Investigation of the quasi-biennial oscillations of aerosol and ozone content in the stratosphere over Tomsk during the period from 1986 to 2003

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Detailed analysis is presented of quasi-biennial oscillations in the time behavior of the integrated aerosol backscattering coefficient and the total ozone content over Tomsk. For analysis of time behavior of the aerosol characteristics, we used lidar-sensing data, while ozone variations were analyzed using measurements with M-124 instrument and TOMS spaceborne data.

Introduction

The concept of quasi-biennial oscillations (QBO) or quasi-biennial cyclicity (QBC) is connected with the variation, in the altitude range from 20 km to 40 km of the equatorial stratosphere, of the direction of east and west winds by the opposite direction with periods from 20 to 40 months (on the average about 28 months).[1] This phenomenon was detected early in the 1960 s.[2,3] It is generally accepted that the east and west phases of QBC are the periods with east and west directions of the zonal wind (D) at the 30-mbar surface (at an altitude of about 24.5 km). Because the equatorial zone is a generator of general circulation of the atmosphere, the phenomenon of QBC in the stratosphere must modulate the entire stratospheric circulation on a global scale. The ozone and aerosol are passive tracers of stratospheric circulation in the middle and high latitudes. Therefore it is reasonable that the variations caused by QBC were recorded later in the oscillations of both general ozone content[4] and aerosol optical thickness.[5]

The first results of joint analysis of the QBC in the oscillations of aerosol content of the stratosphere (ACS) and the total ozone content (TOC) over Tomsk were presented in Ref. 6. This paper presents some results of a detailed analysis of time data sets characterizing the ozone and aerosol content in the stratosphere over Tomsk and zonal wind velocity at the level of 30-mbar surface in the equatorial stratosphere over a long period starting from 1986 and until 2003.

The initial data and their preparation for correlation analysis

Aerosol content of the stratosphere from lidar data can be characterized by the value of the integral aerosol backscattering coefficient ΣB_a (sr^{-1}) in the form:

$$\Sigma B_a = \int_{15\,\text{km}}^{30\,\text{km}} \beta_{a\pi}(h)\,\mathrm{d}h, \tag{1}$$

where $\beta_{a\pi}(h)$ is the aerosol backscattering coefficient at the altitude h, its dimensional representation is [sr$^{-1}\cdot$ km^{-1}]; 15–30 km is altitude range, over which the integration is performed. This parameter is determined from data of laser sensing of the stratospheric aerosol layer (SAL).

At the Siberian Lidar Station (SLS) in Tomsk the laser sensing of SAL at the wavelength $\lambda = 532$ nm has been performed since 1986.[7] The time series of SAL in the form of monthly mean values is given in Fig. 1*a*.

The time segment of the series ΣB_a from January 1986 to July 1991 is characterized by a stationary state of the aerosol load of the stratosphere with weak winter maxima and summer minima and certain long-period variations (Fig. 1*a*). The behavior of SAL over a period of July 1991–December 1994 is of the pulse shape with a sharp leading edge (July 1991–January 1992) and with a subsequent smooth fall off of the values of ΣB_a (February 1992–December 1995) to the level observed in 1986–1991. Such a behavior of ΣB_a was conditioned by the presence in the stratosphere of mid-latitudes of the Northern hemisphere of volcanic aerosols after the Mt. Pinatubo eruption in June, 1991 on the Philippines. Over the period of 1996–2003 the behavior of ΣB_a is similar to that observed in 1986–1991.

The ozone content in the stratosphere dominates in its total content in the atmosphere (ΣO_3), therefore all the variations of TOC are determined mainly by variations of the ozone content in the ozone layer maximum in the lower stratosphere.[7] Regular observations of TOC at the SLS have been carried out since 1993 using an M-124 instrument. These observations show a good fit to the values of ΣO_3 obtained by TOMS spaceborne instrument for Tomsk location.[8] For example, the coefficient of

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correlation of TOC series measured at the SLS in Tomsk and using the TOMS instrument in the period from August 1996 to July 2002 is 0.95.[9] This enables us to extend a series of TOC observations over Tomsk retrospectively back to 1986 supplementing it by TOMS data.

This series of monthly mean values of ΣO_3 is shown in Fig. 1*b*. The TOC temporal series all the way can be considered stationary with the marked seasonal variations showing maxima during the winter–spring periods and minima during the summer–fall periods.

