RESEARCH PAPER

THE AEROSOL POLLUTION OF THE ATMOSPHERE ON THE EXAMPLE OF LIDAR SENSING DATA IN ST. PETERSBURG (RUSSIA), KUOPIO (FINLAND), MINSK (BELARUS)

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ABSTRACT. The results of lidar sensing of aerosol pollution in St. Petersburg (Russia) were compared with ones located in Minsk (Belarus) and Kuopio (Finland) to assess the impact of large cities on atmospheric pollution by aerosol particles. For comparison, aerosol optical depth (AOD) data obtained at the three stations from 2014 to 2021 were used. Lidar sounding of atmospheric aerosols was carried out using aerosol Nd:YAG lasers operating at three wavelengths: 355, 532 and 1064 nm. Due to differences in the lidar station equipment characteristics and, consequently, in the lower limit for determining aerosols, the aerosol optical depth was compared in the range of heights from 800 to 1600 m at 355 and 532 nm. Since the compared stations do not have data for all years, the period from 2014 to 2016 was analyzed separately. The average annual AOD 355 in Minsk in the period 2014-2016 is almost the same as the average annual AOD in St. Petersburg. When comparing data in St. Petersburg and Minsk for the period 2014-2020, AOD 355 in St. Petersburg exceeds AOD 355 in Minsk by 1.46 times. AOD 532 nm in Minsk is larger than in St. Petersburg, regardless of the chosen comparison period. The average annual AOT 355 in Kuopio is lower than in Minsk and St. Petersburg by 2.1 times, while at a wavelength of 532 nm they are 3.6 times lower than in Minsk and 2.6 times in St. Petersburg. The calculated Angstrom exponent coefficient shows that the coarse mode in Minsk is higher than in St. Petersburg. The atmosphere over Kuopio has a lower content of aerosol particles. Since 2017, there was a steady excess of aerosol content over St. Petersburg compared to Minsk. Additionally, a comparison of the lidar data with the total AOD of AERONET stations located in Kuopio, Minsk and Peterhof (25 km from the lidar station in St. Petersburg) was carried out. The AOD obtained by lidar and AERONET method is in good agreement.

KEYWORDS: aerosol, air pollution, aerosol optical depth, environmental monitoring of the atmosphere, lidar

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INTRODUCTION

The formation of atmospheric pollution in megacities is influenced by various factors – the number of sources of pollution, patterns of emissions distribution due to different landscapes, weather conditions, type of development, and other factors. Currently, the pollution from transport, emissions from industrial enterprises, as well as organic fuel combustion products can be distinguished from the main sources of anthropogenic air pollution. Naturally formed aerosols also contribute to atmospheric pollution (Kondratyev 2006). The natural sources of pollution are those whose formation does not depend on human activity. For example, the release of salt particles during evaporation of sea foam drops, production of pollen by plants, dispersion of soil particles and dust by wind (Zuev 1992).

In megacities, an aerosol cap is often formed in a layer up to one or two kilometers due to the rise of aerosol particles. The presence of windless weather worsens the situation: the resulting dense aerosol layer leads to environmental degradation, as well as an increase in surface temperature results in adverse effects on the health of population living in megacity.[1]

Back in the late 18th century, it was found that dust carried by air adversely affects human health. Thus, it was observed that chimney sweepers who often came into contact with high concentrations of soot often had cancer. In the second half of the 20th century, active research began, which showed the relationship between lung diseases and airborne aerosol particles. A large number of studies has been and is being currently conducted all over the world to assess the impact of aerosol particles on human health. The relationships between human exposure to aerosol particles and cardiovascular diseases, eye diseases, allergies, asthma, cancer, well-being and hospitalization of the population, and mortality among residents of aerosol-contaminated territories have been established. It also has been established that the smaller the diameter of aerosol particles in the atmosphere, the greater

[1]Doklad ob ekologicheskoj situacii v Sankt-Peterburge (Report on the environmental situation in St. Petersburg) // 2022.

the danger they pose to health (Agarwal 2017; Pandey 2020; Schraufnagel 2016; Schraufnagel 2020; Subramanian 2020; Wei 2019). Aerosol particles less than 1 micrometer penetrate deep into the lungs, reaching the alveoli. Recently, more and more studies are focused specifically on the effects of the smallest aerosol particles PM2.5, PM1 (Chen 2017; Hext 1999; Sharma 2020). Also, the danger of aerosols is associated with their ability to accumulate other pollutants on their surface, including carcinogens. It is worth noting that the effects caused by aerosol particles separately are often discussed in the literature, while their interaction with other pollutants taking the form of a synergistic effect, can have a much more significant impact on human health (Forest 2021). Another reason to pay special attention to pollution by aerosols is their ability to have an impact over hundreds of kilometers from the place of their formation due to their atmospheric transfer (Mallone 2011; Mona 2006).

