# Lidar investigations of characteristics of background stratospheric aerosol over Siberian regions

**V.V. Zuev, V.E. Zuev, V.D. Burlakov, S.I. Dolgii,**
**A.V. Elnikov, A.V. Nevzorov, and V.L. Pravdin**

*Institute of Atmospheric Optics,*
*Siberian Branch of the Russian Academy of Sciences, Tomsk*

Received December 20, 2002

The paper presents and discusses some results of stationary and field lidar measurements of characteristics of the background stratospheric aerosol layer over Siberian regions from the middle to subpolar latitudes. The summer–fall period in the studied region is characterized by uniform distribution of stratospheric aerosol with its minimum content. Insignificant excess of stratospheric aerosol overburden in the winter–spring period, as compared with the summer–fall level, is due to specific features of the stratospheric circulation and distribution of reservoirs of the background aerosol.

## Introduction

As the background stratospheric aerosol, the aerosol of non-volcanic origin is considered, which determines the aerosol loading of the stratosphere in the periods of long-term absence of explosive volcanic eruptions. We can consider that during a few years of observations using the present-day ground-based and spaceborne measurement instruments the periods of background state of stratospheric aerosol layer (SAL) were recorded in 1979, 1989–90, and then starting from 1996. The sulfuric acid background aerosol is mainly formed as a result of transport to the stratosphere of relatively inert in the troposphere sulfur-containing gas of industrial origin carbonylsulfide COS. When appearing in the stratosphere, COS undergoes photodissociation to sulfur and after a series of chemical reactions forms vapor of sulfuric acid. As a supplementary source of background stratospheric aerosol (SA) the emissions of sulfur-containing gases of the high-altitude aviation, as well as the $SO_2$ as a product of industrial activity are considered .

The mass content of the background SA is tens times smaller than the aerosol mass over periods of volcanic perturbation of the stratosphere. Thus, after the most powerful in the 20th century eruption of Mt. Pinatubo (June 1991) the global mass ($H_2SO_4$–$H_2O$) of stratospheric aerosol was estimated from 21 to 40 Mt, while for the background periods the estimates were from 0.6 to 1.2 Mt (Ref. 1). In this case, the stratospheric aerosol optical thickness, which is considered as the main parameter determining the SAL effect on the radiation regime of the atmosphere and climatic effects,[2] is estimated, at the wavelength of 0.55 μm, for the Northern Hemisphere during background periods to be from 0.004 to 0.007, while after the Mt. Pinatubo eruption the optical thickness was 0.2.[1,3] In the periods of maximum aerosol load of the stratosphere significant radiation–temperature effects were recorded by direct measurements, i.e., a decrease of the surface temperature by a factor of several tenths of degree due to the scattering of shortwave solar radiation by volcanic aerosol and the temperature increase at altitudes of aerosol layer localization by a factor of several degrees due to the infrared radiation absorption of the outgoing radiation of the Earth.[4,5]

Considerable temperature variations can be caused by the background aerosol when its content is accumulated in the stratosphere as a result of the growth of industrial production. The hypothesis on the anthropogenic increase of the mass of background stratospheric aerosol up to 5% per year was proposed based on a comparison of aerosol content during background periods of 1979 and 1989–90.[6] According to the model calculations at annual 4.5% increase of the anthropogenic flux of carbonylsulfide in the stratosphere the optical thickness of stratospheric aerosol will increase by 2050 by more than one order of magnitude, and the mean ground temperature will decrease by 1.5° (Ref. 7). In connection with the problem of possible climatic results of the anthropogenic increase of stratospheric aerosol layer much attention is given to the investigations in this field.

A detailed knowledge is necessary of the nature, sources, characteristics, and dynamics of the background stratospheric aerosol. Besides, the background SA should be taken into account in model analysis of balance of small gas components of the atmosphere. Taking into consideration that the characteristics of the stratospheric aerosol layer have geographic peculiarities, seasonal and other cycles of variability, the long-term on a large spatial scale climatological studies of SAL are necessary. In this case it is possible, using the stratospheric aerosol as a tracer of dynamic processes in the lower stratosphere, to investigate processes of meridian transport in a wide range of its distribution.

