

Article

Trend Pattern (1980–2025) of Total Ozone Column over Antarctica in Winter–Spring Season, Derived from Heatmap Analysis—A New Approach to Detecting Ozone Hole Recovery

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Highlights

What are the main findings?

- The “ozone hole” recovery can be observed after 2001 as a clear separation of blue–red fields on the winter–spring trend heatmaps of total ozone column amount, which confirms the trend reversal.
- The unusual behaviour of the “ozone hole” in the years 2019–2023 is present on the heatmaps as a distinct blue region.

What is the implication of the main finding?

- The final closure of the ozone hole may be delayed by changes in the stratosphere caused by current climate change.

Abstract

Numerous attempts have been made to detect signs of ozone layer recovery over Antarctica, which has been expected since the beginning of the 21st century as a result of the reduction in concentrations of ozone-depleting substances in the Antarctic stratosphere, in accordance with the provisions of the 1987 Montreal Protocol and subsequent amendments aimed at protecting the ozone layer. Large year-to-year variability in the Antarctic ozone, driven by changes in atmospheric dynamics, has made it difficult to draw definitive conclusions about the rate of Antarctic ozone recovery. In this paper, we present an alternative approach to analyse ozone recovery by examining patterns in blue–red heatmaps of total ozone column (TOC) trends during the winter–spring period from 1980 to 2025. Three annual TOC time series (winter average, 15 September value, and spring minimum) were analysed to monitor the ozone hole development over the Syowa and Amundsen–Scott stations. Various sources of the daily TOC data were examined, including reanalysis data, ground-based measurements, and satellite observations. Regardless of the data source, we found that, for both stations, blue cells (negative trends) dominated in the areas of the heatmap where the TOC trends ended before 2000, while red cells (positive trends) appeared mostly afterwards. These results confirm the hypothesis of a trend reversal, i.e., a recovery beginning in the early 2000s, which was obscured in the original, noisy TOC time series.

Keywords: ozone; stratosphere; ozone hole; ozone recovery; Antarctica



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1. Introduction

Changes in the total ozone column (TOC) over Antarctica have been of scientific interest for almost 40 years, since the discovery of the spring ozone hole over Antarctica by Chubachi [1] and Farman et al. [2]. Subsequent studies [3–5] revealed that the dramatic decline in ozone layer thickness during the 1980s in this season was due to the catalytic destruction of O₃ by chlorine, occurring in the vicinity of particles (droplets and/or ice crystals) forming in polar stratospheric clouds (PSCs). PSCs typically appear during the polar night, when the stratospheric temperature is below -78°C (for droplets, the so-called PSC Type I) or below -90°C (for ice crystals, PSC type II). Such conditions were common over Antarctica even before 1980, but the subsequent sharp decrease in springtime ozone stemmed from the release of active chlorine from its inert reservoirs (HCl and ClONO₂) accumulated in the Antarctic during the 1970s because of the global increase in the production and use of freons in various industrial technologies (e.g., [6]). Man-made ozone-depleting substances (ODS) are still present in the atmosphere, as they are long-lived substances (e.g., for freons CFC-x, the life time could be over 100 years), but their concentration in the stratosphere has been steadily decreasing since the 2001 peak as a result of the Montreal Protocol 1987 and its subsequent amendments setting a ban on the production of ODS [7]. In 2024, the ODS concentration over Antarctica was about 28% below the ODS peak [8]. This value means that the rate of TOC changes in the declining phase (1980–2000) of the Antarctic ozone evolution forced by anthropogenic chemicals was about three times more intense (in terms of the absolute values) than the increasing rate in the recovery phase starting in 2001. Therefore, if this recovery rate continues in the 21st century, the full recovery of the Antarctic ozone, when ODS levels return to their pre-ozone hole benchmark level in 1980, will be predicted to appear around 2070. This estimate corresponds with the estimates derived by previous, more advanced chemical model studies [9–11].

The ongoing recovery of the Antarctic springtime ozone is not in question, as the strict phasing out of ODS production is a key result of the implementation of the Montreal Protocol. However, the final closure of the ozone hole may be delayed because ozone trends are influenced not only by ODS-induced chemical destruction, but by changes in the stratosphere caused by recent climate change. Tropospheric global warming is associated with stratospheric cooling (e.g., [12–14]), which fosters conditions conducive to polar stratospheric clouds (PSCs) in the Antarctic lower stratosphere, subsequently delaying the anticipated recovery. Additionally, stratospheric cooling is due to the ozone hole itself (less UV radiation absorption in this region), which affects the strength of the Antarctic stratospheric vortex [15,16]. It has been suggested that the warming of sea surface temperatures in the extratropics has caused a decrease in the propagation of Rossby waves into the Antarctic stratosphere since 2000, resulting in vortex strengthening [17,18] and delaying ozone recovery. Recently, Sweeney et al. [19] provided evidence for the weakening of the Southern Hemisphere Brewer–Dobson circulation, which cools the Antarctic lower stratosphere and slows the healing of the Antarctic ozone.

Certain weather phenomena and natural disasters, e.g., Australian bushfires and volcanic eruptions occurring in 2020–2023, inevitably lead to the excessive growth and strengthening of ozone holes over several successive years [20]. The ozone hole is expected to resume its customary behaviour in 2024–2025, consistent with declining ODS levels.

Current modelling of the Antarctic ozone recovery has focused on calculations of the anthropogenic component of O₃ variability due to man-made ODS-induced chemical destruction, as well as internal O₃ variations strongly influenced by recent climate changes. Two basic approaches have been employed: chemical–climate models solving the equations dealing with the dynamical and chemical variables, and the statistical (regression) models.

The key point in such modelling is the appropriate parameterisation of the dynamical component of O₃ variability influencing the Antarctic polar vortex in the context of PSC formation and its effect on hole development. As mentioned in previous paragraphs, the vortex behaviour is influenced by many interrelated processes, making it difficult to extract the component of O₃ variability clearly related to long-term anthropogenic ODS variability.

Here, we propose an alternative approach to detecting the TOC trend reversal at the beginning of the 2000s, taking into account a set of sliding trend values in the TOC time series with a length of at least 10 years and starting points between 1980 and 2016, visualised using heatmaps drawn from the various TOC data sources, including the Dobson spectrophotometer observations, reanalyses (ERA5, MERRA-2, and MSR-2), and satellite data (SBUV). Data from two stations, Amundsen–Scott and Syowa (representing an inner Antarctic location and a coastal location, respectively), are analysed.

We hypothesise that the overturning signal is so strong that a prevalence of negative trends before 2000 and positive trends since 2001 can be claimed, despite large ‘natural’ variations existing in the considered TOC time series. This would support the trend overturning and thus also the Antarctic springtime TOC recovery. In this case, the parameterisation and delineation of the sources of TOC variability over Antarctica would not be necessary.

Both in situ and remote sensing methods are used in the TOC monitoring. Ground-based methods nominally provide high reliability of the measurements. The Dobson and Brewer spectrophotometers retrieve TOC values from absorption of the surface solar UV radiation from a global TOC monitoring network with the data archived in the World Ozone and Ultraviolet Radiation Data Centre (WOUDC, woudc.org/en/data-search-and-download). In polar regions, such observations are unavailable during polar night and have low accuracy at the beginning/end of the sunlight period under low solar elevations. Rarely, these instruments are used for the lunar TOC observations using UV solar radiation scattered by the moon. Using solar light absorption in the IR range, the TOC can be retrieved from the high-resolution IR spectral measurements by a ground-based Fourier transform infrared spectrometer (FTIR). However, such measurements have appeared rather sporadically over Antarctica [21] and have not participated in regular long-term TOC monitoring.

Satellite observations using backscatter solar light in the UV range began on board the NASA NIMBUS-4 satellite (launched in April 1970) and continued to the present with various versions of the solar backscattered UV spectrometers (SBUV) on NOAA satellites and the Ozone Monitoring Instrument (OMI) measuring (since October 2004) onboard the NASA Aura satellite. The thermal emission of the Earth’s atmosphere can also be utilised using the Microwave Limb Sounder (MLS), the Michelson Interferometer for Passive Atmospheric Soundings (MIPAS), and the Infrared-Atmospheric Sounding Interferometer (IASI). These satellite measurements provide global coverage, but when analysing the station’s overpasses, daily gaps may appear because of the large distance (sometimes >300 km) between the measurement and station location.