Due to the extensive increase in the number of cars, the road transport is currently one of the main sources of pollution in the surface layer of the atmosphere in St. Petersburg, as well as in many other large cities (Nagy 2014). Constant traffic jams make things worse, because the discharge of pollutants mainly occurs at the time a car sets speed. Additionally, due to friction, a large number of abrasion products of automobile spikes, tires and asphalt is formed, which, in turn, are mixed with exhaust gases (Fussell 2022; Baensch-Baltruschat 2020; Kovochich 2021). Also, the soil layer brought onto the road by cars gets into this mixture. Further, all this multicomponent dust rises into the air and can be transferred by wind over long distances. In St. Petersburg in 2021, compared with 2020, the total number of motor vehicles increased by 1.67% (33886 units), while the number of passenger cars increased by 1.65% (29180 units), and the number of trucks – by 2.14% (4948 units).[2] There is an increase in the number of road transport in St. Petersburg. So in 2021, compared to 2020, the number of passenger cars increased by 1.65%, which is 29,180 cars, the number of trucks - by 2.14%, which is 4,948 units of trucks.

One of the methods that currently allow monitoring the aerosol pollution is the lidar method (Chazette 2023; Ma 2019). Lidar systems are an effective method for tracking the transport of aerosol particles. Lidar complexes find their applications for assessing the current state of the atmosphere and monitoring environmental pollution. (Aggarwal 2018; Ansmann 2005; Flamant2000; Ma 2019; McGill 2003; Yin 2021) The use of remote methods makes it possible to conduct research on the transfer of aerosol particles (Campbell 2016), calculate the atmospheric aerosol particle size distribution (Shi 2022; Samulenkov 2020).

Lidar data are used to obtain the addition information on the aerosol pollution of the atmosphere, including for spatial distribution of aerosol particle emissions in industrial areas and aerosol characteristics around highways (Yegorov 1995; Lisetskii 2019). Multiwave lidar complexes are used to monitor the transfer of aerosols of natural formation, which can also play an important role in total aerosol content under certain conditions (Ansmann 2021; Di Girolamo 2012; Kovalev 2009; Mona 2012; Vaughan 2021), and depend on the difference in air mass route and the ambient atmospheric conditions (Xie 2008). AOD studies provide an important information about the aerosol content in the atmosphere, understanding aerosol properties and improving the incorporation of aerosol effects into climate models (Kafle 2013; Khor 2014; Kong 2022; Xie 2010).

The lidar method is actively used and, therefore, there are many lidar measuring networks in the world: the Network for the Detection of Atmospheric Composition Change (NDACC, https://www.ndsc.ncep.noaa.gov) for global control of aerosol, ozone, temperature and humidity; the European Aerosol Research Lidar Network (EARLINET), the purpose of which is to track aerosol pollution on the European continent (Papagiannopoulos 2020); the NASA Micro-Pulse Lidar Network (MPL-Net) (Welton, 2018) for monitoring tropospheric aerosol. Studies of dust aerosol from the desert territory of China are carried out within the framework of the Asian Dust and aerosol lidar observation network (AD-Net) (Nishizawa, 2016); the Regional East Atmospheric Lidar Mesonet (REALM) in the Eastern USA was designed to monitor air quality (Hoff, 2002). Atmospheric aerosol monitoring in the Commonwealth of Independent States (CIS) is carried out by the CIS Lidar Network (CIS-LiNet), located in Russia, Belarus and Kyrgyzstan (Chaikovsky, 2006).

