# Climatology of stratospheric aerosol and ozone according to data of multiyear observations at Siberian Lidar Station

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Received April 30, 2003

We analyze and generalize the data of multiyear lidar and spectrophotometric measurements of integrated characteristics of vertical distribution of stratospheric aerosol and ozone, obtained over 17 years at Siberian Lidar Station, Tomsk. We consider seasonal and quasi-biennial oscillation cycles of integrated and seasonal characteristics of vertical aerosol and ozone distribution at different heights in the stratosphere. Data of multiyear measurements, obtained at a single observation point, well reflect the global-scale stratospheric variations, associated with evolution of stratospheric general circulation.

## Introduction

It is necessary to take into account scattering and absorption properties of stratospheric aerosol and ozone layers in radiative blocks of the models of general circulation of the atmosphere, because they affect the processes of radiative transfer and thermal regime of the atmosphere. Also it is necessary to take into account variation of the stratospheric aerosol content in analyzing the balance of trace gases in the atmosphere, especially of those that are involved in the chemical cycles of destruction of the stratospheric ozone layer. Climatology of the stratospheric aerosol and ozone layers provides for the study of geographical peculiarities of their distribution as well as seasonal, annual, quasi-biennial, and other cycles of variability of their characteristics. Natural and anthropogenic factors affect the state of ozonosphere and stratospheric aerosol layer (SAL). They can exhibit short-time powerful disturbance (for example, explosion volcanic eruptions) or gradually accumulating effect, so climatological research could be fruitful in analyzing the long-term series of observations.

Regular lidar measurements of the SAL characteristics have been carried out at the Siberian Lidar Station (SLS) in Tomsk (56.5°N, 85.0°E) since 1986. Laser sounding of the ozone vertical distribution (OVD) in the stratosphere has been carried out at SLS since 1989, and regular monitoring of the total ozone content (TOC) since 1993 by means of the M-124 spectrophotometric ozonometer. Observations carried out in this period show the state of the stratosphere under conditions of its long-term disturbance due to the explosion eruption from Mt. Pinatubo in June, 1991) and its background states before and after the volcanic disturbance. The measurement data collected at one site mostly show global changes in the stratospheric circulation rather than regional peculiarities of the stratospheric variations. The results of these investigations have been summarized earlier.[1,2]

In this paper we consider seasonal and quasi-biennial cycles (QBC) of variability of the total aerosol content in the stratosphere and seasonal peculiarities of the aerosol vertical distribution. The elements of statistical analysis are applied. The seasonal mean profiles of OVD are calculated, and the seasonal variations of the ozone concentration at different heights are analyzed. Special attention is paid to analysis of data obtained in recent years of measurements in the so-called "new" background period characterized by long-term (since 1991) absence of explosion volcanic eruptions. Such a state of the stratosphere was not observed yet during the period of measurements by means of modern technical tools and was not studied. The data of lidar observations in other regions of Siberia obtained during field measurements in summer and fall of 2001–2002 in Omsk (55°N, 73°E) and Noril'sk (69°N, 89°E) are also considered in analyzing the stratospheric aerosol vertical profiles.

## 1. Long-term variations of stratospheric aerosol and ozone layers over Tomsk

The 11-year series of the total aerosol backscattering coefficient $\Sigma\beta_\pi^a$ obtained from the data of laser sounding of the stratosphere at the wavelength 532 nm is shown in Fig. 1*a*. This parameter is the aerosol backscattering coefficient $\beta_\pi^a$ integrated over the stratospheric height range (in our case from 15 up to 30 km). It characterizes the aerosol content in the stratosphere. It is seen in Fig. 1*a* that the aerosol content in the stratosphere in the aforementioned period of lidar observations underwent strongest variations after Mt. Pinatubo eruption in June 1991 with a well pronounced increase by almost two orders of magnitude in 1992 and slow decrease by the end of the presented period of observations. High variability of the values $\Sigma\beta_\pi^a$ in the considered

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period does not allow us to clearly distinguish seasonal and other cycles of their variations.

