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Assessment of the zonal asymmetry trend in Antarctic total ozone column using TOMS measurements and CCMVal-2 models

Abstract. In the paper the seasonal trends in the zonal asymmetry in the quasi-stationary wave pattern of total ozone column (TOC) at southern polar latitudes have been investigated. We evaluated and compared seasonal trends in the zonal TOC asymmetry from modern era satellite measurements using the Total Ozone Mapping Spectrometer data and the second Chemistry Climate Model Validation (CCMVal-2) assessment. The model longitude phase shifts in asymmetry are in general consistent with the eastward phase shifts observed in historical period 1979—2005, however, there are underestimated values in individual seasons. Future trends in zonal asymmetry from the eleven CCMVal-2 models up to 2100 are presented. They demonstrate the appearance of reverse (westward) future phase shifts, mainly in austral summer. The results are in agreement with previous study and highlight that the general eastward/westward phase shift is caused by both greenhouse gases changes and ozone depletion/recovery. The greenhouse gases change drives a basic long-term eastward shift, which is enhanced (decelerates or reverses) in austral spring and summer by ozone depletion (recovery). The trends in the TOC asymmetry are forced by a general strengthening of the stratospheric zonal flow, which is interacting with the asymmetry of the Antarctic continent to displace the quasi-stationary wave-1 pattern and thus influences the TOC distribution. The results will be useful in prediction of seasonal anomalies in ozone hole and long-term changes in the local TOC trends, in ultraviolet radiation influence on the Southern Ocean biological productivity and in regional surface climate affected by the zonally asymmetric ozone hole.

Keywords: Antarctica, asymmetry, CCMVal-2, climate change, ozone, stratosphere

1 Introduction

Quasi-stationary planetary waves (QSW) are generally recognized as dynamic processes that play an important role in the global distribution of temperature and ozone. The QSW impact on the polar stratosphere is dependent to a large degree on the El Niño phenomenon in the tropical Pacific. In the last decades, El Niño events occur more frequently in the central Pacific than in conventional El Niño region in the eastern Pacific (Ashok et al., 2007). The central Pacific events are associated with the strong effects in the Southern Hemisphere stratosphere due to planetary wave propagation (Yang et al., 2015) accompanied by zonal asymmetry in the Antarctic stratosphere (Lin et al., 2012; Evtushevsky et al., 2019), particularly, in temperature and ozone (Wirth, 1993; Bodeker & Scourfield, 1995; Ialongo et al., 2012). Since El Niño evolution tends to be predictable at several months lead time (Domeisen et al., 2019), the conditions in the Antarctic stratosphere could also be predicted on a seasonal time scale based on zonal asymmetry metrics (Kravchenko et al., 2012; Milinevsky et al., 2020). This suggests the need for a detailed study of the zonal asymmetry to better understand and predict not only the seasonal development of the Antarctic ozone hole, but also its long-term changes.

Studies have shown that there is a statistically significant spatial correlation between total ozone column (TOC) wave structure and the planetary wave in temperature perturbation (Wirth, 1993). In the Southern Hemisphere (SH), the QSW of zonal wave number 1 (QSW1) is a prominent feature in the TOC (Wirth, 1993; Quintanar & Mechoso, 1995; Grytsai et al., 2007; Grytsai et al., 2017). Analysis of the mean geopotential height fields has shown that the amplitude of QSW1 is the largest of any of the quasi-stationary waves both in Northern and in Southern Hemispheres (Hobbs & Raphael, 2007; Turner et al., 2017). Moustaoui et al. (2003) have shown that the stratospheric QSW1 perturbs the isentropic surfaces, redistributing ozone in such a way that the ozone fields closely mimic the observed pattern in the stratospheric geopotential height field. In addition, Agosta and Canziani (2011) found that a considerable fraction of the interannual TOC variability occurs primarily in response to QSW1 phase changes. Therefore, a relationship between the TOC evolution and planetary wave variability, in amplitude and phase, could provide a link between the observed ozone variability and stratospheric dynamics.