At the Resource Center "Observatory of Environmental Safety" of the St. Petersburg State University Science Park, the studies of aerosol pollution have been conducted since December 2013;the lidar station became a part of the EARLINET in 2014 . The station is located in the center of St. Petersburg on Vasilievsky Island, which is one of the most polluted parts of the city. This allows obtaining unique data on the aerosol pollution of the urban atmosphere. Minsk and St. Petersburg have the most extensive network of industrial enterprises, as well as a large population. About 5.4 million people lives in St. Petersburg, and 2 million people – in Minsk. The industry of St. Petersburg is based on more than 750 large and medium-size enterprises, some of which are among the leading manufacturing companies in Russia. Economic activity in the field of industrial production is also carried out by more than 23 thousand small enterprises, including microenterprises[3]. There are more than 3,100 industrial enterprises in Minsk, and more than 2,700 in the Minsk region[4], which also has a serious impact on the environment.

Kuopio is the eighth largest city in Finland, which is located in the Savo district near numerous lakes. The number of residents is about 120 thousand people. The city is included in the comparison as an example of a relatively environmentally safe territory[5].

The aerosol optical depth (AOD) of the atmosphere is one of the main characteristics determining the total aerosol air pollution (Cogliani 2001; Zhu 2011; Chubarova 2022; Zhdanova 2020). The influence of aerosols on atmospheric processes, the high variability of aerosol particles and harmful effects on humans determines the importance of studying the optical characteristics of aerosols. The purpose of this paper is to analyze the AOD data obtained by lidar stations in St. Petersburg, Minsk and Kuopio in order to assess the level of aerosol particle pollution in different regions, namely in two megacities, such as St. Petersburg and Minsk, and to perform a comparison with the pollution level in the relatively small city of Kuopio located in an environmentally safe region of Finland. The stations were selected based on their location. Minsk and Kuopio are the aerosol observation sites closest to St. Petersburg and have different levels of anthropogenic load. Our study will provide more information about the patterns of aerosol distribution in the studied regions.

MATERIALS AND METHODS

The main technical characteristics of three lidar systems are presented in Table 1.

The lidar equipment is used in conjunction with specialized software that allows processing the backscattered signal received by the telescope. The magnitude of the signal depends on the amount of

[2]World Health Organization. Regional Office for Europe & Joint WHO/Convention Task Force on the Health Aspects of Air Pollution. (2006). Health risks of particulate matter from long-range transboundary air pollution. Copenhagen : WHO Regional Office for Europe.
[3]Promyshlennost' i innovacii Sankt-Peterburga (Industry and innovations of St. Petersburg), 2017.
[4]Promyshlennost' respubliki Belarus' statisticheskij sbornik (Industry of the Republic of Belarus statistical compilation), 2019.
[5][Internet] – https://www.kuopio.fi/en/etusivu (date of access: 07.02.2023).

Table 1. Characteristics of lidar stations in Russia, Finland and Belarus

Parameter	St. Petersburg, Russia	Kuopio, Finland	Minsk, Belarus
Geographical coordinates	59.9427 N, 30.2730 E	62.7333 N, 27.5500 E	53.9170 N, 27.6050 E
Height above sea level, m	35	190	200
Used wavelengths, nm	355, 532	355, 532	355, 532
Initial height resolution, m	7.5	30; 60	7.5; 15
Minimum detection height, m	300-500	800-1000	455-800

aerosol present in the atmosphere. The attenuation and backscattering coefficients of the aerosol obtained from lidar sensing data were calculated using the Klett method (Klett 1985).

The lidar equation formulates the relationship between the sum of photons emitted by the laser and the sum of photons absorbed. Laser beam is transmitted in the atmosphere and there is a physical reaction between the laser beam and the probed object. The lidar equation characterizes the mathematical model of the physical processes that occur in the atmosphere when exposed to the laser beam (Kovalev 2004; Tuan 2017):

$$N_S(\lambda,R)=N_L(\lambda_L)\cdot\left[\beta\left(\lambda,\lambda_L,\theta,R\right)\cdot\Delta R\beta\right]\cdot\frac{A}{R^2}\cdot\left[T\left(\lambda_L,R\right)\cdot T(\lambda,R)\right]\cdot\left[\eta\left(\lambda,\lambda_L\right)\cdot G(R)\right]+N_B \quad (1)$$

where $N_S(\lambda, R)$ is the photon counts registered at a wavelength λ and distance R; $N_L(\lambda_L)$ is the number of transferred photons; $[\beta(\lambda, \lambda L, \theta, R)\Delta R]$ is the probability that a transferred photon is scattered into a unit solid angle at an angle θ; β is the volume scatter coefficient; ΔR is the layer thickness; A is the receiver aperture; A/R^2 is the probability that a scattered photon is collected by the receiving telescope; $[T(\lambda_L, R)T(\lambda, R)]$ is the light transmission during its propagation from a laser source to distance R and from distance R to a receiver; $\eta(\lambda, \lambda_L)$ is the hardware optical efficiency; $G(R)$ is the geometrical form factor; N_B is the background and detector noise.

