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Vertical profiles of aerosol and absorbing matter over settlements in the north of Russia

Polina N. Zenkova*, Dmitriy G. Chernov, Mikhail Yu. Arshinov, Boris D. Belan, Mikhail V. Panchenko

V.E. Zuev Institute of Atmospheric Optics SB RAS, Tomsk, Russia

ABSTRACT

The results of measurements of aerosol and absorbing substance vertical profiles from onboard of the TU-134 "Optic" laboratory aircraft during Arctic flights in the fall of 2020 are presented. The vertical distributions of mass concentrations of aerosol and absorbing matter over Arkhangelsk, Tiksi and Anadyr are analyzed. The aerosol optical characteristics over three cities in the north of Russia are reconstructed and compared with the measurement data.

Keywords: model, atmospheric aerosol, number concentration, submicron and coarse particles, multi-year series of observations

1. INTRODUCTION

Climate change at high latitudes is a predictor of changes on a global scale[1-4]. It is important to understand the feedbacks that lead to increased warming in the Arctic. Assessment of climate change in the poorly studied Arctic and subarctic regions is impossible without detailed data on the absorbing and scattering properties of atmospheric aerosol[3-7]. The tropospheric aerosol optical characteristics and the parameters of the radiative forcing, such as the single scattering albedo, directly depend on the ratio of the volume concentrations of absorbing and non-absorbing substances[1].

Last decade, a lot of publications devoted to the study of aerosol in the Arctic region have appeared[8-11]. In the Russian sector of the Arctic, in situ measurements are regularly carried out at polar stations[12-17], in annual marine expeditions[13-21]. In order to fill in the missing data over the ocean, studies performed from aircraft-laboratory[22-24] or from the satellites[25-27] are used.

Measurements of the angular scattering coefficients ($\varphi = 45°$, $\lambda = 0.53$ μm) and the concentration of the absorbing matter (soot , BC - Black Carbon) were carried out as part of a comprehensive experiment on the study of the composition of the troposphere in the Russian sector of the Arctic from onboard the TU-134 "Optic" aircraft-laboratory on September 4 till 17, 2020.

In this paper we analyze the vertical profiles of the mass concentrations of submicron aerosol and absorbing matter, and determine the columnar mass concentrations of aerosol and BC over three settlements: Arkhangelsk (64.54 ° N, 40.54 ° E), Tiksi (71.69 ° N, 128.86 ° E), and Anadyr (64.73 ° N, 177.30 ° E). A model calculation of the scattering coefficient in the visible wavelength range, at altitudes of 1 - 8 km with a step of 1 km, out over the three northern cities under study was carried taking into account the absorbing and hygroscopic properties of particles.

2. ANALYSIS OF THE EXPERIMENTAL DATA

2.1. Instrumental and measurement techniques

The automated aerosol complex consisted of a MDA-02 three-wavelength aethalometer designed at IAO SB RAS capable of measuring the absorbing matter mass concentration MBC and a PhAN nephelometer capable of recording the angular scattering coefficient of the aerosol dry matter at $\varphi = 45°$ and $\lambda = 0.53$ μm. The Tu-134 "Optic" aircraft-laboratory, instrumentation, techniques for calibration and measurements are described in detail in Ref. 28.

* zpn@iao.ru; phone +7 (3822) 492-848; fax +7 (3822) 492-086

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2.2. Vertical profiles of the aerosol and BC mass concentrations

The mass concentrations of aerosol and absorbing matter over Arkhangelsk, Tiksi, and Anadyr at different altitudes were averaged over take-off and landing, and thus a mean vertical profiles were calculated. The aerosol mass concentration was estimated using an empirical relationship $M_A = 2.4 \cdot \mu_d(45°)$, where M_A is measured in μg/m^3 and μd is in Mm^{-1}sr^{-1}.[29]

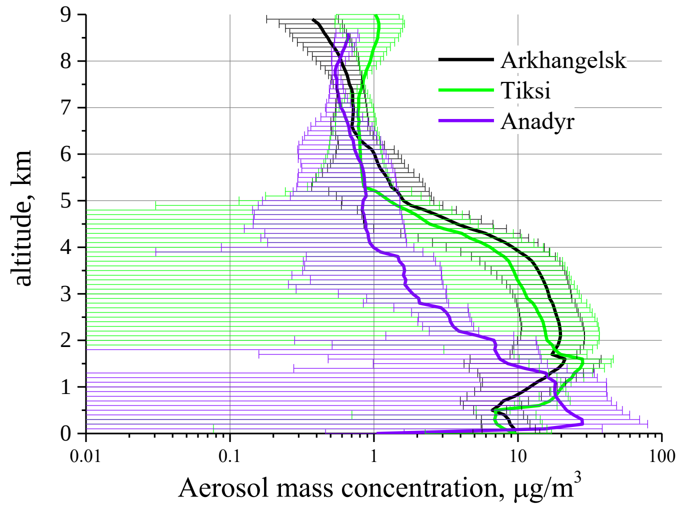

Figure 1 – Mean values and standard deviations of the aerosol mass concentrations at different altitudes in the atmosphere over northern settlements of Russia

The vertical profiles of the aerosol (Fig. 1) and absorbing matter (Fig. 2) mass concentrations over three settlements of the north of Russia are similar to each other. The maximum values are observed near the ground and decrease with altitude. The vertical profiles of M_A and M_{BC} over Arkhangelsk and Tiksi have a well pronounced 5-km high mixing layer. The maximum values of M_{BC} in the near-ground layer are recorded in Arkhangelsk, which is located near the European industrial regions. Two other settlements, Tiksi and Anadyr, situated at the north of Yakutia and Chukotka, are far from the permanent powerful sources of "soot". The minimum values of the concentration of absorbing matter are observed here in the near-ground layer, and great deviation of the values over altitude is noted.