A reanalysis of the datasets enables the creation of a consistent, long-term record of past geophysical fields by correcting for the inherent measurement errors of the instruments used during different periods of atmospheric observation, combining both ground-based and satellite data. Reanalysis involves using various data synthesis methods to combine different datasets into a single grid with regular spacing, without gaps. The following reanalyses have frequently been used in TOC studies, among many others: the European Centre for Medium-Range Weather Forecast (ECMWF) fifth-generation reanalysis (ERA5), the Multi-Sensor Reanalysis version 2 (MSR-2), developed by the Royal Netherlands Meteorological Institute (KNMI), and Modern-Era Retrospective analysis for Research and

Applications, Version 2 (MERRA-2), managed by the NASA Goddard Earth Sciences (GES) Data and Information Services Centre (DISC).

This paper is organised as follows. The introduction is in Section 1. Section 2 provides details of the data used and the data analysis method. Section 3 contains the results, which are divided into two parts. The first part presents a comparison of the daily TOC values (for each calendar month separately) using all the considered data sources, including observations from the Dobson spectrophotometer using the latest temperature-dependent ozone absorption coefficients. The latter part of Section 3 deals with statistical analyses of trend patterns presented on the blue–red heatmaps for the annual TOC time series: winter mean, 15 September, and spring minimum values. Section 4 contains the discussion, and Section 5 provides conclusions.

2. Materials and Methods

2.1. Total Column Ozone Data

Trend patterns were analysed in the TOC measurements taken at two Antarctic sites, Syowa (69.0°S, 39.6°E, 29 m) and the Amundsen–Scott South Polar Station (89.997°S, 24.8°W, 2841 m), over the period from 1980 to 2025. The Syowa station is a typical coastal station where the TOC is more variable, as the ozone-poor polar vortex sometimes, in spring, moves out of the station’s location. By contrast, the South Polar station is located in the vicinity of the South Pole, experiencing an extended polar night of six months. It is situated at the high plateau and is always within the winter–spring polar vortex.

In situ long-term measurements by the Dobson spectrophotometer, (R. & J. Beck, London, UK) (since 1961 up to 2022 and since 1963 up to the present in Syowa and at the South Pole, respectively) have been carried out over the stations and the daily mean TOC data are archived in the WOUDC at <https://woudc.org/archive/products/ozone/total-column-ozone/totalozone/1.0/> (accessed on 28 May 2026). Nowadays, the WOUDC provides, in addition to the standard TOC values by the Dobson instrument calculated with Bass–Paur (BP) ozone absorption coefficient (O_3AC) fixed at a temperature $T_{const} = -46.3\text{ }^{\circ}C$ [22,23], the preliminary TOC values derived with Serdyuchenko and Gorshelev O_3AC version 2014 (SG14). The SG14 values were derived in laboratory measurements [24,25] at a variable temperature. For TOC retrieval, the temperature for the SG14 O_3AC calculation was set as the temperature profile in the stratosphere weighted by the vertical O_3 distribution (i.e., the so-called effective temperature, T_{eff}). The new TOC values, which are still in the developing phase, are available at https://woudc.org/archive/tmp/TotalOzone_1.0_1_corrected_v6/ (accessed on 28 May 2026) [26].

In addition, the satellite overpasses for Syowa from the SBUV merged data ver. 8.7 is considered for the period 1980–2023. The overpass TOC data, comprising nearly continuous observations on many platforms, including Nimbus7 (1980–1990), NOAA 9-19 (1985–2022), and SUOMI National Polar-orbiting Partnership (NPP) (2011–2022), are available at <https://acd-ext.gsfc.nasa.gov/anonftp/toms/sbuV/AGGREGATED/> (accessed on 28 May 2026). As SBUV data over the South Pole is unavailable, the TOC values from the OMI aboard the NASA Aura spacecraft are used instead. These values were obtained using the OMI Time Series Generator for any site from October 2004 to the present. The generator is available at <https://gml.noaa.gov/grad/neubrew/SatO3DataTimeSeries.jsp> (accessed on 28 May 2026).

For both considered stations, the continuous daily mean TOC values are taken from the reanalyses: ERA5, MERRA-2, and MSR-2, with horizontal resolution (latitude $\times$ longitude) $0.25^{\circ} \times 0.25$, $0.5^{\circ} \times 0.625^{\circ}$, and $0.5^{\circ} \times 0.5^{\circ}$, respectively, as the TOC values from the grid point being the closest to the station locations. The data web addresses and examples of papers dealing with the reanalysed TOC were given by Krzyścin et al. [27].

2.2. Methodology

2.2.1. Heatmap for TOC Trends

The heatmap is constructed using all possible TOC trend values that appear in the 1980–2025 period, assuming a minimum series length of 10 years, with a starting year of $1980 + i$ ($i \in \{0, \dots, 36\}$) and an ending year of $1989 + j$ ($j \in \{0, \dots, 36\}$). The (i, j) trend value from the standard least-squares regression is represented by a 1-year by 1-year box centred at $(x_i = 1980 + i, y_j = 1989 + j)$ in the XY coordinate system. Positive (negative) values are marked in red (blue), with the colour intensity depending on the trend strength. If the trend was not detected, the box colour is white.

We omitted the extreme years (1988, 2002, and 2019) with strong disruption of the SH polar stratosphere and abnormal polar vortex behaviour (splitting and early breaking of the polar vortex) due to the sudden Southern Hemispheric stratospheric warmings [28–30]. This is to prevent the occurrence of falsely significant trends not related to changes in the ODS abundance over Antarctica.

A comparison of the heatmaps using an index defined in Section 2.2.2 allows us to discuss whether the trend pattern depends somewhat on the data type used. The percentage of blue (red) boxes in the total number of boxes for a triangle in the XY plane, where the trend ends before 2000 (or starts after 2000), will be used to assess the recovery status (Section 3.4).

The following annual TOC time series were considered when constructing the heatmaps: the winter mean (the average of the daily values from 15 June to 15 August), $\text{TOC}_{\text{WINTER}}$; the daily value on 15 September, $\text{TOC}_{15\text{Sep}}$; and the minimum value after 30 September, TOC_{min} . These Antarctic ozone characteristics for the winter and spring conditions were selected to identify TOC variability: during the polar night, just before the formation of the ozone hole, at the beginning of ozone destruction due to heterogeneous reactions caused by polar stratospheric clouds (PSCs), and during the maximum phase of ozone destruction over the sites.

The TOC linear trends (%/10 years) were calculated using the standard least-squares method. The significance of the trends was assessed using the Mann–Kendall non-parametric test [31], modified for an autocorrelation in the analysed time series [32–34]. The percentages of statistically significant trends in the above-mentioned triangles provide evidence for the presence or absence of signs of recovery.

The MATLAB functions `fitlm` (inside the MATLAB by The MathWorks Inc., Natick, MA, USA, version 2025b) and `Modified_MannKendall_test` (from the official MATLAB file exchange repository, <https://ch.mathworks.com/matlabcentral/fileexchange/130004-modified-mannkendall-test> (accessed on 28 May 2026)), were implemented in the trend calculations, respectively.

2.2.2. Structural Similarity Index (SSIM) in Trend Analyses

The SSIM is an index invented to assess image quality by comparing each pixel locally in terms of image structure using luminance, contrast, and normalisation of the signal [35]. To compare two images, we need one value, so the SSIM is usually averaged for the whole image. Although the SSIM was defined for the quality image assessment, one can use it to compare two images (of the same size and scale). Such an approach was used to compare weather patterns by Hoffman et al. [36], Winderlich et al. [37] and Hokson et al. [38].

In this paper, we used the averaged SSIM to compare the trend patterns of $\text{TOC}_{\text{WINTER}}$, $\text{TOC}_{15\text{Sep}}$, and TOC_{min} . We used the mask for the pictures to assess only the left upper triangle of the image, as the right lower triangle is the same for all pictures, which affects the mean SSIM value. The SSIM was calculated using the function `ssim()` inside the MATLAB (by MathWorks) version 2025b, which follows the classical Wang et al. [35] approach.

The images created for comparison were the same size, without axes, subtitles, or dots, indicating statistical significance. Also, the colour scale for each TOC type was the same for all TOC sources.

