Vertical wind transport of aerosols in the stratosphere

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Received December 26, 2006

The latitudinal and seasonal dependence of vertical profiles of the vertical wind averaged for different time intervals from 1992 to 2006 based on the data of the UKMO general circulation model is analyzed. It is shown that monthly average amplitudes of the vertical wind are approximately ±5 mm/s, while annual average ones are ±1 mm/s. The upward wind can provide the vertical lifting against gravity for sufficiently large (up to 3–5 μm) aerosol particles with a density up to 1.0–1.5 g/cm^3 at stratospheric and mesospheric altitudes. The vertical wind probably is a substantial factor of particle motion up to altitudes of 30–40 km and can change essentially the sedimentation rate and the residence time of stratospheric aerosols. The structure of the averaged field of the vertical wind leaves room for formation of dynamically stable aerosol layers in the middle stratosphere.

Introduction

The wind is understood in meteorology as a motion of air relative to the Earth's surface. Horizontal components of this motion are usually considered, but the vertical component of wind is concerned as well. This component is usually much smaller than horizontal ones and more difficult to determine instrumentally. That is why it is mostly calculated in some or other way.[1]

It was noted in Ref. 2 that for description of vertical motions in the baroclinic atmosphere (that is, for description of the vertical wind), the following characteristics are equivalent: $\omega = \mathrm{d}p/\mathrm{d}t$ in the isobaric coordinate system (the so-called omega-characteristic of the vertical motion, in Pa/s) and $U_W = \mathrm{d}z/\mathrm{d}t$ in the absolute-height coordinate system (velocity of the vertical wind, in m/s). Assuming that wind ageostrophicity is low and using the hydrostatic approximation, it is possible to demonstrate that these characteristics are related, as follows from the continuity equation[2]:

$$\omega = \partial p/\partial t + V_\mathrm{a}\nabla p - g\rho U_W,$$

where p and ρ are the pressure and density of air at the height z; t is the time; g is the free-fall acceleration; V_a is the velocity of the ageostrophic wind at the height z; ∇p is the corresponding pressure gradient. The further estimates of parameters for motions of synoptic and global time scales allow this relation to be simplified[2] as

$$\omega = -(Mgp/RT)U_W, \quad (1)$$

where T is the temperature at z; M is the molar mass of air; R is the absolute gas constant.

There are two main methods to determine characteristics of the vertical wind from analysis of horizontal components of meteorological fields: kinematic and adiabatic.[2] The former is complicated by possible large errors in estimates of U_W, while the latter requires the knowledge of comprehensive data on meteorological fields, which are not always available in observations. At the early stages of investigations (see, for example, Refs. 3 and 4), the monthly average velocity of the vertical wind U_W were overestimated as units (and even tens) of mm/s. It was found that they vary with the season and height, and the wind velocity in the mesosphere is higher than in the stratosphere. The more recent development of ideas on mechanisms of the stratosphere–troposphere exchange[5] yielded refined values of the vertical wind velocity, which is estimated now as fractions of mm/s (see, for example, Ref. 6). As was noted in Ref. 2, the vertical wind velocity of units and fractions of mm/s is still much lower than the resolution of existing direct instrumental methods (ground-based or satellite). Thus, the vertical wind velocity is not usually measured directly, but should be obtained from other meteorological fields accessible for direct measurements.

The necessity of valid data on average seasonal, latitudinal, and vertical dependence of the vertical wind velocity is obvious. The vertical wind is efficiently taken into account in investigations of large-scale processes of transport of gas tracers, but in analysis of the motion of stratospheric aerosol particles this approach faces some principal difficulties. In particular, the Kasten model[7] is widely used in analysis of sedimentation of atmospheric aerosol particles. This model assumes that the atmosphere is static and stationary (free of vertical air motions), the vertical dependences of air and pressure satisfy the data on the standard atmosphere, and the resistance of the air medium to the motion of particles of different size and density under the effect of gravity is described by the well-known Millikan's empirical formula.[8]

