

An improved model of energetic electron precipitation providing a long-term ionization dataset for CMIP7

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Received 16 April 2026 / Accepted 7 September 2026

Abstract – Medium-energy electron precipitation (MEE; energies between about 30 keV and 1 MeV) in the upper atmosphere is a source of a chain of chemical reactions which ultimately affect temperature and circulation in the lower atmosphere, and is therefore a significant component to be taken into account in chemistry climate models. In this paper, a new electron precipitation model is presented, offering several upgrades and improvements over earlier versions. The model was developed using the electron flux observations of the Polar-orbiting Operational Environmental Satellites (POES) from 1998–2023. The electron content of the bounce loss cone was derived from both the 0-degree and 90-degree channels of the latest generation of the instrument onboard POES in combination with a theoretical model of pitch-angle diffusion. The data were corrected and calibrated for proton contamination and instrument sensitivity. The electron fluxes are modeled separately in three separate energy ranges (30–100, 100–300 and 300–1000 keV), with a 1-day time resolution, as functions of corrected geomagnetic latitude and of time series of the geomagnetic index *Ap*. In the model, the *Ap* index is integrated over a convolution function in time, to account for a latitude- and energy-dependent delay in response to geomagnetic disturbances. The energy spectrum between 30 and 1000 keV was constructed from the three modeled energy bins by fitting a two-section power-law model. The resulting energy-flux spectra are used to calculate atmospheric ionization rates, which provide the solar forcing from medium-energy electrons, to serve as input into long-term atmosphere and climate simulations.

Keywords: Electron precipitation / Mesosphere / Ionization / Geomagnetic activity / Modelling

1 Introduction

Solar-driven energetic particle precipitation plays a crucial role in shaping Earth's upper atmosphere. These particles are typically classified on the basis of their origin in near-Earth space and the depth at which they deposit energy in the atmosphere. Precipitating electrons are primarily energized through complex processes within the magnetosphere (Borovsky & Valdivia, 2018). In the plasma sheet, electrons commonly reach energies of up to 30 keV, leading to ionization in the lower thermosphere and upper mesosphere causing auroral emissions. Wave-particle interactions in the ring current – and more prominently in the radiation belts – can acceler-

ate electrons to several hundred keV or even into the MeV range. Upon entering the atmosphere, these high-energy electrons cause ionization throughout the mesosphere and penetrate as deep as the upper stratosphere (Nesse Tyssøy et al., 2022).

The ionization triggered by energetic particle precipitation (EPP) initiates a complex sequence of chemical reactions, enhancing the production of reactive species such as odd nitrogen (NO_x) and odd hydrogen (HO_x). These constituents engage in catalytic cycles that contribute to ozone depletion in the middle mesosphere and upper stratosphere (Sinnhuber et al., 2012). This depletion affects the radiative balance and can influence temperature, wave propagation, and atmospheric circulation patterns – linking energetic electron precipitation (EEP) to broader climate processes

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(Andersson et al., 2014; Salminen et al., 2024; Seppälä et al., 2025; Nesse et al., 2026).

Over the past decade, the importance of precipitating medium-energy electrons (MEE) (>30 keV) has gained increasing attention, particularly in the context of its potential impact on winter circulation patterns affecting the entire atmosphere. This has been addressed by the Coupled Model Intercomparison Project (CMIP)¹. CMIP is a project of the World Climate Research Program (WCRP)² providing climate projections to understand past, present and future climate changes. CMIP and its associated data infrastructure have become essential to the Intergovernmental Panel on Climate Change (IPCC)³ and other international and national climate assessments.

Phase 6 of CMIP (CMIP6) introduced a standardized EPP forcing dataset for use in high-top models (those extending above 60 km) (Matthes et al., 2017). In this dataset, the MEE ionization rates are driven by the geomagnetic index A_p . The modeled flux levels and geomagnetic latitude distribution are based on electron flux measurements from the Medium Energy Proton and Electron Detectors (MEPED) onboard the Polar-orbiting Operational Environmental Satellites (POES)⁴, covering the period from 2002 to 2012. As output, the model provides daily spectral parameters of precipitation, including the integrated electron flux above 30 keV and a power-law spectral gradient (van de Kamp et al., 2016). An atmospheric ionization dataset was then generated for the energy range of 30–1000 keV using a computationally efficient ionization scheme (excluding Bremsstrahlung contributions) as described by Fang et al. (2010), along with background atmospheric composition from the NRLMSISE-00 model⁵ (Picone et al., 2002).

The daily geomagnetic index A_p (Matzka et al., 2021), which the CMIP6 model uses as a proxy for MEE ionization, is the daily average of the 3-hourly global magnetic index K_p , after converting from logarithmic to linear scale. The index K_p is based on the disturbance levels in the horizontal magnetic field component observed at 13 selected, sub-auroral stations (between 44° and 60° northern or southern geomagnetic latitudes). A_p and K_p can be obtained from the data services page of GFZ Helmholtz Center for Geosciences⁶.

The integration of MEE into the CMIP6 solar forcing dataset represented a significant advancement toward a more comprehensive characterization of natural solar influences. However, this inclusion also sparked scientific

debate regarding the extent to which the approach accurately reflects actual energy flux levels (Clilverd et al., 2020; Mironova et al., 2019; Tyssøy et al., 2019; Nesse Tyssøy et al., 2022; Pettit et al., 2019; Sinnhuber et al., 2022).

The main concern was that the electron fluxes were derived solely from one (the vertical) detector on MEPED, which sees only a rather small portion of the total precipitating flux near the center of the bounce loss cone, thereby leading to a systematic underestimation of electron precipitation (Tyssøy et al., 2019; Pettit et al., 2019; Nesse Tyssøy et al., 2022). This is because the degree of pitch-angle anisotropy varies significantly with electron energy, geomagnetic latitude, and geomagnetic activity. MEE typically exhibits decreasing flux toward the center of the loss cone, which means that measurements from the vertical detector tend to underestimate the true flux of precipitating electrons (Nesse-Tyssøy et al., 2016).

Another concern is that studies on the nature of MEE have shown that the higher-energy tail (>300 keV) of the spectrum responds more slowly to geomagnetic disturbances than lower-energy electrons (30–300 keV) (Tyssøy et al., 2021; Salice et al., 2023; Nesse & Salice, 2024; Salice et al., 2024). This results in a low bias in ionization rates below ~ 70 km (Nesse Tyssøy et al., 2022; Sinnhuber et al., 2022). The model, based on data from 2002–2012 – a period characterized by relatively weak EEP forcing – also raised concerns about its ability to represent flux levels from earlier, more active solar cycles (Tyssøy et al., 2019). Furthermore, questions were raised about how well the model captures both short-term and long-term variability. It is also significant that the model did not distinguish between the hemispheres, even though significant long-term differences have been observed between the hemispheres, both in MEE precipitation and the resulting ozone depletion (e.g. Andersson et al., 2014). These differences are likely caused by the hemispheric asymmetries in the Earth’s internal magnetic field.

In preparation for defining solar forcing in the next phase of CMIP, CMIP7 (Dunne et al., 2025), a new reconstruction of MEE fluxes has been recommended (Funke et al., 2024). This updated reconstruction extends the dataset to cover the period from 1998 to 2023 and employs physics-based methods to estimate loss cone fluxes. It introduces a lagged or accumulated response model, utilizing a piecewise power-law energy spectrum to extract fluxes in the 30–1000 keV range. Importantly, it provides separate representations for the Southern and Northern Hemisphere fluxes. The outcome of this community-wide effort is presented in this paper and forms the foundation for the updated MEE ionization rates recommended for solar forcing in CMIP7.

2 Data

2.1 POES satellites and MEPED instrument

The reconstruction of MEE particle forcing presented here is based on the uniquely long series of energetic

¹ CMIP – Coupled Model Intercomparison Project; <https://wcrp-cmip.org/>

² WCRP; <https://www.wcrp-climate.org/>

³ IPCC; <https://www.ipcc.ch/>

⁴ Polar Operational Environmental Satellite (POES); <https://www.nasa.gov/goddard/earth-science-projects-division/poes/>

⁵ NASA: Naval Research Laboratory, Mass Spectrometer and Incoherent Scatter model up to Exosphere (NRLMSISE); <https://ccmc.gsfc.nasa.gov/models/NRLMSIS-00/>

⁶ Helmholtz-Zentrum für Geoforschung (GFZ) Data Services; <https://doi.org/10.5880/Kp.0001>

particle measurements made by the low-altitude POES satellites since 1979. POES satellites orbit the Earth at an altitude of about 850 km, in high-inclination sun-synchronous orbital configurations that change very slowly over several years. The satellites include a SEM (Space Environment Monitor) instrument package for measuring energetic protons and electrons. We processed data from the following POES satellites from the National Oceanic and Atmospheric Administration (NOAA) and METeorological OPERational satellites (METOP): NOAA-6, NOAA-7, NOAA-8, NOAA-10, NOAA-12, NOAA-15, NOAA-16, NOAA-17, NOAA-18, METOP-2, NOAA-19, and METOP-1.

The satellites up to NOAA-12 had the SEM-1 version of the instrument package, while onwards from NOAA-15 (launched in mid-1998), the satellites carry a modified version called SEM-2. The SEM-1 and SEM-2 versions of the MEPED electron detector have some significant differences in instrument construction, as well as detector orientation, which lead to differences in the preprocessing procedures. The earlier CMIP6 reconstruction of energetic particle forcing was based on SEM-2 data. In order to maintain better comparability to the earlier version, in this work we also concentrate on the data measured by SEM-2, but extend the measurement period, spanning from 1998 to present. More detailed information about the SEM-2 instrument and its use is given by [Evans & Greer \(2000\)](#); [Rodger et al. \(2010\)](#); [Green \(2013\)](#).

While detecting energetic electrons, the MEPED detectors are also sensitive to energetic protons. We use here data which have been corrected and calibrated for proton contamination as well as non-ideal electron instrument sensitivity, based on the raw MEPED data processing pipeline developed at the University of Oulu, as described by [Asikainen & Mursula \(2011, 2013\)](#); [Asikainen et al. \(2012\)](#). Note that these procedures are different compared to the NOAA processing methodology described by [Green \(2013\)](#). The main differences are (1) the correction of proton data for instrument degradation and correction of electron data for proton contamination (with the corrected proton data) and (2) the use of different instrument sensitivity curves for SEM-1 and SEM-2 versions of the instrument, as estimated by [Asikainen & Mursula \(2013\)](#). The entire data processing used here is therefore an upgrade to the procedure used to produce the data on which the CMIP6 model was based.

