CIS-LiNet lidar network for monitoring aerosol and ozone: methodology and instrumentation

A.P. Chaikovsky,[1] A.P. Ivanov,[1] Yu.S. Balin,[2] A.V. Elnikov,[2] G.F. Tulinov,[3] I.I. Plusnin,[4] O.A. Bukin,[5] and B.B. Chen[6]

[1] B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk
[2] Institute of Atmospheric Optics, Siberian Branch of the Russian Academy of Sciences, Tomsk
[3] E.K. Fedorov Institute of Applied Geophysics, Moscow
[4] Surgut State University
[5] V.I. Il'ichev Pacific Oceanological Institute, Far Eastern Branch of the Russian Academy of Sciences, Vladivostok
[6] Kyrgyz-Russian Slavic University, Bishkek, Kyrgyzstan

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CIS-LiNet lidar network has been established by lidar teams from Belarus, Russia, and Kyrgyz Republic. Its objective is carrying out coordinated lidar observations on the territory from Minsk to Vladivostok in cooperation with the observations under EARLINET, AD-Net, and AERONET Programs. All stations will carry out aerosol observations in the troposphere and stratosphere. Two stations in Minsk and Tomsk will implement ozone sounding in the stratospheric layer. Regular measurements of aerosol parameters are carried out in combination with radiometric observations. Joint analysis of air mass transfer trajectories and observation data is used for estimating impact of long-range transfer processes on the aerosol parameters.

Introduction

Monitoring of the atmospheric aerosol and ozone is an important prerequisite for the development of climatological investigations and solution of ecological problems. Global and regional measurement networks are being arranged for obtaining reliable data on spatiotemporal transformations of the atmospheric constituents. Primarily these are aimed at regular coordinated measurements and compilation of the corresponding databases. The global network for remote monitoring of atmospheric aerosol parameters (AERONET) has been arranged using scanning sun photometers[1] as the instrumentation basis. The results of AERONET data processing are the spectra of the atmospheric aerosol optical thickness, column density of aerosol particles, particle size distribution, and the estimate of the complex extinction coefficient.[2]

Lidars are used as the main tool for monitoring of the vertical distribution of the atmospheric components. Development of the lidar techniques and increased attention of the world community to the global ecological problems laid a foundation for the formation of lidar networks. Lidar systems for investigation of ozone and aerosol in the stratosphere are the basis of the NDSC network (Network for the Detection of Stratospheric Change).[3] The Micro-pulse lidar Network MPL-Net[4] was created for monitoring the tropospheric aerosol. It coordinates its operation with AERONET. The European Aerosol Research Lidar Network EARLINET[5] was founded in year 2000. EARLINET provides for coordinated operation of more than 20 lidar stations from Wales to Belarus in order to investigate the processes of large-scale transport of aerosol over Europe. Lidar investigations of the emission of Asian dust to the region of Pacific Ocean are carried out at AD-Net (Asian Dust Network).[6] Regional East Atmospheric Lidar Mesonet REALM[7] and lidar network in Latin America (AliNe)[8] are under development.

International working group of specialists representing regional lidar networks EARLINET, AD-Net, REALM, AliNe, MPL-Net, and CIS-LiNet was arranged in 2004. Its task is the coordination of operation of regional lidar networks and preparation of the conditions for the arrangement of the global lidar network (FARLINET).

In 60s of the 20th century the development of lidar methods and instrumentation in the USSR was initially begun at the Central Aerological Observatory (Moscow), Institute of Physics of Academy of Sciences of Belarus (Minsk), and at the Institute of Atmospheric Optics SB RAS (Tomsk). First lidar network for monitoring of the stratospheric aerosol was arranged in the USSR in 1988.[9]

However, except for the lidar station at the Institute of Physics NAS of Belarus involved in the EARLINET network, no regular lidar observations coordinated with international networks were carried out until recent dates on the territory of the former Soviet Union. The absence of systematic data on the vertical distributions of the atmospheric components over vast territory of the former Soviet Union is an important factor of uncertainty in predicting climatic and ecological processes. It is impossible to study global processes of transformation of the atmospheric

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components and effectively solve ecological problems on the Eurasian continent without data on the parameters of atmospheric admixtures in the regions of the former Soviet Union.