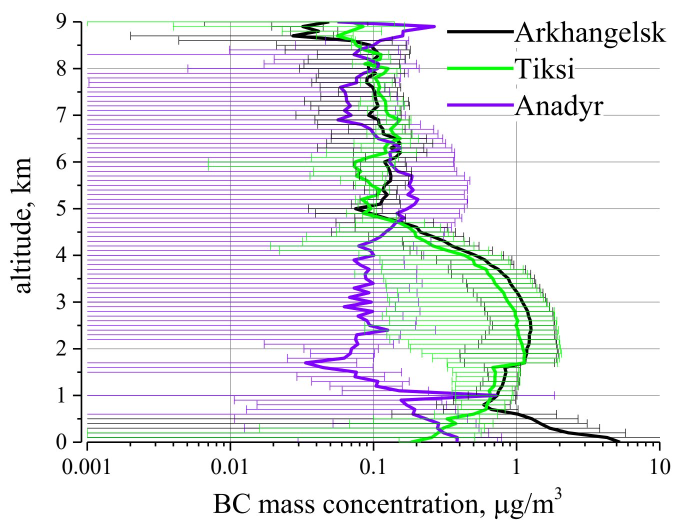

Figure 2 – Mean values and standard deviations of the of the absorbing substance concentration at different altitudes in the atmosphere over northern settlements of Russia

Let us note that the principal quantity of absorbing particles us transported to the eastern sector of Russian Arctic from remote industrial regions and from forest wildfires[30]. Analysis of back trajectories obtained using the HYSPLIT model has shown that during flights over Tiksi and Anadyr the air masses arrived from the south of Yakutia, where wildfires were observed at that moment. As was shown[30-33], wildfires in the south Yakutia and Irkutsk region in warm season make the main contribution into air pollution with soot in eastern sector of Arctic.

2.3. Columnar concentrations of submicron particles and absorbing matter

Comparison of the columnar mass concentrations of submicron aerosol M_A (col) and soot M_{BC}(col) up to 9 km obtained over Arkhangelsk, Tiksi and Anadyr are shown in Fig. 3 as histograms. It is seen that the columnar mass concentrations of aerosol particles over Arkhangelsk is 1.5 times greater, and the concentration of soot is 3 times greater than over Tiksi, and M_A (col) is 4 times greater and M_{BC}(col) is 1.6 times greater than over Anadyr.

Let us note that the values M_{BC}(col) in the eastern part of Arctic are in good agreement with the data obtained earlier during the airborne campaign POLARCAT – 2008 on the route Novosibirsk – Salekhard – Khatanga – Chokurdakh – Pevek – Chokurdakh – Yakutsk – Mirmyj – Novosibirsk[34].

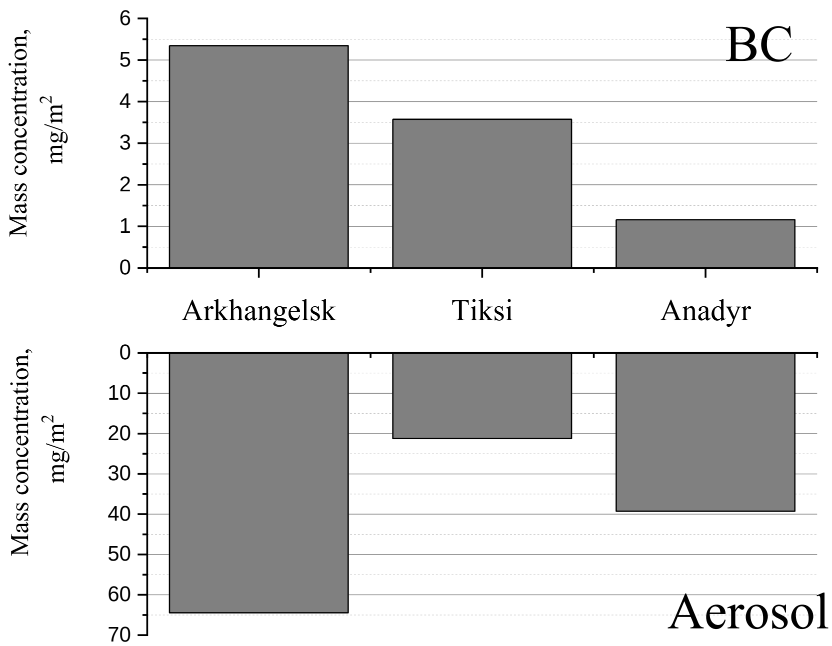

Figure 3 – columnar concentrations of aerosol and BC over northern settlements.