Further in the text, following Winderlich et al. [37], we conclude that for an $SSIM \geq 60\%$, there is a strong similarity between images of the TOC trend heatmap, for an $SSIM$ between 40% and 60% the images are similar, and if the $SSIM < 40\%$, the images are weakly similar.

3. Results

3.1. Comparison of the TOC Values from Various Data Sources

Figure 1a–d show the seasonal profiles of the monthly TOC means, calculated by averaging the daily TOC values. These profiles were obtained for the Amundsen–Scott and Syowa stations using all available TOC data and are presented separately for the periods 1980–1999 (when the ozone hole evolved) and 2001–2025 (when it is expected to begin to diminish or stabilise). The spring ozone hole (with an October minimum in the monthly TOC mean) is clearly visible in all figures. The October minimum is deeper in the second period, as evidenced by statistical tests comparing the October TOC means and medians in the first and second periods (calculated using the *t*-test and Wilcoxon rank-sum test, respectively). This difference arises because the ozone hole only began at the start of the 1980s. Afterwards, the daily TOC values became lower due to a higher concentration of ODS in the stratosphere until the year 2000, as well as intense O₃ depletion triggered by PSCs.

Tables 1 and 2 show the monthly statistics (bias and root mean square error (RMSE)) for Amundsen–Scott and Syowa, respectively. These statistics were derived from the monthly averaging of the relative differences between the daily Dobson total ozone column (TOC) values and the corresponding values from other TOC sources (i.e., the reanalyses and satellite observations; see Section 2.1) expressed as a percentage of the Dobson TOC.

These statistics were derived using two types of Dobson TOC values, which were retrieved using BP and SG14 O₃AC. Furthermore, the results for the second O₃AC are discussed, with the agreement between the Dobson and other TOC sources mostly improving, as evidenced by the smaller absolute value of bias and RMSE. The TOC data were considered for the winter/spring months (June–December). They are mostly in the range between −5% and 3%, in about 80% and 90% of cases for Amundsen–Scott and Syowa, respectively. Monthly biases are smaller during the October–December period, with 100% of the observations at Syowa in the range −1.1% to 0.8%, whereas all monthly biases at Amundsen–Scott are within the range −5.8% to 4.5%.

The RMSEs were around 10% for these stations in the June–October period, but the RMSEs were about twice as small in the November–December period, with more than 1000 daily data pairs contributing to the statistical estimates. The largest deviation relative to Dobson observations was found at Amundsen–Scott when compared with MSR-2 (with biases and RMSEs of approximately −10% and 13%, respectively). However, only 46 pairs were used in the statistical calculation. In Syowa, the largest deviation was revealed relative to MERRA-2 in June, with a bias and an RMSE of approximately 6% and 11%, respectively; however, the number of pairs used in the calculation was larger, at around 200.

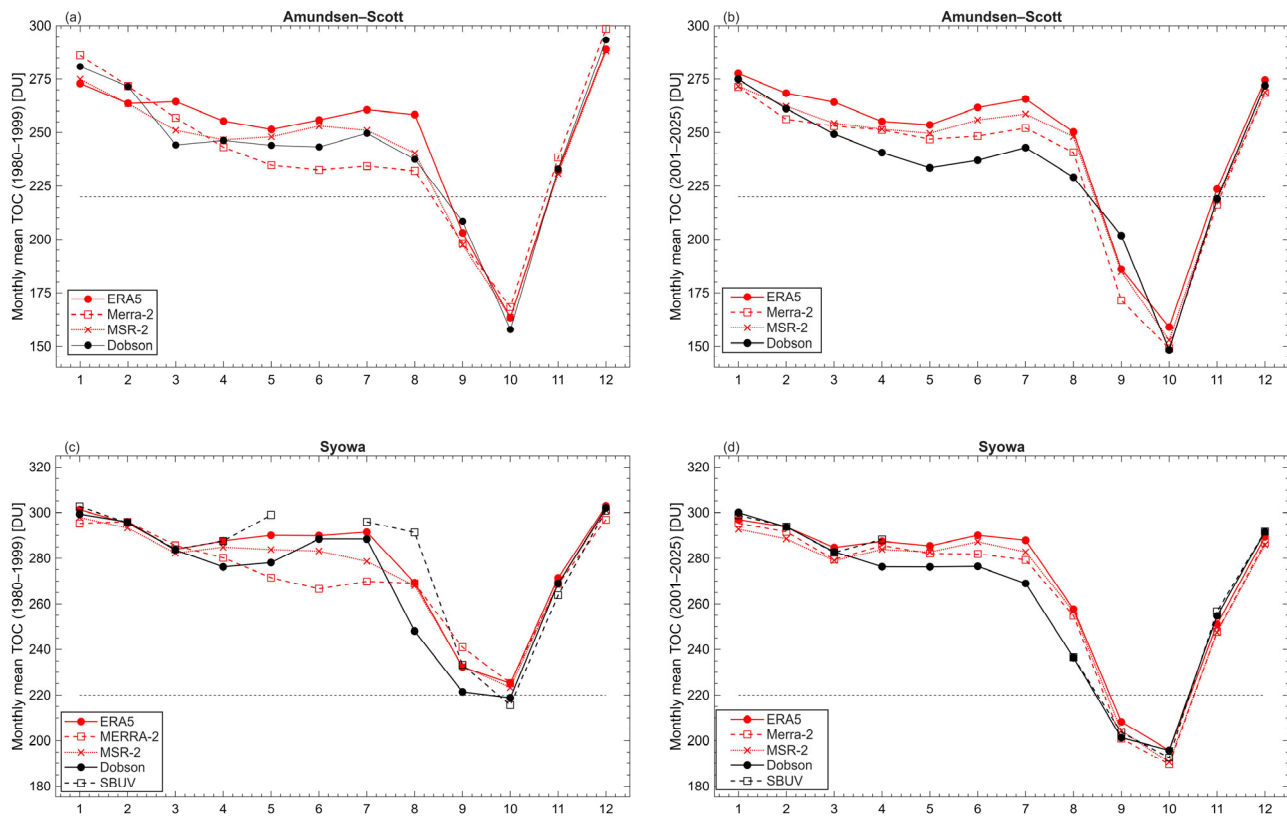


Figure 1. Monthly means of the total ozone column (TOC) at stations Amundsen–Scott (a,b) and Syowa (c,d) for the periods 1980–1999 (a,c) and 2001–2025 (b,d). Red colour indicates reanalyses: ERA5 (solid line, dots), MERRA-2 (dashed line, squares), MSR-2 (dotted line, crosses), black colour indicates measurements by Dobson spectrophotometer (solid line, dots) and solar backscattered UV spectrometers (SBUV) (dashed line, squares). The dashed line shows the 220 DU level, below which the “ozone hole” occurs.

Table 1. Monthly statistics (June–December) of the relative differences between the daily mean TOC by the Dobson spectrophotometer operated in the Amundsen–Scott station and corresponding TOC values from the reanalyses (ERA5, MERRA-2, and MSR-2) and satellite measurements (OMI) expressed as a percentage of the Dobson TOC. The results, taking into account standard BP ozone absorption coefficients in the TOC retrieval (with fixed temperature), are denoted as “Tconst” rows, whereas those obtained with the newest SG14 ozone absorption coefficients (temperature dependent) are in “Teff” rows of the Table. “RMSE” denotes relative root mean square error.