2.2 Estimating the precipitating electron flux

The MEPED electron instrument measures electrons in three integral energy channels: E1 (>30 keV), E2 (>100 keV) and E3 (>300 keV). Estimating the amount of electrons that are within the local loss cone (i.e., which precipitate into the atmosphere) with POES/MEPED is challenging because the MEPED instrument only includes two orthogonal telescopes with rather large 30° field of view. At high geomagnetic latitudes, where most of the

precipitation occurs, the local loss cone at satellite altitude is 55°–60° wide depending on geomagnetic latitude. Thus, while the local vertical (0°) telescope measures electrons inside the loss cone at high geomagnetic latitudes, a large part, even the majority, of the loss cone contents are typically missed. In contrast, the local horizontal (90°) telescope measures electrons mostly outside the loss cone, although some of these particles are precipitating.

The previous (CMIP6) version of the MEE reconstruction assumed a uniform population in the bounce loss cone, i.e., the average flux (per solid angle) as measured by the 0° telescope is the same as the flux over the whole bounce loss cone ([van de Kamp et al., 2016](#)). This assumption is valid only during strong disturbances, when pitch-angle diffusion is strong. During weaker disturbances, weak diffusion keeps the electrons closer to the edge of the bounce loss cone and away from the 0° detector, causing an underestimation of these fluxes.

Perhaps the most advanced estimate of precipitation based on the MEPED measurements was suggested by [Nesse-Tyssoy et al. \(2016\)](#) who considered a theoretical form of an electron pitch-angle distribution obtained as a solution of a Fokker-Planck equation under the effect of steady pitch-angle diffusion due to wave-particle interactions. This solution was originally derived by [Kennel & Petschek \(1966\)](#). For the CMIP7 model, the total precipitating electron flux inside the local loss cone has been estimated separately for the three electron energy channels by broadly following the approach of [Nesse-Tyssoy et al. \(2016\)](#), to which the reader is referred for further details. First, the theoretical pitch-angle distribution, which essentially contains two free parameters, was fitted for each 16 s-averaged observation onto the measurements from the two MEPED telescopes. After this, the pitch-angle distribution was integrated over the entire range of the loss cone to compute the total flux of electrons j_0 penetrating perpendicularly into the atmosphere. This calculation takes into account that particles with different pitch angles have different angles of incidence to the atmosphere and must be weighted with the cosine of this angle.

During the time when NOAA-12 (SEM-1) and NOAA-15 (SEM-2) were simultaneously measuring (1998–2007), they were found to produce slightly different average flux levels from the above procedure, even after the correction of zonal variation described in the next subsection. The difference between them was about 5% for large fluxes, and up to 16% overall. The cause of this was ascribed to the different orientations of the detectors in the two instrument models, combined with a remaining imperfection in the pitch-angle distribution model. A further correction to the pitch-angle distribution estimate was therefore applied by adjusting the flux levels of NOAA-12 and -15 to their mutual average, and adjusting the other data from the same detector models (resp. SEM-1 and -2) accordingly.

Finally, an equivalent isotropic flux was calculated as

$$F_{\text{iso}} = j_0 / \pi \quad (1)$$

which corresponds to a flux penetrating vertically through the horizontal atmosphere equal to j_0 . The equivalent isotropic flux F_{iso} was calculated separately for the three integral energy channels and forms the input data used in our work.

2.3 Daily homogeneous composite data

For estimating the zonal variations of the fluxes, data from all POES satellites were used. Because the POES satellites are in sun-synchronous polar orbits, each satellite is locked in two specific opposite magnetic local time (MLT) zones, one for each half of the orbit. Meanwhile, they cover almost all geomagnetic latitudes on each orbit. The following procedures were used to obtain the daily average fluxes for different geomagnetic latitudes from these data.

The isotropic fluxes of the three POES electron energy channels were averaged into 2° wide bins of Corrected GeoMagnetic (CGM) latitude for each day separately for the two hemispheres and the two opposite MLT sectors of the satellite orbit. This was done for data from each satellite separately. These datasets were processed and normalized into a spatially and temporally homogeneous composite using the methods outlined by [Asikainen & Ruopasa \(2019\)](#); [Asikainen \(2019\)](#).

Essentially, the processing is divided into the following steps. First, the daily latitude distributions are cleaned from temporally varying noise background (mostly due to cosmic rays), the procedure of which has been detailed by [Asikainen & Ruopasa \(2019, Sect. 3\)](#). Second, the changes related to the slow drift in the orientation of the satellite orbits relative to the Sun-Earth line are compensated for. This compensation uses data from all satellites at different MLT sectors to estimate the average MLT variation of the fluxes. These are then used to estimate what the fluxes at each time would have been if they were sampled at the MLT that each satellite had when launched. This orbital compensation prevents aliasing of variations in sampling location (MLT) onto temporal variations. The methodology of the orbital compensation has been explained by [Asikainen & Ruopasa \(2019, Sect. 4\)](#).

The above processing was done for all POES satellites (both SEM-1 and SEM-2 versions). In this work, though, we use only the data measured using SEM-2 at satellite NOAA-15, on a dawn-dusk oriented orbit.

To produce the final dataset for the MEE reconstruction, we averaged the processed NOAA-15 data over the two opposite MLT sectors. The composite dataset therefore contains daily-averaged latitude distributions of precipitating isotropic electron fluxes in the three energy channels separately for the Northern and Southern Hemispheres in 2° wide bins of CGM latitude.

The development of the model in [Section 3](#) of this paper follows the CGM-latitude-dependent description of this dataset. Because of this, throughout this paper, ‘latitude’ always refers to CGM latitude, even when not explicitly indicated.

2.4 Spectral separation

The electron fluxes are measured by the MEPED telescopes in three integrated energy ranges, i.e., energy ranges with only a lower limit: >30 keV, >100 keV and >300 keV. In the model development, we aim to estimate fluxes at different separate parts of the energy spectrum to allow them to vary more independently of each other. This is done by subtracting the observed fluxes in the three energy channels from each other, as follows:

$$F_{30-100} = F(E > 30 \text{ keV}) - F(E > 100 \text{ keV}) \quad (2)$$

$$F_{100-300} = F(E > 100 \text{ keV}) - F(E > 300 \text{ keV}) \quad (3)$$

$$F_{300-} = F(E > 300 \text{ keV}). \quad (4)$$

2.5 Resulting data

[Figure 1](#) shows the flux in the three separate energy ranges as functions of CGM latitude and A_p . For this purpose, an array of 160 A_p values (equally spaced on a logarithmic scale) is defined ranging from 1 to 100. For each energy range (30–100 keV, 100–300 keV, >300 keV), each Hemisphere (N and S) and each CGM latitude ($40-80^\circ$), the flux data are binned according to the concurrent value of the A_p in the defined A_p -array. For each bin, the median value of the flux is plotted in [Figure 1](#). [Figure 2](#) shows the numbers of measured flux data points (days) for each A_p -bin. This is the same for all CGM latitudes and energy channels, and is almost equal to the number of actual days, as the availability of the data in this period is 99% and independent of A_p .

As expected, the flux increases with A_p and decreases with electron energy. The fact that the equatorward edge of the area of high flux moves equatorward with increasing A_p is due to stronger magnetospheric convection and the erosion of the plasmasphere during substorms, which causes the radiation belts to move closer to the Earth. It is also interesting to note that for any particular A_p value, the CGM latitude where the highest flux occurs depends on energy: for higher energies it is more equatorward than for lower energies. This is consistent with the fact that the deeper the electrons are pushed by magnetospheric convection during substorms, the more they are accelerated.

Note that the apparently stronger variations in [Figure 1](#) at high A_p values do not mean that these data contain more outliers or stronger variations than the data at lower A_p . These are merely affected by the low numbers of data points, as can be seen in [Figure 2](#). In the middle of the graphs, the medians are smooth due to the high number of data points, but when A_p is high, each bin contains only a few data points (≤ 3 for $A_p > 80$). As a result of this, data in adjacent bins can originate from different events showing different behaviour.

In some of those high A_p bins, one can see high fluxes throughout the polar cap, extending all the way down to the main precipitation zone. These data correspond to times of solar particle events where large amounts of

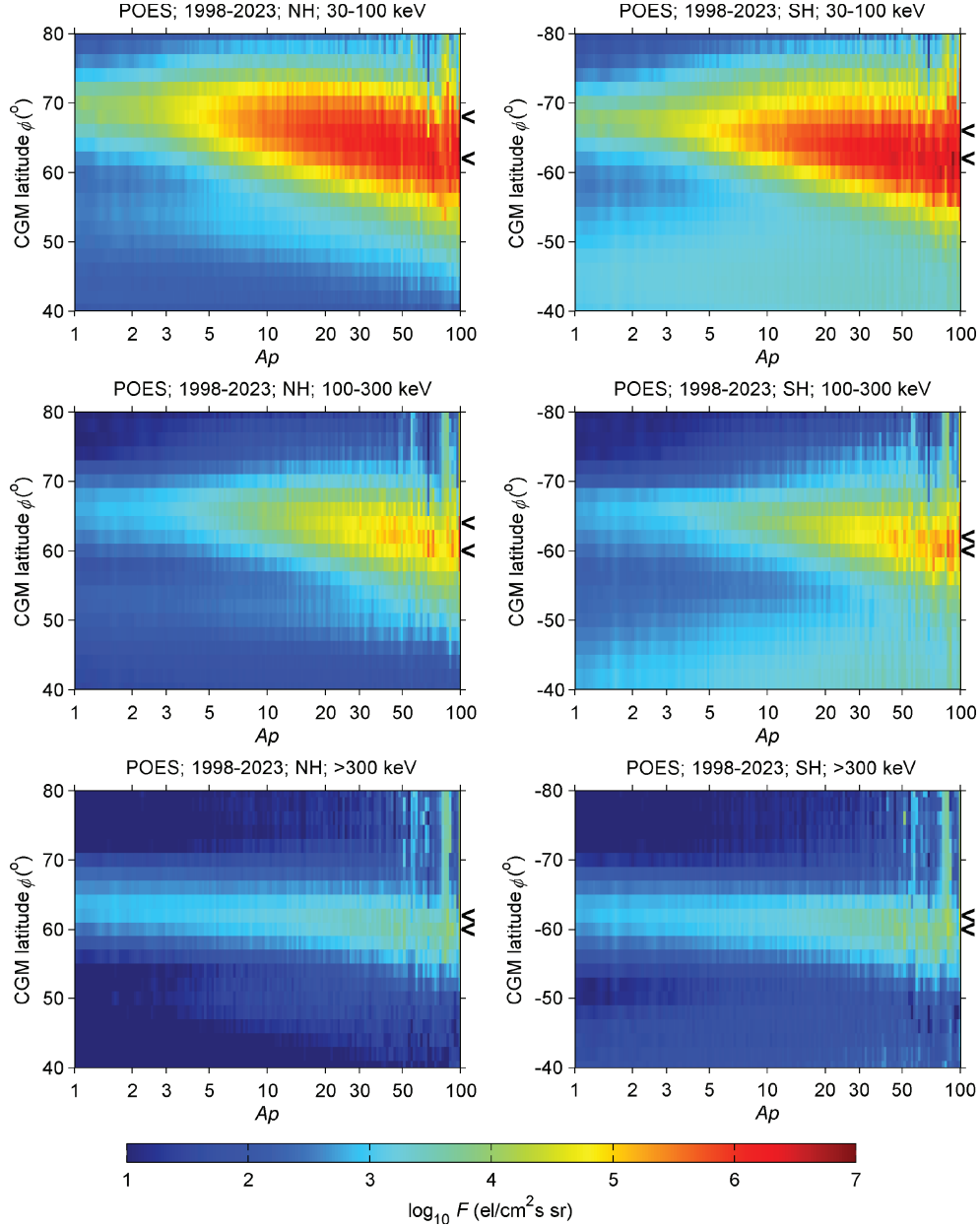


Figure 1. Median flux measured by the POES satellites after preprocessing, depending on CGM latitude, concurrent A_p -value, hemisphere and energy channel. The ‘v’-marks on the right-hand y -axis indicate the CGM latitudes used in Figure 3.

