

Classifying the severity of the annual Antarctic ozone hole

Hannah Kessenich

hannah.kessenich@otago.ac.nz

University of Otago <https://orcid.org/0009-0005-1591-8898>

Annika Seppälä

University of Otago <https://orcid.org/0000-0002-5028-8220>

Dan Smale

Laura Revell

University of Canterbury <https://orcid.org/0000-0002-8974-7703>

Craig Rodger

<https://orcid.org/0000-0002-6770-2707>

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Classifying the severity of the annual Antarctic ozone hole

Hannah E. Kessenich^{1*}, Annika Seppälä¹, Dan Smale²,
Laura E. Revell³, Craig J. Rodger¹

¹Department of Physics, University of Otago, Dunedin, New Zealand.

²Earth Sciences New Zealand, Lauder, New Zealand.

³School of Physical and Chemical Sciences, University of Canterbury,
Christchurch, New Zealand.

*Corresponding author(s). E-mail(s): hannah.kessenich@otago.ac.nz;

Contributing authors: annika.seppala@otago.ac.nz;
dan.smale@earthsciences.nz; craig.rodger@otago.ac.nz;
laura.revell@canterbury.ac.nz;

Abstract

Antarctic ozone hole summary metrics, such as area, have been long-established. However, such metrics must be examined alongside other years of observations to be meaningful: e.g. how severe is a 20 million km² ozone hole? Here, we address this gap by introducing a three-tiered ‘Minor’, ‘Moderate’, and ‘Major’ ozone hole classification system. Classifications are derived from existing metrics, tailored to unify varying datasets. The annual severity of the Antarctic ozone hole can now be summarised using a numerically-defined term, accessible to both scientific and general audiences. We use this system to demonstrate that Major ozone holes have recently become more frequent during the late spring, driving changes in circulation. When assessing CMIP6 simulations using this common framework, we find that Major and Moderate ozone holes will likely occur for several more decades. Minor ozone holes are unlikely to disappear before the year 2100, dependent on the future state of the climate.

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047 Introduction

048
049 The Antarctic ‘ozone hole’ has been an annual phenomenon since the 1970s, a decade
050 prior to its landmark discovery in 1985 [1–3]. The hole’s dramatic formation has been
051 directly attributed to anthropogenic emissions of chlorine-containing compounds and
052 their subsequent chemical reactions with ozone [1, 4]. The Montreal Protocol on Sub-
053 stances that Deplete the Ozone Layer was signed in 1987, swiftly banning further
054 emissions of ozone depleting substances (ODSs). The Protocol’s global success has
055 led to steadily declining levels of equivalent effective stratospheric chlorine (EESC)
056 since 2001 [5, 6]. Complete ozone recovery will take several more decades [7–9], and
057 at present, the Antarctic ozone hole follows a consistent seasonal pattern. Every late
058 austral winter, total column ozone (TCO) levels within the stratospheric polar vortex
059 drop below the threshold required for an ozone hole (ubiquitously set at 220 Dobson
060 Units (DU)) [6]. By the end of September, the hole usually grows to cover an area
061 upwards of 20 million km² [10, 11]. Provided that the polar vortex remains sufficiently
062 stable, the ozone hole then persists through the rest of the austral spring. During
063 either November or December, the vortex begins to dissipate: westerly winds reverse
064 direction and the ozone hole breaks up for the year [6, 12].

065 Summary metrics can be used to characterize the Antarctic ozone hole. Resources
066 such as [NASA Ozone Watch](#) and [Copernicus Atmosphere Monitoring Service](#) have
067 provided daily monitoring services during the ozone hole season, reporting metrics
068 such as area, ozone mass deficit (OMD), and average polar cap TCO. Ozone hole area,
069 defined as the area contained by the region of TCO below 220 DU [14, 15], captures
070 the areal extent of ozone loss and is also highly intertwined with the footprint of the
071 polar vortex [16]. OMD combines elements of ozone hole size and depth, defined as
072 the mass of ozone required to raise TCO levels within the ozone hole to 220 DU [17].
073 The 220 DU threshold used for both of these metrics was originally chosen based on
074 ozone hole observations in the 1980s [14] and has since been widely adopted. Alter-
075 native thresholds, such 175 DU and 130 DU, have also been used to quantify deeper
076 areas of ozone depletion [18]. The broadest summary metric, however, is average polar
077 cap TCO. Often calculated over latitudes 63°S–90°S [6], polar cap TCO captures the
078 size/depth of the ozone hole in addition to the magnitude of ozone transported into
079 the collar region just outside of the polar vortex [19].

080 Ozone hole summary metrics allow a given year’s ozone hole to be compared to
081 the past. Many long-term trend assessments have been conducted using metrics such
082 as polar cap TCO, ozone hole area, and OMD [e.g., 6, 18, 20–27]. Metrics which rely
083 on absolute Dobson Unit thresholds tend to be sensitive to instrumental variation,
084 requiring careful merging of the observational record over time. Ozone holes can also
085 be assessed using severity rankings, as in Klekociuk et al. [28]. For example, the 2020
086 ozone hole’s maximum 15-day area was ranked the 15th largest and its total inte-
087 grated OMD across the full spring season was ranked the 2nd most-severe since 1979
088 [28]. Signatures of ozone hole recovery should gradually become more evident in such
089 assessments. Summary metrics can also be used to inform short-range predictability
090 within a single ozone hole season. For example, polar cap TCO is closely linked with
091 the Southern Annular Mode (SAM) [29]. Ozone hole–SAM interactions cascade wind
092

and precipitation effects across the Southern Hemisphere during the austral spring and summer [30, 31, and references therein].

Despite the many established ozone hole summary metrics, there is no clear definition to distinguish a ‘mild’ or ‘severe’ ozone hole from one that is ‘typical’. More than forty years since the emergence of the ozone hole, we now have sufficient historical data to statistically produce such designations. In this work, we formulate an Antarctic ozone hole severity classification system. An early version of this framework was first presented by Kessenich et al. [32], and we now formalize the methodology and backdate classifications to 1979. Our classification system uses a k -means clustering analysis to categorize ozone holes into three severity tiers for September through November: **Minor**, **Moderate**, and **Major**. We present the classification results for all ozone holes from 1979 to 2025. Threshold values of common ozone hole metrics are provided allowing future ozone holes to be readily classified. We further demonstrate how this classification system can be used to gain understanding into decadal shifts in the ozone hole, its links to the Southern Annular Mode, and future recovery projections from the Coupled Model Intercomparison Project Phase 6 (CMIP6) simulations.

Results and Discussion

Observed Minor, Moderate, and Major Ozone holes

Antarctic ozone hole classifications are produced from a three-step process. More information on the datasets and Steps (1)–(3) below is contained in the Methods section. The resulting Antarctic ozone hole classifications are presented in Table 1 from 1979 to 2025.

