Anomalous aerosol scattering in atmosphere above Tomsk in autumn–winter of 2006–2007

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Long-term lidar observations have shown somewhat increased aerosol concentration in the autumn–winter of 2006–2007 in the lower stratosphere above Tomsk (56.5°N; 85.0°E). The integral aerosol scattering exceeded 2–3 times the many-year mean value of the reference period 1997–2006. At the end of January, 2007, at a height of about 19 km a distinct aerosol layer with the scattering ratio in its maximum up to 1.6 was recorded. The analysis of the aerosol pollution dynamics allows us to attribute this phenomenon to eruption products of Mt. Rabaul (Papua, New Guinea: 4.3°S; 152.2°E), the emission height of which on October 7, 2006 reached 18 km. The background state of the stratosphere aerosol layer in conditions of the long volcanically quite period 1997–2006 was violated, that should be taken into account when analyzing long-term trends in variations of the stratosphere aerosol content. Dust aerosol clouds in the beginning of February, 2007 were recorded at heights 5–8 km above Tomsk. This can be attributed to dust storms in Kazakhstan or even in farther south-west desert areas.

Introduction

Networks of lidar stations are widely used now in the world for investigating regional peculiarities of atmospheric aerosols. Measurements of aerosol, ozone, and temperature are mainly carried out by means of lidars at the most wide network of discovering stratospheric changes (NDSC). The European aerosol lidar network (EARLINET) includes 22 lidar stations for investigations of the transfer processes of aerosol pollutions, including the Sahara dust, in the atmosphere over Europe. The network of lidar stations of CIS countries "CIS-LINET" was built in 2004. It unites six stationary lidar stations in Russia, Belarus, Kirgizia, including the Siberian Lidar Station of the Institute of Atmospheric Optics, Tomsk, Siberian Branch of the Russian Academy of Sciences.[1]

Regular lidar measurements of the stratospheric aerosol layer (SAL) characteristics were started at the Siberian Lidar Station in January, 1986. Main results of investigations of the SAL background state under conditions of long-term volcanic-quiet period are presented in Refs. 2–4. Relatively stable long-term structure of SAL was formed during this period under the effect of chemical, radiative, and dynamic factors.

Since 1997, scattering characteristics of stratospheric aerosol (SA) had stable average values (over this period of observations) with periodic seasonal and quasi-biannual cycles of variations due to dynamic factors in the atmosphere. However, noticeably enhanced values of the scattering characteristics were recorded from the end of October, 2006 to February, 2007.

In the first section of the paper we present the description of the dynamics of anomalous aerosol scattering in the stratosphere over Tomsk for the long background period and discuss the volcanic origin of such scattering.

Regular observations of the tropospheric aerosol behavior at a height of 5 km and higher are carried out at SLS throughout two years. We consider the episodes of anomalous aerosol scattering in the troposphere, which was observed in February, 2007, in the second section. The well pronounced aerosol layers at heights of about 6 km can be attributed to dust emissions from Kazakhstan or even from farther desert regions of Middle East or Northern Africa.

1. Traces of the stratosphere disturbance caused by aerosol of volcanic origin

Regular sensing of SAL characteristics is carried out at a unified wavelength of 532 nm, that makes it possible to compare the measurements at the worldwide network of lidar stations. We receive lidar signals by the mirror of 0.3 m diameter and record them in the photocurrent pulse counting mode. To estimate qualitatively the particle size spectrum, the sensing is carried out simultaneously at two wavelengths: 532 and 355 nm since the end of 2006; 355 nm is the third harmonics of the basic frequency of the Nd:Yag laser radiation. The technical specification of the lidar complex is presented in detail in Ref. 5.

The vertical profile of the aerosol backscattering coefficient $\beta_\pi^a(H)$ was determined in the height range H from the laser sensing data. As the height increases, its values decrease following the exponential law. The scattering ratio is used for more distinct representation of the aerosol stratification

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$$R(H) = \left[\beta_\pi^{a}(H) + \beta_\pi^{m}(H)\right] / \beta_\pi^{m}(H), \quad (1)$$

where $\beta_\pi^{m}(H)$ is the molecular backscattering coefficient.

