Long-term trends, seasonal and anomalous short-term variations of background stratospheric aerosol

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Based on many-year (1986–2007) observations at Siberian Lidar Station of Institute of Atmospheric Optics SB RAS in Tomsk (56.5°N; 85.0°E), we identified the periods of background state of the stratospheric aerosol layer and determined the trends of variations the background, non-volcanic component of the stratospheric aerosol (SA). For the period 1999–2006, the weak negative trend is statistically insignificant. The content of the background SA in the long volcanically quiet period 1997–2007 does not suffer significant long-term changes under the impact of the natural or anthropogenic factors. It is possible to observe short-term (few-day) anomalous variations of SA content under impact of the natural factors. The seasonal variations of the content of background SA show pronounced behavior with maximum in the winter period and minimum in summer.

Introduction

The stratospheric aerosol (SA) plays a significant role in a number of processes, influencing the radiative, temperature, and chemical balance in the atmosphere, including the balance of gases of ozone cycles. These effects are particularly bright after powerful volcanic eruptions, when the mass of the sulfuric acid SA increases by the orders of magnitude and the direct measurements record considerable radiation-temperature effects.[1,2] The source of the nonvolcanic, i.e., background aerosol is the surface emission of the natural and anthropogenic sulfur-containing gases and primarily carbonyl sulfide (COS) and sulfur dioxide (SO_2) which, via a number of chemical reactions form in the stratosphere the sulfuric acid aerosol.

The knowledge of long-term trends of the background SA is required for determination and prediction of possible SA effects on the radiation and chemical balance of the atmosphere. For instance, by comparing the aerosol contents in the background periods 1979 and 1989–1990, the anthropogenic increase of the mass of the background SA up to 5% per year was hypothesized.[3] By the model estimates,[4] the SA optical mass would increase by 2050 by more than an order of magnitude, while the mean near-ground temperature would decrease by 1.5°. However, further detailed study of the background SA dynamics does not support this hypothesis.

At the Siberian Lidar Station (SLS) of Institute of Atmospheric Optics SB RAS in Tomsk (56.5°N; 85.0°E), the characteristics of the stratospheric aerosol layer are regularly measured with lidars since January, 1986. The main results of the study, obtained for Tomsk, as well as during field measurements in Siberian regions, are published in Refs. 5–8. In this paper, we consider the long-term trends of background SA content variations, as well as its seasonal, monthly averaged features and short-term anomalous variations.

1. Long-term trends of variations of integrated aerosol loading of the stratosphere

Figure 1 presents the time series of variations of the aerosol backscattering coefficient B_π^a, integrated in the altitude range 15–30 km. This quantity reflects the time dynamics of the total aerosol loading of the stratosphere. The measurements are made at a sensing wavelength of 532 nm, which is unified for a network of lidar stations and makes it possible to compare the observational results. The lidar signals are received by a mirror of 0.3 m in diameter; the signal are recorded in photocurrent pulse counting mode. The accuracy of the B_π^a measurements is no less than 5%. Technical description of the lidar complex can be found in Ref. 9. Each point data are averaged over the decada. For comparison, dots show certain measurement data for the midlatitude station in Minsk (54°N; 28°E).[6] In this paper, they are not analyzed. Also, no analysis is made for the period June, 1991–1996, because at that time the SA content was determined by the aerosol of volcanic origin (Pinatubo volcano).

Arrows show the volcanic eruptions of the tropical belt and midlatitudes of the Northern Hemisphere. The characteristics of the eruptions are given in Table, compiled from data of Ref. 10. Data on the time and height of the emission of the last eruption of the volcano Rabaul are available on the site of the Rabaul volcanic observatory.[13]