0235-6880/03/02 111-05 $02.00

## 1. Technology and experimental procedure

For climatological research of SAL it is effective to use networks of lidar stations and mobile lidars in combination. In Tomsk at the Siberian Lidar Station of the Institute of Atmospheric Optics SB RAS the regular lidar measurements of SAL characteristics have been performed since 1986. At the same time, Tomsk is the only point on the vast territory of Siberia where these measurements are being carried out. A mobile lidar version has been developed by us to extend the geography of measurements.

The lidar has been developed on the basis of Nd:YAG laser of the Minsk firm "SOLAR LS." The measurements are conducted at the wavelength of 532 nm, the pulse energy is up to 150 mJ at the pulse repetition rate of 200 Hz. The absence of an external cooling contour makes it possible to use a laser under field conditions. The lidar design is of unit type that enables us to carry it by road to the place of measurement. The signals are received using a 30-cm-diameter mirror. The lidar can be used when it is installed on a river ship and under stationary conditions.

The first field measurements were made in July–August 2001 onboard a motor-vessel in the area of Omsk (55°N, 73°E). In October 2001 the measurements were made in Surgut (61°N, 74°E). In August 2002 the measurements were made in Norilsk (69°N, 89°E) on the territory of the Complex Magnetic-Ionospheric Station of ISTP SB RAS. During all the expeditions simultaneous measurements were performed of optical characteristics of SAL in Tomsk (57°N, 85°E) at a copper-vapor laser wavelength of 511 nm. The small difference in the used wavelength enabled us to compare the measured characteristics.

The measurements were taken at nighttime and the signals were recorded in the photon counting mode. From the laser sounding data at the height interval $H$ from 12.5 to 30 km the vertical profile of the aerosol backscattering coefficient $\beta_\pi^a(H)$ is determined. With the increasing height its values decrease following the exponential law. For obtaining a more pronounced aerosol stratification we use the scattering ratio $R(H)$:

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

where $\beta_\pi^m(H)$ is the molecular backscattering coefficient. Methodical problems in reconstructing SAL optical characteristics are considered in detail in Ref. 8.

## 2. Integral characteristics of the stratospheric aerosol layer

In lidar measurements the complete overall pattern of time dynamics of the aerosol load of the stratosphere is given by the integral aerosol backscattering coefficient $B_\pi^a$ within certain range of stratospheric heights from $h_1$ to $h_2$:

$$B_\pi^a = \int_{h_1}^{h_2} \beta_\pi^a(h)\,\mathrm{d}h. \qquad (2)$$

Figure 1 shows the time dependence of decadal mean value $B_\pi^a$ obtained in Tomsk since 1986. For a comparison the data of midlatitude station of Minsk are presented.[10] With the account of a certain difference in the height ranges of integration a coincidence of the results was observed that favors the concept of the global character of SAL distribution. We have analyzed the time dependence of $B_\pi^a$ until 2000 in detail in Refs. 9 and 10. The integral scattering before the Mt. Pinatubo eruption was observed already in 1996–97 and the values of the integral scattering became less than in the background period from 1989 to 1990. This paper considers mainly the results of the measurements in years 2000–2002. In 2000–2002 the value of $B_\pi^a$ during the summer–fall period decreases to minimum values of $5 \cdot 10^{-5}$ sr$^{-1}$ as compared with the mean values $(1.5–2) \cdot 10^{-4}$ sr$^{-1}$ in 1989–90. This fact does not confirm the hypothesis about the annual anthropogenic growth of background stratospheric aerosol that is observed at other lidar stations including those in industrial regions.[11,12]

