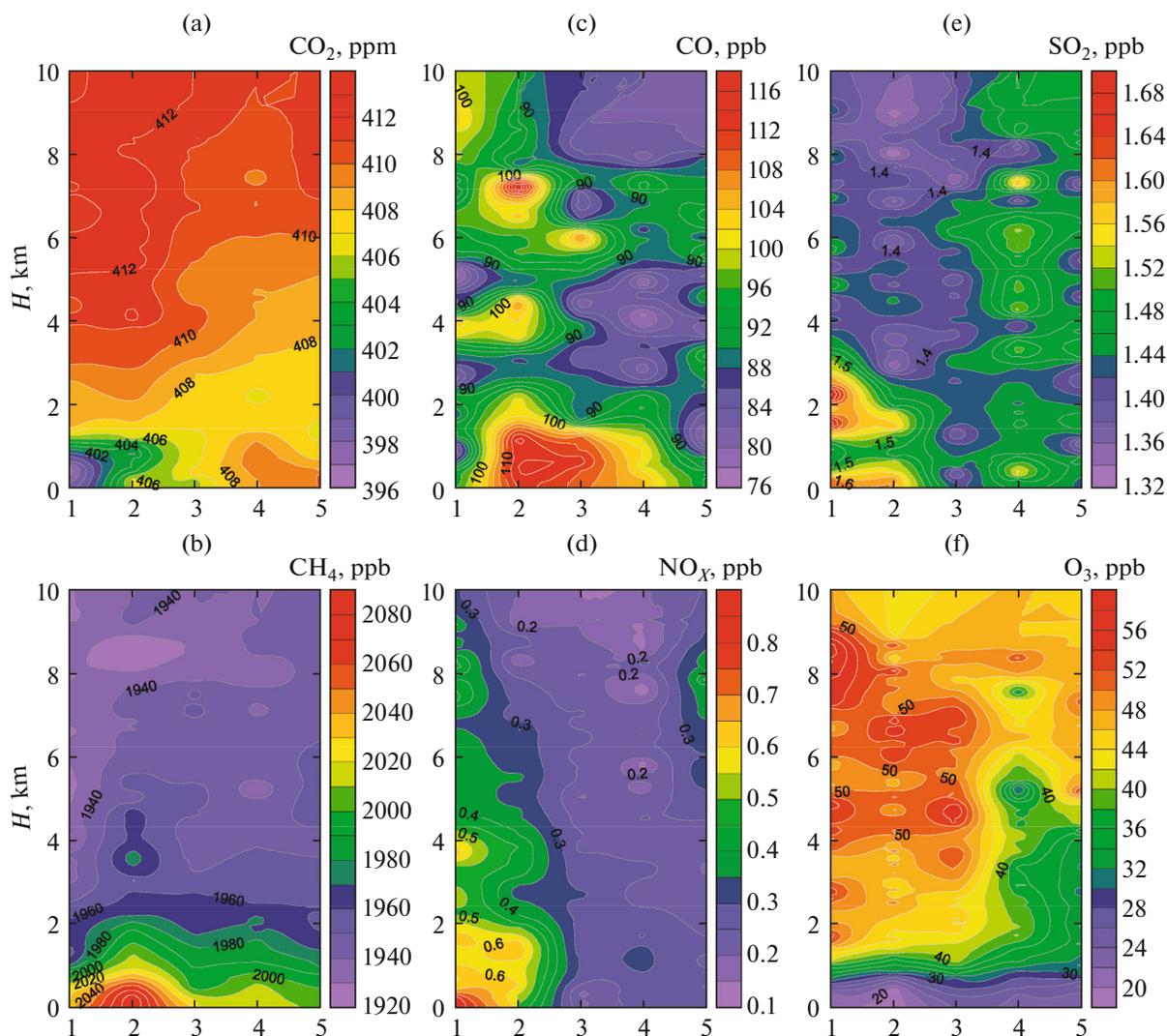


Fig. 2. Vertical distribution of the concentration of trace gases: (a) CO_2 , (b) CH_4 , (c) CO , (d) NO_x , (e) SO_2 , and (f) O_3 over Russian Arctic seas: the Barents Sea (1), Kara Sea (2), Laptev Sea (3), East Siberian Sea (4), and Chukchi Sea (5) (plotted along the abscissa).

above the sea, i.e., the stronger the CO_2 absorption. Thus, the assimilation of CO_2 by microorganisms inhabiting in the upper ocean layer predominated in the Russian Arctic seas during the experiment.