The part of the series of $\Sigma\beta_\pi^a$ since 1986 until 1991 with minimum variability is shown in Fig. 1*b*. Winter maxima and summer minima are well seen in the time behavior of $\Sigma\beta_\pi^a$ in Fig. 1*b*. The solid curve obtained by smoothing of seasonal variations by a 1-year window characterizes the quasi-biennial cycle. The QBC with the mean period of 28 months is related to almost yearly change of the direction of westward and eastward zonal wind in the stratospheric height range 20 to 40 km over equatorial zone to contrary one and modulates the stratospheric circulation as a whole. In this connection, it is accepted to divide the QBC to alternative eastward and westward phases. The time intervals of westward (W) and eastward (E) phases of QBC shown in Fig. 1 are determined based on the time series of the vertical section of monthly mean values of zonal wind speed at the level of 30 hPa (about 24 km) over Singapore (1°N, 104°E).[3] It is seen from Fig. 1*b* that eastward phases of QBC correspond to a decrease and minimum of aerosol content in the stratosphere, while the westward phases correspond to the increase and maximum of the aerosol content. Both seasonal and quasi-biennial cycles apparent in the behavior of $\Sigma\beta_\pi^a$ are related to changes in the stratospheric circulation, which determine the meridional transfer of stratospheric air masses from tropical zone to the middle and high latitudes.[4]

