CORRELATION MATRICES AND EIGENVECTORS OF OZONE CONCENTRATION, AEROSOL SCATTERING RATIO, TEMPERATURE AND WIND VELOCITY IN THE STRATOSPHERE

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In this paper we analyze, using the method of orthogonal expansions, the ensembles of vertical profiles of the ozone concentration (measured with lidars) as well as the profiles of the scattering ratio, temperature, and wind velocity obtained using balloon sounding. The eigenvectors of these stratospheric components and parameters occurred to be similar.

INTRODUCTION

In the late 50s and in early 60s of the 20th century it was developed the method of statistical analysis of empirical functions, based on the application of "natural" orthogonal expansions.[1,2] The method has first been applied to studies of the meteorological fields and the geopotential field. The idea of this method is in that the behavior of a particular function, from an ensemble of the stationary random functions (with height H in this study), can be presented in the following form:

$$R(H) = \overline{R(H)} + \sum_i k_i \cdot S_i(H),$$

where $\overline{R(H)}$ is the ensemble mean function; k_i are the random-valued coefficients having the dimension of the parameter considered; $S_i(H)$ is the system of orthonormal vectors (normally the eigenvalues of covariance or correlation matrices of the ensembles studied are used as this system); i is the dimension of the system of vectors. From this equation it is seen, that the system of orthonormal vectors describes the variable part of the statistical ensemble. When there are conditional interconnections in the ensemble, the first several vectors give the basic contribution in the variable part (more than 70%). If this accuracy is acceptable, then it is possible to limit oneself to the consideration of these vectors only, when developing the prognostic models of the empirical functions under study. As a consequence, the problem of forecasting reduces to a few-parameter problem.

Active development of laser sensing in 70-90ths and its intensive use in the atmospheric research have allowed the application of the method of statistical analysis of empirical functions to processing the laser sensing data on the stratospheric aerosol.[3] This, in turn, enabled creation of a few-parameter optical model of the backscattering coefficient of the low tropospheric aerosol.[4]

In this paper we use this method to analyze the results of lidar sensing of the stratospheric ozone (O_3) and aerosol (R), as well as the data on temperature (T) and wind velocity (V) acquired with radiosondes. As to the wind, we have analyzed both the meridional (V_m) and zonal (V_z) components of its velocity. However, no difference has been revealed in their variability. Therefore, hereinafter, in this paper we consider only the meridional component.

Lidar sensing of the ozone and aerosol has been carried out in Tomsk. The parameter reconstructed from the lidar (the differential absorption technique) data on ozone is the ozone concentration. In the case of aerosol (the technique of calibration by the molecular scattering) it is the scattering ratio (the total-to-molecular backscatter ratio). Examples of applying this technique to reconstruction of these parameters from lidar data have been described in Refs. 5–7. To reconstruct the scattering ratio, an actual profile of the molecular scattering is needed. The profile of this quantity has been being calculated using data on vertical distributions of temperature and pressure obtained at the meteorological stations in Kolpashevo and Novosibirsk cities, which are located at 240 km to the north and 210 km to the southwest from Tomsk, respectively. We used these same vertical profiles of temperature together with the vertical profiles of the wind velocity as the initial data in the studies we discuss in this paper.

All the initial data on O_3, R, T, and V_m have been approximated onto a kilometer-cell grid in the altitude range 14–31 km (15–32 km for O_3), that determined the dimension of the orthogonal vector system to be 18.

Table I represents the number of vertical profiles, i.e., the empirical functions of the relevant components and parameters of the atmosphere used in analysis and also the time when these profiles have been acquired. The number of vertical profiles of temperature and wind velocity (see Table) used is determined by the fact that only 84 profiles (from

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about 200 available ones) have been obtained up to the heights, close to 30 km.

TABLE I.

