ESTIMATES OF THE TREND IN TOTAL OZONE CONTENT OVER EUROPE AND VARIATIONS OF THE GLOBAL CIRCULATION OF THE ATMOSPHERE

A.M. Zvyagintsev and G.M. Kruchenitskii

Central Aerological Observatory, Dolgoprudnyi

Received November 25, 1996

The causes of ozone layer degradation are examined by statistical analysis of time series of total ozone content from European ozonometric stations from 1958 to 1991, including the influence of the Azores anticyclone. It is shown that the dynamic factors must be taken into account in quantitative estimations of the total ozone content trends because the long-period changes of the factors affect the trends significantly. The January pressure at the center of the Azores anticyclone can be used as a dynamic factor determining permanent changes of the annual mean total ozone content over Europe (at least as the first approximation).

At present the fact of the global decrease in total ozone content (TOC) over the past 15–30 years is doubtless. Besides, a sharp increase in local short-lived anomalies (1000–3000 km in extent and lifetime of 2–7 days) was recorded in recent years. However, considering TOC observations 30–70 years ago, one can see that low TOC values close to the present-day ones were observed earlier. Most often, foreign literature[2,3] treats the photochemical decomposition of ozone by chlorine (and partly by bromine) oxides as the main factor of ozone layer depletion. The oxides are accumulated in the stratosphere due to decomposition of the anthropogenic fluorocarbons (freons and halons).

However, the opinion that natural processes leading to changes in global circulation are the primary cause is more and more popular during the past 10–15 years.[9–13] The solution of the problem is not only of a scientific but also of a practical importance for national economies because the steadily increasing rate of ozone layer depletion served as a decisive argument for the so-called Montreal report[1] prohibiting further production and use of freons and halons (since 1996 for Russia). However, dynamical factors, e.g., observed changes of climate-forming atmospheric centers characteristics, in fact were not taken into account in calculations of the rate.[2,3] The dynamic factors strongly influence the ozone layer characteristics in different regions.[14–17] This paper shows how the dynamic factors, namely, variations of the parameters of the most important for the European region atmospheric zones, of the Azores anticyclone, affect the TOC trend estimates for this region.

In calculations, we used the conventional way of computing TOC trends[18–23] by regression analysis of the data from European stations included into the world ozonometric network.[24] The calculations are performed using the following statistical model:

$$X(y) = \text{const} + \text{trend} + \text{QBO} + \text{Solar} + \text{NAO} + \text{Residue}, \quad (1)$$

where $X(y)$ is the annual mean TOC for the year y; trend = $A(y - 1970)$ describes the linear trend; QBO = $B_1 w_{30}(y) + B_2 w_{30}(y + 7/12)$ describes the influence of quasi-two-year fluctuations (QTF); $w_{30}(y)$ is the velocity of the equatorial wind at the level of 30 hPa in Singapore; Solar = $CF_{10.7}$ describes the influence of solar activity; $F_{10.7}$ is the intensity of solar radiation at the wavelength 10.7 cm; NAO = Dp_{an} describes the influence of the North Atlantic fluctuation; p_{an} is the pressure at the center of the Azores anticyclone in January (in the sequel, AAJ pressure); Residue is the time series of the residues; const (A, B_1, B_2, C, D) are constants for the given ozonometric station.

Criteria for the model's quality are presented in Ref. 23. The model differs from the standard one[18–23] by the additional term NAO which, like the QBO term, takes into account variations in the atmospheric dynamics affecting the ozone layer over Europe to a considerable extent. The influence of the Azores anticyclone on TOC seems to be as follows: the increase in monthly mean AAJ pressure is accompanied by a growth of the frequency of Southern advection occurrence that not only decreases ozone content in the lower stratosphere but also leads to ascending vertical flows which cause the ozone decrease too. A detailed treatment of this mechanism may be found in Refs. 15 and 17. The term NAO is introduced into Eq. (1) in the form similar to that of the term describing the influence of the El Nino phenomenon (Southern fluctuation) on TOC[19–20] (this influence is well manifested in the equatorial region but it is insignificant at middle latitudes of the Northern hemisphere, so we do not take it into account).

