Variability of ozone layer in 1979–1999

A.A. Chernikov, Yu.A. Borisov, A.M. Zvyagintsev, G.M. Kruchenitsky, and S.P. Perov

Central Aerological Observatory, Dolgoprudnyi, Moscow Region

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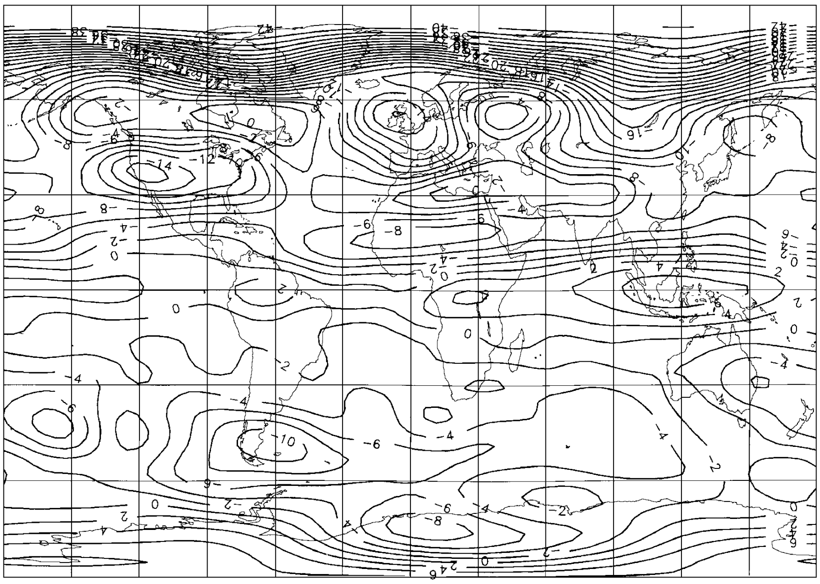
During the period from 1979 to 1999 the rate of the decrease in the global annual mean value of total ozone content (TOC) is found to be about 2.5% per decade. In midlatitudes and high latitudes of the northern hemisphere this decrease is mainly due to more frequent occurrence and higher magnitudes of negative anomalies in TOC observed in the period from 1987 to 1997. In the past two years in mid and high latitudes of the northern hemisphere the increase of TOC up to the magnitudes typical for the middle 70s was observed. Satellite observations show that the Antarctic ozone «hole» during the spring period, which was clearly revealed in the annual variation of TOC at southern latitudes higher than 60°S in 1960–1970, either continues to grow or reached its maximum in 1998. The TOC increase observed in the past two years cannot be caused by the efforts taken to overcome the anthropogenic effect on ozone layer since the TOC increase is observed under conditions of maximal concentration of stratospheric chlorofluorocarbons. Nowadays, scientific concepts on the state and causes of the observed evolution of the ozone layer are not clearly understood, and, in particular, prevent prediction of the observed sharp changes in ozone layer and the occurrence of isolated anomalies in the northern hemisphere.

Regular observations of essentially most important parameter of ozone layer, the total ozone content (TOC), have been performed using spectrophotometric equipment at isolated points since 1920.[1] Since the beginning of the International Geophysical Year in 1957 the number of observation stations increased up to several tens in a period of a few years; the stations were located on all continents except Africa and South America. The ozonometric network of the USSR incorporating the Dobson spectrophotometer No. 108 (St–Petersburg) and filter ozonometers M–83 (later – M–124) designed by Prof. G.P. Gushchin are being operated since 1958. Starting in October 1978 the observations of ground-based ozonometric network were supplemented by the observations coinciding closely in the accuracy, made using the spaceborne equipment TOMS installed onboard Nimbus–7 satellites (1978–1993); this equipment was later placed onboard the satellites Meteor–3M (1991–1994) and Earth Probe (since 1996). When analyzing the time variations of ozone layer, we are capable now of understanding the principal causes of variations of ozone layer, which so far remain the subject of scientific discussions.[2–7] At present in the world the scientists follow the point of view[2,3] that up to 1979 the TOC experienced only annual variations and since 1979 the systematic variation manifested itself, i.e., the trend connected with the anthropogenic pollution of the atmosphere by ozone destructive compounds – chlorofluorocarbons (CFC). In contrast to this understanding the "nonfreon" hypothesis of variation of planetary ozone layer was greatly supported by the Russian scientists. This hypothesis was discussed in detail at the scientific session of DOPAG RAS in the fall of 1995 organized by the Academician–secretary V.E. Zuev.