The lidar network for monitoring the atmospheric aerosol and ozone over the regions of the former Soviet Union has been arranged in 2004 as a result of joint activity of scientific institutions of Belarus, Russia, and Kyrgyzstan in cooperation with the measurement networks of EARLINET, AD-Net, and AERONET under support of the International Science and Technology Center (ISTC). The main purpose of the CIS-LiNet is in coordinated observations of the atmospheric parameters over Eurasian continent in cooperation with other international measurement networks.

1. Structure of the lidar network and its main tasks

The CIS-LiNet lidar network was arranged by scientific groups from six institutions of Belarus, Russia, and Kyrgyzstan (Table 1). The diagram of the CIS-LiNet lidar network covering the territory from Minsk to Vladivostok is shown in Fig. 1. The diagrams of lidar networks in Europe (EARLINET) and South-East Asia (AD-Net) are also shown here.

The lidar station of IP is included simultaneously into EARLINET and CIS-LiNet. Geographical position of the stations enables CIS-LiNet to become a link uniting regional lidar networks to a structure which makes it possible to carry out coordinated lidar observations over Eurasian continent, to study the processes of large-scale transport of aerosol and to carry out ground support measurements to validate spaceborne experiments.

The main investigation problems solved in the frameworks of CIS-LiNet are:

– regular coordinated observations of the vertical profiles of tropospheric aerosol parameters for investigation of the large-scale spatiotemporal variability of the aerosol component of the atmosphere and the study of the processes of large-scale transport of aerosol, and compilation of corresponding database;

Table 1. Institutes and stations comprising the CIS-LiNet lidar network

Institute	Station	Country
B.I. Stepanov Institute of Physics, NAS of Belarus (IP)	Stationary lidar station, Minsk, 53.917 N, 27.383 E	Belarus
Institute of Atmospheric Optics, SB RAS (IAO)	Stationary lidar station, Tomsk, 56.48 N, 85.05 E	Russia
	Seasonal lidar station based on a mobile lidar in the region of Lake Baikal, 51.44 N, 105.06 E	
E.K. Fedorov Institute of Applied Geophysics (IAG)	Stationary lidar station, Moscow, 55 N, 37 E	Russia
Surgut State University (SSU)	Stationary station, Surgut, 61.25 N, 73.50 E	Russia
V.I. Il'ichev Pacific Oceanological Institute, FEB RAS (POI)	Stationary lidar station, Vladivostok, 43.01 N, 131.9 E	Russia
Kyrgyz-Russian Slavic University (KRSU)	Mountain stationary lidar station Teploklyuchenka, Central Asia, 42.5 N, 78.4 E	Kyrgyzstan

Fig. 1. Lidar networks on Eurasian continent: EARLINET (∗), CIS-LiNet (**O**), and AD-Net (■).

– investigations into the dynamics of the characteristics of aerosol fields in the boundary layer of the atmosphere with temporal scales from days to seasons;

– regular observations of stratospheric aerosol and ozone for the study of the factors determining their variations and trends;

– investigations of regional variations of the parameters of aerosol fields caused by phenomena characteristic of the region: anthropogenic pollution of the atmosphere, forest fires, emission of dust from North China and Mongolia, volcanic activity in the regions of Kamchatka and Kuril Islands, transformation of the aerosol characteristics at vertical transfer in mountain regions, peculiarities of the formation of aerosol fields in the hollow of Lake Baikal, and stratospheric clouds.

The important part of the studies in the frameworks of CIS-LiNet is the development and unification of lidar instrumentation, intercalibration of the instrumentation and algorithms for data processing, compilation of databases, and maintenance of the information web site.

2. Lidar instrumentation of the CIS-LiNet

Technical requirements to the lidar systems of CIS-LiNet provide for sensing of tropospheric aerosol at three wavelengths (355, 532, and 1064 nm) and a channel for recording Raman scattering by nitrogen at the wavelength of 387 or 607 nm. Measurements of depolarization of the scattered radiation are performed at some stations. All stations provide for sensing of stratospheric aerosol. Sensing of stratospheric ozone is carried out at stations in Minsk and Tomsk. The program of modernization of the instrumentation of the CIS-LiNet provide for achievement of the technical capabilities presented in Table 2.

The list of parameters studied at the stations of CIS-LiNet was determined on the basis of the experience of operation of the EARLINET and caused by the desire to provide for measurements of the optical characteristics of aerosol layer (coefficients of the aerosol backscatter and extinction), as well as the parameters of aerosol microstructure.[5,10,11] Mobile lidars in CIS-LiNet are intended not only for research, but also for realization of the program of intercalibration of lidar instrumentation.

