Atmospheric odd nitrogen response to electron forcing from a 6D magnetospheric hybrid-kinetic simulation

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Abstract. Modelling the distribution of odd nitrogen (NOₓ) in the polar middle and upper atmosphere has proven to be a complex task. Firstly, its production by energetic electron precipitation is highly variable on hourly time scales. Secondly, there are uncertainties in the measurement-based but simplified electron flux data sets that are currently used in atmosphere and climate models. The altitude distribution of NOₓ is strongly affected by atmospheric dynamics also on monthly time scales, particularly in the polar winter periods when the isolated air inside the polar vortex descends from lower thermosphere to mesosphere and stratosphere. Recent comparisons between measurements and simulations have revealed strong differences in the NOₓ distribution, with questions remaining about the representation of both production and transport in models. Here we present for the first time a novel approach, where the electron atmospheric forcing in the auroral energy range (50 eV – 50 keV) is derived from a magnetospheric hybrid-kinetic simulation with a detailed description of energy range and resolution, and spatial and diurnal distribution. These electron data are used as input in a global whole atmosphere model to study the impact on polar NOₓ and ozone. We will show that the magnetospheric electron data provides a realistic representation of the forcing which leads to considerable impact in the lower thermosphere, mesosphere and stratosphere. We find that during the polar winter the simulated auroral electron precipitation increases the polar NOₓ concentrations up to 200 %, 50 %, and 7 % in the lower thermosphere, mesosphere, and upper stratosphere, respectively, when compared to no auroral electron forcing in the atmospheric model. These results demonstrate the potential of combining magnetospheric and atmospheric simulations for detailed studies of solar wind – atmosphere coupling.

1 Introduction

Understanding the polar mesosphere–lower thermosphere–ionosphere (MLTI) region presents a unique challenge. The MLTI covers the approximate altitude range 80–200 km, and is hence simultaneously too high for many ground-based observations and too low for efficient in-situ satellite-borne measurements (Palmroth et al., 2021). Therefore accurate modelling of the
MLTI is required to complement the scarce direct measurements to further our knowledge of the region. The polar MLTI (polewards of 60°) depends on solar radiation, which drives both diurnal and seasonal effects due to the planet’s rotation and axis of inclination. The magnetosphere, with its many poorly understood mechanisms, also controls the physical state of the polar MLTI through its electromagnetic forcing (e.g. Sarris et al., 2023). Hence the polar MLTI is characterized by complex dynamics between the neutral atmosphere and the electromagnetic ionosphere, leading to great uncertainties in our understanding of the region.

Nitric Oxide (NO), a member of the odd nitrogen family (NOx, defined as the sum of N, NO, and NO2), is one of the most important species in the polar MLTI energetics (e.g. Mlynczak et al., 2005). NOx is produced in the atmosphere as the result of solar energetic radiation while in the polar regions energetic particle precipitation (EPP) also becomes a major source (Barth et al., 2001). Through its descent inside the polar vortex, NOx also provides a dynamical connection between MLTI and stratospheric altitudes (Funke et al., 2014). In the upper stratosphere, NOx transport from above leads to depletion of ozone which can be measured using satellite-based instruments (Damiani et al., 2016). Because ozone strongly absorbs solar ultraviolet radiation, it is one of the main constituents determining the thermal structure of the stratosphere. Through ozone, NOx can have an impact on the radiative balance of the polar atmosphere beyond just within the MLTI.

