The response of the ozone vertical distribution stratification to stratospheric changes

V.V. Zuev and S.V. Smirnov

Institute of Atmospheric Optics,
Siberian Branch of the Russian Academy of Sciences, Tomsk

Received November 16, 2000

We present analysis of the stratospheric changes that occurred in the spring of 2000 and their influence on the stratification of ozone vertical distribution (OVD). Special attention is given to revealing the cases with fine layer structure in the OVD and meteorological situations favorable for the formation of layers. Analysis is made based on data of aerological and lidar sensing of the atmosphere and ozone. It was found that the pronounced layer structure of the OVD could be formed under the action of horizontal and vertical transport of ozone in the high-gradient parts of the high-altitude trough of a vast high-power central cyclone. In this case, the layer structures differ from each other depending on the place of their origin. In the front part of the high-altitude trough in the region of a well-developed high-altitude frontal zone, the layer structure consists of the rapidly variable layers below the ozone maximum. In the rear part of the trough (at the entrance of the high-altitude frontal zone) the layer structure is formed as the high-power secondary maximum of ozone in the lower stratosphere over the tropopause.

Introduction

At present, there are many urgent problems in the physics and chemistry of atmospheric ozone that call for more thorough studies. Among those, there are the problems in understanding the transport, turbulent mixing (redistribution), and photochemical destruction of the stratospheric ozone in the transition latitudinal zone between the middle and high latitudes – where the boundary of the circumpolar stratospheric vortex is located. These processes, as it has been found,[1] directly affect the transformation of the ozone vertical distribution (OVD) and the formation of the layered or fine structure (FS).

Special attention was first given to the layer structure in OVD in one of the papers by Dobson[2] as well as in one of the first domestic monographs on ozone.[3] The investigations into spatiotemporal variations of the OVD summarized in Ref. 4 have shown that FS of the OVD is often observed during winter-spring period at extratropical latitudes. As was noted in Ref. 5, the number of layers in the OVD and their quantitative characteristics (thickness and horizontal length of the layer and, accordingly, the ozone content in it, the lifetime of the layer, the altitude of the layer localization) directly depend on the type of synoptic situation. For example, in Central Europe there exist three groups of such situations, i.e., favorable, unfavorable, and neutral for the occurrence of the pronounced layer structure.[5] Statistical analysis of the layer structure in OVD over this region during the period of observations from 1968 to 1993, presented in Ref. 6, revealed a decrease of the number of pronounced layers in the OVD and, accordingly, the ozone content. An increase in the number of synoptic situations with a pronounced western zonal transport and a decrease of the number of situations with a pronounced meridian transport correspond to the above-mentioned results of the tropospheric circulation based on the results of objective analysis of aerological data.[7]

Nowadays the relationship is determined between the filamentary structure in the ozone horizontal distribution and the layer structure in the OVD, which are observed in the lower stratosphere of midlatitudes along the boundary of the circumpolar vortex.[8–10] Here these structures appear under the action of large-scale quasi-horizontal advection in a high-gradient field of the potential vortex of the velocity, characteristic of the vortex boundary, where the layer structure of zonal stratospheric transport is broken, because of the destruction of the long planetary waves.[8,11,12] This results in both partial and total isolation of the air masses and the formation in the ozone field of horizontal filamentary strips and structures of the cat's eye type.[12,13] Further development of these local vortices can be their independent migration in midlatitudes. The lifetime of such filamentary and vortex structures in the ozone horizontal field and the associated lamination in the OVD is considered to be about two weeks and more[1] that is comparable to the time of photochemical impact of the ozone destructive matters on the stratospheric ozone in midlatitudes.[14] Therefore the occurrence of migrating smallest ozone holes in midlatitudes in the late 90's is, probably, connected with the intensification of the above-mentioned dynamic processes.

The aim of this paper is to analyze the stratospheric changes in the spring 2000 and their effect

0235-6880/00/12 1043-05 $02.00

on the OVD stratification based on the data of aerological sensing of the atmosphere and lidar sensing of ozone as well as to reveal the cases with FS in the OVD and the meteorological conditions in the atmosphere favorable for their occurrence.