3. RECONSTRUCTION OF THE AEROSOL OPTICAL CHARACTERISTICS

3.1. Technique

The model for reconstruction of the aerosol optical properties is described in detail in Ref. 38. Let us present here only the main stages. The mean values of the aerosol scattering coefficient at the wavelength of 0.53 μm at the angle of 45° at different altitudes are used for reconstruction of the set of optical characteristics. The microstructure of dry particles is taken in the form of superposition of two lognormal distributions of submicron and coarse fractions. Non-absorbing particles with the refractive index n = 1.5 were considered at the first stage of calculations. The parameters of the fractions (median radius, half-width and amplitude of the distribution) for the aforementioned set of altitudes were selected so that the angular scattering coefficient $\mu(\varphi = 45°, \lambda = 0.52\ \mu m)$ of the dry submicron fraction calculated by Mie formulas coincides with the mean values measured at this altitude. Then the complex refractive index was modeled taking into account the content of the absorbing matter. Based on the results of Ref. 35 and 36, the absorbing matter was represented by a lognormal distribution in submicron fraction. The change of the particle radius with relative humidity was considered in the framework of the Laktionov's semi-empiric theory of equilibrium condensation growth of atmospheric aerosol[37]. The complex refractive index at the change of relative humidity was determined as the function of particle radius according to the mixing rule assuming that the particle volume increases during humidification only due to condensation of water vapor. The parameter of condensation activity was not directly measured during the described flights, so we used its values obtained earlier under continental conditions over Western Siberia.

3.2. Reconstructed vertical profile of the scattering coefficient

The following input data were used for reconstruction of the optical characteristics: the angular scattering coefficient of the dry matter of submicron aerosol $\mu_d(\varphi = 45°, \lambda = 0.53\ \mu m)$, the mass concentration of absorbing matter M_{BC}, parameters of the size distribution function of the dry matter of aerosol and absorbing substance[29,35], characteristics of the aerosol condensation growth[39] and the parameter of condensation activity γ. The values of the parameters are presented in Table 1, where r_{sub}, r_c, and r_{BC}, respectively, are the median radii of distributions of submicron and coarse aerosol fractions and black carbon; s_{sub}, s_c, and s_{BC}, respectively, are the variances of the distributions of submicron and coarse aerosol fractions and black carbon; and A_c is the amplitude of distribution of the coarse aerosol fraction. It was shown in Ref. 38 and 39 that, when using this set of the input parameters, the aerosol optical characteristics in the visible wavelength range are reconstructed quite reliable. Calculation was carried out at four wavelengths λ = 0.45, 0.53, 0.63, and 0.69 μm at the altitudes of 1 – 8 km with the step of 1 km over three considered northern cities.

Table 1. Input parameters

H, km	μ_d(45°, 0.53 μm), $Mm^{-1}sr^{-1}$	M_{BC}, μg/m^3	RH, %	γ	s_{sub}	r_{sub}, μm	A_c	s_c	r_c, μm	r_{BC}, μm	s_{BC}
Arkhangelsk											
1	5.06±2.76	0.73±0.27	46	0,35±0,13	0.6	0.04	0.7	0.5	1.6	0.088	0.56
2	8.11±3.97	1.18±0.74	53	0,45±0,15	0.62	0.05	0.4	0.7	1.5	0.089	0.6
3	6.80±2.96	1.1±0.53	44	0,54±0,16	0.42	0.06	0.5	0.7	1.5	0.06	0.4
4	3.84±2.51	0.51±0.3	32	0,54±0,24	0.52	0.07	0.05	0.7	1.5	0.085	0.5
5	0.67±0.42	0.08±0.04	20	0,56±0,18	0.5	0.05	0	0	0	0.065	0.5
6	0.42±0.19	0.12±0.05	20	0,56±0,18	0.7	0.03	0.02	1	4	0.08	0.6
7	0.30±0.07	0.09±0.06	23	0,56±0,18	0.7	0.03	0.02	1	2	0.079	0.64
8	0.25±0.08	0.09±0.06	22	0,56±0,18	0.7	0.03	0.02	0.8	2	0.067	0.5
Tiksi											
1	8.42±0.16	0.66±0.29	62	0,35±0,13	0.53	0.09	0.3	0.3	1	0.08	0.53
2	6.64±8.61	1.11±0.92	38	0,45±0,15	0.65	0.06	0.1	0.3	1	0.086	0.65
3	4.69±6.42	0.87±0.74	43	0,54±0,16	0.6	0.04	0	0	0	0.08	0.6
4	2.68±3.58	0.43±0.35	40	0,54±0,24	0.5	0.06	0	0	0	0.082	0.5
5	0.53±0.48	0.1±0.01	34	0,56±0,18	0.5	0.06	0	0	0	0.078	0.53
6	0.34±0.14	0.07±0.07	29	0,56±0,18	0.6	0.04	0.4	0.3	1.2	0.08	0.6
7	0.33±0.09	0.13±0.02	22	0,56±0,18	0.51	0.04	0	1	0	0.074	0.49
8	0.39±0.07	0.13±0.03	18	0,56±0,18	0.6	0.03	0.19	0	0.4	0.07	0.5
Anadyr											
1	7.52±9.71	0.72±1.13	75	0,35±0,13	0.5	0.037	0.1	1	0.4	0.06	0.46
2	2.84±2.72	0.07±0.04	61	0,45±0,15	1.4	0.001	0	0	0	0.075	0.8
3	0.78±0.54	0.1±0.11	63	0,54±0,16	0.5	0.04	0.1	0.5	2	0.06	0.5
4	0.41±0.38	0.1±0.12	38	0,54±0,24	0.57	0.045	1	0.5	0.06	0.085	0.7
5	0.35±0.28	0.17±0.26	24	0,56±0,18	0.62	0.038	0	0	0	0.065	0.6
6	0.32±0.19	0.13±0.23	19	0,56±0,18	0.65	0.05	0	0	0	0.08	0.6
7	0.25±0.05	0.07±0.07	16	0,56±0,18	0.63	0.048	0	0	0	0.079	0.64
8	0.24±0.03	0.11±0.11	16	0,56±0,18	0.8	0.06	0	0	0	0.067	0.5