Component, parameter	Number of profiles	Observation time
Scattering ratio	226	January 1987 – June 1991
Ozone	92	July 1995 – June 1997
Temperature	84	January 1987 –June 1991
Wind	84	January 1987 – June 1991

CORRELATION MATRICES

The correlation matrices (COM) of the analyzed ensembles of empirical functions showing their *inter-layer correlation* are presented in Fig. 1 (circles denote the correlation coefficient below 0.5). Though all correlation matrices differ, however the COM of meteorological parameters (temperature and wind velocity) have considerably larger similarity as compared to COM of the ozone and the scattering ratio. The vertical behavior of the latter includes the interval with a sharp fall off of the correlation (within the 20–22 km range). The singularity of this altitude range, from the view point of general atmospheric circulation, is the velopause, i.e., the layer where in summer the transformation from the westerly transfer in the troposphere and lower stratosphere to the easterly one in the atmospheric layers above it takes place, Ref. 8. Therefore, in summer the air masses, which are lower and upper of the velopause, are generated in different geographical regions. Therefore the inter-layer correlation of the conservative admixtures (those which are entrained by the air motion) is lower on the boundary.

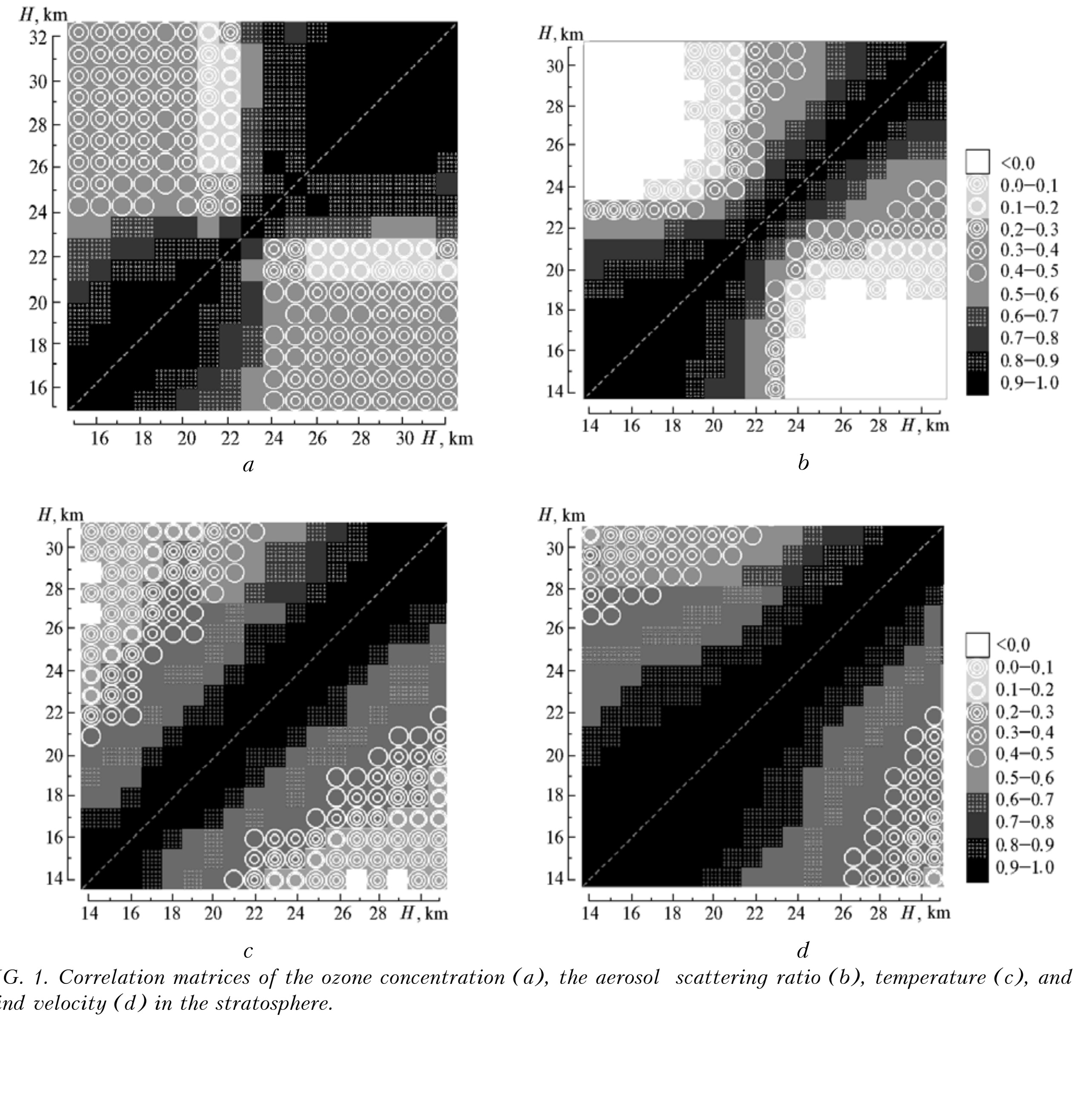

FIG. 1. Correlation matrices of the ozone concentration (a), the aerosol scattering ratio (b), temperature (c), and wind velocity (d) in the stratosphere.

For the aerosol scattering ratio in the lower interval (below 20 km) one may see a closer interconnection as compared to that in the upper one. For the ozone concentration the situation is just the opposite (see Fig. 1). Moreover, the correlation coefficient of the inter-layer correlation of O_3 at altitudes higher than 26 km, even at the spacing between the levels up to 5 km, does not fall lower than 0.9 (see Fig. 1). Most likely, this fact indicates the photochemical origin of the ozone at these