The integral aerosol backscattering coefficient B_π^{a} at the given height range between h_1 and h_2 gives the most complete pattern of temporal dynamics of the aerosol filling of the stratosphere:

$$B_\pi^{a} = \int_{h_1}^{h_2} \beta_\pi^{\alpha}(h)\, dh. \quad (2)$$

The methodical problems of retrieval of the SAL optical characteristics were considered in Ref. 6. The lidar measurement error increases with the sensing height because of decrease of the lidar signal from big heights. In our measurements, the error in measuring $R(H)$ within height range 10–20 km changes from 3 to 4%, and then grows to 6.5% at a height of 30 km. The error in determining B_π^{a} is no more than 5%.

The explosive volcanic eruptions are the main source of stratospheric aerosol, which, in average, contains the sulfuric acid water solution of 75%, at which the sulfur-containing gases (mainly, sulfur dioxide) come directly to the stratosphere and form there sulfuric acid vapors through a series of chemical reactions. The volcano-origin aerosol determines the SAL state during long time. According to data of SA balloon-borne size distribution measurements with optical particle counters during 1971–2001 in Laramie, Wyoming (41°N, 105°E), the volcanoes determined the aerosol content for 20 years from 30 years of observations.[7]

Three periods of the SAL background state with minimum of the volcanic activity effect and SA content are usually selected from the whole period of observations[7,8]: 1978–1980, 1988–1991, and from 1997 to now. These periods were observed after a several-year relaxation of global aerosol disturbances in stratosphere, caused by three greatest explosive volcanic eruptions in tropic zone: Fuego (14°N, 91°W, October 1974, total mass of sulfuric-acid SA generated after the eruption was 3–6 Mt),[7] El-Chichon (17°N, 93°W, March–April 1982, 12 Mt), and Mt. Pinatubo (15°N, 120°E, June 1991, 30 Mt). Estimates of the SA total mass in the background periods are 0.6–1.2 Mt.[9] Less significant eruptions can occur between the large ones, when the SA mass increases from one to tens of percent as compared to the background aerosol mass. Relaxation of the aerosol disturbance in the stratosphere after such eruptions proceeds during several months, but nevertheless, it additionally contributes into the content of SA of volcanic origin and increases the total time of its relaxation.

The SAL background state observed since 1997 is determined by conditions of the long-term volcano-quiet period. Such period has been studied for the first time through regular long-term measurements, which allowed the term itself of the background SA to be defined; to determine the natural and anthropogenic sources of its generation; to develop and specify its seasonal and latitudinal models; and to determine the long-term trends of its variation.[2,4,7,8,10,11] In particular, it was shown that generation of new SA particles by homogeneous nucleation takes place mainly in the lower tropical stratosphere.[10,11] The main source for generation of ($H_2SO_4 : H_2O$) particles is the emission of sulfur dioxide and carbonylsulfide (COS, the gas of technogenic origin) from the ground surface. Although the emission of gas precursors of SA from the surface in mid-latitudes of the Northern hemisphere is higher than at the equator, the convection from the troposphere to the stratosphere in tropical zone is higher than in mid-latitudes, that stipulates the availability in tropics of the background SA reservoir.

Examples of profiles of the scattering ratio during this period (Fig. 1) illustrate the dynamics of the vertical aerosol filling of the stratosphere in September–February, 2007.

One of the examples (September 22) shows a typical autumn profile of the background period[3] with minimum and almost homogeneous over height aerosol content, with $R \sim 1.1$ at a sensing wavelength of 532 nm.