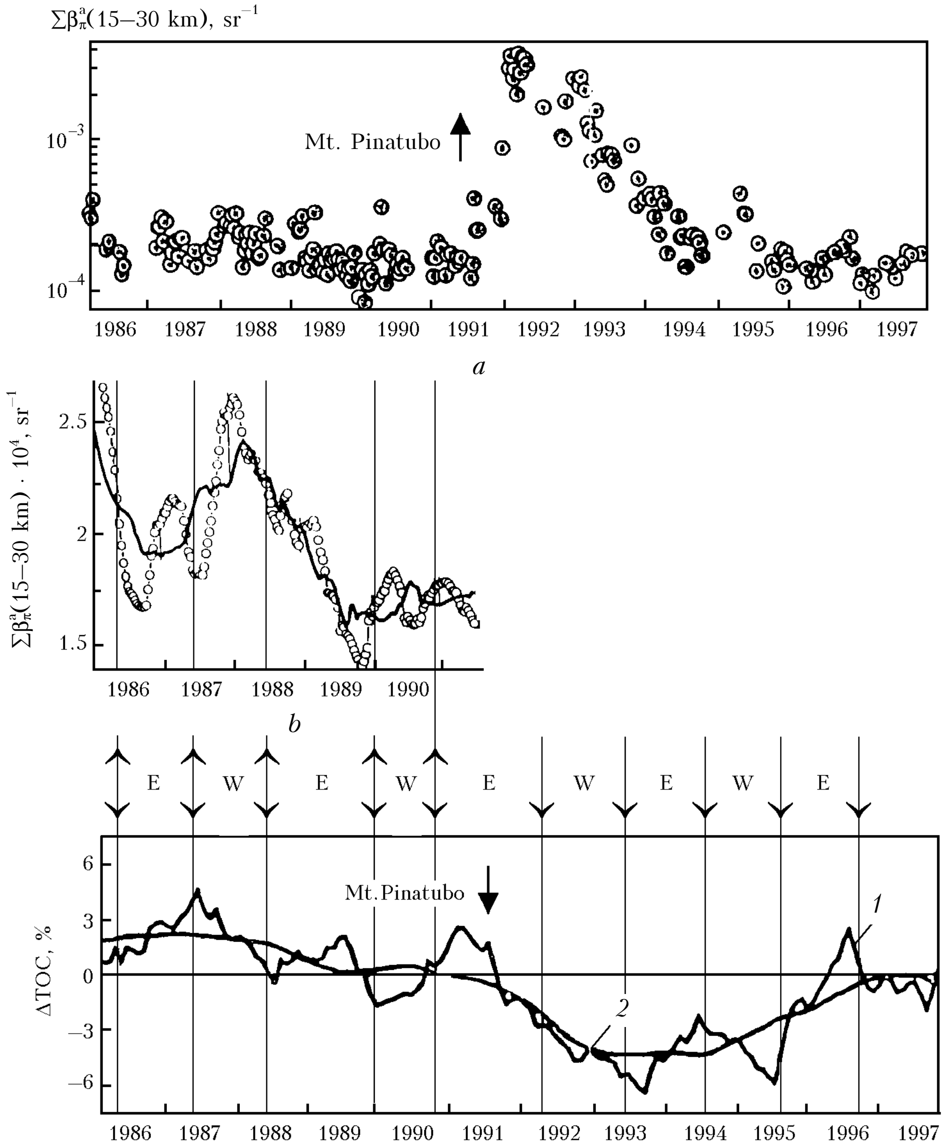


**Fig. 1.** Temporal variations of the aerosol content in the stratosphere and TOC over Tomsk in 1986–1997: general behavior of $\Sigma\beta_\pi^a$ (*a*), behavior of $\Sigma\beta_\pi^a$ in 1986–1991 (circles) and its smoothing by 1-year sliding average (solid curve) (*b*); deviations of monthly mean values of TOC relative to the long-term mean at smoothing by 1-year (curve *1*) and 2-year (curve *2*) sliding average (*c*). Arrows show the time intervals of westward (W) and eastward (E) phases of QBC.

Intensification of this transfer in winter and periods of the westward phase of QBC determines the peaks of $\Sigma\beta_\pi^a$ in the mid-latitude zone of Tomsk because of replenishment of the stratospheric aerosol from tropical reservoir.

The series of deviations of the monthly mean values of TOC from the long-term average smoothed using a one- and two-year sliding windows are shown in Fig. 1*c*. The series are compiled from the data of ground-based measurements of TOC over Tomsk by means of an M-124 ozonometer and the TOMS satellite data.[5] The effect of QBC is well seen in Fig. 1*c* with maxima of increase of TOC over Tomsk in the eastward phase and minimum or decrease in the westward phase. The same as aerosol, ozone in the low stratosphere of mid-latitudes is a passive tracer of circulation processes. Intensification of the meridional transfer of the stratospheric air masses from the tropical zone with the exhausted ozone content in the westward phase of QBC causes a decrease in TOC in the mid-latitudes, and its weakening in the eastward phase causes the TOC increase.

The series of the TOC deviations smoothed by a two-year window in Fig. 1*c* allows one to present most clearly the long period of stratospheric ozone depression correlated with the period of volcanic aerosol disturbance of the stratosphere over Tomsk after the Mt. Pinatubo eruption.

## 2. Stratospheric aerosol in the "new" background period

Minimum aerosol content in the stratosphere during the period of measurements by means of modern ground-based and spaceborne instruments were observed in 1979. Then during almost 20 years, the stratosphere was disturbed by volcanic aerosol produced by successive explosive volcanic eruptions such as El Chichon (1982) and Mt. Pinatubo. The Mt. Pinatubo eruption in 1991 was the last in this series. Subsequent sedimentation of volcanic aerosol resulted in a slow cleaning of the stratosphere and reaching the "new" background period in 1998. The mean values of $\Sigma\beta_\pi^a$ reached the level of 1979.

The values $\Sigma\beta_\pi^a$ obtained at SLS in Tomsk in "new" background period by laser sounding of the stratosphere at the wavelength of 532 nm are shown in Fig. 2. Indeed, the mean values $\Sigma\beta_\pi^a$ of about $10^{-4}$ sr$^{-1}$ reached the level of 1979, but the slope of the linear regression line is an evidence of the continuous process of decreasing the aerosol content in the stratosphere in the unique period of the long-term (more than 10 years) absence of volcanic disturbances of the stratosphere.

We have revealed[6] that the absence of significant differences (less than two of rms deviation) between seasonal (winter and summer) mean profiles of the scattering ratio $R(H)$ (the ratio of the sum of aerosol and molecular backscattering coefficients to the molecular backscattering coefficient) should be considered as a principal criterion of the background state of the stratospheric aerosol layer in mid-latitudes. The correctness of this criterion has been confirmed in the period of relaxation of the stratospheric disturbances after Mt. Pinatubo eruption.[7]

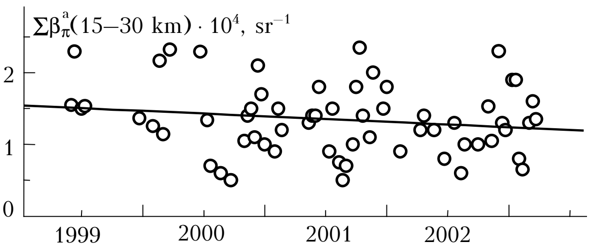


**Fig. 2.** Temporal behavior of mean values of $\Sigma\beta_\pi^a$ in "new" background period. The straight line shows the linear regression.