In this paper, we take the January pressure at the center of the Azores anticyclone as a quantitative parameter of the dynamic processes connected with the influence of the anticyclone. The pressure was considered in Ref. 15 and it well correlates with the index of North Atlantic fluctuation in December–

0235-6880/97/09 654-05 $02.00

March[16] (in model calculations, both factors yield close results but, nevertheless, AAJ pressure turns to be more efficient). From the formal viewpoint, the NAO term is introduced because the time series of Residue obtained traditionally (i.e., by Eq. (1) from which the NAO term is excluded and other terms are retained; certainly, the trend changes here significantly, and the coefficients at other factors do not change so sharply) can be significantly decomposed in the regression form with respect to NAO series for the overwhelming majority of the European ozonometric stations. One should take into account that the observation points used to compute the AAJ pressure are 2000–4000 km far from TOC observation points. So, the factor chosen seems to be only the first approximation suitable for quantitative description of the atmospheric dynamics influence on TOC.

Significant change of climate-forming factors in the atmosphere over the North Atlantic did not manifest themselves strongly during the past decades. It is illustrated by Fig. 1 and Table I. Perhaps, this change, in correspondence with the conclusions of the Intergovernment UN committee on climate changes, was the result of human activity due to, first of all, emissions of carbon dioxide and aerosols.[26] Among the trends presented in Fig. 1, only the trend in the index of North Atlantic fluctuation in May–August is statistically significant at the confidence level $P = 0.95$; but all the trends are significant during 1960–1991. Table I clearly demonstrates that the AAJ pressure trend calculated using linear approximation is distinctly seen for the past years. So, introduction of the AAJ pressure into the model must affect the TOC trend, and practical influence on calculation of the TOC trend can be expected only from the NAO term. The terms QBO and Solar have periods about 28 months and 11 years, so they are practically insignificant in computing trends in middle latitudes of the Northern hemisphere when the time series are longer than 10 years; their influence amplitudes are less than 3 and 2% of the TOC value, respectively.

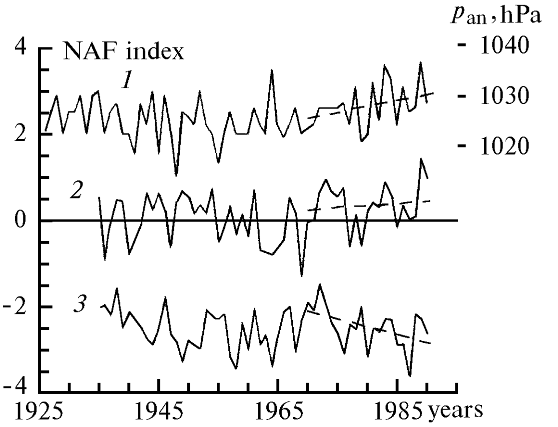

FIG. 1. Temporal behavior of the average January pressure at the center of the Azores anticyclone (curve 1) and mean arithmetic indices of the North Atlantic fluctuation (NAF) from December to March (curve 2) and from May to August (curve 3, shifted down by 2.5). Their linear trends are shown by dashed lines from 1970 to 1991.

TABLE I. Trends of the parameters of the center of the Azores anticyclone in January (pressure and latitude) in different periods.

Period	Pressure		North latitude	
	Average ± RMSD	Trend ± RMSD	Average ± RMSD	Trend ± RMSD
	hPa	hPa/year	degree	degree/year
1891–1991	1024.3 ± 4.7	0.02 ± 0.02	34.9 ± 7.6	0.05 ± 0.05
1960–1991	1025.4 ± 5.1	0.22 ± 0.09	35.1 ± 7.2	0.29 ± 0.13
1970–1991	1026.4 ± 5.0	0.28 ± 0.17	36.9 ± 7.2	0.39 ± 0.24
1979–1991	1027.3 ± 5.8	0.45 ± 0.45	38.3 ± 6.6	0.47 ± 0.51

Table II presents the results of the trend calculation (with the error equal to a doubled rms deviation) for different European ozonometric stations in 1970–1991 and 1979–1991 in the model including and ignoring the NAO term and, for a comparison, data from Ref. 2 (as the data of the most expert foreign sources). After calculations, the regression coefficient of the annual mean TOC with respect to the AAJ pressure throughout the entire observation time turned out to be statistically significant (confidence level $P = 0.95$) for all the European stations (except Brecknell) situated in the latitude zone from 40 to 60°N.