To assess the quality of reconstruction, the angular scattering coefficients of the dry matter of submicron aerosol $\mu_d(\varphi = 45°, \lambda = 0.53\ \mu m)$ were compared with the measured data (Fig. 4). The values of the input parameters $\mu_d(\varphi = 45°, \lambda = 0.53\ \mu m)$ and M_{BC} were selected taking into account their standard deviations (Table 1). As is seen, the discrepancy between mean measured and reconstructed values of $\mu_d(\varphi = 45°, \lambda = 0.53\ \mu m)$ does not exceed 15%. An exception is the profile over Anadyr, where the discrepancy reaches 35% at the altitudes of 3 – 5 km. There are the altitudes where the mass concentration of soot over Anadyr (see Fig. 2) varies within a wide range. Minimum discrepancy between the measured and reconstructed values $\mu_d(\varphi = 45°, \lambda = 0.53\ \mu m)$ is observed over Arkhangelsk and does not exceed 7%.

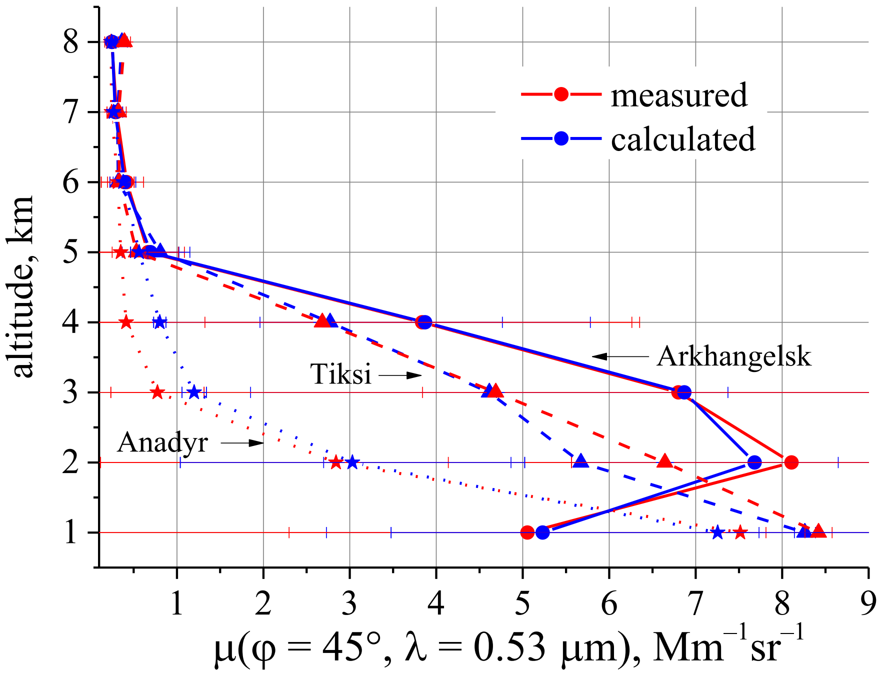

Figure 4 – Vertical profiles of the measured and reconstructed angular scattering coefficient of submicron aerosol fraction over Arkhangelsk, Tiksi, and Anadyr.

Then the vertical profiles of the ambient scattering coefficient were reconstructed taking into account the average values of relative humidity RH at corresponding altitude obtained from measurements at take-off and landing in each city. The reconstructed profiles of the scattering coefficient and the profiles of relative humidity used for reconstruction are shown in Fig. 5. Let us omit the detailed analysis of individual profiles of the aerosol scattering coefficients over three cities under study and pay attention to the fact that in spite of significant variability of the input parameters, the characteristic features of the vertical distribution of σ generally correspond to the profiles of the aerosol mass concentration (Fig. 1).

Spectral behavior of the single scattering albedo in the visible wavelength range was calculated for Arkhangelsk, because the minimum discrepancy between the reconstructed and measured values of the angular scattering coefficients of the aerosol dry matter was observed over this city. The results of such calculation are demonstrated in Fig. 6.