TYPE DOB	ERA5			MERRA-2			MSR-2			OMI		
	Bias	RMSE	N	Bias	RMSE	N	Bias	RMSE	N	Bias	RMSE	N
June												
Tconst	−7.2	11.7	287	−0.6	9.3	286	−6.8	10.4	287	Na	Na	Na
Teff	−4.0	9.8	287	2.4	9.3	286	−3.6	8.4	287	Na	Na	Na
July												
Tconst	−7.8	12.0	289	−0.2	9.2	289	−5.1	9.1	289	Na	Na	Na
Teff	−4.4	9.8	289	3.0	9.4	289	−1.8	7.5	289	Na	Na	Na
August												
Tconst	−9.7	12.9	220	−3.6	9.9	220	−6.5	11.1	220	Na	Na	Na
Teff	−6.3	10.3	220	−0.4	9.0	220	−3.2	9.3	220	Na	Na	Na

Table 1. *Cont.*

TYPE DOB	ERA5			MERRA-2			MSR-2			OMI		
	Bias	RMSE	N	Bias	RMSE	N	Bias	RMSE	N	Bias	RMSE	N
September												
Tconst	−9.5	11.8	46	−5.1	8.1	46	−13.0	15.5	46	Na	Na	Na
Teff	−6.5	9.4	46	−2.1	6.5	46	−9.9	12.8	46	Na	Na	Na
October												
Tconst	−6.6	11.3	948	−3.7	14.7	948	−3.5	9.3	948	−0.7	5.0	485
Teff	−5.8	10.6	943	−2.9	14.2	943	−2.7	8.6	943	0.1	4.9	484
November												
Tconst	−1.1	5.2	1222	−0.3	5.2	1222	0.7	4.6	1222	0.5	4.2	571
Teff	−1.4	5.2	1199	−0.5	5.2	1199	0.5	4.5	1199	0.3	4.1	569
December												
Tconst	0.4	3.8	1226	0.4	4.1	1226	1.8	3.9	1226	1.3	3.9	598
Teff	−0.4	3.9	1205	−0.4	4.1	1205	1.0	3.6	1205	0.5	3.8	597

Table 2. The same data as Table 1 but the results are for the Dobson measurements in the Syowa station and the SBUV overpasses are taken into account instead of the OMI measurements.

TYPE DOB	ERA5			MERRA-2			MSR-2			SBUV		
	Bias	RMSE	N	Bias	RMSE	N	Bias	RMSE	N	Bias	RMSE	N
June												
Tconst	−2.3	7.5	221	3.7	9.7	221	−2.0	7.5	221	Na	Na	Na
Teff	−0.4	7.0	221	6.2	10.7	221	−0.7	7.1	221	Na	Na	Na
July												
Tconst	−4.5	8.6	217	1.2	9.6	217	−2.1	8.5	217	Na	Na	Na
Teff	−1.5	7.3	217	4.0	10.1	217	0.8	8.1	217	Na	Na	Na
August												
Tconst	−4.4	8.4	540	−5.3	13.0	540	−5.8	9.8	540	−7.0	8.6	19
Teff	−1.8	7.1	540	−2.6	11.9	540	−3.1	8.3	540	−4.4	6.5	19
September												
Tconst	−3.1	6.2	994	−4.2	14.8	994	−2.3	5.5	994	−1.4	5.8	312
Teff	−1.3	5.5	994	−2.3	14.1	994	−0.5	4.9	994	0.4	5.5	312
October												
Tconst	−1.8	5.3	1094	−0.4	6.9	1094	−0.1	4.4	1094	0.4	6.9	445
Teff	−1.0	5.0	1094	0.5	6.8	1094	0.8	4.4	1094	1.2	6.9	445
November												
Tconst	−0.2	3.9	1177	0.8	4.4	1177	0.9	3.9	1177	0.0	4.4	494
Teff	−0.3	3.9	1177	0.7	4.3	1177	0.8	3.9	1177	−0.1	4.4	494
December												
Tconst	0.2	2.8	1250	1.4	3.6	1250	1.0	3.0	1250	−0.5	3.2	548
Teff	−0.4	2.9	1205	0.8	3.4	1250	0.4	2.9	1250	−1.1	3.4	548

3.2. Heatmaps of the TOC Trends

Figures 2–4 show heatmaps based on the Amundsen–Scott and Syowa TOC data from all the reanalyses considered (ERA5, MERRA-2, and MSR-2), as well as Dobson spectrophoto-

tometer ground-based measurements and satellite overpasses (SBUV) for $\text{TOC}_{\text{WINTER}}$, $\text{TOC}_{15\text{Sep}}$, and TOC_{min} .

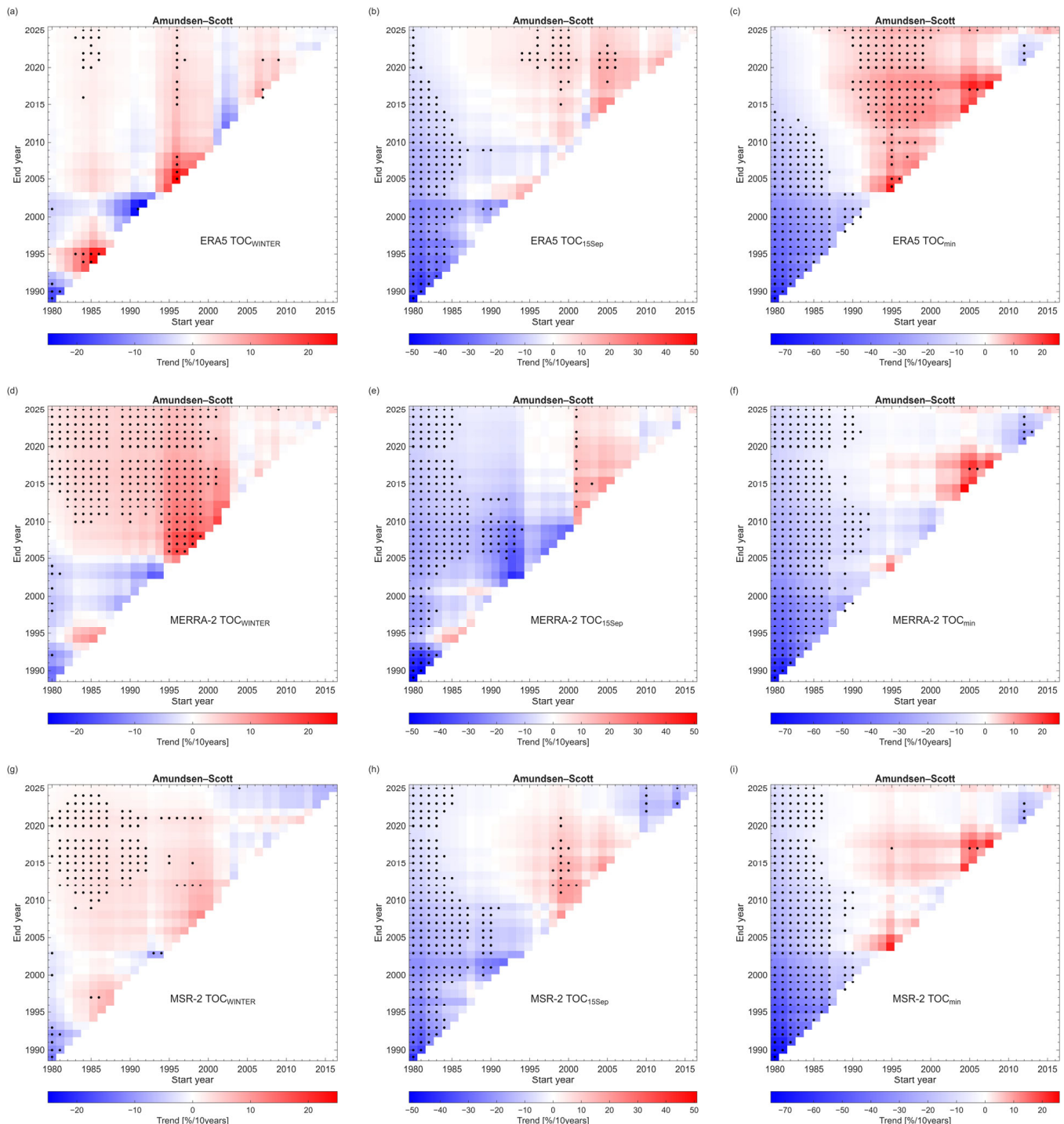


Figure 2. Heatmap of linear trends of the total ozone column (TOC) for winter ($\text{TOC}_{\text{WINTER}}$), 15 September ($\text{TOC}_{15\text{Sep}}$), and minimum value (TOC_{min}) at the Amundsen–Scott station (reanalysis) calculated starting from 1980 to 2016 and ending from 1989 to 2025: (a–c) for ERA5, (d–f) for MERRA-2, and (g–i) for MSR-2. Blue colour is a negative trend, while red is for positive trends. Black dots represent statistically significant trends for $p \leq 0.05$, tested with the Mann–Kendall test modified for autocorrelation.