In correspondence with the model (1), in the reviews[2,3] the interpretations of the temporal TOC behavior suppose that, after considering dynamical factors (in practice, only QTF is taken into account) and solar activity influence, the whole TOC trend is caused by the anthropogenic depletion of the ozone layer. So, for comparisons with the results of photochemical model calculations of the ozone decrease ignoring the change of atmospheric circulation, one should subtract the trend connected with varying atmospheric circulation from the total TOC trend. In the report,[3] the trends are computed for the period from January, 1979 to February, 1994. The comparison of trends for this and the previous periods (for instance, 1970–1991[2]) is used to conclude[3] that negative ozone trends sharply increased in recent years (what, in its turn, is thought to be connected with the increase in freon content in the atmosphere). However, this conclusion seems to be insufficiently

TABLE II. Trends in the total ozone content and corresponding regression coefficients with respect to pressure at the center of the Azores anticyclone in January at different European stations in different periods.

Stations, observation years	North latitude, degree	Kind of trend	Ignoring the influence of the Azores anticyclone				Regression coefficient with respect to p_{an} D.u./hPa	With account for AAJ influence	
			1970–1991	1970–1991	1979–1991	1979–1991		1970–1991	1979–1991
			Trend, %/10 years	Trend [2], %/10 years	Trend, %/10 years	Trend [3], %/10 years		Trend, %/10 years	Trend, %/10 years
Reykjavik	64	Annual	0.0 ± 3.8	−0.3 ± 1.4	−3.3 ± 4.0	–	−2.2 ± 2.0	−0.6 ± 1.9	−1.7 ± 1.7
1976–1991		Dec.-March	−0.9 ± 5.7	0.2 ± 2.8	−4.7 ± 7.9	–	−1.5 ± 4.1	−2.4 ± 4.0	−3.3 ± 5.8
Lervik	60	Annual	−1.8 ± 2.2	−0.1 ± 1.4	−7.2 ± 4.6	–	−1.0 ± 2.1	−1.9 ± 1.5	−5.7 ± 3.0
1958–1990		Dec.-March	−0.6 ± 3.0	0.9 ± 3.0	−1.6 ± 6.9	–	−0.6 ± 3.0	−0.7 ± 2.0	0.3 ± 4.4
St.-Petersburg	60	Annual	−4.1 ± 1.6	−3.1 ± 1.0	−5.1 ± 2.7	−6.0 ± 2.3	−3.0 ± 2.7	−2.9 ± 1.5	−3.7 ± 2.5
1973–1991		Dec.-March	−4.9 ± 2.8	−4.5 ± 2.2	−4.7 ± 5.1	−7.4 ± 5.5	−2.7 ± 3.8	−3.3 ± 2.6	−3.7 ± 5.3
Moscow	56	Annual	−2.5 ± 1.8	–	−4.5 ± 3.5	–	−2.1 ± 2.6	−2.1 ± 1.7	−3.5 ± 3.1
1973–1991		Dec.-March	−3.5 ± 2.4	–	−5.3 ± 3.9	–	−2.0 ± 3.0	−2.6 ± 2.3	−4.4 ± 3.5
Bel'sk	52	Annual	−1.4 ± 1.5	−2.2 ± 1.0	−4.0 ± 3.1	−5.5 ± 2.3	−3.0 ± 1.5	−0.7 ± 1.3	−2.5 ± 2.5
1964–1991		Dec.-March	−0.8 ± 2.4	−3.8 ± 2.0	−1.5 ± 4.8	−9.1 ± 5.4	−5.1 ± 2.3	0.5 ± 1.8	1.0 ± 3.6
Brecknell	51	Annual	−1.7 ± 1.6	−3.4 ± 1.0	−4.3 ± 4.1	–	−1.6 ± 2.3	−1.3 ± 1.4	−2.5 ± 3.2
1969–1989		Dec.-March	−2.9 ± 3.0	−4.3 ± 2.0	−4.2 ± 8.5	–	−4.1 ± 3.4	−1.3 ± 2.4	0.9 ± 5.6
Uckl	51	Annual	−1.6 ± 1.6	−2.9 ± 1.2	−3.2 ± 2.8	−4.0 ± 2.2	−2.4 ± 1.8	−1.2 ± 1.2	−1.9 ± 1.5
1972–1991		Dec.-March	−1.6 ± 3.1	−2.5 ± 2.6	−4.7 ± 6.3	−5.9 ± 5.4	−3.2 ± 3.6	−0.7 ± 2.7	−3.2 ± 4.8
Hradec Kralone	50	Annual	−1.2 ± 1.4	−1.8 ± 1.0	−4.1 ± 2.8	−4.9 ± 2.2	−2.7 ± 1.4	−0.7 ± 1.1	−2.6 ± 2.4
1962–1991		Dec.-March	−1.7 ± 2.7	−4.0 ± 1.8	−5.3 ± 5.9	−7.3 ± 5.3	−4.9 ± 3.1	−0.2 ± 2.5	−2.9 ± 5.8
Hohenpeisenberg	48	Annual	−0.5 ± 1.7	−2.3 ± 1.0	−4.6 ± 3.4	−5.2 ± 2.4	−2.4 ± 1.7	−0.4 ± 1.2	−3.2 ± 2.4
1969–1991		Dec.-March	−2.0 ± 3.0	−3.1 ± 2.0	−7.6 ± 6.0	−8.4 ± 4.7	−4.5 ± 3.4	−0.7 ± 2.5	−5.4 ± 5.2
Arosa	47	Annual	−2.0 ± 1.5	−2.4 ± 0.8	−1.3 ± 4.0	−4.5 ± 1.8	−3.4 ± 1.3	−1.0 ± 1.2	0.4 ± 3.0
1958–1991		Dec.-March	−3.0 ± 2.5	−3.4 ± 1.6	−2.9 ± 5.7	−5.9 ± 4.7	−4.7 ± 2.2	−1.2 ± 2.1	−0.7 ± 4.4
Vina-di Valle	42	Annual	−1.6 ± 1.5	−0.8 ± 0.8	−3.4 ± 4.1	−5.6 ± 2.4	−1.9 ± 1.3	−1.4 ± 1.1	−2.3 ± 2.6
1958–1989		Dec.-March	−2.5 ± 2.5	−2.3 ± 1.8	−6.2 ± 5.7	−8.0 ± 4.3	−2.3 ± 2.1	−1.2 ± 2.3	−3.4 ± 5.6
Cagliare	39	Annual	−2.1 ± 2.0	−0.4 ± 1.0	−0.2 ± 5.1	–	−1.3 ± 2.9	−1.8 ± 1.8	0.8 ± 3.4
1958–1989		Dec.-March	−3.6 ± 2.8	−1.8 ± 2.0	−1.5 ± 6.9	–	−0.8 ± 3.0	−2.8 ± 2.5	−0.6 ± 4.7