This paper presents some results obtained from analysis of the latest variations in the Earth's ozone layer based on the data of spaceborne equipment TOMS and the world-wide ground-based ozonometric network for revealing the latest trends in these variations. In the paper the data on TOC used were obtained at the world-wide ground-based ozonometric network that are a part of the world ozone data base,[8] as well as data obtained with TOMS equipment deployed onboard a Nimbus–7 satellite from November 1978 to April 1993, onboard a Meteor–3M satellite – from May 1991 to November 1994,[9,10] and onboard the Earth Probe (USA, NASA) space-based platform – from August 1996 to July 1999.

There is a reason to think[3] that the absolute error of the TOC measurements, using Nimbus-7/TOMS equipment (and, evidently, Earth Probe/TOMS), is ± 3% and the random error is ± 2%; and the uncertainty due to the instrument drift is ± 1.5% during 14 years; for the TOC measurements using Meteor–3/TOMS equipment the random error is ± 3%, ± 3%, and ± 1% during 3 years, respectively. From the comparison we note that the error of the best modern ground-based spectrophotometric measurements is ± 1% in direct sun and ± 3% in zenith. In 1970s the above-mentioned error was twice as large. The magnitude of observation error obtained using the ozonometers M–124 is ± 5%.[3] It should be noted that the ozonometric network of the former USSR has detected successfully the same trends in TOC variations as the world-wide network of high-precision spectrophotometers,[11] but not so promptly.



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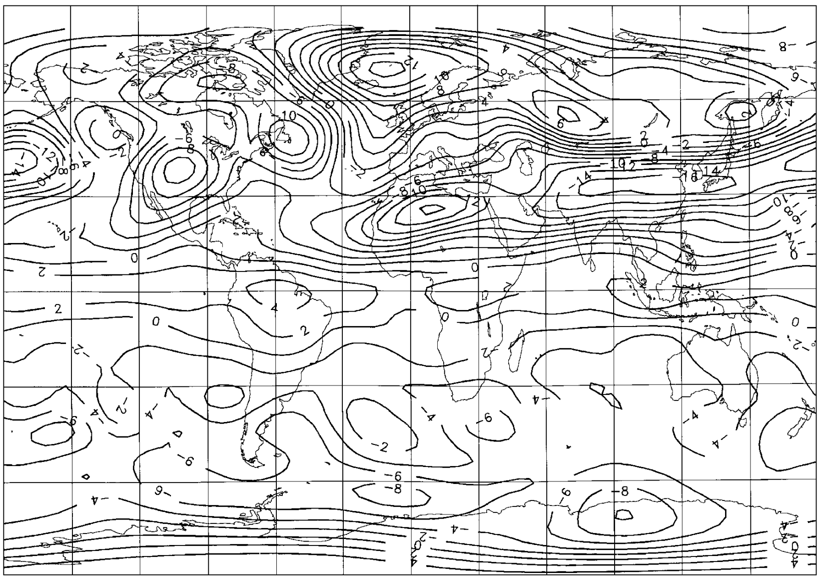

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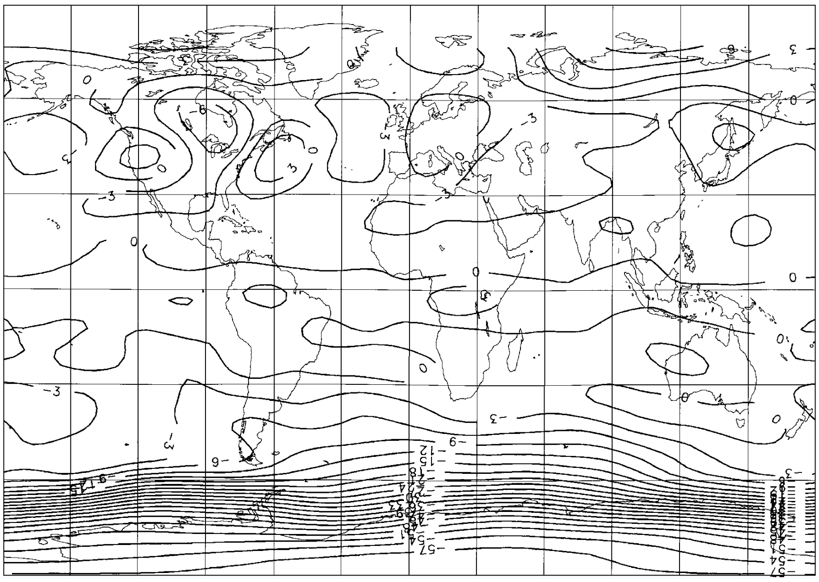
Fig. 1. Deviation fields of the monthly mean total ozone content from the long-term mean values of 1974–1984 in March 1997 (*a*), March 1999 (*b*), October 1998 (*c*), and October 1999 (*d*) based on the data of TOMS equipment.