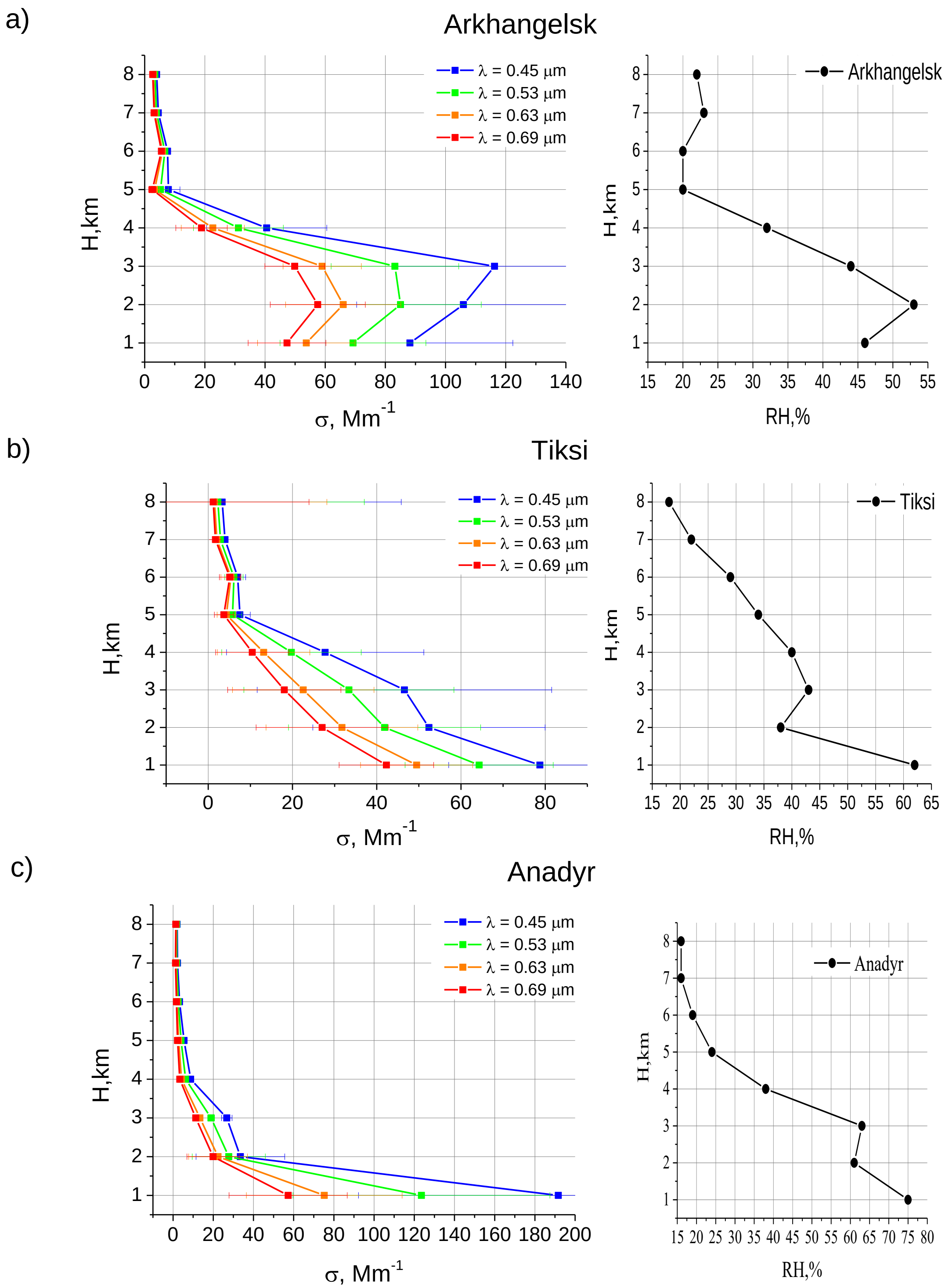

Figure 5 – reconstructed spectral behavior of the aerosol scattering coefficient (left plots) and mean relative humidity (right plots) over Arkhangelsk (a), Tiksi (b), and Anadyr (c)

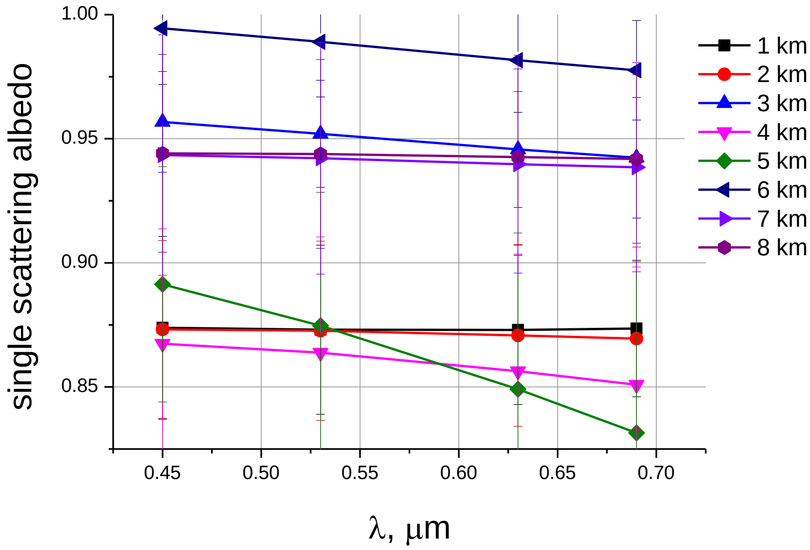

Figure 6 – reconstructed spectral behavior of the single scattering albedo in visible wavelength range at different altitudes over Arkhangelsk

CONCLUSION

Vertical profiles of the mass concentration of submicron aerosol and absorbing matter were determined according to the data of airborne sounding of the troposphere, obtained in the comprehensive experiment on the study of the composition of the troposphere in the Russian sector of the Arctic in September 2020, over Arkhangelsk, Tiksi and Anadyr. The analysis has shown that the vertical distributions of the mass concentrations of aerosol and absorbing matter in three settlements in northern Russia have a similar character: maximum values are observed near the ground, and then they decrease with altitude. The total submicron aerosol content in the atmospheric column 0 to 9 km over Arkhangelsk is 1.5 times greater than over Tiksi and 4 times greater than over Anadyr. The content of absorbing matter over Arkhangelsk is 3 times greater than over Tiksi and 1.6 times greater than over Anadyr.