justified due to incomplete consideration of the dynamic factors' change and influence of volcanic eruptions.

In our opinion, grounds for the conclusion about durable TOC changes can be obtained only from a more comprehensive analysis of time TOC series, especially the longest ones. First of all, it is the coincidence of experimental results with *a priori* model predictions. In statistical analysis of the observation series, there are difficulties connected with their limited duration and well-known in classical climatology (where it is conventionally accepted to work with time series of at least 100 and more years duration) and mathematical statistics. As applied to analysis of TOC series, these difficulties are aggravated by two following facts.

The first is that, in the past two decades, the global TOC was affected at least twice by powerful short-time forcings. They are eruptions of the volcanos El Chichon (1982) and Pinatubo (1991).

The second fact is that the analyzed series are inhomogeneous to a considerable extent due to a variety of measuring devices for TOC and some specific metrological and methodical difficulties (the measurement errors at different ozonometric stations are not known even for the initiators, although it is well-known that they differ from each other and arbitrarily vary in time). So one should consider the values of calculated TOC trends very carefully, regardless of the calculation technique used. Taking into consideration the trends for the period from the end of 1991 to the beginning of 1994, as it is done in Ref. 3, seems to be incorrect because of the action of the Pinatubo eruption,[27–29] the strongest in the 20th century, on the ozone layer in 1992–1994. So, in this paper, the calculation period is limited by 1991. As seen from Table II, the results of our calculations ignoring the AAJ pressure well agree with those in Ref. 2. If the pressure is taken into account, the trends considerably decrease (on the average, by 0.7 and 1.7% for 10 years in 1970–1991 and 1979–1991, respectively); their statistical significance also decreases.

