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Current trends in the zonal distribution and asymmetry of ozone in Antarctica based on satellite measurements

Abstract. The development of the Antarctic ozone hole in late winter and spring (September—November) is the most noticeable phenomenon in the polar stratosphere. It has appeared every season since the early 1980s within the stratospheric polar vortex, preventing air mass from mixing with middle latitudes and affecting the distribution of minor atmospheric constituents, including ozone. The ozone hole strongly depends on dynamic factors, mainly planetary wave propagation from the troposphere to the stratosphere. This study aims to identify the total ozone longitudinal distribution for austral spring and individual months, September, October, and November, and consider the observed trends in detail. We provide an analysis to retrieve trends in total ozone during the development of the ozone hole. Time averaging of the total ozone longitudinal distribution was performed using the three-month ozone means in the austral spring. This procedure eliminates fluctuations and impacts of traveling waves. The latitudinal range of 55—80°S was analyzed to characterize the total ozone distribution in the ozone hole edge and inner regions. Distributions for individual months (September, October, and November) were considered to describe the observed trends in detail. The analysis of the obtained results indicates a close-to-linear negative total ozone trend during the ozone hole intensification (the 1980s—early 1990s). This trend was determined at all the analyzed latitudes, with total ozone decreasing by 150 DU during 15 years in the zonal longitudinal minimum region. However, the analysis of the trends shows that ozone layer recovery is not observed in the Antarctic spring, taking into account low ozone levels in 2020—2023. No clear trends were noted after the period of decline, but the October values in zonal maximum have slightly decreased in the last decade. The zonal minimum has drifted eastward during the decline in total ozone, but the subsequent time range shows large interannual changes without any significant long-term tendency in both maximum and minimum longitudes.

Keywords: ozone hole, ozone trend, planetary wave, polar vortex, sudden stratospheric warming

1 Introduction

The most noticeable phenomenon in ozone distribution in the Antarctic atmosphere is the development of an ozone hole at the end of winter-spring (Kessenich et al., 2023). An ozone hole has appeared every season since the early 1980s (Stolarski, 1988) within the stratospheric polar vortex which prevents the exchange of air masses with temperate latitudes, affecting the distribution of both ozone and other minor atmospheric constituents (de Laat et al., 2023). The hole's appearance is associated with chemical reactions on the polar stratospheric cloud particles surface (Stolarski, 1988), which lead to the release of chlorine atoms acting as a catalyst for destroying ozone molecules. Low temperatures in the stratosphere, which intensify the formation of polar stratospheric clouds, lead to the occurrence of ozone depletion events even in the Arctic, with total ozone column (TOC) values comparable to Antarctica (Varotsos et al., 2012).

The ozone hole has a mostly chemical origin. Still, its state is controlled by dynamic factors, first of all, by the penetration of planetary waves from the troposphere and their dissipation in the stratosphere. The atmospheric dynamics determines the interannual changes in the planetary wave (PW) parameters in the stratosphere and the stratospheric polar vortex (Asikainen et al., 2020; Grytsai et al., 2022), which require additional research. The PW activity is higher in the high latitudes of the Northern Hemisphere (Wang et al., 2019), and the polar vortex is more stable in the Southern Hemisphere. At the same time, the total ozone column value serves as an indicator of the distribution of PW (low values inside the polar vortex, high values outside the polar vortex) and as a characteristic whose distribution changes significantly under the influence of the sudden stratospheric warming (SSW) events (Varotsos, 2002; Varotsos & Tzanis, 2012; Mukhtarov et al., 2023).

The identification of PWs and their parameters requires global-scale data. That is why it is convenient to use satellite observations to study this problem, although ground-based measurements can also provide some valuable information, primarily about traveling PWs. Systematic satellite observations of the TOC distribution have been available since late 1978. The polar vortex in the Southern Hemisphere is asymmetric despite lower PW activity compared to the Arctic (Grytsai et al., 2005a; 2007; Alexander & Shepherd, 2010; Ialongo et al., 2012; Siddaway et al., 2020). The primary role is played by a quasi-stationary wave (QSW) with a zonal number of 1, the influence of which leads to a displacement of the vortex relative to the pole. The shift of the vortex, and therefore the location of the maximum and minimum in the ozone distribution, depend on the properties of the underlying surface. QSWs, however, are characterized by a phase shift with height (Rhodes et al., 2023), causing their position in the stratosphere to vary from year to year. The role of quasi-stationary components with zonal numbers 2–3 is insignificant, in contrast to the Northern Hemisphere. Instead, the amplitude of traveling wave 2 can be comparable with the amplitude of wave 1 (Butler & Domeisen, 2021), and their interaction belongs to the factors that influence the development of the SSW. For the Northern Hemisphere, where SSWs occur relatively often, a classification of displacement (wave 1) and split (wave 2) warming has been developed (White et al., 2021).

This study aims to identify the total ozone longitudinal distribution for individual months (September, October, and November) and consider the observed trends in detail. We provide an analysis of the results to retrieve trends in total ozone during the ozone hole increase. We also analyzed the trends to evaluate the processes of ozone layer recovery and the movement of ozone zonal minimum position.

The paper is organized as follows. Data and methods used in this study are described in Section 2. Section 3.1 introduces the quasi-stationary ozone distribution, and Section 3.2 explains long-term variations of TOC maximum and minimum values, followed by a discussion and conclusions.

2 Data and method

Since the end of the 1970s, satellite instruments have continuously monitored the ozone layer in the Earth's atmosphere. Available data are accessible at https://ozonewatch.gsfc.nasa.gov/data/;

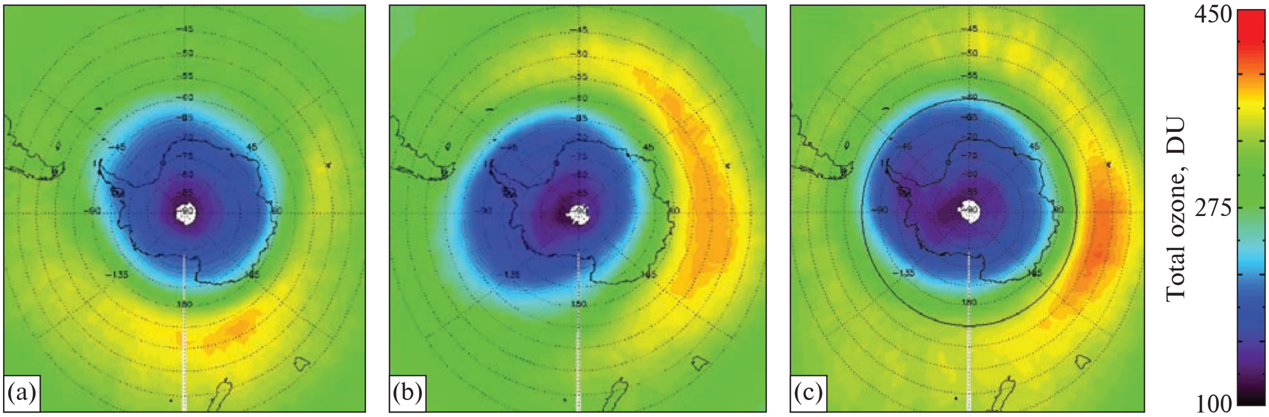

Figure 1. Total ozone distribution in September (a) 2010, (b) 2013 and (c) 2023 from the Ozone Monitoring Instrument (https://ozonewatch.gsfc.nasa.gov/data/). The black circle in (c) shows the 60°S latitude, white area means no data