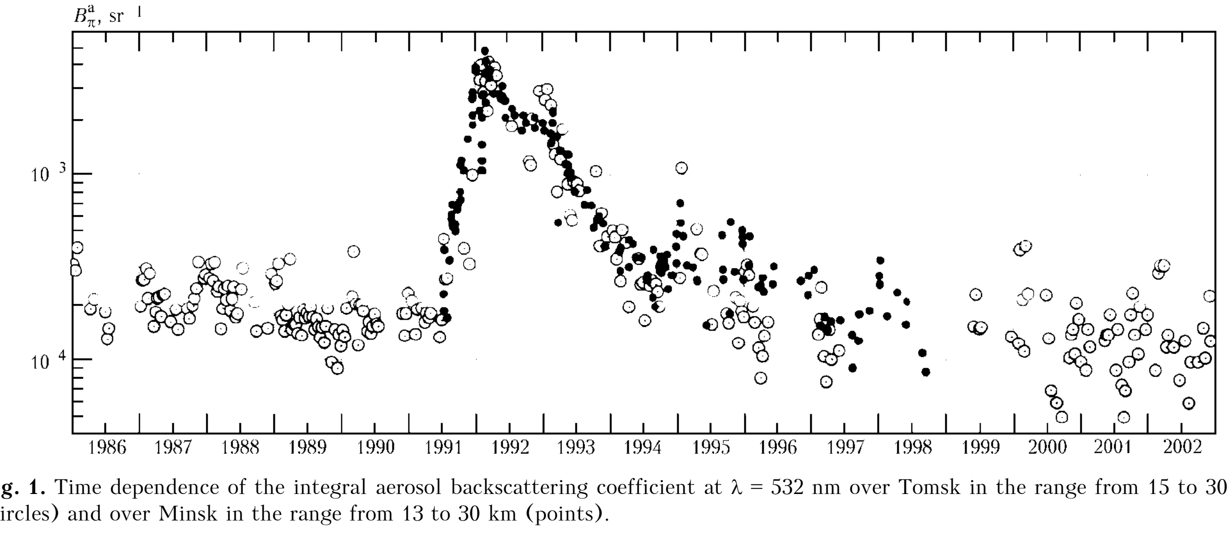

**Fig. 1.** Time dependence of the integral aerosol backscattering coefficient at λ = 532 nm over Tomsk in the range from 15 to 30 km (circles) and over Minsk in the range from 13 to 30 km (points).

The second peculiarity, which is seen from these measurements of $B_\pi^a$ in 2000–2002, is a lower aerosol load of the stratosphere during the summer–fall period as compared with the winter–spring period. This peculiarity can also be seen in a large number of the $R(H)$ profiles.

## 3. Vertical profile of the layer

Figure 2 shows examples of typical $R(H)$ profiles for different seasons in 2000–2002. Expeditionary and regular measurements in Tomsk have shown the identity of vertical distribution of stratospheric aerosol during the summer–fall period with the same aerosol content, characterized by the mean values of scattering ratio of 1.05–1.1 (profiles *4*, *5*, *6*, *9*, *10*, *11*, *12* in Fig. 2.) These values keep practically in the entire altitude range and no marked Junge layer is observed.

A possible explanation of the phenomenon of anomalous aerosol scattering in the altitude range from 25 to 30 km, which was observed in Norilsk in August 15, 2002 (the profile *11* in Fig. 2) and was of more pronounced in August 16, 2002 with the growth of the