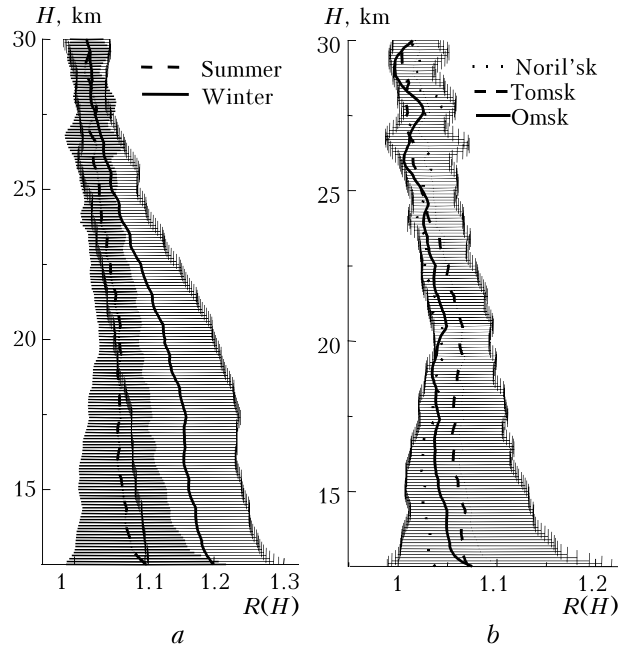


**Fig. 3.** Stratospheric aerosol vertical distribution over Tomsk during 2000–2003: seasonal mean (summer and winter) profiles of $R(H)$ (*a*); examples of summer profiles of $R(H)$ in different regions of Siberia in the range of summer rms deviations for Tomsk (*b*). Rms deviations and their boundaries are shown by thin-line shading.

The mean profiles of $R(H)$ (winter and summer) in the stratosphere over Tomsk obtained from the results of lidar observations during the period since November 2000 until March 2003 are shown in Fig. 3*a*. Mean summer profile of $R(H)$ and its rms deviation were determined from 24 profiles obtained in 2001–2002. Forty two profiles obtained in 2000–2003 were used for determination of the mean winter profile and its rms deviation. It is seen that the rms deviation ranges of different seasons cross that corresponds to the principal criterion of the background state of the stratospheric aerosol layer.

As the continuous process of cleaning the stratosphere from aerosol passes, the seasonal mean profiles of $R(H)$ steadily approach each other. On the other hand, it is clear that seasonal differences in radiative and thermal state of the stratosphere always cause the excess (though insignificant) of the mean winter profile $R(H)$ over the mean summer one.

The background state of SAL is characterized by uniformity in the distribution of $R(H)$ not only in time but also on big space. Individual summer profiles $R(H)$ obtained not only in Tomsk but also in Omsk and Noril'sk at big distances of about 800 km to the west and 1400 km to the north from Tomsk are shown in Fig. 3*b*. These profiles not only fall into the range of summer rms deviation for Tomsk, but also are significantly similar to each other. It is evidence of the high homogeneity of the spatial distribution of SAL on great scales.

## 3. Climatology of stratospheric ozone in a background period

The long-term ozone depression caused by the same long disturbance of the stratosphere by volcanic aerosol after Mt. Pinatubo eruption finished by 1996. The background undisturbed period of the state of the stratospheric ozone layer continues since this moment until now. The mean annual profile of the ozone vertical distribution in the stratosphere over Tomsk obtained from the results of individual lidar observations at SLS since 1996 until 2003 is shown in Fig. 4*a*.