all TOC values are in Dobson Units (DU), which we use by default. The data is Level 3, allowing analysis without additional calibrations and refinements. The data files are TOC values across the planet's atmosphere at a given latitude and longitude step. In this study, we used Total Ozone Mapping Spectrometer (TOMS) data onboard the Nimbus-7 satellite for 1979—1992, TOMS/Earth Probe data for 1996—2004, Ozone Monitoring Instrument (OMI)/Aura measurements for 2005—2023 from the NASA Ozone Watch service (https://ozonewatch.gsfc.nasa.gov/data/), and the Multi-Sensor Reanalysis TOC values (https://temis.nl/protocols/O3global.php) derived from satellite observations and assimilation, which provide ozone fields over Antarctica and on the global scale, to fill in a gap in TOMS data in 1993—1995. An example of the monthly ozone distribution is displayed in Figure 1. The September distribution includes two main features: an ozone hole with low total ozone values (<150 DU) and an ozone collar with values near 400 DU. Zonal asymmetry is evident, in particular, from ozone values at the 60°S latitude displayed by the black circle in Figure 1c.

The data processing procedure was created as a sequence of software codes to retrieve the total ozone longitudinal distribution for individual months. We sampled measurements from the array of OMI initial TOC data files to study atmospheric ozone in the South Polar area. The OMI observational files contain TOC data along the parallel with a longitude step of one degree separately for all days of the month. Our pre-processing creates files with a matrix structure. The data is presented as a table, where a row includes the daily measurements for a given longitude (the total number of columns is equal to the number of days in a month) with a total of 360 rows (one for each degree of longitude). To identify seasonal features, we averaged the longitudinal distributions during the three austral spring months, September, October, and November, to identify the meridional and zonal asymmetry of the ozone distribution during the ozone hole period. Then, the ozone longitudinal distributions were averaged to determine the positions (i.e., the longitude at the studied latitude) of the QSW maximum and minimum and analyze their changes. To estimate possible periodicity, we calculate autocorrelation function and provide wavelet transform based on Morlet function $f(x) = \exp(-x^2/2)*\exp(iax)$ for $a = 5$. The data approximation was carried out by a third-degree polynomial (cubic parabola) with the coefficients determined by the least-squares method. We performed time averaging of the total ozone longitudinal distribution considering both seasonal (September, October, November (SON)), and

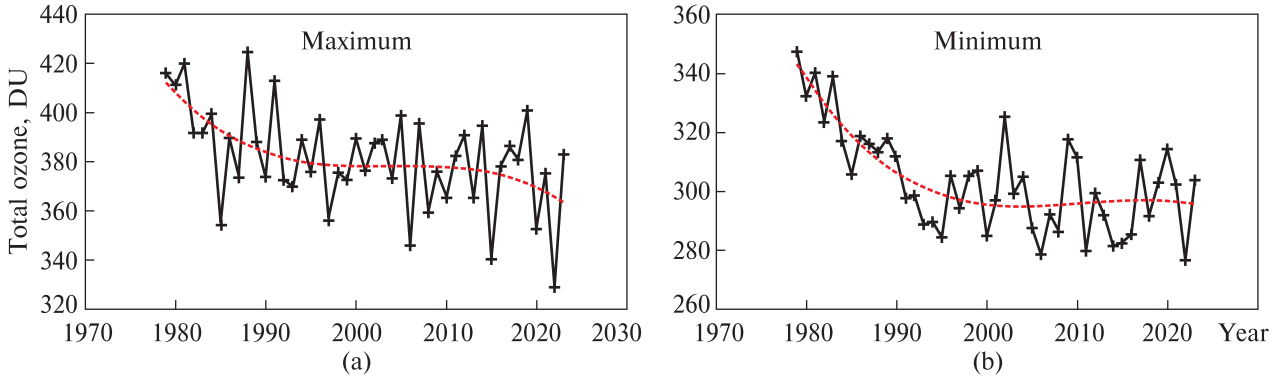

Figure 2. Dependence of the total ozone column values (a) in the QSW zonal maximum area and (b) in the QSW zonal minimum area in the spring (SON) at the latitude of 55°S by satellite observations

monthly data series. The latitudinal range of 55–80° S was analyzed to characterize total ozone distribution in the ozone hole edge and inner regions.

3 Results

3.1 Quasi-stationary ozone distribution

We calculated the three-month (September, October, November) averaged wave parameters in the TOC for the range of annual data from 1979 to 2023. This allowed us to retrieve both the long-term variations in ozone column with its expected recovery and the possible effect of the large-scale eruption of the Hunga-Tonga volcano (Wang et al., 2023). Figure 2a shows the spring (SON) results at the 55°S latitude, including the measurements in 2023.

The plot in Figure 2a shows that over the past two years, 2022 and 2023, there has been no significant deviation of the TOC maximum value from the usual variation in recent years. However, there is a noticeable difference between the 2022 and 2023 data. The TOC value for 2022 is the lowest for the entire observation period. The maximum of the zonal distribution in the considered latitudinal range is determined by mid-latitude air masses, so there are reasons to associate such an anomaly with the eruption of the Hunga-Tonga volcano in 2022, which affected the stratosphere of tropical and higher latitudes of the Southern Hemisphere.

Ivy et al. (2017) also discussed the previous decrease in the quasi-stationary distribution in 2015, which is associated with the eruption of the Calbuco volcano in Chile, in support of this version. The volcano effect is short-lasting, and the value for 2023 exceeds the obtained trend. Note that the values in the zonal maximum have shown little change since the mid-1990s without signs of ozone layer recovery.

