# RESULTS OF AEROSOL LIDAR STUDIES IN THE FREE TROPOSPHERE OF THE ARCTIC

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*The paper presents the results of tropospheric aerosol studies in different regions of the Arctic. The data have been obtained on the spatial distribution of the Arctic haze in north regions of Russia, Atlantic, and Canada. The haze was investigated by means of a lidar placed onboard the "Tsiklon" IL–18 aircraft–laboratory. The paper gives the data on the vertical and horizontal distributions of the scattering coefficient that characterizes the optical density of the tropospheric aerosol, including the Arctic haze. It has been found that the values of the arctic haze scattering coefficient differ insignificantly in different regions of the Arctic. However, in summer the values of this characteristic without haze are 2–3 times less than those with haze in the same region.*

## 1. INTRODUCTION

In the 1970s a start has been made on the study of radiation budget and the processes that govern it in the Arctic as part of a number of national and international programs. The data of these and other observations accumulated in the middle 80s, particularly, the results of airborne investigations, have shown that the so–called Arctic haze, i.e., the aerosol accumulation in the atmosphere of the Arctic,[1–6] significantly affects the radiative transfer.

The aerosols are considered to be removed from the mid–latitudes or formed by chemical reactions of industrial gases. Winter and spring are seasons at which the haze is most often encountered in the ground air layers. This is connected with weak aerosol sedimentation due to high static stability of air and small amount of clouds and precipitation as well as due to more pronounced meridian atmospheric circulation as compared with summer.[1,3] The special airborne measurements carried out in the 1980s in the North American and partly in the Atlantic sectors of the Arctic have shown that the great bulk of aerosol mass is concentrated in the lower troposphere (at altitudes up to 1.5–2 km), and only individual layers whose thickness vary from several tens to several hundreds of meters are observed at higher altitudes. High aerosol concentration, i.e., thick arctic haze caused by fast removal of air masses to the Arctic from some industrial region of mid–latitudes[1,6] was occasionally observed. At the same time individual airborne measurements in Russian sector of the Arctic show that the aerosol accumulation also can be observed in the air masses that stayed in the Arctic for a long time (more than 6–8 days) and had no contact with sources of aerosol and gases producing it.[7]

In general, the quantity of experimental data on the Arctic haze and, particularly, on its optical parameters, is still deficient for the elucidation of the hypothetic mechanisms of its formation.

The joint Russian–German airborne investigations of aerosol and gas composition and optical characteristics of the lower and middle troposphere of the Arctic were carried out in March–April, 1994. Simultaneously the meteorological parameters were measured. The German scientists of the Institute of Atmospheric Physics at the Mainz University and of the Lindenberg Meteorological Observatory took part in the airborne investigations.

Contrary to previous airborne investigations that were regional in character,[2,5,7] during the Russian–German flight mission we succeeded in collecting the data on optical and meteorological atmospheric characteristics in the 0.15–8.8 km layer in three sectors of the Arctic: Russian, Atlantic, and North American.

In this paper we consider the vertical profiles of the scattering coefficient $\sigma$ derived from lidar data obtained in nine regions of different sectors of the Arctic. The summer and winter values of $\sigma$ averaged over 1 km thick layers are compared. The hypothesis on the origin of Arctic haze is verified on the basis of these data.

## 2. INSTRUMENTATION AND TECHNIQUE FOR MEASUREMENTS AND DATA DESCRIPTION

To study atmospheric aerosol from onboard an aircraft, we used a lidar–polarimeter described in Ref. 8. An analysis of measuring errors is also given there. In this experiment the errors in determining the individual values of $\sigma$ and of the polarization coefficient $\delta$ were 22 and 9%, respectively.

Sounding of the atmosphere was carried out upwards or downwards as well as in the horizontal direction at a wavelength of 0.53 μm.

The data were recorded and processed along the sounding path every 10–20 m by means of automated system using an IBM PC–AT 386.

The technique of airborne investigations included vertical sounding of the atmosphere at altitudes from 0.15 to 8.5–8.8 km in order to determine the vertical profiles of the parameters and flight along 3–4 horizontal measurement paths 50–150 km long located in the layers with local maxima of the aerosol concentration.