high-energy protons and electrons penetrate the polar cap directly from the solar wind. These events are often associated with concurrent large A_p values (magnetic storms). They can also occur during small A_p values not associated with large geomagnetic activity, but these events can not be seen in the graph because at low A_p the data are smoothed by the much larger number of data points.

Figure 3 illustrates the year-to-year variability of the fluxes by plotting the probability density function (pdf) of the fluxes for each year, for a few example CGM latitudes, in the three separated energy channels (30–100 keV, 100–300 keV, >300 keV) and at both hemispheres. The latitudes chosen for this figure are chosen as the ones where

the fluxes are highest in quiet conditions and those where they are highest in disturbed conditions. These latitudes were found by calculating, for every latitude, the median flux during times when $A_p < 5$ (quiet conditions), and finding the latitude where this was highest. Similarly during times when $A_p > 80$ (active conditions). The values of the corresponding CGM latitudes are given in the graphs, and are marked on the right-hand vertical axes of the graphs in Figure 1.

This figure shows that the fluxes vary strongly with the solar cycle: they are low in 2009 and 2020 and high in 2003. Also, it can be seen that the ‘maximum while active’- latitudes (lower panel of each pair), which are always the more equatorward of the two, show a stronger

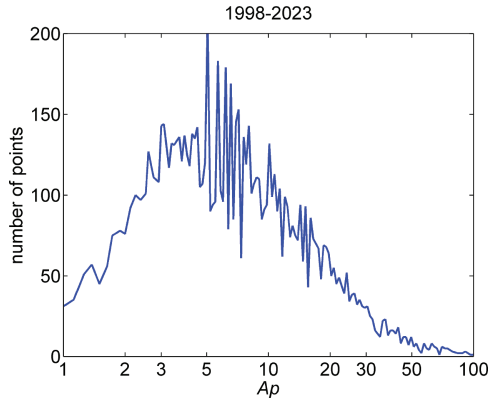


Figure 2. Number of data samples in the measurement period for each Ap -bin.

variation with year. This is because these latitudes are mostly in the plasmasphere during quiet years, but during disturbed times, due to plasmasphere erosion, they can end up in the radiation belt at the maximum of electron precipitation.

3 Model construction

3.1 Spectral shape

In the electron precipitation model used in CMIP6, and other previous versions (van de Kamp et al., 2016, 2018), the electron flux spectrum was assumed to decrease with energy according to a power law between 30 keV and 1 MeV, with spectral slope ≤ -1 . Although it had been found that the shape can differ from the straight line on a log-log scale, the measurements of only three energy channels by POES did not allow a much more detailed analysis of the spectral shape. Li et al. (2012) had shown measurements of the drift loss cone with a much higher spectral resolution, which indicated that the single-spectral-slope assumption was generally found to be reasonable.

However, in this analysis for CMIP7, the single-slope decreasing spectrum is considered too rigid. This is mainly because it causes the fluxes in the three energy channels to vary coherently with each other, whereas the observations show that they can behave independently. For instance, in Figure 1, it is seen that for a given value of Ap , the fluxes at the three energy bins maximize at three different latitudes. To address this issue, the fluxes in the three energy channels are modeled independently, rather than being forced to vary coherently.

After that, the full spectrum can be reconstructed from these three modeled fluxes (we will return to this reconstruction later in the paper). This reconstructed spectrum will generally still decrease with energy but not with a single spectral slope; the entire spectrum has more freedom to be described by different shapes.

3.2 Timing of response: Convolution of Ap

The response time of the flux to a given magnetic disturbance is found to depend on latitude and energy. In many cases, the flux continues to increase for one or several days after a rise in Ap , resulting in a delay between the maximum in Ap and the peak flux.

Figure 4 (left-hand panel) gives an example of how the >300 keV flux can evolve compared to the evolution of Ap . On 14 October 2003, the Ap strongly increased and so did the flux at -60° , but at some other latitudes the flux peaked a few days later. A similar case is seen around 10 November. Also, on 1 November, when the Ap strongly decreased, the fluxes remained high for several days before decreasing. On 20 November, Ap shows a strong peak followed by a decrease, but the fluxes show a bulge about 5–8 days later, when Ap was already decreasing.

This observed time lag is consistent with that seen in earlier studies, suggesting that after significant sub-storm activity it typically takes a few days for wave-particle interactions in the radiation belts to accelerate the seed population of electrons (30–100 keV) to relativistic energies (e.g. Horne et al., 2005). Moreover, the diffusion timescale for relativistic electrons is also of the order of a few days (e.g. Summers et al., 2007). Both of these factors contribute to the observed time lag from the Ap enhancement to the electron flux enhancement at the higher energies.

Because of this time delay, we decided to apply a temporal convolution function to the Ap time series before parameterizing the electron flux with it, so that the flux at a particular energy, latitude and day, is driven by a weighted average of Ap values from up to a month before that day. The convolution function of Ap is derived on the logarithmic scale, to make sure it works equally for fluxes in higher and lower orders of magnitude. It is derived to maximize the correlation between $\log_{10} Ap$ and $\log_{10} F$. Before conversion to a logarithmic scale, all zero Ap values are replaced by 0.125, to make them finite on the logarithmic scale.

Furthermore, it was found that at latitudes equatorward of $\pm 52^\circ$, the response of the flux to Ap can be stretched over a very long time (up to months). This is likely associated with slot region filling events, the decline of which does not follow the behavior of the Ap -index (Nesse et al., 2023). Because of this, it is decided to derive the convolution function only for data at CGM latitudes poleward of $\pm 52^\circ$. At more equatorward latitudes, the convolution function is assumed to be equal to that at 52° .

We assume that the convolution function for any CGM latitude is equal in both hemispheres, because both latitudes are connected to the same field lines, and any delaying effect on the precipitating flux must be the same for the northern and southern end of the field line. Therefore, when deriving the convolution function for Ap at any energy and CGM latitude, the measured flux data for that latitude from both hemispheres are considered together. The technical procedure used to derive the convolution function of Ap is described in Appendix A. The

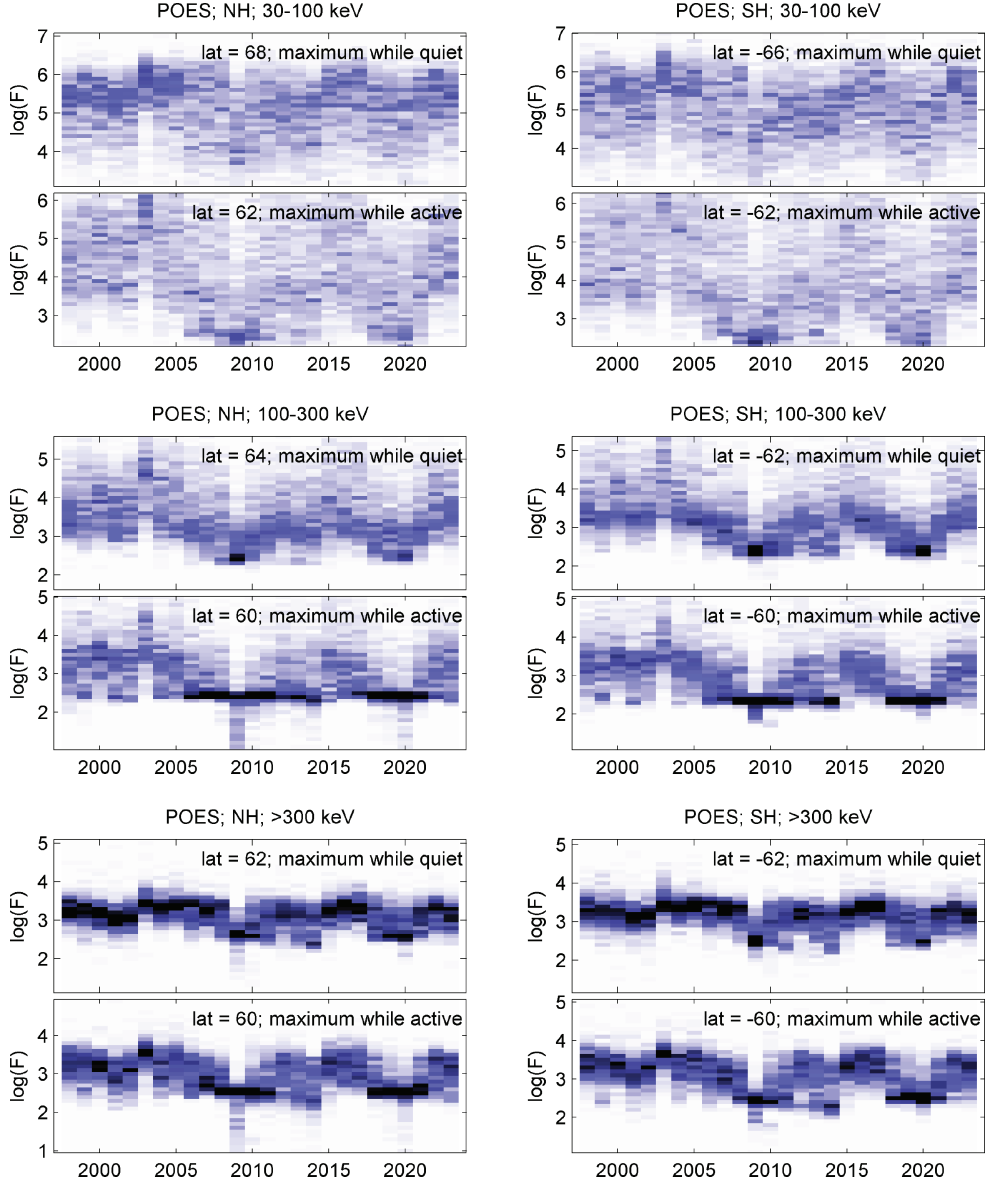


Figure 3. Distribution of flux measured by the POES satellites after preprocessing, for different years of the period used, for a few CGM latitudes, for both hemispheres and all energy channels.

exact convolution functions resulting from this are also given there.