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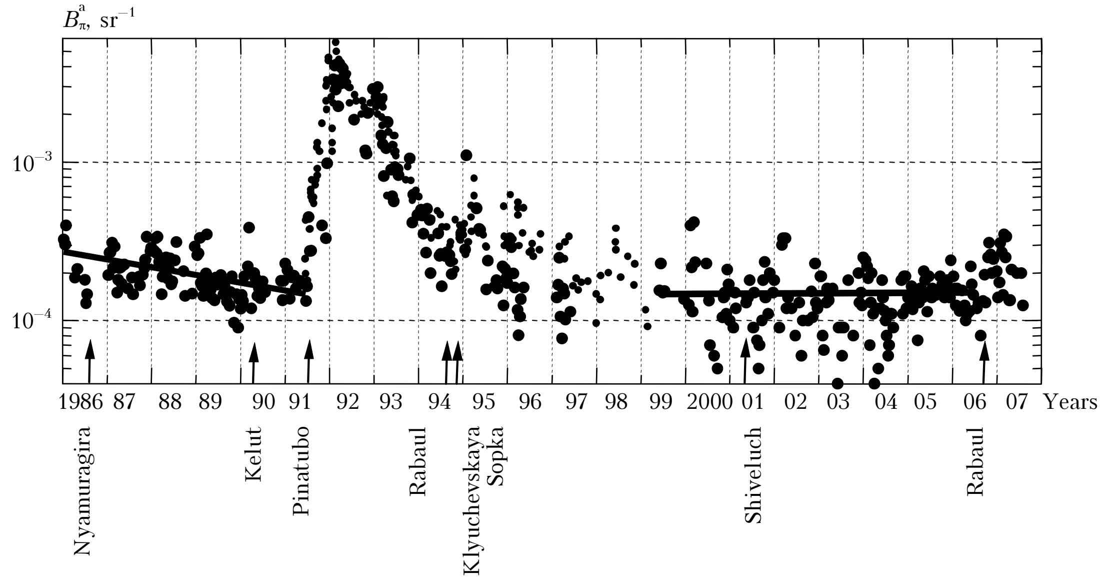

Fig. 1. Time behavior of integrated aerosol backscattering coefficient for the period 1986–2007.

Table. Chronology and characteristics of volcanic eruptions (VEI is the volcanic explosivity index)

Volcano	Coordinates, deg	Date	VEI	SO_2, Mt	Aerosol, Mt
El Chichon	17.0°N; 93.2°W	March – April, 1982	4	8.1	12
Del Ruiz	4.9°N; 73°W	November 13, 1985	3	0.66	–
Nyamuragira	1.4°S; 29.2°E	July 16, 1986	4	0.8	–
Pinatubo	15°N; 120.3°E	June 12, 1991	6(5+)	17–20	30
Kelut	7.9°S; 112.3°E	February 10, 1990	4	0.15	–
Rabaul	4.3°S; 152.2°E	September 19, 1994	4?	0.2	–
Klyuchevskaya Sopka	56.1°N; 160.6°E	October 1, 1994	4(3?)	0.1	–
Shiveluch	56.6°N; 161.4°E	May 22, 2001	4?	–	–
Rabaul	4.3°S; 152.2°E	October 7, 2006	4?	–	–

Data of this observatory suggest that the height of emission on October 7, 2006 reached the 18-km level, which exceeded the literature-based height of the tropical tropopause for October (16.3 km). Other characteristics of the eruptions are unknown to us yet. Eruptions which could have effect in Tomsk were taken from Ref. 11. Eruption products of the tropical belt spread with time throughout the globe, the products of the midlatitudes propagate in the hemisphere where the eruption took place, and those of the high latitudes – predominately by polar transport to the corresponding polar region. Moreover, the rate of the spread of the eruption products from the volcanoes of the tropical belt to high latitudes depends on the season and phase of the quasibiennial oscillation (QBO) of equatorial zonal winds. The transport from the tropical reservoir to the middle and high latitudes is intensified in the winter period and in the westerly QBO phase.[14]

The Table presents the volcanic Explosivity index (VEI) values: 3 corresponds to an emission height of 3–15 km, 4 corresponds to 10–25 km, and 5 corresponds to a height higher 25 km. In addition, for the characterization of the volcanic explosion, the amount of the emitted sulfur dioxide and the mass of the formed SA are also considered. The former is determined using the total ozone mapping spectrometer (TOMS) satellite instrument and the latter from measurements by Stratospheric Aerosol and Gas Experiment (SAGE) satellite instruments of the solar radiation extinction.

Measurements in Tomsk show with confidence that the remnants of Del Ruiz volcano were recorded in January – April, 1986, remnants of Pinatubo volcano in 1991–1996, and remnants of Rabaul volcano from October, 2006 to spring, 2007. This dynamics of development of aerosol perturbation by the last eruption was considered in Ref. 12. Figure 2 presents the dynamics of the stratospheric aerosol loading over Tomsk from the end of 2004 to spring 2007.