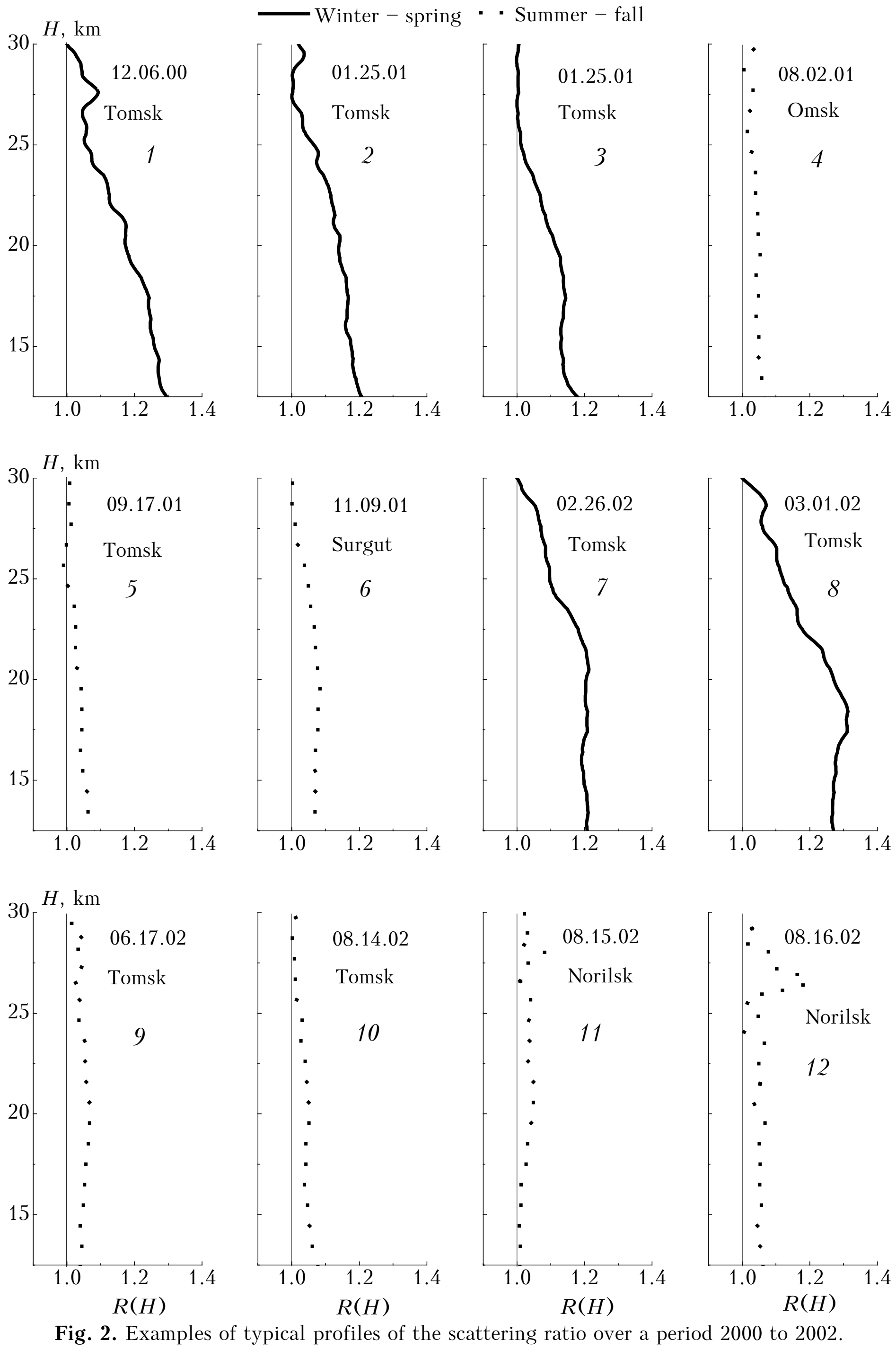

**Fig. 2.** Examples of typical profiles of the scattering ratio over a period 2000 to 2002.

scattering ratio in the layer peak up to 1.2 (profile *12* in Fig. 2) can be connected with the passage of meteor flux Perseids. This meteor flux is one of four most powerful ones observed annually. By some estimations, this meteor flux accounts for 5% of total cosmic matter reaching the Earth's surface annually. In 2002 the peak of meteor flux Perseids fell out on August 12–13. During measurements on August 7 and 13 the anomalous layers were not observed, i.e., the layers appeared in 3–4 days after the intensive phase of the flux that agrees with the data published by different authors[13] based on the observations of anomalous scattering in the mesosphere-stratosphere after the passage of meteor fluxes.

