ANOMALIES AND TRENDS IN THE OZONE CONTENT IN 1979–1992

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Received March 30, 1998

Based on the satellite TOMS (version 7) data on the total ozone content the monthly mean anomalies and trends are investigated on the global scale for different seasons in 1979–1992 with a special emphasis on the longitudinal structure. In contrast to analyses by Randel and Cobb [J. Geophys. Res. **99**, *5433–5447 (1994)] and Stolyarski et al. [Geophys. Res. Lett.* **18**, *1015–1018 (1991)], the linear trends in the total ozone are calculated; the interannual anomalies are analyzed by means of calculation of several empirical orthogonal functions that describe most of the substantial features of the interannual variability. The total ozone anomalies and trends are shown to be significantly variable, especially in the middle and high latitudes of the Northern Hemisphere during winter/spring, when the stationary planetary waves may penetrate into the stratosphere. Together with the global ozone depletion, the local positive trends of the total ozone are revealed in some regions (for example, northwestward from Greenland in January and southward from South Africa in July). These trends can be associated with interannual variations of the stratospheric wave activity. The effect of long-term variations in the ocean–atmosphere system on interannual and decade-scale variations of the ozone layer is discussed.*

INTRODUCTION

Numerous observations[3] have shown that the depletion of the ozone layer occurs permanently during two last decades. The interannual ozone variations in the atmosphere strongly vary depending on a season, latitude, and longitude. This evidences of the fact that not only anthropogenic factors affect the ozone layer, but also natural long-term variations of the atmosphere can play a significant part in the observed ozone trends. The mechanism of natural long-term variations of the ozone layer is related to the interannual and decade-scale variations in wave activity of the atmosphere, especially with the vortex ozone and heat transfer by stationary planetary waves.[4–6] The total ozone trends were estimated earlier from the measurements made both at the ground-based stations[7] and from satellites.[2] The results have shown that the largest negative trends of the ozone content are observed in the ozone hole area over Antarctic and in the middle and high latitudes of the Northern Hemisphere in winter and spring. The relations between the ozone content variations and known geographical indicators were analyzed as well. Among such indicators there are the long-term trends, the cause of which was *a priori* assumed to be anthropogenic; quasi-biennial cycle; index of Southern Oscillation describing the phenomena of El Niño/La Niño; and the 11-year cycle of the solar activity.[1,2] Note that the results of the regression analysis[1,2] with the aim to separate out the response of the ozone layer to these geophysical indicators may contain some ambiguities due to the effects from other unknown factors in the ocean–atmosphere interacting system[4,8] on the ozone layer anomalies. The results of these investigations were mostly presented for zonal mean values without analyzing the longitudinal nonuniformity in the trends and interannual variations of the ozone content.

The purpose of this paper is to study the interannual anomalies and trends of the ozone content for different seasons based on the TOMS data and to analyze their longitudinal structure.

THE DATA USED AND METHOD OF CALCULATION

In our calculations we have used the data acquired with the satellite TOMS (version 7) on the ozone content measured in 1979–1992 with the 1.25×1° resolution in latitude and longitude. Comparison with the data measured at the ground-based network[3] has shown good agreement within the 2–4% error.[3] However, unlike the ground-based measurements, the satellite data allow analysis on the global scale. The

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monthly mean data were used, and deviations (anomalies) from the mean values for every month averaged over 1979–1992 were calculated taking into account the large seasonal differences in interannual variations and trends of the ozone content. To study the trends, a uniform data array should necessarily be used. Therefore, we analyzed only the ozone variations measured from 1979 to 1992, because then TOMS measurements were stopped.[3]

The data array is the function $f(x, y, m, t)$, where x is the longitude, y is the latitude, m is the month, and t is the year. The monthly mean values of the ozone content were calculated for $n = 14$ years

$$\bar{f}(x, y, m) = \frac{1}{n} \sum_{t=1}^{n} f(x, y, m, t) \qquad (1)$$

along with their anomalies

$$f'(x, y, m, t) = f(x, y, m, t) - \bar{f}(x, y, m). \qquad (2)$$

Linear trends were calculated by use of the following procedure. Let we have some data $y_1, y_2, \ldots, y_n$ measured at the times $1, 2, \ldots, n$. The regression equation can be written in the form

$$y = \bar{y} + \hat{\omega}(t - \bar{t}), \qquad (3)$$

where

$$\bar{y} = (1/n) \sum_{t=1}^{n} y_t; \qquad \bar{t} = (n + 1)/2,$$

and the slope of the linear regression (the trend rate) can be written as

$$\hat{\omega} = \sum_{t=1}^{n} (t - \bar{t})(y_t - \bar{y}) / [\sum_{t=1}^{n} (t - \bar{t})^2]. \qquad (4)$$

Deviations from the measured data can be determined as

$$r_t = y_t - [\bar{y} + \hat{\omega}(t - \bar{t})].$$

The degree of freedom is $n - 2$, and the variance is equal to

$$s^2 = \frac{1}{n-2} \sum_{t=1}^{n} r_t^2 .$$

The standard error of the trend estimates is

$$SE(\hat{\omega}) = s / \sqrt{\sum_{t=1}^{n} (t - \bar{t})^2} . \qquad (5)$$

It can be shown[9] that the trend estimates are statistically significant, at the 95-% probability level, when doubling the standard error $\hat{\omega} \pm 2SE(\hat{\omega})$, i.e. at the 2σ level.

