



Comparative Analysis of Middle Atmospheric Ozone Response to Four Large Geomagnetic Storms of Solar Cycle 25

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Abstract. Solar Cycle 25 (SC25) produced several major geomagnetic storms with distinctly different combinations of energetic electron precipitation (EEP) and solar proton event (SPE) forcing, providing a unique opportunity to investigate short-term ozone responses in the mesosphere-thermosphere system (MTS). We analyse four major storms occurring in May 2024, October 2024, November 2025, and January 2026 using Microwave Limb Sounder (MLS) observations and specified-dynamics WACCM-D simulations. Significant mesospheric ozone depletion was observed during all four events, with maximum ozone losses ranging from approximately 30% to 80%. Model-observation comparisons show that the dominant particle forcing varied substantially among the storms. The May 2024 superstorm was predominantly EEP-driven, whereas the October 2024 event was largely SPE-driven. The November 2025 and January 2026 storms represent mixed SPE-EEP cases, with a stronger proton contribution during January 2026. Negative ozone anomalies were consistently observed in the lower thermosphere during all four events. Although these features are not reproduced by WACCM-D, their repeated occurrence suggests a lower-thermospheric response to major geomagnetic storms. Model simulations further reveal the indirect energetic particle precipitation (EPP) effect in the stratosphere, characterised by descending ozone depletion features dominated by EEP.

The four SC25 storms demonstrate the value of combining satellite observations with chemistry-climate models to separate the contributions of SPEs, EEP, and atmospheric dynamics, while also revealing several areas where current representations of particle forcing and upper-atmospheric coupling can be further improved. Maintaining long-term satellite observations of both EPP and atmospheric composition remains crucial for improving our understanding of atmosphere-space coupling during geomagnetic storms.



1 Introduction

Solar Cycle (SC) 25 has passed its maximum phase. From either solar activity radio index F10.7, ultraviolet irradiance index Lyman- α , or global geomagnetic activity index Ap point of view, SC25 has turned out to be noticeably stronger than SC24, but still weaker than SC23 overall (Figure 1a). SC25 brought an elevated frequency of solar eruptive events and associated geomagnetic disturbances. During 2024 – 2026, several intense geomagnetic storms occurred. Among them, the May 2024 storm is perhaps the most widely recognised, as it was one of the strongest geomagnetic storms of the past two decades (Grandin et al., 2024; Hayakawa et al., 2025) and reached an exceptionally high Ap index that exceeded that of the 2003 Halloween storm.

In the space environment, major geomagnetic storms affect auroral activity, ionospheric conditions, satellite operations, and technological infrastructure (e.g., Pulkkinen, 2007; Parker and Linares, 2024). In Earth's neutral middle atmosphere, particularly the mesosphere–thermosphere system (MTS), their effects arise primarily through enhanced energetic particle precipitation (EPP) and storm-induced changes in upper-atmospheric dynamics. Both processes strongly influence ozone in the polar atmosphere.

Energetic electron precipitation (EEP), especially medium energy electron (MEE) precipitation, defined as precipitating electrons with energies of approximately 30 keV to several MeV, is one of the major sources of mesospheric ozone depletion during geomagnetic storms (e.g., Andersson et al., 2014; Lee et al., 2021). Enhanced precipitation of radiation belt and magnetospheric electrons increase atmospheric ionisation and lead to the production of odd nitrogen (NO_x) and odd hydrogen (HO_x), which catalytically destroy ozone (see Nesse et al., 2026, and the references therein). During major storms, the magnetospheric slot region between inner and outer radiation belts can become filled and deposit sustained weak electron precipitation down to approximately 50° geomagnetic latitude, thereby exposing a larger fraction of the atmosphere to particle precipitation (e.g., Nesse et al., 2023; Grandin et al., 2024). Some storms are also accompanied by solar proton events (SPEs). Proton-induced ionisation reaches deeper into the atmosphere than that caused by electrons, and produce ozone depletion extending into the upper stratosphere (e.g., Jia et al., 2020). During polar winter, long-lived NO_x further descends within the polar vortex and causes ozone depletion that can persist for weeks to months, commonly referred to as the indirect EPP effect (Randall, 2007; Damiani et al., 2016; Funke et al., 2017).

While the fundamental EPP-ozone pathways presented above are well established, large uncertainties remain in quantifying particle precipitation, the associated ionisation rates, and, ultimately, the resulting variations in key atmospheric constituents. Several studies have suggested that current ionisation-rate datasets may underestimate the atmospheric impact of electron precipitation, particularly during strong geomagnetic storms and their recovery phases (e.g., Smith-Johnsen et al., 2018; Mironova et al., 2019; Nesse Tyssøy et al., 2022). At the same time, increasing attention has been given to storm-induced MTS dynamical variability and transport processes (Jia et al., 2024; Liu et al., 2024; Liu, 2025; Sinnhuber et al., 2025; Zhang et al., 2025; Pedatella et al., 2026). In our previous studies, thermospheric ozone variations were found to be statistically associated with geomagnetic activity, suggesting that geomagnetic disturbances may modify coupling between atmospheric layers within the

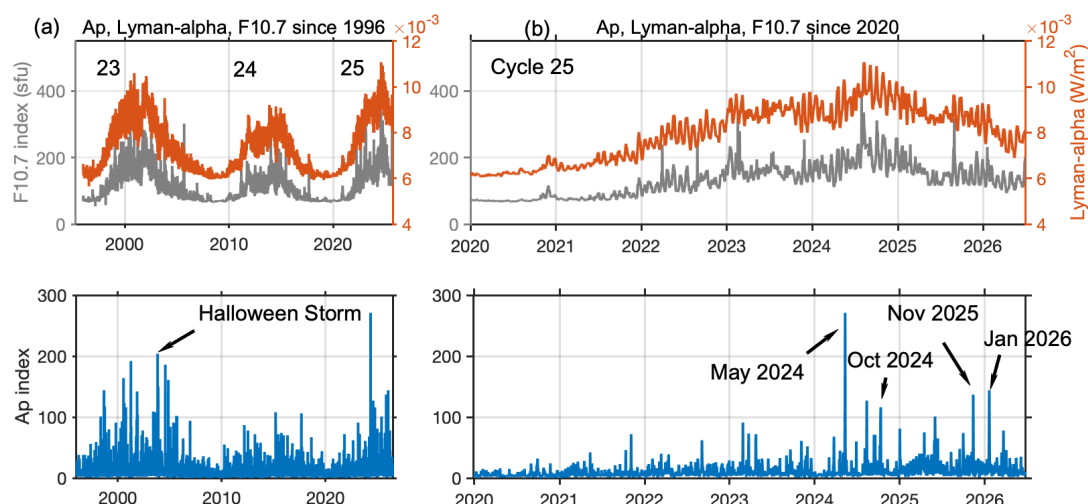


Figure 1. Solar and geomagnetic activity conditions during solar cycles 23–25. (a) Variations in the solar radio flux F10.7, Lyman- α irradiance, and geomagnetic activity index Ap throughout solar cycles 23, 24, and 25. (b) Detailed temporal evolution during solar cycle 25, with the four selected geomagnetic storm events indicated on the Ap time series.

MTS (Jia et al., 2024). Whether these statistically inferred responses can be identified during individual geomagnetic storms remains an open question.

The major geomagnetic storms during SC25 provide a valuable opportunity to examine ozone responses under a wide range of EEP and SPE forcing conditions. Using satellite observations and model simulations, we investigate four major storms occurring between 2024 and 2026 (May 2024, October 2024, November 2025, and January 2026; Figure 1b). We examine how ozone variability depends on storm characteristics, pre-storm space-weather conditions, atmospheric dynamics, and the dominant source of particle precipitation. Particular attention is given to ozone responses in the mesosphere, lower thermosphere, and stratosphere, as well as to the relative contributions of SPEs and EEP.

In addition, we investigate whether the observed ozone response during the May 2024 superstorm contains information about the precipitating electron spectrum. This exploratory analysis serves as a proof-of-concept study linking atmospheric ozone loss to particle-induced ionisation and examining whether neutral atmospheric observations can provide additional constraints on electron precipitation during extreme geomagnetic storms.