The planetary waves show a large inter-annual variability in both amplitude and phase. In the wintertime, southern mid-latitudes wave activity influenced polar stratospheric temperatures (positive correlation) and thus the severity of ozone depletion (Kravchenko et al., 2012).

The distribution of the TOC at extra-tropical latitudes in the SH exhibits zonal asymmetry which varies with season. Unlike the Polar Regions, where the ozone hole dominates, SH mid- to high latitudes (50°–70° S) demonstrate high TOC values (especially in spring) — ozone 'collar', but the ozone distribution is not uniform. A measure of zonal asymmetry in stratospheric ozone is longitudinal variations of TOC with respect to the zonal mean, where zonal asymmetry is represented by a region of low ozone (TOC minimum) and another region of high ozone level (TOC maximum).

The zonal asymmetry in the TOC distribution over latitudes south of 50° S in October 2014 (Fig. 1a) is shown by the data from Ozone Monitoring Instrument (OMI) aboard the Aura satellite platform (http://ozoneaq.

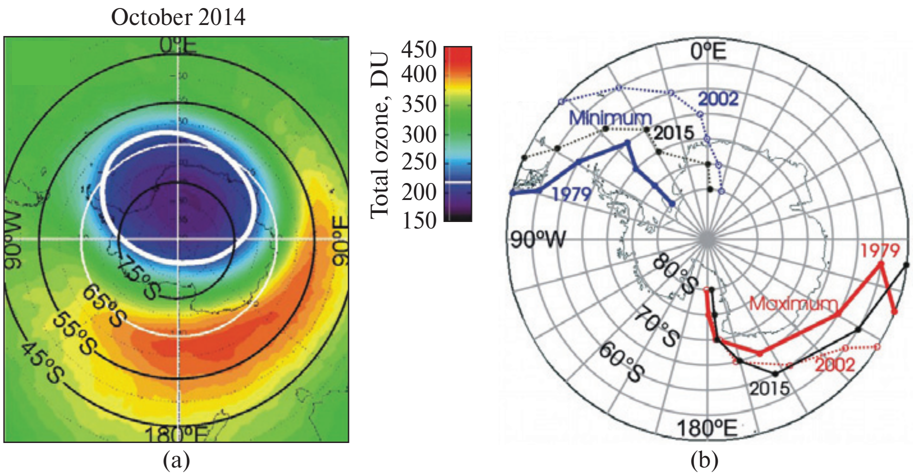

Figure 1. (a) Total ozone in the SH middle/high latitudes in October 2014. (b) Map of longitudinal locations of zonal QSW1 maximum (red) and zonal QSW1 minimum (blue) at seven latitudes between 50° S and 80° S; westernmost (easternmost) longitudes in 1979 (2002) determined from the polynomial fit using TOMS–OMI data. Black dotted (solid) line marks longitudes of ozone minimum (maximum) for 2015. Modified from Grytsai et al. (2017)