In contrast to Refs. 1 and 2, we did not assume *a priori* some relations between the ozone variations and known anthropogenic or natural factors. The high-frequency seasonal fluctuations were removed by calculating anomalies and trends of the ozone content for each month of the period from 1979 to 1992 separately.

To separate out the principal features of the ozone layer evolution, we have calculated several first empirical orthogonal functions (EOFs)[10] of the ozone content anomalies for winter and spring of the Northern and Southern hemispheres. These calculations may be useful for investigation of the relations between the observed ozone layer anomalies and long-term natural[8,5,11] and anthropogenic variations of the atmospheric parameters, as well as for estimation of their relative contribution into the ozone trends in different regions of the Earth.

CALCULATED RESULTS

The processes of both regular and vortex transfer strongly affect the ozone distribution in the atmosphere and its interannual variations. The stationary planetary waves, which penetrate from the troposphere into the stratosphere in winter and spring, cause longitudinal inhomogeneities in the distribution of the total ozone content. Generation of stationary planetary waves occurs due to the orographic and thermal excitation, which depends on the long-term variations of the ocean temperature. The interannual and decade-scale variations in wave activity of the atmosphere may lead to significant variations in the ozone distribution, including that during the formation of the ozone hole over Antarctic.[5,11–13] So the longitudinal asymmetry manifests itself not only in the interannual variation of the ozone content, but also in the ozone trends, especially in winter and spring.

The rates of change of the ozone content (trend) calculated by Eq. (4) are shown in Fig. 1 for some months in the period from 1979 to 1992. It is seen that the trends are mostly negative, i.e. the global decrease of the ozone layer took place from 1979 to 1992. The strongest ozone decrease (down to 30–50% of the values observed in late 70s) occurred over Antarctic in the ozone hole area in September and October. The maximum of the negative trends in the Northern Hemisphere is observed over North Atlantic, Europe, Russia, the Aleuts, and in the USA midlatitudes. The estimates of the standard errors (5) have shown that these trends are statistically significant at the 95-% probability level. In February, the negative trends become more intense in the middle and high latitudes of the Northern Hemisphere. Note that some positive trends of the ozone content (1–2 D.u. per year) are observed in January northwestward from Greenland.

The intraseasonal variability is observed in the areas with positive ozone trends. For example, a small increase in the ozone content took place northeastward of Caspian Sea in 1979–1992. The analysis has shown that these positive trends are not statistically significant. A slight positive trends (~ 0.5 D.u. per year) have also been observed in some regions of the Northern Hemisphere in summer. As to the Southern Hemisphere, strong negative trends are observed in September–October over Antarctic, and some weaker ones are observed in the middle and high latitudes. The latter trends are characterized by almost zonal symmetry.