As an illustration of spatiotemporal variations of ozone layer in recent years, Fig. 1 shows the fields of monthly mean TOC deviations from "standards" (long-term mean ones in 1974–1984) for the seasons when in the northern hemisphere (March) and in the Southern hemisphere (October) the most significant anomalies of TOC are observed. Figure 1 shows that while in the southern hemisphere the anomalies of ozone layer are still observed (in particular, the Antarctic ozone anomaly of 1998 was one of the most significant), though even in this case the rates of the TOC decrease strongly fall down, in the Northern hemisphere during the past 2 years the ozone layer practically returns to the level of TOC values, typical for the middle of 1970s. These data are also valid for the time dependences of annual mean and March values of TOC based on the data from Ref. 8 acquired with a Dobson spectrophotometer at the station Arosa (46°N, 10°E) where the longest series of regular observations (Fig. 2) has been compiled since September 1926.

Figure 3 shows the time dependence of TOC deviations from the standards after transmission through the low-pass filter with the boundary period $T = 12$ months based on the observations using TOMS equipment for latitudinal belts: 80–60°S (curve *1*), 60–40°S (curve *2*), 40°S–40°N (curve *3*), 40–60°N (*4*), 60–80°N (*5*) and the mean over the entire stations of ground ozonometric network of the former USSR (*6*). Note that the Earth's surface areas of the above latitudinal belts are: 5.9, 11.2, 64.3, 11.2, and 5.9% of



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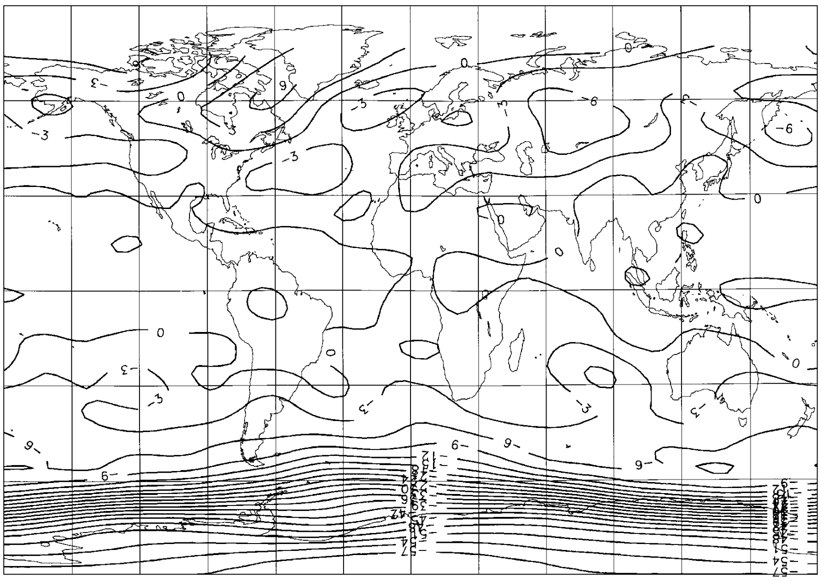

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Fig. 1 (continued). Deviation fields of the monthly mean total ozone content from the long-term mean values of 1974–1984 in March 1997 (*a*), March 1999 (*b*), October 1998 (*c*), and October 1999 (*d*) based on the data of TOMS equipment.

the total area of the Earth's surface, respectively. The correlation coefficients of the observation series (for the time interval common for those) shown by curves *6* and *4* is 0.74, and by curves *5* and *6* is 0.62, i.e., in the observation series obtained using the network of filter ozonometers and spaceborne equipment, the variability is described in a similar way. In the latitude range of 40°S–40°N the sunspot cycle of 11-year period does clearly manifest itself in the TOC. The TOC variability at 1–2% level with the 11-year period is cophased with the index of solar activity $F_{10.7}$ that agrees well with the reference data.[12] In midlatudes and high latitudes the 11-year-periodic variability of TOC is statistically insignificant against the background of essentially greater variability due to other causes.