The basic equation of lidar sensing is used for the calculation (Zuev, 1992):

$$P(z)=A\frac{\beta(z)}{z^2}exp\left[-2\int_0^z \alpha(z')\,dz'\right] \quad (2)$$

where $P(z)$ is the power of the detected backscattered signal from height z, A is the instrumental constant that includes all range-independent instrumental parameters (as the detector's efficiency, receiving telescope area and laser pulse width), $\beta(z)$ is the backscattering coefficient, $\alpha(z')$ is the extinction coefficient. The AOD from z_{min} to z_{max} can be calculated as:

$$AOD=\int_{z_{min}}^{z_{max}} \alpha(z)\,dz \quad (3)$$

The errors in calculating the attenuation and backscattering coefficients by the Klett method are about 20 % (Althausen 2000; Klett 1985; Klett 1981) and depend on the state of the atmosphere, the type and amount of aerosols. The range of lidar sensing also depends on atmospheric conditions.

The Angstrom exponent coefficient was calculated using the formula below to understand the nature of the aerosol particle size distribution:

$$a=-\frac{\ln\left(\frac{AOD_i}{AOD_j}\right)}{\ln\left(\frac{\lambda_i}{\lambda_j}\right)} \quad (4)$$

where a is the Angstrom exponent coefficient, $AOD_{i,j}$ is the aerosol optical depth at wavelength λ_i and λ_j.

A large array of data obtained during measurements in the most polluted part of St. Petersburg, as well as Minsk and Kuopio, allows analyzing changes in the AOD over time, and identifying sequences in the distribution of aerosols for the period from 2014 to 2021. The variability of aerosol pollution over such large megacities as St. Petersburg and Minsk and comparing the data with the relatively environmentally safe area of Kuopio, allows assessing the degree of urban pollution.

The limitation in the height of determining the aerosol optical depth is due to differences in the lower limit of measurements by the instruments (Guerrero-Rascado 2010; Halldórsson 1978). In Kuopio, the data in most cases are provided from 800 m, therefore, the lower limit of observations at all three stations is a height of 800 m. The upper level of observations is limited by 1600 m. This is due to the fact that a part of the available data ends at an altitude of 1600 m.

The number of processed measurements to obtain the AOD average values is presented in Table 2.

The distance between the observation station is: between St. Petersburg and Kuopio 343 km, between Kuopio and Minsk 980 km, and 689 km between St. Petersburg and Minsk.

Due to the coronavirus restrictions, the number of measurements performed in 2019-2021 decreased significantly.

RESULTS AND DISCUSSION

Table 3 and Figure 1 show the median values of AOD 355 and AOD 532 obtained at three monitoring stations in St. Petersburg, Minsk, and Kuopio from 2014 to 2021 at altitudes from 800 to 1600 m. The median is a stable estimate of the distribution center and does not tend to shift with significant deviations from the main data array. Unfortunately, due to the complexity of research equipment that requires periodic maintenance and repair, data for comparison in Kuopio and Minsk were not obtained for each year.

Unfortunately, the data at 800 m at the station in Kuopio are available only for three years from 2014 to 2016. According to the processed AOD data at 355 nm (Fig. 1a), the atmosphere at the location of the station in Kuopio has a lower content of aerosol particles. The AOD at 355 nm in St. Petersburg is higher than that in Minsk, with the exception of 2016. Since 2017, there was a steady excess of aerosol content over St. Petersburg compared to Minsk, with a maximum excess by 2.4 times in 2020 (Fig. 1a).