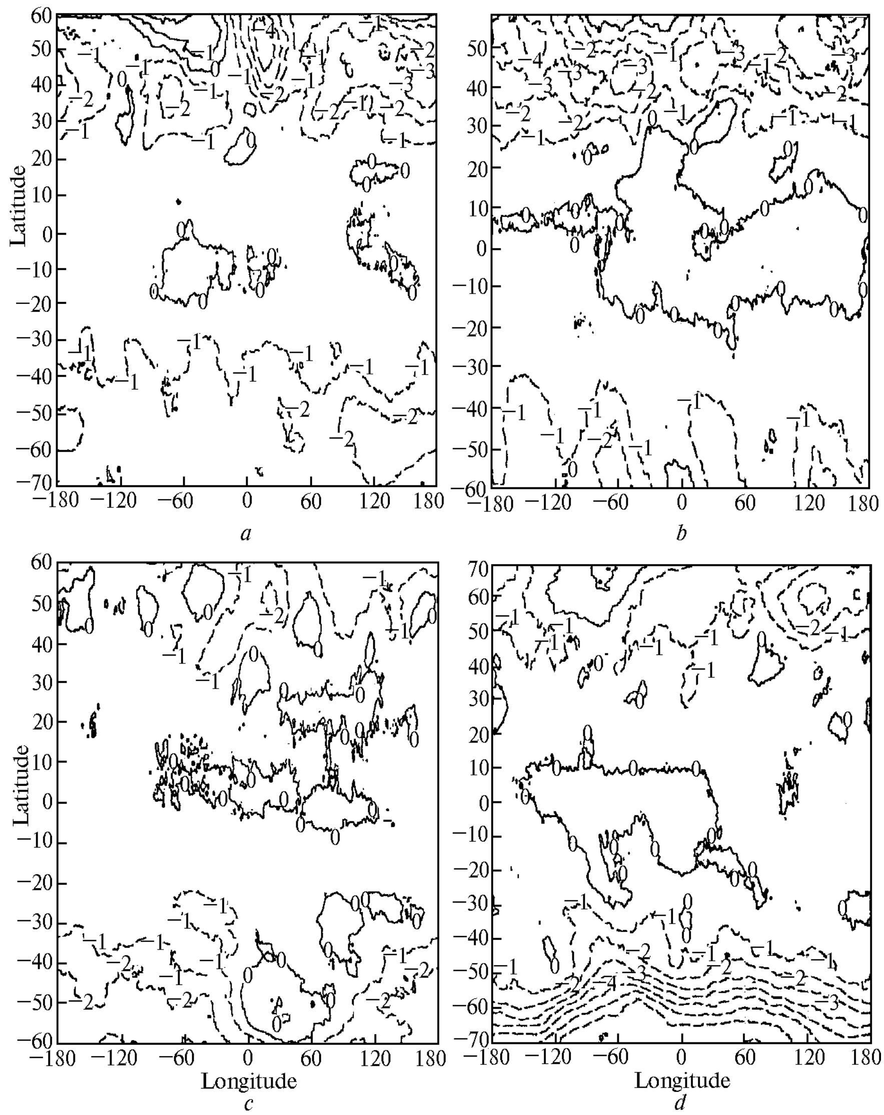

FIG. 1. Trends of ozone content, in D.u. *per year, for January (a), February (b), July (c), and October (d) in 1979–1992.*

The positive trends (~ 0.5 D.u. per year) also took place in winter in the high latitudes of the Southern Hemisphere. Some increase of the ozone content was observed in July southward from the South African coast in the period from 1979 to 1992. At the same time, the ozone decrease occurred in other high-latitude regions. Note also that the ozone layer depletion occurred not only in winter and spring, but in other seasons as well in both the Northern and Southern hemispheres.

Figure 2 shows the calculated ozone content anomalies in January and March of the analyzed period at 55°N and their behavior at some points of the Northern Hemisphere with well pronounced negative and positive trends of the ozone layer. The analysis has shown that the longitudinal nonuniformity of anomalies increases in winter and spring away from the equator. This can be explained by the effect of the planetary waves on the vortex ozone transfer, which is more intense in the stratosphere out of tropics.

The areas with low ozone content are often next to the areas with the enhanced ozone. For example, in January of 1985 the low ozone content was observed over Alaska, and high ozone content was observed over North Atlantic. In other years, for example, since January and until March of 1983 and 1992, the negative anomalies had almost zonal structure. The same is true with the positive anomalies since January until March of 1982 and in March of 1981. It should be noted that there are intraseasonal differences in interannual anomalies of the ozone content. It is interesting that the positive trends in the area northwestward from Greenland (Fig. 1*a*) correspond to low values in January (March) of 1979 and high values in January of 1982, 1985, and 1991 (1981, 1986, and 1989). Negative ozone trends in East Siberia near Yakutsk[14] became stronger in 1992.