Figure 4 shows the annual mean time dependences of the zonal mean TOC for different latitudinal belts over different observation periods. From this figure we notice that in midlatitudes of both hemispheres and also in high latitudes of the northern hemisphere the annual maximum of TOC is observed in early spring. In high latitudes of the Southern hemisphere at the beginning of the TOC measurements using TOMS equipment in 1979 its spring anomaly is clearly seen, that is, in early spring (in the Antarctic – since September) when in the latitudinal belts 30–90°S the

TOC maximum is observed, the gap of TOC maximum occurs over the Antarctic. Such an anomalous behavior of TOC over the Antarctic continent was first recorded in the first observations in the middle 50s by Dobson[13] and other groups of researchers.[14] After the publication in 1985 of a well-known paper by Farman with coauthors[15] this phenomenon was given in mass media the name the Antarctic ozone "hole" (then this name has been widely used in scientific publications) and the papers by the discoverers of this phenomenon turned out to be undeserved forgotten. Figure 4 shows the course (in fact – monotony) of the increase in TOC "gap" depth, whose maximum occurs in the vicinity of the South pole and practically insignificant in midlatitudes during the past 20 years. As is seen from Fig. 4, in recent few years the depth of the spring TOC "gap" over the Antarctic far exceeds the amplitude of the annual TOC harmonic in the appropriate latitudes of the northern hemisphere. So far we have observed no evidence of "gaps" in the TOC annual variation in the northern hemisphere comparable in the intensity even with insignificant Antarctic "gaps" observed in 1950–1960.

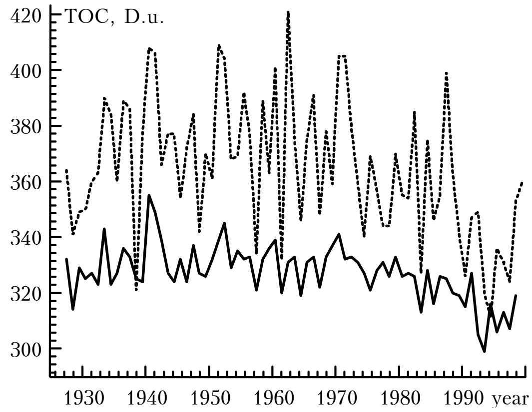

Fig. 2. Time dependence of the annual mean (solid line) and March (dashed line) of the total ozone content in Arosa since 1927 (46°N, 10°E).

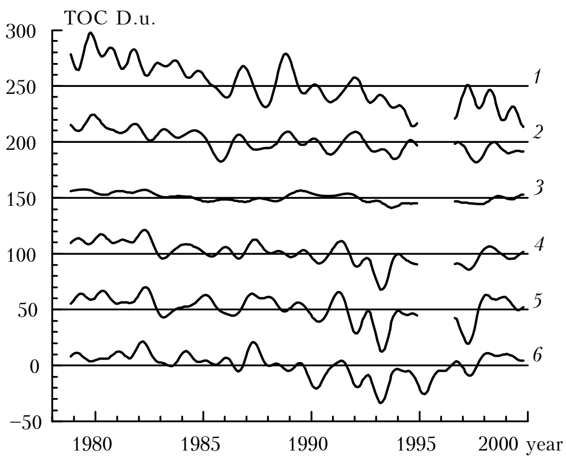

Fig. 3. Time dependence of deviations of the total ozone content from the long-term mean values.

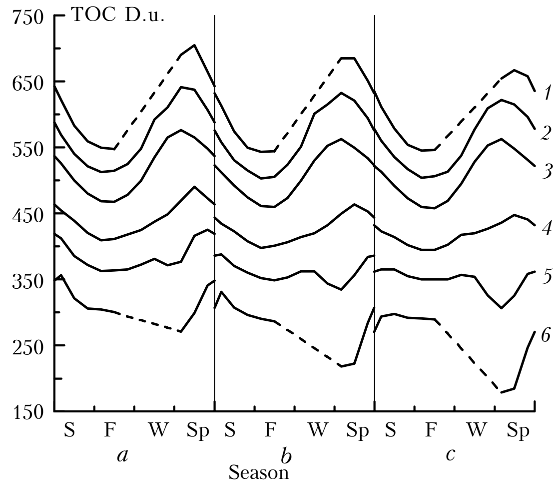

Fig. 4. The annual mean variation of zonal mean TOC for different latitudinal belts: 80–70°N (*1*); 70–60°N (*2*); 60–50°N (*3*); 50–60°S (*4*); 60–70°S (*5*) and 70–80°S (*6*) (for lower curve the numerical values plotted on the ordinate correspond to reality; each subsequent curve is elevated by about 50 D.u.), during different observation periods: (*a*) December 1978–November 1982; (*b*) December 1990–November 1994; (*c*) August 1996–July 1999.