The smoothing procedure shows the presence of the enhanced aerosol content for about 5 months after the eruption. Fast increase of the stratospheric aerosol loading, noted in Tomsk, in 10 days after the eruption and subsequent its preservation are possibly associated with the fact that the time of the eruption and subsequent period were characterized by the westerly QBO phase of zonal tropical wind.

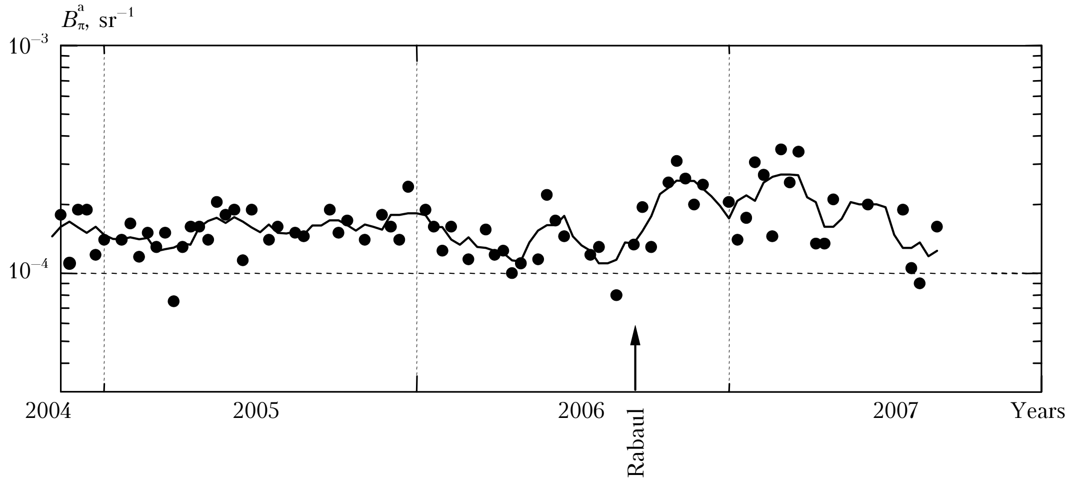

Fig. 2. Time dependence of the integrated aerosol backscattering coefficient over Tomsk in the height interval 15–30 km (dots); line shows 5-point smoothing for period 2004–2007.

In this phase, the meridional transport from the tropical belt to the midlatitudes intensifies.[14] Moreover, this transport was increased in the subsequent winter period of the observations.

This eruption affected the trends of SA content variations in the background period 1999–2006. The trends were calculated using linear regression of B^a_π, approximated by the straight line of the form $B^a_\pi = A + Bt$, where A and B are constants; and t is the time (in months). Trend for the last period 1999–2006 was found to be positive: $A = 1.42476 \cdot 10^{-4}$, $B = 4.79285 \cdot 10^{-8}$, $SD = 5.39 \cdot 10^{-5}$, the confidence probability $P = 0.84$, trend is $(0.4 \pm 4)\%$ per year. If to exclude from analysis data for October – December, 2006, when the presence of the volcanic aerosol was already noticeable, the linear approximation is defined by the values $A = 1.49816 \cdot 10^{-4}$, $B = -1.48511 \cdot 10^{-7}$, $SD = 5.11 \cdot 10^{-5}$, the confidence probability $P = 0.53$, and the trend = $(-1 \pm 4)\%$ per year.

For the period 1986–1990: $A = 2.5062 \cdot 10^{-4}$, $B = -1.50251 \cdot 10^{-6}$ for the $SD = 5.09 \cdot 10^{-5}$, $P = 0.0042$; the trend is $(-7 \pm 4)\%$ per year.

Thus, for the period 1986–1990, there is a pronounced negative trend in the SA temporal behavior, caused by the relaxation of the remnant aerosol after eruption of volcanoes El Chichon, Del Ruiz and, possibly, from weaker volcanoes Nyamuragira and Kelut. We cannot state that purely background, nonvolcanic SA component was present in the stratosphere in that period.

In the period 1999 – September, 2006, there was a weak, statistically insignificant negative trend. The aerosol loading of the stratosphere in this period was determined by the background, nonvolcanic component and experienced no significant long-term variations. The linear trends for the periods 1986–1990 and 1999 – September, 2006 are presented in Fig. 1 (straight lines).

The comparison of the levels of SA content in 1990 and after 1996 shows the absence of the anthropogenic increase of the background SA content.

