# ON CONTRIBUTION OF DYNAMIC PROCESSES TO THE FORMATION OF ABNORMALLY LOW TOTAL OZONE IN THE NORTHERN HEMISPHERE

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*Reasons for the ozone layer depletion have been investigated by means of a statistical analysis of vertical ozone profile variations at nine stations of the Global Ozone Network (including four Canadian, American, three Japanese, and German stations) and time series analysis of total ozone at twenty-five stations, including the longest time series started at Arosa, Switzerland, in 1926. Significant positive trends of the height (at seven stations) and width (at five stations) of the ozone maximum (for the significance level $P = 0.95$) have been revealed; at the other stations the trends are shown to be insignificant (but positive too). An analysis of the most significant forty-one total ozone anomalies indicates that practically always the ozone depletion becomes most pronounced below the ozone maximum. The widespread model description of the total ozone time series by "hockey stick" is not statistically optimal. The dynamic mechanism of the ozone depletion should dominate over the anthropogenic one. The existing observational data are insufficient for adequate description of the long-term ozone depletion tendencies, to say nothing of their reasons (or the data are too noisy). The adequate temporal description of the total ozone should consider the global climate changes.*

The fact of the total ozone (TO) depletion is generally recognized nowadays.[1–3] In particular, on a global scale it is manifested through much more frequent cases of negative ozone anomalies (holes).[4] Photochemical ozone destruction by chlorine (and partly bromine) oxides accumulated in the stratosphere after destruction of anthropogenic halocarbons (freons and halides) are usually considered in foreign literature[1–3] as the principal reason for the ozone layer destruction. However, an analysis of concrete TO anomalies in the northern hemisphere demonstrates that they can be satisfactorily explained by dynamic processes in the atmosphere and climate changes in the character of atmospheric circulation, whereas the anthropogenic influence can be only added[5–10] (the influence of chlorine oxide on the formation of ozone anomalies is argued only for the Antarctic,[3,7] but this conception is also open to question[11,12]).

Successful prediction of global ozone layer behavior for at least 5–10 years ahead instead of generally accepted forecasts for many decades could be a serious argument in favor of a particular version. It is also necessary to explain the sharp increase of the frequency of local short-lived anomalies (1000–5000 km in extent and 2–7 days in lifetime)[4] and the transformation of vertical ozone profiles (VOPs). Meanwhile, the character of evolution and disappearance of ozone anomalies over the territory of the former USSR in recent years[4] favors the dynamic version. For instance, by comparing the maps drawn in Figs. 1*a* and *c*, one can see topographical closeness of TO isopleths in "quiet" 1994 with isopleths of the climatic norm as well as sharp differences of the latter with isopleths of abnormal 1995. It is difficult to explain this fact from the viewpoint of the anthropogenic version because for two-month averaging one should expect only the change of the TO nominal values rather than rotation of isopleths.