The aerosol optical characteristics over three settlements under study are reconstructed based on the results of measurements of the angular scattering coefficients of the dry matter of submicron aerosol in the frameworks of the developed empirical model in the visible wavelength range at the altitudes of 1 – 8 km with the step of 1 km.

A significant range of variability in the mass concentrations of aerosol and "soot" in the troposphere over Arkhangelsk, Tiksi, and Anadyr, observed in different sounding cycles, affected the results of reconstructing the optical characteristics.

In is shown that, in general, the discrepancy between the mean measured and reconstructed values $\mu_d(\varphi = 45°, \lambda = 0.53$ μm) does not exceed 15%.

Minimum discrepancies no more than 7% are obtained for the data array of Arkhangelsk, and maximum discrepancies up to 35% are in Anadyr, where big variations of the mass concentration of the absorbing matter were observed.

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REFERENCES

[1] Klonecki, A., Hess, P., Emmons, L., Smith, L. and Orlando, J., "Seasonal changes in the transport of pollutants into the Arctic troposphere-model study", J. Geophys. Res., 108, 8367 (2003).

[2] IPCC 2014, "Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change," Core Writing Team, 151 IPCC, Geneva, Switzerland (2015).

[3] Andreae, M. O. and Gelencsér, A., "Black carbon or brown carbon? The nature of light-absorbing carbonaceous aerosols", Atmos. Chem. Phys., 6, 3131–3148 (2006).

[4] Barrie, L. A. "Arctic air pollution: an overview of current knowledge", Atmos. Environ., 20, 643–663 (1986)

[5] Nasrtdinov, I. M., Zhuravleva, T. B., Chesnokova, T. Y., "Estimation of direct radiative effects of background and smoke aerosol in the IR spectral region for Siberian summer conditions," Atmos. Ocean Opt., 31, 317–323 (2018).

[6] Zhuravleva, T. B., Nasrtdinov, I. M., Vinogradova, A. A., "Direct Radiative Effects of Smoke Aerosol in the Region of Tiksi Station (Russian Arctic): Preliminary Results," Atmospheric and Oceanic Optics, 32(3), 96–305 (2019).

[7] Golovushkin N.A., Kuznetsova I.N., Konovalov I.B., Nahaev M.I., Kozlov V.S. and Beekmann M. Analysis of Brown Carbon Content and Evolution in Smokes from Siberian Forest Fires Using AERONET Measurements // Atmospheric and Oceanic Optics, 2020, V. 33. No. 03. pp. 267–273.

[8] Tomasi, C., Kokhanovsky, A.A., Lupi, A., Ritter, C., Smirnov, A., Mazzola, M., Stone, R.S., Lanconelli, C., Vitale, V., Holben, B.N., Nyeki, S., Wehrli, C., Altonen, V., de Leeuw, G., Rodriguez, E., Herber, A.B., Stebel, K., Stohl, A., O'Neill, N.T., Radionov, V.F., Zielinski, T., Petelski, T., Sakerin, S.M., Kabanov, D.M., Xue, Y., Mei, L., Istomina, L., Wagener, R., McArthur, B., Sobolewski, P.S., Butler, J., Kivi, R., Courcoux, Y., Larouche, P., Broccardo, S., Piketh, S.J., "Aerosol remote sensing in polar regions", Earth-Sci. Rev., 140, 108–157 (2015).

[9] Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen T., Deangelo B. J., Flanner, M. G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P. K., Sarofim, M. C., Schultz, M. G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., Bellouin, N., Guttikunda, S. K., Hopke, P. K., Jacobson, M. Z., Kaiser, J.W., Klimont, Z., Lohmann, U., Schwarz, J. P., Shindell, D., Storelvmo, T., Warren, S. G. and Zender, C. S., "Bounding the role of black carbon in the climate system: a scientific assessment" J. Geophys. Res. Atmos. 118(11), 5380–555 (2013).

[10] Abbatt, J. P. D., Leaitch, W. R., Aliabadi, A. A., Bertram, A. K., Blanchet, J.-P., Boivin-Rioux, A., Bozem, H., Burkart, J., Chang, R. Y. W., Charette, J., Chaubey, J. P., Christensen, R. J., Cirisan, A., Collins, D. B., Croft, B., Dionne, J., Evans, G. J., Fletcher, C. G., Galí, M., Ghahremaninezhad, R., Girard, E., Gong, W., Gosselin, M., Gourdal, M., Hanna, S. J., Hayashida, H., Herber, A. B., Hesaraki, S., Hoor, P., Huang, L., Hussherr, R., Irish, V. E., Keita, S. A., Kodros, J. K., Köllner, F., Kolonjari, F., Kunkel, D., Ladino, L. A., Law, K., Levasseur, M., Libois, Q., Liggio, J., Lizotte, M., Macdonald, K. M., Mahmood, R., Martin, R. V., Mason, R. H., Miller, L. A., Moravek, A., Mortenson, E., Mungall, E. L., Murphy, J. G., Namazi, M., Norman, A.-L., O'Neill, N. T., Pierce, J. R., Russell, L. M., Schneider, J., Schulz, H., Sharma, S., Si, M., Staebler, R. M., Steiner, N. S., Thomas, J. L., von Salzen, K., Wentzell, J. J. B., Willis, M. D., Wentworth, G. R., Xu, J.-W., and Yakobi-Hancock, J. D., "Overview paper: New insights into aerosol and climate in the Arctic", Atmos. Chem. Phys., 19, 2527–2560 (2019).