The right-hand panel of Figure 4 shows the correlation coefficients between the flux in both hemispheres and the convoluted Ap , compared to those calculated using the original Ap . This figure shows that, especially at the highest energy range, a significant improvement in the correlation is achieved, which can lead to a better model accuracy if the convoluted Ap is used as a proxy in the model.

3.3 Modeling of the flux vs. convoluted Ap and CGM latitude

For specific CGM latitudes, it is observed that the flux roughly follows a power law with respect to the convoluted Ap . As an example, Figure 5 (left-hand panel)

shows a scatterplot of the 30–100 keV electron flux at 62°N. Therefore, linear regression is used to determine a power law fit in the log-log domain for each CGM latitude, energy, and hemisphere:

$$F = a (Ap_{co}/10)^b \quad (5)$$

which is shown in Figure 5 with the red line, where b is the slope of the line, and a is the intercept at $Ap_{co} = 10$. The light green curve shows the median flux calculated for specific bins on a logarithmic scale of convoluted Ap . In the central part of the range, this curve agrees well with the red line.

The slopes b of these fitted lines are shown versus CGM latitude in the middle graph of Figure 5, showing a clear maximum around CGM latitudes 60–65°. This behavior is modeled using the hyperbolic secant function:

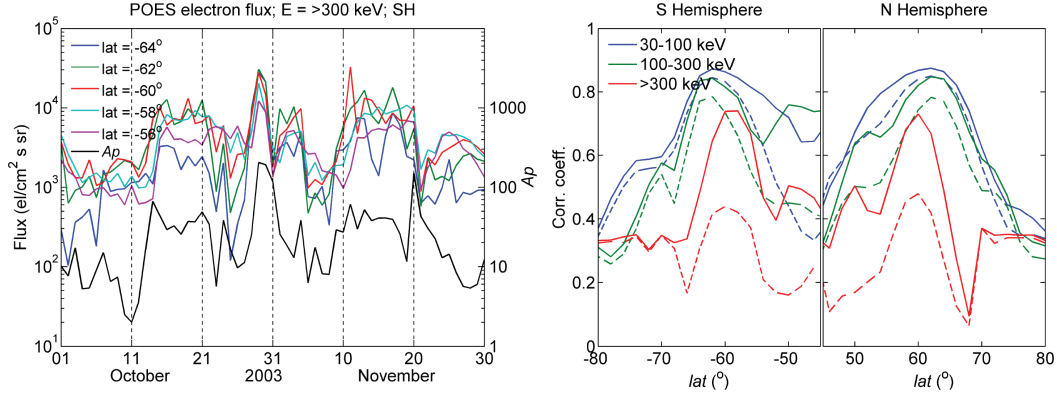


Figure 4. Left: the electron flux >300 keV in the Southern Hemisphere at different latitudes during the autumn of 2003, and the A_p index (black; axis on the right-hand side). Right: The correlation coefficients between the flux at different latitudes and the A_p (dashed lines), and between the flux and the convoluted A_p (solid lines). All correlation coefficients are calculated on the log scale, and for fluxes larger than $100 \text{ el/cm}^2 \text{ s sr}$.

$$b = b_1 \operatorname{sech}(b_2(\phi - \phi_b)) \quad (6)$$

where ϕ is the CGM latitude in degrees. This function is shown in the graph with a green curve. The coefficients b_1 , b_2 and ϕ_b depend on energy and hemisphere. (Note that this function has been fitted by minimizing the absolute error of b , not the relative error, as it is the agreement in absolute terms which matters for the modeling of the flux.)

With this fitted expression for b , the expression of equation (5) is again fitted to the log-flux as a function of $\log Ap_{co}$ for every latitude, but with b forced to equation (6). The vertical offsets a resulting from these are shown versus CGM latitude in the right-hand graph of Figure 5. These also show a maximum, at a higher latitude, around 65 – 70° . This is also modeled by a hyperbolic secant function:

$$a = a_1 \operatorname{sech}(a_2(\phi - \phi_a)) \quad (7)$$

which is shown in the graph by the green curve. The coefficients a_1 , a_2 and ϕ_a depend on energy and hemisphere.

3.4 Leveling off

In the left-hand graph of Figure 5, in the top right corner it can be seen that during the highest values of Ap_{co} , the measured flux values level off to values just over $10^6 \text{ el/cm}^2 \text{ s sr}$, while the fitted model would, in these cases, indicate much higher fluxes. We consider it possible that this is an indication of a certain maximum flux level, which at certain locations will never be exceeded, although confirmation of this, and a physical explanation of the effect, would require further study. In any case, even though these high Ap_{co} values are rare, we consider it risky to have the model predict fluxes which are in reality never measured. For this reason, it is decided to include this level-off effect in the model. This can be

expressed by modifying equation (5) as follows:

$$F = \frac{1}{\frac{1}{a(Ap_{co}/10)^b} + \frac{1}{c}} \quad (8)$$

where c is the ‘ceiling’ level of flux that is never exceeded. This value can be determined by fitting equation (8) to the data, with a and b fixed according to equations (6) and (7).

It is reasonable to assume that if it exists, physically this ceiling value would depend on latitude. However, for most latitudes, it is very hard to determine the value of c from the data, as the fluxes do not reach such high values. Therefore, it is decided to determine c as one value for all latitudes, and dependent only on energy and hemisphere.

The left-hand panel of Figure 6 shows the flux at 30 – 100 keV and CGM latitude 62° in the Northern Hemisphere, and the fitted model according to equation (8).

Looking at this graph, one might consider that the flux values should level off at the low end as well. However, we decided not to include this in the model for two reasons. Firstly, this lower leveling off is likely an effect of the quantization noise of the MEPED-detectors. A count of a single electron corresponds to a flux of $100 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ (Evans & Greer, 2000), making all data near and below this value highly inaccurate. Secondly, even if a certain quiet-time leveling off exists, an underestimation of these fluxes which are already very small, would have an insignificant effect on the long-term total fluxes.

3.5 Low-latitude component

In the right-hand panel of Figure 5, it can be seen that on the low-latitude side, the model underestimates the measured value of a significantly. This is due to an effect that can also be seen in Figure 1: in all left-hand panels, at CGM latitudes around 50°N , there is an extra ‘sidelobe’ of flux beside the main maximum. This flux is

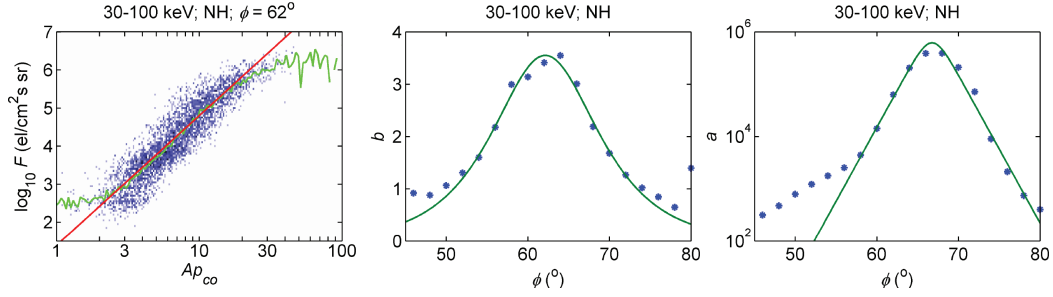


Figure 5. Examples of the fitting procedure for the 30–100 keV energy channel at the Northern Hemisphere. Left: for CGM latitude 62°, the flux as a function of the convoluted Ap (blue); fitted line according to equation (5) (red), and median flux dependent on Ap_{co} (green). Middle: slopes b of the red lines in the left-hand graph for different latitudes ϕ (blue), and fitted curve according to equation (6) (green). Right: vertical intercepts a at $Ap_{co} = 10$ of the red line for different latitudes (blue), and fitted curve according to equation (7) (green).

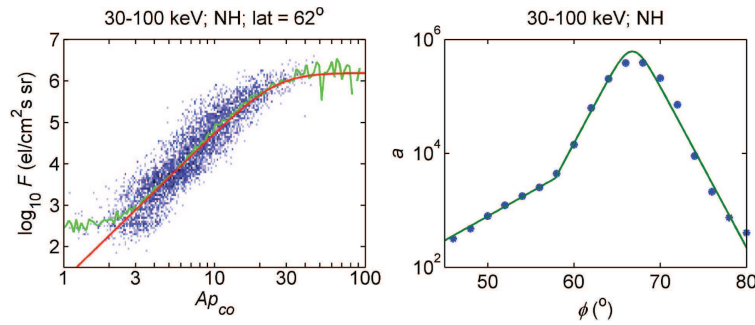


Figure 6. Left: For the 30–100 keV energy channel, and for the Northern Hemisphere, CGM latitude 62°: the flux as function of the convoluted Ap (blue); fitted line according to equation (8), which includes leveling off (red), and median flux for narrow bins of Ap_{co} (green). Right: the coefficients a as function of latitude, and the curve according to equation (11), which includes the low-latitude part of the flux.

most likely associated with slot-region filling events, during which enhanced radiation-belt electron populations penetrate into the normally depleted slot region and produce prolonged energetic electron precipitation at low latitudes following geomagnetic disturbances (Nesse et al., 2023). In the Southern Hemisphere (right-hand panels of Fig. 1), this low-latitude flux region is even more pronounced, consistent with enhanced radiation-belt particle precipitation associated with the South Atlantic Anomaly (Abel & Thorne, 1999).