2. Seasonal and anomalous variations in the level of the background stratospheric aerosol content

The seasonal (monthly mean) variations of the level of SA content were also determined for two periods free of significant volcanic eruptions, namely, 1986–1990 and 1999 – September, 2006. For technical reasons we have no data for the most part of 1997 and 1998, when the aerosol perturbation of the stratosphere after eruption of Pinatubo volcano had already relaxed.

Figure 3 presents monthly mean values of B^a_π for particular years of the two measurement periods, for sum of the two periods, and its averaged values over the corresponding period within the SD corridor.

General behavior of the curves shows the normal wintertime increase of aerosol content as compared to minimal summertime content. This takes place both under conditions of the volcanic perturbation of the stratosphere and under background conditions, therefore, it is associated with intensification of the meridional transport from the tropical belt to the midlatitudes in the summer period. As a result, the aerosol from the tropical reservoir arrives at the middle and high latitudes.

The question on the presence of the background aerosol tropical reservoir had long been debatable. The last models of the background sulfate aerosols, obtained using the atmospheric general circulation models with incorporation of the chemical processes show[15,16] that the formation of new particles by homogeneous nucleation takes place predominately in the tropical lower stratosphere. And, despite the fact that the emission from the surface of SA gas precursors (SO_2 and COS) in the midlatitudes of the Northern hemisphere is stronger than at the equator, the convection from the troposphere to the stratosphere is stronger in the tropical belt than in midlatitudes.