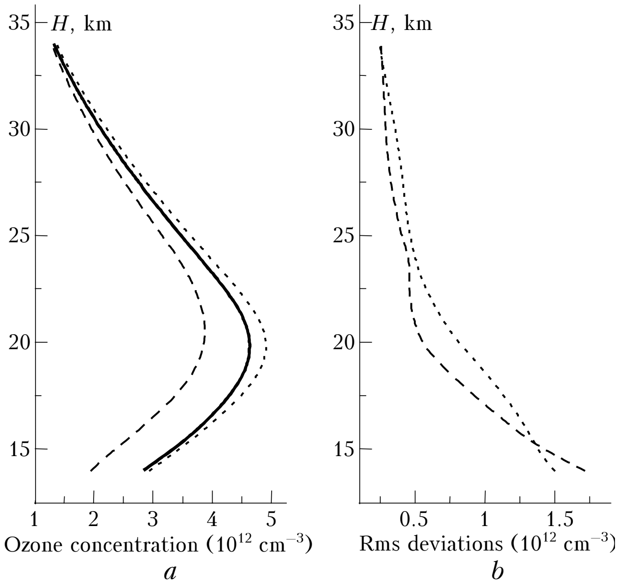


**Fig. 4.** Stratospheric ozone vertical distribution over Tomsk during 1996–2003: annual mean (solid line) and seasonal mean profiles of the OVD (spring – points, fall – dashes) (*a*); corresponding profiles of the rms deviations for spring (points) and fall (dashes) (*b*).

The seasonal mean profiles of OVD at spring maximum and fall minimum are also shown here, and the vertical profiles of OVD rms deviation in spring and fall are shown in Fig. 4*b*. Maximum of the stratospheric ozone layer over Tomsk occurred at the height of 20 km. The variability of the OVD is stronger in the lower stratosphere, and it is, on the average, higher during spring maximum than during fall minimum.

The histograms of seasonal variations of the ozone concentration at different heights in the stratosphere and the standard deviations determined from seasonal mean profiles obtained in 1996–2003 are shown in Fig. 5. It is well seen in Fig. 5 that maximum of the ozone concentration in the lower stratosphere (below 26 km) is observed in winter and spring, and maximum at the heights of 30 km and above is observed in summer. It reflects the dominant effect of the dynamic factor on the changes in OVD in the lower stratosphere and the effect of photochemical factor at the heights of 30 km and above. The well-pronounced boundary between two ranges of the stratosphere is observed in the region of velopause (about 26 km), where the dynamic or photochemical process prevails. Seasonal variations of the stratospheric ozone concentration shown in Fig. 5 are in a good agreement with similar results presented in Ref. 8.

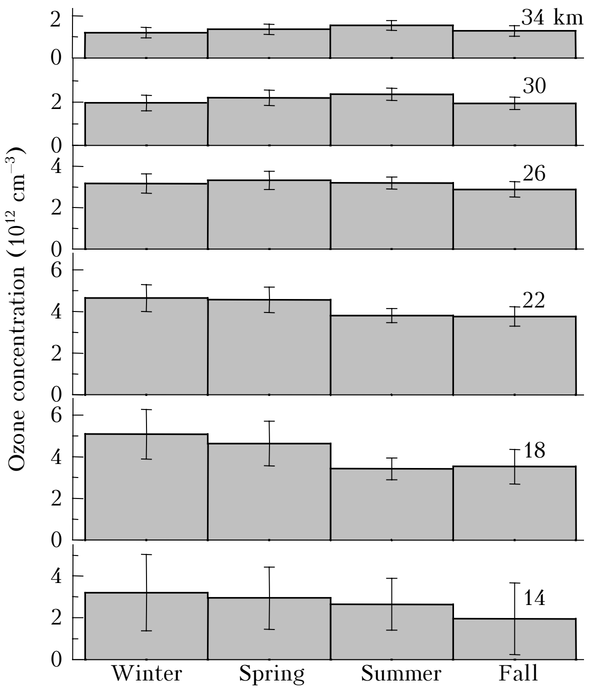


**Fig. 5.** Seasonal variations of the ozone concentration at different heights. Vertical lines in the upper part of the histograms show the rms deviations.