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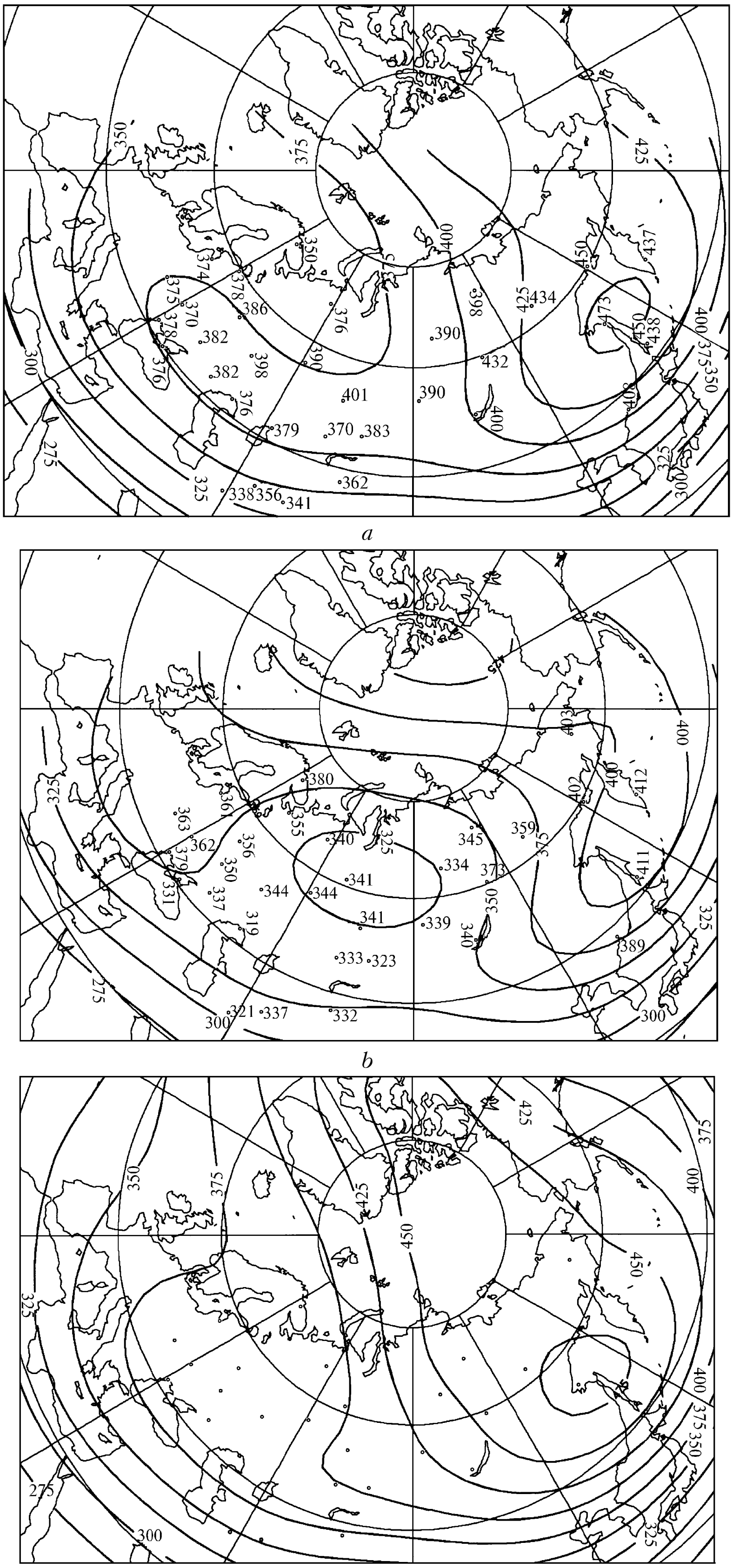

*a*

*b*

*c*

*FIG. 1. Maps of total ozone distribution over the territory of the former USSR averaged over periods from February* 1 *to March* 31 *of* 1994 *(a) and* 1995 *(b) and climatic norms (c) in Dobson units.*

*TABLE I. Values and trends of the height and width of the vertical ozone distribution maximum recorded at ozonometric stations of the northern hemisphere.*