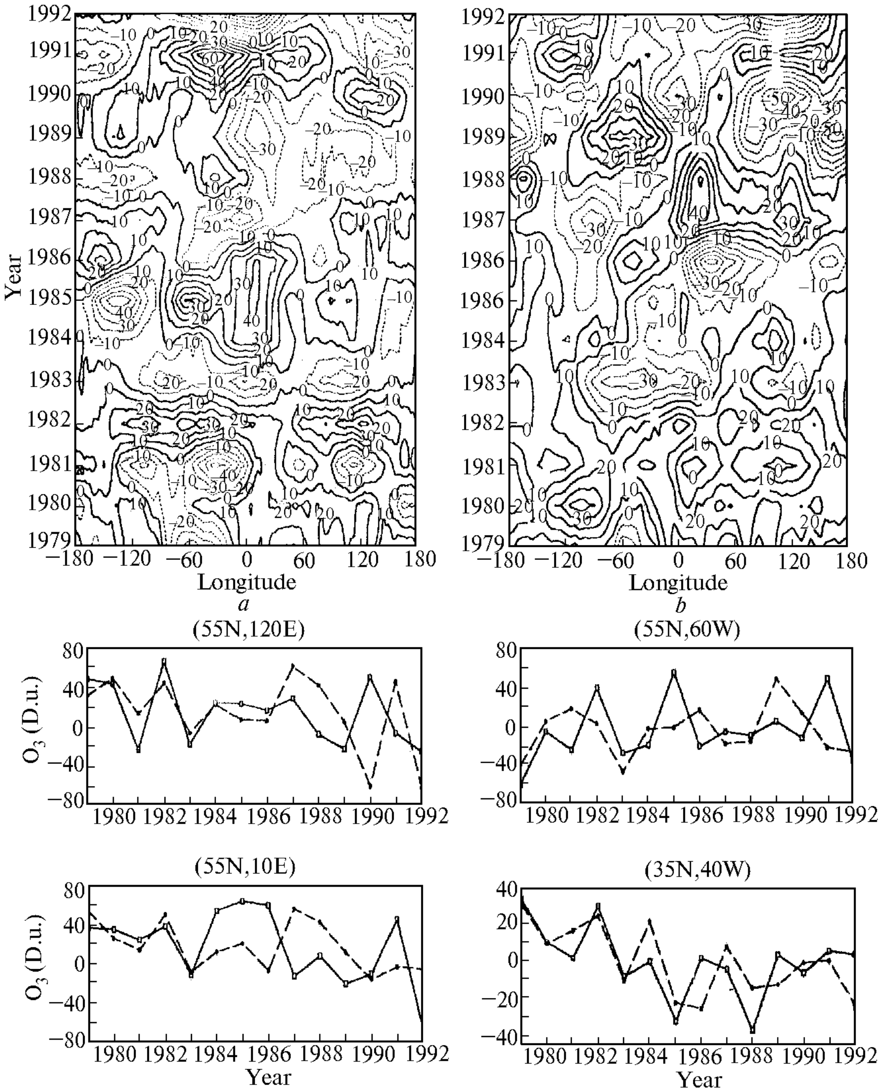

FIG. 2. Monthly mean anomalies of the ozone content for January (a) and March (b) at 55°N *and their behavior in some regions for January (solid curve) and March (dashed curve).*

Figure 3 shows the structure and temporal behavior of the coefficients of two first empirical orthogonal functions of the monthly mean anomalies of the ozone content, which make the principal contribution into the interannual ozone variations in January and March in the Northern Hemisphere. The first EOF for January (its contribution is 31.5% of the total variability) is associated with the long-term ozone trend (see Fig. 1*a*), while the structure of the second EOF (27.9% of variability) has the dipole structure over the longitude to the north from 40°N. The "oscillations" of the ozone content are observed between the Arctic and Pacific oceans (especially in the region of the Aleuts), on the one hand, and Greenland and North Atlantic, Europe and Russia, on the other hand.

The signal associated with the quasi-biennial circulation (QBC) is well pronounced in the behavior of the second EOF coefficient. It is also seen in the long-term trend of the first EOF coefficient. Comparison of the second EOF coefficient with the zonal wind phase at 30–50 hPa of the equator area (Singapore) has shown that in January of 1979–1986 the west (east) wind in Singapore corresponded to the maximum (minimum) in the second EOF coefficient, i.e. the west (east) phase of the equatorial QBC is related to the decrease (increase) in QBC of ozone in middle and high latitudes of the Northern Hemisphere, especially over North Atlantic.

The counter relation is observed over the Aleuts. However, after 1986 such a relation of the ozone content anomalies with the equatorial QBC of the zonal wind breaks down, what can be explained by the long-term change in the relations between the equatorial stratospheric circulation and the circulation in the middle and high latitudes after 1986–1987 (Ref. 13). The ozone anomalies shown in Fig. 2 can be explained, in principle, by the constructive or destructive interference of the first and second EOFs.