2 Data and method

2.1 Data

Satellite ozone observation



Microwave Limb Sounder (MLS) and Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) both provide long-term ozone observations spanning the MTS (Waters et al., 2006; Russell et al., 1999; Rong et al., 2009; Schwartz et al., 2026). To ensure sufficient nighttime measurements and improve the comparability of the results across events, MLS observations were used in this study instead of SABER data, as the SABER yaw cycle substantially affects nighttime data coverage in the polar regions during some of the selected event periods. The MLS instrument onboard EOS Aura satellite observes the thermal microwave emissions from the limb of the atmosphere, providing ozone volume mixing ratios from the radiance measurements near 240 GHz. This study utilises MLS v6 ozone data, with useful vertical range from 261 hPa to 0.001 hPa (~ 10 km to 95 km) (Livesey et al., 2026). Nighttime ozone is selected based on a solar zenith angle greater than 100° to ensure the atmosphere is in darkness from the ground to over 100 km. Subsequently, the data is processed to daily zonal mean at 55 pressure levels from 84°S – 84°N with a 4° interval. The analysis covers October 2004 to February 2026.

MEPED Electron fluxes

We consider the electron fluxes from the Medium Energy Proton and Electron Detector (MEPED) on board NOAA Polar Orbiting Environmental Satellites (NOAA/POES) and EUMETSAT MetOp satellites (Evans and Greer, 2004) during the four geomagnetic storms. MEPED includes a set of solid-state detectors targeting electrons and protons of energies greater than ~ 40 keV, placed in two telescopes with viewing directions roughly perpendicular to each other and named 0° and 90° telescopes. In this study, we consider the electron data from the 0° telescope, which in the polar cap gives an approximate estimate of the precipitating particle fluxes – although more accurate estimates can be obtained by combining the measurements from both telescopes, see Nesse Tyssøy et al. (2016) for details. The energetic electron fluxes are provided in three energy channels: >40 keV, >130 keV, and >287 keV.

GOES proton fluxes

As an indicator for the precipitating proton fluxes we used Geostationary Operational Environmental Satellite (GOES) Solar and Galactic Proton Sensor Level-2 flux data (Kress et al., 2018). The data for the four events are obtained from GOES-18. The integral proton fluxes were calculated for the west-facing sensor by integrating a piecewise powerlaw fitted to the differential flux data for the lower-energy channels and adding the final integral channel (>500 MeV) to the result. The effective energies for the differential flux channels were estimated with an iterative method described in Kress et al. (2021).

SD-WACCM-D

We used the Whole Atmosphere Community Climate Model version 6 (WACCM6) which is the atmospheric component of the Community Earth System Model version 2 (CESM2). WACCM6 is a state-of-the-art chemistry-climate model that extends from the surface to approximately 140 km altitude and includes comprehensive representation of middle and upper atmospheric chemistry (Gettelman et al., 2019). The model has a horizontal resolution of 0.9° latitude $\times$ 1.25° longitude and 88 vertical levels. For this study, WACCM6 was configured in the specified-dynamics (SD) mode, in which the model winds and temperatures below 50 km are constrained by the Modern-Era Retrospective analysis for Research and Applications (MERRA-2) reanalysis data (Molod et al., 2015). This approach provides meteorological conditions that are consistent with observations and limits the influence of model-generated dynamical variability on the simulated chemical response. In this work, we apply



also the lower-ionospheric (D-region) chemistry scheme, which accounts for ion–neutral processes, including negative-ion and cluster-ion chemistry (Verronen et al., 2016).

SIC model

The Sodankylä Ion and Neutral Chemistry (SIC) model is a detailed one-dimensional (1D) ion and neutral chemistry model designed for ionospheric D-region studies (Verronen et al., 2005; Turunen et al., 2009). The model calculates the time-dependent number densities of 72 ionic species (comprising 43 positive and 29 negative ions) and 34 neutral species (including 16 minor species, such as HO_x , NO_x , O_x) across an altitude range of 20 to 150 km with a resolution of 1 km. The SIC model couples middle atmospheric ion and neutral chemistry by simulating atmospheric ionisation driven by solar radiation and EPP—such as solar proton events, auroral electron precipitation, and galactic cosmic rays. SIC includes molecular and eddy diffusion, which can be switched on or off, but no other atmospheric transport processes are included. In this study, the SIC model version 8 (Turunen et al., 2016) is used to investigate the ozone response to MEE at mesospheric altitudes. The chemistry component of this version remains identical to that of the previous version detailed by Verronen et al. 2005.

F10.7, Lyman- α and Ap index

The daily solar radio flux density at 10.7 cm, i.e., the F10.7 index, is employed to characterise variations in solar cycle radiance. F10.7 is expressed in solar flux units (sfu), where $1 \text{ sfu} = 10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}$. Lyman- α is used as a proxy for solar ultraviolet (UV) forcing related to MTS photochemistry (Machol et al., 2019), including the photolysis of O_2 and of H_2O , which influences the abundances of atomic oxygen and HO_x radicals, and eventually ozone (Brasseur and Solomon, 2005). It is presented together with F10.7 as an indicator of solar irradiance variability in the MTS background state.

To quantify the extent of EPP entering the atmosphere, we use the geomagnetic activity daily index Ap. The daily Ap index, ranging from 0–400, is derived from the three-hourly Ap planetary index. The Ap index predominantly reflects electrons, encompassing both auroral electrons (energy $< 10 \text{ keV}$) and MEE. Ap is established as a reliable indicator of EPP, and has been commonly employed to investigate the effects of EPP on the atmosphere (e.g., Seppälä et al., 2007, 2009; Damiani et al., 2016; Asikainen et al., 2020; Crack et al., 2025). It is thus also used as a basis for parameterising electron-induced ionisation rates in climate-model simulations (van de Kamp et al., 2026).

2.2 Research method

MLS ozone processing

Figure 2 shows an example of our data processing steps for different study purposes. Figure 2a presents the MLS ozone time series at different pressure levels, averaged over latitudes of $60\text{--}84^\circ$ in the polar region. For the May 2024 event, the Southern Hemisphere was selected as the target region to ensure adequate nighttime data coverage. The color shading and the white contours represent the observed ozone concentration, expressed in parts per million by volume (ppmv). The black contour lines represent the corresponding daily climatological conditions for May, derived from the MLS record over the period 2004–2026. The red dashed line marks the onset of the major geomagnetic storm.

The ‘direct ozone anomalies’ are defined as the difference between the observed ozone values and the corresponding daily climatological values, and is shown in Figure 2b. White dots indicate regions where the ozone anomaly is statistically significant

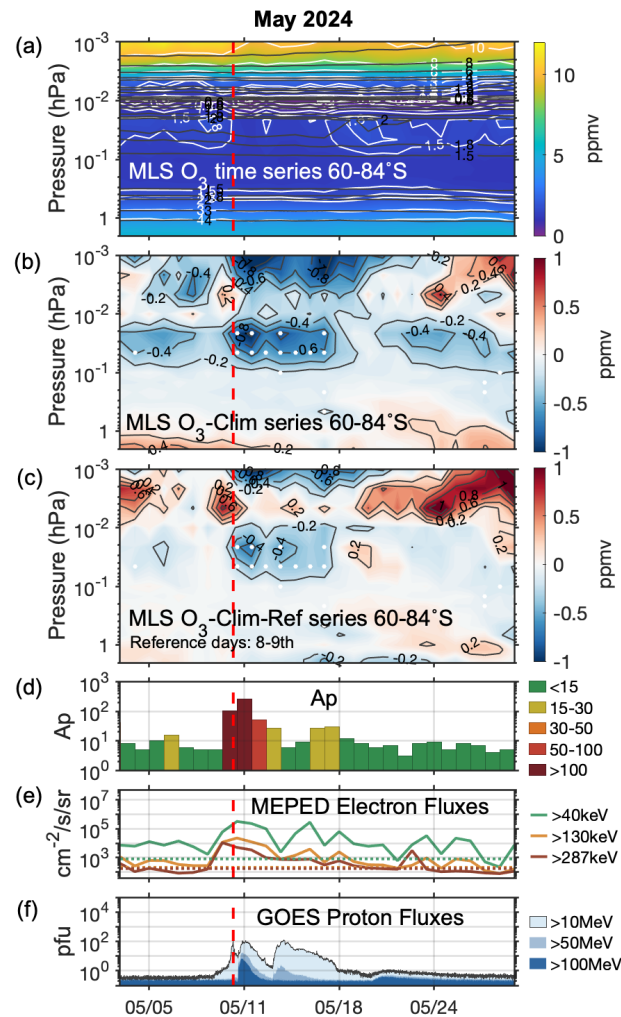


Figure 2. Winter polar zonal-mean daily nighttime ozone variations during the May 2024 geomagnetic storm event and the corresponding space weather conditions. (a–c) Ozone variations derived from MLS observations along pressure levels. (a) Observed ozone time series, with color shading and white contours representing ozone values, and black contours indicating the corresponding daily climatological ozone distribution. (b) Ozone anomalies obtained by removing the daily climatological mean. Statistically significant anomalies at the 95% confidence level are marked by white dots. (c) Ozone anomalies after removing both the daily climatological mean and the ozone variation on the reference days. (d–f) Associated space weather conditions: (d) Daily Ap geomagnetic activity index; (e) Daily integral MEPED electron flux derived from the 0° telescope over the geomagnetic latitude range $-80^\circ < GLAT < -65^\circ$, with dotted lines indicating quiet-time flux levels for different energy channels; and (f) integral proton flux derived from GOES measurements.



at approximately 95% confidence level, based on the two standard deviations of the ozone changes for the corresponding day.