Analysis of lidar sensing data on ozone

During three months in the spring 2000, a 15 nighttime series of lidar observations of the OVD in the stratosphere have been carried out. Each of the series consisted of four to six measurements with 9-minute integration time of lidar returns with 100 m spatial resolution up to 18 km altitude and 200 m and 400 m resolution up to 24 km altitude and higher, respectively.

The altitude range, where the layer structure in the OVD can be considered, covers the lower stratosphere, the layer from the tropopause to 20–23 km where the ozone maximum variability is observed. The OVD stratification was evaluated based on analysis of the ozone profiles according to the shape of their contour and the presence of narrow pronounced layers both in the form of the dips and in the form of peaks relative to the mean contour. In this case, a basic criterion is a comparison of horizontal and vertical dimensions of layers with the root-mean-square deviation (RMSD) typical for a given altitude. The excess was considered an anomaly, and this profile was selected for further analysis.

As a result, two cases have been revealed when the pronounced layers were observed, namely, ozone profiles obtained on March 14 and 20 and shown in Fig. 1 as the mean night profiles. In the OVD of March 14, in the altitude ranges from 16 to 17 km and from 17 to 20 km, the layers with the increased and decreased ozone content were observed. On March 20, a high-power ozone layer was observed at altitudes from 13 to 16 km. This layer was a typical example of the OVD with the high-power secondary ozone maximum in the lower stratosphere. On the whole, both of the ozone profiles corresponded to the increased total ozone content (TOC) in the atmosphere. Thus, the TOC observations during this period showed the values of 424 and 431 D.U., which exceeded the monthly mean level by 6 and 8%, respectively.

When sensing on March 14, we managed to follow the process of rapid transformation of the FS in the OVD. Figure 2 shows these changes and Table 1 gives basic characteristics of the layer where a short-duration increase of TOC was observed (UBL is the upper boundary of the layer, LM is the layer maximum, LBL is the lower boundary of the layer, $\Delta h = h_{\rm UBL} - h_{\rm LBL}$ is the bottom layer thickness, $\Delta n = n_{\rm LM} - (n_{\rm UBL} + n_{\rm LBL})/2$ is the relative magnitude of the layer).

Traditionally, when investigating the layer structure, the layers up to 500 m and more in thickness are considered separately. In the first case the lifetime of the layers, occurred, as expected, due to intrusion, depends on the intensity of turbulent mixing due to vertical turbulent diffusion, which washes out thin layers during several tens of minutes or hours. In the second case, when layers are formed due to the large-scale horizontal advection, their lifetime may be from several days to two weeks and longer and depends on the intensity and duration of the advection. In our case, as is shown in Fig. 2 and Table 1, destruction of the layer structure occurred during half an hour when the horizontal length (magnitude) of the "positive" layer varied by almost 4 times and its thickness – 1.5 times.

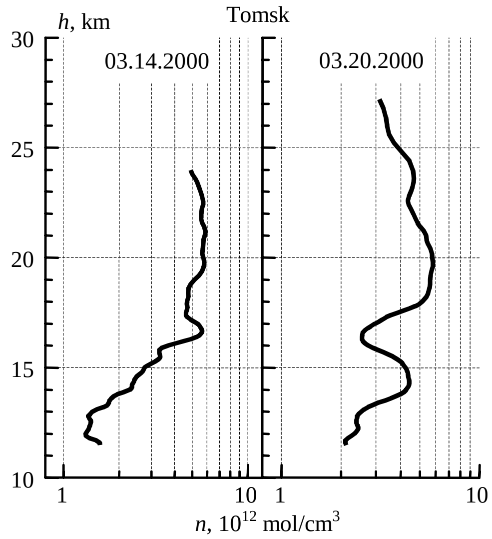

Fig. 1. The ozone vertical distribution with the pronounced thin layer structure based on the lidar sensing data on 14 and 20 of March, 2000, in Tomsk.