To illustrate the differences between the vertical structures of winter-spring anomalies in the Antarctic (a regularly observed anomaly) and in the northern hemisphere (irregular anomalies), Fig. 5 shows the typical profiles of the ozone vertical distribution (VOD) during these events. The Antarctic anomaly is characterized by the presence of a significant gap of the ozone mixing ratio in the lower stratosphere (i.e., in the range of a major contribution to the TOC) that points to the presence of chemical (or photochemical) mechanisms of ozone depletion in this region (Fig. 5*a*). In all the ozone anomalies observed in the northern hemisphere, the ozone mixing ratio observed at altitudes of 30 km and higher increased always monotonically (Fig. 5*a*), that is, a serious argument contrary to the hypothesis on the determining factor of chlorofluorocarbons of anthropogenic origin in forming these anomalies (especially as there are no serious arguments in support of such a hypothesis and only the similarity of certain formal characteristics of these anomalies is stated, conventionally the gap in the VOD profiles in units of mass concentration or partial pressure, for example, given in Fig. 5*b* together with the similar Antarctic ones). In Ref. 6 the additional arguments are given in favor of dynamic and not chemical nature of the ozone anomalies observed in the Northern hemisphere, in particular, the plus sign of trends of altitude and width of the ozone maximum (in units of mass concentration) and the fact that in the anomalies the basic decrease of ozone concentration is always observed in the region below the ozone maximum. The other arguments against the "freon" hypothesis of the ozone layer decrease on a global scale are described in the papers.[4,7,14]

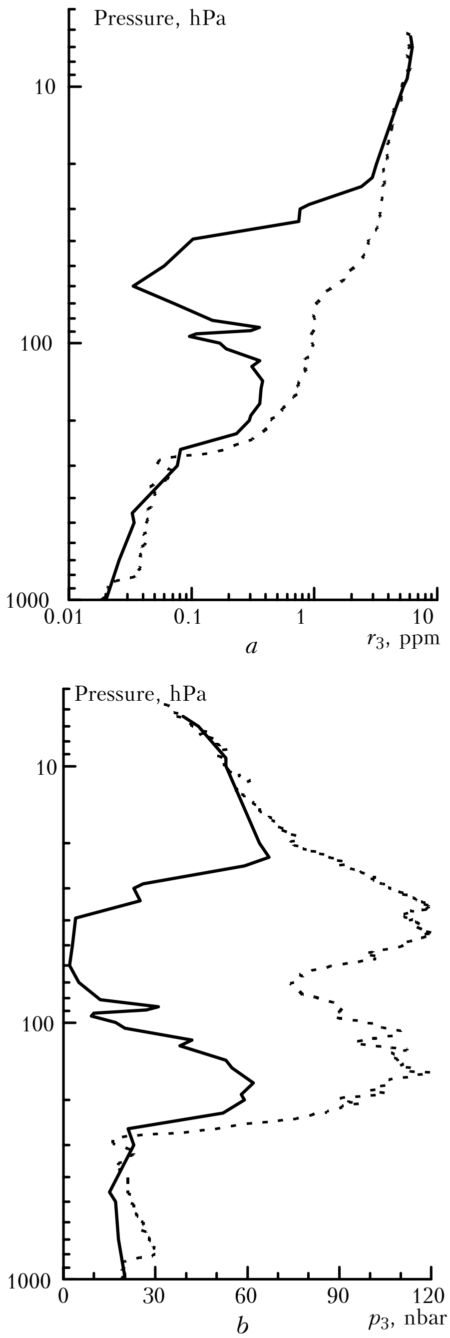

Fig. 5. The VOD profiles at the stations Syova (69°S, 40°E) on 22 September 1998 (solid curve) and Yakutsk (62°N, 130°E) on 19 March 1995 (dashed curve); (*a*) the values are given in the units of the mixing ratio (ppm); (*b*) in the units of partial pressure (nbar).