135 This ozone anomaly represents the departure of the observed ozone concentration from the climatological background state, obtained by averaging observations over the full MLS record. We also performed sensitivity tests to assess the influence of long-term trend corrections and found that long-term ozone trends have a negligible impact on the anomaly patterns presented here (not shown). This approach highlights the EPP-related ozone response particularly well in the mesosphere, where ozone changes associated with space weather forcing can be larger than those arising from atmospheric dynamical variability. In contrast, the results are less informative in the stratosphere and lower thermosphere, where ozone variability is more strongly influenced by the prevailing atmospheric dynamical conditions. Consequently, the 'direct ozone anomaly' in these regions reflects the combined effects of external forcing and atmospheric dynamics, and it is more challenging to isolate the contribution of space weather forcing alone.

To best isolate the ozone response to the major geomagnetic storms, we applied a background correction to the results shown in Figure 2b, whereby the the mean ozone value from a set of reference days before each storm were subtracted from the corresponding values during and after the event. The reference days were selected based on the electron and proton fluxes and the Ap index, and were defined as the quietest space weather days within the 10-day period before the onset of each major storm. At least two reference days were identified for each event and used to define the background state. This 'correction' is expected to minimize the influence of interannual differences in the atmospheric dynamical background and solar irradiance conditions. However, as a consequence, any EPP-induced ozone anomalies that are already present before the onset of the targeted storm are removed as well. The resulting ozone anomalies are called the 'additional ozone anomalies' induced by the major geomagnetic storms and are shown in Figure 2c. For mesospheric studies, outside periods of rapid seasonal ozone variability, one can skip the "direct ozone anomaly" step and use the ozone values measured on the reference day directly as the background state to isolate the short-term ozone response to geomagnetic storms. The correction method applied here was specifically developed to better isolate and monitor the lower-thermospheric response. Even so, we emphasize that, owing to the rapidly varying dynamical conditions, interpretation of the additional ozone anomalies should primarily focus on the first 7 days following storm onset. Beyond this period, dynamical variability may become comparable to, or even exceed, the storm-induced ozone response, particularly in the lower thermosphere and stratosphere.

Many major geomagnetic storms are also associated with SPEs (Figure 2f), which may contribute to mesospheric ozone variability. Based on previous studies (e.g. Jia et al., 2020; Kalakoski et al., 2020), a practical rule of thumb can be used to ignore the effects of relatively weak SPEs, typically those with proton fluxes below approximately 100–400 pfu, on mesospheric ozone. For larger SPEs, however, the effect cannot be ignored, and the contributions of storm-induced EEP and SPE-induced precipitation cannot be reliably separated from observations alone. Quantifying their respective contributions requires dedicated atmospheric model simulations. In our paper, WACCM-D with specified dynamics is applied for this purpose.

165 **WACCM-D experiment setting and CMIP7 ionisation rates**

Considering the particle forcing, WACCM can readily use data recommended by the Coupled Model Intercomparison Project (CMIP, e.g. Phase 6, Matthes et al., 2017). The latest available dataset is CMIP Phase 7 (CMIP7) historical forcing Version 4.6¹.

¹ www.solarisheppa.kit.edu, accessed in August, 2026



However, this CMIP7 dataset currently extends until 2023 only. Therefore, we extended the forcing data until March 2026 using the same tools and methods that were used to produce the official CMIP7 data. The lower energy (auroral) electron forcing is calculated in WACCM with the parameterised auroral oval model of Roble and Ridley (1987), driven by the daily Kp index. Auroral ionisation is computed assuming a Maxwellian energy distribution with a characteristic energy of 2 keV. MEE forcing is calculated using the electron flux model by van de Kamp et al. (2026) and the atmospheric ionisation rate calculation method by Fang et al. (2010). The particle input to in CMIP solar forcing also includes omnipresent slowly variable Galactic Cosmic Rays (GCR) and SPEs. For GCRs the methodology remains unchanged from CMIP6 to CMIP7 (see Matthes et al., 2017), the values of the solar modulation potential (Usoskin et al., 2017) were taken from the Oulu Cosmic Ray group website². For SPEs, we mainly used data from the Solar and Galactic Proton Sensor (SGPS), an integral part of the Space Environment In-Situ Suite (SEISS) onboard the GOES-R series satellites³. We applied procedures similar to the methodology of Raukunen et al. (2022) to identify SPE periods and reconstruct omnidirectional differential solar proton fluxes in the energy range 1–500 MeV. For rare but powerful high-energy SPEs, we supplemented satellite data with the data from the neutron monitor network, following the methodology described in Koldobskiy et al. (2021). The resulting differential fluxes were coupled with the Oulu cosmic-ray atmospheric ionization model (Usoskin et al., 2024) to produce daily atmospheric ionisation profiles induced by SPEs. The treatment of the geomagnetic cutoff for both GCRs and SEPs did not change in the CMIP7 update and follows CMIP6 procedure (Matthes et al., 2017).

The simulations covered the period from January 2021 to February 2026, and three experiments were carried out to isolate the effects of the different particle forcings. The first was a reference simulation (REF) in which both MEE and SPEs forcing were switched off, providing a baseline atmospheric state. The second simulation included both MEE and SPEs forcing, hereafter referred to as the EPP simulation, to represent the combined effects of energetic-particle precipitation. The third simulation included MEE forcing only, allowing the atmospheric response to MEE precipitation to be separated from SPEs. GCR and auroral forcing were switched on in all three simulations.

190 Space weather condition data processing

The space weather condition data are Ap index (Figure 2d), MEPED electron flux (Figure 2e), and GOES proton flux (Figure 2f). We aim to use these data merely as an approximate proxy for energetic electron and proton precipitation in the polar cap during the geomagnetic storms. Given that, for MEPED electron fluxes we do not perform any correction for proton contamination as has been done in some past studies (e.g. Lam et al., 2010; Sandanger et al., 2015; Nesse Tyssøy et al., 2016; Ødegaard et al., 2016). For each geomagnetic storm, we retrieve the processed Level-1b MEPED data from NOAA's National Centers for Environmental Information (NCEI) database. The available satellites providing MEPED measurements during those storms are NOAA-15, NOAA-18, NOAA-19, MetOp-01 and MetOp-03. Beyond June 2025, only the two MetOp satellites have been in operation. We calculate the daily average of the 0°–telescope electron flux in each channel by combining the measurements from all available satellites, within the northern-hemisphere or southern-hemisphere (depending on the season when the storm occurred) polar cap. For this specific purpose, we define the polar cap as the region located between

²<https://cosmicrays.oulu.fi/phi/phi.html>

³<https://www.nesdis.noaa.gov/our-satellites/currently-flying/goes-east-west/goes-r-series-spacecraft-instruments>