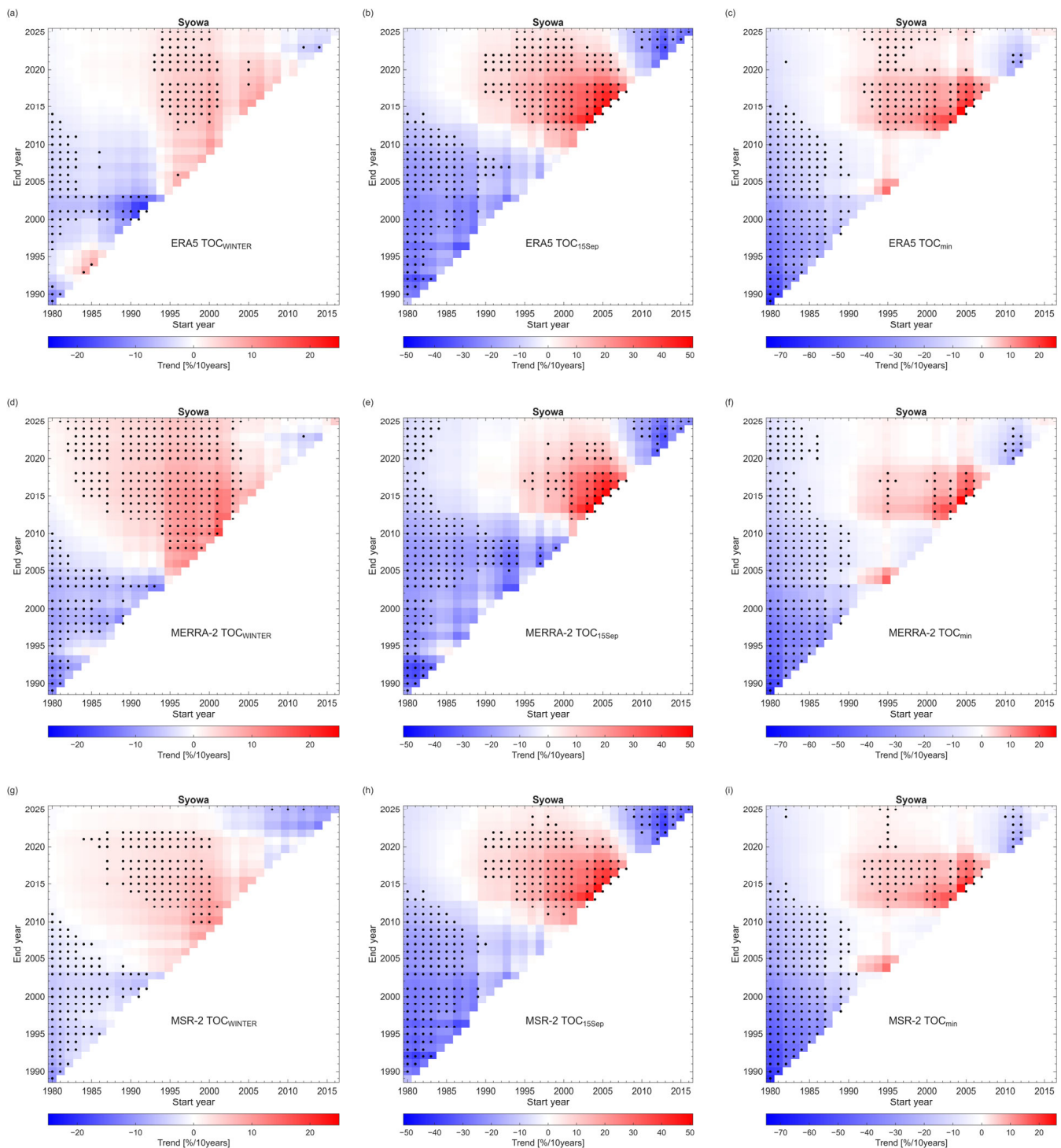


Figure 3. Heatmap of linear trends of total ozone column (TOC) for winter ($\text{TOC}_{\text{WINTER}}$), 15 September ($\text{TOC}_{15\text{Sep}}$), and minimum value (TOC_{min}) in Syowa station (reanalysis) calculated starting from 1980 to 2016 and ending from 1989 to 2025: (a–c) for ERA5, (d–f) for MERRA-2, and (g–i) for MSR-2. Blue colour is a negative trend, while red is for positive trends. Black dots represent statistically significant trends for $p \leq 0.05$, tested with the Mann–Kendall test modified for autocorrelation.

Figure 4 provides a series of heatmaps obtained from the TOC measurements by the Dobson instrument (for both considered stations) and SBUV overpasses (only for Syowa). Because such observations deal with the UV spectrum only, the analyses of the ozone minima occurring in the sunlit period were considered, as there were only limited TOC

observations during winter. The trend patterns shown in Figure 4 correspond with those appearing in the third column of Figures 2 and 3.

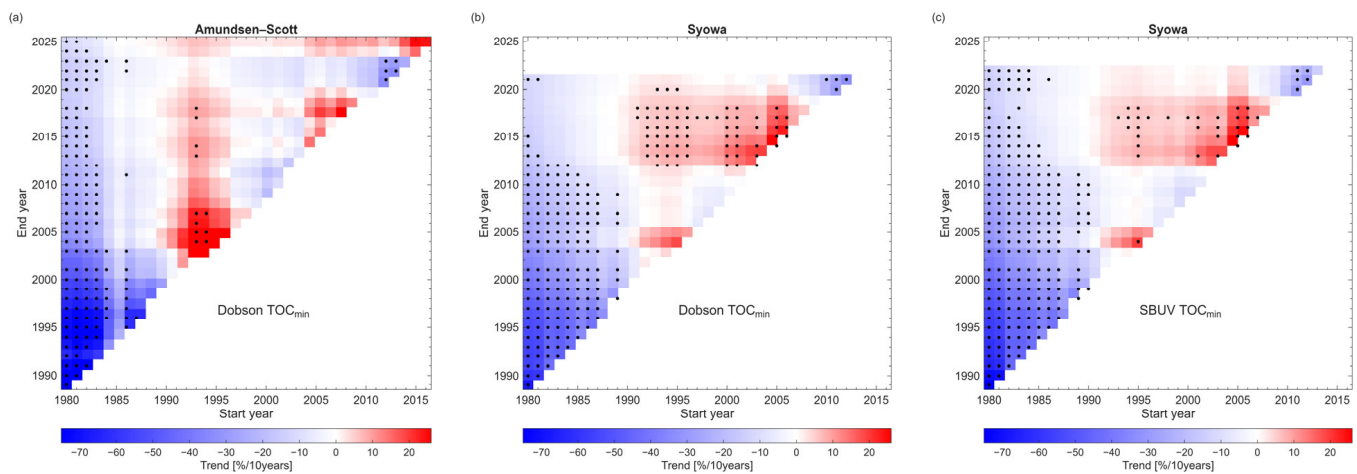


Figure 4. Heatmap of linear trends of total ozone column (TOC) for minimum value ($\text{TOC}_{\min}$) at the Amundsen–Scott and Syowa stations (measurements) calculated starting from 1980 to 2016 and ending from 1989 to 2025: (a,b) for Dobson Spectrophotometer and (c) for Solar Backscatter Ultraviolet (SBUV) measurements. Blue colour is a negative trend, while red is for positive trends. Black dots represent statistically significant trends for $p \leq 0.05$, tested with the Mann–Kendall test modified for autocorrelation.

For some combinations of the start and end of the time series, the linear trend values (%/10 years) may reach high values exceeding (in absolute value) 70%. This occurs for the $\text{TOC}_{\min}$ series (Figure 2c,f,i and Figure 3c,f,i) when the start year is around 1980, i.e., at the beginning of the ozone hole, and the end is in the year when the strong hole existed (since about 1990).

At first glance, the common graphical patterns appear on the corresponding charts, i.e., the areas that coincide in colour and intensity. These are negative trends in the lower and upper corners of the upper half of the heatmap and positive trends in the centre, which are clearly visible in the second and third types of the considered time series for all data types, e.g., Figure 2b when compared to Figure 2e,h. The close correspondence is also seen in Figure 3b when compared to Figure 3e,h. This suggests that similar dynamic–chemical mechanisms influence the ozone distribution in each of the three aforementioned phases of winter–spring TOC development. Clearly, here, we are not dealing with a patchwork of random small-scale features on the heatmaps. The SSIM tool will be used to objectively classify the overall level of similarity in the large-scale features observed (see Section 3.3).