To smooth seasonal variations in the temporal series presented in Fig. 1, which are predominant, especially in the TOC time behavior, we used the procedure "moving average method" over 12 points (i.e., with a one-year "window"). Curves, obtained after the application of smoothing procedure to the appropriate initial temporal series are represented by heavy lines in Fig. 1. As a result, the variations are well manifested in periods more than two years (QBC) as well as other long-term variations. For example, in a smoothed temporal behavior of TOC the minimum is well-defined (in late 1991 – late 1995), which duration coincides in the time interval of the period of existence in the stratosphere of the volcanic aerosol that reduces the ozone content.[10]

Further preparation of original data for a correlation analysis was in arranging data in a series with zero mean and in leveling of strong perturbations of SAL and ozonosphere over the period from 1991 to 1995. For example, the procedure of removing the TOC pocket, due to a detrimental effect of the volcanic aerosol, was performed as follows. For a series ΣO_3 we used a 26-months fast Fourier transform filter (Φ_{26}), and further it was subtracted from a smoothed series ΣO_3:

$$\Delta O_3(t) = \Sigma O_3(t) - \Phi_{26}(t), \qquad (2)$$

where t is the time.

The absence of stationary parts in the ΣB_a series caused by the presence of aerosol of volcanic origin in 1991–1995 significantly complicates the approximation of its long-term variations by a unified function and its further subtraction from ideal values. Therefore, the series ΣB_a was subdivided into three independent time intervals (January 1986–June 1991; January 1992–December 1995; March 1996–December 2003).

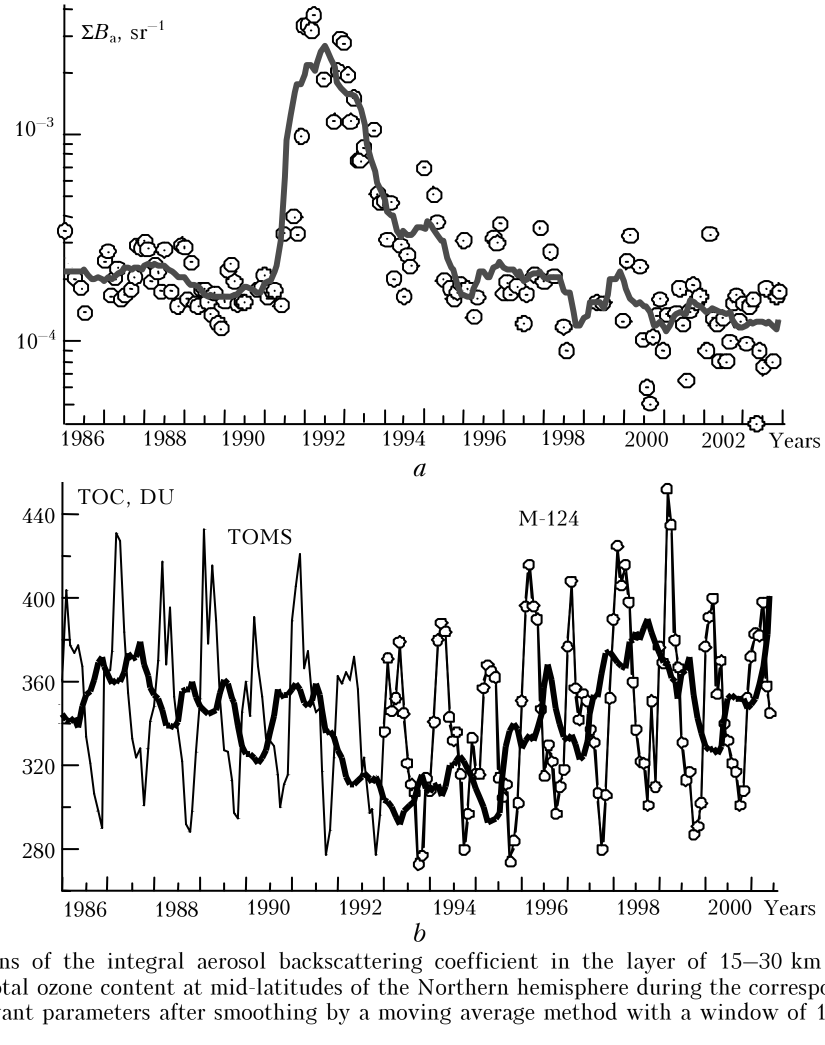

Fig. 1. Time variations of the integral aerosol backscattering coefficient in the layer of 15–30 km for the wavelength of 532 nm (*a*) and the total ozone content at mid-latitudes of the Northern hemisphere during the corresponding period (*b*). Time variations of the relevant parameters after smoothing by a moving average method with a window of 12 months are shown by heavy lines.