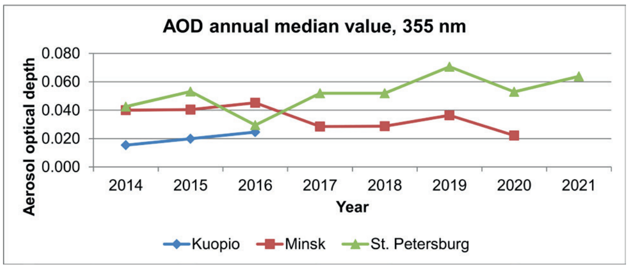
Table 2. Number of measurements by year[6]

City	Channel, nm	2014	2015	2016	2017	2018	2019	2020	2021	Total
Saint-Petersburg	355	40	40	18	50	21	9	9	5	192
	532	40	45	18	50	21	9	9	5	197
Minsk	355	3	29	26	16	15	12	7	-	108
	532	7	29	28	17	16	13	8	-	118
Kuopio	355	7	22	20	-	-	-	-	-	49
	532	12	42	30	-	-	-	-	-	84

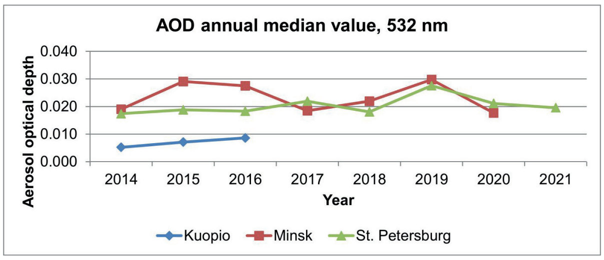
Table 3. Distribution of optical depth median value by year during the 2014-2021 period for three stations in the layer from 800 to 1600 m.

Year	St. Petersburg, Russia		Minsk, Belarus		Kuopio, Finland	
	355 nm	532 nm	355 nm	532 nm	355 nm	532 nm
2014	0.043	0.017	0.040	0.019	0.015	0.005
2015	0.053	0.019	0.040	0.029	0.020	0.007
2016	0.030	0.018	0.045	0.028	0.025	0.009
2017	0.052	0.022	0.028	0.018	-	-
2018	0.052	0.018	0.029	0.022	-	-
2019	0.071	0.028	0.036	0.030	-	-
2020	0.053	0.021	0.022	0.018	0.013*	0.010*
2021	0.064	0.020	-	-	0.048*	-
Mean	0.052	0.020	0.034	0.023	0.020	0.007

* – data only from 1000 m.



(a)



(b)

Fig. 1. Distribution of optical depth median value by year in the period from 2014 to 2021 for three stations in a layer from 800 to 1600 m at wavelengths of 355 nm (a) and 532 nm (b)

The Angstrom parameter at wavelengths of 355 and 532 nm was also considered, separately for the period 2014-2016 for all three stations and from 2014 to 2020 for lidar stations in St. Petersburg and Minsk. The Angstrom parameter allows us to conclude about the nature of the particle size distribution. The Angstrom parameter above 2 indicates the prevalence of a fine aerosol, whereas the values below 1 indicate the predominance of large aerosol particles. In the period from 2014 to 2016, the value of the Angstrom parameter was 2.60 in Kuopio, 1.26 in Minsk and 2.05 in St. Petersburg. In the period from 2014 to 2020, the average Angstrom parameter has values of 0.92 in Minsk and 2.18 in St. Petersburg. This indicates the predominance of fine aerosol over St. Petersburg.

As an additional source of information on the annual course of the AOD near St. Petersburg, we used the data from the AERONET station in Peterhof located 25 km from the lidar station, as well as data from the AERONET stations in Kuopio and Minsk (Filonchyk 2021; Volkova 2018). On average, for the measurement period from 2013 to 2016, the AOD in Peterhof at a wavelength of 500 nm is 0.12 ± 0.05 with maximum values in summer 0.14–0.19. For the AERONET station in Kuopio, the average AOD at a wavelength of 500 nm is 0.10 ± 0.03. Authors of this study also notes that the AOD values in Peterhof are higher than the results of observations in Kuopio, which is associated with the contribution of anthropogenic aerosol, which is typical for large metropolitan areas. The AOD distribution patterns obtained in work (Volkova 2018) are in good agreement with the data obtained by the lidar method for stations in Kuopio and St. Petersburg. The Angstrom parameter (440–870 nm) in Peterhof according to the AERONET changes from 1.0 to 1.6 with maximum values in the warm season. This indicates a mixed bimodal distribution of aerosol, with a finely dispersed fraction up to 60%. Taking into account the distance between the observation sites, an additional contribution of the secondary fine aerosol of anthropogenic origin in St. Petersburg is possible, which gives higher values of the Angstrom parameter. At the AERONET station in Kuopio, a similar relationship is observed.

[6][Internet] – https://data.earlinet.org (date of access: 07.02.2023).