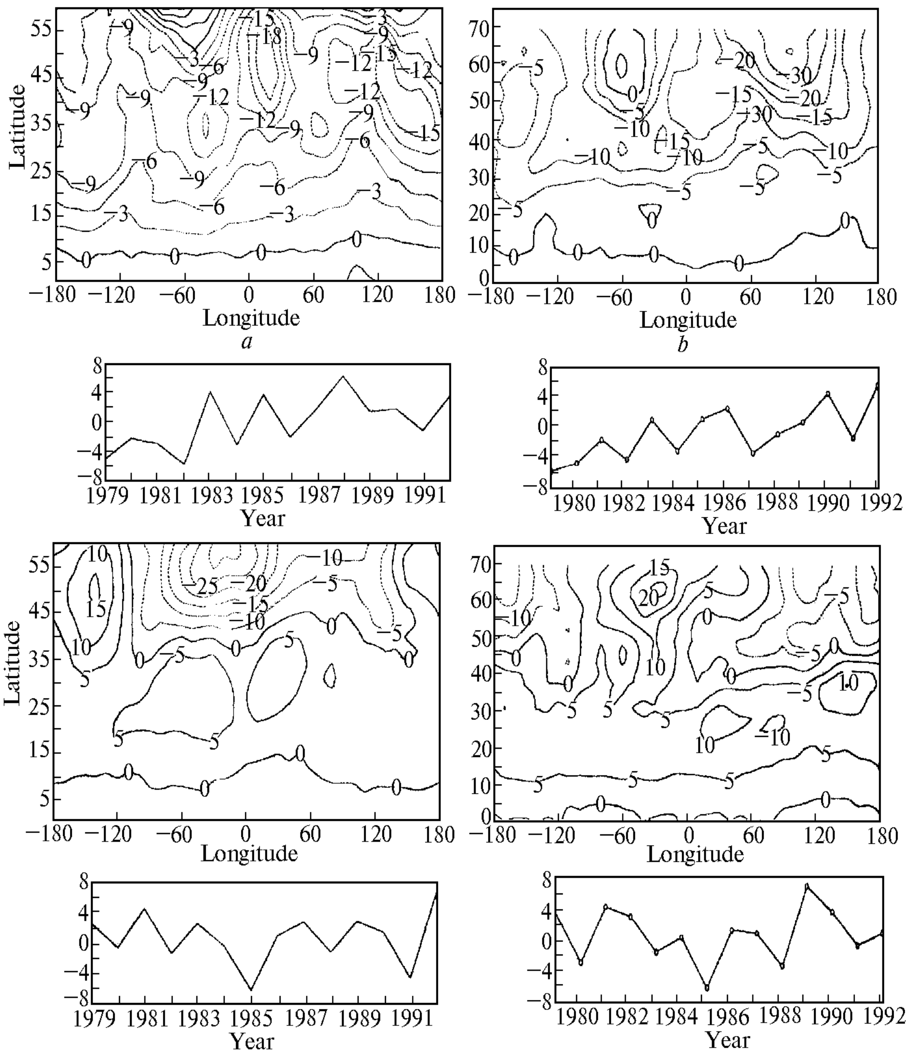

FIG. 3. Structure of the first (top) and second (bottom) empirical orthogonal functions of ozone content anomalies, in D.u., *for January (a) and March (b), and interannual variations of their coefficients.*

For example, large positive anomalies at 55°N, 60°W in January of 1985 were caused by the constructive interference (positive total contribution) of the first and second EOFs. At the same time, the ozone maximum in January of 1991 is mainly related to the contribution from the second EOF. Note that the behavior of the EOF2 coefficient in March is similar to its temporal behavior in January, as well as its structure, but with the opposite sign.

The quasi-biennial ozone variations in the middle and high latitudes of the Northern Hemisphere have a well-pronounced dipole character of the variability along the longitude with the sign alternating from January to March. Thus, if the second EOF of the ozone anomalies is related to the QBC of the ozone layer, then "oscillations" of the ozone content with the opposite sign should be observed over the northern part of the Pacific and Atlantic oceans. It should be noted that the signs of the ozone content change in these regions are opposite in January and March for most years (1979–1992).

Figure 4 shows the ozone content anomalies in July and October in the Southern Hemisphere, where weaker longitudinal asymmetry in the ozone anomalies and trends is observed in comparison with the Northern Hemisphere. The amplitude of the interannual ozone variations over Antarctic in spring is larger than the corresponding values in high latitudes of the Northern Hemisphere, what is related to the strong negative trends in the area of the ozone hole over Antarctic. The positive ozone trends in the area southward from the South African coast (Fig. 1*c*) are mostly caused by an increase in the ozone content in July of 1988 and, especially, in 1992 (Fig. 4*c*). The low ozone content was observed in October of 1979 near 45°S, 120°W in the southern latitudes of the Pacific Ocean, causing a slight positive trends in October (Fig. 1*d*).

The structures of the first (35.99%) and second (17.4%) EOFs of the ozone content anomalies in winter (July) in the Southern Hemisphere (Fig. 5) are surprisingly similar (accurate to sign) to the structures of the corresponding EOFs of the anomalies in January

