RESULTS OF AIRBORNE LIDAR STUDIES OF THE TROPOSPHERIC AEROSOL IN THE NORTHERN HEMISPHERE

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The paper describes the results of aerosol investigations in the free troposphere of the Northern Hemisphere. The data have been obtained on the spatial distribution of the Arctic haze and background aerosol in the northern and middle latitudes of Russia, North America, Canada, and North Atlantic. The aerosol is studied using a lidar placed onboard the Cyclone IL–18 aircraft-laboratory. The data are presented on the vertical distribution of scattering and depolarization coefficients. It has been found that the profiles of the scattering coefficients for the Arctic haze in different regions of the Arctic undergo strong fluctuations, however, their mean values differ only slightly. The results of summer investigations as well as the measurements made in winter and spring in the regions without the Arctic haze have shown that the tropospheric aerosol has fine-cellular and stratified structure. The aerosol volume scattering and depolarization coefficients are within the range $(0.8–8.4)\cdot10^{-5}$ m^{-1} *and* 0.01–0.15, *respectively. These characteristics significantly depend on atmospheric pollution and geographical position of the measurement region relative to industrial regions as well as on the meteorological conditions. In particular, they depend on the direction of motion of air masses and temperature distribution.*

1. INTRODUCTION

The investigations of the tropospheric aerosol in the Northern Hemisphere performed over a period of many years until the 1980s were mainly local in character and therefore provided only insufficient information on the spatial distribution of this component of the atmosphere. The latest complex airborne investigations of aerosol at the north and middle latitudes greatly extended the spectrum of data on the aerosol nature, its microphysical and structural parameters, its influence on the atmospheric pollution and hence on the radiation balance and the climate of the Northern Hemisphere as well as on tropospheric chemistry. In the course of these investigations, considerable attention has been given to the investigation of the arctic aerosol, in particular, the arctic haze representing the aerosol accumulation within the troposphere of the polar region. This paper describes the results of investigations of the coefficients of scattering σ and depolarization δ of the tropospheric aerosol, including the arctic haze, obtained using a lidar placed onboard the IL–18 aircraft-laboratory in the course of the joint Russian-German experiment at the north and middle latitudes of Russia, North America, Canada, North Atlantic, and so on in summer and winter-spring 1993–1995. In the course of these studies the lidar sensing of the atmosphere was performed along vertical or horizontal paths at a wavelength of 0.53 μm. The data were recorded and processed along a sounding path in 10–20 m using an automated system.

The errors in measuring the coefficients of scattering σ and depolarization δ were equal to 22 and 9%, respectively.

This paper is a continuation of aerosol studies in the Northern Hemisphere and the results of their first stage are given in Ref. 1.

2. SPATIAL DISTRIBUTION OF THE ARCTIC HAZE

The study of the arctic haze is urgent for several reasons. The underlying reasons are the following:

– the effect of the arctic haze on the radiation balance and the climate of the Northern Hemisphere;

– physics of haze formation, i.e., whether it is the phenomenon of anthropogenic or natural origin;

– the effect of haze on the tropospheric pollution of the Arctic regions as a function of the meteorological state of the atmosphere in this region;

– spatial haze distribution versus the geographical position of the Arctic region being studied, and so on.

The airborne investigations of the arctic haze[1–9] have shown that this meteorological phenomenon is of anthropogenic origin. It is observed not only in case of fast transport of air masses from any industrial region at mid-latitudes[2,7] but also in the air masses which have

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had no contact with industrial aerosol sources for a long time. In the course of Russian–German studies, unlike the preceding airborne measurements[3,6,8,9] regional in nature, we succeeded in obtaining the data on the optical and meteorological characteristics of the troposphere in 17 regions of different sectors of the Arctic.

Figures 1 and 2 show the vertical profiles of the scattering coefficient obtained for Atlantic, Russian and Canadian sectors in 1994 and 1995. These profiles were averaged over 100-m altitude ranges.