To represent the observed trends of ozone layer variations, Fig. 6 shows the latitude dependences of zonal mean trends in TOC over the periods of operation of TOMS equipment within the total period of operation using Nimbus–7 and Meteor–3M satellites and also over the same period and supplementary three years of operation on the Earth Probe satellite. The mean trends of TOC over the period from November 1978 to July 1999 all over the world and in the northern hemisphere (with consideration for distinctions of areas in different latitude zones of 10°N) were 2.5 and 2.2% per decade, respectively. In the review[2] it was concluded that within the period from January 1979 to the spring 1994 the rate of the TOC decrease in midlatitudes of both hemispheres was 4–5% per decade (these estimates were used repeatedly to give reasons for the bans of the Montreal protocol on the production of the so-called "ozone destructing" substances). In the latest overview of the World Meteorological Organization[3] describing the observations made by the end of 1997 it was stated that over midlatitudes of the Northern and Southern hemispheres the long-term (decade) ozone decrease since 1991 slowed down, and the linear extrapolation of ozone characteristics is inapplicable to date (although the models, describing the behavior of ozone layer, indicate detectable deviations from the linearity but in the distant future). According to Refs. 3 and 16 the total content of the ozone destructing gases in the troposphere reached its maximum in 1994 and at present it begins to decrease gradually. In the stratosphere the maximum of the ozone destructing gas content is expected before 2000, and then the ozone layer minimum should be observed during the next 10–20 years. At a later time the ozone layer will be slowly restoring. It should be mentioned that the process of reconstruction of the ozone layer to the level of 1970s cannot be revealed during the next 20 years because of natural variability and the effects of observed global climate changes in the ozone layer. It should be mentioned that Fig. 6 shows that the account of the observations during the past three years contributes to drastic changes of estimates of the TOC trends in midlatitudes and high latitudes of the Northern hemisphere[17] that casts some doubt upon the truth of the assumption of the determining factor of anthropogenic emissions of chlorofluorocarbons in variations of the ozone layer.

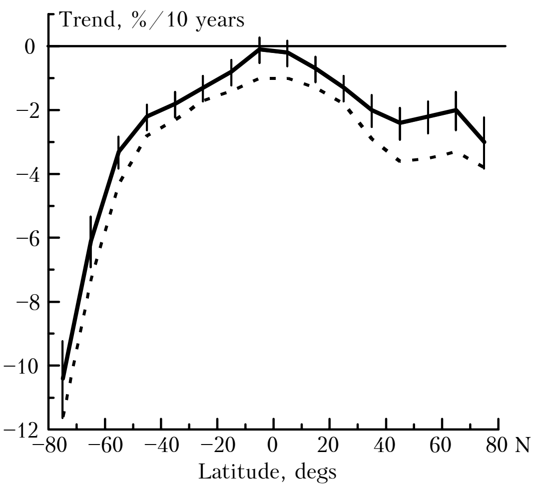

Fig. 6. Zonal mean TOC trends over a period from November 1978 to October 1994 (dashed curve) and from November 1978 to October 1999 (solid line within the error ± 2σ) based on the data of TOMS equipment.

At present scientists have determined the interconnection of variations of the ozone layer and climate-forming factors, in the first place, solar activity,[3,12,18] the phenomenon of El Ninjo/South Oscillation (ENSO),[19] the North–Atlantic Oscillation (NAO).[20,21] In particular, it is well known that the parameters, characterizing the NAO, vary with time that may also manifest itself in the long-term variations of TOC.[22] The problem of variations of water vapor content in the atmosphere and the effect of these variations on the ozone layer is a complicated one and it should be solved.

On the whole, in evaluating the ozone layer condition based on data of satellite observations during the past two decades, the following conclusions can be drawn:

– during the above period the decrease in the global annual mean TOC value is observed. The rate of the decrease is about 2.5% over past decade;

– in midlatitudes and high latitudes of the Northern hemisphere this annual mean TOC value decrease is largely due to the increase in the frequency of occurrence and magnitude of negative anomalies of TOC in 1987–1997. Over the period of 1995–1997 in high latitudes of the northern hemisphere the TOC deficit reached 40%, the duration of anomalies was up to 2 months and the spatial distribution of anomalies spread over a major part of the territory of Russian Federation;