The value of the ozone column in the minimum of a quasi-stationary wave is displayed in Figure 2b. A noticeable decrease in the ozone column took place in the 1980s and the first half of the 1990s, when the ozone hole area increased with an ozone layer reduction inside it. The ozone hole reaches the latitude of 55°S only in individual cases, but the negative trend is still clearly visible. In the following, no clear trend is observed. A slight drop in the minimum value was noted in 2022, and in 2023, it changed to a slight increase. But, on average, ozone column in the zonal minimum had not significantly changed over the past two years. At the same time, the expected ozone layer recovery at the studied latitudes has not yet been observed. Moreover, in the three consecutive years 2020–2022, the ozone hole has a large area, clearly visible at the higher latitudes (Kessenich et al., 2023).

The longitude position of the maximum ozone column at 55°S is shown in Figure 3a. Also, no significant change in the position of the wave is

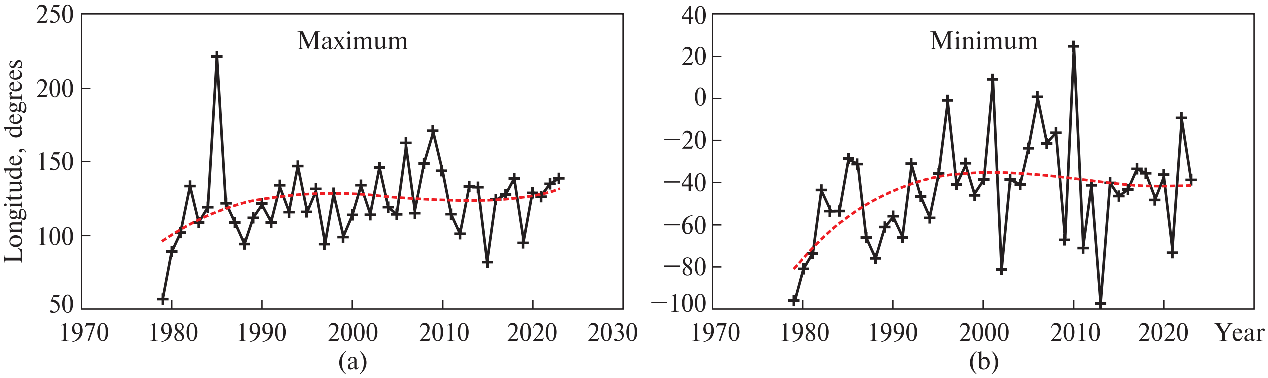

Figure 3. Variations in the longitude position of the (a) QSW maximum and (b) minimum in the TOC distribution at the 55°S latitude, SON average data are presented

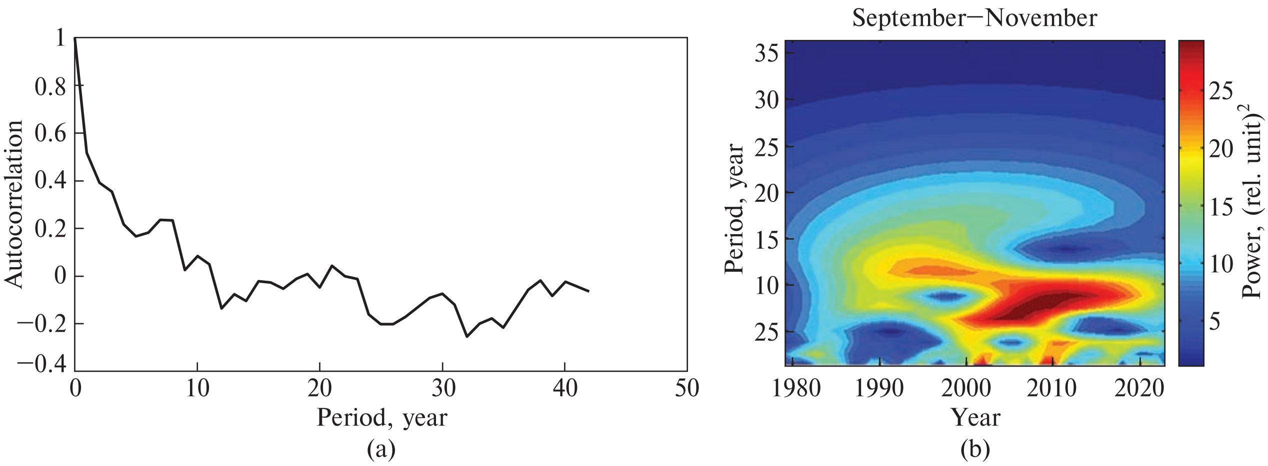

Figure 4. (a) The autocorrelation function of the TOC dependence in the ozone QSW minimum area shown in Figure 2b; (b) wavelet power spectrum, wavelet transform was applied to the series in Figure 2b after its detrending by elimination of the trend shown in Figure 2b

seen in the last two years. A clear shift to the east, as in 1980–2000 (Grytsai et al., 2017), is not observed, nor is a return to the values before the ozone hole. However, individual years show a significant spread of the minimum position, as in 2021 and 2022. A wide range of fluctuations is generally characteristic of the time interval from the beginning of the 2000s. The value calculated for 2023 is close to the average trend (Fig. 3b).

In Figure 2b, visible quasi-wave variations of the ozone column in the QSW minimum are seen, which are unlikely random changes. To investigate this phenomenon in more detail, an autocorrelation function was calculated (Fig. 4a). In general, the autocorrelation function of the value in the ozone minimum indicates a possible cycle at time intervals of 7–8 years. Assessing the reality and origin of this periodicity requires a series of additional observations. Wavelet analysis shows changes in variation periods from 7 years to 10 years (Fig. 4b) in the years 2000–2020.

The minimum of the TOC quasi-stationary wave is located at the longitudes of South America or the Atlantic (Fig. 3b). The position of the wave minimum showed fluctuations near the average value for the last twenty years. Characteristics of the ozone hole and the stratospheric polar vortex containing it are variable at the interannual scale.