1. **Step (1) Combining datasets:** The monthly mean polar cap TCO (63/65°S–90°S, see Table 3) is designated as the benchmark summary metric for the analysis. We calculate a combined and normalized TCO dataset for September, October, and November from 1979 to 2025 using three sources of polar cap TCO data: the Solar Backscatter Ultraviolet (SBUV) Merged Ozone Data set, Copernicus Climate Change Service (C3S), and the Goddard Earth Observing System Data Assimilation System (GEOS DAS). The resulting dataset, *Combined_TCO*, is provided for reference in Table S1.
2. **Step (2) Selecting a statistically stable time period:** From the *Combined_TCO* dataset, a ‘stable period’ of trend-free TCO data is designated, per month, for September, October, and November. We emphasize that stable period here simply refers to the absence of a significant linear trend, not physical or chemical conditions. Only years within the stable period will be used to determine ozone hole classifications. The resulting year ranges are 1993–2025 for September, 1987–2025 for October, and 1985–2025 for November.
3. **Step (3) K -means clustering:** A 3-cluster k -means analysis is performed on the *Combined_TCO* dataset separately for September, October, and November over their corresponding stable periods. From the cluster results, years within the category with the highest mean TCO are classified as ‘Minor’ ozone

holes, and years within the category with the lowest mean TCO are classified as ‘Major’ ozone holes. Years in the centremost TCO category are classified as ‘Moderate’ ozone holes. These category names are selected as they have accessible, universal definitions. Years outside of the designated stable periods are retroactively classified based on the midpoints between k -means clusters.

We further add an ‘Annual’ classification result in the rightmost column of Table 1 based on the monthly results. The annual classification is the monthly classification which is most-frequent for that year, or Moderate when all three classifications are present. For example, the annual classification for a Moderate-Minor-Minor ozone hole is Minor, and the annual classification for a Major-Moderate-Minor ozone hole is Moderate. September 1994 is omitted from Table 1 due to missing data. Considering that the October 1994 ozone hole is classified as Major, the most-likely classification for September 1994 was also Major (see the Supplement: Fig. S1 demonstrates that the majority of past Major October ozone holes began as Major during September, and Table S2 shows that the Major-Major-Moderate progression has occurred more than twice as often as the Moderate-Major-Moderate progression). As such, we designate the annual classification for 1994 as Major.

Figure 1 presents a visualization of the ozone hole classification results from Table 1 for September (a), October (b), and November (c). The y -axis presents the value for the combined and normalized TCO (*Combined.TCO*, Table S1) for each month and year from 1979 to 2025. We note that a corresponding Dobson Unit value cannot be provided for the y -axis, as the *Combined.TCO* dataset is formed using three different polar cap TCO datasets with varying values (see Methods). Years within the corresponding stable period are shown with black dots, and years outside this period are shown with grey dots. The calculated boundaries between k -means clusters, and hence classifications, are indicated with a horizontal dashed green line (Minor boundary) and a dash-dotted red line (Major boundary). Labels have been added to Minor years in green and Major years in red across the full times series.

Most years classified into the Minor/Major categories in Fig. 1 from 2001 onward have well-established links to anomalous driving mechanisms. For example, 2002 and 2019 both had sudden stratospheric warming events [33–35] which yielded Minor ozone holes from September onward. The ozone hole during 2015 was found to be notably impacted by the Chilean Calbuco eruption in April of that year [20, 23, 36, 37] and is Major across the three-month season. Each year in the recent run of Major ozone holes from 2020–2023 has been linked to wildfire and volcanic events leading up to the austral spring which increased the severity of ozone depletion during September [16, 28, 38–41]. The 2023 ozone hole is the only exception within this unique period which became Moderate during October and then Major again by November. The years 2020 through 2022 had notably decreased horizontal ozone resupply during October [32] and remained Major all season. The only series of Major ozone holes comparable to this 2020–2023 period occurred before the ‘peak’ of EESC loading in the 1990s [5, 6]. Interestingly, and unlike in recent years, Fig. 1 indicates the majority of Major September ozone holes during the 1990s were downgraded to Moderate by November. All ozone holes prior to the mid-to-early 1980s were Minor. Some years have borderline

Table 1 Antarctic ozone hole classifications. Each year from 1979 to 2025 is classified as having a Minor/Moderate/Major ozone hole during September, October, and November (excluding September 1994) from a k -means clustering analysis performed on the *Combined_TCO* dataset (Table S1, see Methods). Annual classifications correspond to the most-frequent monthly classification. In the case of Major-Moderate-Minor (as in 2000 and 2005), the annual classification is Moderate. The year 1994 is designated as Major based on its October classification.

Year	Monthly			Annual
	September	October	November	
1979	Minor	Minor	Minor	Minor
1980	Minor	Minor	Minor	Minor
1981	Minor	Minor	Minor	Minor
1982	Minor	Minor	Minor	Minor
1983	Minor	Minor	Minor	Minor
1984	Moderate	Minor	Minor	Minor
1985	Moderate	Moderate	Moderate	Moderate
1986	Minor	Moderate	Minor	Minor
1987	Moderate	Major	Major	Major
1988	Minor	Minor	Minor	Minor
1989	Moderate	Moderate	Minor	Moderate
1990	Moderate	Major	Moderate	Moderate
1991	Moderate	Moderate	Minor	Moderate
1992	Major	Moderate	Moderate	Moderate
1993	Major	Major	Moderate	Major
1994	–	Major	Moderate	Major
1995	Major	Major	Moderate	Major
1996	Major	Major	Moderate	Major
1997	Moderate	Major	Moderate	Moderate
1998	Major	Major	Major	Major
1999	Major	Major	Major	Major
2000	Major	Moderate	Minor	Moderate
2001	Major	Major	Major	Major
2002	Minor	Minor	Minor	Minor
2003	Major	Moderate	Moderate	Moderate
2004	Moderate	Moderate	Moderate	Moderate
2005	Major	Moderate	Minor	Moderate
2006	Major	Major	Major	Major
2007	Moderate	Moderate	Moderate	Moderate
2008	Major	Major	Major	Major
2009	Major	Moderate	Moderate	Moderate
2010	Moderate	Moderate	Major	Moderate
2011	Major	Major	Moderate	Major
2012	Moderate	Minor	Minor	Minor
2013	Moderate	Moderate	Minor	Moderate
2014	Moderate	Moderate	Moderate	Moderate
2015	Major	Major	Major	Major
2016	Moderate	Moderate	Minor	Moderate
2017	Moderate	Moderate	Minor	Moderate
2018	Major	Major	Moderate	Major
2019	Minor	Minor	Minor	Minor
2020	Major	Major	Major	Major
2021	Major	Major	Major	Major
2022	Major	Major	Major	Major
2023	Major	Moderate	Major	Major
2024	Moderate	Moderate	Moderate	Moderate
2025	Moderate	Moderate	Minor	Moderate