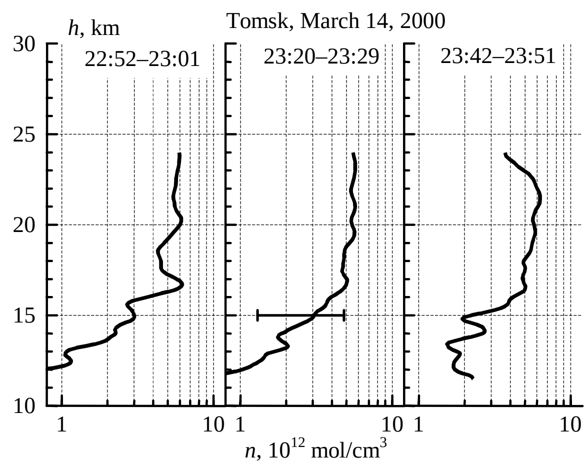

Fig. 2. High-speed changes in the layer structure of the ozone vertical distribution during the night of March 14, 2000. The confidence interval shows the RMS deviation.

As noted in Ref. 3, the turbulent mixing, at typical for the stratosphere value of the vertical component of the turbulent diffusion coefficient of $2\ {\rm m}^2 \cdot {\rm s}^{-1}$, would destruct a 400-m thick layer during 6 hours if advection does not support it.

Table 1. Characteristics of the layer with the enhanced ozone content observed with a lidar on March 14, 2000

Local time	Altitude h, km			Ozone concentration n, 10^{12} mol.·cm^{-3}			Δh, km	Δn, 10^{12} mol.·cm^{-3}
	UBL	LM	LBL	UBL	LM	LBL		
22:52–23:01	17.6	16.7	15.6	4.51	6.23	2.69	2.0	2.63
23:20–23:29	17.3	16.9	16.0	4.74	5.05	3.96	1.3	0.70
23:42–23:51	17.0	16.5	16.0	4.82	5.01	4.17	1.0	0.51

However, in the presence of a significant horizontal-vertical wind shear observed in the contrast altitude frontal zones (AFZ), the destruction of layers can occur more rapidly. Therefore, insignificant quasi-horizontal variations of the AFZ in the lower stratosphere, where ozone, as is known, is a long-lived component, can result in strong variations of its content.

Analysis of data of aerological sensing of the atmosphere and TOC measurements

To assess the stratospheric changes and their effect on the OVD stratification, we have analyzed the data of aerological sensing in Novosibirsk (the distance from Tomsk is about 200 km to the south-southwest) and in Aleksandrovskoe (600 km to the north-west) as well as the data on spectro-photometric observations of TOC in Tomsk obtained over a period from March to May 2000. Since we are only interested in the lower stratosphere and large-scale synoptic processes, in analyzing the above processes we consider two levels, namely, the tropopause (8–12 km) and the level of 100 hPa isobaric surface (15.5–16.5 km). Thus, the variations of thermodynamic parameters at the tropopause level (TP) adequately reflect tropospheric circulation–synoptic processes, and at the level of 100 hPa the wave activity of stratospheric circulation is also depicted. At each level we consider the pressure p(hPa) or the geopotential altitude $H = 0.11\,gh$ (gp m), and the temperature T(K). We have also calculated the speed of zonal u(m·s^{-1}) and meridian v(m·s^{-1}) components of wind as well as the potential temperature θ(K):

$$u = V\cos(D + 90); \quad v = V\sin(D - 90);$$

$$\theta = T/(1000/p)^{0.288},$$

where V and D are the wind speed and direction, respectively.

The splitting of wind to components was made to simplify the wind diagram. We used the potential temperature because it adequately characterizes the stability of atmospheric stratification. If $\partial\theta/\partial t > 0$, the stability increases. This is observed at the amplification of anticyclone circulation and the pressure increase and vice versa.

To remove small-scale and short-period variations, caused by the fronts of atmospheric mesoscale processes like wave cyclones and blocking anticyclones, from the time series the data were smoothed by use of the 5-day moving mean. Time series obtained after this procedure are shown in Figs. 3 and 4 (the data obtained on March 14 and 20 are shown by asterisks, when the fine layer structure in the OVD was observed based on the data of lidar sensing), and Table 2 shows the values of correlation coefficients calculated for these series.