0235-6880/07/06 492-07 $02.00

This scheme is obviously limited, but its replacement by a more adequate model is hindered due to the absence of a reliable and convenient database on dependences of the average (at synoptic and global scales) stratospheric vertical wind. Aerosol transport models often use rather rough approximations of vertical wind fields.[9–11]

Back-trajectory techniques are now popular in climatologic investigations. These techniques allow one to identify origins and trajectories of aerosols transported by air masses to a given geographic site through calculation by general circulation models (see, for example, Ref. 12). But even these techniques can hardly pretend to the reliable consideration of the vertical wind transport of aerosols: the emphasis in them is on the horizontal air mass transport (whose intensity is many times as high as that of the vertical transport); in addition, it is believed that even micron-sized aerosol particles follow flow lines similarly to gas tracer molecules.

Meanwhile, there are problems requiring the consideration of the vertical wind in analysis of the stratospheric aerosol transfer. These problems include, first, the phenomenon of migration of soot particles emitted by air transport against gravity to altitudes above flight corridors[13,14] and the growing pollution of the Arctic region with soot aerosol from ground-based burning of hydrocarbon fuel and biomass.[15,16] The action of forces of radiometric photophoresis can partly explain this phenomenon,[17] but the positive (upward) vertical wind may have even greater transport capabilities. Second, the action of the vertical wind on aerosol particles (reducing to the intensification or counteraction to gravitational sedimentation) can help in explanation of not fully clear details of the relative stability and long lifetime of well-known aerosol formations in the stratosphere (see, for example, Ref. 18).

This paper presents a new data array on average vertical wind velocities obtained from satellite measurements, as well as a tentative analysis of the influence of the vertical wind velocity component on the motion of aerosol particles in the stratosphere is performed.

1. Vertical wind field in the UKMO assimilation model

The UKMO (United Kingdom Meteorology Office) unified model is a large meteorological model taking into account atmospheric and ocean transport processes and their coupling. The atmospheric block of this model is assimilation, implied the method, in which the results of regular meteorological observations are included in the computational process to obtain estimates of the atmospheric state maximally close to the actual situation.[19] The data obtained in the stratospheric block – Met Office Stratospheric Data Assimilation System – are of primary interest for analysis.[20]

The regular measurements of required meteorological fields were conducted in 1991–2006 by the NASA UARS (Upper Atmosphere Research Satellite) satellite placed in a circular orbit at an altitude of 585 km. The UARS was equipped with two instruments allowing measurements of the horizontal wind components: HRDI high-resolution Doppler interferometer measured wind in the stratosphere, mesosphere, and lower stratosphere, while the WINDII interferometer conducted measurements at altitudes of the upper mesosphere and thermosphere.[21] The HRDI interferometer measured the components of stratospheric wind in daytime using the Doppler shift in the absorption spectrum of O_2 in reflected light. In measurements of stratospheric wind, the HRDI horizontal resolution was about 500 km, while the vertical one was about 2.5 km for altitudes of 10–40 km. The data were sorted by latitude, longitude, and standard pressure levels (geopotential height), which were determined as $p_i = 1000 \cdot 10^{(-i/6)}$ hPa, where i varies from 0 to 44. The latitudinal step in a range 80° S to 80° N was 4° [Ref. 21]. The HRDI operating principles and the technique of measurements and interpretation of data are described in detail in Ref. 22. The HRDI resolution allowed the direct determination of horizontal zonal and meridional winds up to altitudes of 60–65 km, but was insufficient for the direct measurement of the vertical wind velocity. Invoking the stratospheric block of the UKMO model, the quantitative estimation of the vertical stratospheric wind becomes possible, and this allows the detailed analysis of the vertical wind profiles and their latitudinal and seasonal dependences.