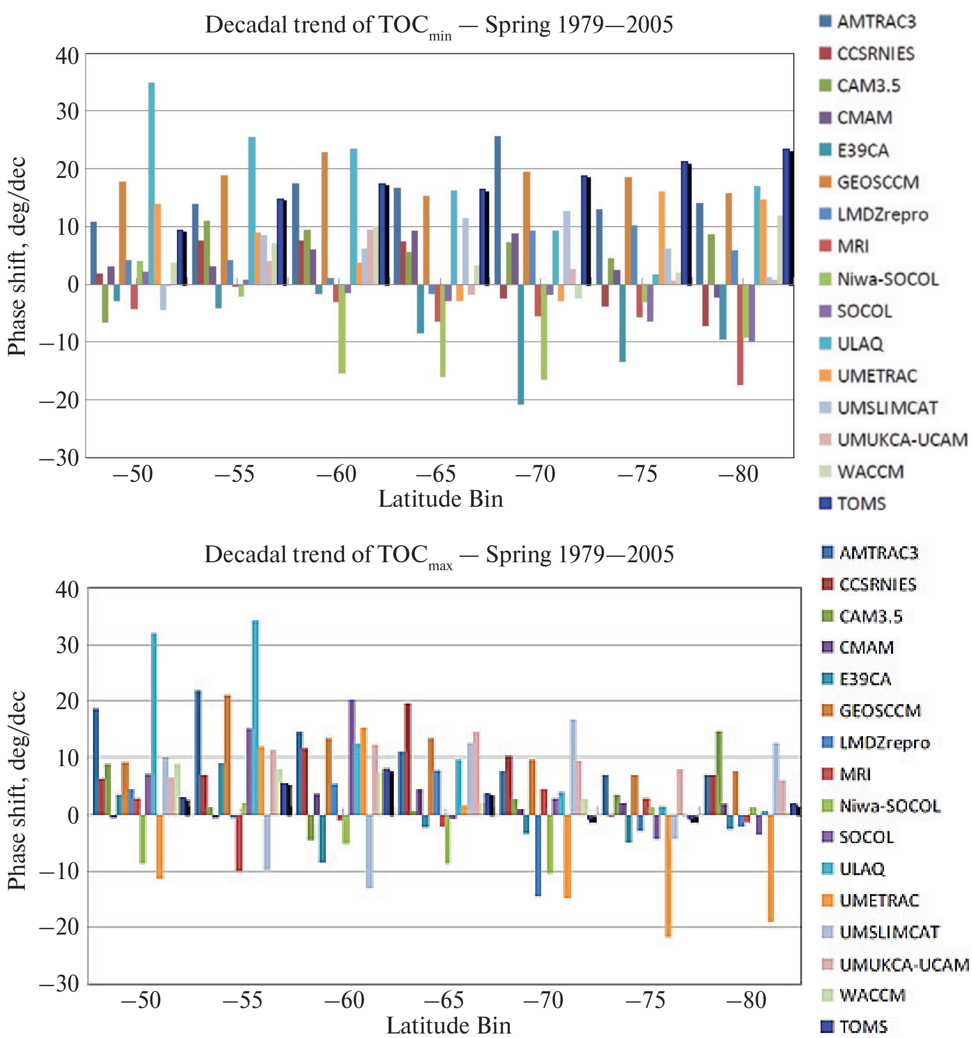

Figure 2. Austral spring trends in (a) zonal minimum and (b) maximum phase shift for REF-B1 model ensembles (1979—2005)

gsfc.nasa.gov/). White oval contour in Fig. 1a corresponds to the ozone hole boundary with TOC value of 220 Dobson Units (DU). The longitude zonal QSW1 phase shift (in ozone minimum and maximum) in South Polar region over 50—80° S latitudes in 1979—2015 is shown in Fig. 1b.

As shown by Grytsai et al. (2007; 2017), the longitudes of the spring TOC minimum (λ_{min}) and maximum (λ_{max}) positions in the collar region have exhibited a general eastward shift over the years 1979 to 2005. The magnitude of the shift is larger for the λ_{min} than for the λ_{max}, and varies with latitude. The cause of this effect has been linked to feedback of the ozone hole on excitation of the stratospheric wave-1 QSW outside the polar vortex (Grytsai et al., 2007), however a detailed assessment of the underlying physical mechanism is yet to be reported.

It should be noted that, in a changing climate, Southern Ocean phytoplankton will experience increased irradiances (Deppeler & Davidson, 2017). Because the shift of λ_{min} is potentially exposing a larger area of the biologically productive Weddell Sea region to progressively higher levels of ultra-violet radiation during spring, it is important to understand the cause of the TOC asymmetry and its future regional trends. The effects of asymmetric TOC recovery (Grytsai et al., 2017) must also be considered.