Some blocks and systems of lidar stations are designed and produced on a commercial basis by small batches in order to unify instrumentation and decrease the cost of lidars. The compact photo detection module for recording analog signal in UV and visible wavelength ranges has been successfully tested and installed at the stations of CIS-LiNet. It includes a PMT, high-voltage power supply, amplifier, 14-bit ADC, channel for recording the pulse energy, and an interface for USB port. Analogous module based on avalanche photodiode is designed for recording radiation in the IR range.

3. Methods and approaches

Methodology of lidar monitoring of tropospheric aerosol applied in the CIS-LiNet is mainly based on the developments and experience gained under EARLINET research program. Simultaneously, new techniques are being developed for sensing aerosol and ozone in the frameworks of CIS-LiNet, as well as the approaches to coordinated investigations of the processes of large-scale transport of aerosol at the stations of the network.

3.1. Combined lidar and radiometric monitoring of aerosol

An important peculiarity of monitoring the aerosol at the stations of CIS-LiNet is joint lidar and

Table 2. Technical specifications of lidar stations in CIS-LiNet

Institute	IP		IAO		IAG	SSU	POI		KRSU
Parameters	St.	M.	St.	M.	St.	St.	St.	M.	St.
β-355	day		day		day				day
β-532	day	day	day	day	day	day	day	day	day
β-1064	day	day			day		day		day
$E(R)$-355	night		night		night				night
$E(R)$-532	night		night	night					
D-532	day		day		day				day
β-355	night		night		night				night
β-532	night		night		night	night	night	night	night
D-532	night				night				night
O_3	night		night						
Temperature in the stratosphere			night						

N o t e . St. denotes stationary lidar station; M. denotes mobile lidar station. β-λ are measurements of backscattering coefficient at the wavelength λ; $E(R)$-λ is measurement of extinction by means of the channel of spontaneous Raman scattering SRS by molecular nitrogen at sensing at the wavelength λ; O_3 is measurement of the ozone concentration; D-λ is measurement of the backscatter depolarization at the wavelength λ.

radiometric measurements. The CIS-LiNet lidar network is simultaneously formed as a part of the AERONET radiometric network. Lidar data on the vertical profiles of the aerosol parameters and the measurement data on the integral parameters of aerosol layer performed at AERONET by means of scanning sun photometers complement each other. New data on the vertical distribution of microstructure parameters of aerosol are obtained from coordinated measurements and joint processing of the data of lidar and radiometric measurements.[11–14] In processing data of the combined lidar and radiometric experiments, the results of radiometric measurements are used as *a priori* data for construction of the initial aerosol model of the atmosphere, as well as for formation of restrictions on the possible solutions of the inverse problem of retrieving the profiles of concentration of the aerosol fractions.

The results of data analysis in AERONET have shown[15] that the column-mean particle volume distribution usually contains two fractions with boundary radius of about 0.5 μm. It is supposed in the initial model of aerosol layer, used for processing the data of the combined lidar and radiometric experiment, that the ensemble of aerosol particles contains two fractions, the concentrations of which change with altitude. The shape of the size distribution of each individual fraction and the refractive index of aerosol particles are constant and correspond to the characteristics of the integral distribution obtained from radiometric measurements.

The basis system of equations includes the following relationships[12]:

– the set of lidar equations for the working wavelengths of the lidar containing the data on the vertical profiles of aerosol parameters;

– equations for the column-mean aerosol parameters obtained from radiometric measurements;

– restrictions on the smoothness of the vertical distributions of the aerosol parameters:

$$L^*(\lambda_j,z_n) = L\left[\lambda_j,\mathbf{C}_\text{v}(z_n),m_j,z_n\right] + \mathbf{\Delta}_L^j;$$
$$\mathbf{F}^*(\lambda_i) = \mathbf{F}^*\left[\mathbf{C}_\text{v}(z_n)\right] + \mathbf{\Delta}_\mathbf{F}; \quad (1)$$
$$\mathbf{0}_\text{v}^* = \mathbf{S}_2\,\mathbf{C}_\text{v} + \mathbf{\Delta}_{0_\text{v}},$$

where

$$L^*(\lambda_j,z_n) = \frac{P^*(\lambda_j,z_n)z_n}{P^*(\lambda_j,z_N)z_N^2}$$

is the measured normalized lidar return signal;

$$L\left[\lambda_j,\mathbf{C}_\text{v}(z_n),m_j,z_n\right] = \frac{P(\lambda_j,z_n)z_n}{P(\lambda_j,z_N)z_N^2}$$

is the nonlinear function of the parameters C_v and m_j, respectively, the aerosol particle size distribution and the complex refractive index of aerosol particles;

$$P(\lambda_j,\theta,z) = \frac{A_i P^0(\lambda_j)}{z^2}\beta(\lambda_j,z)\exp\left[-2\int_0^z \sigma(\lambda_j,z')\text{d}z'\right].$$