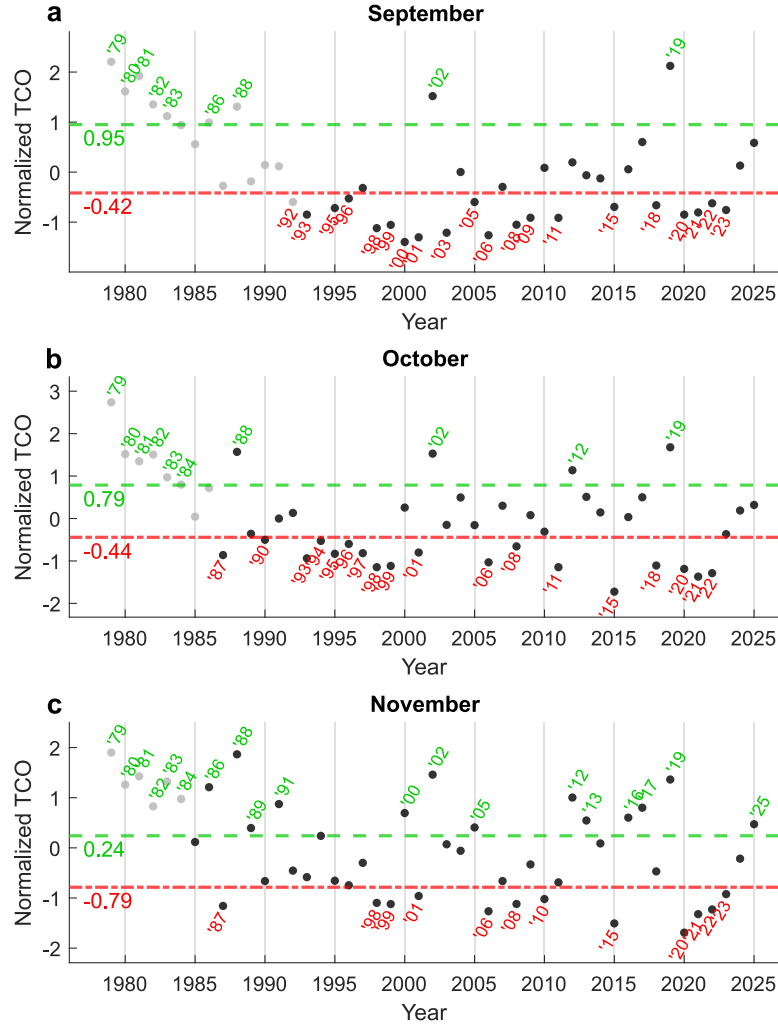


Fig. 1 Antarctic ozone hole classifications. (a) September, (b) October, and (c) November results are presented for a *k*-means cluster analysis from 1979 to 2025 (see Methods). The *y*-axis of each panel indicates the *Combined_TCO* value for each year (Table S1). Years are shown on the *x*-axis: those included in the *k*-means analysis as black dots and those excluded as grey dots. Minor ozone holes years (highest TCO) are labelled with green text, Major years (lowest TCO) with red text, and Moderate years are left unlabelled. The boundary between Minor(Major) and Moderate categories is shown with a dashed green(dash-dotted red) line.

designations (see the November 1994 marker in Fig. 1c), but most fall into one of the three distinct classifications.

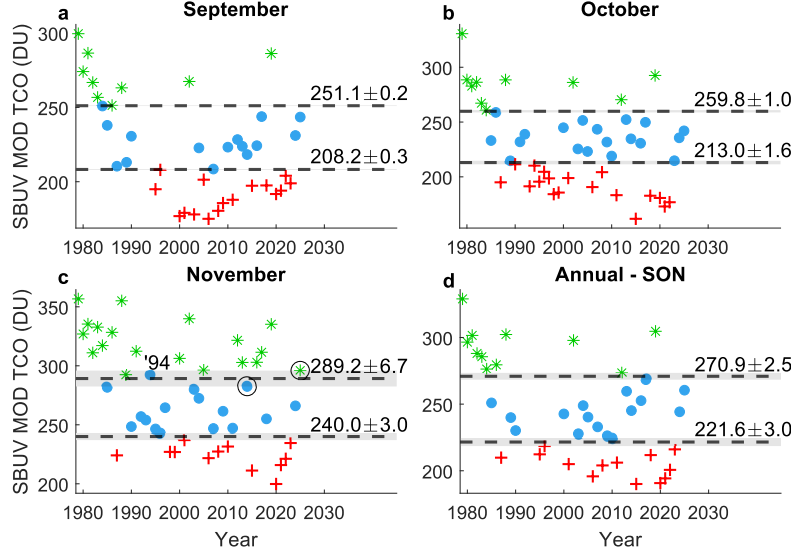


Fig. 2 An example of the threshold calculation process. The *SBV.MOD.TCO* dataset is used as an example for (a) September, (b) October, (c) November, and (d) Annual classifications. In each panel, the classifications from Table 1 are masked onto the individual monthly mean total column ozone (TCO) data points (*y*-axis) from 1979 to 2025 (*x*-axis) and are marked accordingly: Minor = green star, Moderate = blue dot, Major = red cross. Annual TCO is calculated as the springtime (SON) average. Thresholds (dashed black lines) are drawn at the midpoints between the minimum/maximum members of neighbouring categories, with errors (grey shading) reported as the gap between those members. In November (c), there is < 0.1 DU separation between the Minor and Moderate categories. As explained in the text, the second-lowest Minor year and the second-highest Moderate year (both circled in black) are used to determine the threshold and error instead. As a result, the Moderate November 1994 data point (labelled in the panel) is 2.8 DU above the Minor threshold, representing the only outlier.

Threshold values

As noted earlier, the cluster boundaries presented in Fig. 1 are determined from a combined and normalized TCO dataset (Table S1) and thus do not correspond to absolute Dobson Unit thresholds. However, the classification results from Table 1 can be used to determine cluster boundary thresholds for individual datasets. Here, we will describe this threshold-finding process and provide ready-to-use thresholds for a number of well-known datasets.

We consider seven individual datasets from four sources: *SBV.MOD.TCO*, *C3S.TCO*, *GEOS.DAS.TCO*, *SBV.MOD.TCO.ex*, *GEOS.DAS.Area*, *GEOS.DAS.OMD*, and *CAMS.TCO* (see Methods for dataset details and processing). We first apply the categories presented in Table 1 to each dataset for all overlapping years (e.g. the *CAMS.TCO* dataset spans from 2003 to 2024, thus classifications from Table 1 are applied for these years only). A visual example of this process for the *SBV.MOD.TCO* dataset is shown in Figure 2, where the applied categories are presented using different symbols from 1979 to 2025. Thresholds are then drawn at the midpoints between the outermost category members (dashed black lines in Fig. 2). Where outermost category members are very close in value (within

0.1 DU/million km²/million tons), the second outermost members are used instead. An example of such case is shown in Fig. 2c for November. In cases where category members may overlap (particularly with the *GEOS_DAS_Area* and *GEOS_DAS_OMD* datasets), thresholds are chosen to best split category members. Errors are reported as the difference between the midpoint and the category members used to calculate each threshold (grey shading around the dashed lines in Fig. 2)

The resulting thresholds for each time period and dataset are presented in Table 2. The three datasets used previously in the *Combined_TCO* dataset from which the ozone hole classifications are set (*SBUV_MOD_TCO*, *C3S_TCO*, and *GEOS_DAS_TCO*) are displayed in bold. Table 2 also reports the agreement (%) between the classifications from Table 1 and those reproduced using the individual thresholds. With the exception of November 1994 in *SBUV_MOD_TCO* (a Moderate year which is 2.8 DU above the Minor threshold) all three datasets used to create the *Combined_TCO* dataset individually reproduce the classifications shown in Table 1. We note that the *Combined_TCO* value for November 1994 is also very close to the boundary between Moderate and Minor in Fig. 1c (dashed green line). In the extended SBUV MOD dataset, *SBUV_MOD_TCO_ex*, the Moderate October 1989 ozone hole is 2.1 DU below the Major threshold and is also an outlier. Both of these outlier differences are relatively small in comparison to their corresponding thresholds ($\leq 1\%$). While the October SBUV MOD thresholds vary slightly from those previously presented by Kessenich et al. [32], the years included in each category remain unchanged. The area and OMD datasets have reasonably high agreements with Table 1, between 89% and 98%. However, outliers can vary substantially from their correct classification threshold: up to 7.7 million km² (50.9%) for the *GEOS_DAS_Area* dataset and 7.1 million tons (41.9%) for the *GEOS_DAS_OMD* dataset.