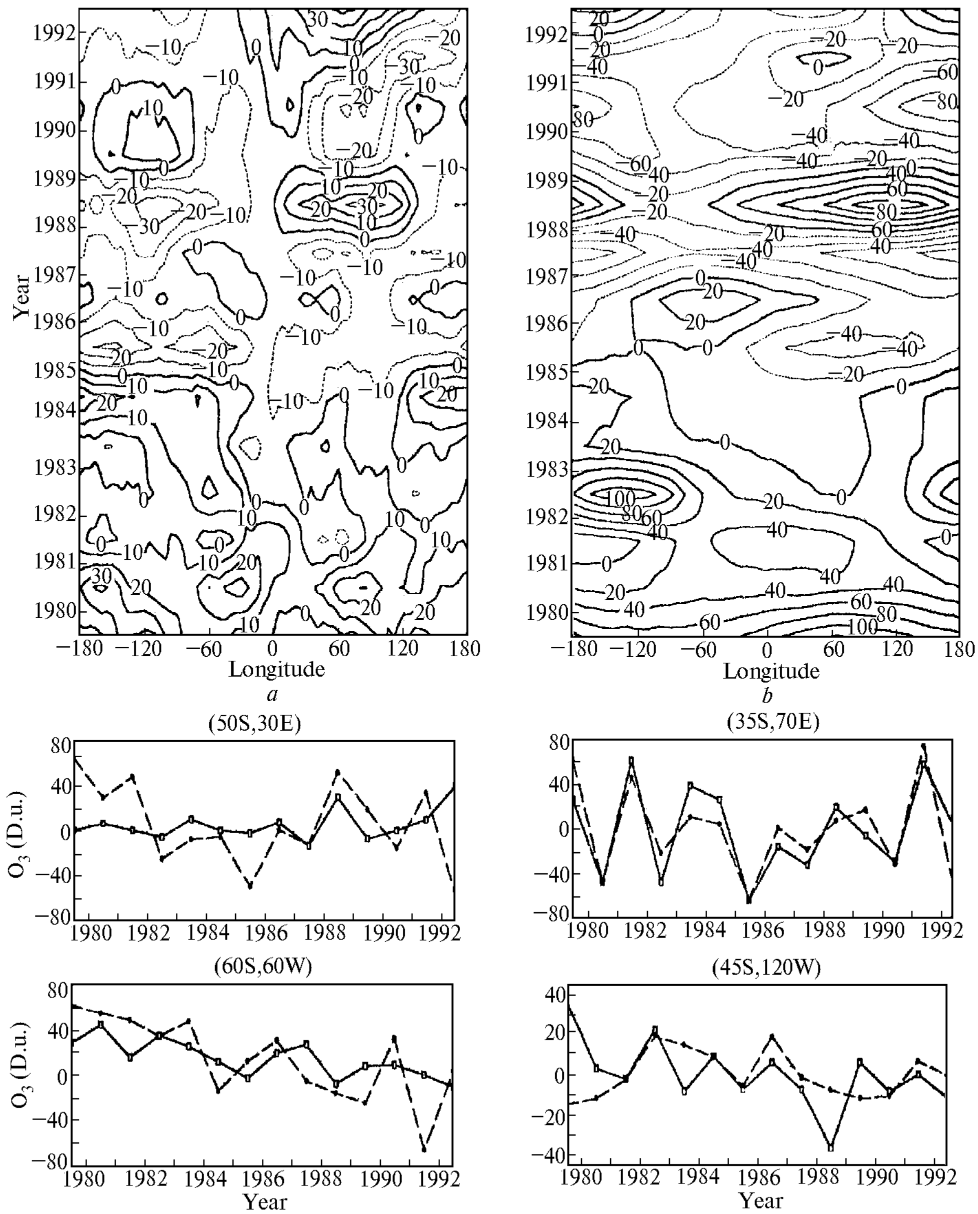

FIG. 4. Monthly mean anomalies in the ozone content for July (a) at 55°S *and October (b) at* 75°S *and their behavior in some regions for July (solid curve) and October (dashed curve).*

in the Northern Hemisphere. There is a "spotB in the area 50–55°S, 5–45°E with positive ozone trends (see Fig. 1*c*) for the first EOF and the dipole longitudinal structure of the second EOF in the middle and high latitudes of the Southern Hemisphere.

Very high ozone content was observed in July of 1988 southward from the South African coast (Fig. 4*a*), where the constructive interference of the EOF1 and EOF2 contributions took place (see Fig. 5). The third EOF (14.86%) (not shown) makes a large positive (negative) contribution in July of 1980, 1988, and 1992 (July of 1989) in the southern part of Indian Ocean. The comparison of the EOF2 coefficient behavior with the phase of QBC of the equatorial wind at 30–50 hPa (Singapore) has shown that the maxima (minima) of the coefficient mainly correspond to the east (west) phase of the QBC. However, there are some breaks of this relation, especially in July of 1988, when the west phase of equatorial QBC occurred.

Similar, in principle, pattern is observed in October. The first EOF (56.67%) has a strong negative minimum at the east coast of Antarctic and slight local positive maximum at southern middle and high latitudes of the Pacific Ocean. The EOF1 coefficient behavior well agrees with the evolution of the ozone hole over Antarctic[3] and the calculated[1,11] EOF1 coefficients of the zonal mean anomalies in the ozone content on the global scale.