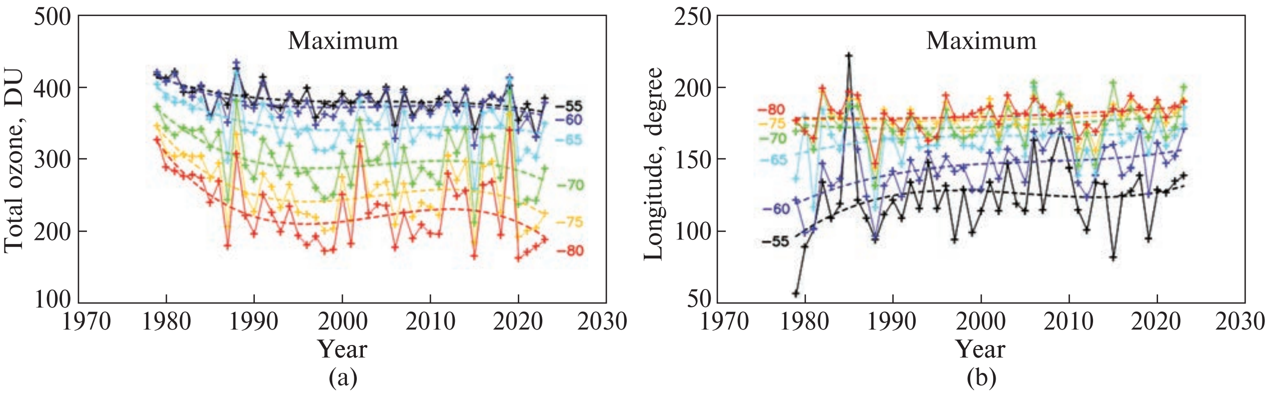

Figure 5. Dependence of the (a) value of the spring (SON) ozone column in the area of the zonal maximum of ozone distribution for the period from 55°S to 80°S and (b) the corresponding longitudes of the QSW TOC zonal maximum. The numbers near the curves show the corresponding latitudes

A clear shift to the east, as in 1980–2000 (Grytsai et al., 2017; Siddaway et al., 2020), is not observed, nor is a return to the values before the ozone hole. However, it should be noted that individual years show a significant spread of the minimum's position, as in 2021 and 2022. An extensive range of fluctuations is generally characteristic of the time interval from the beginning of the 2000s against revealed in previous studies (Grytsai et al., 2007; Siddaway et al., 2020). The value calculated for 2023 is close to the average trend (Fig. 3b).

3.2 Long-term variations of TOC maximum and minimum values in Antarctica

In this section, the 55°S–80°S latitudinal range will be considered. In Figure 5a, the values of the area ozone maximum at the Southern Hemisphere high latitudes are represented by curves of different colors (from blue to red for latitudes from 55°S to 80°S) and variations of the QSW TOC maximum longitude are shown in Figure 5b.

It can be seen from Figure 5a that at the higher latitudes (70–80°S) in recent years, there has been some tendency to a decrease in ozone column in the location of the zonal maximum. In the inner region of the ozone hole, the values for 2020–2023 are low, but when we move to temperate latitudes, an increase in the TOC in 2023 is seen. At the same time, significant spikes in the TOC values are characteristic for the years when sudden stratospheric warmings weakened the polar vortex in 1988, 2002, and 2019.

Figure 6a shows the TOC values in the quasi-stationary wave minimum at different latitudes of the southern hemisphere, and the color scheme is similar to that of Figure 5a. As can be seen from Figure 6a, at higher latitudes in the zonal minimum, the lower TOC values are observed for the last four years, from 2020 to 2023. The ozone destruction in the inner region of the stratospheric polar vortex resulted in a more significant trend in the 1980s – the first half of the 1990s; it is also the reason for the TOC decline towards the pole in the following years. It should also be noted that the position of the TOC minimum at high latitudes steadily deviates to the east compared with the average value for the last two decades.

The long-term tendency in total ozone approximated by cubic polynomials in Figures 5a, 6a explains about a half or even more of total variations. Values of the coefficient of determination (R^2) for our approximation are in the range of 0.47–0.57 for zonal maximum (Fig. 5a) and 0.51–0.66 for zonal minimum (Fig. 6a). The values of R^2 are higher in the minimum due to a more pronounced trend in the 1980–1990s when total ozone at the latitudes of 65–80°S decreased by 100–120 DU. Short-term (interannual) changes cause

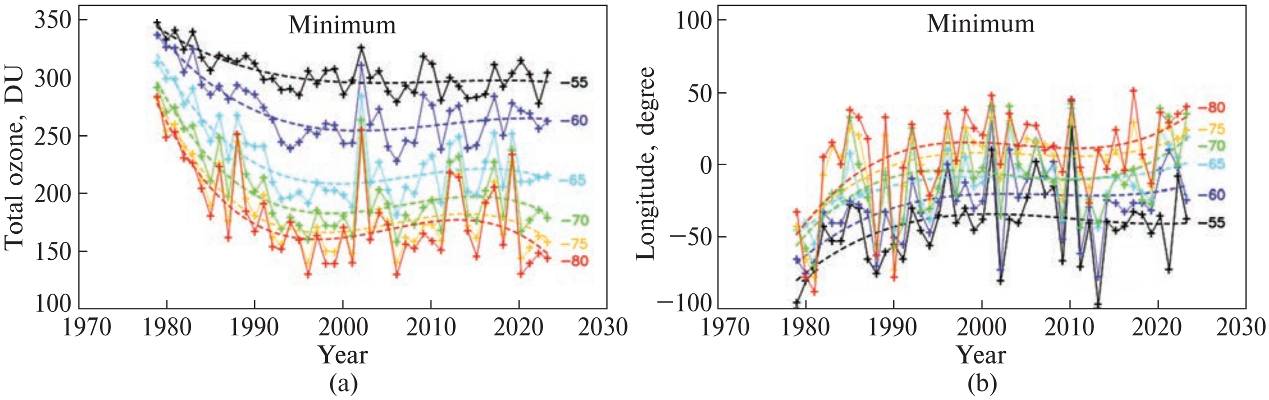

Figure 6. Dependence of the (a) value of the spring (SON) ozone column in the area of the zonal minimum of ozone distribution for the period from 1979 to 2023 for the southern latitudes from 55°S to 80°S and (b) the corresponding longitudes of the QSW TOC minimum. The numbers near the curves show the corresponding latitudes