It is found that in the Southern Hemisphere, the most equatorial part of this low-latitude flux is not well correlated with Ap and therefore it is not possible to include it in the current model. However, the fluxes between about 45° and 60° do show some significant correlation with Ap , as does the smaller low-latitude flux near 50°N. Because of this, it is decided to include this effect in the model for CGM latitudes above 45°. This is done by modifying equation (7) as follows:

$$a_A = a_1 \operatorname{sech}(a_2(\phi - \phi_a)) \quad (9)$$

$$a_B = a_3 \times a_4^{|\phi|} \quad (10)$$

$$a = \begin{cases} a_A & (|\phi| > \phi_a) \\ \max(a_A, a_B) & (|\phi| \leq \phi_a) \end{cases} \quad (11)$$

where equation (10) corresponds to a linear section in the lin-log plot of a vs. ϕ , and the coefficients a_3 and a_4 are

found by fitting this expression to the data, dependent on energy and hemisphere. The right-hand panel of Figure 6 shows the resulting curve for 30–100 keV in the Northern Hemisphere.

3.6 Statistical correction factor

All of the fitting of curves and values to the measured data above is done on the logarithmic scale. The reason for this is to make sure that the behavior of the model is not just dominated by the behavior of the largest measurements of the flux, but emulates the measured behavior equally well in lower and higher orders of magnitude. As a result, the model is likely to be similar to the median values of the measured flux for various latitudes and Ap values, such as shown in e.g. Figure 1.

However, the purpose of the model is to emulate a long-term effect of the electron flux on the atmosphere. This long-term effect can be assumed to be related to the long-term integration of the flux over time, which is equal to the linear long-term average of the flux multiplied by the time. When it comes to representing this linear average, a model which represents the median value will inevitably underestimate.

This underestimation is due to the difference between the mean and the median of any quantity which has

(approximately) a normal distribution on the log scale, i.e. a lognormal distribution. The amount of underestimation depends on the amount of spread of the quantity, i.e. the standard deviation of the log of the quantity.

One way to deal with this issue is to add to the modeled (deterministic) flux a stochastic component, with a distribution equal to the distribution of the measured flux. This requires an accurate determination of this measured distribution. In addition, this method has the disadvantage that it will reduce the reproducibility of the data set when used in simulations.

An easier way to fix this underestimation is to scale the result so that its long-term average is equal to the measured long-term average flux. This method is adopted in the current model. This means that equation (8) is modified as

$$F = \frac{d}{\frac{1}{a(Ap_{co}/10)^b} + \frac{1}{c}} \quad (12)$$

where d is the ratio between the average measured flux and the average flux modeled according to equation (8), where this average is in both cases the linear long-term average over the full period, and all latitudes. The factor d is dependent only on energy level and on the hemisphere.

3.7 Full model

The resulting equations for the CMIP7-model are summarised in [Appendix B](#). To enable a comparison of model fluxes to the measured fluxes in [Figure 1](#), the electron fluxes have been computed using these equations for the full time period and on the same CGM latitude grid as the observations. Next, the modeled data have been binned with respect to the concurrent Ap (not convoluted) value, using the same Ap -array as used in [Figure 1](#). For each Ap -bin, the median flux was calculated (for each energy, hemisphere and CGM latitude). [Figure 7](#) shows the result in the three energy channels and in both hemispheres, as functions of CGM latitude and Ap .

When comparing this figure to [Figure 1](#), note that, due to the statistical correction factor ([Sect. 3.6](#)), the long-term medians of this model are now somewhat higher than those of the measured fluxes. However, the general behavior, varying with Ap and ϕ , is in agreement with the measured fluxes.

As explained in [Section 3.6](#), the statistical correction factor was needed because of the different stochastic properties of the model and observations: within each bin of the graphs in [Figure 7](#), the observations vary more around the median than the model. The extent of this difference in variability is also illustrated by the following error analysis. The relative modeling error has been calculated as:

$$\text{Err} = \log_{10} (F_{\text{model}} / F_{\text{observ}}) \quad (13)$$

where F_{model} is the modeled flux calculated as described in [Appendix B](#), and F_{observ} is the observed flux according to equations (2)–(4). Equation (13) was calculated for each day, each energy range and each latitude. Next, this parameter was binned as function of latitude and Ap likewise as [Figures 1](#) and [7](#). The root-mean-square (RMS) of Err was calculated for every bin. The result is shown in [Figure 8](#).

This figure shows that where the fluxes are largest and the data are most abundant, the RMS error is often around 0.5, corresponding to a relative error of a factor of 3. The error is larger for small fluxes, but these are not very significant in absolute terms. For high Ap values, the error is seen to be sometimes larger due to the smaller amount of data.

3.8 Reconstruction of flux spectrum

From the modeled fluxes integrated over the three limited energy ranges, the full spectrum can be reconstructed as follows. Given by three values, it can obviously have three degrees of freedom. Therefore, the spectrum is assumed to be determined by a vertical offset and two partial slopes. The transition between these two slopes is arbitrarily chosen to be at 100 keV. So the spectral density is assumed to be as:

$$S(E) = \begin{cases} C E^{k_1} & 30 \leq E \leq 100 \text{ keV} \\ C 100^{(k_1-k_2)} E^{k_2} & 100 < E \leq 1000 \text{ keV} \end{cases} \quad (14)$$

Outside of the modeled energy range, the flux spectrum is assumed to be zero. Note that this implies that the energy range of the precipitating electrons is limited on both sides, while the MEPED observations did not impose an upper limit on the energy range of observed electrons, so that higher energies are included in the observed data of F_{300-} . However, an upper limit to the energy range of the model is necessary, because without it, the integral over the range becomes infinite for $k_2 \geq -1$.

In a previous measurement campaign in the drift loss cone at high spectral resolution, [Whittaker et al. \(2013\)](#) found that the power law model is roughly applicable in the medium-energy range, but that the electron spectrum falls off faster from a limit which varies around 1 MeV. This is the reason that an upper limit of 1 MeV is chosen for this model. The same strategy was applied in the CMIP6 model ([van de Kamp et al., 2016](#)).

The three limited-range integrated fluxes are related to $S(E)$ as:

$$F_{30-100} = \int_{30}^{100} S(E) dE = \frac{C}{k_1 + 1} (100^{(k_1+1)} - 30^{(k_1+1)}) \quad (15)$$

$$F_{100-300} = \int_{100}^{300} S(E) dE = \frac{C 100^{(k_1-k_2)}}{k_2 + 1} (300^{(k_2+1)} - 100^{(k_2+1)}) \quad (16)$$

$$F_{300-} = \int_{300}^{1000} S(E) dE = \frac{C 100^{(k_1-k_2)}}{k_2 + 1} (1000^{(k_2+1)} - 300^{(k_2+1)}) \quad (17)$$

The parameters C , k_1 and k_2 can be calculated from the modelled F_{30-100} , $F_{100-300}$ and F_{300-} , by inverting these

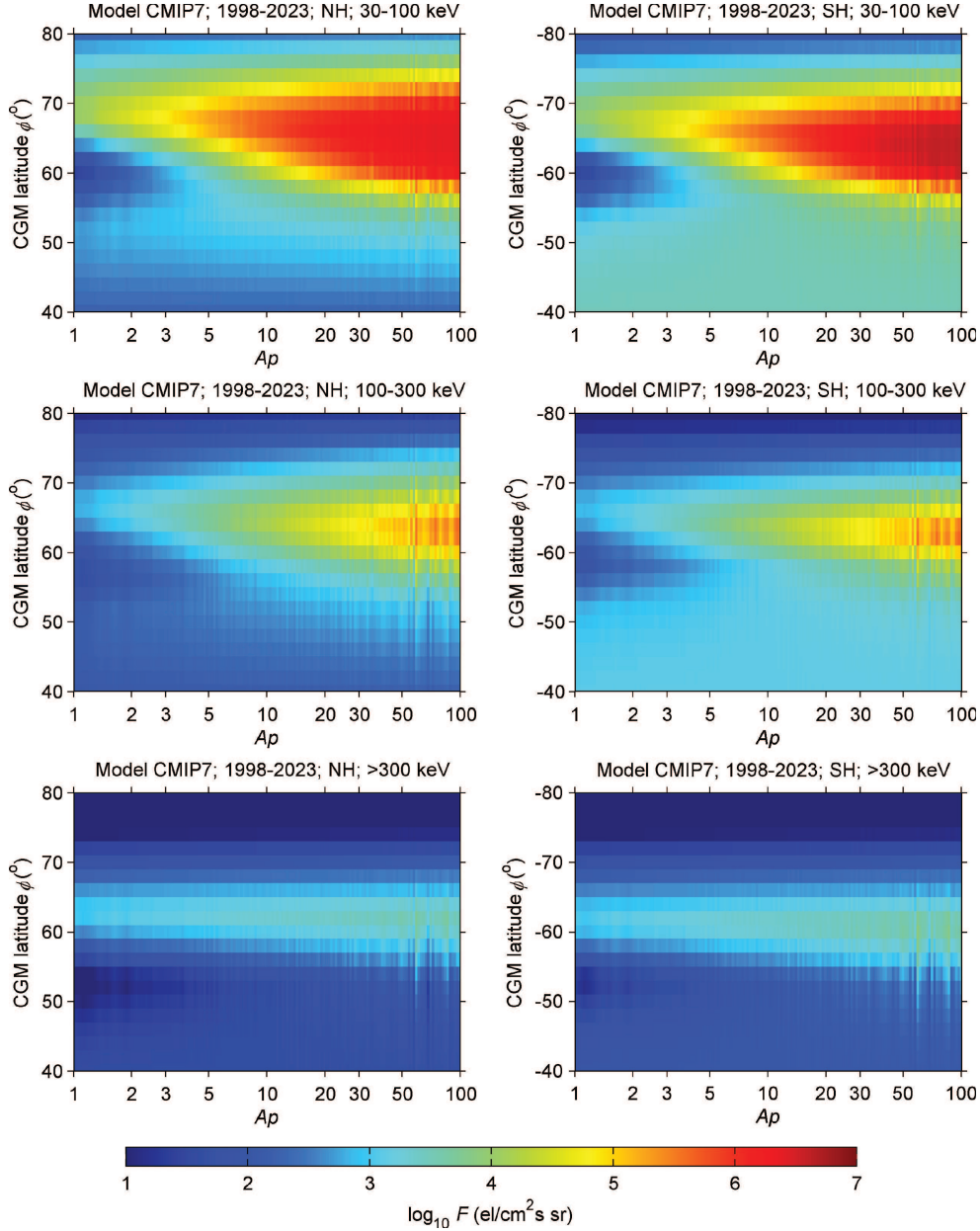


Figure 7. Median flux resulting from the CMIP7 model described in this paper, depending on CGM latitude, concurrent A_p -value, hemisphere, and energy channel.

three equations. For k_1 and k_2 , this inversion is done numerically. After that, the inversion for C is straightforward. The spectral density of flux at any energy between 30 and 1000 keV can then be calculated from equation (14).