altitudes under the action of solar radiation, thus causing close correlation of the ozone concentration variations at all altitudes above 26 km. The correlation matrices for temperature and wind velocity exhibit a uniform fall off of the correlation through the entire height range considered. The values of the elements of the inter-layer correlation matrix of pressure in the entire 14–31 km range are higher than 0.85.

THE EIGENVECTORS

We consider the eigenvalues of the correlation matrices (see Fig. 1) of the system of orthonormal vectors or eigenvectors (EV) corresponding to the high-altitude variability of the ensemble of empirical functions. The histograms of the EV contributions to the total variability of the relevant stratospheric parameters are presented in the top panels of Fig. 2. The histograms show that the first vectors (S_1) represent the major part of the meteorological quantities total variability. Thus, S_1 for temperature exceeds the contribution from the second vector (S_2) by more than two times and that of the wind velocity by three times. At the same time for the ozone and aerosol scattering ratio, the contribution of the second vector to the total variability is essentially higher. On the whole, first three vectors determine more than 80% of the variability for the ensembles of empirical functions analyzed.

The vertical structure of these vectors is represented in the bottom panels of Fig. 2. As seen from the figure, no essential differences between vertical behaviors of the second and third vectors are observed for all the parameters analyzed. Among the group of the first vectors, the highest identity takes place between the vectors of the ozone concentration and temperature. The vector S_1 of the scattering ratio has the strongest difference among this group. For this vector a sharp change of its value takes place in the altitude range of 20–22 km already mentioned above, when analyzing correlation matrices. The values S_1 vary from − 0.15 up to − 0.3 at the altitudes from 20 up to 23 km.