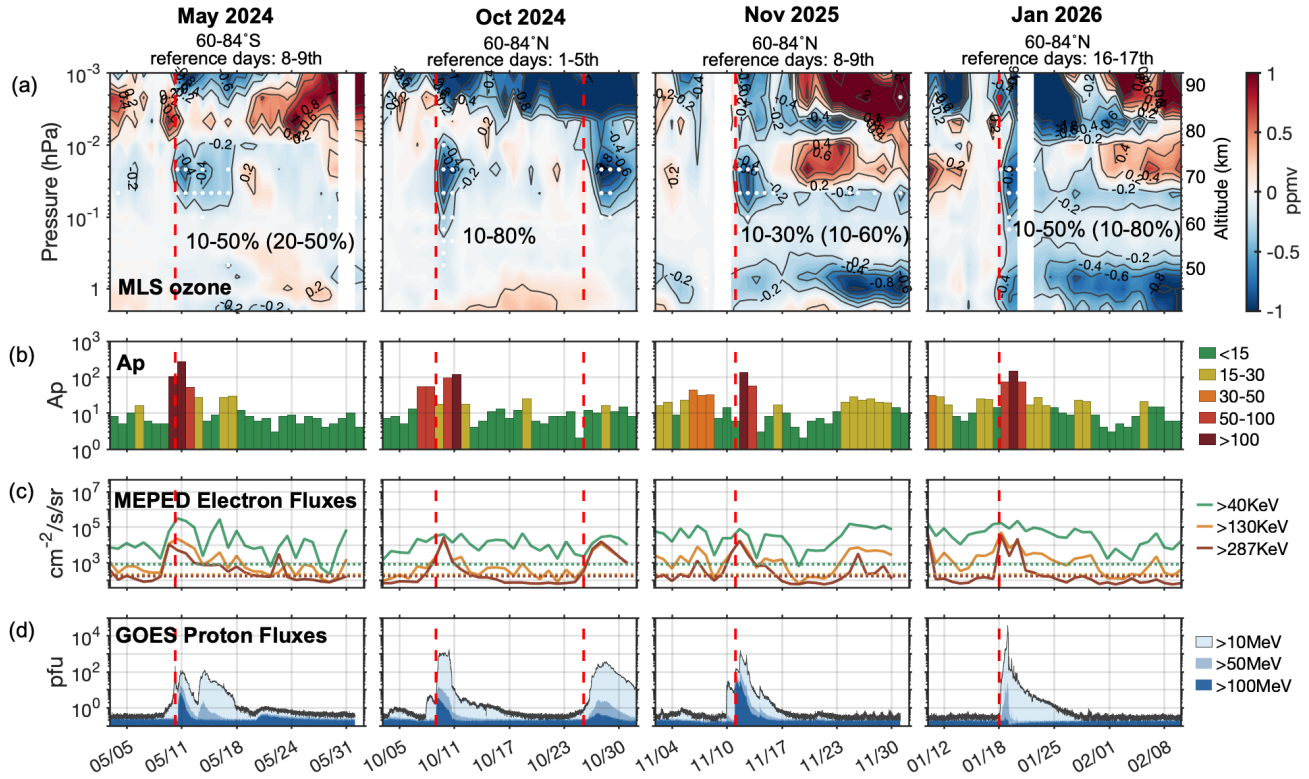


Figure 3. Same as Fig. 2(c–f), but for the four selected geomagnetic storm events and their corresponding winter polar regions.

65° and 80° geographic latitude, in a given hemisphere. The obtained daily, polar-cap-averaged fluxes of electrons are given in units of $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$.

To compare the electron fluxes during the storms with quiet-time values, we select the four quietest days in terms of Kp index in spring 2024 (16–17 March 2024) and in spring 2025 (24–25 April 2025), during which $K_p \leq 1$. We calculate quiet-time
205 0°–telescope energetic electron fluxes as the average of the daily, polar-cap-averaged fluxes over those four days, and present them as dotted lines in Figure 2e. Note that the quiet-time levels of the >130 keV and >287 keV electron fluxes almost overlap.

3 Results and discussions

3.1 Polar-averaged ozone anomalies during individual major geomagnetic storms

Figure 3 presents the storm-induced additional nighttime ozone anomalies associated with the four selected major geomagnetic
210 storms during SC25 (Figure 3a) and the corresponding space weather conditions (Figure 3b–d). These ‘additional’ ozone anomalies were calculated following the same procedure used for Figure 2c (Sect. 2.2), with the aim of better isolating the ozone response attributable to space weather forcing during the major geomagnetic storms. The contours and color shading



represent the isolated ozone concentration changes in ppmv. In some cases, gaps appear in ozone time series because the corresponding days exhibit unusually low global value and are therefore considered unreliable for analysis. As emphasized in the Methods section, we recommend focusing the interpretation on the period from storm onset to 7 days afterward, when the correction method is expected to be most robust. The unbracketed percentage values marked next to the storm onsets (red dashed lines) are the range of isolated relative ozone changes in the mesosphere at $\sim 60\text{--}80$ km ($0.2\text{--}0.01$ hPa) with ozone depletion exceeding 0.2 ppmv. They are calculated as the 'additional ozone anomalies' divided by the corresponding climatological ozone values and multiplied by 100. For the four selected events, peak ozone depletions of approximately 50%, 80%, 30%, and 50%, respectively, were observed. The percentage values in brackets represent the corresponding relative ozone changes calculated in the same manner, but using the 'direct ozone anomalies', i.e., without applying the reference-day correction. The 'direct ozone anomalies' results are only presented later (Figures 5a) together with the model results to avoid figure repetition. The differences of the two groups of percentage values indicate that substantial ozone depletion of approximately 30% had already occurred prior to the November 2025 and January 2026 events.

The pre-storm conditions are also reflected in the Ap index (Figure 3b) and the MEPED electron fluxes (Figure 3c), both of which show enhanced activity prior to all four events. At altitudes of 60–80 km, electrons with energies above 130 keV are expected to directly contribute to atmospheric ionisation and subsequent ozone depletion. Compared with the other events, the electron fluxes above 130 keV prior to the November 2025 and January 2026 events were approximately 1–2 orders of magnitude higher than the quiet-time levels. These elevated MEE fluxes are very likely to have contributed substantially to the approximately 30% pre-storm ozone depletion observed before these events, although part of the anomaly may also be attributable to year-specific dynamical conditions that differ from the climatological mean. In contrast, the October 2024 event exhibited relatively clean pre-storm mesospheric conditions when the reference period was defined as 1–5 October. The famous May 2024 event showed about 10% pre-storm ozone anomaly when 8–9 May were used as reference days. We will further discuss the causes of the pre-storm conditions and ozone anomalies associated with each event in Sect. 3.3.

It is also striking that the electron fluxes above 40 keV remained elevated for most of the event months, typically by approximately 1–2 orders of magnitude relative to quiet-time levels. Electrons in this energy range predominantly deposit their energy in the lower thermosphere, where ionisation enhancements are expected to increase the production of odd nitrogen, particularly nitric oxide (NO). Observational evidence for NO enhancement associated with electrons within this energy range has been well studied (e.g., Barth et al., 2001; Sheese et al., 2011; Sinnhuber et al., 2011). Enhanced NO can be transported downward into the mesosphere through MTS coupling during the polar winter (e.g., Smith-Johnsen et al., 2018; Liu, 2025), and cause additional mesospheric ozone depletion all over the examined time periods.

Nevertheless, when considering only the additional (isolated) mesospheric ozone anomalies following the four major geomagnetic storms, clear differences emerge in their duration, vertical extent, and magnitude. The ozone depletion following the May 2024 superstorm persisted the longest, lasting for at least 7 days. The October 2024 event produced the deepest ozone depletion, extending into the upper stratosphere and resulting in the largest absolute ozone loss, although the depletion persisted for only about three days. The November 2025 and January 2026 events produced additional ozone anomalies of comparable magnitude. We stress that these results are derived from observations. As discussed in the Methods section, the



reported duration and magnitude of the isolated ozone anomalies become increasingly uncertain beyond approximately 7 days after storm onset, as the signal can be masked or modified by evolving atmospheric dynamics and other sources of natural variability. Therefore, while the observations provide valuable constraints on the timing and vertical structure of the ozone response, model simulations are required to more robustly assess its duration and magnitude. Such a comparison is presented in Sect. 3.3.