From the above, the integrated flux over any energy range can also be calculated by integrating equation (14) over E .

3.9 Ionization

The input to CMIP from the model is in the form of ionization rates produced by the electron precipitation

at various pressure levels. The ionization is calculated here using the parameterization of the electron impact ionization by Fang et al. (2010). The calculation is done by calculating the differential spectrum of electrons at energy values corresponding to an array of 50 logarithmically spaced grid points between 30 and 1000 keV. The rates are calculated on a fixed atmospheric pressure grid, with 30 pressure levels. This calculation gives the ionization rates in units of ions/(gs), which were converted to the unit of ions/(cm³s) using the atmospheric density obtained from the NRLMSISE-00 atmosphere model (Picone et al., 2002).

Some examples of the resulting ionization rate profiles are shown in Section 4.

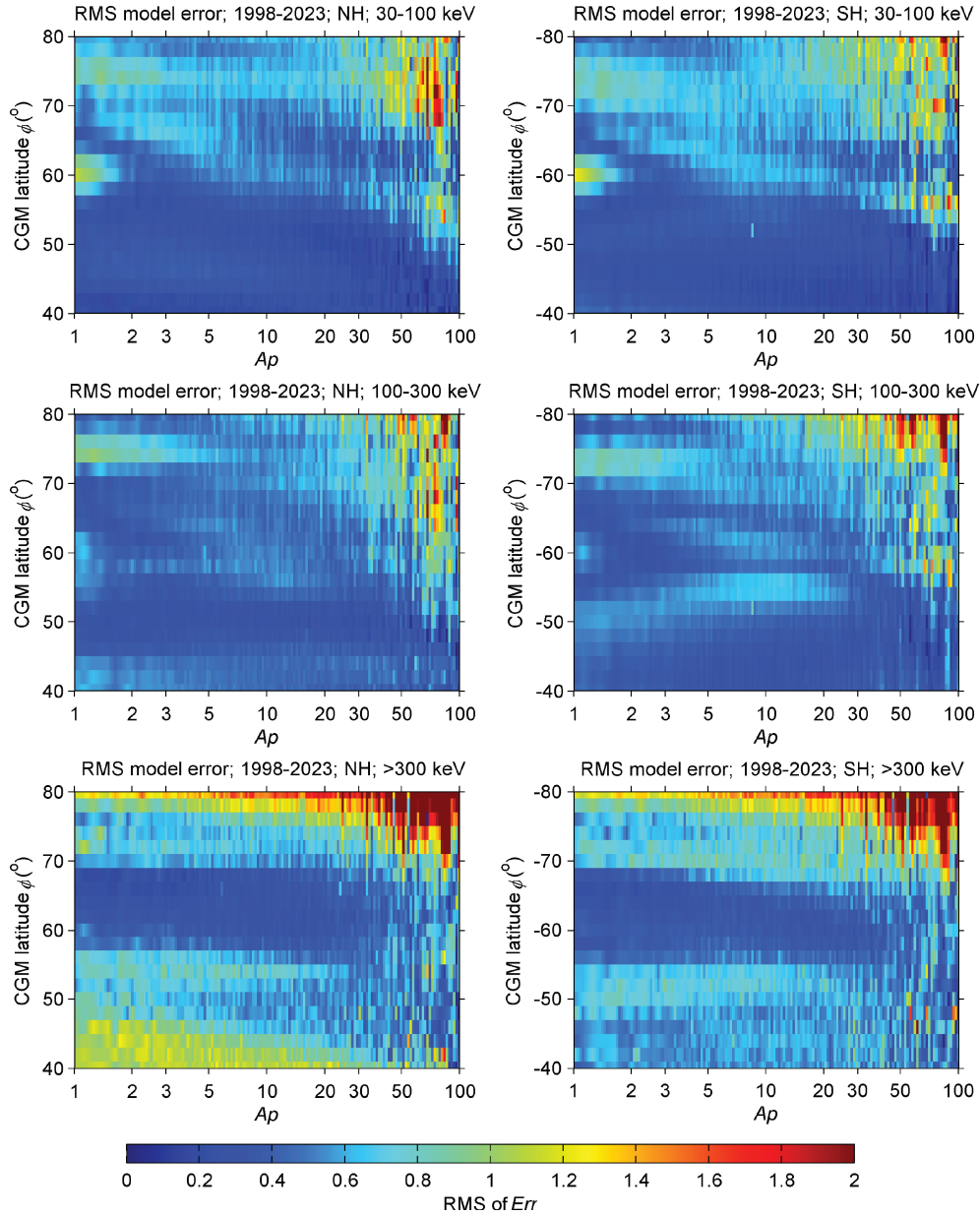


Figure 8. RMS of the error calculated as equation (13) of the CMIP7 model described in this paper, depending on CGM latitude, concurrent A_p -value, hemisphere, and energy channel.

4 Comparison with CMIP6

There is a considerable number of significant differences between the modeling approach of this model for CMIP7 and that of the model used in CMIP6 (van de Kamp et al., 2016):

- First of all, the CMIP6 model was fitted to data from the POES satellites of the period 2002–2012, i.e. about one solar cycle. Since then, more data have been accumulated, allowing a whole extra solar cycle to be added to the data, so that the CMIP7 model is based on data from 1998–2023.
- More importantly, the data on which the CMIP6 model was based were measured only by the 0° tele-

scope, which was expected to give a reasonable indication of the content of the bounce loss cone. The data used for the CMIP7 model is a more advanced estimate of the content of the bounce loss cone based on the measurements from both the 0° and 90° telescopes.

- During magnetic disturbances, the plasmasphere erodes, causing the radiation belt to move equatorward. In the CMIP6 model, this was taken into account by using the modeled position of the plasmapause by O'Brien & Moldwin (2003). The latitudinal position of the electron precipitation was modeled relative to the plasmapause location. In the CMIP7 model, the plasmapause location is not treated

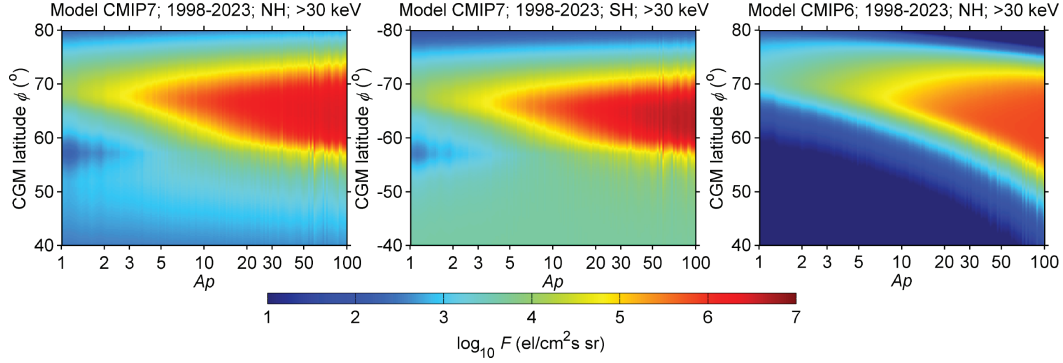


Figure 9. Median flux integrated over the energy range 30–1000 keV, depending on CGM latitude and concurrent A_p -value, for the CMIP7 model described in this paper in the Northern Hemisphere (left) and Southern Hemisphere (middle) and the model used in CMIP6 (right), in which the Northern and Southern Hemispheres were identical.

separately, and the equatorward motion of the precipitation region is incorporated directly into the model equations.

- Unfortunately, the POES MEPED measurements in (only) three distinct energy channels do not allow for a very detailed analysis of the spectral shape of the precipitating electrons. For this reason, in the CMIP6 model, the flux spectrum was assumed to be decreasing with energy according to a power law between 30 keV and 1 MeV, with spectral slope ≤ -1 . In the CMIP7 model, the spectral shape is assumed to be a two-section power law, with one spectral slope for the energy range 30–100 keV, and the other between 100 and 1000 keV. These two spectral slopes and the offset are the three degrees of freedom of the spectrum. In this model, both spectral slopes can have any value between $-\infty$ and $+\infty$.
- In the CMIP6 model, the daily electron flux was parameterized with the simultaneous daily A_p . Hence, no time-integrating effect of A_p was included, except in the plasmopause model, which was dependent on the maximum of A_p of the same day and the previous day (in the original model by O'Brien & Moldwin, 2003, it was a maximum value over 1.5 days). In the CMIP7 model it was noted that the time lag between A_p variations and resulting variations in the electron precipitation can depend on latitude and energy. To accommodate this behavior, a temporal convolution function for A_p is included which depends on CGM latitude and energy. Therefore, the daily precipitation is parameterized as a suitably weighted sum of past daily A_p values.
- The CMIP7 model includes a ceiling level to avoid an extrapolation effect that would otherwise produce unrealistically high electron fluxes if A_p exceeds the range observed in the data set. The CMIP6 model did not include such a feature.

For comparison with the model used in CMIP6, the electron flux resulting from the model described in this paper has been calculated for the entire period 1979–2023 with a 1-day resolution, and for CGM latitudes at a resolution

of 0.1 deg from 40 to 80 deg in both hemispheres, and integrated over the entire energy range 30–1000 keV. The same has been done for the model used in CMIP6. Both modeled data sets have then been binned according to the concurrent A_p value in narrow bins on the log scale, and for each bin the median value was calculated, similarly to Figure 7. The result is shown in Figure 9. The Southern Hemisphere is not shown here for the CMIP6 model, because this model did not distinguish between the hemispheres.

This figure clearly brings out a few differences between the behavior of the new model and that of the previous one. Firstly, the CMIP7 model predicts higher fluxes than the CMIP6 model for almost all conditions. Furthermore, at CGM latitudes equatorward of 55° , the CMIP6 model showed very low fluxes during quiet conditions, and strongly increasing fluxes when disturbances are strong. This behavior in the CMIP6 model was a direct result of the plasmopause model which was used in that model. This model defines the plasmasphere to be eroded very strongly with increasing disturbance. However, the observations showed a weaker equatorward progression of the fluxes with increasing disturbance (see Figure 1). This weaker progression is reproduced in the CMIP7 model.

Finally, the observations show a clear hemispheric difference in precipitation (see Figure 1) with higher fluxes in the Southern Hemisphere in disturbed conditions, and at low latitudes. This is mainly due to the weaker magnetic field in the Southern Hemisphere at the same CGM latitude, which allows a larger fraction of the particles to precipitate into the atmosphere. This interhemispheric difference is well captured by the CMIP7 model, whereas the earlier CMIP6 model could not differentiate between hemispheres.