Since we were interested in the scattering coefficient of the aerosol haze, it was important to exclude the effect of ice crystals. To do this, we processed only the measurements of $\sigma$ with the depolarization coefficient of light being less or equal to 0.1.

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### 3. METEOROLOGICAL CONDITIONS OF THE IMPURITY TRANSPORT

During investigations in the Canadian sector of the Arctic, air masses were transported to the measurement regions from northern or western regions, while in Russian and Atlantic sectors of the Arctic, air was transported from southern latitudes. In all cases (except March 31, 1994) the air entering the measurement region did not pass over industrial regions at least during 2–7 days and therefore was polluted neither by primary aerosols nor by gases transforming into the secondary aerosols. The air passed over the Central Arctic fully covered by ice or over snow–covered Asian and North American continents. This led to deep cooling and formation of thick inversions that prevent turbulent mixing of pollutants emitted into the atmosphere.

On March 31, 1994 the air mass was transported to the measurement region from the east of the Atlantic Ocean through Norway and Spitsbergen to the north end of Greenland. In this case, unlike the others, the air mass first passed over the regions with comparatively strong sources of $NO_2$ and $SO_2$ in Norway, then over non–freezing ocean where turbulent mixing was comparatively intense and therefore the vertical profile of impurity was smoothed out.

### 4. SPATIAL DISTRIBUTION AND SEASONAL VARIATIONS OF THE LIGHT SCATTERING COEFFICIENTS

The researchers previously classified the layers with haze of different intensity by the total light scattering coefficient at a wavelength of 0.55 μm. This procedure required no ice crystals in the air. For $\sigma < 2\cdot10^{-5}$ m$^{-1}$ the haze was considered to be absent, for $2\cdot10^{-5} < \sigma < 3\cdot10^{-5}$ m$^{-1}$ the haze was considered to be thin, and in the layers with $\sigma > 3\cdot10^{-5}$ m$^{-1}$ the haze was considered to be thick. Let us use the same classification for comparison of data.

The airborne measurements carried out earlier in the Canadian sector of the Arctic[2] showed that layers of thick haze with the thickness from several tens to several hundreds of meters alternated with "clear" layers where the values of σ were by 1–2 orders of magnitude less. Our measurements confirmed this pattern not only for Canadian but also for Russian sectors of the Arctic as well as for the region of Spitsbergen. Typical vertical profiles of σ are shown in Fig. 1.

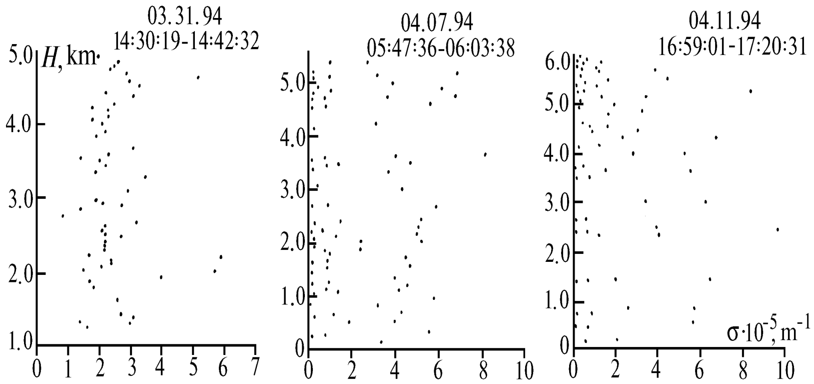


*FIG. 1. Typical vertical profiles of scattering coefficients in Atlantic (March 31, 1994), Russian (April 7, 1994), and Canadian (April 11, 1994) sectors of the Arctic.*

As was noted, the only exception was the vertical profile of σ obtained near the north–eastern end of Greenland on March 31, 1994.

Table I lists the integrated recurrence of the scattering coefficient values in the layers located within the 1–2 and 5–6 km altitude ranges in Canadian and Russian sectors of the Arctic, derived from the data of vertical sounding, and at altitudes of 0.15 and 4 km, derived from the data of horizontal sounding of the atmosphere. As is seen, the recurrence of the values $\sigma > 3\cdot10^{-5}$ m$^{-1}$, that correspond to haze according to classification from Refs. 2 and 3, was 15–30%. At the same time 50–70% of the volume was filled by optically "clear" layers with $\sigma < 2\cdot10^{-5}$ m$^{-1}$.