Taking into account the fact that ΣB_a, at the time interval of January 1992–June 1994, decreases by the exponential law,[11] its log values were taken. Within each of the three time intervals its linear trend was determined

$$\Lambda(t) = A + Bt, \tag{3}$$

which then was subtracted from data of the corresponding intervals:

$$\Delta \ln B_a(t) = \ln \Sigma B_a(t) - \Lambda(t). \tag{4}$$

The above leveled and reduced to zero mean series $\Delta \ln B_a(t)$ and $\Delta O_3(t)$ are shown in Figs. 2*a* and *c*, respectively. Besides, Fig. 2*b* shows the temporal behavior of deviations of the zonal wind velocity (ΔD) from the mean one at the altitude of 24.5 km in the equatorial stratosphere based on data taken from Ref. 12.

Figure 2 shows the parts of the time series ΔD denoted by letters E and W for the eastern and western zonal wind, determining the appropriate QBC phases.

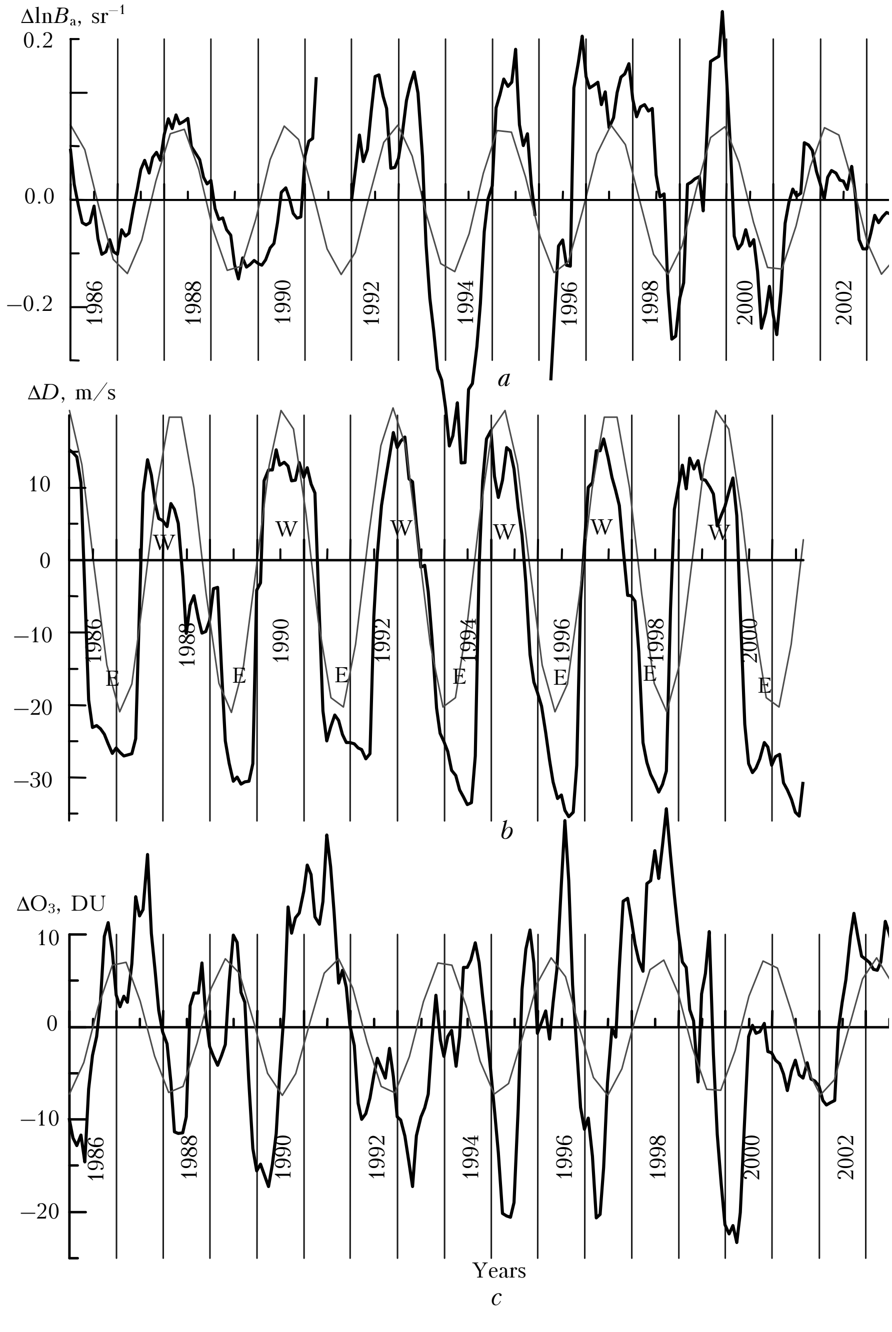

Fig. 2. Time variations of $\Delta \ln B_a$ (*a*), deviations ΔD of the zonal wind direction from the mean one (*b*), and ΔO_3 (*c*). Thin lines, superimposed on the presented series, show their approximation by the sine function.

It has been known that the variations of the stratospheric aerosol content (SAC) and TOC over Tomsk in different QBC phases are antiphase. In the case of the western phase the increase of SAC and the decrease of TOC are mainly observed, and in the eastern phase, on the contrary, the decrease of SAC and the increase of TOC are observed. Because the equatorial zone is the main global reservoir of stratospheric aerosol,[5] the increase of SAC in mid-latitudes of the northern hemisphere in the western phase of QBC should point to the strengthening of meridional mass transfer in the lower stratosphere from the south to the north from the equator to mid-latitudes. Such a strengthening of meridional transfer from the south to the north in the western phase of QBC should lead to the TOC decrease in mid-latitudes, because the equatorial stratospheric air masses have lower ozone content as compared with the mid-latitude air masses. It is precisely that sequence of events, which is shown in Fig. 2.