| Station | Country | °N | Observation period | Maximum height | | | | Maximum width | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | $m$, km | $A_H$, m | Trend, m/year | $Q$ | $W$ | $A_W$, m | Trend, m/year | $Q$ |
| 1 Kagoshima | Japan | 32 | 12/68–08/93 | 24.5 | 750 | 24±22 | 0.27 | 4.1 | 230 | 22 ±16 | 0.12 |
| 2 Tateno | Japan | 36 | 11/68–08/93 | 22.8 | 1220 | 57±30 | 0.42 | 5.1 | 180 | 7±12 | 0.11 |
| 3 i.Wallops | U.S.A. | 38 | 05/70–04/93 | 23.4 | 1480 | 12±24 | 0.50 | 4.7 | 300 | 2±10 | 0.17 |
| 4 Sapporo | Japan | 43 | 12/68–08/93 | 21.9 | 1600 | 15±44 | 0.25 | 4.9 | 250 | 15±20 | 0.10 |
| 5 Höhenpeisenberg | Germany | 48 | 09/69–08/93 | 22.0 | 1750 | 26±22 | 0.73 | 4.8 | 550 | 1±8 | 0.54 |
| 6 Goose | Canada | 53 | 06/69–08/93 | 20.6 | 1870 | 36±28 | 0.50 | 4.7 | 490 | 20±14 | 0.18 |
| 7 Edmonton | Canada | 53 | 10/70–08/93 | 21.1 | 1310 | 40±26 | 0.37 | 4.3 | 440 | 29±10 | 0.37 |
| 8 Churchill | Canada | 58 | 10/73–08/93 | 20.1 | 1740 | 40±36 | 0.47 | 4.7 | 460 | 27±12 | 0.36 |
| 9 Resolute | Canada | 75 | 01/66–07/93 | 18.3 | 1230 | 22±18 | 0.42 | 4.4 | 250 | 20±7 | 0.22 |

In this paper, reasons for the ozone layer depletion are elucidated by way of analysis of temporal changes of the VOPs. This is based on the fact that different reasons for the ozone layer depletion must differently influence the change of the ozone concentration at different levels.[1–3,5,6] Since regular and sufficiently high-quality measurements of the VOPs have been performed with electrochemical ozonesondes carried aloft by aerological balloons at some stations of the Global Ozone Network (at present they are more than 40 in number) during more than 30 years, it is natural to expect that, according to the opinion of many specialists,[6,13] it is precisely these measurements that have much potential for yielding earliest and persuasive information about the reasons for ozone layer changes.

The initial data of vertical ozone sounding for the present analysis were taken from the databank of Ref. 14. We analyzed only the data recorded at the stations of the northern hemisphere for more than 20 years (see Table I). Two parameters of VOPs, namely, the height $H$ and width $W$ of the ozone maximum were analyzed. The width of the maximum is taken to mean the vertical extent of the layer in its vicinity $(H-W/2,\ H-W/2)$ in which quarter of total ozone amount is contained. The incompleteness of the initial data was as follows: for all Japanese stations, the relative number of months without ozonesonde launching was about one third; for other stations, it varied from 0.014 in Höhenpeisenberg to 0.14 in Resolute. The trend and the seasonal behavior of both parameters were determined by the standard procedure.[15]

The results of the analysis of the above-mentioned VOP parameters are presented in Table I (in addition, the expansion efficiency $Q$ (see Ref. 16) and the average annual amplitudes $A_H$ and $A_W$ are also given; the errors are presented for the confidence level $P = 0.95$). A positive trend of the ozone maximum height is seen at all nine stations. It proves to be insignificant only at two stations; the largest trend is observed at mid-latitudes (50°–60°N) and the smallest trend is observed near the equator. A trend of the maximum width is also positive but insignificant already at four stations. A significant positive trend for the maximum width is observed at middle and high latitudes of the northern hemisphere; it becomes insignificant closer to the equator. The observed temporal changes of the ozone profile shape near the ozone maximum in general correspond to those obtained in Refs. 17–19.

At present, there are the following explanations of the observed TO changes[1–6]: 1) decrease of productivity of the active photochemical layer when photodissociation products of ozone-destructive compounds are included in the ozone cycle; 2) conservation of anthropogenic ClO followed by its release in formations similar to polar stratospheric clouds (PSC; this factor is a widespread explanation for the formation of the well-known Antarctic hole); 3) southern advection of air masses leading to TO depletion due to the decrease of the ozone amount in the altitude range below the local climatic maximum. Each of them must modify the shape of the VOP in a different way.

In the fundamental survey,[1] it was established that the ozone layer depletion caused by anthropogenic factors occurs primarily in the photoactive layer located near 40 km. In this case, the effect of ozone "corrosion" should spread from top to bottom and lead to lower ozone maximum height.[2,3] The second of the above-enumerated factors must lead to corrosion of the ozone concentration maximum in the altitude range corresponding to PSC location (this leads to corrosion of the maximum center and its bifurcation in the Antarctic). As for dynamic reasons that are mainly reduced to more frequent penetration (advection) of low-latitude air masses relatively deficient in ozone[13] into higher latitudes, they must lead to the TO depletion and increase of the VOP maximum height.