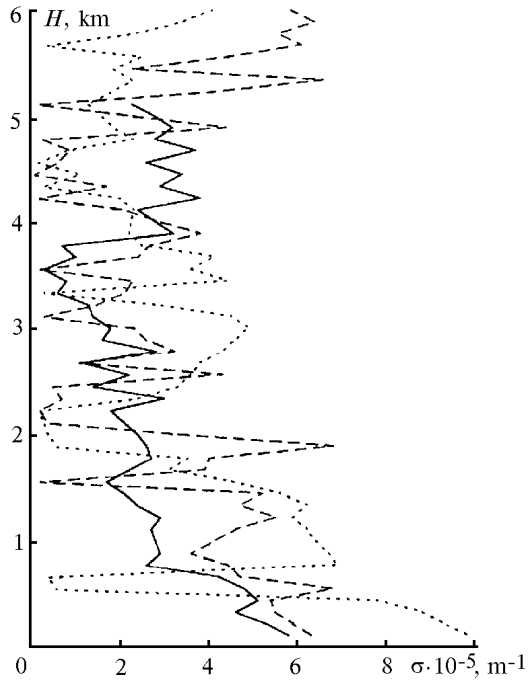

FIG. 1. Vertical profiles of the scattering coefficients for the arctic haze: the solid curve shows the data for the Atlantic sector at 79°N, 04°E *obtained on March* 30, 1994; *the dashed curve shows the data for the Russian sector at* 85°N, 85°E *obtained on April* 7, 1994; *the dotted curve shows the data for the Canadian sector at* 75°N, 95°W *obtained on April* 11, 1994.

Analysis of the data shows that the arctic haze has layered structure because the scattering coefficient undergoes large fluctuations with the altitude. The arctic haze is most dense in the atmospheric boundary layer at altitudes up to 1.5–2 km. At higher altitudes separate layers of thicknesses from several tens to several hundreds of meters are observed. Here, the optical density of haze layers is estimated by the previously accepted classification[1,3,4] according to which at $\sigma < 2 \cdot 10^{-5}$ m^{-1} the haze is absent, at $2 \cdot 10^{-5}$ m$^{-1} < \sigma < 3 \cdot 10^{-5}$ m^{-1} it is weak, and the regions with $\sigma > 3 \cdot 10^{-5}$ m^{-1} are considered as dense haze.

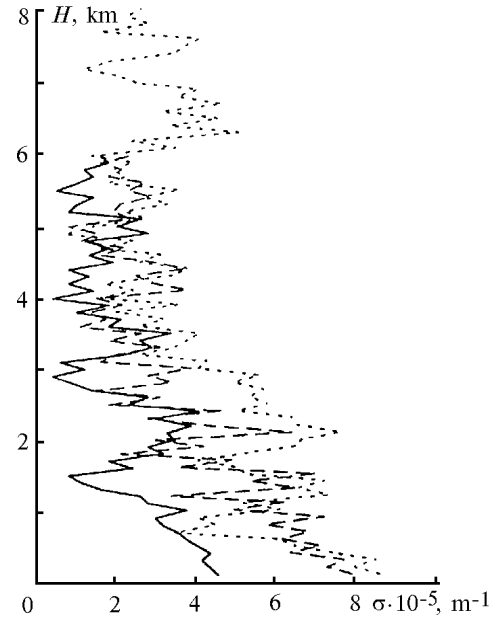

FIG. 2. Vertical profiles of the scattering coefficients for the Arctic haze: the solid curve shows the data for the Greenland Sea at 84.5°N, 05°W *obtained on April* 7, 1995; *the dashed curve shows the data for the North Land at* 78°N, 98°E *obtained on March* 24, 1995; *the dotted line shows the data for the Beaufort Sea at* 75°N, 95°W *obtained on March* 31, 1995.

The haze optical density and the thickness of its layers considerably depend on the meteorological conditions and the underlying surface type. We have discovered that the haze layered structure becomes most clearly defined when strong cooling and formation of deep inversions take place, which hinder the turbulent mixing of pollutant in the atmosphere. Above the open water surface where turbulent mixing was rather strong, for example, in the region of the Greenland Sea on March 30, 1994 and April 7, 1995, the vertical profiles of the scattering coefficient were smoother.

For a more vivid comparison of the vertical profiles of the scattering coefficients σ for different regions, the above coefficients were averaged over the layers 1 km thick. In this case, the number of individual measurements averaged in every layer was varied from 16 to 48. The mean values of σ in 1-km layers and their 95% confidence intervals are given in Table I from which we see that the values of σ varied no more than twice from layer to layer at altitudes higher than 2 km and only in the boundary layer the variations of σ were slightly higher.

As a result of lidar sensing of the troposphere along horizontal paths it was found that the profiles of the scattering coefficient are inhomogeneous not only in the vertical but also in horizontal direction. In

flights along horizontal routes 150–200 km long the values of σ varied by 1 or 2 orders of magnitude. The large variability of vertical and horizontal profiles of σ testifies to the fact that the arctic haze is a very inhomogeneous medium that occupies all the troposphere of the Arctic region.