3.3. Similarity in TOC Trend Pattern Derived from Various Data Sources

The trend patterns presented in the upper part of Figures 2 and 3 (above the diagonal line of the heatmap square) were analysed using the SSIM tool (Section 2.2.2). The SSIM values were calculated separately for each station, considering all possible pairs of the reanalysis data used for the three above-mentioned time series characterising the long-term winter–spring TOC variability. These results appear in the first three columns of Table 3. In addition, the SSIM values were obtained between the stations for the relevant heatmaps.

Table 3 displays the SSIM values for the aforementioned pairs of heatmaps. According to the image similarity criterion proposed by Winderlich et al. [37], all pairs of heatmaps are similar, with SSIM values above 40% indicating a high degree of similarity. Approximately 85% of these pairs have an SSIM value of at least 60%, indicating a very high degree of similarity. The three pairs (out of a total of four pairs) with an SSIM value below 60% are

found among the ERA5 vs. MERRA-2 pairs in the Amundsen–Scott data (see the second column in Table 3). The remaining pair is between the ERA5 heatmaps calculated for winter TOC trends (see the rightmost column of Table 3). In this case, the SSIM value was 58.2%, which is quite close to the 60% threshold that defines strong similarity.

Table 3. The structural similarity index (SSIM) for the heatmap pairs derived from all possible reanalyses and between the heatmaps for the corresponding TOC time series with the same type of reanalysis. A value above 60%, which denotes strong similarity, is in bold font.

Station Selected: Similarity for the Reanalysis Pair	SSIM for Amundsen–Scott	SSIM for Syowa	Reanalysis Selected: Similarity Between the Stations	SSIM Value
TOC _{WINTER}				
ERA5 vs. MERRA-2	49.6	63.6	ERA5	58.2
ERA5 vs. MSR-2	64.2	62.0	MERRA-2	74.7
MERRA-2 vs. MSR-2	58.1	74.2	MSR-2	69.2
TOC _{15Sep}				
ERA5 vs. MERRA-2	51.2	77.8	ERA5	70.0
ERA5 vs. MSR-2	73.6	95.4	MERRA-2	70.0
MERRA-2 vs. MSR-2	57.7	77.1	MSR	77.9
TOC _{min}				
ERA5 vs. MERRA-2	49.2	88.9	ERA5	78.4
ERA5 vs. MSR-2	68.8	93.1	MERRA-2	80.8
MERRA-2 vs. MSR-2	77.0	94.5	MSR-2	89.3

The SSIM values for Syowa are higher than the corresponding values obtained for Amundsen–Scott, with only one exception: the ERA5 vs. MSR-2 pair, calculated with the winter trend pattern (i.e., 64.2% vs. 62.0% for the stations' SSIM values). However, the SSIM values at the Amundsen–Scott station remain above the 0.4 threshold, indicating a high degree of similarity between reanalyses. Smaller SSIM values may be due to the way the reanalysis data is created, involving adjustments to the measured data, which may differ between reanalyses (a further discussion of this issue is beyond the scope of this study). TOC observations at the South Pole are usually less frequent than those at Syowa, especially in winter and early spring. Furthermore, the TOC data from the SBUV satellite overpasses of the South Pole are not available.

For six heatmap pairs (around 22% of the total heatmaps), the SSIM value exceeds 80%. This applies to all SSIM values for Syowa (note the SSIM values of around 95% for the ERA5 vs. MSR-2 and the MERRA-2 vs. MSR-2 pair) when trend patterns were calculated using TOC_{min}. SSIM values of $\geq 80\%$ are also found for MERRA-2 and MSR-2 in the 'between stations' similarity comparison (the rightmost column in Table 3) when the TOC_{min} time series is considered. The one pair with an SSIM $\geq 80\%$ (ERA5 vs. MSR-2) was found by examining the trend patterns based on the TOC_{15Sep} time series. Interestingly, in this case, the SSIM values reached a maximum of 95.4%, as shown in Table 3.

3.4. Signs of the Ozone Recovery

The time series of the man-made ODS concentration in the stratosphere over Antarctica indicates a turning point in 2001 [8], with the concentration rising prior to this turning point and falling thereafter. Assuming that the ozone layer is affected solely by chemical factors, the trends in the characteristics of the ozone hole would have a different sign for those ending before the turning point and those starting after it. This indicates negative (positive) trends in the TOC time series analysed before (after) the turning point. This

prompts a calculation of the proportion of such cases based on the heatmap pattern. The trends were calculated using a standard least-squares approach. In this case, the analysis focuses on counting the relative number of blue (red) cells within a triangle encompassing all trends that end (or begin) before (or after) 2000. In addition, the number of red cells was counted for trends starting after 2000 and ending before 2019. This is because the period from 2019 to 2023 was atypical due to exceptional factors unrelated to changes in ozone-depleting substances, affecting the Antarctic ozone hole, such as stratospheric warming in 2019, bushfires in Australia, and the Hunga Tonga eruption [20,30,39].

Table 4 shows the proportions of blue cells (negative trends ending before 2000) and red cells (positive trends beginning after 2000 and ending before 2025 or before 2019) in the total number of cells in these heatmaps' regions. In total, there were 617 cells, i.e., fewer than the theoretical number of cells in the upper diagonal area, as the years with stratospheric warming (1988, 2002, 2019) were excluded a priori. This resulted in the following total number of cells: 63 (for trends ending before 2000), 112 (for trends starting after 2000), and 37 (for trends starting after 2000 and ending before 2019). These values represent 10.2%, 18.1%, and 6% of the total number of cells available in these heatmaps' regions, respectively.

Table 4. The proportions of negative and positive TOC trends in % of all possible trend values for the heatmap area comprising trends before 2000, after 2000, and after 2000 with the trend end before 2019.

Data Type	Amundsen–Scott TOC			Syowa TOC		
	Winter	15 Sep	Min	Winter	15 Sep	Min
Negative before 2000 (start year $\geq$ 1980, end year $<$ 2000)						
ERA 5	41.3	100.0	100.0	76.2	100.0	100.0
MERRA-2	69.8	87.3	100.0	96.8	96.8	100.0
MSR-2	44.4	96.8	100.0	100.0	100.0	100.0
Dobson	-	-	100.0	-	-	100.0
SBUV	-	-	-	-	-	100.0
Positive after 2000 (start year $\geq$ 2001, end year $\leq$ 2025)						
ERA 5	51.8	88.4	80.4	79.5	67.0	62.5
MERRA-2	81.2	83.9	53.6	78.6	65.2	54.5
MSR	36.6	49.1	51.8	44.6	58.9	49.1
Dobson	-	-	46.4	-	-	72.4
SBUV	-	-	-	-	-	68.6
Positive 2001–2018 (start year $\geq$ 2001, end year $\leq$ 2018)						
ERA 5	40.5	78.4	97.3	100.0	100.0	97.3
MERRA-2	80.1	100.0	91.9	100.0	100.0	95.6
MSR-2	51.3	100.0	89.2	91.9	97.3	97.3
Dobson	-	-	59.5	-	-	94.6
SBUV	-	-	-	-	-	94.6

In order to discuss the trend reversal in 2001, we require the prevalence of blue boxes for the period before 2000 and red boxes for the period after. This means that the proportion of boxes of the prescribed colour should be significantly higher than 50% in both cases. The standard error of the proportion P is equal to the square root of $P(1 - P)/N$, where N is the number of data points used to calculate the proportion. In this case, we have 63 (or 37) boxes in the heatmap region, with a start year of 1980 (after 2000), and an end year before 2000 (2019). Taking the smaller N value, the standard error of the proportion is 0.08. Therefore, if we apply the z -score formula and calculate the significance of $P = 0.7$ using one of the aforementioned data categories, this estimate will differ significantly from 0.5

at a level exceeding two standard errors (the so-called 2σ level). For $P = 0.9$, this level is $(0.9 - 0.5)/0.08 = 5$. Therefore, a colour threshold (CT) is proposed to objectively assess the prevalence of each colour (blue or red) in the heatmap. CT values of 70% (CT70) and 90% (CT90) are selected as the benchmark levels when discussing the prevalence of each colour in the selected areas of the heatmaps in relation to trend signs in the aforementioned three time series.