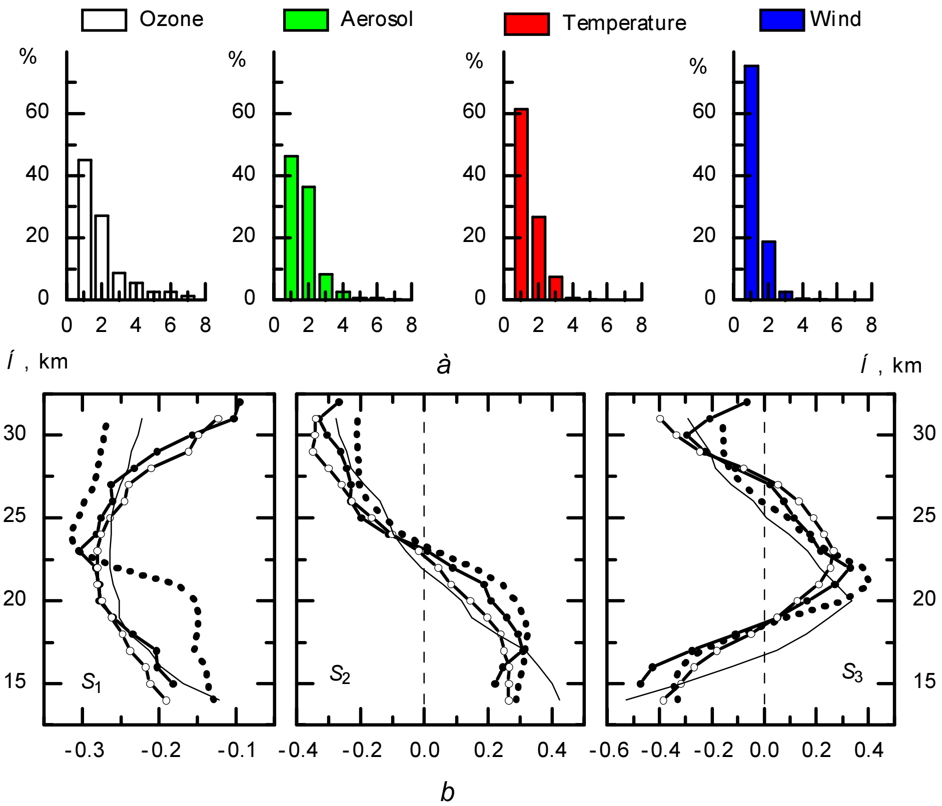

FIG. 2. The histogram of contributions described by the eigenvectors of the correlation matrices of ozone, scattering ratio, temperature, and wind velocity to total variability of these quantities (a). First three eigenvectors S_1, S_2, and S_3 of the correlation matrices of ozone concentration (closed circle-and-solid line), the scattering ratio (dotted line), temperature (open circle-and-solid line), and of the wind velocity (solid line) in the stratosphere (b).