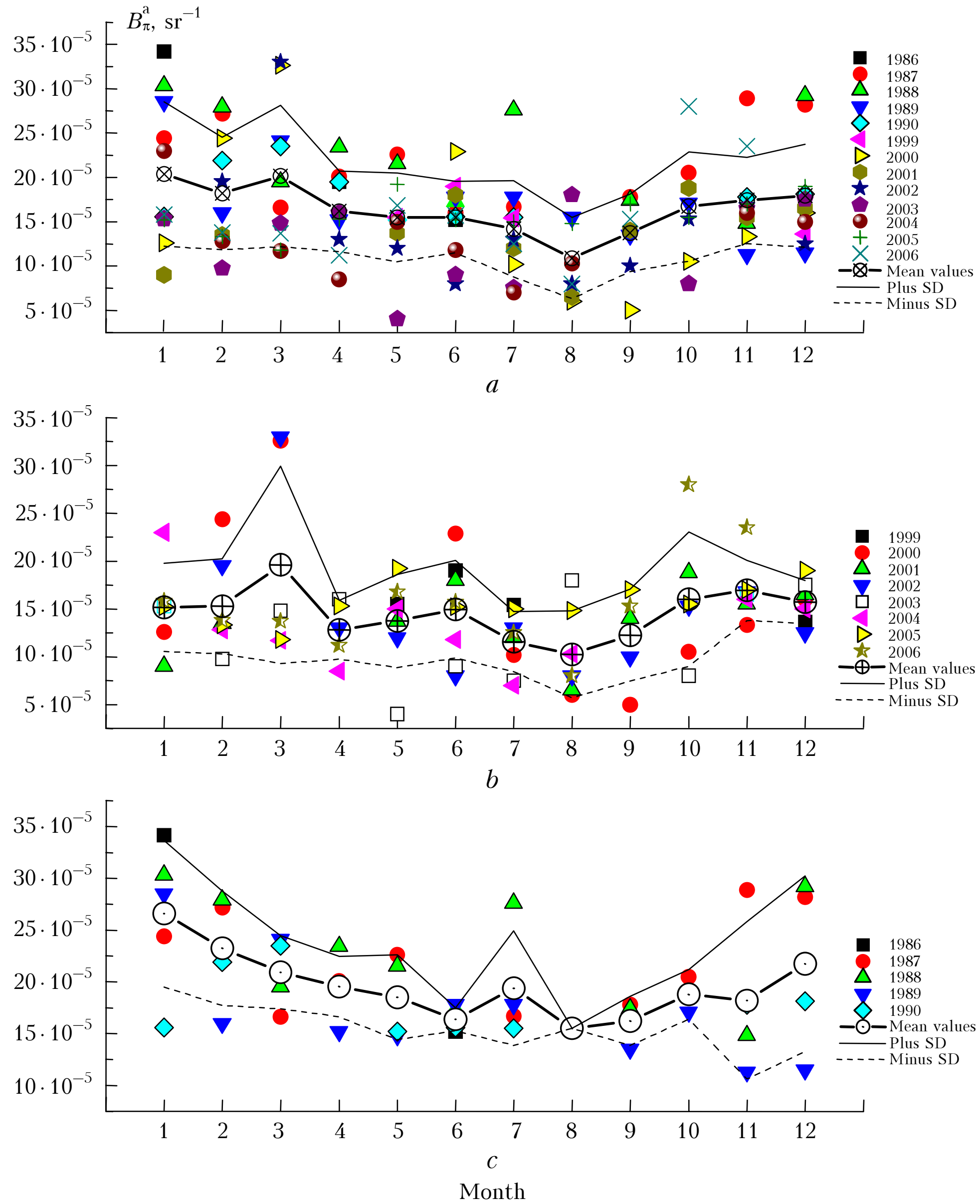

Fig. 3. Monthly mean values of the integrated aerosol backscattering coefficient for certain years of measurements and its values, averaged over the corresponding period in the SD corridor.

At the same time, in Fig. 3 certain anomalous deviations of B_π^a values are noticeable, exceeding the SD corridor. These deviations are transient (few-day) in character and may be associated with different physical processes in the stratosphere. For instance, in January, 1995 (see Fig. 1) we observed a rapid increase of the integrated aerosol scattering and well-defined aerosol layers at altitudes of 15–20 km. Qualitative analysis of sizes of the scattering aerosol particles, based on the data of two-frequency (532 and 1064 nm) sensing, as well as analysis of temperature regime of the stratosphere using data of aerologic sensing, has shown that the aerosol layers have the character of polar stratospheric clouds (PSCs).[18] Rare episodes of the wintertime PSC observations are also recorded at other midlatitude lidar observatories. In summer 2002, during field measurements in Norilsk at altitudes higher than 25 km, we observed well-defined aerosol layers, associated with passage of intense Perseid meteor shower.[7]

In Fig. 3*a* we clearly see the March deviations in period 1999–2006 (Fig. 3*b*) as compared to the period 1986–1990 (Fig. 3*c*). They were the result of the increased aerosol content in these months in 2000 and 2002. The process of formation of these anomalous aerosol layers at heights predominately higher than 20 km was considered in Ref. 17. Analysis has shown that their formation is associated with the processes of sudden stratospheric warmings.

The wintertime increases of SA content in 1986–1988 (see Figs. 3*a* and *c*) may be associated with the remnant volcanic aerosol (Del Ruiz and Nyamuragira) carried by air flows from the tropical reservoir. The increase of the aerosol scattering in October – December, 2006, as was already noted above, is associated with eruption of Rabaul volcano. We did not timely analyze some other short-time anomalous SA increases. In particular, July, 1988 (see Figs. 3*a* and *c*) and June, 2000 (see Figs. 3*a* and *b*), as well as some less significant episodes. Quite possibly, the summertime increases are also associated with the meteor showers.

For determination of the seasonal behavior of the background SA content, we used absolute monthly mean B_π^a for the period 1999–2006. In this case, the anomalous March, 2000 and 2002 values were reduced to the March-average values over the period 1999–2006. The B_π^a values for October – December, 2006 were excluded from analysis because they were influenced by the volcanic aerosol. The results of the calculations are presented in Fig. 4. To obtain a well-defined seasonal behavior, the smoothing procedure was applied two times by two. Also shown in Fig. 4 are SD corridors. There is a clear wintertime increase of SA content in comparison with summer one.

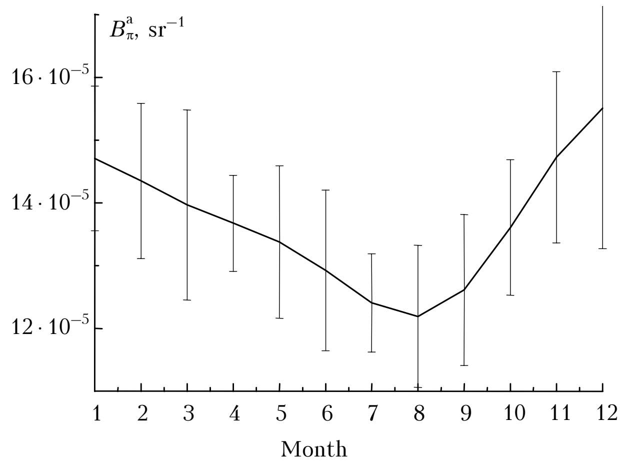

Fig. 4. Time behavior of the background monthly mean B_π^a values for the period 1999–2006. Error bars indicate the SD corridor.