Table 2. Correlation of thermodynamic parameters with the total ozone content during the period from March to May 2000

Correlation coefficient	Novosibirsk	Aleksandrovskoe
TOC · T_{TP}	0.11	− 0.19
TOC · T_{100}	0.20	< − 0.10
TOC · p_{TP}	0.51	0.15
TOC · H_{100}	− 0.49	0.50
TOC · u_{TP}	< 0.10	− 0.23
TOC · u_{100}	0.47	0.23
TOC · v_{TP}	0.13	< 0.10
TOC · v_{100}	0.49	0.40
TOC · θ_{TP}	− 0.78	− 0.60
TOC · $\theta_{16\ km}$	0.59	0.17
$T_{TP} \cdot T_{100}$	0.86	0.87
$H_{100} \cdot T_{100}$	0.71	0.78
$P_{TP} \cdot T_{TP}$	0.81	0.88
$u_{TP} \cdot u_{100}$	0.21	0.57
$v_{TP} \cdot v_{100}$	0.75	0.72
$\theta_{TP} \cdot \theta_{16\ km}$	− 0.47	− 0.56

Now, based on the obtained data on the behavior of thermodynamic parameters (see Figs. 3 and 4) and their correlation (see Table 2), we can easily reconstruct the pattern of stratospheric changes that occurred in the spring of 2000. In this case, special attention was given to the dates, 14 and 20 of March.

Early in March the atmospheric circulation over the points of observation was caused by the high, warm, blocking Siberian anticyclone – seasonal center of atmospheric impact, whose active phase ended on 5–7 March and, evidently, was associated with the process of warming of the Arctic upper stratosphere inside the circumpolar vortex. In this case, at the vortex boundary above the anticyclone in the lower stratosphere the anomalous low temperatures and wind strengthening should be observed as well as low TOC values. It is exactly these data of sensing the atmosphere and ozonometric observations, which are indicative of this fact. Then meteorological conditions and anticyclone circulation over the observation points gave way to cyclonic circulation. This process was progressing most rapidly in the middle and the end of March.

The pressure system formed was a vast, high, low-power, cold central cyclone, whose center slowly moved from the North Europe to Taimyr during almost three weeks. This cyclone caused the temperature elevation in the tropopause and lower stratosphere as well as the increase in the wind speed. The cyclone activity over the observation points was temporarily reduced only in the third decade of March, when the Siberian anticyclone again became stronger, especially over Novosibirsk. The subsequent development of circulation–synoptic processes over the vast expanses of the European–Asian part of Russia during more than two weeks in April was due to the small-gradient field of high pressure. In the north periphery of this field the planetary high-altitude frontal zone was located and to the right and below it, at the anticyclone side, there were the observation points. At last, during more than two weeks in May the region again was in the trough of high-power central cyclone.

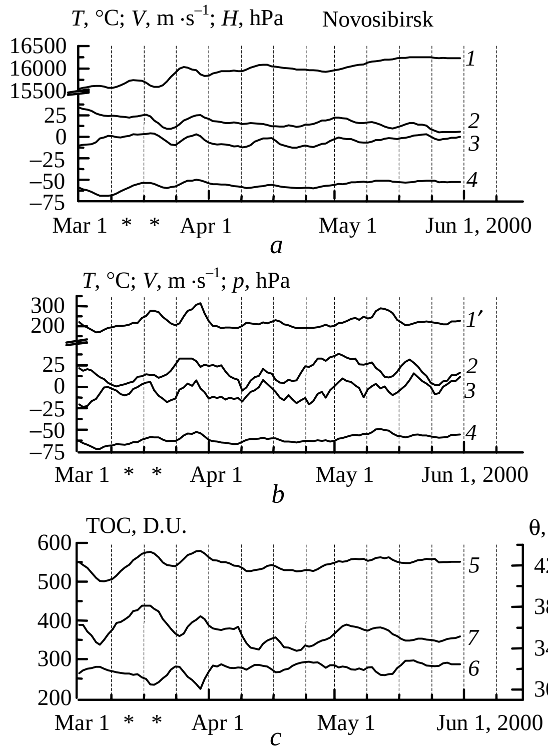

Fig. 3. Time variation of meteorological elements at the level of 100 hPa (*a*) and at the level of the tropopause (*b*) according to data of aerological sensing of the atmosphere in Novosibirsk and variations of the potential temperature and the total ozone content (*c*): curve *1* is the geopotential altitude of 100 hPa of isobaric level, curve *1′* is the pressure at a level of the tropopause, curve *2* is the zonal wind component, curve *3* is the meridian wind component, curve *4* is the temperature, curve *5* and curve *6* denote the potential temperature at 100 hPa and the tropopause, respectively, curve *7* denotes the total ozone content over Tomsk. All curves are the 5 day glancing means. The dates 14 and 20 of March 2000 are denoted by asterisks.