Guidelines for users

The results in Table 1 and Table 2 should be used according to the following guidelines:

1. For any historical ozone hole from 1979 to 2025, Table 1 should be used as a classification lookup table.
2. For ozone holes from 2026 onward, classifications may be available in the extended record of Table 1 [42] (see Data Availability). Otherwise, Table 2 should be used instead, if using one of the defined datasets in this study:
 - Polar cap TCO datasets offer the most accurate classification results and should be used when possible. Area and OMD datasets should always be considered in conjugation with at least one other dataset. The Methods section provides information on how to pre-process each dataset (e.g. latitude ranges, etc.).
 - Select the Major and Minor thresholds in Table 2 which correspond to the appropriate time period and dataset.
 - The ozone hole is classified as Major when the average TCO falls below the listed Major threshold and Minor when the average TCO is above the Minor threshold (or vice versa for the area and OMD

Table 2 Classification thresholds for individual datasets. Thresholds are provided for seven representative datasets (see Methods, Table 3) to classify September, October, November, and Annual ozone holes as Minor/Moderate/Major. Each listed metric corresponds to its monthly average, or the springtime (SON) average for the Annual classification. Thresholds are given in Dobson Units (DU), million km² (Mkm²), or million tons (Mt). Errors are reported as the difference between dataset members used to calculate thresholds. The agreement between the classifications in Table 1 and those reproduced by each threshold set is reported as a percent. The three datasets used for the *Combined_TCO* dataset in Table S1 are shown in bold.

September			
Dataset	Major threshold	Minor threshold	Agreement
<i>SBUV_MOD_TCO</i>	208.2±0.3 DU	251.1±0.2 DU	100%
<i>C3S_TCO</i>	214.4±4.3 DU	260.0±1.0 DU	100%
<i>GEOS_DAS_TCO</i>	207.4±2.8 DU	255.2±1.3 DU	100%
<i>SBUV_MOD_TCO_ex</i>	232.2±0.1 DU	273.6±1.8 DU	100%
<i>GEOS_DAS_Area</i>	21.1±0.4 Mkm ²	15.2±0.9 Mkm ²	91%
<i>GEOS_DAS_OMD</i>	16.9±0.4 Mt	5.0±0.2 Mt	89%
<i>CAMS_TCO</i>	214.9±2.6 DU	272.2±25.5 DU	100%
October			
Dataset	Major threshold	Minor threshold	Agreement
<i>SBUV_MOD_TCO</i>	213.0±1.6 DU	259.8±1.0 DU	100%
<i>C3S_TCO</i>	222.1±0.2 DU	267.4±1.8 DU	100%
<i>GEOS_DAS_TCO</i>	221.5±3.2 DU	266.7±1.8 DU	100%
<i>SBUV_MOD_TCO_ex</i>	243.2±0.7 DU	283.3±1.0 DU	98%
<i>GEOS_DAS_Area</i>	19.5±0.5 Mkm ²	12.9±1.7 Mkm ²	94%
<i>GEOS_DAS_OMD</i>	24.3±0.8 Mt	10.6±1.5 Mt	94%
<i>CAMS_TCO</i>	220.2±6.4 DU	270.2±11.9 DU	100%
November			
Dataset	Major threshold	Minor threshold	Agreement
<i>SBUV_MOD_TCO</i>	240.0±3.0 DU	289.2±6.7 DU	98%
<i>C3S_TCO</i>	244.3±3.5 DU	293.1±0.4 DU	100%
<i>GEOS_DAS_TCO</i>	246.5±3.8 DU	288.8±4.4 DU	100%
<i>SBUV_MOD_TCO_ex</i>	260.3±1.1 DU	301.8±2.8 DU	100%
<i>GEOS_DAS_Area</i>	13.9±0.6 Mkm ²	6.5±0.5 Mkm ²	96%
<i>GEOS_DAS_OMD</i>	12.0±0.1 Mt	2.6±0.3 Mt	94%
<i>CAMS_TCO</i>	246.6±2.2 DU	287.5±4.4 DU	100%
Annual - SON			
Dataset	Major threshold	Minor threshold	Agreement
<i>SBUV_MOD_TCO</i>	221.6±3.0 DU	270.9±2.5 DU	100%
<i>C3S_TCO</i>	227.9±3.0 DU	273.8±4.9 DU	100%
<i>GEOS_DAS_TCO</i>	225.0±1.8 DU	274.3±2.4 DU	100%
<i>SBUV_MOD_TCO_ex</i>	245.5±2.7 DU	288.0±2.1 DU	100%
<i>GEOS_DAS_Area</i>	18.0±0.5 Mkm ²	10.8±0.3 Mkm ²	98%
<i>GEOS_DAS_OMD</i>	18.6±0.2 Mt	6.3±1.2 Mt	94%
<i>CAMS_TCO</i>	229.2±2.5 DU	274.9±2.8 DU	100%

metrics). Values between the two thresholds correspond to Moderate ozone holes.

- For borderline years (values within the quoted error estimates from a threshold), we recommend checking at least one other dataset for verification.
 - The annual classification can either be determined directly from Table 2 using springtime (SON) metric averages, or from monthly ozone hole classifications. If monthly classifications are used, the annual classification is the most-frequent monthly classification, or Moderate when all three classifications are present.
3. To classify a post-2025 ozone hole using a dataset not listed in Table 2, including reanalysis datasets, users should follow the procedure described in the Results section and demonstrated in Fig. 2. For model outputs that do not replicate historical annual variability, an alternative process will be demonstrated later using CMIP6 model simulations.

Insights from ozone hole classifications

Categorical changes over time

Figure 3 presents a decadal time series of ozone hole classifications starting in 1980 and ending with the current (incomplete) decade which started in 2020. Ozone hole classifications for each month are shown by colour, with Major in red (vertical hatching), Moderate in blue (diagonal hatching), and Minor in green (horizontal hatching). The zero line is placed between the Major and Non-Major (Moderate and Minor) years, for visualization purposes. The September (a), October (b), November (c), and overall annual (d) decadal distributions are shown separately.

As the ozone hole era first developed in the 1980s, most years had Minor ozone holes during the full spring season (Fig. 3a–c). Over the 1990s, the quantity of Major September and October ozone holes rapidly increased over time with observed EESC levels [5, 6]. November ozone holes (Fig. 3c) became predominantly Moderate in the 1990s. For September (Fig. 3a), the 2000s were the peak decade of Major ozone holes, and the categorical distribution shifted back towards Non-Major by the 2010s. A number of trend analyses were conducted around this time (with data through 2020 or earlier), producing evidence of possible significant recovery trends in September [20, 22, 25]. October (Fig. 3b) also showed improvement during the 2000s and 2010s compared to the 1990s. November remained relatively stable with 1–2 Major ozone holes per decade. The current decade appears to deviate from these patterns: In September, there have been four Major ozone holes within the last six years, more than during the 2010s. For October, another Major year before 2030 would also tip this decade qualitatively below the two before. The 2020s already has the highest amount of Major November ozone holes recorded within a single decade. Such decadal shifts are not entirely unexpected, given the long timeline of complete ozone hole recovery and the large role of natural variability [6–8, 43]. However, dynamical conditions may be changing over time, and reduced October ozone resupply in recent years [32] is likely producing prolonged impacts into November.