In this paper, we investigated the seasonal trends in the zonal asymmetry in the quasi-stationary wave pattern of total ozone column at southern polar latitudes. The trends were evaluated using observations with the Total Ozone Mapping Spectrometer and were compared with the second Chemistry Climate Model Validation (CCMVal-2) assessment.

In Section 2, the model, data and model runs for the zonal minimum and maximum phase shift in historical period and future projections are considered, followed by discussion and summarizing conclusions in Section 3.

2 Model, data and simulations

We examine the monthly mean TOC fields produced for the second Chemistry Climate Model Validation (CCMVal-2) activity of Stratospheric Processes and their Role in Climate (SPARC) (Eyring et al., 2010; Siddaway et al., 2013). CCMVal-2 involved contributions from 15 chemistry climate models (CCMs) with the aim of improving CCMs through an evaluation process and to produce robust projections of stratospheric ozone and its impact on climate (Morgenstern et al., 2010). These models simulate 3-dimensional atmospheric circulation with fully interactive stratospheric chemistry: external forcing such as greenhouse gases (GHG), ozone-depleting substances (ODS) and stratospheric aerosols are prescribed but ozone is evaluated.

A review of the models used in CCMVal-2 can be found in (Eyring et al., 2010) and (Morgenstern et al., 2010). Here we examine a subset of the models, and focus on the austral winter June, July and August (JJA), spring September, October, November (SON) and summer December, January and February (DJF) months for the 'modern era' (1960–2005; REF-B1 reference runs, see Fig. 2 and Fig. 3, left) and the 'prediction era' (1960–2100; REF-B2 reference runs, see Fig. 3, right). We extend the analysis of (Grytsai et al., 2007) to include results for JJA and DJF (Fig. 3). REF-B2 simulations represent internally consistent data output from the past to the future in order to produce best estimates of future ozone–climate change up to 2100. These include specific assumptions about GHG increases and decrease in halogen emissions, in relation to anthropogenic forcing only. Additionally we include results from CCMVal-2 sensitivity control simulations (SCN-B2d) run over the same time period as the REF-B2 model runs.

Data from these simulations are designed to address the impact of the natural variability of the REF-B2 simulations. Additional natural forcings, including a repeated solar cycle, together with an internally generated Quasi-Biennial Oscillation, under volcanically clean conditions are included.

We compare the spring trends obtained from observations (Grytsai et al., 2007), shown as 'TOMS' in Fig. 2, with results from CCMVal-2 models by restricting the REF-B1 runs to 1979–2005 (Fig. 2). Data from REF-B2 model runs were also restricted to 2005–2100 for continuity (Fig. 3, right). To statistically examine TOC asymmetry for each reference period, seasonal zonal averages within 5° latitude steps from 50–80° S

Table. Summary of linear trends for λ_{min} and λ_{max} at 55° S with 95% confidence limits in brackets. Statistically significant trends are highlighted in bold

Trend (deg/decade)	JJA		SON		DJF	
	λ_{min}	λ_{max}	λ_{min}	λ_{max}	λ_{min}	λ_{max}
Observations 1979–2005	**13.3** [7.6]	4.0 [9.3]	**13.7** [4.9]	**7.6** [4.9]	9.2 [13.1]	11.7 [12.0]
REF-B1 ensemble 1979–2005	3.3 [4.7]	0.4 [4.0]	**7.2** [4.0]	**8.2** [4.5]	**14.4** [6.0]	**10.6** [4.7]
REF-B2 ensemble 2005–2100	0.5 [1.0]	0.13 [0.9]	–0.7 [0.8]	–0.2 [0.8]	**–2.4** [1.0]	**–1.4** [1.0]