The database used (http://badc.nerc.ac.uk) contains a standard set of meteorological parameters (temperature, pressure, zonal, meridional, and vertical winds) for a certain period (days and months). The data are presented for UARS standard pressure levels from 1000 to 0.316 hPa (21 levels). This allows the vertical profiles of meteorological parameters to be obtained roughly up to 55 km with a horizontal resolution of 2.5° in latitude and of 3.75° in longitude. To retrieve the interesting information from this database, we used the capabilities of the FIRE-ARMS applied program package.[23] The data for the vertical wind velocity U_W were obtained through recalculation from $\omega = \mathrm{d}p/\mathrm{d}t$ by Eq. (1), and all the meteorological parameters necessary for this recalculation are already available in the database. It should be noted that today it becomes possible to use another database (NCEP/NCAR), allowing the reconstruction of vertical wind fields at different altitudes for the past many-year period.[24]

2. Results and discussion

Figure 1 shows the typical vertical wind profiles averaged for one month (equator, 0°N, 0°E). Analogous data can be also presented for other geographic regions for the period since September, 1992 till February, 2006.

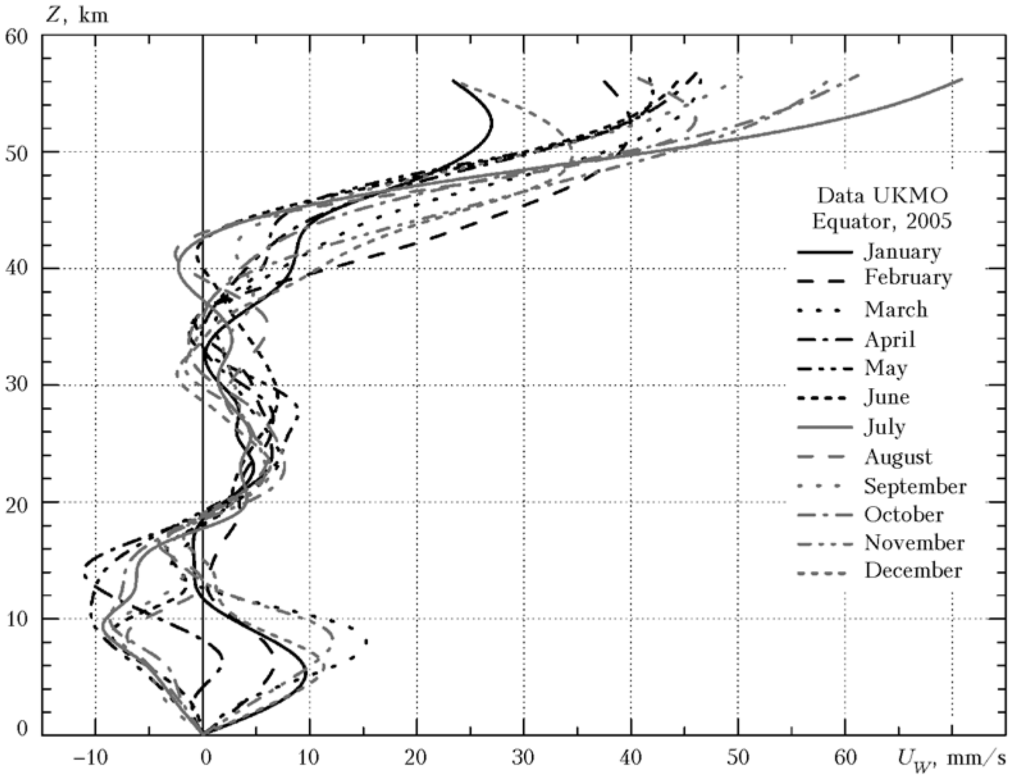

Fig. 1. Monthly average vertical profiles of the vertical wind velocity for the equator in 2005 according to the UARS-UKMO data.

Positive velocity values correspond to the upward wind, while negative ones stand for the downward wind. One can see that monthly average amplitudes of the vertical wind in the troposphere are roughly ±10 mm/s, in the lower and middle stratosphere they are ±5 mm/s, achieving 50 mm/s in the upper stratosphere and mesosphere. Without doubt, the average wind profiles carry rich information about different reasons causing the wind: deep tropic convection,[25] large-scale turbulence,[26] and others.