Depending on the conditions of the experiment, the aerosol optical thickness $\tau^\text{a}(\lambda_i,C_\text{v},m_j)$ or the total concentration of the aerosol fractions W_v^* are used as the integral characteristics of the aerosol layer. In the latter case, the second group of equations in Eq. (1) is as follows:

$$W_\text{v}^* = \int C_\text{v}\text{d}z + \Delta_C^\text{v}. \quad (2)$$

The likelihood function for the present experiment has the form

$$P(C_\text{v}|\mathbf{L}^*,\mathbf{W}_\text{v}^*) \sim$$
$$\sim \exp\left\{-\frac{1}{2}\left[\sum_{n=1}^{N-1}\sum_{j=1}^{J}\left(L_n^{*j} - L_n(C_\text{v})\right)^\text{T}\mathbf{\Omega}_L^{-1}\left(L_n^{*j} - L_n(C_\text{v})\right) + \right.\right.$$
$$\left.\left. + \sum_{i=1}^{I}\left(W_\text{v}^* - \sum_{n=1}^{N}C_{\text{v},n}\Delta z_n\right)^\text{T}\mathbf{\Omega}_W^{-1}\left(W_\text{v}^* - \sum_{n=1}^{N}C_{\text{v},n}\Delta z_n\right) + \frac{E_m}{\sigma_\text{v}^2}\right]\right\}, \quad (3)$$

where $\mathbf{\Omega}_L$ and $\mathbf{\Omega}_W$ are the covariation matrices of the error in measurements L^{*j} and in the estimates of the parameters W_v^*; σ_v^2 are the *a priori* estimates of the finite differences of the vertical profiles of the parameters C_v.

The solutions of the system of equations (1) are the parameters $\tilde{C}_\text{v}$, providing for the maximum of the likelihood function (3)

$$P\left(\tilde{C}_\text{v}\middle|L_1^*,\tau^*,\mathbf{0}_\text{v}^*\right) = \max. \quad (4)$$

The technique for joint radiometric and lidar measurements has been developed in the field experiments at different states of the aerosol layer in 2002–2004 at the lidar stations in Minsk and Belsk (Poland). Both stations were equipped with the three-wavelength lidar systems operated at the wavelengths of 532, 694, and 1064 nm.

Figure 2 shows the column-mean aerosol volume distributions

$$Q(r) = \int_0^\infty \frac{\text{d}V(r)}{\text{d}\ln r}\text{d}z,$$

retrieved from the measurements data acquired with a sun photometer under conditions of clean atmosphere, pollution by forest fire smokes and Saharan dust. The retrieved values of the profiles of the concentration of fine and coarse aerosol fractions are shown in Figs. 2*b–d*. In processing the data obtained during dust emission from Sahara desert, the model of spheroids was used for description of aerosol particles.

The data on the vertical profiles of concentrations of the aerosol fractions were used for calculation of the lidar signals, which then were compared with measured ones. In the majority of cases, the difference was within the limits of possible measurement errors. Thus, the model of aerosol layer used in this technique and the retrieved profiles of the concentrations of the