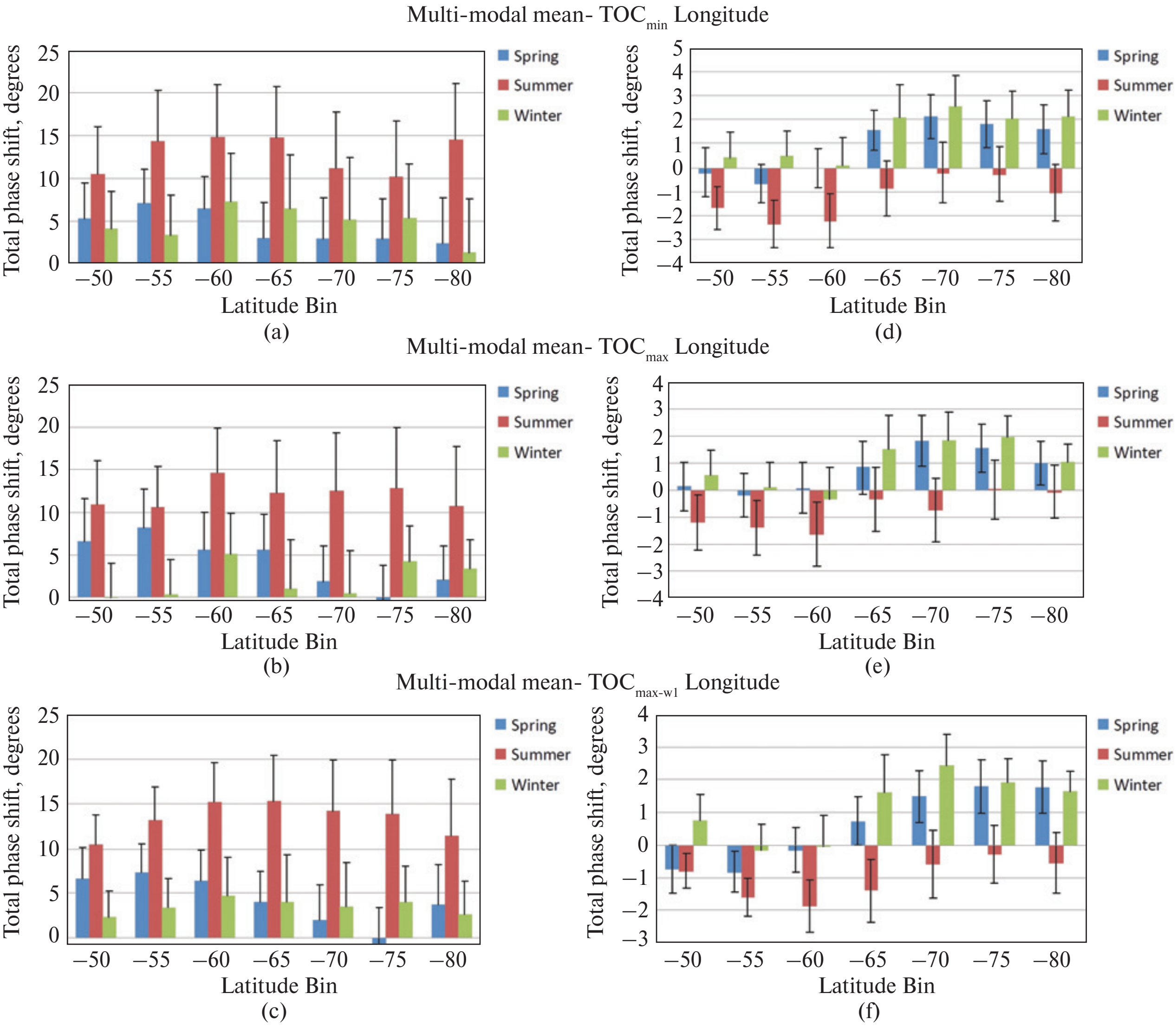

Figure 3. Multi-modal means in phase shift for three austral seasons — spring, summer and winter, in 1979–2005 for zonal minimum (a), zonal maximum (b) and wave-1 patterns (c); (d), (e), (f) same as (a), (b), (c), but for 2005–2100

were extracted. This was performed in order to include the ozone 'collar' region outside the ozone hole where wave perturbations are significant (Grytsai et al., 2007).