In the troposphere, the amplitude of the vertical velocity reaches its maximum at altitudes of 3–5 km and, decreasing, vanishes near tropopause. It should be noted that this behavior of the vertical wind is explained in Ref. 27 by the cyclonic and anticyclonic activity. One can see that the seasonal variability is characteristic of the troposphere, and semi-annual oscillations are clearly seen. In the stratosphere, average velocities are much lower, and for the equator at altitudes of 20–30 km a pronounced zone of the positive vertical wind vanishing at altitudes of about 40 km is observed. It can be seen also that the positive vertical wind with a very high velocity (up to 50 mm/s) predominates in the mesosphere. The analysis of such monthly average data for other geographic regions suggests the existence of the latitudinal-longitudinal dependence of the vertical wind and the behavior of this dependence may differ qualitatively from that of the equatorial one.

The characteristic time scales of the "residual" stratospheric circulation are known to exceed significantly those of the tropospheric one (up to several years),[5,6] which assumes the analysis of annual average velocities of the vertical wind. The obtaining of annual average profiles of the vertical wind from the UARS-UKMO data for the equator for the period 1993–2005 (Fig. 2) required the development of a data averaging technique, since the UARS-UKMO database does not contain annual-averaged wind velocities.

At the UARS standard pressure levels, the absolute heights and the corresponding temperature and vertical wind fields were determined for particular geographic regions and time intervals. Then the arithmetic-mean heights and wind velocities were calculated for all months at a fixed pressure. Then the same technique can also be used to average velocities for 13 years of observations (since 1993 to 2005).

It can be seen from Fig. 2 that the annual-average velocities with characteristic values of about ±1 mm/s are an order of magnitude lower than the monthly average ones. It is interesting that for the period 1993–2005 the annual average vertical wind velocity increases in the absolute value, and this increase is characteristic of the entire altitude range and for all geographic regions under study. The rise of zones in which the vertical wind alternates its direction is characteristic as well.