Figure 2 presents the temporal TOC behavior as it follows from observations during the whole period shown in the Table and the regression model taking into account the linear trend, AAJ pressure, and QTF for Arosa and Hohenpeisenberg.

The root-mean-square deviations (RMSD) of the initial annual mean TOC series in Arosa and Hohenpeisenberg are 6.8 and 8.0 Dobson units. The change of the time regression and QTF by expansion over AAJ pressure and QTF leads to a decrease in the RMSD of residual series in Arosa and Hohenpeisenberg from 5.4 and 7.3 to 5.0 and 6.4 D.u., respectively. This demonstrates that, for both stations, the efficiency of the regression expansion over AAJ pressure is noticeably higher as compared to that over time, and it is (jointly with QTF) about 0.4.

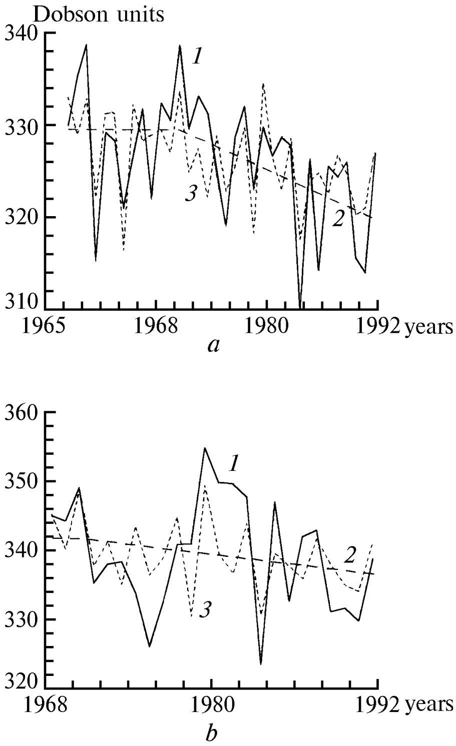

FIG. 2. Temporal behavior of the total ozone content, observational results (curve 1), the model of the piecewise linear trend beginning from 1970 (broken line 2) and the regression model of the total ozone content, including quasi-two-year fluctuations and January pressure at the center of the Azores anticyclone (curve 3), in Arosa (a) and in Hohenpeisenberg (b).

Thus, as follows from the data presented, the Atlantic action center of the atmosphere, i.e., the Azores anticyclone, is a significant source of TOC field perturbations for the European region what well agrees with the results of other investigations.[15–17] The contribution of changes in the North Atlantic fluctuation parameters must be taken into account for a correct quantitative description of the long-term behavior of the total ozone content at middle latitudes of the Northern hemisphere, at least for the European region.

The use of January pressure at the center of the Azores anticyclone as a dynamic factor seems to be not optimal, and one can propose more efficient atmospheric parameters which will improve quantitative estimates of the atmospheric dynamics influence on the ozone layer. Nevertheless, even the calculated the results on TOC trend with the account for pressure at the center of the Azores anticyclone in January demonstrate that:

1. The global circulation of the atmosphere must be taken into account in a quantitative description of the temporal behavior of total ozone content. Their variations are essentially connected with those of the

total ozone content. Long-term variations of these dynamical factors can significantly influence the trends' numerical values in quantitative estimations of the TOC trends.

2. The pressure in January at the center of the Azores anticyclone can be used as a dynamic factor determining long-term variations of annual mean total ozone content over Europe (at least as the first approximation). With the allowance for it, the calculated trend value decreases by 1–2% per 10 years for the past 10–20 years.

For other regions, there are apparently similar climate-forming meteorological factors (connected, for instance, with the Siberian and Aleutian anticyclones[17]) that significantly determine the long-term ozone layer variations.

ACKNOWLEDGMENTS

The authors are thankful to J. Staehelin and A. Renaud from the Swiss Federal Institute of Atmospheric Studies, Zurich, for the presented data on TOC in Arosa, and to V.I. Bekoryukov and an anonymous reviewer for helpful remarks.