[11] Watson-Parris, D., Schutgens, N., Reddington, C., Pringle, K. J., Liu, D., Allan, J. D., Coe, H., Carslaw, K. S., and Stier, P. "In situ constraints on the vertical distribution of global aerosol", Atmos. Chem. Phys., 19, 11765–11790 (2019).

[12] Sakerin, S.M., Kabanov, D.M., Radionov, V.F., Chernov, D.G., Turchinovich, Yu.S., Lubo-Lesnichenko, K.E. and Prakhov, A.N., "Generalization of Results of Atmospheric Aerosol Optical Depth Measurements on Spitsbergen Archipelago in 2011–2016", Atmospheric and Oceanic Optics, 31, 163–170 (2018).

[13] Stohl, A., Klimont, Z., Eckhardt, S., Kupiainen, K., Shevchenko, V.P., Kopeikin, V.M., Novigatsky, A.N., "Black carbon in the Arctic: The underestimated role of gas flaring and residential combustion emissions", Atmos. Chem. Phys, 13, 8833–8855 (2013).

[14] Popovicheva, O., Diapouli, E., Makshtas, A., Shonija, N., Manousakas, M., Saraga, D., Uttal, T., Eleftheriadis, K., "East Siberian Arctic background and black carbon polluted aerosols at HMO Tiksi", Sci. Total Environ, 655, 924–938 (2019).

[15] Asmi, E., Kondratyev, V., Brus, D., Laurila, T., Lihavainen, H., Backman, J., Vakkari, V., Aurela, M., Hatakka, J., Viisanen, Y., Uttal, T., Ivakhov, V., Makshtas, A., "Aerosol size distribution seasonal characteristics measured in Tiksi, Russian Arctic", Atmos. Chem. Phys, 16, 1271–1287 (2016).

[16] Sakerin, S.M., Golobokova, L.P., Kabanov, D.M., Kalashnikova, D.A., Kozlov, V.S., Kruglinsky, I.A.,

Makarov, V.I., Makshtas, A.P., Popova, S.A., Radionov, V.F., Simonova, G.V., Turchinovich, Yu.S., Khodzher, T.V., Khuriganowa, O.I., Chankina, O.V., and Chernov, D.G., "Measurements of Physicochemical Characteristics of Atmospheric Aerosol at Research Station Ice Base Cape Baranov in 2018", Atmospheric and Oceanic Optics, 32, 511–520 (2019).

[17] Manousakas, M., Popovicheva, O., Evangeliou, N., Diapouli, E., Sitnikov, N., Shonija, N. and Eleftheriadis, K., "Aerosol carbonaceous, elemental and ionic composition variability and origin at the Siberian High Arctic, Cape Baranova", Chemical and Physical Meteorology, 72:1, 1-14 (2020).

[18] Popovicheva, O.B., Evangeliou, N., Eleftheriadis, K, Kalogridis, A.C., Sitnikov, N., Eckhard, S., Stohl, A., "Black carbon sources constrained by observations in the Russian High Arctic", Environ. Sci. Technol., 51, 3871–3879 (2017).

[19] Sakerin, S.M., Bobrikov, A.A., Bukin, O.A., Golobokova, L.P., Pol'kin, Vas.V., Pol'kin, Vik.V., Shmirko, K.A., Kabanov, D.M., Khodzher, T.V., Onischuk, N.A., Pavlov, A.N., Potemkin, V.L., Radionov, V.F., "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).

[20] Golobokova, L.P., Khodzher, T.V., Izosimova, O.N., Zenkova, P.N., Pochyufarov, A.O., Khuriganowa, O.I., Onishyuk, N.A., Marinayte, I.I., Polkin, V.V., Radionov, V.F., Sakerin, S.M., Lisitzin, A.P. and Shevchenko, V.P., "Chemical Composition of Atmospheric Aerosol in the Arctic Region and Adjoining Seas along the Routes of Marine Expeditions in 2018–2019", Atmospheric and Oceanic Optics, 33, 480–489 (2020).

[21] Sakerin, S.M., Kabanov, D.M., Makarov, V.I., Polkin, V.V., Popova, S.A., Chankina, O.V., Pochufarov, A.O., Radionov, V.F., Rize, D.D., "Spatial distribution of atmospheric aerosol physicochemical characteristics in Russian sector of the Arctic Ocean", Atmosphere, 11, 1170 (2020).

[22] Antokhina, O.Yu., Antokhin, P.N., Arshinova, V.G., Arshinov, M.Yu., Belan, B.D., Belan, S.B., Davydov, D.K., Ivlev, G.A., Kozlov, A.V., Nédélec, P., Paris, J.-D., Rasskazchikova, T.M., Savkin, D.E., Simonenkov, D.V., Sklyadneva, T.K., Tolmachev, G.N. and Fofonov, A.V., "Vertical Distributions of Gaseous and Aerosol Admixtures in Air over the Russian Arctic", Atmospheric and Oceanic Optics, 31, 300–310 (2018).