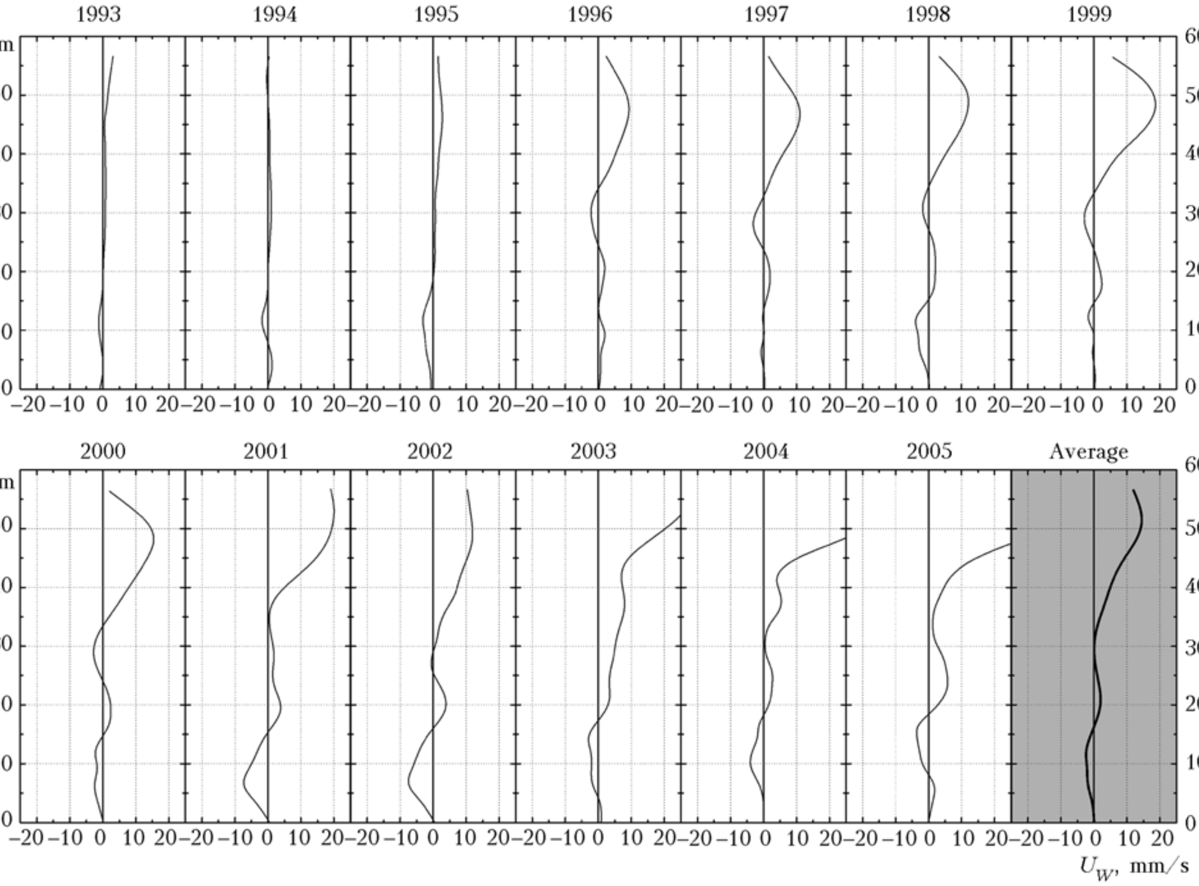

Fig. 2. Annual-average vertical profiles of the vertical wind velocity for the equator according to the UARS-UKMO data.

The most astonishing fact is that the vertical wind averaged over 13 years has the pronounced height dependence as well.

To use these data in applied calculations, a scheme of height approximation can be proposed. It was found that a seventh-order polynomial is the optimal approximating function for the height range 0–60 km. For sub-polar regions, the deviation of the approximating function from true values of the wind velocity did not exceed 1%, while for the equator it did not exceed 5% for the entire height range.

The comparison of the horizontal and vertical wind components at different heights is shown in Fig. 3, which reflects the well-known regularities for the total atmospheric wind.[1,2,27] The zonal (latitudinal) wind with velocities of tens of m/s is most intense, the meridional (longitudinal) wind has velocities of units of m/s, while the vertical wind is nearly invisible against their background.

However, the action of the vertical wind in the stratosphere and mesosphere may be decisive for the vertical transport of aerosol particles. As will be shown below, the vertical wind with velocities of fractions and units of mm/s can efficiently influence the motion of particles having different sizes and densities.

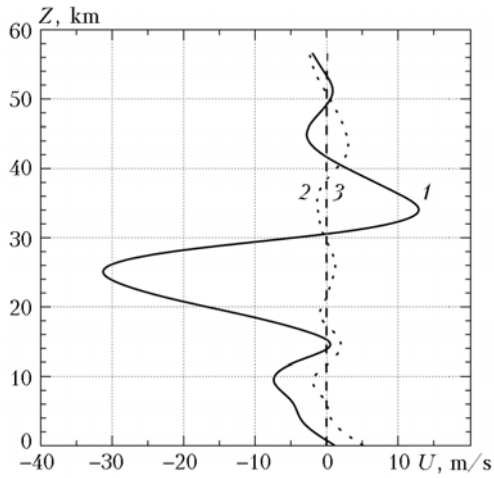

Fig. 3. Monthly average wind velocity components for the equator according to the UARS-UKMO data for October, 2005: zonal (*1*), meridional (*2*), and vertical (*3*) wind component.

3. Dynamics of stratospheric particles in the vertical wind field

The technique for calculation of velocities of the one-dimensional motion of a particle taking into account the action of the average vertical wind on the global time scale is based on the solution of the equation of motion in the coordinate system fixed on the Earth's surface:

$$m_p \frac{dU_p(z,t)}{dt} = F_d(z,t) + F_{mg}(z,t) + F_W(z,t), \quad (2)$$

where m_p is the mass of an aerosol particle; U_p is the total velocity of its motion; F_d is the resistance force of the gas medium, F_{mg} is the force of gravity, F_W is the force of wind entrainment. This approach allows us, on the one hand, to avoid the extreme complication of the problem owing to the consideration of the different-scale turbulent diffusion and convection and, on the other hand, to obtain the limiting estimates of the influence of the vertical wind on the aerosol transport in the stratosphere.