The obtained results point to the uniform character of the background state of SAL from middle to subpolar latitudes of Siberian region with minimum aerosol content in the summer–fall period. At the same time regular measurements in Tomsk indicate that in winter–spring period the aerosol load of the lower stratosphere (below 25 km) is higher than in the summer–fall period, with the $R(H)$ values increasing to 1.2 and more (profiles *1*, *2*, *3*, *7*, *8* in Fig. 2).

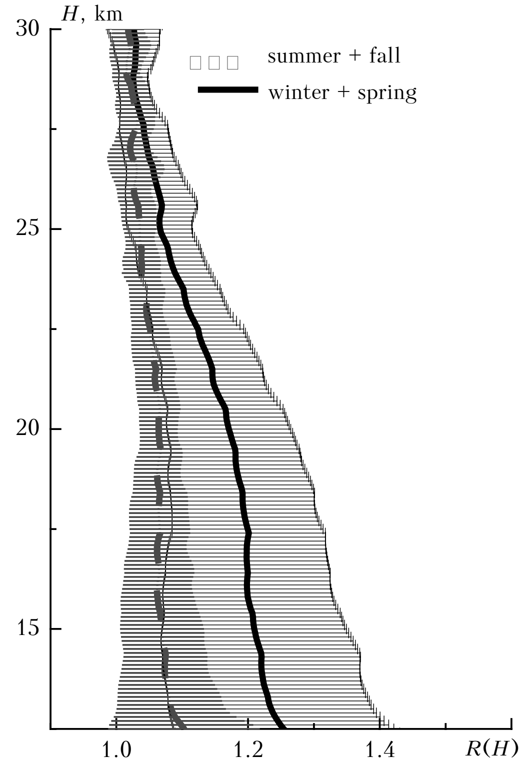

**Fig. 3.** Seasonal mean profiles [winter + spring/summer + fall) of the scattering ratio over a period from December 2000 to November 2002. Rms deviations and their limits are denoted by thin lines.

Based on averaging of the summer–fall $R(H)$ profiles, about 28 profiles, each of the profiles was obtained by averaging over 2 or 3 profiles recorded during one night, and of 31 profiles of the winter–spring period, the mean by half year (winter + spring/summer + fall) profiles of the scattering ratio were calculated. Data were taken over a period of measurements from December 2000 to November 2002. The results are shown in Fig. 3. For half a year, the summer–fall period, the values of $R(H)$ are in the range of 1.05–1.1 in the entire altitude range. The values of $R(H)$ of the winter–spring period, starting from 25 km altitude, exceed the summer–fall values, being increased in the lower layers up to 1.2. Nevertheless, within the limits of the root-mean-square deviation (RMSD) the mean profiles of $R(H)$ for both seasons coincide.

## 4. Discussion of the results and conclusions

Based on long-term lidar measurements of SAL characteristics, both under background conditions and under conditions of volcanic perturbation of the stratosphere it has been suggested by the authors to consider, as one of the criteria of the background state of the mid-latitude layer of the Northern Hemisphere, the absence of seasonal (winter–summer) distinctions in the vertical aerosol distribution.[9,10] Winter excess of aerosol content, due to intense winter meridian transport of volcanic aerosol to high latitudes from the torrid zone of active volcanoes, is smoothed out as the tropical stratosphere looses aerosol. The measurement data of 2000–2002 obtained under conditions of long-term (since 1996) background state of the stratosphere, which was not yet observed and investigated over the period of measurements using the present-day technical means, have supported the above criterion. Within the root-mean-square deviation the background seasonal mean profiles of $R(H)$ coincide.

Nevertheless, even under conditions of extreme background state in the lower stratosphere a slight excess remains of the aerosol content in the winter–spring period of intense meridian transport to high latitudes as compared with the summer–fall period. Taking into account the fact that the low-latitude gradient of potential vorticity determines the vigorous tropospheric–stratospheric exchanges mainly at the equator,[14] one can consider the torrid zone, its natural and anthropogenic sources, as one of basic reservoirs not only of volcanic but also of the background stratospheric aerosol.