The high summer values of the Angstrom parameter in Peterhof are attributed by the authors (Volkova 2018) to an increase in the amount of finely dispersed secondary aerosol. The overestimation of the angstrom parameter in St. Petersburg and Kuopio, obtained from lidar data in relation to the AERONET angstrom parameter, is apparently due to the limitation of the observation height from 800 to 1600 m, the location of the lidar station in the center of St. Petersburg also affects.

In Minsk, the Angstrom parameter (440-870 nm) calculated according to AERONET station data from 2002 to 2019 (Filonchyk 2021) changes significantly throughout the year, while the average annual values of the Angstrom parameter according to AERONET data exceed 1.3, which also indicates the predominance of fine aerosols, and is not entirely consistent with the results obtained by the lidar method. The average daily AOD 440 nm and Angstrom exponent (440-870 nm) values of the AERONET station in Minsk vary from 0.03 to 2.08 and from 0.11 to 2.35, and the average monthly values vary from 0.14 to 0.27 and from 1.19 to 1.58, respectively. The obtained annual mean AOD 440 is 0.22 ± 0.17. The average Angstrom parameter (355–532 nm) in Minsk according to lidar data is 0.92, which is much lower than the coefficient in St. Petersburg and Kuopio, and not quite typical for Minsk. The resulting discrepancy can be attributed to a small number of lidar observations in Minsk in the period from 2018 to 2020. Measurements during this period were carried out mainly in early spring and winter, and the Angstrom parameter (355-532 nm) shows underestimated values – 0.54, which undoubtedly affects the final value of the AOD and the Angstrom parameter for the entire period from 2014-2020. At the same time, the average Angstrom parameter (355–532 nm) for the period from 2014 to 2017 is 1.23, which is close to the readings of the AERONET station in Minsk. It can be noted that both AOD 355 and AOD 532 in St. Petersburg and Minsk on average exceed the AOD values in the city of Kuopio by 2-3 times. The results obtained allow the conclusion that the atmosphere in the city of Kuopio is less polluted by aerosol particles, which, according to the authors of this article, is due to the low number of industrial plants located in this region, as well as the low intensity of automobile traffic. At the same time, it should be noted that the natural aerosol can also contribute to the total content of aerosol pollution in cities (Chubarova 2022). The increased content of aerosols over St. Petersburg and Minsk may lead to an additional adverse effects on the health of the population due to the processes of aerosol deposition.

Since the compared stations do not have data for all years, the comparison was carried out according to the following procedure. The period from 2014 to 2016 was analyzed separately, since for these three years all three stations have measurements (fig. 2a). A separate comparison was made for Minsk and St. Petersburg from 2014 to 2020 (fig. 2b). Figure 2 clearly shows the predominance of the Minsk and St. Petersburg average AOD at 355nm and 532 nm over Kuopio. Average AOD 355 in St. Petersburg and Minsk exceeds AOD 355 in Kuopio by 2.1 times. Average AOD 532 in Minsk exceeds AOD 532 in Kuopio by 3.6 times, in Saint-Petersburg AOD 532 higher in Kuopio in 2.6 times. The average AOD values for all the years of measurements are shown in Figure 2.

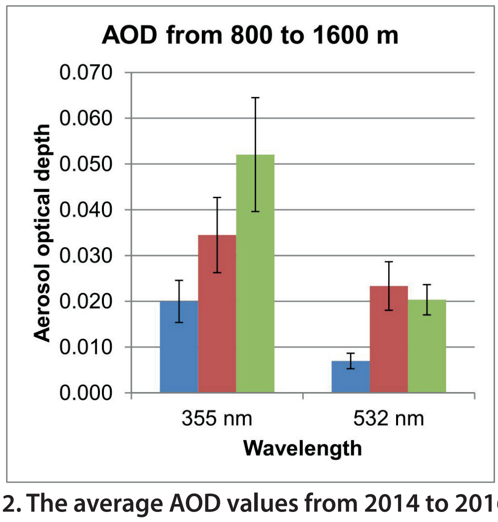
As follows from the processed data, the average AOD in the selected height range in Kuopio is less than in St. Petersburg and Minsk. At the same time, in Minsk AOD 532 exceeds St.Petersburg's AOD 532, with the exception of 2017 and 2020. In the period from 2014 to 2016, there is no difference between AOD 355 in St. Petersburg and Minsk, while for AOD 532 it was clearly expressed.. AOD 355 in St. Petersburg is 1.43 times higher than AOD 355 in Minsk, and lower by 1.25 times at a wavelength of 532 nm.