– over the past two years in midlatitudes and high latitudes of the Northern hemisphere the TOC increase is observed up to the values typical for the mid 70s. The process of the TOC increase in the Northern hemisphere during the past two years is of global nature and over the Russian territory it was manifested, in particular, in the disappearance of the major anomaly in the ozone layer that existed over Russia – the spring "Yakut anomaly" – which by a number of characteristics approaches the well-known Antarctic anomaly, as well as in the disappearance of a significant negative trend of TOC over the European territory of Russia;

– the global TOC increase observed in the past two years cannot be explained by the measures taken to eliminate the anthropogenic effect on the ozone layer since this effect is observed under conditions of increased chlorofluorocarbons concentrations in the atmosphere (practically different from the values of concentrations over the before industrially active period);

– in high latitudes of the Southern hemisphere the process of the ozone layer decrease in the spring period continued, at least, prior to 1998, and, probably, to date this process has already completed.

From the above discussion it follows that the currently available scientific concepts on the state and causes of the observed ozone layer evolution are still not understood quite clearly, and, in particular, do not allow one to predict the observed wide fluctuations of the ozone layer. As a result, it is necessary to continue the investigation of ozone problem as a whole. An obligatory criterion for estimating the true value of models, predicting the future changes of the ozone layer, must be their capability of explaining the observation data compiled earlier.

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References

1. H.U. Duetsch, I. Stachelin, Planet and Space Sciences **7**, No. 2, 1587–1599 (1989).
2. WMO, Scientific Assessment of Ozone Depletion, WMO Ozone Rep., No. 37 (1994).
3. WMO, Scientific Assessment of Ozone Depletion, WMO Ozone Rep. No. 44 (1998).
4. A.P. Kapitsa, Atmos. Oceanic Opt. **9**, No. 9, 740–742 (1996).
5. V.V. Zuev, Atmos. Oceanic Opt. **9**, No. 9, 743–744 (1996).
6. G.M. Kruchenitsky, V.I. Bekoryukov, V.M. Voloshchuk, et al., Atmos. Oceanic Opt. **9**, No. 9, 787–792 (1996).
7. O.A. Volkovitsky, A.A. Gavrilov, and O.V. Kaidalov, Bulletin of the Russian Academy of Sciences, **66**, No. 9, 783–786 (1996).
8. *Ozone and Ultraviolet Data for the World* (Canad. Environ. Service / WMO, Downsview–Ontario, 1974–1999).
9. R. McPeters and F. Beach, CD–ROM: NIMBUS7/TOMS Version 7. O_3 data: 1978–1993, NASA Goddard Space Flight Center.
10. R. McPeters and F. Beach, CD–ROM: METEOR 3 / TOMS. Version 7. O_3 and Reflectivity Data: 1991–1994, NASA Goddard Space Flight Center.
11. R. Bojkov, V. Fioletov, and A. Shalamiansky, J. Geophys. Res. **99**, No. D11, 22985–22999 (1994).
12. R.D. Bojkov, V. Fioletov, and A. Shalamiansky, Meteorol. and Atmosph. Phys. **58**, 223–240 (1996).
13. G.M. Dobson, *Exploring the Atmosphere* (Clarendon Press, Oxford, 1968).
14. R. Maduro and R. Schauerhammer, *Ozone: Un trou pour rien* (Alcuin, Paris, 1992), pp. 280.
15. J.C. Farman, B.G. Gardiner, and I.D. Shanklin, Nature **315**, 207–210 (1985).
16. A. Engel, U. Schmidt, SPARC Newsletter, No. 13, 14–16, III (1999).
17. R.D. Bojkov and V. Fioletov, J. Geophys. Res. **100**, No. D8, 16537–16551 (1995).
18. A.A. Chernikov, G.M. Kruchenitsky, A.M. Zvyagintsev, et al., Meteorol. Gydrol., No. 9, 118–124 (1999).
19. A.A. Chernikov, Yu.A. Borisov, A.M. Zvyagintsev, et al., Meteorol. Gydrol., No. 3, 104–110 (1998).
20. A.M. Zvyagintsev and G.M. Kruchenitsky, Meteorol. Gydrol., No. 7, 72–77 (1996).
21. A.M. Zvyagintsev, T.V. Kadygrova, G.M. Kruchenitsky, et al., in: *Proc. of XVIII Quadr. Ozone Symp.* (1996), pp. 101–104.
22. A.M. Zvyagintsev and G.M. Kruchenitsky, Atmos. Oceanic Opt. **10**, No. 9, 654–658 (1997).