Then we consider the dynamics of the aerosol scattering characteristics at the same wavelength. The data of 355 nm sensing wavelength have a similar qualitative behavior, but with less $R(H)$ and B_π^{a}. For example, increase of the aerosol content in the lower stratosphere up to 22 km is observed on October 17 and 27, with increase of R in the lowest part up to 1.2–1.3, that is not typical for the long-term mean values of R (1.05–1.1) for the summer–autumn period.[3]

The enhanced R values, in comparison with the background long-term means, are kept in November with some variations. The R values in December–January are close to the background ones or insignificantly exceed their winter long-term means (1.15–1.2), which are greater than summer–autumn values. The latter is explained by intensification of stratospheric meridional transfer in winter, resulted in additional aerosol transfer to middle and high latitudes from the tropical reservoir.[3]

However, a significant increase of aerosol scattering was recorded again in the end of January. The R values in the lower stratosphere on January 25 and 27 reached 1.3 and 1.4, respectively. The well pronounced aerosol layer was formed on January 27 at a height of about 19 km, where $R = 1.6$. The enhanced R values in the lower part of the stratosphere (1.3–1.4) were kept in February, but pronounced aerosol layers were not observed.

General aerosol filling of the stratosphere is characterized by the integral aerosol backscattering coefficient B_π^{a}. In our case, it was calculated for a height range 15–30 km. The means of B_π^{a} in the background period 1997–2006 were at the level of $1.5 \cdot 10^{-4}\,sr^{-1}$ and did not exceed $2.5 \cdot 10^{-4}\,sr^{-1}$ in winter period of the maximal aerosol filling of the stratosphere. The B_π^{a} values in October, 2006 reached $3.3 \cdot 10^{-4}\,sr^{-1}$.