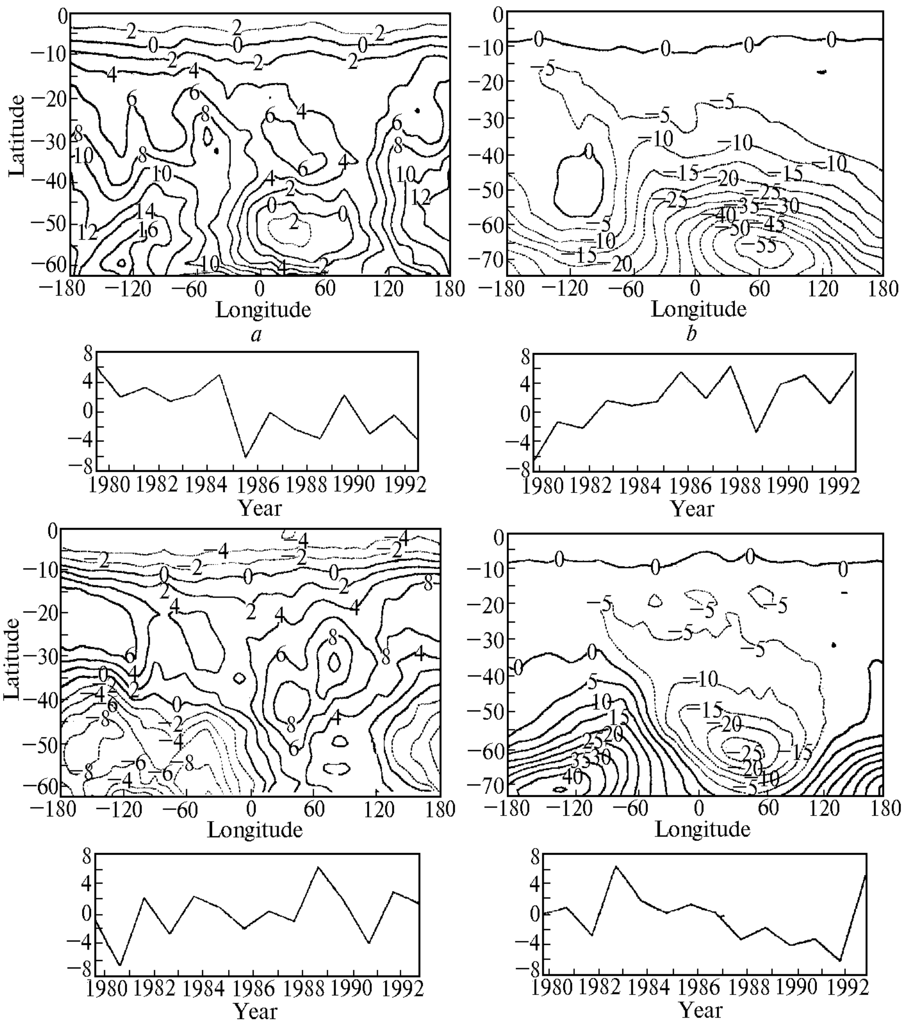

FIG. 5. Structure of the first (top) and second (bottom) empirical orthogonal functions of ozone content anomalies, in D.u., *for July (a) and October (b), and interannual variations of their coefficients.*

The second EOF (23.77%) has the dipole structure. The long-term trend is observed in its coefficient, with sharp changes in 1981–1982 and 1991–1992. The west (east) phase of the QBC of zonal equatorial wind in Singapore[15] agrees with the maxima (minima) of the EOF2 coefficient for October. However, breaks of these relations, especially noticeable in 1987–1988, are also observed. It should be emphasized that the quasi-biennial signal is also present in the behavior of other EOFs, so there are some difficulties in identification of the quasi-biennial ozone cycle.

DISCUSSION

The seasonal and latitudinal distribution of the calculated ozone content trends is in a good qualitative agreement with the results of other investigations,[1,2] in spite of different techniques used for calculation. The strongest negative ozone trends are observed in the area of the ozone hole over Antarctic and in the middle and high latitudes of the Northern Hemisphere in winter and spring. The longitudinal structure of the trends is also in satisfactory agreement with the general peculiarities of the calculated results from Ref. 7. However, there are some differences between our results and the results of Ref. 7 for both the Northern and Southern hemispheres, especially in relation with the presence of positive trends of the total ozone content. The reasons for these differences may be both averaging of the calculated results over four months (from December until March) in Ref. 7 and the aforementioned differences in the technique for calculating trends.