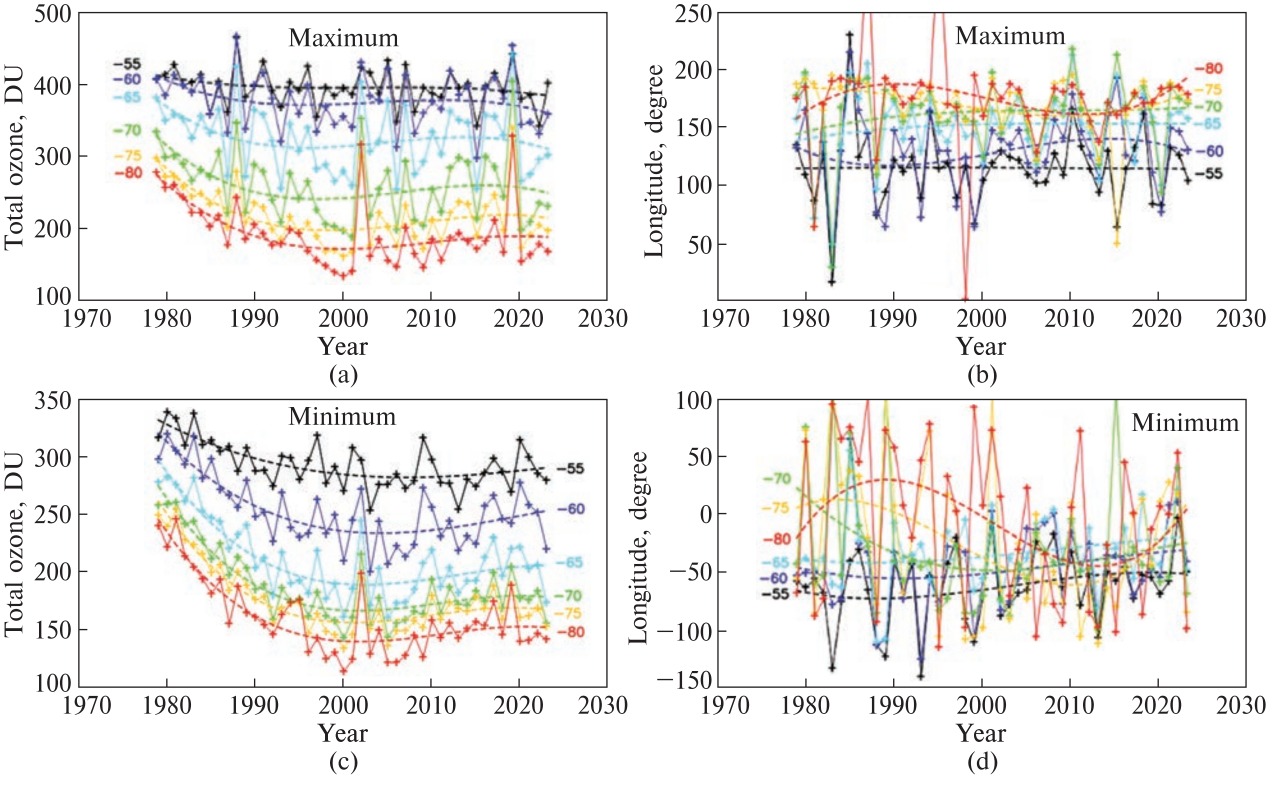

Figure 7. Dependence of the *September* total ozone column values in the area of the (a) the QSW TOC zonal maximum in the longitudinal ozone distribution and (c) the QSW TOC zonal minimum for the period from 1979 to 2023 for southern latitudes from 55°S to 80°S and corresponding longitudes of the zonal TOC (b) maximum and (d) minimum. The numbers near the curves show the corresponding latitudes

the rest of the total ozone variability, the influence of which increased in the 2000s – early 2020s after the negative trend of chemical origin ceased.

Monthly data in the maximum and minimum position in the ozone distribution at the latitudes 55–80°S were obtained similarly to the three-

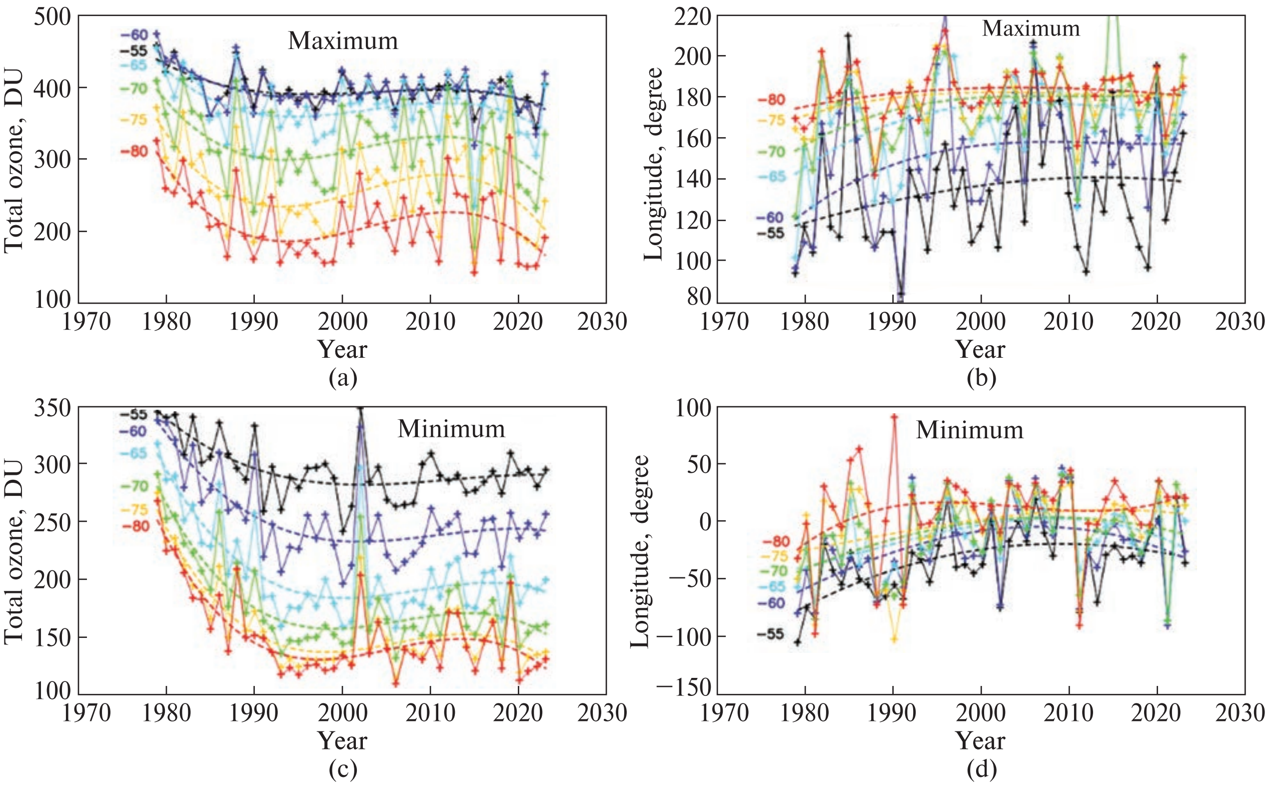

Figure 8. Dependence of the *October* total ozone column values in the area of the (a) the QSW TOC zonal maximum in the longitudinal ozone distribution and (c) the QSW TOC zonal minimum for the period from 1979 to 2023 for 55–80°S latitudes, and corresponding longitudes of the zonal TOC (b) maximum and (d) minimum

month averages. We processed observations for September, October, and November.