A combination of the general patterns exhibited in the monthly decadal series can be observed in the annual classification series (Fig. 3d): the 1990s was the peak decade

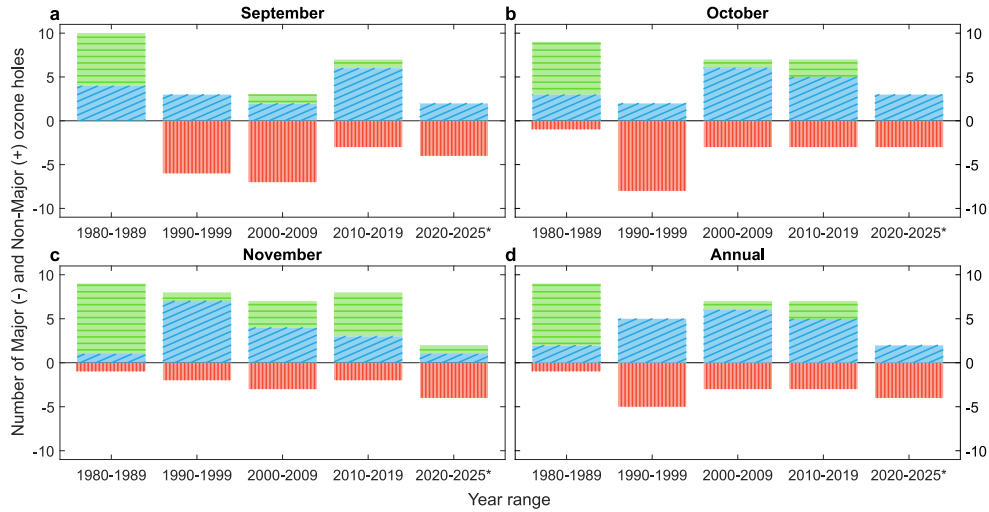


Fig. 3 A decadal time series of Major and Non-Major ozone holes. (a) September, (b) October, (c) November, and (d) Annual ozone hole types (see Table 1) are grouped into decadal bins on the x -axis, starting at 1980. In each bin, the quantity of Major ozone holes is shown in red (vertical hatching), Moderate ozone holes are shown in blue (diagonal hatching), and Minor ozone holes are shown in green (horizontal hatching). On the y -axis, the Major years are quantified with negative values and the Non-Major (Moderate plus Minor) years are quantified with positive values. The last decadal bin (indicated with *) covers 2020 to 2025 and thus only includes 6 years.

of Major ozone holes, a transient shift towards Non-Major ozone holes occurred in the 2000s and 2010s, with the ongoing decade shows a resurgence of Major ozone holes. Further investigation is warranted into the driving mechanisms behind the increased frequency of Major ozone holes in the last decade and their links to dynamical variability.

Major ozone holes drive a positive summer Southern Annular Mode

Causal links between the ozone hole and the Southern Annular Mode (SAM) have been proposed, whereby variability in springtime stratospheric ozone couples to the troposphere and influences summertime near-surface temperature gradients via both radiative and dynamic mechanisms [30, 31, and references therein]. Periods with significant polar ozone loss, such as during the ‘ozone hole era’, have been found to shift the SAM toward a high-index polarity (a more positive phase of the SAM) [30, 31]. Here, we assess whether ozone hole classifications alone, rather than TCO values, are sufficient to draw generalizations about the SAM during the austral summer within a given year.

We first categorize ozone holes into their classification types from Table 1 for September, October, November, and the overall annual classification. For the purposes of increasing the sample size of each distribution, we group Minor and Moderate types together as Non-Major ozone holes. Monthly historical records of the 700 hPa SAM index are then retrieved from the [NOAA Climate Prediction Center](#). For each year

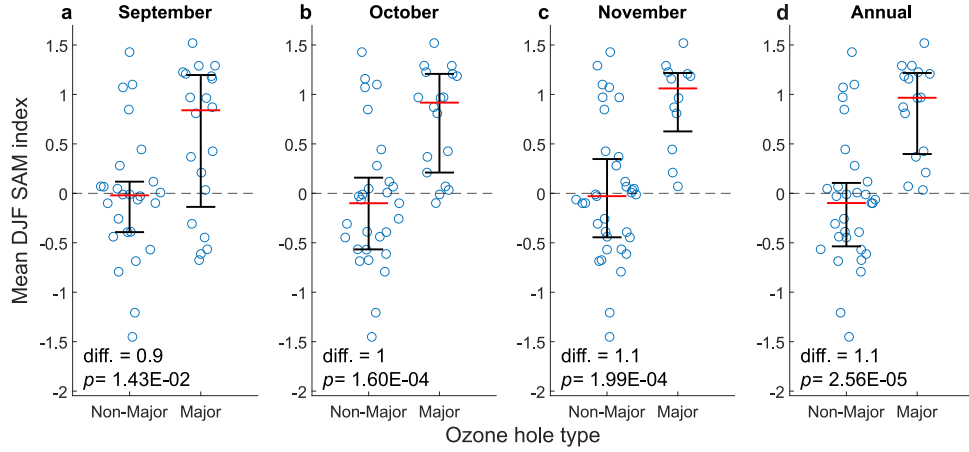


Fig. 4 Ozone hole categorical links to the following summer Southern Annular Mode (SAM). (a) September, (b) October, (c) November, and (d) Annual ozone holes types are separated into Non-Major (Moderate & Minor) and Major distributions for 1979 to 2025 (see Table 1). For each year, the mean summertime SAM index from December to February (DJF) is presented with a blue circle along the y -axis. The median values of each distribution are represented by red horizontal lines and lower/upper quartiles are represented by black error bars. The zero-line for SAM is shown with a black dashed line. A Mann-Whitney U-test [45, 46] is performed to determine whether the medians of the Non-Major and Major SAM distributions differ, with the resulting difference (diff.) and p -value shown in each panel.

on record, we calculate the mean austral summer SAM index (December–February, DJF) as in Polvani et al. [30] and Thompson et al. [31]. Summertime SAM indexes are then matched with their preceding ozone hole, and the results for each time period of Non-Major/Major ozone holes are shown in Figure 4.

In Fig. 4, the red horizontal lines indicate the median DJF SAM index of each distribution, and the error bars indicate the upper and lower quartiles. A Mann-Whitney U-test [45, 46] is performed for each pair, to test whether the two groups have the same median. The resulting p -values are presented in each panel. We find a significant positive shift ($p < 0.05$, $>95\%$ significance) in the median summertime SAM index following Major ozone holes across all time periods. Overall, the median summertime SAM index following Non-Major ozone holes is near zero, and the SAM index following Major ozone holes is between 0.9 and 1.1 points higher. As seen in Fig. 4, as the months progress, the impact of a Major ozone hole appears to grow. The lower quartile of the SAM index distribution is the most-positive following November Major ozone holes (Fig. 4c). The annual ozone hole classifications in Fig. 4d show the most-significant difference between medians (a difference of 1.1, $p = 2.56 \times 10^{-5}$). These results indicate that in nearly all cases, a Major ozone hole is followed by a high-index summertime SAM. The SAM has been trending positive in recent years with increased variability [31, 47]. This positive trend is in-line with the shift we observe towards Major ozone holes within the last decade, particularly during November (see Fig. 3).