Table 3. Average gas concentrations over the Arctic seas at an altitude of 200 m depending on water temperature

Sea	$T_{\text{water}}, ^\circ\text{C}$	CO_2, ppm	CH_4, ppb
Barents	11	397.2 ± 0.5	2027.4 ± 10.4
Karskoe	8	406.2 ± 1.9	2088.2 ± 6.30
Laptev	7	407.9 ± 1.6	2007.8 ± 16.8
East Siberian	5	409.5 ± 0.4	2013.5 ± 1.50
Chukchi	4	410.3 ± 1.8	2003.3 ± 13.3

Figure 2b shows that the methane concentration in the ABL (>2040 ppb) is significantly higher than in the FT (<1940 ppb). The Kara Sea stands out against a general trend in decreasing methane content from west to east (Fig. 2b and Tables 2 and 3). A surge in CH_4 content is pronounced in Fig. 2b. This is partly confirmed by the results of work [29]. However, our earlier analysis [21] showed the transfer of CH_4 from the mainland to the ocean in that case. As proof, Fig. 3 shows a vertical section of the concentration distribution for coastal areas.

The comparison between Figs. 2b and 3 shows the methane concentration to be higher over the coast than over the Kara Sea. Considering that a southwest-erly transport was observed in that region during the experiment [20, 21], the increase in the CH_4 content

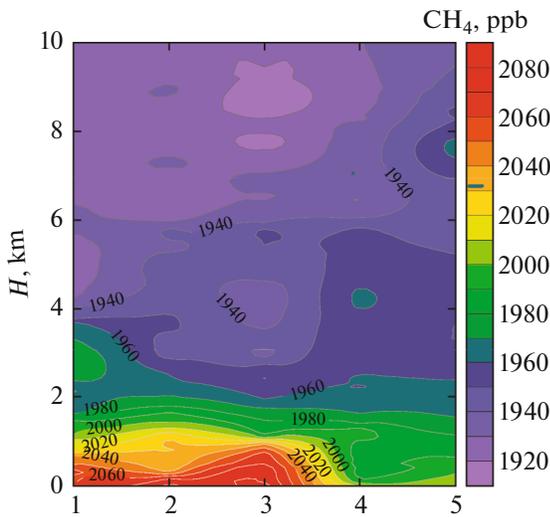


Fig. 3. Vertical methane distribution of over coastal areas of the Russian Arctic: Arkhangelsk (1), Naryan-Mar (2), Sabetta (3), Tiksi (4), and Anadyr (5) (plotted along the abscissa).

over this sea was obviously caused by the advection of methane-rich air from Western Siberia bogs.

The concentrations of carbon monoxide shown in Fig. 2c also support this conclusion. This gas is usually considered an indicator of human activity or wildfires, which could only occur on the mainland. The comparison between Figs. 2b and 2c reveals the proximity of regions with high concentrations of methane and carbon monoxide. In the Russian Arctic, the concentrations of CO (Fig. 2c), as well as of NO_x (Fig. 2d) and SO₂ (Fig. 2e) are very low (Table 2) and typical for remote background areas [30, 31].

It is clear from Fig. 2d that the concentrations of nitrogen oxides is within the range 0.2–0.3 ppb over most of the water area, and it increases to 0.6–0.7 ppm only in the western part. This most likely reflects the transport of these gases from Western Europe or the Kola Peninsula.

The concentrations of SO₂ over the Arctic seas was also low, within 0.3–0.6 ppm (Fig. 2e). The distribution of this gas is similar to the distribution of nitrogen oxides, which indicates possible anthropogenic causes for the increase in its content (see the left side of Fig. 2e).

Tropospheric ozone behaves completely differently in Arctic regions (Fig. 2f): its concentration is significantly lower in the ABL than in the FT. This means that its photochemical generation is completely absent [32]. Ozone coming from the stratosphere is consumed due to the interaction of halogens emitted by the ocean, fluorine and chlorine (the so-called depletion effect) [33, 34].

Thus, during the experiment, the gas composition of the atmosphere over the Russian Arctic was characterized by high concentrations of CH₄ and very low content of CO, NO_x, and SO₂ nucleation aerosol particles (NUC), Aitken nuclei (AN), and accumulation (ACM) and coarse (CA) aerosol fractions.