As expected, negative trends ending before 2000 are more frequent than positive trends. In other words, the proportion of blue cells is higher than the CT70 in the second (TOC_{15Sep}) and third (TOC_{min}) series. The same is true of the first series (TOC_{WINTER}), which was taken at Syowa. Notably, blue CT90 was exceeded in 15 out of a total of 21 cases (approximately 71%), as presented in Table 4.

Positive trends were found more frequently among those starting after 2000 and before 2019. The proportion of red cells lower than CT70 was observed in only three out of a total of 21 cases (approximately 14%). This was observed in the Amundsen–Scott Station series using ERA5 and MSR-2 for the TOC_{WINTER} series, and in the Dobson data for the TOC_{min} time series. In this heatmap region, the proportion of red cells exceeding CT90 was found in 13 cases (62% of the total number of cases in Table 4). This proportion was much lower when considering cells with trends that started after 2000 and ended by 2025 at the latest. There were no cases over CT90, with only seven cases (33%) exceeding CT70. The difference in the proportion of red cells in these two heatmap regions is due to abnormal ozone layer forcing during the period 2020–2023 (see the first paragraph of this subsection).

Similar to Table 4, Table 5 shows the proportion of cells with a negative or positive trend value; however, these trends must be statistically significant at the 95% level. A key issue is that the number of degrees of freedom in trend estimates can sometimes be lower than $N-2$ (as was assumed in the t-test for the linear trend estimate), where N is the number of data points used. This is the case here, as there are substantial autocorrelations with a one-year lag in the analysed series (see Appendix A for the examples of one-year autocorrelation in previously considered time series used in heatmap construction). Therefore, the Mann–Kendall test for autocorrelated data was implemented to determine the significance of the trend (see the comments on the performance of this test at the following web address: <https://www.utoronto.ca/~butler/climate-lab/mann-kendall-correlated.pdf> (accessed on 28 May 2026)).

As shown in Table 5, the proportion of statistically significant negative trends exceeds CT90 for almost all TOC sources when using the TOC_{min} prior to 2000, except for the Dobson data for Amundsen–Scott, for which the proportion exceeds CT70. For the trend starting after 2000 and ending before 2019, the proportion of statistically significant positive trends over CT70 is found in all the reanalysis data for Syowa, using TOC_{15Sep} and TOC_{min} time series (regardless of MERRA-2). It is worth mentioning that the proportions of statistically significant positive trends are close to CT90 when analysing the TOC_{15Sep} time series for Syowa. There were no statistically significant positive trends for either station before 2000 in the heatmaps for TOC_{15Sep} and TOC_{min}. Consequently, no statistically significant negative trends were observed in cases where the trend began after 2000 and ended before 2019 (see Table 6). Some cases show statistically significant negative trends starting after 2000 and ending by 2025 at the latest, with a maximum proportion of around 20% in Syowa for the TOC_{15Sep}. These correspond with the presence of blue regions in the top right-hand corner of the heatmaps (see Figure 3b,e,f), which are related to abnormal TOC behaviour during the period 2019–2023.

Table 5. The same data as Table 4, but for proportions of statistically significant trends at the 95% confidence level derived from the Mann–Kendall modified test.

Data Type	Amundsen–Scott TOC			Syowa TOC		
	Winter	15 Sep	Min	Winter	15 Sep	Min
Negative significant before 2000 (start year $\geq$ 1980, end year $<$ 2000)						
ERA 5	6.3	69.8	100.0	15.9	52.4	95.2
MERRA-2	4.8	44.4	93.6	66.7	47.6	98.4
MSR-2	11.1	68.2	100.0	73.0	68.2	98.4
Dobson	-	-	71.4	-	-	96.8
SBUV	-	-	-	-	-	100.0
Positive significant after 2000 (start year $\geq$ 2001, end year $\leq$ 2025)						
ERA 5	3.6	10.7	5.4	8.0	46.4	31.2
MERRA-2	6.2	9.8	1.8	29.5	40.2	18.7
MSR	0.0	0.9	1.8	0.9	37.5	23.2
Dobson	-	-	0.0	-	-	34.5
SBUV	-	-	-	-	-	24.3
Positive significant 2001–2018 (start year $\geq$ 2001, end year $\leq$ 2018)						
ERA 5	5.4	2.7	8.1	13.5	89.2	73.0
MERRA-2	8.1	16.3	5.4	51.3	86.5	56.6
MSR-2	0.0	2.7	5.4	2.7	89.2	70.3
Dobson	-	-	0.0	-	-	54.0
SBUV	-	-	-	-	-	45.9

Table 6. The same data as Table 5, but for inverted signs for the trend values.

Data Type	Amundsen–Scott TOC			Syowa TOC		
	Winter	15 Sep	Min	Winter	15 Sep	Min
Positive significant before 2000 (start year $\geq$ 1980, end year $<$ 2000)						
ERA 5	9.5	0.0	0.0	3.2	0.0	0.0
MERRA-2	0.0	0.0	0.0	0.0	0.0	0.0
MSR-2	3.2	0.0	0.0	0.0	0.0	0.0
Dobson	-	-	0.0	-	-	0.0
SBUV	-	-	-	-	-	0.0
Negative significant after 2000 (start year $\geq$ 2001, end year $\leq$ 2025)						
ERA 5	0.0	0.0	2.7	1.8	15.2	3.6
MERRA-2	0.0	0.0	4.5	0.9	18.7	8.9
MSR	0.9	5.4	2.7	2.7	22.3	9.8
Dobson	-	-	4.5	-	-	6.9
SBUV	-	-	-	-	-	7.1
Negative significant 2001–2018 (start year $\geq$ 2001, end year $\leq$ 2018)						
ERA 5	0.0	0.0	0.0	0.0	0.0	0.0
MERRA-2	0.0	0.0	0.0	0.0	0.0	0.0
MSR-2	0.0	0.0	0.0	0.0	0.0	0.0
Dobson	-	-	0.0	-	-	0.0
SBUV	-	-	-	-	-	0.0

4. Discussion

The time series of man-made ODS concentrations in the stratosphere above Antarctica shows a turning point in 2001: concentrations increased before this date, but decreased afterwards [8]. This is a direct consequence of the Montreal Protocol 1987 and its subsequent amendments concerning the removal of ODS from the atmosphere. The stratospheric

ozone layer acts as the Earth's sole shield against harmful solar UV-B radiation (280–315 nm) [7]. There have been many attempts to find evidence that the stratospheric ozone layer responded to the turning point in ODS concentrations, which caused the recovery of the ozone layer to start in the early 2000s [40–45].

One widely used method of searching for the recovery is the application of a multiple regression model (MRM) using proxy variables, which allows for the elimination of variations in ozone time series resulting from non-chemical causes [46,47]. From a statistical point of view, the explanatory variables in MRMs should be independent of one another and not influenced by the dependent (explained) variable. This is not always the case when analysing the springtime ozone hole. Some important dynamic drivers of the Antarctic ozone, e.g., eddy heat flux towards the polar region, have been affected by recent climate changes in the Southern Hemisphere. Stratospheric cooling is associated with tropospheric warming, which is caused by an increasing concentration of greenhouse gases in the troposphere. However, the shrinking ozone layer over Antarctica leads to additional stratospheric cooling. In other words, the dependent variable may be affected to some extent by the independent variables. In this case, nested feedbacks can compromise the assumption of strict independence of variables in MRMs. Furthermore, the contribution of the proxies to the variability of ozone characteristics is not always linear, as is usually assumed in MRMs. For example, weakening the Brewer–Dobson circulation would result in less ozone being transported between the tropics and the South Pole. This would also cause the stratosphere to cool, thereby promoting greater ozone destruction by PSCs.

Chemical–climate (CC) models allow dynamic–chemistry coupling to be resolved, which might not be captured with standard MRMs [10,44,45]. These CC models have revealed large year-to-year variability in the Antarctic ozone, driven by variations in atmospheric dynamics, which hamper drawing definite conclusions on the recovery rate of the Antarctic ozone.

In this paper, we present an alternative method of analysing the blue–red heatmaps of winter–spring TOC trends to reveal signs of recovery using various TOC sources. Our objective is not to provide a model that better describes the sources of Antarctic ozone variability in order to resolve the man-made signal from the TOC time series. Nor do we claim to overcome the difficulties of modelling the dynamical component of the Antarctic ozone, thereby improving existing models. We propose a heatmap tool to support the hypothesis that the trend reversal occurred at the beginning of the 2000s. This could be delineated without a detailed parameterisation of the sources of TOC variability, which was the main objective of the existing recovery studies.