The mean annual profiles of OVD over Tomsk are shown in Fig. 6 in comparison with the mean profile for the entire period of observations 1996–2001. The height range near the maximum of the ozone layer (17 to 23 km) is specially shown in Fig. 6 to make clear the manifestation of QBC. It is seen that stratospheric ozone over Tomsk is strongly modulated by QBC in the range of its maximum that leads to quasi-biennial oscillations of the mid-latitude TOC (see Fig. 1*c*).

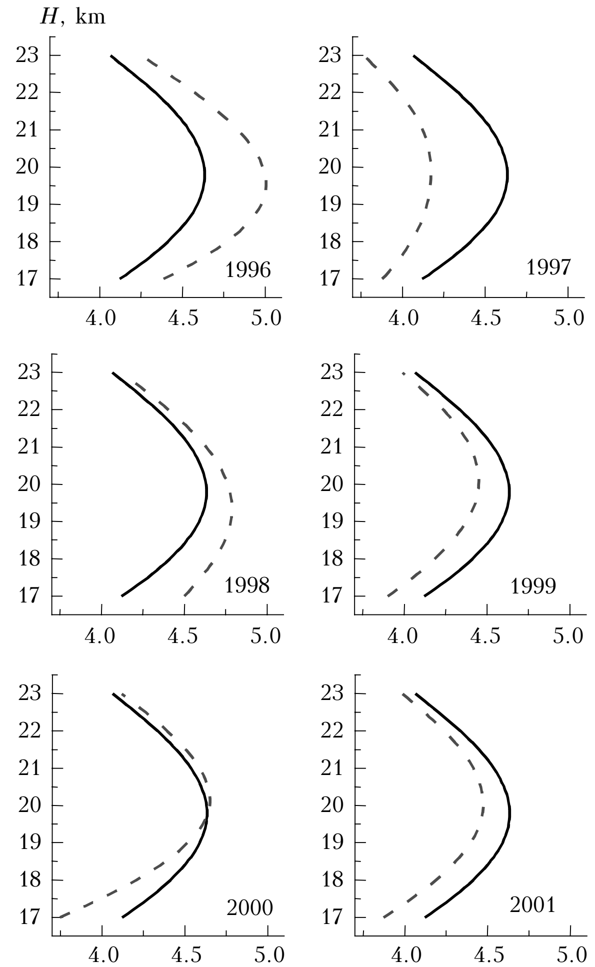


**Fig. 6.** Quasi-biennial oscillations of stratospheric ozone over Tomsk in 1996–2001 in the range of the maximum of the ozone layer: solid line shows mean over 1996–2001, dotted lines show mean over individual years.

# Conclusion

Long-term regular laser sounding of the stratosphere over Tomsk carried out at the Siberian Lidar Station during more than 15 years makes it possible to lead out investigations of stratospheric aerosol and ozone to climatological level. The long-term series of observation obtained at one site reflect the processes of planetary scale rather than the regional processes.

Aerosol and ozone in the lower stratosphere of mid-latitudes are the tracers of stratospheric circulation processes. Not only seasonal but also quasi-biennial cycles are seen in their behavior.

Of course, the most significant event during lidar observations was Mt. Pinatubo eruption in June 1991. Injection of a great amount of volcanic aerosol and sulfur gases into the stratosphere resulted in an increase of the aerosol content in the stratosphere over Tomsk in winter 1992 by almost two orders of magnitude. The aerosol disturbance of the stratosphere over Tomsk lasted during almost 5 years that caused the well-pronounced depression of ozonosphere in this period.

The "new" background state of the stratosphere observed in recent years at long-term absence of volcanic disturbances of the stratosphere makes it possible to reveal:

– high homogeneity of spatiotemporal distributions of the stratospheric aerosol. The process of cleaning the stratosphere from aerosol continues in all latitude zones.

– well-pronounced dependence of seasonal variations of the ozone concentration in the lower stratosphere (lower than 26 km) on the dynamic factor, and on the photochemical factor at the heights of 30 km and above. The height of velopause (about 26 km) is the boundary of these two ranges.

## Acknowledgments

The work was supported in part by Ministry of Science of RF at Siberian Lidar Station (reg. No. 01–64) and Russian Foundation for Basic Research (Grants No. 01–05–64644, No. 03–05–65105, No. 02–05–79082, and No. 03–05–79100).

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