Figures 7a and 7c show the TOC values in the QSW zonal maximum and minimum in the longitudinal distribution, in Figures 7b and 7d the longitudinal position of the TOC zonal maximum and minimum at different latitudes from 1979 to 2023 are shown according to the September observations. At the higher latitudes (70°S–80°S), the TOC in the September 2023 was somewhat lower than in the previous years, but at the lower latitudes (55°S–65°S) it even increased. We saw a noticeable increase in TOC during the sudden stratospheric warmings in 1988, 2002, and 2019, which in the last two cases reached 100–150 DU in the high latitudes.

Figure 8a and Figure 8c show the values of the maximum and minimum, respectively, in the TOC QSW longitudinal distribution for different latitudes from 1979 to 2023 according to the observations in October. The downward TOC values trend is evident at all analyzed latitudes with different rates. At the same time, the values for 2023 exceed the long-term trend, unlike the previous three years.

Note that the unprecedented major sudden stratospheric warming of 2002 (Varotsos, 2002) did not significantly impact the region of the maximum in the lower latitudes, which may be due to the intense mixing of midlatitude and polar air masses during the major warming. As for the longitudes of the maximum, their average values are slightly variable for the entire considered latitude range.

In Figures 8b and 8d, the longitudinal position of the TOC maximum and minimum are shown by the October observations. In the years after

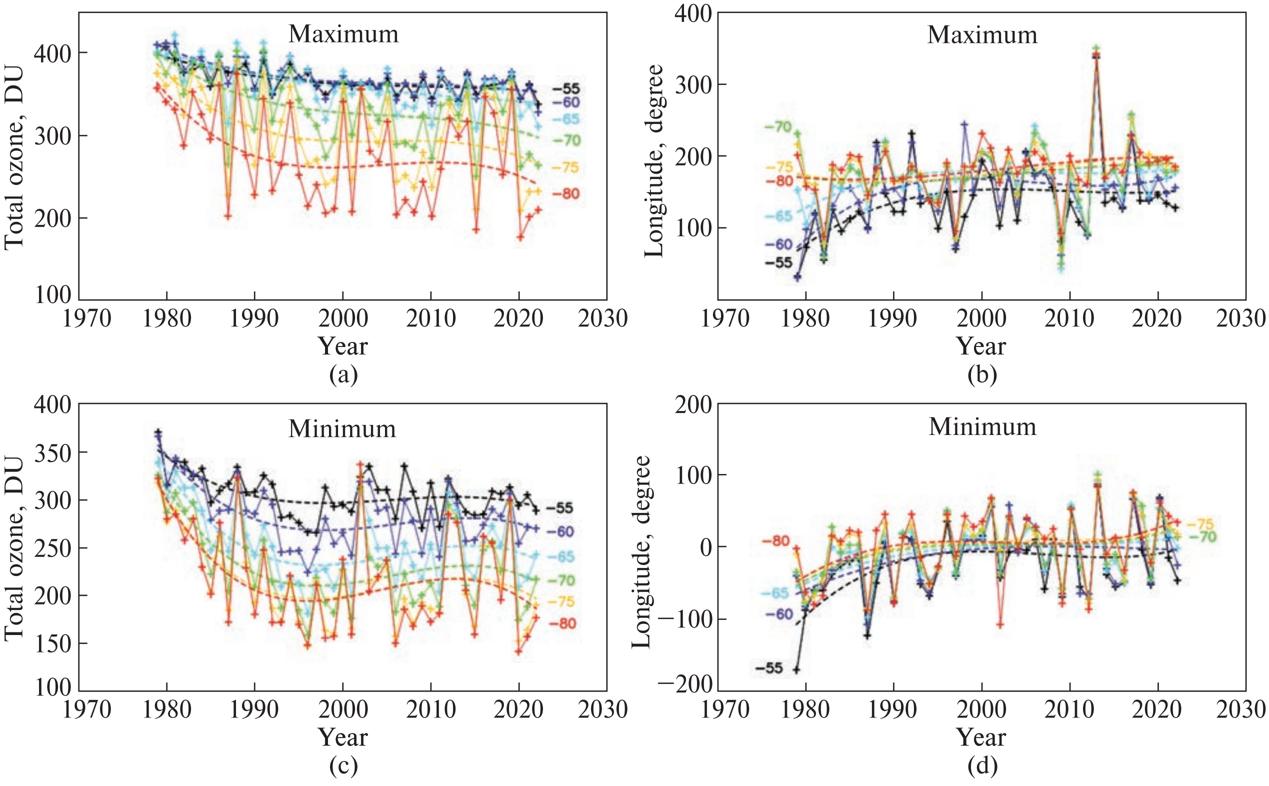

Figure 9. Dependence of the *November* total ozone column values in the area of the (a) the QSW TOC zonal maximum in the longitudinal ozone distribution and (c) the QSW TOC zonal minimum for the period from 1979 to 2023 for 55–80°S latitudes, and corresponding longitudes of the zonal TOC (b) maximum and (d) minimum

the 2019 stratospheric warming, the October TOC values correspond to the general trend, and typical values were observed, particularly in 2023. This detail indicates a change from the downward trend observed in September (Fig. 7c) to an increase in the TOC level. A comparison of the TOC values for the latitudes 60–65°S shows that the ozone hole began to shrink in October and did not show the same rate of development as, in particular, in 2020. The most noticeable features in October are the near-linear downward trend in the 1980s – the first half of the 1990s and an increase by 100–150 DU in the latitudes of 60–75°S during the 2002 major stratospheric warming.

In Figures 9a and 9c, the behavior of the TOC values and in Figures 9b and 9d longitudinal positions in the TOC QSW zonal maximum and minimum in November from 1979 to 2022 are shown. The November TOC level in the maximum remains relatively low compared to the noticeable growth in 2019. TOC in the QSW minimum value is gradually recovering after a sharp drop in 2020, especially at the high latitudes. The eastward shift in the TOC minimum longitude (Fig. 9d) in the 1990s was observed at all the considered latitudes, and evident tendencies were absent in the next decades. The eastward shift in TOC maximum (Fig. 9b) was observed at 55–65°S latitudes only and there is no shift after year 2000.

4 Discussion

Long-term ozone variations in Antarctica are determined by chemical factors predominantly, but interannual variations are controlled by the dynamical processes mainly by planetary waves with zonal numbers 1 and 2 (Grytsai et al., 2005b; 2007; Ialongo et al., 2012; Shen et al., 2022; Li et al., 2024). The first is a quasi-stationary wave, and the second is the eastward traveling wave. According to these general circumstances, satellite data show total ozone decrease during the 1980s–1990s with noticeable differences in the individual years (Fig. 2). The maximum asymmetry was noticed at the latitudes 60–65°S (Figs. 5a, 6a) where the edge of the ozone hole is observed during the southern spring. The corresponding conditions with significant total ozone variations are typical, in particular, for the Akademik Vernadsky station. The Antarctic ozone asymmetry is an essential climatological feature (Ialongo et al., 2012) and requires a careful study.