Fine curves in Fig. 2 illustrate the approximations of complete series of experimental data based on the method of least squares by functions of the following form:

$$Y(t) = A\sin\left(\pi\frac{t-t_c}{w}\right), \quad (5)$$

where t is the time in months; A is the amplitude, and w is the oscillation half-period; t_c is the phase shift (the same formula was used to approximate the series of experimental data within the three time subintervals but the obtained model series are not shown in Fig. 2 lest the figure be overloaded).

Results of correlation analysis and their discussion

Calculated results on the oscillation periods $2w$ and coefficients of determination R^2, representing a square of the correlation coefficients R between an empirical series and its model set by the formula (5), are given in Table 1. From Table 1 we notice that the oscillation periods of the entire model series for all the three parameters are the same (within the limits of the approximation error) and are ~ 27.8 months.

The best approximation of the series of empirical data was obtained for $\Delta D (R^2 = 0.65)$. The value ΔD is the characteristics of an equatorial generator of QBC and has the most regular structure of the series (Fig. 2*b*). For $\Delta\ln B_a$ and ΔO_3 the quality of approximation decreases ($R^2 = 0.37$ and 0.26, respectively). It is clear that the variations of these parameters are influenced by local impacts at the paths of transfer of aerosols and ozone in the mid-latitude stratosphere. Nevertheless, not only for ΔD but also for $\Delta\ln B_a$ and ΔO_3, values of the correlation coefficients R exceed greatly the level of significance (0.8, 0.6, and 0.5, respectively).