Ozone hole recovery in CMIP6

We now consider ozone hole classifications in the context of CMIP6 model simulations [48]. We consider simulations representing both the historical time period (1850–2014) and a future period of 2015–2100. For the future period, we choose a ‘middle-of-the-road’ Shared Socioeconomic Pathways (SSPs) [49], SSP2-4.5 (henceforth SSP245). SSP245 is one of the SSPs that predict TCO recovery to 1960s values midway through the twenty-first century [50]. We select three CMIP6 models with fully interactive ozone chemistry: CESM2-WACCM, CNRM-ESM2-1, and UKESM1-0-LL (see Methods). Figure 5 presents the 10-year rolling average for the September, October, and November monthly polar cap (63°S–90°S) TCO for CESM2-WACCM (a–c), CNRM-ESM2-1 (d–f), and UKESM1-0-LL (g–i). The shaded areas represent the $1.96\sigma_{10}$ boundaries from the rolling average, indicating the variation represented by the models during 95% of years (see Methods).

We then determine three representative thresholds for each model and month in Fig. 5: (1) The ‘No ozone hole’ threshold, and (2)–(3) Minor and Major ozone hole thresholds (see Methods). The ‘No ozone hole’ thresholds, labelled with a dashed line in Fig. 5, represent the theoretical upper limit on the Minor ozone hole category, specific to each individual CMIP6 model. These thresholds vary between approximately 285 DU and 395 DU, depending on the month and model considered. Minor, Moderate, and Major ozone hole boundaries are also presented in Fig. 5 with dashed black lines, and the $1.96\sigma_{10}$ shaded areas are coloured accordingly: No ozone hole in grey, Minor in green, Moderate in blue, and Major in red. We use the σ_{10} -boundary to determine the last year when an ozone hole of each type would be expected with a likelihood of ~ 1 in 40 years (from the 95% confidence interval).

When comparing the three CMIP6 SSP245 model outputs used in Fig. 5, CESM2-WACCM (a–c) has the earliest predicted recovery dates for each type of ozone hole, with Major ozone holes becoming unlikely across all three months by 2026–2030. CESM2-WACCM is also the only model predicting the disappearance of Minor ozone holes altogether before 2100 (between 2092 and 2094). Both CNRM-ESM2-1 and UKESM1-0-LL (Fig. 5d–f and g–i, respectively) project a slight delay between the disappearance of September and November Major ozone holes (from 2035 to 2046 in CNRM-ESM2-1 and from 2035 to 2038 in UKESM1-0-LL). This delay hints at dynamical impacts on late-spring ozone within the SSP245 scenario, such as a shift towards later stratospheric final warmings [51]. In all model projections, Moderate ozone holes are expected to become infrequent after the 2040s. The results from Fig. 5 demonstrate: (1) The thresholds for ‘No ozone hole’ conditions depend on each model’s background ozone conditions, and (2) Estimated recovery dates for each type of ozone hole vary substantially, even within the SSP245 scenario. While SSP245 is chosen as an example here, other SSPs could also be considered in a similar manner.

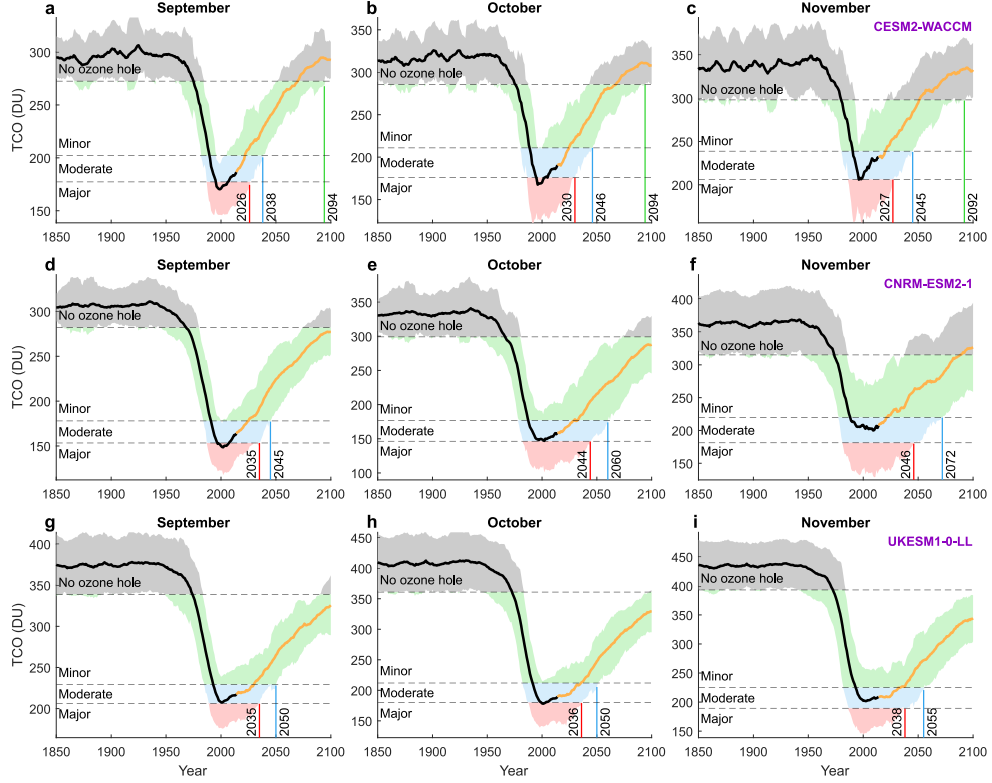


Fig. 5 Ozone hole classifications for the Coupled Model Intercomparison Project Phase 6 (CMIP6). CMIP6 total column ozone (TCO) results are presented for (a)–(c) CESM2-WACCM, (d)–(f) CNRM-ESM2-1, and (g)–(i) UKESM1-0-LL for September (left), October (centre), and November (right). A 10-year rolling average of the monthly polar cap (63°S–90°S) TCO is shown as a black line for the historical period (pre-2015), and as an orange line for the SSP245 scenario to 2100 (see Methods). Shading indicates the $\pm 1.96\sigma_{10}$ bounds on the rolling average, where σ_{10} is a 10-year rolling standard deviation of the individual realization from the rolling average. The ‘No ozone hole’ threshold (labelled black dashed line) is set at $1.96\sigma_{1850-1929}$ below the 1850–1929 mean TCO. Minor/Moderate/Major ozone hole categories are labelled and separated with dashed horizontal black lines. Shading is coloured according to the ozone hole classifications: Minor in green, Moderate in blue, Major in red. The last year when a Major/Moderate/Minor ozone hole is expected (occurrence rate of $\lesssim 1/40$ years) is determined from the $\pm 1.96\sigma_{10}$ bounds and is indicated on the x -axis with vertical coloured line.

Methods

Datasets

The Antarctic ozone hole classifications and thresholds presented in this work are based on data from four sources: the Solar Backscatter Ultraviolet (SBUV) Merged Ozone Data set, Copernicus Climate Change Service (C3S), Copernicus Atmosphere

monitoring service (CAMS), and the Goddard Earth Observing System Data Assimilation System (GEOS DAS). Each source and its corresponding datasets are described in detail below and summarized in Table 3.