2.2. Atmospheric Aerosol

Table 4 shows the average and median values of the total aerosol (N_{Σ}), nucleation (N_{NUK} ; 0.003–0.025 μm), Aitken (N_{AN} ; 0.025–0.200 μm), accumulation (N_{ACM} ; 0.25–1.0 μm), and coarse aerosol (N_{CA} ; >1.0 μm) count measured over the Arctic Ocean seas in the period from September 4 to 16, 2020. Vertical

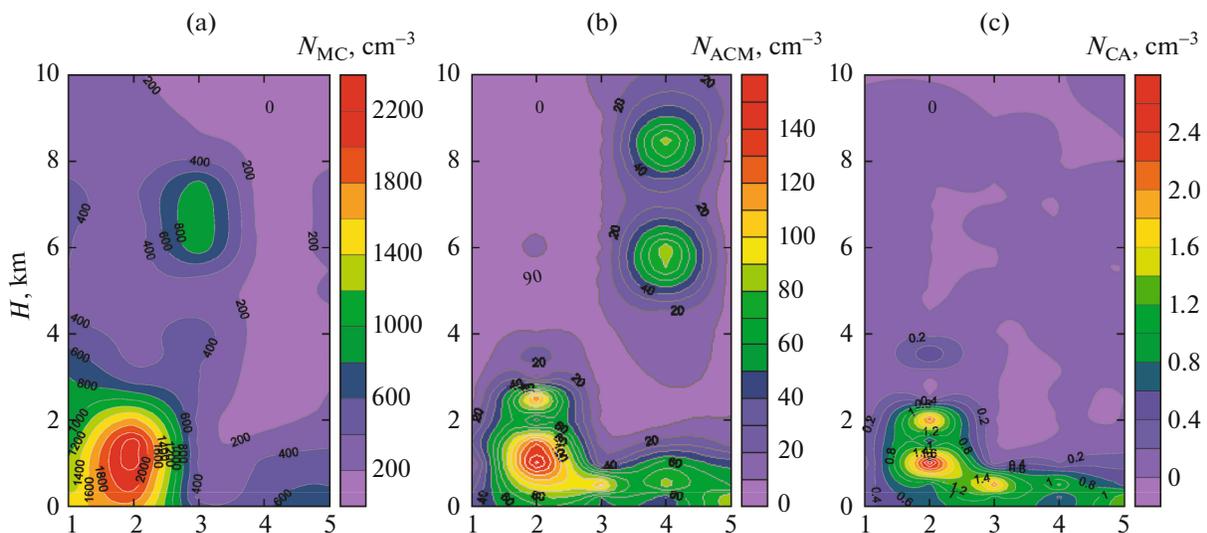


Fig. 4. Vertical sections of the concentration distributions of (a) microdisperse, (b) accumulation, and (c) coarse aerosols over the Russian Arctic seas (abscissa is numbered like in Fig. 2).

Table 4. Average and median counts of different fractions aerosols, cm^{-3} , over the Russian Arctic seas

Sea	Layer, km	N_{Σ}	N_{NUM}	N_{AN}	N_{ACM}	N_{CA}
<i>Average \pm SD</i>						
Barents	ABL < 1.9	1797 \pm 937	464 \pm 471	1081 \pm 544	290 \pm 144	0.414 \pm 0.291
	FT > 1.9	374 \pm 302	166 \pm 128	162 \pm 180	53 \pm 105	0.075 \pm 0.536
Karskoe	ABL < 1.8	2049 \pm 700	317 \pm 315	1287 \pm 484	538 \pm 177	1.295 \pm 2.024
	FT > 1.8	370 \pm 399	139 \pm 172	167 \pm 199	88 \pm 128	0.170 \pm 0.919
Laptev	ABL < 1.6	369 \pm 173	83 \pm 104	192 \pm 64	199 \pm 156	0.473 \pm 1.263
	FT > 1.6	350 \pm 366	145 \pm 239	166 \pm 143	48 \pm 23	0.010 \pm 0.027
East Siberian	ABL < 1.8	570 \pm 558	282 \pm 302	243 \pm 273	177 \pm 358	0.450 \pm 0.831
	FT > 1.8	136 \pm 50	46 \pm 32	66 \pm 26	37 \pm 9	0.015 \pm 0.028
Chukchi	ABL < 1.3	704 \pm 227	273 \pm 174	358 \pm 114	159 \pm 135	0.927 \pm 0.904
	FT > 1.3	213 \pm 120	61 \pm 73	129 \pm 64	27 \pm 14	0.020 \pm 0.066
<i>Median value (IQR)</i>						
Barents	ABL < 1.9	1603 (1688)	343 (551)	1039 (732)	249 (212)	0.375 (0.375)
	FT > 1.9	252 (206)	122 (142)	105 (93)	19 (21)	<0.07
Karskoe	ABL < 1.8	1804 (513)	262 (262)	1172 (334)	579 (195)	0.700 (0.500)
	FT > 1.8	325 (145)	101 (93)	129 (105)	36 (71)	<0.1
Laptev	ABL < 1.6	324 (148)	54 (56)	179 (49)	120 (154)	0.150 (0.225)
	FT > 1.6	230 (98)	77 (68)	124 (79)	46 (36)	<0.01
East Siberian	ABL < 1.8	184 (1016)	94 (475)	80 (243)	54 (121)	0.250 (0.500)
	FT > 1.8	140 (44)	45 (39)	69 (30)	38 (10)	<0.01
Chukchi	ABL < 1.3	710 (342)	246 (327)	336 (158)	108 (162)	0.775 (0.900)
	FT > 1.3	186 (57)	42 (46)	125 (57)	23 (19)	<0.1