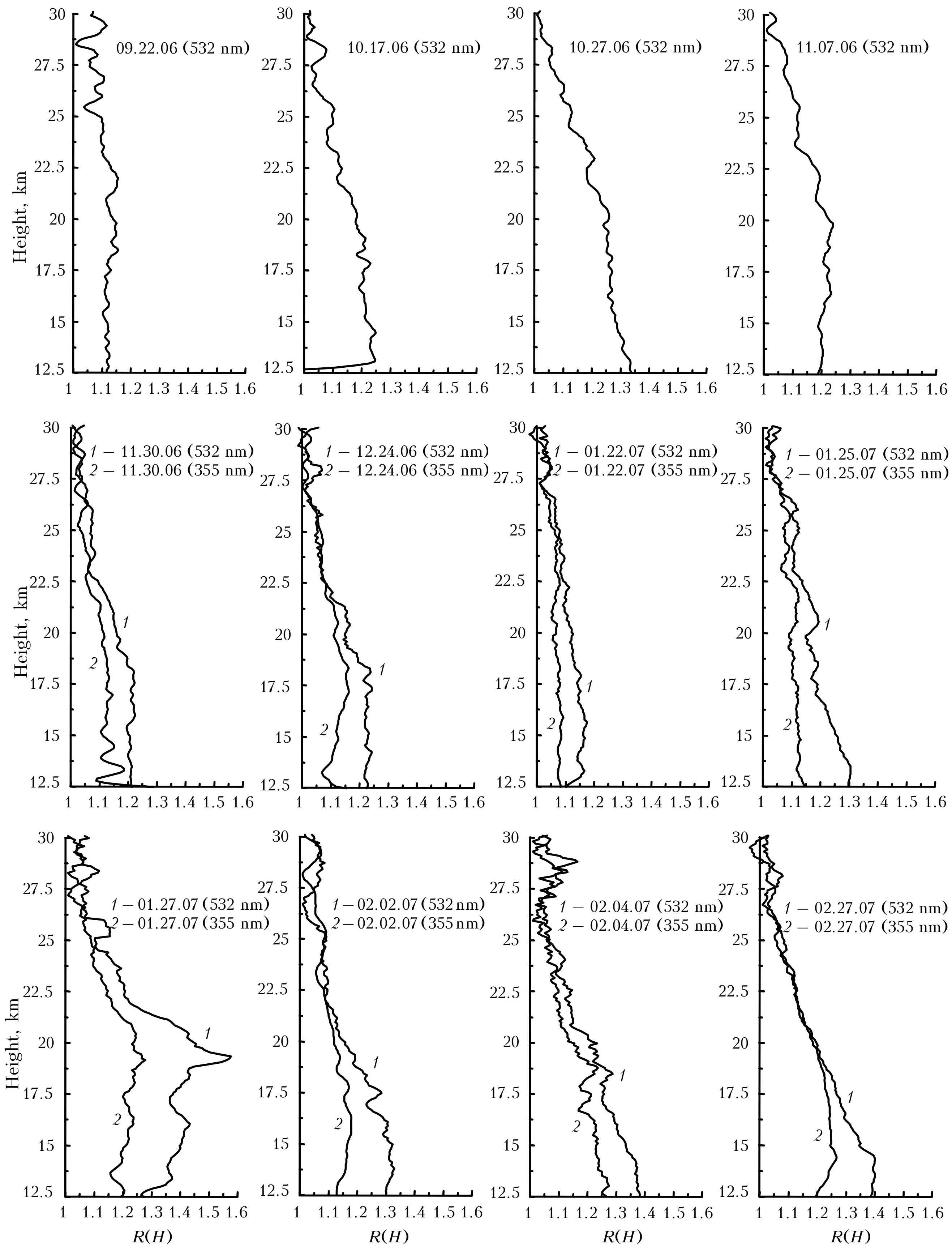

Fig. 1. Dynamics of vertical distribution of stratospheric aerosol during the period September, 2006 – February, 2007.

Mean values of B_π^a in the end of January – beginning of February were $3.2 \cdot 10^{-4}$ sr^{-1} and increased up to $4.6 \cdot 10^{-4}$ sr^{-1}, i.e., mean measured values were more than twice greater than the mean long-term values, and maximal values were almost twice greater than individual maximal values observed in winter 1997–2006.

The results of two-frequency sensing at wavelengths of 355 and 532 nm are also shown in Fig. 1. These results make it possible to qualitatively estimate vertical variations of the size distribution of scattering particles by means of the modified Angstrom parameter $X(H)$ [Ref. 6]:

$$X(H) = \frac{\ln\{[R(\lambda_1, H) - 1]/[R(\lambda_2, H) - 1]\}}{\ln(\lambda_1/\lambda_2)}, \quad (3)$$

where $\lambda_1 = 355$ nm, $\lambda_2 = 532$ nm. The increase of the $X(H)$ values, as a rule, characterizes a relative increase of the larger particle contribution into the total aerosol scattering.

The vertical profile of X, obtained on January 27, when the well pronounced aerosol layer was observed, is shown in Fig. 2. The X increase in range 19–20 km shows that particles of larger size are concentrated in this layer. Thus, particles of greater diameter in comparison with the particles of background aerosol below and above this layer are concentrated in the observed layer of anomalous aerosol scattering, i.e., these particles have a specific origin.

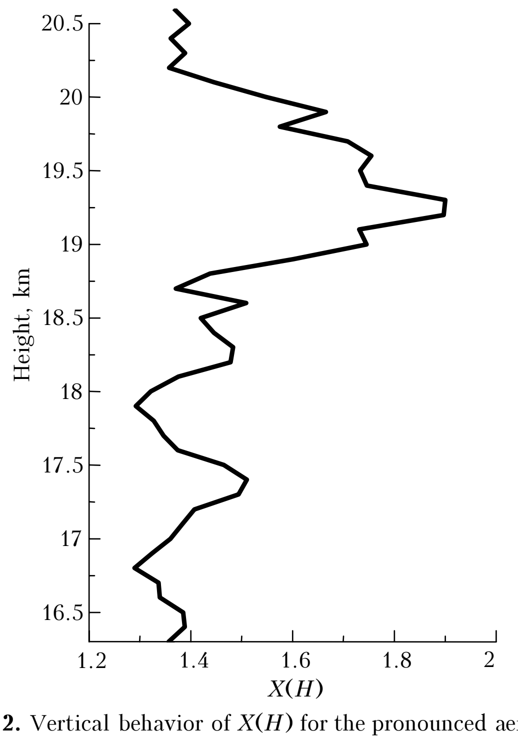

Fig. 2. Vertical behavior of $X(H)$ for the pronounced aerosol layer on January 27, 2007.