The existence of regions with positive ozone trends raises a question on what may be the causes of the ozone layer variations. Chemical mechanisms can lead only to the ozone decrease in the lower stratosphere as the emission of freons and halogen containing substances into the atmosphere increases (at least, at the modern level of knowledge about heterogeneous reactions). Besides, the increase of the ozone content is observed only in some regions, what may be indicative of the dynamic causes for such an increase. Note that the positive ozone trends take place in the areas of climatic minimum of the planetary wave activity and the minimum ozone content. So it is reasonable to suppose that the cause for the appearance of positive ozone trends in January, northwestward from Greenland, is the interannual and decade-scale variations in the activity of stationary planetary waves, which are related to the long-term variations in the ocean–atmosphere interacting system.

Trenberth[16] has shown that the late 70s were the time of sharp transition to the new mode in interannual variations of pressure at the sea level in the northern part of Pacific Ocean in cold season. This interdecadal climatic displacement may be related to El Niño phenomenon that occurred more frequently during the last two decades in comparison with previous decades of the 20th century. The analysis of satellite data on variations in the sea level and sea surface temperature (SST)[17] has revealed that a decade after the strong El Niño of 1982–1983 its effects manifest themselves in the northern part of Pacific Ocean and lead to the displacement of the Kurosio stream. This, in turn, can lead to decade-scale variations in the activity and circulation of the troposphere and, especially, stratosphere due to the change of thermal source of the stationary planetary waves,[4] which penetrate into the stratosphere in winter and spring. The existence of regions with dominating negative and positive ozone trends can also be caused by the long-term variations of the wave activity of the stratosphere. Thus, in the analysis of variations of Eliassen-Palm 3-D flows,[18] it was shown that the appearance and trajectories of motion of the areas with anomalously low ozone content (ozone mini holes) over North Atlantic, Europe, and Siberia are closely related to changes in the direction of propagation and the intensity of vortex transfer processes during winters of 1986 and 1987.

It should be noted that the long-term (with the period of 10–12 years) cyclic behavior of the atmospheric parameters is observed in midlatitudes of the Northern Hemisphere over Pacific and Atlantic oceans.[19] Labitzke and van Loon have supposed that the cause for these decade-scale oscillations is the effect of the 11-year cycle of solar activity. However, Ref. 20 argues for the fact that the real cause of these oscillations is the decade-scale variations of the OST of Atlantic and Pacific oceans, which can change the activity of the stationary planetary waves and the vortex ozone transfer on the interannual and decade temporal scales. The analysis of the North Atlantic OST anomalies during the last 90 years[21] has shown the presence of decade-scale oscillations in their spectrum. The limited period (14 years) of TOMS measurements of the ozone content does not allow now a detailed study of the relations between the decade-scale variations of OST of the World Ocean and the ozone layer. However, the strong correlation was revealed[8] between the interannual anomalies of the North Atlantic surface temperature and the ozone content variations over Europe assessed from the data of the ground-based network, as well as between the OST anomalies in the central part of the Pacific Ocean and development of the ozone hole over Antarctic[22–24] in winter and spring. The relations of the long-term pressure variations in the center of the Azores anticyclone and its migrations with interannual variations of the ozone content in Europe also emphasize large role of the decade-scale natural processes in the ozone trends.[25]

The results of analysis of relations between interannual anomalies of the ozone content and the stratospheric angular moment[5,11–13] can serve as a direct confirmation of the assumption that the observed variations in the ozone layer, including the appearance of the ozone hole over Antarctic, may be initiated by the long-term variations of the dynamic transfer processes in the stratosphere. It was shown that the sharp transition from the east anomalies of the zonal wind to the strong west anomalies occurred in subtropics in summer of 1980; then the west anomalies gradually moved to high latitudes in winter, following the so-called V-structure.[5,26]

The long-term perturbations of the atmospheric circulation appear first near the equator and then slowly (during some years) move to the polar regions of the Northern and Southern hemispheres. Starting from the first half of the 80s, these anomalies in the stratospheric circulation have reached the Antarctic, having caused strong isolation of the polar vortex and cooling of the lower stratosphere, what created favorable conditions for formation of polar clouds and heterogeneous reactions. These reactions have led to chemical destruction of the ozone layer and appearance of the ozone hole. In order to assess the relative effects of the natural long-term variations in the ocean–atmosphere system and the anthropogenic factors on the ozone layer, further analysis and theoretical investigations are needed using general circulation models of the atmosphere, which could describe the ozone layer chemistry in the parametric form.

ACKNOWLEDGMENTS

Authors would like to thank Yu.A. Borisov (Central Aerological Observatory) for the kindly presented TOMS database and N.A. Diansky (Institute of Computer Mathematics RAS) for his consultations in the calculations.

The work was supported in part by NASA (USA), Grant No. NAG–5–3495.

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