Latitudinal means for the 3 seasons were calculated for total ozone at the quasi-stationary wave ridges and troughs (TOC_{max} and TOC_{min}) along with their longitudinal positions (Fig. 3), as previously stated. To illustrate the extent of zonal asymmetry, the amplitude of the zonal wave (A_{zw}) was calculated as the half-difference of TOC_{max} and TOC_{min}, along with the relative zonal asymmetry as a percentage difference between the TOC at the wave extremes.

To further compare the CCMVal-2 results with observations (Grytsai et al., 2007), Fourier decomposition of the QSW maxima was performed in order to analyze zonal wave-1 (Fig. 3c) and wave-2 (not shown) patterns, as they vary with latitude. Decadal linear trends of wave parameters for each model over each reference period were obtained to consider the long-term behavior of Antarctic ozone zonal asymmetry. For the ensemble mean, a simple average was calculated, together with a 95% confidence interval as an uncertainty. Examples for 55° S are given in Table.

Results in Table indicate the robust trends in phase shift. Overall we find that the ensemble REF-B1 linear trends in λ_{min} and λ_{max} are of the same sign as for the historical observations, with the magnitudes of the model trends compared with observations being smaller in winter and spring, and comparable in summer.

Statistically significant linear trends occur in winter (i.e. before the ozone hole formation) in the observations, but are not evident in the model data. The REF-B2 scenarios generally suggest a continuation of the eastward shift, though with reduced magnitude, in the first half of the 21st century (not shown in Table).

Most models show a dominant eastward shift at lower latitudes that weakens at high latitudes for zonal maximum, but remains mostly stable for zonal minimum (Fig. 2b and 2a, respectively). This contradicts TOMS observations over the same time period, which suggest an increasing eastward shift in the zonal minimum towards the pole (Fig. 1b and 'TOMS' in Fig. 2a). However, model trends in the zonal maximum broadly agree with TOMS observations with a decreasing eastward shift (but with smaller magnitude) approaching the South Pole.

Multi-modal means in phase shift for three austral seasons — spring, summer and winter, for the 'observation era' of 1979—2005 are shown in Fig. 3a, b, c for zonal minimum, maximum and QSW wave-1 component. Error bars in Fig. 3 represent the 95% confidence interval. An eastward phase shift for each 5° latitude bin, which is dominant for all seasons, was found to be strongest, up to 15°/decade, in the austral summer months around 60° S (Fig. 3, left). The spring phase shift in zonal maximum (for both the QSW and its wave-1 component) is stronger than the winter shift at lower latitudes, but is weaker than that at higher latitudes. This result generally agrees well with TOMS observations (Grytsai et al., 2007), in particular for the wave-1 component phase shift. Future trends in zonal asymmetry from the eleven CCMVal-2 models are shown in Fig. 3d, e, f. The decadal trend across all model ensemble runs for the first part of the 21st century, 2005—2050 (not shown) is more statistically significant, than that shown in Fig. 3d, e, f for 2005—2100, but still of reduced magnitude when compared with the depletion time period of 1979—2005. Note appearance of the reverse (westward) future trends, mainly in summer (Fig. 3, right).

3 Discussion and conclusions

The seasonal trends in the zonal asymmetry of total ozone column over the Antarctic region have been analyzed. The trends were evaluated using the second Chemistry Climate Model Validation (CCMVal-2) assessment and were compared with observed trends from the Total Ozone Mapping Spectrometer data. The model evaluations for historical period show general consistency with observations except for underestimated eastward shift in λ_{min} and λ_{max} in winter and in λ_{min} in spring (Fig. 2a and Table). This means that the ability to represent zonal asymmetry change in the model can be improved. For this, more detailed analysis of the causes that lead to the different trends observed in individual seasons (Table) can be helpful.