Following the approach proposed by Johnson et al. [39], three annual TOC time series (the winter average, 15 September value, and the spring minimum) were analysed for the period 1980–2025 in order to characterise the development of the ozone hole at the Syowa and Amundsen–Scott stations. Various sources of the daily TOC data were examined, including the reanalysis data (ERA5, MERRA-2, and MSR-2), the ground-based measurements by the Dobson spectrophotometers (applying standard BP and newly proposed SG14 O₃AC), and the satellite data (SBUV and OMI). Analyses of the differences between the seasonal TOC profiles (Figure 1), the monthly statistics (bias and RMSE from June to December) of the differences between the Dobson and other TOC sources (Tables 1 and 2), and the SSIM values between the reanalysis pairs of the trend heatmaps (Table 3) support the data consistency and robustness of the results obtained with the proposed heatmaps method to search for a recovery signal. In spite of using different spatial resolutions for the global reanalyses, the trend TOC patterns exhibited a high degree of similarity, with the SSIM values exceeding the 40% threshold. A total of 85% of the compared data pairs show

the SSIM value over the 60% threshold, providing that the similarity reached a very high degree of similarity.

A set of all possible linear trend values is calculated based on the aforementioned time series, which must be at least 10 years long with a start in any year between 1980 and 2016, and ending in 2025 at the latest. The trend heatmaps are then constructed using blue and red cells for negative and positive trends, respectively, with the colour intensity depending on the trend strength (in percentage terms per decade). If blue cells predominate in the heatmaps area for trends ending before 2000, and red cells are more common in the area covering trends beginning after 2000, this will confirm the hypothesis of a trend reversal in the TOC trends at the beginning of the first decade of the 21st century, forced by the reversal in man-made ODS concentration in the stratosphere. In other words, the trends can be of any sign and value. However, the hypothesis that trend variations caused by interannual atmospheric perturbations are superimposed on a strong baseline pattern, which is related to the ODS changes, would be supported by an apparent blue–red separation seen in the heatmaps, with a turning point in 2001. A much larger proportion of negative trends before 2000 and positive trends afterwards would clearly indicate ongoing ozone recovery.

Counting the proportion of blue and red cells on the heatmaps reveals whether such colour separation exists. Additionally, as abnormal ozone holes appeared during the period from 2019 to 2023, the proportion of red cells was also evaluated for trends starting after 2000 and ending before 2019. In these calculations, the proportion of each colour in the total number of cells often exceeded the CT70 and CT90 threshold levels (defined in Section 3.4) using the $\text{TOC}_{15\text{Sep}}$ time series and the TOC_{min} in the spring ozone (see Table 4). The colour separation is more apparent for the region of the heatmaps comprising trends before 2000 and trends after 2000, but ending before 2019. A similar procedure was applied to statistically significant negative or positive trends, revealing that negative trends were more frequent than positive trends for trends ending before 2000, and the opposite was true for trends starting after 2000 and ending before 2019 (see Tables 5 and 6 for the results). This provides further evidence for the blue–red separation in the aforementioned region of the heatmaps.

5. Conclusions

The proposed analysis of changes in TOC trends between 1980 and 2025, visualised on the blue–red trend heatmaps, offers an alternative approach to search for signs of the ozone layer recovery over Antarctica. Data from reanalysis, ground-based observations (using Dobson spectrophotometers), and satellite TOC measurements provide a consistent picture of the evolution of the ozone hole over Antarctica.

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[sbuv/AGGREGATED/](#) (accessed on 28 May 2026)) and OMI (<https://gml.noaa.gov/grad/neubrew/SatO3DataTimeSeries.jsp> (accessed on 28 May 2026)).

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Abbreviations

The following abbreviations are used in this manuscript:

BP	Bass–Paur
CT70	Colour threshold of 70%
CT90	Colour threshold of 90%
ERA5	European Centre for Medium-Range Weather Forecast fifth-generation reanalysis
MERRA-2	Modern-Era Retrospective analysis for Research and Applications, Version 2
MSR-2	Multi-Sensor Reanalysis Version 2
O ₃ AC	Ozone absorption coefficient
ODS	Ozone-depleting substances
OMI	Ozone Monitoring Instrument
PSCs	Polar stratospheric clouds
TOC	Total ozone column
TOC _{15Sep}	Daily value on 15 September
TOC _{min}	Minimum value after 30 September
TOC _{WINTER}	Average of the daily values from 15 June to 15 August
RMSE	Root mean square error
SBUV	Solar backscattered UV spectrometers
SG14	Serdyuchenko and Gorshelev version 2014
SSIM	Structural Similarity Index

Appendix A. Autocorrelation of the TOC Time Series

Using the function `autocorr()` in MATLAB v2025b, the autocorrelation with a 1-year lag was calculated for all TOC time series, reflecting the trends shown in the heatmaps. The critical correlation values were exceeded multiple times across all TOC types and sources, except for TOC_{WINTER} in ERA5. An example of the heatmaps with statistically significant (black dots) autocorrelation for both stations is presented in Figure A1.

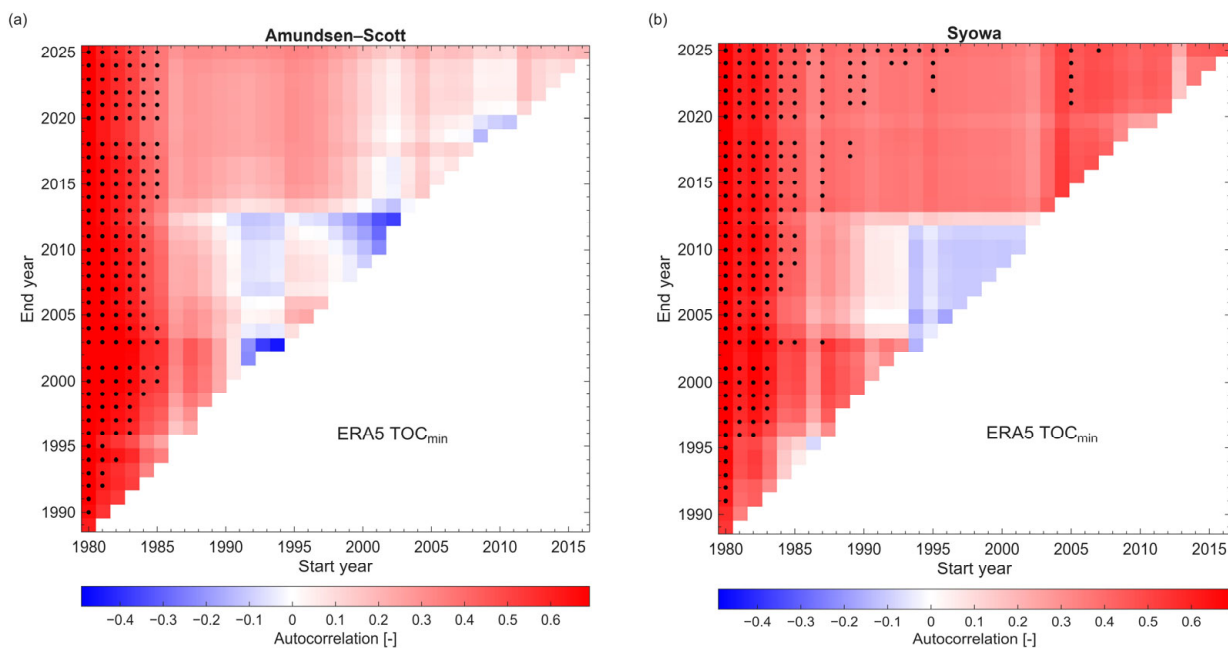


Figure A1. Heatmap of autocorrelation of total ozone column (TOC) for minimum value (TOC_{min}) in Amundsen–Scott (a) and Syowa (b) station (reanalysis) calculated starting from 1980 to 2016 and ending from 1989 to 2025 for ERA5. Blue colour is negative autocorrelation, while red is positive. Black dots represent statistically significant autocorrelation coefficients, which exceeded critical values.

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