As shown in Figure 3d, all four selected major geomagnetic storms were accompanied by SPEs. The associated SPEs exhibited substantial differences in both duration and energy spectrum. At first glance, the close correspondence between the SPE characteristics and the isolated ozone anomalies in terms of their morphology and magnitude may suggest that the ozone responses are largely controlled by the SPEs. However, the relative contributions of SPEs and EEP to the observed ozone changes remain unclear. One clear reason for this uncertainty is that, as discussed in Sect. 2.2, proton fluxes below approximately 100 pfu, such as those observed during the May 2024 superstorm, are generally not expected to produce substantial mesospheric ozone depletion. This apparent inconsistency indicates that EEP may have played an important role in shaping the observed ozone response. The relative contributions of SPEs and EEP are therefore investigated further in the following subsections (Sects. 3.2 and 3.3).

One more feature that is beautifully illustrated in Figure 3a is the thermospheric ozone depletion associated with the geomagnetic storms. As discussed in Jia et al. (2024), enhanced NO in the lower thermosphere is not expected to produce a noticeable in situ ozone response, because nighttime thermospheric ozone is controlled primarily by reactions involving atomic hydrogen, oxygen and by temperature-dependent chemistry. In Jia et al. (2024), we showed that a depletion of the polar secondary ozone maximum associated with EPP can be identified statistically and is likely driven primarily by storm-induced temperature increases, with an additional contribution from the dynamical transport of atomic hydrogen and atomic oxygen. The negative ozone anomalies observed in the lower thermosphere in Figure 3a provide further evidence that a depletion of the secondary ozone maximum can occur during individual geomagnetic storms. Unfortunately, these anomalies are generally not statistically significant, likely because natural variability associated with atmospheric waves and circulation is large in this region (Yiğit and Medvedev, 2015; Li et al., 2018; Pedatella and Liu, 2018; Zhang et al., 2025). Nevertheless, the consistent occurrence of negative anomalies during all four events suggests that these features deserve closer examination.

3.2 Global view of ozone anomalies during individual major geomagnetic storms

Figure 4 presents the global distribution of direct ozone anomalies (observation minus climatology) on the day of peak mesospheric ozone loss following each of the four selected geomagnetic storm events, namely 12th May 2024, 10th October 2024, 13th November 2025, and 21th January 2026. For the four events examined here, the peak mesospheric ozone depletion occurs approximately one day after the peak of geomagnetic activity. This delay is consistent with particle-induced catalytic ozone-destruction processes, which require sunlight to maximise their effectiveness. The lower-thermospheric and mesospheric responses are shown in Figures 4a and 4b, respectively. Note that the color scales for the two parts are different. These results help assess whether the observed lower-thermospheric ozone depletion is spatially and temporally associated with the geomag-

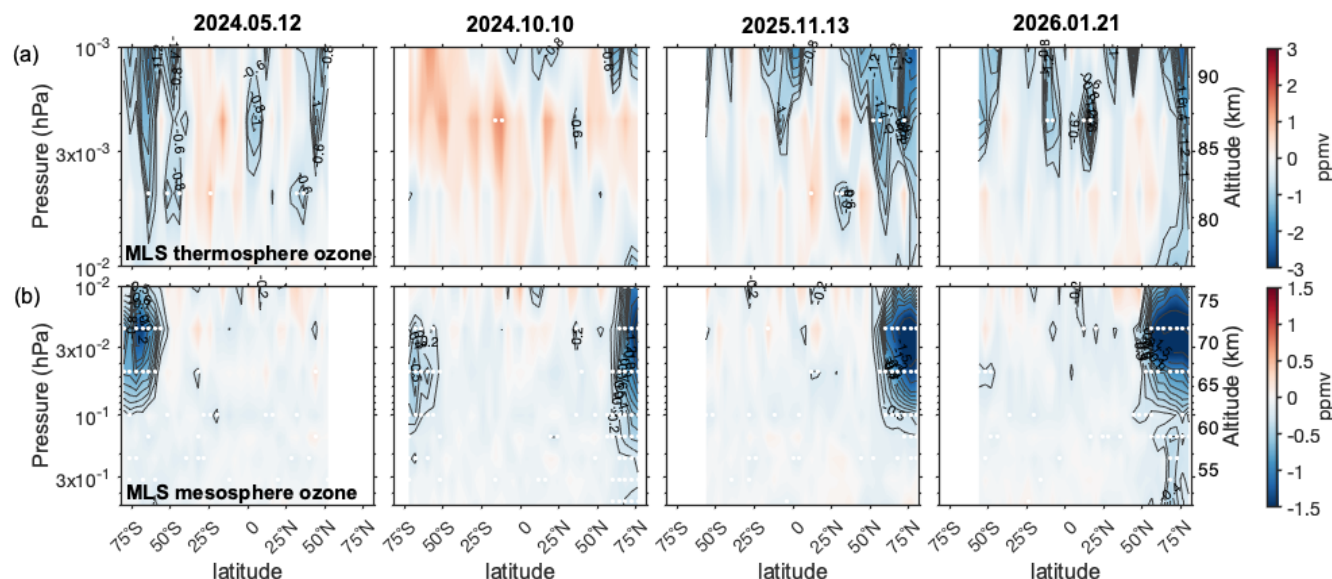


Figure 4. Global (geographic) distribution of nighttime ozone depletion (observation – climatology) as a function of pressure level and latitude at the day of maximum ozone loss following the four selected geomagnetic storm events (a) in the thermosphere and (b) in the mesosphere.

netic storms. They also provide clues to the relative contributions of SPEs and EEP, as the latitudinal extent and the depth of the ozone depletion can often be linked to the dominant source of particle precipitation.

Except for the October 2024 event, the other three cases showed good temporal and spatial consistency between the polar lower-thermospheric and mesospheric ozone responses. The peak ozone depletion occurred at similar latitudes in both regions, with the May 2024 event centered at approximately 60–75° latitude and the November 2025 and January 2026 events concentrated nearer the pole. This consistency indicates a close connection between the ozone responses in the two atmospheric regions.

In the mesosphere, clear differences in the latitudinal extent of ozone depletion can be observed among the events. Once again, the October 2024 event appears unique, exhibiting the narrowest latitudinal coverage, extending from the pole to approximately 60°. Since MLS has better nighttime data coverage in October, we are able to observe mesospheric ozone depletion in both polar regions for this event. The other events showed ozone depletion extending equatorward to about 50°, with the January 2026 event displaying the broadest latitudinal extent and reaching beyond 50°.

Based on Figure 4, several tentative conclusions can be drawn. First, the observed lower-thermospheric ozone depletion appears to be spatially and temporally associated with the geomagnetic storms, as evidenced by both Figure 4 and the temporal evolution shown in Figure 3a. Ideally, a more detailed investigation of lower-thermospheric ozone variability would make use of SABER atomic hydrogen and atomic oxygen data. However, as briefly discussed in the Data section, the SABER yaw



cycle results in insufficient nighttime data coverage in the polar regions during some of the selected event periods. We therefore cannot provide comparative analysis to establish this connection more conclusively. Nevertheless, our companion paper (Zhang et al., 2026) reports in detail the thermospheric variations in atomic hydrogen, atomic oxygen, and circulation during the May 2024 event using model simulations.

Second, Figure 4 provides some insight into the dominant particle forcing during each event. As well demonstrated in Wang et al. (2024), EEP and SPE produce characteristically different latitudinal ozone depletion patterns. EEP-driven ozone depletion tends to peak near the auroral oval, where electron precipitation is most intense, whereas SPE-induced ozone depletion typically extends across much of the polar region. Based on this distinction, the May 2024 event appears to have been more strongly influenced by EEP. In contrast, the October 2024 event appears more consistent with SPE-driven ozone depletion. The relatively weak lower-thermospheric ozone response suggests only a minor contribution from EEP-related thermospheric processes, while the deep vertical extent of the ozone depletion points to a larger role for proton-induced ionisation, which can reach the lower mesosphere and upper stratosphere. The November 2025 and January 2026 events appear to represent mixed SPE-EEP cases. Among them, the January 2026 event may have experienced a relatively larger SPE contribution, as indicated by its weaker lower-thermospheric ozone response and broader equatorward extent of mesospheric ozone depletion. The larger SPE fluxes observed during this event may have contributed to the more equatorward ozone depletion boundary (e.g. Heino and Partamies, 2020) compared with the November 2025 event.

In the next section, we use WACCM-D simulations to further investigate the relative contributions of SPEs and EEP and to evaluate whether the observed patterns are consistent with these proposed mechanisms.