We interpret the results of observations of anomalous aerosol scattering in the stratosphere as follows. The eruption of the Mt. Rabaul in tropical zone (Papua, New Guinea, 4.3°S, 152.2°E) occurred on October 7, 2006. According to the data of observations at the volcano observatory Rabaul,[12] the eruption emission products reached 18 km (59 000 feet). According to this height, which exceeds the reference height of the tropical tropopause in October (16.3 km),[13] this eruption can be classified as explosive, because its products were emitted into the stratosphere. The data on the volcanic explosion index (VEI) are not published yet.

First traces of the volcanic aerosol cloud were recorded over Tomsk on October 17, 2006 as the increase of the SAL optical characteristics in the lower stratosphere. Further the aerosol content increased in October and remained enhanced in November and December. The aerosol scattering characteristics in January 2007 were close to the long-term mean values. But even a greater, in comparison with October – December, increase of aerosol scattering occurred in the end of January – beginning of February with recording the well pronounced aerosol layer at a height of about 19 km (the height of the Junge layer over Tomsk). Analysis of $X(H)$ shows that the increase occurred due to the particles of a greater size as compared to the background, i.e., particles of volcanic aerosol.

Such temporal dynamics of development of aerosol pollution of the stratosphere is related to the initial transfer of aerosol clouds of volcanic ashes injected into the stratosphere after the eruption, and the subsequent process of photochemical formation of sulfuric acid aerosol from the emitted gases containing sulfur (mainly, sulfur dioxide). Analogous pattern, but, naturally, on greater scales, was observed after powerful eruption of Mt. Pinatubo.[14] First traces of the volcanic cloud in the lower stratosphere were recorded over Tomsk in 2 weeks after the eruption. Further situation was characterized by periodic decreases and increases of the power of aerosol layers and their vertical motions. Maximal aerosol content in the stratosphere after Mt. Pinatubo eruption was observed over Tomsk and at other mid-latitude lidar stations in January – February, 1992, in 7–8 months after the eruption.

According to indirect signs, Mt. Rabaul eruption is somewhat weaker, but it is comparable with Del Ruis eruption in tropical zone (5°N, 73°E, November 13, 1985). In January, 1986, when first lidar observations at SLS were started, the well pronounced aerosol layer was recorded over Tomsk at heights of about 20 km with $R \sim 1.4$. Identification of aerosol clouds was possible in April, 1986. The B_π^a values did not exceed $4 \cdot 10^{-4}$ sr^{-1}. The R and B_π^a values were comparable with those recorded in January – February, 2007. One can expect that, analogously to Del Ruis eruption, the aerosol disturbance of the stratosphere caused by Mt. Rabaul eruption will terminate in spring 2007. Further measurements will enable obtaining the complete pattern of the development and relaxation of the stratosphere aerosol disturbance after the weak volcanic eruption.

Thus, it can be concluded that the enhanced aerosol content, recorded in the stratosphere over Tomsk in autumn – winter period 2006/07, is caused by the Mt. Rabaul eruption. The SAL background state under conditions of long-term volcanic-quiet period 1997–2006 is broken, and it is necessary to take into account this fact in analysis of the long-term trends of variations of the SA content.

2. Anomalous aerosol scattering in the troposphere in February, 2007

To study the relation between the aerosol distribution dynamics in the stratosphere and troposphere, first of all, the processes of stratosphere – troposphere exchange, a special instrumentation has been developed at SLS for obtaining the continuous profile of the aerosol vertical distribution in the stratosphere and troposphere from a height of ~ 5 km. It operates as follows.

The radiation flux of the optical lidar signals (sensing wavelength of 532 nm) is divided at the detector into two fluxes in the ratio of 95:5%. After the light-divider, the flux of the high-power signals is transferred to PMT with the electronic control for the amplification coefficient, which is switched on to the mode of recording from heights of ~ 10 km, therefore, signals from near zone are not recorded by this PMT.

The second PMT records the weak radiation flux of the lidar signals containing the data on the near zone (up to heights of about 15 km). Both signal fluxes are recorded simultaneously in the photon counting mode using the two-channel photon counter. The $R(H)$ profile in the stratosphere was firstly retrieved from the sensing data. This profile is related to the tropospheric profile in the part where they should coincide, close to 15 km. Thus, simultaneous measurements both in stratosphere and troposphere are carried out.