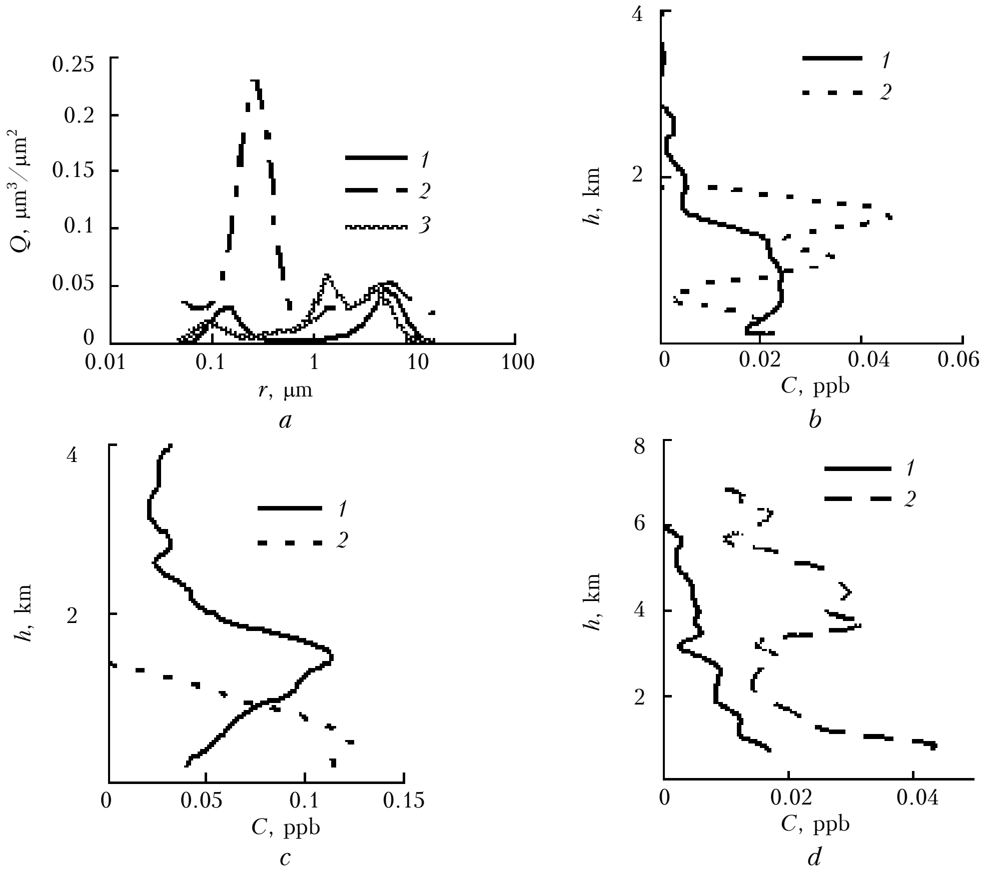

Fig. 2. Particle volume distributions $Q(r)$ (*a*) for background aerosol (*1*), smokes (*2*), and Saharan dust (*3*), as well as the profiles of concentrations (*b*–*d*) of fine (*1*) and coarse (*2*) aerosol particles: background aerosol (*b*), pollution by forest fire smokes (*c*); dust emissions from Sahara desert (*d*).

aerosol fractions agree with the data set obtained experimentally. More detailed retrieval of the aerosol microstructure requires increase of the information content of lidar measurements. It can be achieved by applying an additional channel for recording Raman scattering.

3.2. Estimation of the effect of large-scale transport on the characteristics of the aerosol layer

Investigation of the large-scale temporal and spatial variations of the aerosol component of the atmosphere and the role of the processes of trans-regional transport in the formation of the characteristics of aerosol layer over the regions in CIS is the priority scientific problem of the CIS-LiNet project. The technique for estimation of the effect of the large-scale transport on the characteristics of aerosol was developed on the basis of joint analysis of the data of regular lidar and radiometric measurements and back trajectories of the air mass transfer.[11,16,17] The technique was tested in analyzing the results of observations in 2002–2003 at the station in Minsk.

Transport of air masses to the region of Minsk was described by 5-day back trajectories calculated for the Minsk station by T. Kucsera and A. Thompson (NASA/GSFC). The set of back trajectories was divided into several subsets uniting "close" trajectories upon certain criteria using the cluster analysis. The measurement results on the aerosol parameters were also divided into the corresponding subsets according to coincidence of the time of observation with the time of realization of the back trajectories. Then the statistical analysis was carried out of the measurement results in the selected subsets.

The results of joint analysis of the back trajectories and the data of radiometric measurements are shown in Fig. 3. The subsets of back trajectories at three pressure levels (950, 850, and 700 hPa) were determined for this case. Each subset united the trajectories, the projections of which onto the horizontal plane for all three levels were close to each other. Thus, seven subsets were determined, the mean trajectories of which are shown in Fig. 3. The subset mean values of the measured characteristics are also shown here as a polar diagram. They are proportional to the radius-vector directed to the corresponding trajectory.