The projected eastward phase shift is greatly reduced during the 21st century for all seasons in a decadal trend calculated until 2100. The austral summer months even show a reversed (westward) zonal trend, which is the largest at lower latitudes 50—65° S. This reduction in phase shift is attributed to future ozone recovery. When considering the effect of natural forcing (SCN-B2d model runs), the EMAC-FUB model results (not shown) indicate a dominant westward phase shift in zonal maximum and minimum for the winter and summer months across all the considered latitudes, whilst remaining weakly eastward during the spring months. As ozone recovery can be affected by future increase in the GHG concentrations (Eyring et al., 2010; Siddaway et al., 2013) this coupling should be reflected in the changes of zonal asymmetry in Antarctic ozone. The CCMVal-2 models in this work include contribution from the GHG emissions and ozone depletion/recovery, therefore, the presented results agree with conclusion that the general eastward/westward phase shifts may be mainly attributed to these two processes (Grytsai et al., 2017). GHG changes drive a basic long-term eastward shift, which is enhanced in SON and DJF by ozone depletion, but may be decelerated or reversed by future ozone recovery. We propose to assume that the trends in the TOC asymmetry are forced by a general strengthening of the stratospheric zonal flow, which is interacting with the asymmetry of the Antarctic continent to displace the QSW wave-1 pattern and thus influence the TOC pattern.

The results of this work may be useful in prediction of (i) seasonal anomalies in ozone hole (Kravchenko et al., 2012; Milinevsky et al., 2020) and long-term change in (ii) local TOC trends (Hassler et al., 2011), (iii) ultra-violet radiation influence on the Southern Ocean biological productivity (Deppeler & Davidson, 2017) and (iv) regional surface climate affected by the ozone hole (Thompson et al., 2011) given the ozone hole zonal asymmetry.

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Оцінка тренду зональної асиметрії в розподілі загального вмісту озону над Антарктикою за допомогою вимірювань TOMS та моделей CCMVal-2

Анотація. У статті досліджено сезонні тенденції зональної асиметрії в розподілі загального вмісту озону (ЗВО) в квазістаціонарній хвилі на південних полярних широтах. Ми оцінили і порівняли сезонні тенденції в змінах квазістаціонарної хвилі у ЗВО, використовуючи дані супутникового спектрометра TOMS (Total Ozone Mapping Spectrometer) для картографування ЗВО та другу версію валідації хіміко-кліматичної моделі (CCMVal-2). Модельні зсуви фази по довготі в асиметрії просторового розподілу озону загалом узгоджуються із зсувами фази по довготі на схід, що спостерігалися в історичному періоді 1979–2005 рр. Проте в окремих сезонах існують занижені значення таких довготних зсувів. Представлено майбутні тенденції в зональній асиметрії від одинадцяти моделей CCMVal-2 до 2100 року. Вони демонструють появу зворотних (західних) майбутніх фазових довготних зсувів, головним чином влітку у Південній півкулі. Отримані результати узгоджуються з попередніми дослідженнями і підкреслюють, що загальний довготний зсув фази на схід/захід обумовлений як змінами парникових газів, так і виснаженням/відновленням озонового шару. Зміна парникових газів зумовлює основний довгостроковий зсув на схід, який посилюється (сповільнюється або змінюється) в період південної весни та влітку за рахунок виснаження озонового шару (відновлення). Тенденції в асиметрії ЗВО зумовлені загальним посиленням стратосферного зонального потоку, який завдяки існуванню асиметрії антарктичного континенту витісняє квазістаціонарну хвилю-1 і впливає на просторовий розподіл ЗВО. Результати роботи будуть корисними для прогнозування сезонних аномалій озонової діри та довгострокових змін місцевих тенденцій зміни ЗВО, впливу ультрафіолетового випромінювання на біологічну продуктивність Південного океану та на регіональний клімат, на який впливає зонально-асиметрична озонова діра.

Ключові слова: Антарктика, асиметрія, CCMVal-2, зміна клімату, озон, стратосфера