Some such profiles obtained in January – February, 2007 are shown in Fig. 3.

Measurements were carried out under clear weather conditions in the absence of cloudiness. It is seen in the profile obtained on January 25 that the values of R in the cloudless troposphere in the range of tropospheric heights of 5–10 km are approximately equal to 1.25. The aerosol layers were observed on February 2 and especially on February 4, when under cloudless conditions at heights of 5–8 km R increased up to 1.5 and even to 10.

Analysis of meteorological data of aerological sensing in Barabinsk, Novosibirsk, and Kolpashevo[15] shows that south-westerly wind was prevalent in that period at heights of 5–8 km. So, it can be supposed that the cause of appearance of the observed layers are intensive dust emissions from Kazakhstan and more far desert regions of Middle East or Northern Africa. Ministry of Emergency Situations of Russia relates fall-out of the “yellow” snow in the beginning of February in some areas of Omsk, Tyumen, and Tomsk regions with emissions of the Kazakhstan dust.

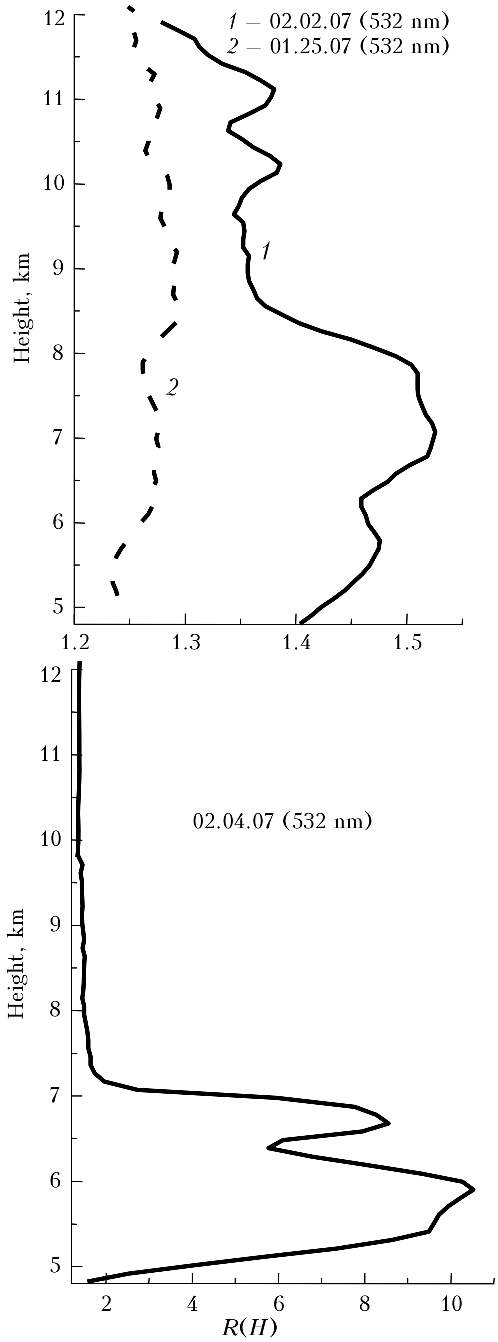

Fig. 3. Layers of dust aerosol in the troposphere in the beginning of February, 2007.

Conclusion

It has been revealed during long-term lidar observations that the enhanced aerosol content, recorded in the stratosphere over Tomsk in autumn and winter 2006/07, can be related with Mt. Rabaul eruption. The total aerosol scattering was 2–3 times greater than the long-term mean values in the period 1997–2006. The background state of SAL under conditions of long-term volcanic-quiet period 1997–2006 is broken, and it is necessary to take into account this fact when analyzing the long-term trends of variations of the SA content. Professor L.S. Ivlev predicted possible increase of the volcanic activity in island regions of South-East Asia at the XIII Workshop "Siberian Aerosols".[16]

Dust aerosol clouds were observed over Tomsk in the beginning of February at heights of 5–8 km. Their source can be dust storms in Kazakhstan or even in farther desert regions of the south-west direction.

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