We note that thin haze layers were visually observed from onboard the aircraft on the horizon, as it was described in Refs. 2 and 3.

It was difficult to compare such very rough vertical profiles of σ (Fig. 1) with each other, so they were averaged over the layers about 1 km thick. The number of individual measurements that were averaged in each layer varied from 6 to 36. Average values $\overline{\sigma}$ in 1 km layers and their 95% confidence intervals are given in Table II.

It follows from Table II that the average values $\overline{\sigma}$ varied with different 1 km thick layers no more than by a factor of 1.5–2, what cannot be considered as a significant difference taking into account large variations of σ within the layer (alternation of thin haze layers with optically "clear" layers). Thus in the cases under investigation, the values of σ did not decrease with altitude as it was in the cases described in Refs. 2 and 3.

Vertical profiles were obtained in nine regions in Russian, Canadian, and Atlantic sectors of the Arctic. Comparison of the values averaged over 1 km thick layers showed their insignificant difference for the available amount of data obtained for different sectors.

We carried out not only vertical airborne sounding of the atmosphere but also flights along horizontal paths 100–150 km long. Measurements of σ performed by means of the lidar showed that the light scattering coefficient was nonuniform not only along the vertical direction but also along the horizontal one and varied by 1–2 orders of magnitude at the distance of several kilometres. The recurrence of horizontal regions with the thick haze ($\sigma > 1\cdot10^{-5}$ m$^{-1}$) was about 30% (Table I).

*TABLE I. Integrated recurrence (in %) of the scattering coefficient σ in different layers (levels) of the troposphere in Russian and Canadian sectors of the Arctic.*

| Sector of the Arctic, date | Vertical sounding. Tropospheric layers, km | Horizontal sounding. Altitude, km | Total number of individual measurements | Scattering coefficient $\sigma\cdot10^{-5}$, $m^{-1}$ | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | <1 | <2 | <3 | <5 | <6 | <7 | <8 | <9 | <10 | <12 | <13 |
| Russian, April 6, 1994 | 1–2 | | 30 | – | 57 | 57 | – | 90 | – | 97 | – | 100 | – | – |
| Russian, April 6, 1994 | | 4.0 | 72 | 40 | 57 | 68 | 85 | – | 93 | – | 100 | – | – | – |
| Russian, April 7, 1994 | 5–6 | | 36 | – | 52 | 64 | – | 89 | – | 100 | – | – | – | – |
| Canadian April 10, 1994 | 1–2 | | 74 | – | 41 | 61 | – | 82 | – | 93 | – | 97 | 97 | 100 |
| Canadian April 11, 1994 | | 0.15 | 84 | 45 | 74 | 80 | 95 | – | 100 | – | – | – | – | – |
| Canadian | 5–6 | | 138 | – | 64 | 69 | – | 89 | – | 94 | – | 96 | 96 | 100 |

*TABLE II. Average values of the light scattering coefficient and their* 95% *confidence intervals against the Student criterion* ($\times10^{-5}$ $m^{-1}$) *in different layers of the Arctic troposphere.*