All the considerable TO anomalies in Europe recorded by the National and Global Ozone Networks in the last decade were accompanied with intrusion of subtropic air masses. This fact is a very important argument in favor of the dynamic version of ozone layer changes.

To study actually observed changes of VOPs under conditions of abnormally low TO values for each station, the profiles corresponding to minimum TO values observed on the days of ozonesonde launching were investigated.[20] We analyzed the anomalies with the ozone deficiency being equal to two or more standard deviations (or 15% or more) of the climatic norm corresponding to the examined date (in all, 41 anomalies were analyzed; the results were presented more comprehensively in Ref. 21). Figure 2 shows the salient features of deviations of the observed VOPs as compared with climatic ones for some anomalies characterized by negative deviations $d$ from the TO norm in units of $\sigma$.

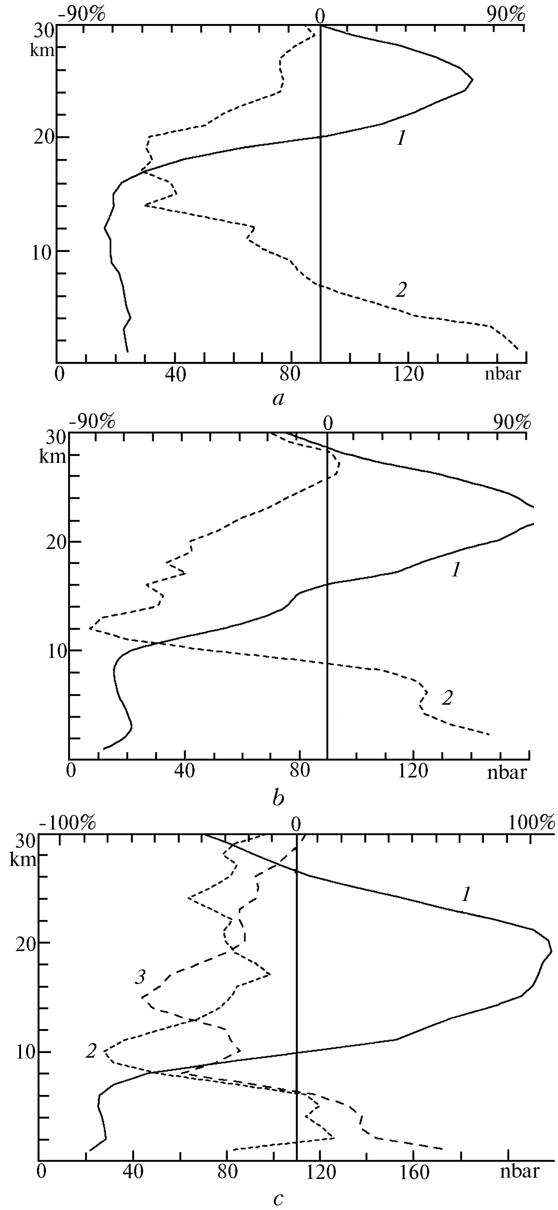

*FIG. 2. Climatic vertical ozone profiles (1) and observed deviations (2 and 3, in per cent of the norm) on the days of TO anomalies at different observation stations: a) Kagoshima* 22.02.89, *TO is* 302 D.u., $d = 2.7\sigma$; *b) Höhenpeisenberg* 22.01.93, *TO is* 342 D.u., $d = 2.3\sigma$; *c) Resolute* 04.04.90, *TO is* 468 D.u., $d = 2.9\sigma$ *(2);* 31.03.93, *TO is* 471 D.u., $d = 2.8\sigma$ *(3).*

Figure 2 demonstrates that the maximum ozone deficiency was observed in the altitude range below the climatic maximum for all anomalies. In practice this means that the TO anomalies at middle latitudes of the northern hemisphere are primarily caused by advection of air masses as described in Refs. 5, 8, and 13. Judging from the shape of VOP, the influence of photochemical heterogeneous factors cannot be excluded for only one ozone anomaly (on March 31 of 1993 at the station Resolute, Fig. 2*c*). However, qualitative similarity of the examined situations at all latitudes and the absence of the Antarctic dip at the maximum makes the assumption about PSC contribution to the examined TO anomalies in the northern hemisphere doubtful.