Conclusion

For period of 1986–1990 observations in the stratosphere over Tomsk, there was a pronounced negative trend in the SA time behavior, caused by the relaxation of the remnant aerosol after eruption of volcanoes El Chichon, Del Ruiz, and, possibly, weaker volcanoes Nyamuragira and Kelut. We cannot state that purely background, nonvolcanic SA component was present in the stratosphere at that period.

In the period 1999 – September, 2006, there is a weak, statistically insignificant negative trend. The stratospheric aerosol loading in this period is determined by the background, nonvolcanic component and do not suffer any significant long-term variations under impact of natural or anthropogenic factors. This agrees with data of observations from SAGE satellite and network of lidar stations.[10] Under conditions of long-term background period, short-term (few-day) anomalous changes of SA content can occur under impact of some natural factor (meteor shower, PSCs, sudden stratospheric warming).

Comparatively weak eruption of Rabaul (October, 2007), the volcano of the tropical belt with volcanic explosivity index of 4 (determined from the height of the emission) already manifests itself in the general aerosol trend for period 1999–2006 in the stratosphere of midlatitudes in Tomsk.

The seasonal variations of the background SA content show a well-defined behavior with maximum in winter and minimum in the summer.

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References

1. M.P. McCormick, L.W. Thomason, and C.R. Trepte, Nature (Gr. Brit.) **373**, 399–404 (1995).
2. K. Labitzke and M.P. McCormick, Geophys. Res. Lett. **19**, No. 2, 207–210 (1992).
3. D.J. Hofmann, Science **248**, 996–1000 (1990).
4. M.L. Asaturov, Meteorol. i Gidrol., No. 3, 5–12 (1998).
5. V.V. Zuev, V.D. Burlakov, and A.V. El'nikov, J. Aerosol Sci. **29**, No. 10, 1179–1187 (1998).
6. 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).
7. V.V. Zuev, V.E. Zuev, V.D. Burlakov, S.I. Dolgii, A.V. El'nikov, A.V. Nevzorov, and V.L. Pravdin, Atmos. Oceanic Opt. **16**, No. 2, 111–115 (2003).
8. V.V. Zuev, V.D. Burlakov, A.V. El'nikov, and A.V. Nevzorov, Atmos. Oceanic Opt. **19**, No. 7, 535–539 (2006).
9. V.D. Burlakov, S.I. Dolgii, and A.V. Nevzorov, Atmos. Oceanic Opt. **17**, No. 10, 756–762 (2004).
10. T. Deshler, R. Anderson-Sprecher, H. Jager, J. Barnes, D.J. Hofmann, B. Clemesha, D. Simonich, M. Osborn, R.G. Grainger, and S. Godin-Beekmann, J. Geophys. Res. D **111**, 01201, doi: 10.1029/2005JD006089 (2006).
11. R.B. Stothers, J. Geophys. Res. D **101**, No. 2, 3901–3920 (1996).
12. V.V. Zuev, V.D. Burlakov, S.I. Dolgii, and A.V. Nevzorov, Atmos. Oceanic Opt. **20**, No. 6, 480–485 (2007).
13. http://www.volcano.si.edu/world/volcano.cfm?vnum=0502-14=&volpage=weekly&VErupt=Y&VSources=Y&VRep=Y&VWeekly=Y#oct2006
14. M.H. Hitchman, M. McKay, and C.R. Trepte, J. Geophys. Res. D **99**, No. 10, 20689–20700 (1994).
15. C. Timmereck, J. Geophys. Res. D **106**, No. 22, 28313–28332 (2001).
16. M. Takigawa, M. Takahashi, and H. Akiyoshi, J. Geophys. Res. D **107**, No. 22, AAC1/1–AAC1/11 (2002).
17. V.V. Zuev, V.D. Burlakov, A.V. El'nikov, S.V. Smirnov, and P.A. Khryapov, Atmos. Oceanic Opt. **13**, No. 11, 930–935 (2000).
18. V.V. Zuev, A.V. El'nikov, and V.D. Burlakov, Atmos. Oceanic Opt. **12**, No. 3, 257–264 (1999).