Another comparison is shown for the ionization rate profiles resulting from both models in Figure 10. Here, the ionization rates are shown, calculated as described in Section 3.9 for every day of the geomagnetically most active year 2003, and of the geomagnetically quiet year 2009, globally averaged (in longitude and latitude), for pressure levels between 2×10^{-4} hPa and 0.5 hPa. These

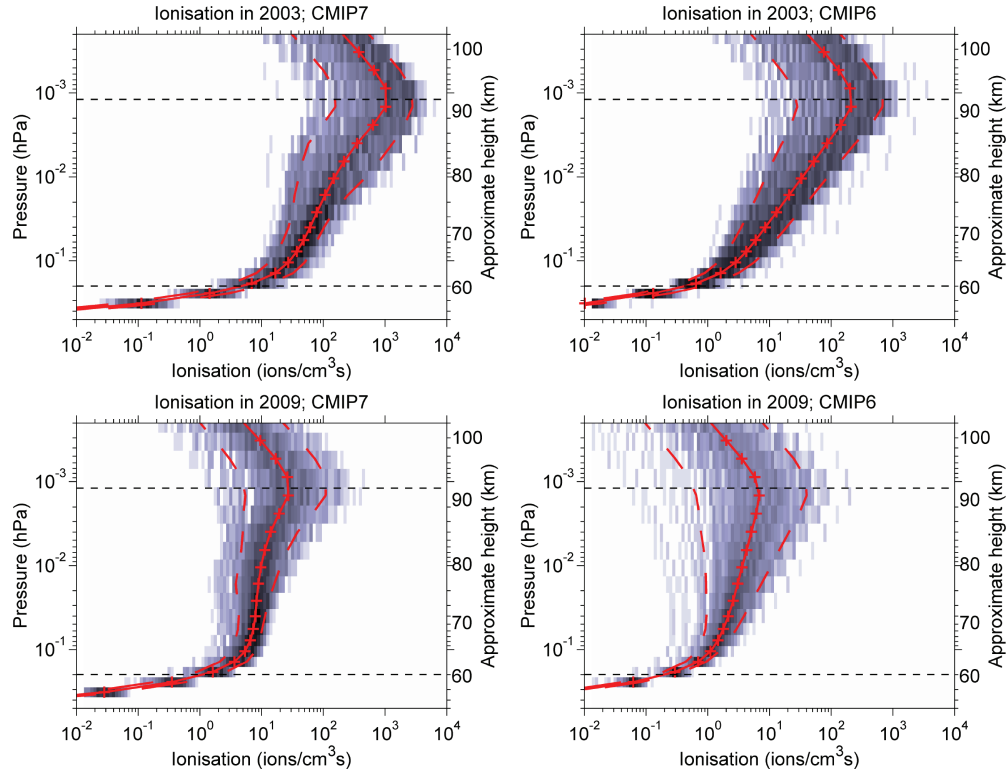


Figure 10. Ionization profiles according to the CMIP7 model (left) and the CMIP6 model (right), in the disturbed year 2003 (upper) and the quiet year 2009 (lower). The ionisations were calculated from the model as described in Section 3.9, at the reference pressure levels indicated by the plus signs in the red curves, and averaged over the entire globe. The darkness of the shaded areas indicates the number of occurrences of the ionization values in the year. The solid red curves are the medians and the dashed curves are 10- and 90-percentiles. Approximate altitudes corresponding to the pressure levels are indicated on the right-hand y -axis. Only the parts of the graphs between the horizontal dashed lines are representative of the *total* ionization at the respective altitudes; above and below this range, the ionization is dominated by electrons at energies not covered by the model.

pressure levels correspond to approximate heights of 102 km and 54 km, respectively.

Note that the model only describes electron fluxes of energies between 30 and 1000 keV, and therefore this graph estimates the total ionization only at a limited range of heights. The ionization caused by electrons of a specific energy peaks at (but is not limited to) a certain specific height. The ionization at about 0.0012 hPa/92 km is dominated by electrons of 30 keV, and that at 0.2 hPa/60 km by those at 1 MeV. Due to this, the shape of the ionization profiles between these two levels (indicated by horizontal dashed lines in the graphs) reflects the shape of the energy spectrum of the models. The ionization at higher altitudes than 92 km will be dominated by lower-energy (auroral) electrons, and at altitudes below 60 km by higher-energy (relativistic) electrons, which are both not included in these models. Those parts of the profiles shown are therefore not representative of the full ionization.

Figure 10 shows that the CMIP7 model on average predicts higher ionization (by about a factor of 3) than the CMIP6 model. This difference is primarily attributable to the stronger EEP forcing used in CMIP7, which in turn results mostly from the use of both POES

telescopes, which yields larger precipitating electron flux estimates. In 2003, the variation around the mean curve is similar for the two models; in the quiet year 2009, the CMIP6 model showed more variation, especially on the low-ionization side, than the new model. The shape of the ionization profiles are roughly similar in the two models, although the difference between the one-slope spectrum of CMIP6 and the two-slope spectrum in the CMIP7 model can be noticed in the profile shapes between 90 and 60 km.

5 Conclusions

In the frame of phase 7 of the Coupled Model Intercomparison Project (CMIP7), an updated model of medium-energy electron precipitation, and a resulting data set of ionization have been developed, as part of the solar forcing input for climate simulation models. The new model is an upgrade of the model used in CMIP6 in various aspects, the most important of which are the following:

While the model is based on measured data by the same (POES) satellites as those for CMIP6, the CMIP7

model uses a longer data period, covering two solar cycles. Also, in this model the data from two telescopes measuring nearly orthogonal directions are used, allowing a better reconstruction of the distribution of electrons in the bounce loss cone.

The data used in the new model have been corrected for noise from cosmic rays, proton contamination and imperfect electron sensitivity, using upgraded methods w.r.t. CMIP6. In the composite satellite data the variations in orbital orientation of the various satellites are estimated using combined data from simultaneous satellites. These variations are subsequently compensated for, thereby avoiding aliasing of the variations in the measurement location as temporal variations of the fluxes.

Data from the Northern and Southern Hemispheres were processed separately, and the model was developed separately for both hemispheres.

The spectral modeling in the new model uses a different approach than in the previous CMIP6 model, which allows more freedom in the shape of the energy spectrum.

While the model uses the same magnetic index A_p as an input parameter as the previous one, the CMIP7 model incorporates a time-integration of this parameter, which allows for a delayed effect of magnetic disturbances on the electron flux of up to 30 days which is dependent on energy and CGM latitude. The delay is largest for the highest energies and for low latitudes.

Comparing the resulting flux of the CMIP7 model with the CMIP6 model, the new model gives a higher flux under almost all conditions. The progression towards lower latitudes with increasing magnetic disturbances is weaker than in the previous model. Significant differences between the two hemispheres in the CMIP7 model are also observed, with higher fluxes in the Southern Hemisphere in disturbed conditions and at lower latitudes.

The higher fluxes of the new model also lead to significantly larger atmospheric ionization rates. As a result, the production of NO_x species by electron precipitation in chemistry-climate models will be significantly higher with this new forcing dataset. It also implies larger ozone loss and potentially stronger impacts on atmospheric dynamics. The quantification of these effects is a task for future chemistry-climate model studies.

Acknowledgments

All authors contributed actively to the conception, development and evaluation of the model described in this paper. The editor thanks Theodoros Sarris and Octav Marghitu for their assistance in evaluating this paper.

Funding

Max van de Kamp was supported by the Research Council of Finland (grant 360433-ANAON) and by the European Union (ERC Starting Grant, LOUARN, 101161971). Views and opinions expressed in this paper are, however, those of the authors only and do not necessarily reflect those of the European Union or the European Research Council. Neither the European Union nor the granting authority can be held responsible for them. Timo Asikainen was

supported by the Research Council of Finland (SOLEMIP Project No. 357249) and the University of Oulu Kvantum Institute (Spearhead project EPICC). Bernd Funke was supported by the European Union's Horizon Europe Framework Programme (HORIZON) under Grant Agreement 101137656 and by the Agencia Estatal de Investigación, MCIN/AEI/10.13039/501100011033, through grant nos. PID2022-141216NB-I00 and CEX2021-001131-S. Dan Marsh was supported by the United Kingdom (UK) Natural Environment Research Council (NERC) grants DRivers and Impacts of Ionospheric Variability with EISCAT-3D (DRIIVE) (NE/W003325/1) and MesoS2D: sub-seasonal to decadal prediction for the mesosphere (NE/V018442/1). Pekka Verronen was supported by the Research Council of Finland (grant no. 354331 GERACLIS; grant no. 365202 SafeEarth) and University of Oulu's Kvantum Institute (Spearhead Project CIEPPAR).

Data availability statement

The NOAA/POES data used in this study are available from the National Oceanic and Atmospheric Administration at <https://www.ncei.noaa.gov/data/poes-metop-space-environment-monitor/access/>. The A_p index data used in this paper were obtained from GFZ Data Services, <https://datapub.gfz.de/download/10.5880.Kp.0001/>. The NRLMSISE-00 model can be obtained from <https://map.nrl.navy.mil/map/pub/nrl/NRLMSIS/NRLMSISE-00/>. The ionization data which resulted from this model and are used in CMIP7 are included in the data set which can be downloaded from: <https://cloud.iaa.es/index.php/s/nJFTpcnFwZ3smTo>. Information about these data can be found at <https://www.solarisheppa.kit.edu/75.php>.

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Cite this article as: van de Kamp M, Asikainen T, Nesse H, Seppälä A, Funke B, et al. 2026. An improved model of energetic electron precipitation providing a long-term ionization dataset for CMIP7. *J. Space Weather Space Clim.* **16**, 35. <https://doi.org/10.1051/swsc/2026032>.

Appendix A Convolution of Ap

A.1 Derivation

In order to include a time-integration effect of the magnetic index Ap into the model, a time convolution of Ap was used. This convolution function was derived as follows.

First, all samples of Ap equal to 0 were replaced by 0.125. Then, for each energy bin ($E = 30\text{--}100\text{ keV}$, $100\text{--}300\text{ keV}$, $300\text{--}1000\text{ keV}$), and for each CGM latitude ($\phi = 52^\circ\text{--}88^\circ$, with a 2° step):

(1) The first term of the convolution function is equal to 1: $w_0 = 1$.

(2) Then, for $k = 1, 2, 3, \dots$ (maximum 30):

(a) The next term w_k was found by adjusting its value to maximize the correlation coefficient:

$$C \left(\sum_{i=0}^{k-1} [w_i \ln Ap(t - it_0)] + w_k \ln Ap(t - kt_0), \ln F(t) \right)$$

where t = time, $t_0 = 1$ day, $C(\dots)$ indicates the correlation coefficient, calculated over the full measurement period, and F is the electron flux at the respective energy channel and CGM latitude, averaged per day for both hemispheres.