Since the anomalies appear in the lower dynamically controlled part of the ozone layer, the changes of the meridional ozone transfer from the tropical zone to high latitudes should be considered as the reason for the anomalies[6] (if there are no photochemical reactions being several hundred times more intensive as compared with those known until now). We are unaware of the experimental data confirming any influence of the decrease of active photochemical layer productivity caused by freon photodissociation.

The positive trend of the ozone maximum width (as defined in the present paper) means that the ozone depletion in the region of its maximum occurs more intensive than far from it. The established character of the trend of both parameters is naturally interpreted as evidence of more frequent intrusions of low-latitude air masses into higher latitudes. From this viewpoint, one can explain the considerable increase of the number of ozone anomalies observed recently due to long-term (with characteristic times of a few decades) changes of the standard meteorological parameters[9] determining the global atmospheric circulation. On the other hand, this behavior of the height and width of the VOP maximum is difficult to understand from the viewpoint of the anthropogenic version because the reasoning similar to that used for explaining the corrosion of the maximum in the Antarctic hole seems to be doubtful at the latitudes where the overwhelming majority of stations being analyzed in this paper are situated.

As a rule, there are no reasons similar to Antarctic ones for the appearance of ozone anomalies at temperate latitudes of the northern hemisphere because of the absence of extremely low temperatures in the stratosphere, which makes the PSC formation difficult and results in lower efficiency of heterogeneous chemical reactions. If the anthropogenic reasons of ozone layer exhaustion are nevertheless supposed to be determining factors, one can naturally expect that this depletion will be approximately uniform for most part of the northern hemisphere.

Meanwhile, observations demonstrate that considerable anomalies are localized. For instance, this is the case for winter-spring anomalies over North-Western Europe and for the anomaly over Siberia in

1995 (Fig. 1*b*). The latter was unprecedented not only in the level of TO deficiency but also in the territory.

Although in Ref. 22 the conclusion was drawn that dynamic factors can explain only 70% of the observed TO depletion in spring of 1995 over Siberia (in order to attribute the rest 30% to possible action of the anthropogenic mechanism), it should be noted that these estimations are incomplete.[5] They do not consider nonlinearity of influencing factors (e.g., the stratospheric temperature), and their errors are comparable to the estimation of the effect itself. The fact that the smallest TO values over Siberia were accompanied, as could be expected,[5] by the appearance of a ridge in the troposphere and the lower stratosphere in this region[23] testifies that the dynamic factors predominate in the latter case.

These conclusions are also confirmed by an analysis of the time TO series, especially the longest ones. In this analysis, difficulties emerge connected with limited length of observation series that are well known in classical climatology (where it is generally accepted to operate with series of 100 and more years) and mathematical statistics. As applied to the analysis of TO series, the difficulties are aggravated by two additional facts. First, there were two strong short-time impacts upon the examined process in the last fifteen years: eruptions of El Chichon (1982) and Pinatubo (1991) volcanos. Second, the examined series are highly diverse because of a variety of hardware used for TO measurements and some specific metrological and methodical difficulties (the measurement errors at different ozonometric stations are not known even for the initiators of these measurements although it is known that they differ and change uncontrollable in time). So one should carefully estimate the values of the TO trends obtained by numerical modeling with series of about 30 years; this is not the case for many present-day papers.[2,3]

The analysis of the available TO series demonstrates the following:

1. The “hockey stick” model[3] being often used to describe the temporal TO behavior since 1957 and illustrating the recent increase of the TO depletion rate is statistically unsubstantiated, for instance, with respect to the model with the quadratic trend.