TABLE I. Mean values of the light scattering coefficient and their 95% *confidence levels according to the Student criterion* (10^{-5} m^{-1}) *in different layers of the Arctic troposphere.*

	Date								
	03.24.95	03.26.95	03.31.95	04.01.95	04.02.95	04.03.95	04.04.95	04.06.95	04.07.95
	Greenwich Mean Time (GMT), hr:min								
H, km	06:32–06:56	23:48–00:09	23:48–00:19	20:50–21:07	19:49–20:13	21:29–21:50	18:20–18:37	16:45–17:32	14:59–15:30
	Coordinates								
	78° N 98° E	75° N 168° W	75° N 155° W	72° N 155° W	75° N 145° W	74° N 105° W	78° N 125° W	78° N 15° E	84.5° N 5° W
	Arctic Sectors								
	Russian	Russian	Canadian	Canadian	Canadian	Canadian	Canadian	Atlantic	Atlantic
6–7	–	–	3.8±1.1	–	–	2.4±1.2	–	2.7±0.9	–
5–6	2.3±0.6	3.6±1.2	2.9±0.8	2.1±1.1	4.3±2.2	3.5±1.9	–	1.9±0.4	1.2±0.6
4–5	3.1±0.7	2.1±0.9	2.2±1.2	1.9±1.2	2.8±1.3	2.1±0.8	3.5±1.2	2.1±0.7	1.4±0.9
3–4	1.9±0.5	2.8±1.6	3.1±0.9	2.7±0.8	2.1±1.0	2.6±1.3	1.7±0.8	1.8±0.8	1.9±1.1
2–3	3.2±1.1	2.1±0.7	5.4±2.2	3.1±1.6	2.6±1.4	3.8±2.2	4.6±2.3	2.7±1.1	2.5±1.6
1–2	4.3±1.3	3.5±2.1	5.8±1.6	4.9±2.1	3.7±2.4	4.6±2.0	2.8±1.6	3.1±1.6	2.3±1.4
0–1	6.4±1.7	5.1±1.7	6.1±2.1	5.4±1.7	5.3±2.1	5.1±1.6	6.1±2.4	3.4±1.2	3.8±1.7

RESULTS OF INVESTIGATIONS OF THE BACKGROUND AEROSOL

The long-term investigations of the atmospheric aerosol in the Northern Hemisphere and in particular in the Arctic have shown that the long-distance transport of pollutant from industrial continental regions has a strong impact on the pollution of these regions. To estimate a degree of pollution as well as to compare the winter and spring measurements with the arctic haze and the summer results without the Arctic haze, the aerosol optical characteristics were investigated in the free atmosphere of high and middle latitudes. These investigations were performed in summer in the above-indicated regions as well as in winter-spring in those regions where the arctic haze was absent.

Our measurements of the scattering coefficients and depolarization showed that the tropospheric aerosol, as well as the haze, had the layered structure. In this case, the layers are not continuous but consist of separate atmospheric cells with sizes of several tens of meters at altitudes greater than 3 km. At lower altitudes their sizes are several hundreds of meters. Typically the values of the coefficients of volume scattering and depolarization are $\sigma = (0.8–8.4)\cdot10^{-5}$ m^{-1} and $\delta = 0.01–0.15$.

The optical and structural parameters of aerosol formations significantly depend on meteorological conditions and the place of measurements. This is most pronounced when the investigations are made in the regions far from industrial centers or close to them or in the region of intensive transport of environmental pollution.

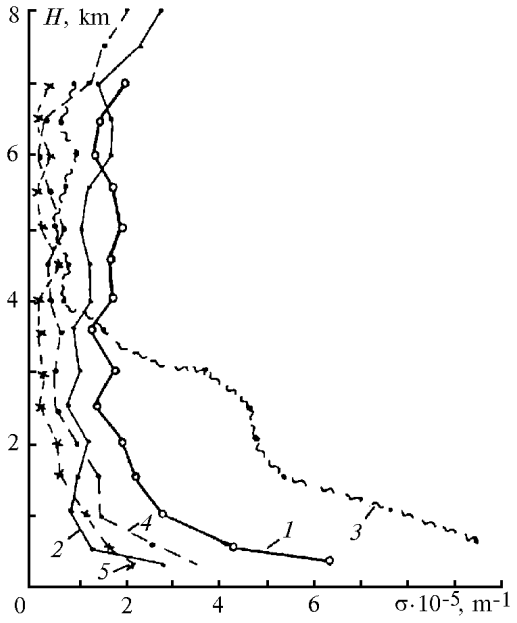

FIG. 3. Vertical profiles of the scattering coefficients for the background aerosol 1) 78°N, 85°E; *June* 14, 1993; *2)* 81°N, 124°E; *June* 15, 1993; *3)* 60°N, 88°E; *June* 16, 1993; *4)* 69°N, 87°E; *June* 17, 1993; *5)* 74°N, 65°N; *June* 18, 1993.