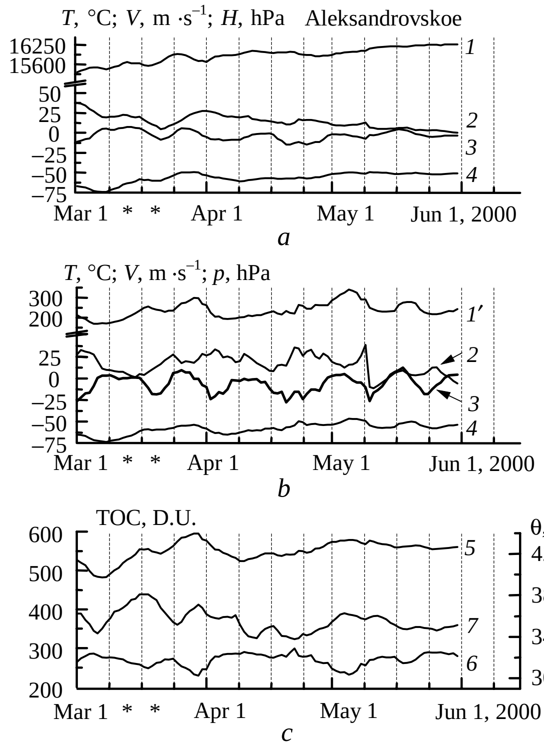

Fig. 4. The same as in Fig. 3 for Aleksandrovskoe.

Analysis of the effect of stratospheric changes on the total ozone content and its vertical distribution

Now we turn our attention to Figs. 3*c* and 4*c*, to notice that the relative minima of TOC correspond to the relative minima of the potential temperature in the lower stratosphere, and at the tropopause level – to its maxima (and vice versa). By this we mean that the increase of stability of the tropospheric stratification under the action of anticyclones is accompanied by the decrease in stability of the lower stratosphere, and vice versa, the increase of instability of the tropospheric stratification under the action of cyclones is accompanied by the increase of stability of the stratification of the lower stratosphere. This fact can be explained in terms of the wave theory of stratospheric circulation (see, for example, Ref. 15), which indicates that in the crests of long planetary waves the ascending currents are induced by the wind, and in the troughs –the descending currents. And further, in the front (rear) parts of troughs (crests) we observe the positive disturbances of the field of potential temperature $\partial\theta/\partial t > 0$ and the meridian wind component directed to the north. Accordingly, in the front (rear) parts of the crests (troughs) we observed the negative disturbances of the field of potential temperature $\partial\theta/\partial t < 0$ and the wind meridian component directed to the south. In this case, an increase of the blocking processes in the troposphere leads to a large deformation of the planetary waves in the stratosphere, i.e., the increase of their amplitude. This results in the increase of convergence of the zonal average turbulent heat flux in higher latitudes, which is compensated for by cooling at the ascending currents. In lower latitudes, the divergence of fluxes increases, which in turn is compensated for by heating at the descending flows. Therefore, the enhanced wave activity in the stratosphere in higher midlatitudes results in an increase of the vertical motions in the wave crests but at the same time it causes a decrease of the descending flows in their troughs, and in lower midlatitudes – it results in the decrease of the vertical motions in wave crests and the increase of descending currents in troughs.

Thus, the ascending vertical flows in the stratosphere carry away the air from sublayers with low ozone content and decrease the total ozone content. Accordingly, the descending vertical currents increase the TOC. Hence, it follows that the farther high anticyclones move to the north, the more intense is the decrease of TOC in the air masses in these anticyclones, and, accordingly, the farther high central cyclones move to the south, the larger are relative TOC values in these cyclones.

Now we consider in detail what stratospheric processes were reflected in the formation of the layer structure of the OVD on March 14 and 20 (see Fig. 1). Figures 3 and 4 show that both of these events were observed during the period of action of the high-power altitude central cyclone. On March 14 the phase of cyclicity amplification was observed as associated with the front part of the cyclone high-altitude trough. According to data of aerological sensing on March 14 in Novosibirsk and Aleksandrovskoe at the 100 hPa level the mean west-southwest wind speed was 21 and 28 m/s, respectively, while at the level of the tropopause the divergence of the vector of wind velocity was observed (northwest – 6 m/s over Novosibirsk and southwest – 10 m/s over Aleksandrovskoe). Simple calculations show that the horizontal variations of the ozone concentration observed in the lower stratosphere correspond to the gradient about $2.8\cdot 10^{12}$ mol·cm^{-3}/100 km. Such high values of the ozone concentration can be observed only in the ozone field in the planetary high-altitude frontal zone separating the Arctic and midlatitude air masses that was observed during this period.