3.3 Causes of the ozone anomalies via WACCM-D simulations

Figure 5 presents SD-WACCM-D simulations of EPP-induced ozone loss, together with the individual contributions from proton and MEE precipitation and their corresponding ionisation rate inputs. 'Direct ozone anomalies' (observation minus climatology) observed by MLS, calculated in the same way as in Figure 2b but for all selected events, are shown in Figure 5a for comparison with the model results in Figure 5b. The pressure/altitude range has been extended from 2 hPa/~41 km downward to 20 hPa/~25 km relative to previous figures to provide additional insight into ozone variability associated with atmospheric dynamics. In particular, ozone at 10 hPa/~30 km serves as a useful reference level, as in-situ space weather effect from the four storm events is not expected to appear much in ozone values at these altitudes (e.g., Damiani et al., 2016; Jia et al., 2020).

WACCM-D-simulated EPP-induced mesospheric ozone anomalies (Figure 5b) generally agree well with the observed direct ozone anomalies (Figure 5a), both in spatial extent and in magnitude. The comparison of observations and simulations suggests that the observed mesospheric ozone anomalies with clear and statistically significant signals are predominantly driven by space weather forcing. Ozone anomalies outside the regions of statistical significance may still contain a contribution from EPP, although this contribution is more difficult to isolate from background variability. For the November 2025 and January 2026 events, the pre-storm ozone depletion discussed in Sect. 3.1 is also reproduced by the model simulations, indicating that EPP-induced ozone depletion had already developed before the onset of the major geomagnetic storms. In contrast, the post-

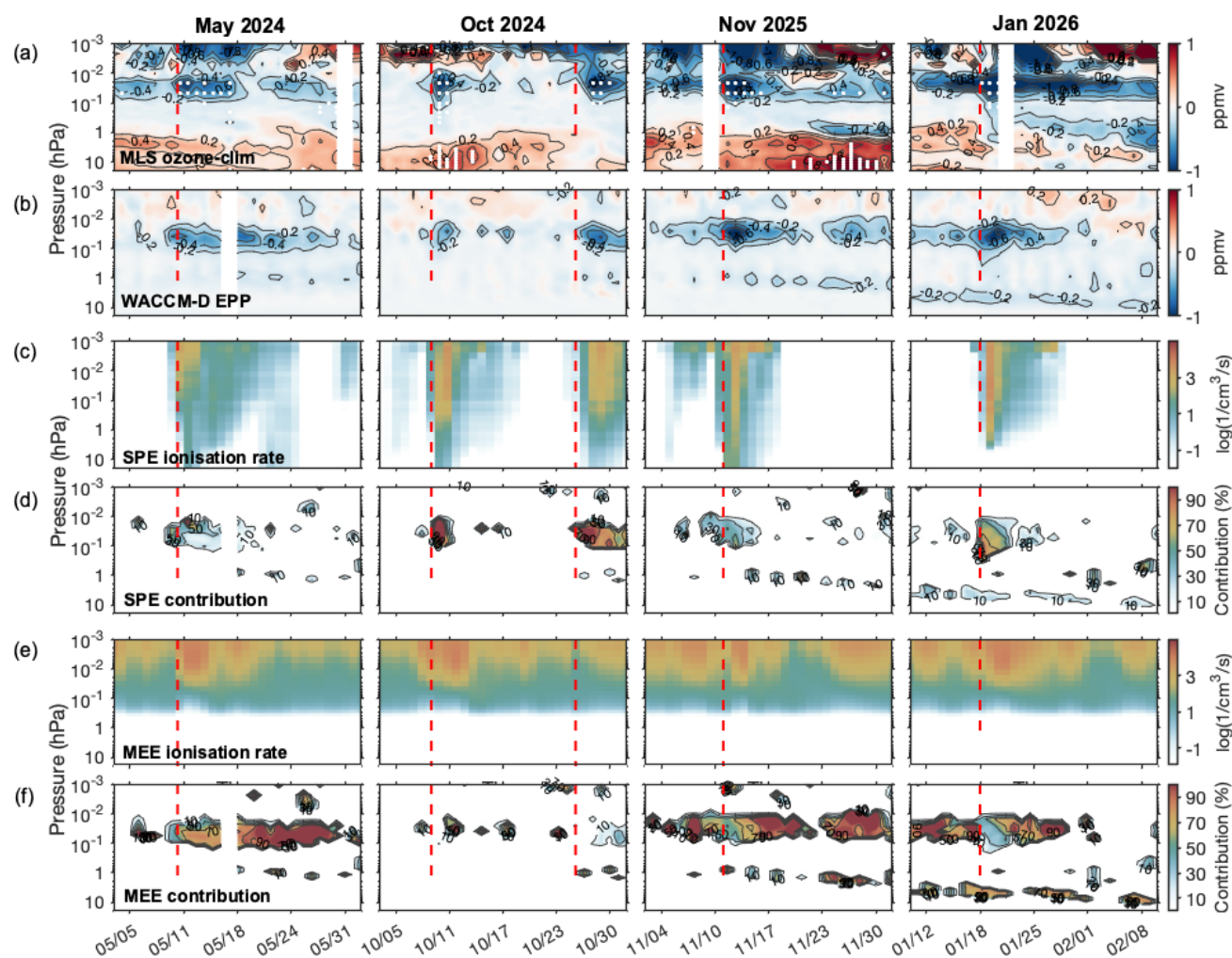


Figure 5. SD-WACCM-D simulated ozone loss caused by EPP and the contributions of proton and medium-energy electron (MEE) precipitation. (a) MLS-observed ozone anomalies (observed-climatology; same as Fig. 2b but for all selected events and extended pressure levels) for comparison with the model results. (b) Total EPP-induced ozone loss simulated by SD-WACCM-D. (c, e) CMIP7 ionisation rates of protons and MEE used as inputs for the simulations. (d, f) Fractional contributions of protons and MEE to the total EPP-induced ozone depletion simulated by SD-WACCM-D.



330 storm disagreement during the January 2026 event strongly suggests an additional contribution from atmospheric dynamics in the observations.

The simulations were also run such that the individual contributions of SPEs and MEE could be quantified through dedicated EPP and MEE-only simulations, as described in Section 2.2. Figure 5c shows the ionisation rates caused by SPEs alone, and Figure 5e that caused by MEE alone. Figures 5d and 5f show the ozone anomalies as resulting from WACCM-D with only SPE
335 and only MEE input, respectively. These partial anomalies are shown as percentages of their contribution to the total anomalies in Figure 5b. For clarity, these contributions are only shown whenever the total ozone anomaly exceeds 0.2 ppmv.

These contribution results largely confirm our interpretation of the dominant particle forcing during each storm period in the previous section. The May 2024 event is shown to be predominantly EEP-driven, with EEP accounting for more than 80% of the total mesospheric ozone loss. The October 2024 event is clearly SPE-dominated, with nearly all of the simulated ozone
340 loss attributable to proton-induced ionization. The November 2025 and January 2026 events represent mixed SPE-EEP cases. As hypothesized in the previous section, proton precipitation dominates the initial ozone response during the January 2026 event, accounting for approximately 70% of the ozone depletion immediately following storm onset, while EEP contributes the remaining ~30%. The November 2025 event exhibited a more balanced contribution from SPEs and EEP, with protons accounting for approximately 40% of the mesospheric ozone depletion and electrons contributing about 60%.

345 As explained in Section 2.2, the ionisation rate inputs presented here were developed for CMIP7 (Funke et al., 2024). Previous major SPEs studies have shown that SPE ionisation rates are generally well modelled, as evidenced by the good agreement between WACCM-D simulations and satellite observations of SPE-induced ozone depletion (Jia et al., 2020; Nilsen et al., 2021). On the other hand, MEE ionisation rates remain more uncertain. A common criticism of the CMIP6 MEE forcing is that it statistically underestimates the true level of electron precipitation and, consequently, the resulting atmospheric ionisation
350 (e.g., Smith-Johnsen et al., 2018; Mironova et al., 2019; Nesse Tyssøy et al., 2022). The CMIP7 MEE ionisation dataset used in this study represents an updated version of the CMIP6 product. CMIP7 MEE yields values that are generally closer to observations. Nevertheless, the contribution of electron precipitation to ozone depletion may be systematically underestimated, although this may not necessarily be the case for extreme events. In fact, one can see that the simulated mesospheric ozone loss (Figure 5b) is often slightly smaller than that observed by MLS (Figure 5a), which is consistent with a possible underestimation
355 of the electron forcing.