For shorter intervals, given in Table 1, the quality of approximation of time variations of all the three parameters by Eq. (5) was, as a rule, improved. The exception is the behavior of the series ΔO_3 within the interval from January 1992 to December 1995, where the aerosol of volcanic origin after the Mt. Pinatubo eruption made a great impact on the stratospheric ozone. On the other hand, a significant scatter in the oscillation periods was observed. In this case, the greatest scatter was detected during the period from January 1986 to April 1991 for oscillation periods of model $\Delta\ln B_a$ and ΔO_3 (37 and 23 months, respectively), characterized by the highest level of determination ($R^2 = 0.83$ and 0.52, respectively). This scatter is most probably due to a significant perturbation of the stratospheric circulation in the 1980s owing to a series of explosive volcanic eruptions (St. Helens, Alaid, Niamuragira, El Chichon, del Ruiz, etc.[4]) in different places over the globe. Aerosol particles are more massive than ozone molecules and therefore they are set in air flows in different ways, especially in vortex and wave motions (light ozone molecules are carried away by air flows totally, and more massive aerosol particles can fall out from vortices). The differences occurring for this reason in the trajectories and transfer velocities of aerosols and ozone in the stratosphere are enhanced at increasing perturbations.

Table 1. Variation periods ($2w$), coefficients of determination (R^2), number of points (n) and the significance of correlation coefficients at the level of 95% probability (r) of the relevant time intervals (calculations made for D were completed in August 2001)

	Entire series		January 1986 – April 1991		January 1992 – December 1995		March 1996 – December 2003	
	$2w$, months	R^2 n r	$2w$, months	R^2 n r	$2w$, months	R^2 n r	$2w$, months	R^2 n r
ΔD	27.8 ±0.1	0.65 188 >0.15	28.2 ±0.7	0.71 63 >0.25	26.4 ±0.2	0.91 48 >0.30	25.3 ±0.3	0.75 68 >0.25
ΔO_3	27.7 ±0.2	0.26 216 >0.15	23.0 ±0.6	0.52 63 >0.25	28.4 ±2.0	0.05 48 >0.30	27.4 ±0.4	0.31 96 >0.25
$\Delta\ln B_a$	27.8 ±0.2	0.37 204 >0.15	37.0 ±0.6	0.83 63 >0.25	33.8 ±1.2	0.73 48 >0.30	27.84 ±0.5	0.39 93 >0.25

Figure 3 shows the cross-correlation functions (CCF) (with the lag of 1 month) for all the combinations of time series of empirical data: ΔD and $\Delta \ln B_a$; ΔD and ΔO_3; ΔO_3 and $\Delta \ln B_a$. We notice that the behavior of CCF ΔD–$\Delta \ln B_a$ is antiphase to the variation of CCF ΔD–ΔO_3 and ΔO_3–$\Delta \ln B_a$, that was mentioned above at a qualitative consideration of Fig. 2. The values of all the coefficients of pair correlation at the zero lag for these three combinations of the series under study are significant and are 0.49; –0.34; –0.22, respectively.

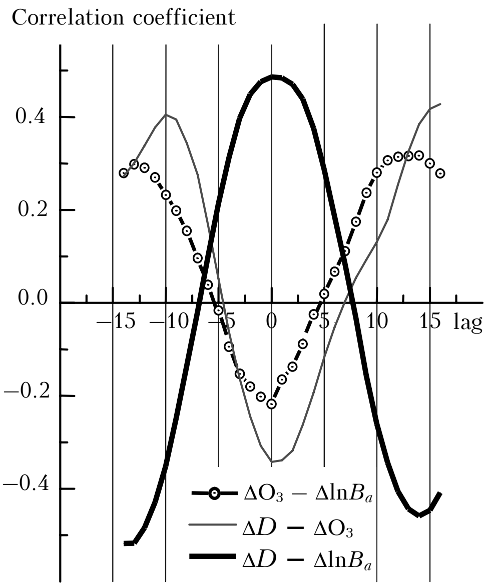

Fig. 3. Cross-correlation functions for the corresponding parameters.

Conclusions

Results of investigations have shown that in the time variation of the integral coefficient of aerosol backscatter and the total ozone content over the Western Siberia the oscillations are sharply manifested modulated by quasi-biennial cyclicity (QBC) of zonal wind in the equatorial stratosphere. In this case, in the western phase in the stratosphere over Tomsk the enhanced aerosol content and the reduced ozone content are mainly observed and in the eastern phase the contrary situation occurs.

When transporting aerosol particles and ozone along a meridional direction the QBC characteristics in the oscillation of SAC and TOC over Tomsk were distorted due to different entrainment of aerosol particles and ozone molecules, which differ essentially by mass. Differences of velocities and trajectories of transfer, in general, bear more information about specificity of stratospheric circulation and can be used for refinements of the trajectory analysis of the stratospheric air masses.

Acknowledgments

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