Figures 3 and 4 show the results of investigations of the vertical distribution of the scattering and depolarization coefficients for the troposphere of the Arctic and mid-latitudes of Siberia. These figures show the profiles of the mean values $\bar{\sigma}$ and $\bar{\delta}$. Here, the data

were averaged over 0.5-km altitude ranges. With this averaging the vertical distributions $\bar{\sigma}$ and $\bar{\delta}$ have no large fluctuations; however, individual profiles of σ may vary within one order of magnitude and even more and the values of δ sometimes are as great as 0.3. The σ profile obtained on June 16, 1993, differs strongly at altitudes up to 4 km. It is evident that the large values of the coefficients σ and δ are due to the atmospheric pollution transported from the southern industrial regions of Siberia as well as due to forest fires frequently occurring in these regions.

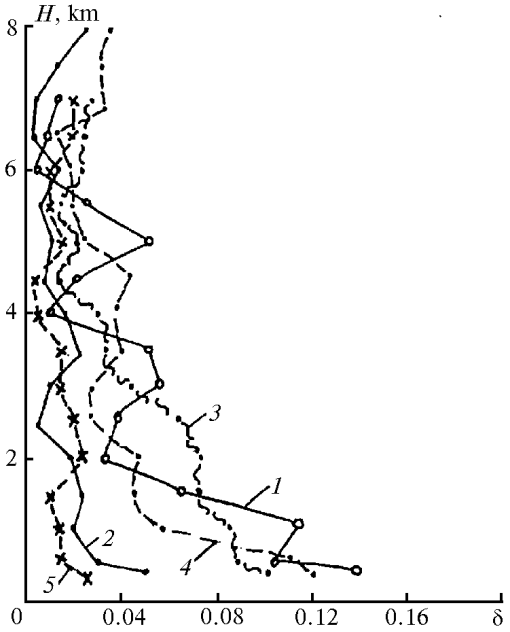

FIG. 4. Vertical profiles of the depolarization coefficients for the background aerosol: 1) 78°N, 85°E; *June* 14, 1993; *2)* 81°N, 124°E; *June* 15, 1993; *3)* 60°N, 88°E; *June* 16, 1993; *4)* 69°N, 87°E; *June* 17, 1993; *5)* 74°N, 65°E; *June* 18, 1993.

When comparing the results of lidar measurements of σ and δ with the meteorological conditions, in particular, the temperature and humidity profiles, high correlation was found between these parameters. In all cases in which the investigations were performed under inversion layers the values of the scattering and depolarization coefficients were larger than those in the adjacent regions. These results indicate that the inversion layers hinder the upward propagation of the atmospheric pollution.

CONCLUSIONS

As a result of our investigations into the tropospheric aerosol optical characteristics in the Northern Hemisphere, the following conclusions can be drawn:

1. In winter-spring in the Arctic troposphere the aerosols are accumulated called the Arctic haze for which the maximum value of σ is $(8–9)\cdot10^{-5}$ m^{-1}.

2. The Arctic haze represents the meteorological phenomenon on a large regional scale.

3. The haze occupies the entire Arctic troposphere rather then the boundary layer, as considered previously.

4. The Arctic haze is distributed over the troposphere in the form of layers. In this case, the layers are more pronounced above the ice and snow-covered surfaces; the haze is distributed more homogeneously above the open water surface where the ascending flow of air masses is more intensive.

5. In addition to the vertical variability of σ, the horizontal variability of σ is observed in the Arctic troposphere. Simultaneous vertical and horizontal variability of σ indicates that the haze layers strongly fluctuate.

6. In summer the layered-cellular aerosol structure is observed. The cell sizes and the thickness of layers vary from several tens of meters to several hundreds of meters.

7. Inhomogeneous structure of the aerosol causes large fluctuations of the scattering and depolarization coefficients with $\sigma = (0.8–8.4)\cdot10^{-5}$ m^{-1} and $\delta = 0.01–0.15$; individual profiles of σ may vary with altitude by an order of magnitude and more, and δ sometimes reaches 0.3.

8. The values of the above coefficients depend strongly on the place of measurements, especially this is manifested when the investigations are carried out in the regions far from industrial centers or close to them or in the regions of intense transport of pollution.

9. Our data on the distribution of the laser radiation scattering coefficient in the Arctic cloudless atmosphere may be explained by the hypothesis of the pollution transport from the continental polluted regions.

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