That said, mismatches between the simulations and observations can still be identified. These discrepancies are important not only for revealing the limitations of using the observations or the model separately, but also for providing additional insight into the mechanisms controlling the ozone response during major geomagnetic storms. In the following, we discuss several key differences between the model and observational results and consider their possible origins.

360 In the mesosphere, the ozone depletion discrepancies between observation and model simulation may arise from various sources, of which we identify four:

- It may reflect a model limitation, namely the underestimation of MEE ionisation rates discussed above, which would lead to an underestimation of the electron-driven ozone response.



- The model may not fully capture mesosphere-thermosphere coupling processes, resulting in insufficient downward transport of NO produced in the thermosphere and consequently an underestimation of mesospheric ozone depletion (Liu, 2025).
- It may result from the observational methodology itself. Because all four events occurred close to solar maximum, enhanced solar UV and Lyman- α radiation may have altered the background ozone state relative to the climatological conditions used as a reference, thereby introducing additional ozone anomalies into the observation-minus-climatology estimates.
- The observations may include ozone variations associated with disturbed atmospheric dynamics. Changes in stratospheric circulation and wave filtering during geomagnetically active periods can modify ozone transport and distribution, producing anomaly patches that are unrelated to direct particle forcing.

Evidence for the first and second sources may, as mentioned above, partly be reflected in the statistically generally larger mesospheric ozone depletion observed by MLS across all events. Evidence for the third source can be found in the stratospheric ozone values, which are generally higher than the climatological background throughout the analysed months. If this source were the dominant source of the model-observation disagreement, the stronger ozone depletion observed by MLS should largely disappear after the background correction method is applied. This is indeed observed for the May 2024 event (Figure 3a), particularly before and during the major storm period. However, when the pre-storm ozone depletion is caused by a combination of MEE forcing and the third source, as is likely the case for the November 2025 and January 2026 events, the correction method removes not only the background bias associated with the third source, but also part of the pre-storm ozone depletion arising from MEE precipitation. The effect of the correction thus becomes more difficult to demonstrate. As a result, the individual contributions of these two effects cannot be easily separated in the corrected ozone anomalies for the two pre-storm periods. In fact, even for the May 2024 event, we can not rule out the contributions from the first and second sources. Evidence for the fourth mechanism is particularly apparent during the October 2024 event. As this event appears to be largely SPE-driven, the simulated ozone depletion is expected to be relatively robust. Nevertheless, the satellite observations show stronger ozone depletion than the model simulations. At the same time, enhanced stratospheric ozone is observed during the storm period, suggesting that additional dynamical processes may have been operating and influencing the observed ozone response. A similar situation may also be present in the November 2025 event after 20 November. However, we cannot rule out the possibility that additional ozone-depleting substances, or changes in their transport and distribution, contributed to the observed stratospheric ozone anomalies.

Another, more obvious, discrepancy between observations and simulations occurs in the lower thermosphere. WACCM-D does not reproduce the secondary ozone depletion seen in the satellite observations. One could argue that this feature is not physically robust and may simply reflect observational variability. However, given its repeated occurrence across multiple events and its consistency with previous observational studies, we consider it more likely that the model fails to capture the processes responsible for the observed secondary ozone depletion. The simulations are performed under specified dynamical conditions up to 1 hPa, and some observed features above this level may therefore be influenced by atmospheric dynamical variability that is not fully represented in the model, as well as by uncertainties associated with internal variability in a single-



ensemble simulation. In addition, WACCM-D may not fully capture the storm-induced heating, expansion and circulation
400 response in the lower thermosphere (Lu et al., 2014; Wang et al., 2022; Liu et al., 2024), which could further contribute to the
mismatch between the simulations and observations.

In the stratosphere, the MLS ozone anomalies are heavily masked by the background conditions discussed above. The
model simulations, however, show distinct descending patches of ozone depletion at altitudes below 1 hPa. These features are
present from early winter onward and occur at progressively lower altitudes when transitioning from the early-winter case of
405 November 2025 to the deep-winter case of January 2026. MEE is the dominant source of these ozone depletions, accounting
for approximately 90% of the simulated anomalies. SPE forcing plays a minor role, contributing the remaining ~10%. These
features are consistent with the expected behavior of EPP's indirect effect on ozone associated with the downward transport of
EPP-produced NO_x , which penetrates to lower altitudes as winter progresses and is dominated by MEE forcing. It should be
noted again that the contribution analysis is only shown where the total ozone anomaly exceeds 0.2 ppmv. Consequently, the
410 apparent discontinuity between the mesospheric and stratospheric depletion features does not imply an absence of downward
transport. Rather, ozone concentrations between approximately 1 and 0.1 hPa are relatively low, such that the associated indirect
EPP ozone depletion often remains low and is therefore masked in the contribution panels.

3.4 One more thing: testbed experiment

The May 2024 superstorm appears to be a rather unique case, characterised by extreme geomagnetic disturbances and a meso-
415 spheric ozone response dominated by MEE precipitation. This allowed us to perform an interesting experiment to explore
whether the vertical structure of the observed ozone depletion can provide additional information about the precipitating elec-
tron spectrum.

Figure 6 presents results from this experiment. Our approach was straightforward. We first calculated the MLS-observed
polar ozone anomaly between 22:00 UTC on 10 May and 22:00 UTC on 11 May 2024, using ozone measurements averaged
420 over the 66–82°S latitude band. The resulting ozone change ratio is shown in Figure 6a. The SIC model provides a lookup table
shown in the color chart in Figure 6b, relating ionisation rates Q and altitude to corresponding ozone changes. Combining this
with the observed ozone anomaly, we derived the ionisation rate profile shown by the orange line in Figure 6b.

Assuming that the inferred ionisation was entirely produced by MEE precipitation, we then can compare the derived ionisa-
tion profile with the CMIP7 MEE ionisation rate shown in Figure 6c. Note that the CMIP7 MEE forcing is modelled on electron
425 precipitation measurements in only three energy channels, which energies effectively correspond to ionisations dominating at
three distinct altitudes. One of those altitudes is 67 km, indicated by the star symbol; the other two are higher than 80 km.
This means that the CMIP7 MEE forcing is based on observations only at these altitudes. In contrast, our experiment provides
ionisation rate estimates at six different altitudes. It is encouraging to see that two estimates agree well near the reference
altitude of approximately 67 km. Above this altitude, the CMIP7 ionisation rates tend to be substantially higher than those
430 inferred using SIC from the ozone observations, whereas below this altitude the CMIP7 ionisation rates are generally lower
than the SIC-derived values.