CONCLUSION

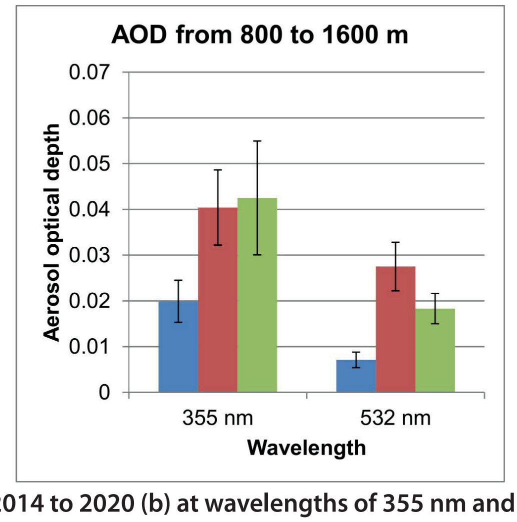
The available AOD data for three stations in St. Petersburg, Minsk and Kuopio, located in three regions with different levels of anthropogenic impact and natural aerosol content, made it possible to evaluate the optical characteristics of aerosol and compare the level of atmospheric air pollution. In St. Petersburg, the location of the lidar station is in the center of the city in the most polluted area.

The average AOD 355 in St. Petersburg and Minsk over the 2014-2016 period exceeds this value in Kuopio by 2.1 times. The average value of AOD 532 in Minsk and St. Petersburg is 3.6 and 2.6 times higher than in Kuopio, respectively. For the 2014–2020 period, AOD 355 shows the following average values: 0.050±0.012 in St. Petersburg and 0.034±0.008 in Minsk, while the average AOD 532 values are: 0.020±0.004 in St. Petersburg and 0.023±0.005 in Minsk. The average AOD 355 and AOD 532 are 1.46 times higher and 1.14 times lower in St. Petersburg than those in Minsk, respectively.

Additionally, a comparison was made with the data of AERONET stations in Peterhof, Minsk, Kuopio with an analysis of the optical characteristics, the Angstrom parameter and an assessment of their variations. The smallest AOD according to AERONET data is recorded in Kuopio, the largest in Minsk, which is consistent with the received lidar data. The station in Peterhof is located far from St. Petersburg, which affects the AOD readings downwards. AOD 355 according to lidar data from 2014 to 2020 in St. Petersburg is gradually increasing, in Minsk there is a decrease.



(a)



(b)

Fig. 2. The average AOD values from 2014 to 2016 (a) and from 2014 to 2020 (b) at wavelengths of 355 nm and 532 nm (black lines are standard deviations)

The distributions of the Angstrom parameter from lidar data in St. Petersburg and Kuopio are in good agreement with the Angstrom parameter obtained from the AERONET data. At the same time, higher values of the Angstrom parameter are noted in St. Petersburg and Kuopio, which can be explained by the limited height of the AOD study from 800 to 1600 m.

In Minsk, according to AERONET data, the Angstrom parameter 440-870 nm from 2002 to 2019 exceeds 1.3, which indicates the predominance of fine aerosols and does not quite agree with the data obtained from lidar measurements if we take the period from 2014 to 2020, for the average parameter. The Angstrom is influenced by data from 2018 to 2020 when there is a small number of measurements that were carried out only in early spring and winter, and the Angstrom parameter 532-355 nm was significantly underestimated - 0.54, and indicates the predominance of coarse aerosol. The calculated Angstrom parameter 532-355 nm for the period from 2014 to 2017 is 1.23, which is already close and consistent with the data obtained in the AERONET network.

The values of both AOD 355 and 532 in the city of Kuopio are significantly lower than those in St. Petersburg and Minsk due to the smaller number of aerosol particles in the atmosphere. Note that both AOD values in St. Petersburg and Minsk exceed the AOD values in Kuopio by 2-3 times (Fig. 2b), which allows us to conclude about the predominant content of aerosol particles over megacities compared to smaller cities. In this paper, the AOD was compared in a layer from 800 to 1600 m. If it was possible to compare AOD at lower heights, it seems that the differences between St. Petersburg, Minsk and Kuopio would be even greater. The main contribution to air pollution in the big cities is most likely to be made by road transport and industrial enterprises with some effects of natural aerosol. ■

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