The mean values of the total content of fine and coarse aerosol particles are shown in Fig. 3*a*, and the estimates of the fluxes of aerosol particles of two fractions are shown in Fig. 3*b*. The results of analysis

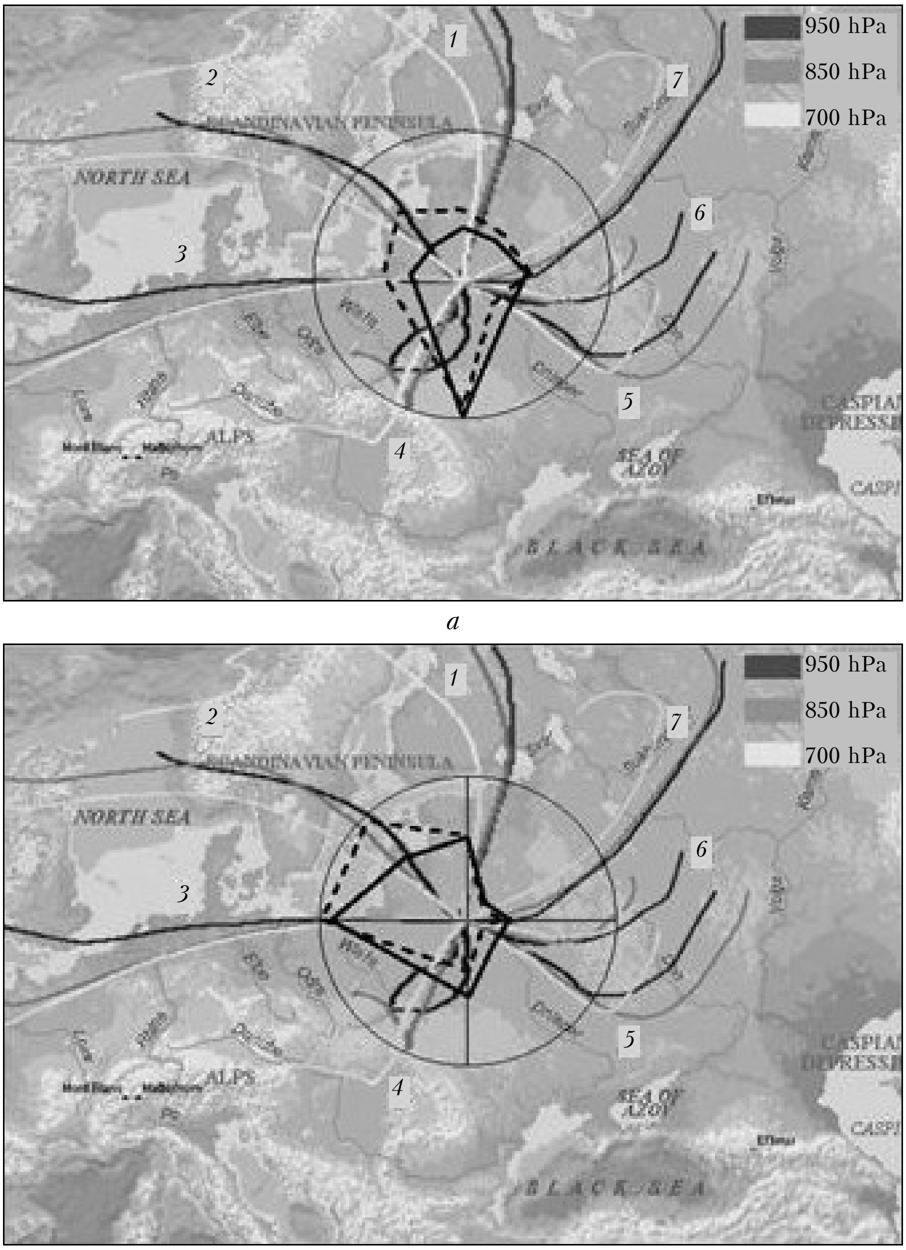

Fig. 3. Distributions of the mean values of the total content (*a*) and fluxes (*b*) of fine (solid line) and coarse (dotted line) particles depending on the trajectory of transfer (*1–7*) for the region of Minsk.

show that the highest concentration of aerosol particles is observed in the region of Belarus at southerly transfer from South-East Europe. At the same time, the total fluxes of aerosol substance are mainly determined by the transfer from western and north-western European regions because of predominant westerly air mass transfer. These data agree with the results from Ref. 16 generalizing the data of EARLINET.

Conclusion

In the second half of 2005, all stations of the CIS-LiNet have started regular measurements. Simultaneously, development of the software and improvement of the lidar instrumentation are continued. The results obtained at the network are available at the http://www.cis-linet.basnet.by website.

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