A question of existence of tropical reservoir of background SA has been hotly debated. But the global models of SA spread, which are constructed on the basis of data of satellite measurements of the aerosol extinction coefficient (with conversion to aerosol optical depth) assume the presence of such a reservoir. At present such models show the structure of "zones" in the SA distribution with the maximum content inside the torrid zone and at high latitudes and with its minimum content inside the zone of 15–45° for both hemispheres, both for the period of volcanic perturbation and for the background conditions.[15,16] The structure of zones occurs mainly from the combination of 2 factors: (1) principal reservoir of aerosol is localized within the tropics, both in the background tropics and under conditions of volcanic perturbation of the torrid zone; (2) meridian transport of aerosol from the tropical reservoir, where the processes of tropospheric-stratospheric exchange are most active, to middle and high latitudes. The observed winter–spring increase of the background SA content is well within the limits of this model.

The results of stationary and field measurements show the uniform character of the background state of SAL from middle to subpolar latitudes of Siberian region with minimum aerosol content in the summer–fall period.

## Acknowledgments

The work has been supported by the Ministry of Industry and Science of Russian Federation (Reg. No. 01–64) and by the Russian Foundation for Basic Research (projects No. 01–05–64644 and No. 02–05–79082).

## References

1. P.B. Russel, J.M. Livingston, R.F. Ruelschel, J.J. Bauman, J.B. Pollack, L.L. Brooks, P. Hamill, L.W. Thomason, L.L. Stowe, T. Deshler, E.G. Dutton, and R.W. Bergstrom, J. Geophys. Res. D **101**, No. 13, 18745–18763 (1996).
2. A. Lacis, J. Hansen, and M. Sato, Geophys. Res. Lett. **19**, No. 15, 1607–1610 (1992).
3. M. Sato, J.E. Hansen, M.P. McCormick, and B. Pollack, J. Geophys. Res. D **93**, No. 12, 22.987–22.994 (1993).
4. M.P. McCormick, L.W. Thomason, and C.R. Trepte, Nature **373**, 399–404 (1995).
5. K. Labitzke and M.P. McCormick, Geophys. Res. Lett. **19**, No. 2, 207–210 (1992).
6. D.J. Hofmann, Science **248**, 996–1000 (1990).
7. M.L. Asaturov, Meteorol. Gidrol., No. 3, 5–12 (1998).
8. V.V. Zuev, A.V. El'nikov, and V.D. Burlakov, in: *Laser Sounding of the Middle Atmosphere*, ed. by V.V. Zuev (RASKO, Tomsk, 2002), 352 pp.
9. V.V. Zuev, A.V. El'nikov, and V.D. Burlakov, Atmos. Oceanic Opt. **12**, No. 3, 257–264 (1999).
10. V.V. Zuev, V.D. Burlakov, A.V. El'nikov, A.P. Ivanov, A.P. Chaikovskii, and V.N. Shcherbakov, Atmos. Environ. **35**, 5059–5066, (2001).
11. H. Jager and F. Homburg, in: *Abstracts of Papers at 19th ILRC,* Hampton, Virginia (1998), pp. 335–338.
*12.* G.S. Kent and G.M. Hansen, Appl. Opt. **37**, No. 18**,** 3861–3872 (1998).
13. O.G. Ovezgeldyev, M.F. Lagutin, M. Berkeliev, K. Kurbanmuradov, Kh. Mammedov, N.P. Mustetsov, C. Mukhamednazarov, and Yu. G. Megel, Izv. Akad. Nauk, Turkmen SSR, Ser. Fiz.-Tekh., Khim. and Geol. Nauk, No. 5, 51–56 (1981).
14. D.G. Andrews, J.R. Holton, and C.R. Leovy, *Middle Atmosphere Dynamics* (Academic Press, San Diego, Calif. 1987).
15. C.R. Trepte, L.W. Thomason, and G.S. Kent, Geophys. Res. Lett. **21**, No. 22, 2397–2400 (1994).
16. G.S. Kent, C.R. Trepte, and P.L. Lacker, J. Geophys. Res. D **103**, No. 22, 28863–28874 (1998).