SBUV Merged Ozone Data Set, SBUV MOD

SBUV MOD version 8.7 [52–54] provides monthly-mean profile and TCO records from 1970 to 2025. The 2024–2025 values in the MOD dataset are preliminary but not expected to change. This series was created by merging overlapping observations from a suite of SBUV instruments and correcting all to a local solar time of 1:30pm. SBUV MOD is ideal for multi-decadal trend analyses, as it presents the longest-running merged TCO record created using the same instrument type. Zonal mean TCO data is provided in 5° latitude bins and is given in Dobson Units.

We create two polar cap TCO datasets from SBUV MOD data: *SBUV_MOD.TCO* and *SBUV_MOD.TCO_ex* (“extended”). Each dataset spans from 1979 to 2025 with monthly TCO values for September, October, and November. A cosine latitude area weighting is applied prior to averaging zonal means across 65°S–90°S for *SBUV_MOD.TCO* and across 60°S–90°S for *SBUV_MOD.TCO_ex*. Where gaps larger than 15° are present at high latitudes, data for the given month and year are omitted (September 1991–1994 and 1997–1999). Otherwise, gaps are filled with data from the nearest available latitude. Given the 5° latitude bin size of SBUV MOD data, neither TCO dataset can match the 63°S–90°S polar cap range typically used in World Meteorological Organization reports. However, 65°S–90°S offers the closest comparison, and this latitude range is often used to track the dynamical response to polar ozone loss [31, 55]. Therefore, *SBUV_MOD.TCO* is assigned as the benchmark SBUV MOD dataset.

C3S Ozone

C3S provides a monthly gridded ozone record from 1970 to present [10, 56]. This series is created by the European Centre for Medium-Range Weather Forecasts (ECMWF) from a suite of Ultraviolet (UV) nadir-viewing satellite sensors, including many of the same instruments used in the SBUV MOD dataset in addition to instruments such as the Ozone Monitoring Instrument (OMI) [56]. The Level 4 ozone total column multi-sensor reanalysis (TC_MSR) product is generated from the assimilation of Level 2 total column ozone data in a three-dimensional chemistry-transport model. The C3S TC_MSR product is designated as an Intermediate Climate Data Record [56], making it a reliable, quality-controlled product for long-term assessments. TC_MSR data is provided on a $0.5^\circ \times 0.5^\circ$ (lat×long) grid in Dobson Units.

A polar cap TCO dataset is created from the C3S TC_MSR product: *C3S.TCO*. This dataset spans from 1979 to 2024 with monthly values for September, October, and November. Zonal means are calculated, and a cosine latitudinal area weighting is applied prior to averaging across 63°S–90°S. Gaps are present in September 1993–1994 high-latitude data, thus these months and years are omitted.

CAMS ozone

CAMS provides a global reanalysis product (ECMWF Atmospheric Composition Reanalysis 4, EAC4) covering the period from 2003 to August 2025 [57]. EAC4 is also produced by the ECMWF. Where the ECMWF C3S ozone record is best suited for long term assessments of ozone, CAMS targets real-time atmospheric conditions and is used to provide ozone monitoring services [11]. Satellite observations are assimilated into ECMWF’s Integrated Forecasting System to produce a set of three dimensional atmospheric composition fields [57]. The monthly total column ozone variable is provided on a $0.75^\circ \times 0.75^\circ$ (lat×long) grid in units of kg m^{-2} .

A polar cap TCO dataset is created from the CAMS total column ozone product: *CAMS_TCO*. This dataset spans from 2003 to 2024 with monthly values for September, October, and November. Data for 2025 is not included, as the CAMS series ends with August 2025. Mass content units (kg m^{-2}) are converted into DU, and zonal means are calculated. A cosine latitudinal area weighting is applied prior to averaging across 63°S – 90°S . The *CAMS_TCO* dataset has similar values as the *C3S_TCO* dataset, with variations ranging from 0–4.9%.

GEOS DAS Ozone

[NASA Ozone Watch](#) provides monthly records for polar cap ozone, ozone hole area, OMD, and other metrics. These metrics are calculated from the Total Ozone Mapping Spectrometer (TOMS) Earth Probe, OMI, and the Ozone Mapping and Profiler Suite (OMPS) instrument series, covering the time period from 1979 to present. GEOS DAS fills missing areas of data with assimilated ozone data [58]. The GEOS DAS polar cap ozone is calculated by averaging TCO from 63°S – 90°S and is given in DU. The GEOS DAS ozone hole area is defined as the region of TCO values south of 40°S which are below 220 DU and is given in million km^2 [14, 15]. The GEOS DAS OMD is defined as the mass of ozone required to raise the TCO levels within the ozone hole to a value of 220 DU and is given in million tons [17]. While GEOS DAS also provides a record for minimum TCO, we found this metric to be the least reliable for ozone hole classification and thus excluded it from our analysis.

All three GEOS DAS datasets (polar cap ozone, area, and OMD) are ready to use without further processing. We will refer to them as *GEOS_DAS_TCO*, *GEOS_DAS_Area*, and *GEOS_DAS_OMD*, respectively. For the purposes of this work, monthly values for September, October, and November are taken for each metric from 1979 to 2025. Gaps are present for September 1994–1995, October 1993 and 1995, and November 1995–1996 and 2004, and thus these months and years are omitted. In our analysis, the benchmark GEOS DAS dataset is *GEOS_DAS_TCO*, to match the other two polar cap datasets from SBUV MOD and C3S.

Classification methodology

We follow a three-step process to produce ozone hole classifications. Each step is described in detail below.

Table 3 Dataset summary table. Each dataset used in the analysis is listed along with its corresponding latitude range, data source, and year range. The months and years excluded due to data gaps are listed in the rightmost column. The three key datasets used for the *Combined_TCO* dataset in Table S1 are shown in bold.

Dataset name	Latitude	Source	Year range	Months/years excluded
<i>SBUV_MOD_TCO</i>	65°S–90°S	SBUV MOD	1979–2025	September 1991–1994,
<i>SBUV_MOD_TCO_ex</i>	60°S–90°S			1997–1999
<i>C3S_TCO</i>	63°S–90°S	C3S	1979–2024	September 1993–1994
<i>CAMS_TCO</i>	63°S–90°S	CAMS	2003–2024	-
<i>GEOS_DAS_TCO</i>	63°S–90°S	GEOS DAS	1979–2025	September 1994–1995;
<i>GEOS_DAS_Area</i>	40°S–90°S			October 1993, 1995;
<i>GEOS_DAS_OMD</i>	40°S–90°S			November 1995–1996, 2004

Step (1) Combining datasets

To mitigate potential bias resulting from a single data source, we employ the following three benchmark polar cap TCO datasets for classifying: *SBUV_MOD_TCO*, *C3S_TCO*, and *GEOS_DAS_TCO*. These datasets are combined for September, October, and November separately, to create a *Combined_TCO* dataset from 1979 to 2025. To produce the combined dataset, each monthly dataset is first normalized to have a mean of 0 and standard deviation of 1. After normalization, the standard deviation between individual data points across the three datasets is about 5.2–8.9% of the total, and inter-dataset correlations are 98.7–99.6%. Individual data points are then averaged across the three datasets to form a single, combined time series from 1979 to 2025. The final *Combined_TCO* dataset is provided for reference in Table S1.