By March 20 the cyclone moved to the east, and the observation points turned out to be in the rear part of the high altitude trough, for which the amplification of anticyclonicity and cold advection are typical. Because the meridian advection intensity, as it follows from the data of radiosondes, was much higher at the level of the tropopause than at 100 hPa level, and descending flows in the upper troposphere in the rear part of the trough already dominated, this resulted in the formation of a pronounced secondary ozone maximum observed in the lower stratosphere above the tropopause.

Conclusion

Complex analysis of data of aerological and ozonometric sensing of the atmosphere has made it possible to study the effect of atmospheric circulation on the OVD and TOC during spring period using small bulk of information, when the seasonal changes occur and maximum variability of ozone is observed.

Analysis has shown that the pronounced layer structure of the OVD can appear under the action of horizontal-vertical transport of ozone in the high-gradient parts of the high-altitude trough associated with the high-power, vast, central cyclone. In this case, the layer structures differ from each other depending on the place of their origin. In the front part of the altitude trough in the region of the developed high-altitude frontal zone (at the mouth of AFZ) in the layer structure the thin fast moving layers below the ozone maximum were observed. In the rear part (at the AFZ entrance) the layer structure is formed as the high-power secondary ozone maximum in the lower stratosphere above the tropopause.

It is undoubtedly that these investigations must be continued, because for providing stronger evidences a greater bulk of statistical data is needed, which, we hope, will be obtained during the next two or three years.

Acknowledgments

The authors would like to thank P.A. Khryapov and A.V. Nevzorov for their data on lidar sensing of the OVD.

The work has been made at the Siberian Lidar Station and supported by the Ministry of Science of RF (Reg. No. 01–64) and the Russian Foundation for Basic Research (Grant No. 99–05–64943).

References

1. D.I. Wardle et al., eds., *Ozone Science: A Canadian Perspective on the Changing Ozone Layer* (Environment, Canada, 1997), 119 pp.
2. G.M. Dobson, Quart. J. Roy. Meteorol. Soc. **99**, 599–607 (1973).
3. S.P. Perov, A.Kh. Khrgian, *Modern Problems of Atmospheric Ozone* (Gidrometeoizdat, Leningrad, 1980), 288 pp.
4. S.J. Reid and G. Vanghan, Quart. J. Roy. Meteorol. Soc. **117**, 825–844 (1991).
5. T. Halenka and P. Mlch, Stud. Geophys. et Geod. **40**, 192–215 (1996).
6. P. Mlch and J. Lastovicka, Ann. Geophysica **14**, 744–752 (1996).
7. W. Enke and A. Spekat, in: *Proc. of 6th Inter. Meet. Stat. Clim.* (Galway, Ireland, 1995) pp. 339–342.
8. D.W. Waugh and R.A. Plumb, J. Atmos. Sci. **51**, 530–540 (1994).
9. Y.J. Orsolini, Quart. J. Roy. Meteorol. Soc. **121**, 1923–1941 (1995).
10. Y.J. Orsolini, P. Simon, and D. Cariolle, Geophys. Res. Lett. **22**, 839–842 (1995).
11. D.W. Waugh, R.A. Plumb, R.J. Atkinson, et al., J. Geophys. Res. **99**, 1071–1088 (1994).
12. K. Ngan and T.G. Shepherd, J. Fluid Mech. **334**, 315–351 (1997).
13. C. Appenzeller, H.C. Davies, and W.A. Norton, J. Geophys. Res. **101**, 1435–1456 (1996).
14. P. van der Gathen, M. Rex, N.R.P. Harris, et al., Nature **375**, p. 131–134 (1995).
15. G. Brasier and S. Solomon, *Aeronomy of the Middle Atmosphere* (Gidrometeoizdat, Leningrad, 1987), 414 pp.