2. To describe the temporal TO behavior in the last 30 years at most of the stations of the northern hemisphere (data of 25 most authoritative stations were analyzed), the TO behavior $Q(t)$ with preliminary separated seasonal behavior is statistically preferable. Its form is the quadratic trend $Q(t) = -At^2 + Bt + C(t)$, where $A$ and $B$ are constants and in the weak dependence $C(t)$ on time $t$, one can resolve impacts of different regressors (quasi-two-year oscillations, North-Atlantic oscillations, solar activity, etc.). For the model with the quadratic trend, the maximum of ozone concentration falls within 1950–1960 years, i.e., is at the beginning of global observations of the ozone layer. Such a description shows that in ozone temporal behavior oscillations can be probably observed with periods of 80 or more years (their indications were manifested through the parameters of the Açores anticyclone, the ground temperature in London,[9] etc.).

3. The results of direct analysis of the longest experimental TO series (in Arosa, Switzerland, since 1926)[24] also indicate the existence of the TO maximum in 1950–1960 (Fig. 3, curve *1*), i.e., in the years that also correspond to the model with the quadratic trend at more than twenty ozonometric stations of the northern hemisphere when no influence of anthropogenic freons was recorded. The activity minimum of the Açores anticyclone having strong effect on the TO behavior in Europe[9] was also observed in these years (we note that the correlation coefficient for curves *1* and *2* in Fig. 3 is 0.94). No inhomogeneities of the time TO series in Arosa since 1926 were discovered by statistical analysis. This indirectly confirms the high quality of the observation series.

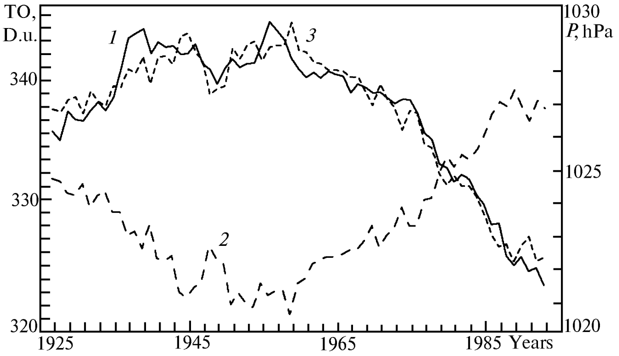

*FIG. 3. Temporal behavior of TO in Arosa (1) and pressure in January at the center of the Açores anticyclone (2) averaged by the sliding average method over* 11 *years. Curve 3 is the regression model of TO for Arosa including pressure at the center of the Açores anticyclone in January, latitude of the center location, and time as regressors.*

This does not mean that one must choose the dynamic version, but the pure anthropogenic version must be completely excluded; as for the combined version, the dynamic mechanism must predominate over the anthropogenic one. Available observation data are, as before, insufficient for assured determination of long-term trends of the ozone layer changes (or they are very noisy) to say nothing of their reasons. When estimating the models of ozone layer depletion by their comparison with observation results, one should first of all take into consideration how adequately they can predict already observed temporal behavior of both TO and VOP (the latter is richer in salient features). Adequate description of the temporal TO behavior can be obtained only for a model considering the observed climate changes.

Thus, the study of long-term changes of VOPs, individual anomalies, and longest TO series demonstrates that the decisive contribution to the formation of abnormally small TO values in the northern hemisphere is caused by dynamic processes, primarily more frequent cases of southern advection. This probably confirms long-term changes in processes of global circulation. The existing mechanism of formation of negative anomalies in the TO field leads to increase of UV–B irradiance of the Earth's surface during these anomalies as compared with the mechanism considered earlier[1–3] (the anthropogenic exhaustion of productivity of the photochemically active layer). This is connected with stronger attenuation of UV radiation at low altitudes due to effects of multiple molecular scattering.

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