Due to the short time of mechanical relaxation, the motion of aerosol particles can be considered as nearly inertialess. This allows us to use the quasi-stationary approximation[8]: at any time in a thin atmospheric layer near the height z a particle moves uniformly along a straight line with the velocity $U_p(z)$ under the action of instantaneous values of the forces taken into account in the right-hand side of Eq. (2). From layer to layer the value of $U_p(z)$ varies, since the forces acting on the particle vary. The total velocity of the vertical motion of the particle is

$$U_p(z) = U_{mg}(z) + U_W(z). \quad (3)$$

The calculation of the resistance force is based on the results of the gas-kinetic theory,[28] which describes the phenomenon in a wide range of Knudsen numbers ($Kn = l/R_p$, where l is the mean free path of air molecules; R_p is the particle radius) and generalizes the well-known Millikan formula.[8] The rate of gravitational sedimentation of a spherical particle is

$$U_{mg}(z) = \frac{2\pi^{1/2} R_p \rho_p g \left(\dfrac{2RT(z)}{M}\right)^{1/2}}{(8+\pi)p(z)\dfrac{Kn}{Kn+0.619}\left[1+\dfrac{0.310Kn}{Kn^2+1.152Kn+0.785}\right]}. \quad (4)$$

In the calculations, the gas pressure and temperature at a height z are set as parameters with the use of standard and reference atmospheric models. The AFGL (USA) model of standard atmosphere[29] was taken as the main computational model. In fact, we consider the extended model of the standard atmosphere taking into account the vertical wind field, which is a constructive generalization of the Kasten technique.[7]

Figure 4 shows the total velocities of particles at $\rho = 1$ g/cm^3 and $R_p = 1$ μm under the action of the gravity and the vertical wind.

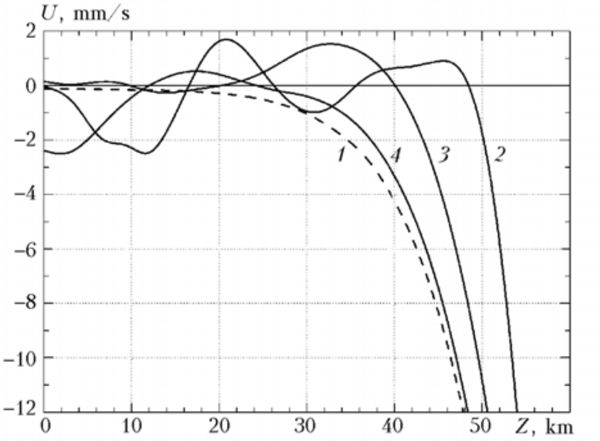

Fig. 4. Particle velocities: rate of gravitational sedimentation (*1*); total velocity of particle motion taking into account the vertical wind: equator (*2*); North Pole (*3*); South Pole (*4*).

In the calculations, we used the 13-year averaged data for the vertical wind discussed above. The positive values of velocities correspond to the lifting of particles against the gravity, while negative ones correspond to the sedimentation of particles. One can see that the vertical wind is a decisive factor of the particle motion up to altitudes of about 30–40 km. At altitudes above 40 km, the gravitational sedimentation becomes a decisive factor, while the vertical wind can only accelerate or slow down the sedimentation process.

The estimates of the time of lifting and sedimentation of particles from a particular altitude z_0 to possible limiting altitudes are of principal significance as well. Altitudes, at which the rate of gravitational sedimentation is equal to the opposite velocity of the vertical wind, are limiting. Taking into account the quasi-stationary character of the particle motion, a particle traverses a small vertical distance between neighboring layers $\Delta z_i = z_{i+1} - z_i$ for the time $\Delta t_i = \Delta z_i / U_p(z_i)$, where the procedure of estimation of the instantaneous value of $U_p(z_i)$ is described by Eq. (3). Figure 5 shows the time of lifting and sedimentation of particles with $\rho = 1$ g/cm^3 and $R_p = 1$ μm under the action of the vertical wind and the gravity for the equator, North and South Poles.

It can be seen that the times of lifting and sedimentation of particles with the vertical wind taken into account differ widely from those with only the gravitational sedimentation considered and are equal to one year for the equator and 2.5–3 years for the South and North Poles.