(b) If $|w_k|$ is smaller than 0.1 times the maximum of $|w_0| \dots |w_{k-1}|$, we stop here. Otherwise, we increase k by 1 and do the next iteration.

(3) All w_k were adjusted to give the function a sum of 1, as:

$$w_{k(\text{adjusted})} = w_k / \sum_{i=0}^{30} w_i \quad \text{for all } k. \quad (\text{A.1})$$

In this way, the full array of convolution coefficients w_k was derived. They are summarised in [Table A.1](#).

Furthermore, the convoluted Ap is multiplied by a scale factor to make its long-term average equal to that of the unconvoluted Ap . These scale factors (dependent on CGM latitude and energy) are summarised in [Table A.2](#).

A.2 Use of the function

The convolution function is used as follows: first, all samples of Ap equal to 0 are replaced by 0.125. Then, for each energy and CGM latitude, the convoluted Ap , referred to as Ap_{co} , is given by

$$\begin{aligned} Ap_{co}(t, \phi, E) &= m_{\phi, E} \exp \left(\sum_{k=0}^{30} w_{k, \phi, E} \ln Ap(t - kt_0) \right) \\ &= m_{\phi, E} \prod_{k=0}^{30} Ap(t - kt_0)^{w_{k, \phi, E}} \end{aligned} \quad (\text{A.2})$$

where the coefficients $w_{k, \phi, E}$ for all CGM latitudes ϕ , energies E and time shifts k , are given in [Table A.1](#). The scale factors $m_{\phi, E}$ for all ϕ and E are given in [Table A.2](#).

Appendix B Model formulation

The CMIP7 electron precipitation model, derived as described in this paper, is formulated as follows. The electron flux at any time t (resolution: 1 day), any CGM latitude ϕ , either hemisphere, and any of the three energy ranges ($E = 30\text{--}100\text{ keV}$, $100\text{--}300\text{ keV}$, $300\text{--}1000\text{ keV}$) is given by:

$$F(t, \phi, E) = \frac{d}{\frac{1}{a (Ap_{co}(t, \phi, E)/10)^b} + \frac{1}{c}} \quad (\text{B.1})$$

with

$$a_A = a_1 \operatorname{sech}(a_2(|\phi| - |\phi_a|)) \quad (\text{B.2})$$

$$a_B = a_3 \times a_4^{|\phi|} \quad (\text{B.3})$$

$$a = \begin{cases} a_A & (|\phi| > |\phi_a|) \\ \max(a_A, a_B) & (|\phi| < |\phi_a|) \end{cases} \quad (\text{B.4})$$

$$b = b_1 \operatorname{sech}(b_2(|\phi| - |\phi_b|)) \quad (\text{B.5})$$

and where $Ap_{co}(t, \phi, E)$ is the convoluted magnetic index Ap (see [Appendix A](#)) and the parameters $a_1, a_2, a_3, a_4, \phi_a, b_1, b_2, \phi_b, c$ and d are given in [Table B.1](#) for each energy range E and both hemispheres.

Table A.1. Convolution factors $w_{k,\phi,E}$ for Ap , for all energies E , CGM latitudes ϕ , and time shifts k .

E: 30–100 keV																			
k	ϕ (°)																		
	52	54	56	58	60	62	64	66	68	70	72	74	76	78	80	82	84	86	88
0	0.109	0.170	0.302	0.477	0.663	0.681	0.648	0.616	0.544	0.493	0.474	0.434	0.403	0.436	0.462	0.378	0.478	0.508	0.384
1	0.070	0.117	0.182	0.238	0.273	0.257	0.249	0.259	0.288	0.293	0.303	0.339	0.361	0.328	0.137	0.074	0.128	0.107	0.156
2	0.037	0.066	0.081	0.070	0.064	0.062	0.067	0.087	0.124	0.163	0.171	0.180	0.176	0.154	0.136	0.109	0.109	0.135	0.116
3	0.047	0.070	0.080	0.065			0.036	0.038	0.043	0.050	0.053	0.046	0.060	0.061	0.098	0.110	0.116	0.100	0.142
4	0.054	0.075	0.076	0.056						0.001				0.022	0.073	0.125	0.123	0.117	0.119
5	0.061	0.076	0.071	0.051											0.051	0.074	0.046	0.033	0.047
6	0.064	0.072	0.062	0.042											0.042	0.052			0.036
7	0.065	0.066	0.051													0.056			
8	0.061	0.058	0.041													0.022			
9	0.061	0.051	0.034																
10	0.053	0.039	0.021																
11	0.047	0.033																	
12	0.045	0.029																	
13	0.037	0.022																	
14	0.033	0.024																	
15	0.029	0.018																	
16	0.024	0.012																	
17	0.021																		
18	0.023																		
19	0.018																		
20	0.016																		
21	0.015																		
22	0.009																		
E: 100–300 keV																			
k	ϕ (°)																		
	52	54	56	58	60	62	64	66	68	70	72	74	76	78	80	82	84	86	88
0	0.062	0.125	0.207	0.269	0.368	0.476	0.458	0.373	0.291	0.385	0.490	0.566	0.508	0.377	0.380	0.476	0.453	0.472	0.480
1	0.079	0.177	0.241	0.257	0.274	0.304	0.325	0.360	0.392	0.368	0.319	0.282	0.152	0.095	0.144	0.169	0.177	0.179	0.218
2	0.069	0.125	0.115	0.106	0.108	0.107	0.119	0.169	0.220	0.189	0.152	0.104	0.122	0.096	0.133	0.122	0.136	0.143	0.121
3	0.075	0.103	0.074	0.067	0.068	0.069	0.065	0.076	0.080	0.055	0.038	0.048	0.099	0.110	0.144	0.128	0.126	0.118	0.160
4	0.078	0.093	0.066	0.060	0.053	0.045	0.032	0.023	0.017	0.004			0.072	0.141	0.135	0.083	0.081	0.083	0.020
5	0.079	0.081	0.060	0.056	0.052								0.046	0.083	0.046	0.022	0.026	0.005	
6	0.081	0.073	0.054	0.051	0.043									0.063	0.019				
7	0.074	0.060	0.051	0.044	0.034									0.034					
8	0.067	0.045	0.042	0.035															
9	0.061	0.037	0.036	0.032															
10	0.053	0.029	0.031	0.024															
11	0.043	0.020	0.021																
12	0.037	0.020																	
13	0.026	0.013																	
14	0.022																		
15	0.023																		
16	0.015																		
17	0.014																		
18	0.014																		
19	0.011																		
20	0.012																		
21	0.004																		
E: >300 keV																			
k	ϕ (°)																		
	52	54	56	58	60	62	64	66	68	70	72	74	76	78	80	82	84	86	88
0	0.013	0.031	0.038	0.044	0.053	0.068	0.060	0.024	0.358	0.974	0.493	0.696	0.588	0.730	0.712	0.723	0.696	0.932	0.544
1	0.125	0.126	0.082	0.084	0.084	0.091	0.081	0.052	0.150	0.026	0.052	0.118	0.120	0.093	0.101	0.088	0.107	0.068	0.083
2	0.182	0.151	0.087	0.099	0.118	0.152	0.221	0.359	0.228		0.070	0.092	0.134	0.136	0.157	0.132	0.156		0.155
3	0.152	0.124	0.075	0.091	0.120	0.169	0.235	0.343	0.155		0.064	0.071	0.063	0.041	0.030	0.056	0.042		0.117
4	0.130	0.104	0.068	0.079	0.107	0.151	0.194	0.179	0.110		0.070	0.022	0.061						0.064
5	0.102	0.103	0.063	0.071	0.092	0.120	0.134	0.043			0.076		0.034						0.038
6	0.075	0.083	0.059	0.067	0.083	0.091	0.062				0.063								
7	0.058	0.070	0.054	0.063	0.072	0.065	0.012				0.113								
8	0.060	0.057	0.050	0.058	0.062	0.047													
9	0.050	0.055	0.047	0.054	0.054	0.032													
10	0.041	0.040	0.043	0.046	0.038	0.013													
11	0.013	0.024	0.037	0.041	0.033														
12		0.023	0.033	0.035	0.025														
13		0.009	0.024	0.030	0.019														
14			0.023	0.028	0.016														
15			0.024	0.023	0.017														
16			0.014	0.019	0.008														
17			0.014	0.014															
18			0.015	0.013															
19			0.014	0.012															
20			0.017	0.010															
21			0.013	0.011															
22			0.011	0.008															
23			0.013																
24			0.019																
25			0.020																
26			0.025																
27			0.019																
28			0.001																

Table A.2. Scale factors $m_{\phi,E}$ in the convolution function for Ap , for all energies E and CGM latitudes ϕ .

E (keV)	ϕ ($^{\circ}$)																		
	52	54	56	58	60	62	64	66	68	70	72	74	76	78	80	82	84	86	88
30–100	1.333	1.310	1.264	1.192	1.094	1.091	1.110	1.118	1.133	1.144	1.146	1.145	1.148	1.155	1.212	1.253	1.207	1.200	1.226
100–300	1.323	1.289	1.269	1.252	1.213	1.159	1.156	1.160	1.159	1.149	1.138	1.129	1.193	1.246	1.225	1.195	1.199	1.190	1.176
>300	1.274	1.290	1.335	1.324	1.304	1.269	1.225	1.164	1.206	1.009	1.233	1.127	1.172	1.112	1.115	1.117	1.121	1.022	1.190

Table B.1. Model parameters for the CMIP7 electron precipitation model, for each energy channel and each hemisphere.

E (keV)	a_1	a_2	ϕ_a ($^{\circ}$)	a_3	a_4	b_1	b_2	ϕ_b ($^{\circ}$)	c	d
Northern Hemisphere										
30–100	4.550×10^5	0.646	66.9	0.2412	1.169	3.530	0.172	62.1	1.55×10^6	1.633
100–300	7.250×10^3	0.474	64.6	1.605	1.102	2.574	0.136	59.4	8.23×10^5	1.924
300–1000	1.733×10^3	0.512	62.3	32.87	1	2.581	0.217	54.7	2.05×10^4	1.360
Southern Hemisphere										
30–100	2.729×10^5	0.652	−65.7	1.780	1	3.565	0.198	−61.4	2.49×10^6	1.777
100–300	6.249×10^3	0.510	−63.8	682.1	1	2.459	0.193	−60.3	1×10^7	1.969
300–1000	1.822×10^3	0.479	−61.2	76.44	1	2.641	0.218	−54.5	3.22×10^4	1.458