| Altitude, km | Date | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 03.31.94 | 04.04.94 | 04.06.94 | 04.07.94 | 04.10.94 | 04.11.94 | 04.11.94 | 04.12.94 | 04.12.94 |
| | Greenwich time, hr:min | | | | | | | | |
| | 14:30–14:42 | 08:05–08:14 | 05:27–05:48 | 05:47–06:06 | 18:29–18:51 | 16:59–17:20 | 21:41–21:53 | 15:44–16:05 | 21:00–21:21 |
| | Coordinates | | | | | | | | |
| | 84° N 28° W | 79° N 92° E | 82° N 116° E | 85° N 85° E | 75° N 135° E | 75° N 95° W | 78° N 121° W | 75° N 73° W | 64° N 68° W |
| | Sector of the Arctic | | | | | | | | |
| | Atlantic | Russian | Russian | Russian | Canadian | Canadian | Canadian | Canadian | Canadian |
| 5–6 | – | – | – | 2.4±1.1 | 8.2±2.1 | 1.8±1.1 | – | 2.7±1.0 | 1.9±0.9 |
| 4–5 | – | – | 1.7±0.7 | 2.1±1.5 | 3.8±1.0 | 2.8±3.4 | 3.2±1.1 | 2.6±1.0 | 2.3±0.8 |
| 3–4 | 2.4±0.7 | 4.9±4.0 | 3.3±0.6 | 2.4±1.2 | 3.0±1.1 | 2.0±1.2 | 2.5 ±0.9 | 2.6±1.0 | 2.8±0.8 |
| 2–3 | 2.3±0.5 | 3.6±3.2 | 3.5±1.1 | 2.1±0.7 | 3.0±1.0 | 2.7±2.2 | 2.6±1.1 | 2.4±1.0 | 2.5±1.0 |
| 1–2 | 2.8±1.0 | 3.1±2.6 | 3.0±1.2 | 2.5±1.3 | 5.0±2.7 | 2.3±3.4 | 2.9±1.3 | 2.3±0.8 | 2.5±0.9 |
| 0–1 | – | – | 3.0±0.5 | 2.8±2.1 | 2.4±0.9 | 2.1±1.4 | – | 2.3±0.6 | 2.3±0.8 |

Simultaneous presence of vertical and horizontal variations of the values of σ confirms the fact that the haze layers fluctuate strongly.

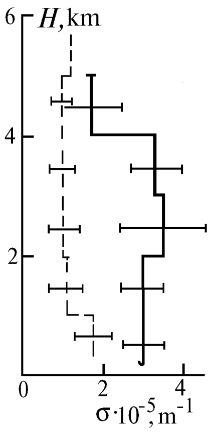


*FIG. 2. Vertical profiles of the scattering coefficient averaged over* 1 km *thick layers over the Laptev sea obtained on April* 6, 1994 *(solid line)* and *June* 15, 1993 *(dashed line). Horizontal bars denote* 95% *confidence intervals.*

According to the present concepts, the aerosol concentration in Canadian and Atlantic sectors of the Arctic is maximum in early spring and minimum in summer.[3,5] Figure 2 shows the vertical profiles of the values of σ averaged over 1 km thick layers, obtained in measurements on June 15, 1993 and April 6, 1994 in Russian sector over central part of the Laptev sea (to the north–west from the Novosibirsk Islands). The trajectories of the air masses transported to the measurement regions differ slightly during these two days: in both cases they were loop–shaped, and the air stayed in the Arctic (to the north of the polar circle) for a long time (more than 5–7 days).

It follows from Fig. 2 that the values $\overline{\sigma}$ were 2–3 times less in June than in April, with these differences being statistically significant.

## 5. CONCLUSIONS

Analysis of the vertical profiles of the light scattering coefficient at a wavelength of 0.53 μm derived from the data of airborne lidar measurements in Russian, Canadian, and Atlantic sectors of the Arctic showed the following:

1. In winter when cloudiness is absent, the layers are observed in the Arctic with the values of σ greater than $3\cdot10^{-5}$ $m^{-1}$ that are classified as layers with the Arctic haze, i.e., aerosol accumulation. The haze layers fill the troposphere by 15–30%. Maximum values of σ reach $(8–9)\cdot10^{-5}$ $m^{-1}$.

2. Taking into account the quantity of the data available, we have found the significant differences in the values averaged over 1 km thick layers neither in the vertical

direction nor from one sector of the Arctic to the other. This allows us to suppose that in winter all the troposphere of the Arctic is filled by haze layers.

3. From the data obtained in the central part of the Laptev sea in June of 1993, the average values $\overline{\sigma}$ were 2–3 times less than those in April of 1994.

4. In addition to the vertical variability, the horizontal variability is also observed in the Arctic troposphere. The recurrence of the haze regions was about 30%. Simultaneous presence of vertical and horizontal variability of $\sigma$ confirms the fact that the haze layers fluctuate strongly.

5. In many cases the data on the distribution of the light scattering coefficient obtained in the cloudless atmosphere of the Arctic can be explained by the hypothesis that industrial pollutants are removed from mid–latitudes.

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