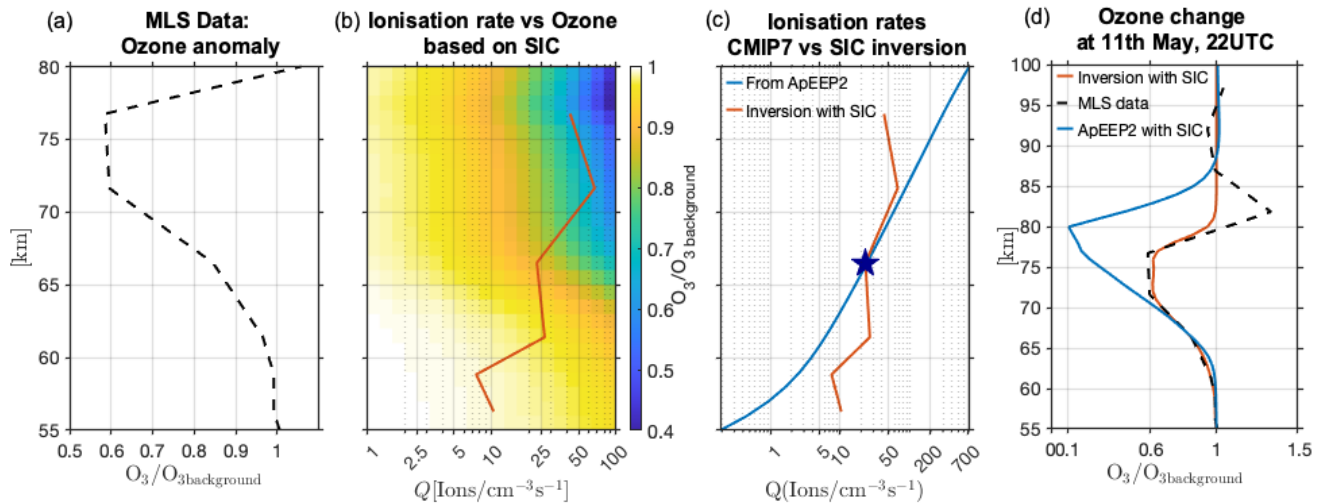


Figure 6. Retrieval of energetic electron precipitation (EEP) ionisation rates from May 2024 MLS-observed ozone anomalies using the SIC model as a testbed for evaluating the MEE ionisation rates prescribed in CMIP7 (ApEEP2). (a) MLS-observed ozone anomaly between 11 May and 10 May 2024 over 66–82°S. (b) SIC model look-up table showing the relationship between ionization rates and the corresponding ozone anomalies. The orange line indicates the ionisation rate required to reproduce the observed ozone anomaly in (a). (c) Comparison between the ionisation rate derived from the SIC model (orange) and the ApEEP2 ionisation rate used in CMIP7 (blue). (d) Ozone variations at 22:00 UTC on 11 May 2024: MLS observations (dashed black line), SIC simulation using the retrieved ionisation rate (orange line), and SIC simulation using the CMIP7 ionisation rate (blue line).

To assess the implications of these differences, we input both ionisation rate profiles back into the SIC model and compared the resulting ozone depletion with the MLS observations (Figure 6d). The dashed black line represents the MLS observations, the orange line shows the SIC simulation driven by the retrieved ionisation rates, and the blue line shows the SIC simulation using the CMIP7 ionisation rates. The analysis was extended to 100 km solely to illustrate the upper extent of MEE ionisation and the lower-thermospheric ozone response observed by MLS. The higher ionisation rates prescribed by CMIP7 at upper mesospheric altitudes produce excessive ozone depletion, reaching nearly 85% at 75 km compared with the observed value of approximately 40%. Conversely, the lower CMIP7 ionisation rates at 60–65 km result in weaker ozone depletion than observed. Although the ionisation-rate offsets above and below the reference altitude are of comparable magnitude, ozone at lower altitudes needs much more ionisation to yield a measureable change. Consequently, the corresponding disagreement in ozone depletion is much smaller at 60–65 km than in the upper mesosphere. Nevertheless, our results suggest that the CMIP7 MEE forcing underrepresents the high-energy portion of the MEE spectrum. It is worth noting here that the high-energy part of the MEE spectrum, the so-called relativistic electrons (>600 keV), is only partly included (up to 1 MeV) in the CMIP7 model (van de Kamp et al., 2026). Because these electrons primarily cause ionisation at altitudes around 60 km and below, the CMIP7



data are, to some extent, expected to underestimate ionisation at these altitudes. This was also pointed out by Nesse et al. (2026).

Although indirect and subject to considerable uncertainty, these estimates potentially contain additional information about the vertical distribution of the precipitating electrons and, consequently, provide a more detailed constraint on the electron energy spectrum than can be obtained from a single measurement point. We also do not expect the CMIP7 MEE ionisation rates to perform perfectly during such extreme events, as they were primarily developed to provide statistically robust forcing for climate model applications rather than to reproduce individual extreme precipitation episodes. The approach presented here, on the other hand, is unlikely to be suitable as a routine retrieval technique. Nevertheless, it demonstrates the potential value of combining neutral atmospheric observations with particle precipitation models to better characterize extreme electron precipitation events and to provide additional constraints on the associated electron energy spectrum.

4 Conclusions

1, SC 25 provided four major geomagnetic storm events with distinctly different combinations of MEE and SPE forcing: May 2024, October 2024, November 2025, and January 2026. This unique set of events offers a valuable opportunity to investigate short-term MTS ozone responses to geomagnetic storms under a wide range of space weather conditions. The four SC25 storms, particularly the May 2024 superstorm, remind us that major geomagnetic disturbances can lead to very different atmospheric ozone responses depending on the dominant particle population and the background state of the atmosphere.

2, By combining MLS observations with WACCM-D simulations, we show that the dominant particle forcing differs considerably among the four events. The May 2024 superstorm produced additional 10-50% mesospheric ozone depletion lasting for at least 7 days and was found to be largely EEP-driven, with EEP accounting for more than 80% of the modeled ozone loss. In contrast, the October 2024 event was primarily SPE-driven, with proton-induced ionization responsible for nearly all of the observed 10-80% ozone depletion. The November 2025 and January 2026 events represent mixed SPE-EEP cases, exhibiting total ozone losses of approximately 60% and 80%, respectively, but isolated major-storm-related ozone depletions of about 30% and 50%, with a stronger SPE contribution during the January 2026 event.

3, The results further suggest that lower-thermospheric ozone appears to respond to major geomagnetic storms. Negative ozone anomalies were identified in association with all four events and exhibited spatial characteristics broadly consistent with the mesospheric response. Although these features are not reproduced by WACCM-D and remain difficult to quantify using current observations, their repeated occurrence supports previous statistical studies linking geomagnetic activity to lower-thermospheric ozone variability. The lower-thermospheric response may also provide a useful first qualitative indication of the dominant particle forcing, helping to distinguish between SPE-dominated, EEP-dominated, and mixed events.

4, We show that satellite-based mesospheric ozone anomalies with clear and statistically significant signals, identified using our methodology, are predominantly driven by space weather forcing. The generally good agreement between MLS observations and WACCM-D simulations provides confidence in the attribution of the observed ozone responses, the methodology



used to isolate the space-weather signal, and the ability of current state-of-the-art models to reproduce the major characteristics of storm-time ozone variability.

5, Nevertheless, substantial uncertainties remain in the quantitative representation of EPP-induced chemical changes. The remaining disagreements between MLS and WACCM-D indicate that accurately representing particle forcing is only part of the challenge. Processes related to upper-atmospheric dynamics, vertical transport, and mesosphere-thermosphere coupling likely remain important sources of uncertainty. Continued satellite observations of both precipitating particle fluxes and key atmospheric chemical constituents remain crucial for constraining model forcing, improving process understanding, and monitoring future extreme space weather events.

6, Finally, an exploratory experiment using the May 2024 superstorm demonstrated that neutral atmospheric ozone observations can, in principle, provide information about the vertical distribution of electron precipitation. Although highly indirect and unsuitable as a routine retrieval technique, the experiment suggests that ozone-derived ionisation estimates can be used as an additional diagnostic of extreme space-weather forcing. Extreme geomagnetic storms like this may leave sufficient information in the neutral atmosphere to provide independent constraints on the precipitating electron population.

Code and data availability. MLS ozone data used in this study are publicly available at Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed: 19 August 2026, <https://doi.org/10.5067/Aura/MLS/DATA2516>. Daily geomagnetic activity Ap-index and daily solar flux F10.7-index are publicly available from the German Research Centre for Geosciences (GFZ) website (<https://kp.gfz-potsdam.de>). Lyman- α is publicly available from Laboratory for Atmospheric and Space Physics (LASP) (https://lasp.colorado.edu/lisird/data/composite_lyman_alpha). GOES-18 proton flux data is publicly available through GOES-R Series Level 2 Space Environment In Situ Suite (SEISS) Products (Kress et al., 2018). The level-1b MEPED data were retrieved from the NOAA/NCEI database at <https://www.ncei.noaa.gov/data/poses-metop-space-environment-monitor/access/> (last access: 2 Sep 2026).

Author contributions. JJ designed the study, carried out most of the data analysis, and wrote most of the manuscript. YO and PJE closely followed the progress of the study and provided suggestions throughout the research process. MES and PTV carried out the WACCM-D simulation and contributed text to Sect. 2. MES also provided the original figures of ionisation rates in Fig. 5. AK and NT carried out the SIC model simulation and electron spectrum retrieval presented in Sect. 3.4. AK also provided the original figures of Fig. 6 while NT contributed text to Sect. 2. MG carried out MEPED electron flux data calculations and contributed text to Sect. 2. S.Käki carried out GOES proton flux data calculations and contributed text to Sect. 2. MK provided the ApEEP model input used in WACCM-D and SIC simulations and contributed text to Sect. 3.3. S.Koldobskiy provided SPE ionisation rate input used in WACCM-D and contributed text to Sect. 2. All co-authors have read the manuscript and provided comments to improve it.

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