Sharp total ozone increases due to sudden stratospheric warmings were observed in 1988, 2002, and 2019 (Milinevsky et al., 2020; Rao et al., 2020), in both the total ozone maximum and minimum regions. Safieddine et al. (2020) considered the SSW event in 2019 resulting in a temperature increase and polar vortex weakening. It was found that total ozone increased by 70% on September 19, with a change of ~100 DU at the zonal minimum region. Our results show evident consequences of this phenomenon for the whole spring period (SON). The TOC anomalies by ~100 DU are observed in comparison with the polynomial long-term trend at the latitudes 70–80°S (Figs. 5a, 6a). The TOC changes are of ~70 DU at 80°S in the zonal maximum, but their values decrease to the lower latitudes. Thus, the warming event predominantly influenced the inner part of the stratospheric polar vortex and ozone hole.

Minor SSW events are relatively common in the Antarctic stratosphere (Vincent et al., 2022) and can also impact the total ozone column. In particular, de Laat and van Weele (2011) pay attention to the ozone hole reduction in 2004 and 2010 due to dynamical factors. In those years, a lesser ozone mass deficit was noticed without evident changes in the ozone hole area. Nonetheless, our results do not show any significant increase in total ozone in 2004 and 2010, which would be typical for a lower ozone deficit. Only the October minimum is 10–20 DU higher than the mean tendency, but these values are usual for interannual variations. Respectively, stratospheric warming should be as large as the 2002 SSW, or, at least, as 1988 and 2019 SSWs (Milinevsky et al., 2020) to influence ozone depletion in a significant degree. Similar events are considered rare, with their frequency estimated as one large warming per 22 years under atmospheric conditions of 1990 and significantly rarer in the case of the current climate changes (Jucker et al., 2021). The influence of the SSW on the ozone layer also depends on chemical factors. In particular, de Laat and van Weele (2011) noted the lower halogen level in 1988 unlike in the dynamically similar event in 2010 that provided the total ozone rising in 1988. Influence of ice particles on the heterogeneous chemistry in the polar stratosphere that leads to ozone depletion, also should be considered (Solomon, 1988; Varotsos & Zellner, 2010). In every case, the possible connection between minor stratospheric warmings and total ozone variations should be studied more thoroughly in the future. The frequency of these phenomena, known also as weak polar vortex events, is estimated as 0.4 per year (Shen et al., 2022).

The last four ozone holes (2020–2023) had large areas exceeding 23 million square kilometers in September (Krzyścin & Czerwińska, 2024). Their consecutive appearance seems unexpected; at least, the previous observation of such a large ozone hole was two decades ago (1998–2001). The probability of a random realization of these conditions is estimated at about 0.05 (Krzyścin & Czerwińska, 2024), making searching for their causes necessary. Our results show low total ozone values in 2020–2022, predominantly at the high latitudes. In 2023, the September levels were low at the ozone hole edge (55–60°S). Still, in October, the values in the whole considered latitudinal range corresponded to the mean tendency or even exceeded it. Respectively, the last ozone hole in the spring of 2023 was not among the largest in the second half period of its existence.

Volcanic eruption influence can be one of the causes of total ozone depletion in recent years. In particular, the Hunga Tonga-Hunga Ha'apai volcano (20.536°S, 175.382°W) eruption on January 15, 2022 led to the penetration of a large bulk of water into the stratosphere and mesosphere with the change in its chemical state. Similar phenomena are well-known from previous observations, in particular after the Pinatubo volcano eruption in 1991. Our calculations clearly indicate total ozone diminution by 60 DU after the Calbuco eruption in 2015, which was noticeable in zonal maximum, where mid-latitude air masses dominate. Another possible factor is Australian wildfires, which could influence the Antarctic ozone in 2020 and 2021 (Ansmann et al., 2022). It is supposed that smoke layers decreased ozone concentration at the 10–12 km height by 20–30%. Moreover, the development of La Niña is also essential for the stratospheric conditions (Blachut & Balasuriya, 2024). Deep and long-lived ozone holes caused an increase in UV levels in recent years (Kessenich et al., 2023).

Ozone recovery is usually forecasted in the nearest decades (de Laat & van Weele, 2011). However, the current tendency in expected ozone recovery needs to be more evident. In particular, Safieddine et al. (2020) note a slow ozone recovery. In (Kessenich et al., 2023), ozone changes from the early 2000s are characterized as insignificant. Estimations of (Krzyścin & Czerwińska, 2024) demonstrate the beginning of the recovery near 2000 with its stopping near 2010. Taking into account the last four years, recovery signs have disappeared, but this can be caused by the aforementioned Australian wildfires and the Hunga-Tonga volcano eruption, which typically are not included in simulations.

Our results indicate the total ozone trend to the mid-1990s as almost linear. This result corresponds to the one from (Herman et al., 2023) where the years 1994–1998 were indicated as a time of the ending of the regular ozone decrease. Later, ozone values demonstrated a clear tendency or showed a partial recovery with the following ozone diminution. The second variant is more common in the high latitudes (70–80°S). Of course, the last four years have impacted the evaluation of time changes to a significant degree (Fioletov et al., 2023). As a result, if volcanic eruptions and wildfires are not regular, the tendency in total ozone can be different from the current one with its possible return to recovery. Nonetheless, the last few years have exhibited a complicated character of the ozone recovery, and even its reality is not evident. The earlier estimates of an increasing trend in total ozone in the southern high latitudes used the data limited by the 1995–2020 period (Coldewey-Egbers et al., 2022).

Ozone zonal asymmetry to the mid-2000s was considered in detail in (Grytsai et al., 2007; 2017). From those data, the September–November minimum reached 200 DU at 70–80°S, and the maximum was near 380 DU at 50–55°S. Our results in this paper show even 170–180 DU in the region of zonal minimum at 70–75°S. We can see in Figure 8c the minimal values in October (near 150 DU). The values are similar in September, and in November, they are higher, equaling ~200 DU on average. The November values are highly variable and dependent on the duration of the ozone hole's existence in a year. The most significant total ozone gradient in the meridional direction is observed at 60°S in the region of zonal minimum and at 70°S in the region of zonal maximum. The most prominent zonal asymmetry is reached at 65°S, corresponding to the estimates in (Grytsai et al., 2005a; 2007; 2017).