sections of the distribution of microdisperse aerosol count ($N_{\text{MC}} = N_{\text{NUC}} + N_{\text{AN}}$), N_{ACM} , and N_{CA} are shown in Fig. 4.

Data from Table 4 and Fig. 4a show a decrease in N_{Σ} and N_{MC} from west to east. The values in the ABL are maximal over the western seas (the Barents and Kara Seas) and minimal over the East Siberian and Chukchi Seas (Table 4). This pattern is partially violated for ACM (Fig. 4b): the maximal concentration is observed over the Kara Sea; there is also a moderately intense layer within the ABL over all the eastern seas (Table 4). A similar distribution was recorded for the coarse fraction (Table 4 and Fig. 4c). This distribution of aerosols over the seas is probably due to their transfer from coastal areas, since the profiles over most seas have the form characteristic of continental regions [24].

It should be noted that the trend to west-to-east decrease in the aerosol concentration in the Russian Arctic from previously recorded during long-term marine expeditions [35, 36]. It was confirmed in the present work during the short flight campaign.

It is impossible to construct above vertical sections for individual chemical components of aerosols, since it is necessary to collect required amount of substances on filters for the analysis. The elemental part of the aerosol over the Arctic identified in individual samples is three to four times larger than that of ions. Over all the seas, the composition of Arctic aerosol mainly includes terrigenous elements Al, Cu, Fe, and Si, which indicates its continental origin. Over some seas, Si dominates in the particle composition, contributing from 67 and 85%. The analysis of air mass back trajectories showed them to pass both over continent and ocean in all the cases under study. Therefore, no matter where aerosol originated, over a continent or a sea, the particles observed over the seas could be enriched with additional ions and elements along the way.

CONCLUSIONS

The short duration of the aircraft experiment made it possible to compare the composition of the air over all the seas of the Russian Arctic. The results allow us to draw the following conclusions.

The concentration of carbon dioxide in the free troposphere decreases from west to east with distance from the main anthropogenic sources located in Western Europe. The absorption of carbon dioxide by the ocean during the experimental period depended on water temperature. This relationship was positive, indicating the predominance of CO₂ assimilation by plankton over its dissolution in water.

No such pronounced trend to change from west to east was observed for methane. The CH₄ concentration at an altitude of 200 m was maximal over the Kara Sea and minimal over the Chukchi Sea. The vertical distribution of methane suggests that its main source is located on the underlying surface (land or sea). The comparison of methane content over the seas and land at the same altitude revealed that the content was higher over the coastal regions than over the Barents and Kara Seas; this excess was created by CH₄ transfer from continent.

The vertical distribution of ozone was characterized by an increase in its concentration with altitude. This indicates the absence of photochemical processes in the boundary layer and the predominance of ozone income from the stratosphere. The drop in concentration within the atmospheric boundary layer also reflects the fact of its destruction by marine halogens. The other measured gases very low concentrations, typical for remote background areas, such as the Arctic.

The aerosol count is characterized by a decrease from west to east. Its values were maximal over the western seas (the Barents and Kara Seas) and minimal over the East Siberian and Chukchi Seas. The “cleanliness” of this region is confirmed by almost complete absence of coarse particles above 2–3 km over all the seas.

Since this experiment was the first of such type in the Russian history of research of the composition of the Arctic atmosphere, it is natural that the results should be considered preliminary. It is necessary to perform similar sounding in other seasons, when some sources and sinks may be “switched off”. For example, in winter, when the ocean is frozen and there is no vegetation.

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CONFLICT OF INTEREST

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

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