[23] AMAP Assessment 2015: Methane as an Arctic Climate Forcer., (2015).

[24] Ancellet, G., Pelon, J., Blanchard, Y., Quennehen, B., Bazureau, A., Law, K. S., and Schwarzenboeck, A., "Transport of aerosol to the Arctic: analysis of CALIOP and French aircraft data during the spring 2008 POLARCAT campaign", Atmos. Chem. Phys., 14, 8235–8254 (2014).

[25] Sodemann, H., Pommier, M., Arnold, S. R., Monks, S. A., Stebel, K., Burkhart, J. F., Hair, J. W., Diskin, G. S., Clerbaux, C., Coheur, P.-F., Hurtmans, D., Schlager, H., Blechschmidt, A.-M., Kristjánsson, J. E. and Stohl, A. "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).

[26] Tollefson, J., "Carbon-sensing satellite system faces high hurdles", Nature, 533, 446–447 (2016).

[27] Popkin, G., "Commercial space sensors go high-tech", Nature, 545, 397–398 (2017).

[28] Anokhin, G. G., Antokhin, P. N., Arshinov, M. Yu., Barsuk, V. E., Belan, B. D., Belan, S. B., Davydov, D. K., Ivlev, G. A., Kozlov, A. V., Kozlov, V. S., Morozov, M. V., Panchenko, M. V., Penner, I. E., Pestunov, D. A., Sikov, G. P., Simonenkov, D. V., Sinitsyn, D. S., Tolmachev, G. N., Filipov, D. V., Fofonov, A. V., Chernov, D. G., Shamanaev, V. S., Shmargunov, V. P., "OPTIK Tu-134 aicraft laboratory", Optika Atmosfery i Okeana, 24, 805-816 (2011)[in Russian].

[29] Panchenko, M. V., Kozlov, V. S., Polkin, V. V., Polkin, Vas. V., Terpugova, S. A., Uzhegov, V. N., Chernov, D. G., Shmargunov, V. P., Yausheva, E. P., Zenkova, P. N., "Aerosol characteristics in the near-ground layer of the atmosphere of the city of Tomsk in different types of aerosol weather," Atmosphere, 11(1), 20–39(2020).

[30] Vinogradova, A.A., Vasileva, A.V. and Ivanova, Yu.A., "Air Pollution by Black Carbon in the Region of Wrangel Island: Comparison of Eurasian and American Sources and Their Contributions", Atmospheric and Oceanic Optics, 34, 97–103 (2021).

[31] Vinogradova, A.A., Titkova, T.B. and Ivanova, Yu.A., "Episodes with Anomalously High Black Carbon Concentration in Surface Air in the Region of Tiksi Station, Yakutiya", Atmospheric and Oceanic Optics, 32, 94–102 (2019).

[32] Vinogradova, A.A. and Vasileva, A.V., "Black Carbon in Air Over Northern Regions of Russia: Sources and Spatiotemporal Variations", Atmospheric and Oceanic Optics, 30, 533–541 (2017).

[33] Vinogradova, A.A., Smirnov, N.S., Korotkov, V.N., and Romanovskaya, A.A., "Forest Fires in Siberia and the Far East: Emissions and Atmospheric Transport of Black Carbon to the Arctic", Atmospheric and Oceanic Optics, 28, 566–574 (2015).

[34] Kozlov, V.S., Panchenko, M.V., Shmargunov, V.P., Chernov, D.G., Yausheva, E.P., Pol'kin, V.V., Terpugova, S.A., "Long-Term Investigations of the Spatiotemporal Variability of Black Carbon and Aerosol Concentrations in the Troposphere of West Siberia and Russian Subarctic", "Chemistry for Sustainable Development", 24, 423-440 (2016).
[35] Schulz, H., Zanatta, M., Bozem, H., Leaitch, W. R., Herber, A. B., Burkart, J., Willis, M. D., Kunkel, D., Hoor, P. M., Abbatt, J. P. D., and Gerdes, R., "High Arctic aircraft measurements characterising black carbon vertical variability in spring and summer", Atmos. Chem. Phys., 19, 2361–2384 (2019).
[36] Sharma, S., Leaitch, W. R., Huang, L., Veber, D., Kolonjari, F., Zhang, W., Hanna, S. J., Bertram, A. K., and Ogren, J. A. "An evaluation of three methods for measuring black carbon in Alert, Canada", Atmos. Chem. Phys., 17, 15225–15243, (2017).
[37] Laktionov, A. G., [Equilibrium heterogenic condensation], Gidrometeoizdat, Leningrad, 28-37 (1988).
[38] Zenkova, P. N., Terpugova, S. A., Pol'kin, V. V., Pol'kin, Vas. V., Uzhegov, V. N., Kozlov, V. S., Yausheva, E. P., Panchenko, M. V., "Development of the empirical model of optical characteristics of aerosol in Western Siberia", Optika Atmosfery i Okeana, 34, 192–198 (2021) [in Russian].
[39] Zenkova, P. N., Terpugova, S. A., Polkin, Vas. V., Polkin, V. V., Kozlov, V. S., Yausheva, E. P., Panchenko, M. V., "Model calculation of the aerosol optical characteristics at different variants of considering hygroscopic and absorbing properties on the example of atmospheric hazes", Proc. SPIE 11560, 26th International Symposium on Atmospheric and Ocean Optics: Atmospheric Physics, 115603G (2020).