The work was performed in spite of the refuse of the Russian Foundation for Basic Research (project 96–7–89508) to financially support it.

REFERENCES

1. E.L. Aleksandrov, Yu.A. Israel', I.L. Karol' et al., *The Earth's Ozone Shield and Its Variations* (Gidrometeoizdat, Leningrad, 1992), 288 pp.
2. WMO. *Scientific Assessment of Ozone Depletion: 1991*, in: WMO Ozone Rep. No. 25 (Geneva, 1991).
3. WMO. *Scientific Assessment of Ozone Depletion: 1994*, in: WMO Ozone Rep. No. 37 (Geneva, 1995).
4. *Bulletin on the Ozone Layer State*, No. 1–10 (Central Aerological Observatory, Dolgoprudnyi, 1991–1997).
5. H.U. Duetsch and J. Staehelin, Planet. and Space Sciences **37**, No. 12, 1587–1599 (1989).
6. K. Henriksen, E.I. Terez, G.A. Terez, et al., J. Atmos. Terr. Phys. **55**, 145–154 (1993).
7. G.M. Dobson, Appl. Opt. **7**, No. 3, 387–405 (1968).
8. A.A. Gavrilov and O.V. Kaidalov, Adv. Space Res. **17**, No. 11, (11)157–(11)160 (1996).
9. H.W. Ellsaesser, Atmos. Environ. **16**, No. 2, 197–205 (1982).
10. H. Claude and W. Steinbrecht, in: *Polar Stratospheric Ozone. Proceedings of the Third European Workshop 18 to 22 September 1995* (Schliersee, Bavaria, Germany, Brussels–Luxemburg, ECSC–EC–EAEC, 1996), pp. 502–505.
11. D. Peters and G. Entzian, Meteorol. Z.N.F. **5**, No. 1, 41–44 (1996).
12. G.M. Kruchenitskii, V.I. Bekoryukov, V.M. Voloshchuk, et al., Atmos. Oceanic Opt. **9**, No. 9, 787–792 (1996).
13. E.A. Zhadin, Meteorol. Gidrol., No. 7, 36–48 (1996).
14. V.I. Bekoryukov, G.R. Zakharov, A.A. Kukoleva et al., Meteorol. Gidrol., No. 12, 103–105 (1990).
15. V.I. Bekoryukov, I.V. Bugaeva, G.R. Zakharov, et al., Izv. RAN, Fiz. Atmos. Okeana **31**, No. 1, 41–45 (1995).
16. A.M. Zvyagintsev and G.M. Kruchenitskii, Meteorol. Gidrol., No. 7, 72–77 (1996).
17. V.I. Bekoryukov, I.V. Bugaeva, G.R. Zakharov, et al., Atmos. Oceanic Opt. **9**, No. 9, 793–796 (1996).
18. R.S. Stolarski, P. Bloomfield, R.D. McPeters, et al., Geophys. Res. Lett. **18**, 1015–1018 (1991).
19. W.J. Randel and J.B. Cobb, J. Geophys. Res. **99**, No. D3, 5433–5447 (1994).
20. G.C. Reinsel, G.C. Tiao, D.J. Wuebbles, et al., J. Geophys. Res. **99**, No. D3, 5449–5464 (1994).
21. J.W. Krzyscin, J. Geophys. Res. **99**, No. D7, 14527–14534 (1994).
22. R. Bojkov and V.E. Fioletov, J. Geophys. Res. **100**, No. D8, 16537–16551 (1995).
23. T.V. Kadygrova and G.M. Kruchenitskii, Izv. RAN, Fiz. Atmos. Okeana **31**, No. 1, 62–68 (1995).
24. *Ozone Data for the World,* Downsview–Ontario: Canad. Environ. Service, WMO (1974–1996).
25. New Scientist **148**, No. 2007, 6 (1995).
26. R.D. Bojkov, C.S. Zerefos, D.S. Balis, et al., Geophys. Res. Lett. **20**, No. 13, 1351–1354 (1993).
27. J.B. Kerr, D.I. Wardle, and D.W. Tarasick, Geophys. Res. Lett. **20**, No. 18, 1979–1982 (1993).
28. W.D. Komhyr, N.D. Grass, R.D. Evans, et al., Geophys. Res. Lett. **21**, No. 3, 201–204 (1994).