The vertical wind can be a potential cause for the formation of dynamically stable aerosol layers in the middle atmosphere at altitudes corresponding to the alternation of the vertical wind velocity sign from positive to negative. For example, it can be seen from Fig. 5*a* that particles starting to move in the altitude range 18–39 km will be entrained by the vertical wind and concentrated at altitudes of about 29 km. The action of gravity cannot move particles out of this zone, and, obviously, we can state the formation of a dynamically stable layer of aerosol particles. This behavior of aerosols will be typical for all altitude ranges with the similar character of alternation of the vertical wind sign.

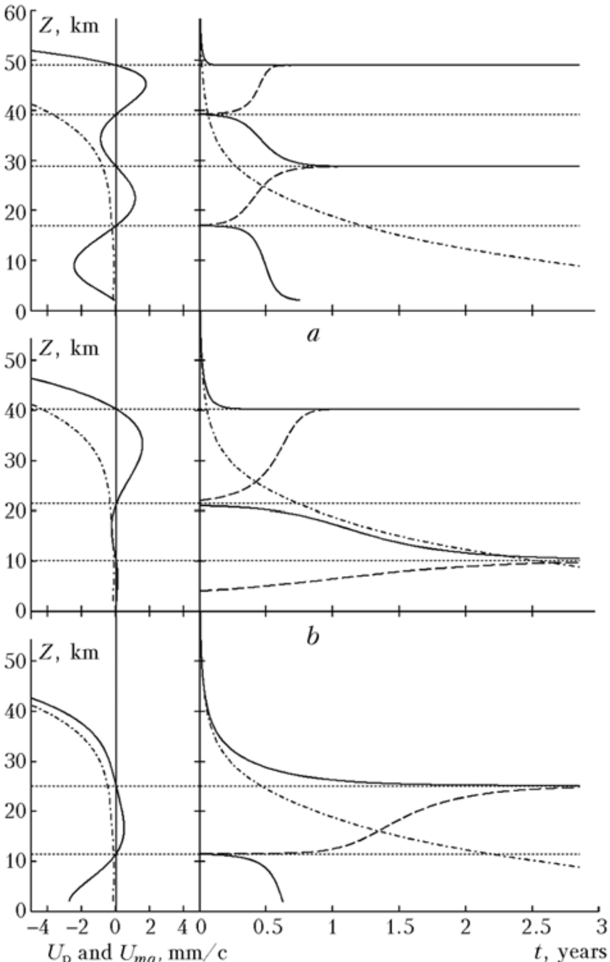

Fig. 5. Times of particle lifting (solid curves) and sedimentation (dashed curves) taking into account the vertical wind: the equator (*a*), North Pole (*b*), South Pole (*c*). Dot-and-dash curves correspond to the action of gravitational sedimentation only.

Conclusions

This work undertakes the first attempt to estimate the influence of the vertical wind on the transport characteristics of the stratospheric aerosol. The technique of investigation is based on the inclusion of the averaged fields of the vertical wind retrieved from satellite data in the statistical models of the standard atmosphere. In our opinion, the results obtained are the limiting estimates of the effect under study and do not replace the analysis of the characteristics of motion of individual particles under variable atmospheric conditions. Later on the climatological analysis of the results is planned in order to reveal seasonal and latitudinal features of the vertical wind.

The more detailed analysis of the structure of the vertical wind field allowing the long lifetime of stratospheric aerosol layers and the comparison with numerous experimental findings for polar stratospheric clouds is of interest. The estimates also show that the transport capabilities of the vertical wind will especially noticeable for fractal-like particles (for example, particles of soot and volcanic aerosol). The approach proposed possibly will allow the mechanisms of accumulation of soot particles from the air transport and the ground-based biomass burning at altitudes of the lower and middle stratosphere to be revealed.

Acknowledgements

The authors are grateful to the British Atmospheric Data Centre for the access to the UKMO database.

This work was supported in part by the Russian Foundation for Basic Research (Grants No. 04-01-96096 and No. 06-01-00669).

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