Evident zonal asymmetry in the total ozone distribution is observed from September till mid-December (Ialongo et al., 2012) depending on the state of the stratospheric polar vortex. The maximal asymmetry is noticed in October with the estimation of 50% of the zonal mean (Ialongo et al., 2012) or close to 90 DU (Ivaniha, 2020). Our results display a typical October ozone maximum near 380 DU and ozone minimum near 190 DU in the 2000s–2010s (Fig. 8a, c). Respectively, half of the difference between these values is very close to the mentioned result (Ivaniha, 2020). Kessenich et al. (2023) denote a complicated tendency in September with an October ozone reduction in the ozone hole core at 75–82°S, 5–50 hPa. Our processing shows the pattern where the October maximum values have evidently decreased during recent years, and the respective changes in the zonal minimum are lesser than in previous years.

The eastward shift of the quasi-stationary wave minimum was described in (Grytsai et al., 2007; 2017) and was analyzed in the following papers. In particular, Siddaway et al. (2020) noticed, based on simulation, that the shift should be reduced during the future ozone recovery. A possible cause of the shift was associated with zonal flow strengthening under the ozone hole conditions. Our results have generally displayed a stopping of the minimum shift after the 1990s. However, the current tendencies at the high latitudes indicate a possibility of its prolongation (Figs. 6b, 9d) accompanied by significant interannual variations. Consequently, future observations can elucidate the answer to this question.

5 Conclusions

We studied long-term tendencies in the Antarctic ozone distribution by the 1979–2023 satellite data. Quasi-stationary structures were considered by averaging the ozone distribution over the austral spring. The choice of this time range and the 55–80°S latitudinal belt allows for characterizing total ozone distribution in the edge and inner regions of the ozone hole. Polynomial approximation of the third degree is carried out to analyze long-term tendencies. Coefficient of determination R^2 for September–November quasi-stationary maximum and minimum was equal to 0.47–0.66. The distributions for individual months, September, October, and November, are also determined to obtain more complete information about the observed changes.

The primary total ozone tendency in Antarctica is well-known from earlier studies, being observed as a decreasing trend during the total ozone development (1980s – early 1990s). This tendency is indicated in all the considered cases, leading to the total ozone decrease by 150 DU during 15 years in the zonal minimum region, however, this tendency clearly changed since 2000s. In addition, we have noticed other details. In particular, the ozone layer's recovery has not been identified in the Antarctic spring in recent years. After the initial decrease, any clear tendency is not reliably revealed, although there is a total ozone decrease in zonal maximum during the last decade.

We also cannot exclude the possible influence of at least two other factors on the observed tendencies in the amount of ozone in the atmosphere over Antarctica. The first one of these is the observed trends in ozone-depleting substances, particularly chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) atmospheric compositions studied in the Advanced Global Atmospheric Gases Experiment (AGAGE, https://agage.mit.edu/data/agage-data). In general, detected trends in these compositions coincide with TOC trends in Figures 7a, 8a, and 9a, where the well-known rapid spring decline in ozone over Antarctica from the 1980s to the mid-1990s changed to an emerging ozone recovery that slowed by the 2000s in the last two decades as atmospheric abundances of five CFCs increased between 2010 and 2020 (Western et al., 2023). The second one is a response of the ozone layer to climate change, which still includes many uncertainties during modeling (see, e.g., Chiodo & Polvani, 2019) and needs a detailed investigation that is out of the framework of this paper.

The influence of the stratospheric warmings in 1988, 2002, and 2019 is another significant phenomenon. One of the warmings (in September 2002) corresponded to the World Meteorological Organization criterion of major warming (WMO, 1978). The stratospheric polar vortex weakening or disruption caused a total ozone increase reaching 100–150 DU in the 60–75°S latitude range. The warmings in 1988 and 2019 were not major, but they had the largest impact on high latitudes and in the region of zonal maximum.

Our analysis shows the absence of a quasi-stationary wave longitudinal shift during the last decades when interannual changes were the most significant. The earlier part of the considered time range includes an eastward shift of the quasi-stationary minimum approximately in the same time interval when total ozone decreased (1980s — early 1990s). However, later, there was an obvious transition from the negative trend in TOC and the shift of the ozone minimum area to the east on average from −60° to −10° of longitude to a quasi-stable state (no visible trend in TOC) and small variations in the longitudinal position of the TOC minimum in the longitudes of the Greenwich meridian in the 2000s—early 2020s.

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Сучасні тенденції у зональному розподілі та асиметрії озону в Антарктиці за даними супутникових вимірювань

Реферат. Утворення антарктичної озонової діри наприкінці зими та навесні (вересень—листопад) є найпомітнішим явищем у південній полярній стратосфері. Озонова діра з'являється кожного сезону з початку 1980-х років у стратосферному полярному вихорі, який перешкоджає змішуванню його повітряних мас із повітрям середніх широт, впливаючи на розподіл малих складових атмосфери, включаючи озон. Озонова діра значно залежить від динамічних факторів, в основному від поширення планетарних хвиль з тропосфери до стратосфери. Наше дослідження має на меті визначити загальний довготний розподіл озону для південної весни та окремих місяців (вересень, жовтень і листопад), і детально розглянути спостережувані тенденції. Проведено аналіз та отримано тенденції динаміки загального вмісту озону під час розвитку озонової діри. Усереднення за часом довготного розподілу загального вмісту озону було виконано з використанням тримісячних середніх значень озону під час південної весни. Ця процедура усуває флуктуації та викиди за рахунок біжучих планетарних хвиль. Діапазон широт 55°—80° пд. ш. був проаналізований, щоб охарактеризувати загальний розподіл озону на краю озонової діри та у внутрішніх її областях. Розподіл за окремі місяці (вересень, жовтень і листопад) розглядався для детального опису спостережуваних тенденцій. Аналіз отриманих результатів вказує на близький до лінійного від'ємний тренд загального вмісту озону під час інтенсифікації озонової діри з початку 1980-х до середини 1990-х років. Ця тенденція була визначена на всіх проаналізованих широтах, причому загальний вміст озону зменшився на ~150 одиниць Добсона протягом 15 років в області зонального довготного мінімуму. Проте аналіз тенденцій показує, що відновлення озонового шару під час південної весни в останні роки не спостерігається, враховуючи низькі значення вмісту озону в 2020—2023 роках. Після періоду зменшення вмісту озону чітка тенденція не простежується, але жовтневі значення зонального максимуму дещо знизилися в останнє десятиліття. Положення зонального мінімуму рухалось на схід під час зниження загального вмісту озону, але у подальшому відбувались значні міжрічні варіації довготного положення області як максимального, так і області мінімального вмісту озону без будь-якої помітної довгострокової тенденції.

Ключові слова: озонова діра, планетарна хвиля, полярний вихор, раптове стратосферне потепління, тренд вмісту озону