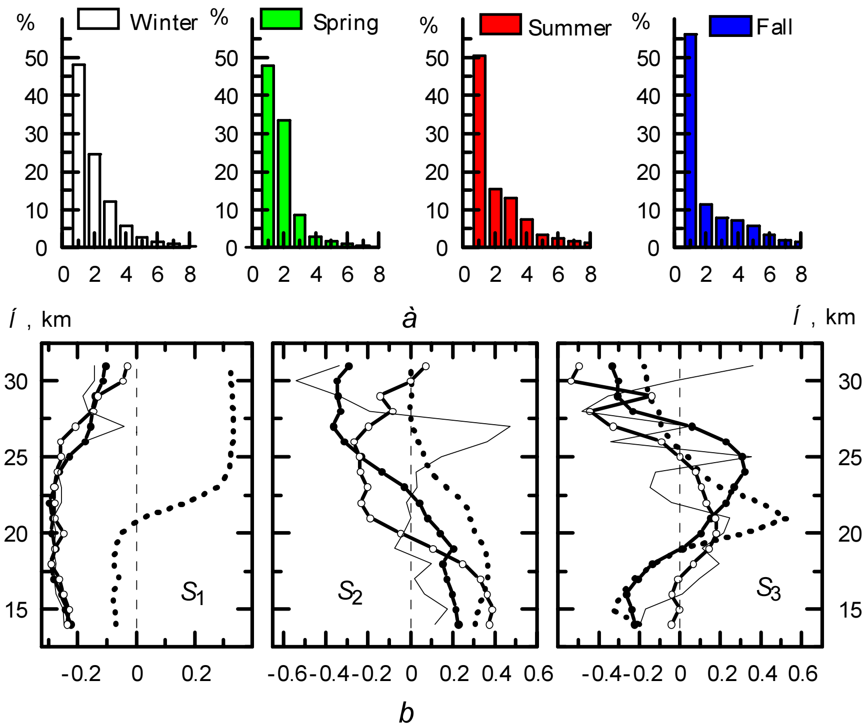

FIG. 3. The histogram of contributions described by the eigenvectors of seasonal correlation matrices of the scattering ratio to its total variability (a). First three eigenvectors (S_1, S_2, and S_3) of the correlation matrices of scattering ratio for winter (closed circle-and-solid line), for spring (dotted line), for summer (open circle-and-solid line), and for fall (solid line) (b).

The similarity of eigenvectors of n $_3$, T, $V_{\rm m}$, and R, indicates, to a certain degree, the existence of a universal cause of the variability of the ensembles of empirical functions under study. This cause, for these stratospheric parameters, is the general circulation of the atmosphere. The largest deviations in S_1 of the scattering ratio point to some other cause influencing the dynamics of the stratospheric aerosol.

SEASONAL EIGENVECTORS OF THE SCATTERING RATIO

The total number of 226 profiles of the scattering ratio as well as their distribution, though nonuniform, over seasons allowed us to consider seasonal variations of the scattering ratio eigenvectors. The histograms and eigenvectors of the scattering ratio for winter, spring, summer, and fall are shown in Fig. 3. As seen from this figure, the first vectors of winter, summer, and fall coincide quite well. Moreover, the similarity may be seen between their vertical behavior and that of the first eigenvectors of ozone, temperature, and wind velocity calculated for the whole year (see Fig. 2).

There fewest number of the profiles (30) were available for the fall. This has led to a strong variability of the second and third vectors of the scattering ratio during the fall because of poor statistics. Though the characteristic seasonal differences in the S_2 and S_3, particularly between winter and summer, are seen quite well. In summer the vertical behavior of S_2 and S_3 repeat the structures of the S_2, S_3 for winter season, but with a certain delay along the height axis.

The eigenvectors calculated for spring have the structure completely different than that of the eigenvectors characteristic of other seasons. And it was just the spring season that has led to a sharp gradient in the first vector of the scattering ratio in the altitude range of 20 to 23 km (see Fig. 2).

The cause of such an essential difference of the first eigenvector of spring season from the first eigenvectors of other seasons, and also from that for other atmospheric parameters and components under study, requires additional investigations.

CONCLUSION

Thus, the vertical behavior of the eigenvectors of the correlation matrices of the ozone concentration, aerosol scattering ratio, temperature and wind velocity calculated using data acquired over the West Siberia are identical (except for spring). Since the eigenvectors describe the variability of the parameters analyzed the similarity of their behavior shows that the nature of the variability is the same. For the parameters considered in this paper this is the *general circulation of the stratosphere*.

The series expansion of the stratospheric temperature and wind velocity over the system of eigenvalues of the relevant correlation matrices converges faster (S_1 = 61.6, S_2 = 27.1, S_3 = 7.6% and S_1 = 75.7, S_2 = 19.1, S_3 = 2.7%, respectively), as compared to that for the stratospheric ozone concentration, S_1 = 45.3, S_2 = 27.6, S_3 = 8.9%, and the aerosol scattering ratio related to the aerosol content, S_1 = 46.7, S_2 = 36.9, S_3 = 8.5%. When creating the regional three-parameter statistical model of the vertical distribution of temperature, wind velocity, ozone concentration, and the scattering ratio in the stratosphere, the accuracy of forecasting these models will be better than 95% for thermodynamic parameters and better than 80 and 90% for the components.

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