Step (2) Selecting a statistically stable time period

Trended data has the potential to bias clustering algorithms. This bias is of particular concern when using ozone records from the 1970s and 80s, where polar ozone was rapidly declining [13]. As such, before we perform the *k*-means clustering method in Step (3), we first identify and exclude time periods with significantly decreasing or increasing polar cap TCO.

Using the *Combined_TCO* dataset, we perform a linear fit starting in 1979 and ending in 2001. We select 2001 as the ending point, as polar concentrations of EESC peaked around the year 2001 [5, 6]. If the fit produces a significant negative trend (at the 95% confidence level), we perform a linear fit using the next starting year instead (starting in 1980 rather than 1979, then 1981 rather than 1980, etc.). We continue this process until we find a starting year which does not produce a significant negative trend, and this year is designated as the classification starting point. Using this method, we find the starting points are 1993 for September; 1987 for October; 1985 for November. We then check the years following 2001 for a significant positive trend from a linear fit starting in 2001. The most recent year without a significant

positive trend is designated as the classification ending point. The ending point was found to be 2025 for September, October, and November. The resulting year range - from the classification starting point to the ending point - will be referred to as the ‘stable period’. We emphasize that stable period here simply refers to the absence of a significant linear trend, not physical or chemical conditions.

Step (3) *K*-means clustering

Using the stable period selections from the *Combined_TCO* dataset (Table S1), we then perform *k*-means clustering separately for September, October, and November. We designate $n = 3$ clusters. The *k*-means clustering method is an iterative process, as follows: (1) All normalized TCO values are initialized into n random clusters. The centroid (median normalized TCO) is calculated for each cluster based on ‘city block’ distances [59]. (2) Normalized TCO values are reassigned to the cluster which has the nearest centroid. (3) Centroids are re-calculated from the normalized TCO values in the new clusters. (4) Steps 2 and 3 are repeated until the cluster assignments remain stable (no further reassignments). This process is repeated 100 times to determine the consensus result. Silhouette scores are calculated, also using city block distances, to evaluate the quality of the clustering results [60]. The resulting silhouette scores are 0.65, 0.64, and 0.55, indicating sufficient separation between clusters and cohesion between cluster members.

CMIP6 simulations

Three CMIP6 models are used, each with fully interactive ozone chemistry: CESM2-WACCM (Community Earth System Model version 2 with the Whole Atmosphere Community Climate Model version 6 as its atmosphere component) [61, 62], CNRM-ESM2-1 (Centre National de Recherches Météorologiques Earth System Model) [63, 64], and UKESM1-0-LL (United Kingdom Earth System Model) [65, 66]. Each model has a different number of available realizations: CESM2-WACCM has 3 historical and 4 SSP245 realizations; CNRM-ESM2-1 has 9 historical and 10 SSP245 realizations; and UKESM1-0-LL has 17 historical and 5 SSP245 realizations. For each model, we use all available realizations to calculate a 10-year rolling average of the September, October, and November monthly polar cap (63°S–90°S) TCO for the historical and SSP245 scenario periods. We use all available realizations to determine a 10-year rolling standard deviation (σ_{10}) estimate from the rolling average TCO.

We determine three representative thresholds for each model and month: (1) The ‘No ozone hole’ threshold, and (2)–(3) Minor and Major ozone hole thresholds. The ‘No ozone hole’ threshold is determined by finding the overall mean and standard deviation (σ) of TCO between 1850 and 1929, and calculating the 1.96σ boundary below the mean TCO. The year 1929 is selected as the ‘No ozone hole’ cut-off year to capture a time period well before the rapid increase in EESC levels that occurred in the mid 1900s [6]. For the Minor/Major ozone hole thresholds: While the simulations are forced with representative emissions of ODSs, greenhouse gases, solar forcing etc. [48], the models’ internal dynamics do not reproduce observed year-to-year ozone hole variability [50]. As a result, the previously presented threshold-finding methodology for

observational and reanalysis datasets cannot be directly applied to such simulations. Instead, we implement the following procedures: First, we select TCO from the ‘stable periods’ identified from Step (2) of the classification process: 1993–2025 for September, 1987–2025 for October, and 1985–2025 for November. We then normalize TCO from these time periods across all realizations. After this, we apply Minor(Major) classification boundaries at the same positions as identified in the right column of Fig. 1: 0.95(−0.42) for September, 0.79(−0.44) for October, and 0.24(−0.79) for November. Corresponding TCO boundaries are determined in Dobson Units and applied to the full model time series.

Conclusion

From the results presented in this work, past and future Antarctic ozone holes can now be consistently distinguished as Minor, Moderate, or Major from September to November, as well for the overall season. A complete record of historical classifications from 1979 to 2025 is provided in Table 1. Threshold values derived from well-known observational datasets are additionally provided in Table 2. The Results section provides a set of guidelines users can follow to readily classify future ozone holes (after 2025) using observations of polar cap TCO.

We put our Antarctic hole classification system into practice to demonstrate the following: (1) Decadal shifts can be detected in the distribution of Major and Non-Major ozone holes over time. The present decade shows a resurgence of Major ozone holes, with November having the most Major ozone holes of any past decade. (2) Categorical data alone can be linked to dynamics across the Southern Hemisphere. In most years, a Major ozone hole is followed by a positive shift in the Southern Annular Mode. (3) The ozone hole classification framework can be applied to chemistry-climate model simulations, such as CMIP6, to anticipate possible disappearance dates for Major, Moderate, and Minor ozone holes in the future.

Our three-tiered ozone hole classification system offers concise terminology for quantifying the severity of the annual Antarctic ozone hole, easily applicable to both general and scientific audiences. Where existing summary metrics rely on single, absolute thresholds (such as the 220 DU threshold) or comparison to other ozone hole years (e.g. “the n^{th} largest ozone hole”), our classification framework is insensitive to choice of dataset and offers an time-invariant standard for use in scientific works and international assessments.

Author contributions

HEK planned the study with suggestions from AS, DS, and LER. HEK analysed the data, prepared the figures, and wrote the manuscript with suggestions from AS, DS, LER, and CJR.

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881

882 Competing interests

883

884 All authors declare no financial or non-financial competing interests.

885

886 Data availability

887 Extensions to the ozone hole classifications from Table 1 will be made publicly
888 available at <https://doi.org/10.5281/zenodo.21485660> [42]. The datasets analysed
889 during the current study are available as follows: SBUV MOD version 8.7 is
890 available at http://acdb-ext.gsfc.nasa.gov/Data_services/merged/ [52–54]; The C3C
891 monthly gridded ozone record is available at [https://cds.climate.copernicus.eu/](https://cds.climate.copernicus.eu/datasets/satellite-ozone-v1)
892 [datasets/satellite-ozone-v1](https://cds.climate.copernicus.eu/datasets/satellite-ozone-v1) [10]; GEOS DAS ozone hole area, OMD, and polar
893 cap TCO data are available at <https://ozonewatch.gsfc.nasa.gov/> [13]; The SAM
894 index is available at [https://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_](https://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/aao/aao.shtml)
895 [ao_index/aao/aao.shtml](https://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/aao/aao.shtml) [44]; CMIP6 data is available at [https://metagrid.esgf-west.](https://metagrid.esgf-west.org/)
896 [org/](https://metagrid.esgf-west.org/) [48].

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898 Code availability

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900 The underlying code for this study is not publicly available but may be made available
901 to qualified researchers on reasonable request from the corresponding author.

902

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