There are essentially three EPP sources of NOx: solar protons, radiation belt electrons, and auroral electrons (Verronen and Rodger, 2015). The energy of solar protons and radiation belt electrons are large enough for them to penetrate and produce NOx in the mesosphere and stratosphere, allowing a more direct impact on ozone. These two sources of NOx can currently be represented in long-term atmospheric and climate simulations although uncertainties are still present in the latter (Matthes et al., 2017; Sinnhuber et al., 2021). Because the precipitation of auroral electrons, the third source of NOx, is restricted to thermospheric altitudes due to its lower energy, its impact on the stratospheric ozone balance is to a larger extent affected by polar atmosphere dynamics and is not fully understood. Auroral electrons originate in the magnetosphere, chiefly via substorms, where the magnetotail suddenly disrupts and launches a vast number of electrons and protons of variable energies towards the ionosphere (Palmroth et al., 2017; Palmroth et al., 2023). Substorms and pulsating aurora, a phenomenon during the substorm recovery phase, have been shown to produce NOx (Seppälä et al., 2015; Turunen et al., 2016). As substorms occur on a regular basis, the forcing from auroral electron precipitation also takes place on a roughly daily basis (Partamies et al., 2013). In long-term climate simulations, models typically include the NOx production from auroral electrons using proxy models based on geomagnetic indices, and typically use a simplistic representation for their energy spectrum (e.g. Marsh et al., 2007).

Atmospheric models are struggling to produce correct amounts of NOx in the MLTI when compared to observations (Randall et al., 2015). This inaccuracy leads to an incomplete representation of the radiative balance within the polar region through the NOx impact on stratospheric ozone (Szelag et al., 2022). The suggested reasons for NOx deficit include underestimation of radiation belt electron forcing (Hendrickx et al., 2018). However, the production from auroral electrons (<30 keV) likely also plays a role in the discrepancy because it is a relatively continuous as well as probably the largest contributor to the overall NOx budget in the polar MLTI (Sinnhuber et al., 2011). The simplified inclusion of auroral electrons in atmospheric simulations is incomplete both in terms of auroral electron fluxes and spectra, and these may account for the missing NOx production. Further, the transport of thermospheric NOx to the mesosphere and lower altitudes remains a challenge in models.
The lack of detailed, long-term auroral electron forcing in climate models could therefore obstruct accurate evaluation of polar climate variability.

In this paper, we report on the first-time combination of magnetospheric and atmospheric modelling, with the aim of quantifying the auroral electron impact on NO\textsubscript{x} and ozone. We use eVlasiator, a variant of the global hybrid-Vlasov model Vlasiator, to simulate the electron fluxes at auroral energies from 50 eV to 50 keV. Compared to proxy-based parameterizations, the modelled magnetospheric electron fluxes characterise the altitude extent and distribution of the forcing in more detail. Atmospheric ionization rates derived from these fluxes are then used in the Whole Atmosphere Community Climate Model (WACCM) to determine auroral electron impact on NO\textsubscript{x} and ozone from the MLTI to the upper stratosphere. Finally, we discuss the potential of the magnetosphere-atmosphere coupling in understanding the solar wind – atmosphere coupling and outline future steps of development.

2 Methods

2.1 Vlasiator and eVlasiator

Vlasiator is a global hybrid-Vlasov model simulating ion-kinetic plasma physics of near-Earth space (Palmroth et al., 2018), which recently became capable of running 6D simulations (Ganse et al., 2023). Vlasiator models the collisionless ion populations directly as velocity distribution functions (VDFs), discretized on Cartesian grids, allowing for accurate representation of phenomena such as wave-particle interactions (Dubart et al., 2020) and precipitating protons (Grandin et al., 2019, 2020, 2023), which cannot be modelled using the magnetohydrodynamic (MHD) codes (Palmroth et al., 2006). The spatial simulation domain is divided into either a uniform Cartesian 2D spatial mesh or a Cartesian 3D mesh with regions of interest refined with an octree cell-based refinement algorithm (Ganse et al., 2023; Kotipalo et al., 2024). Each spatial cell contains a 3D velocity mesh consisting of cubic uniform Cartesian cells. In order to fit the massive amount of simulation data into memory, Vlasiator utilizes a sparse algorithm (von Alfthan et al., 2014) where only those regions of velocity space which are deemed to contribute to plasma moments in a significant fashion are stored and propagated. This is implemented through discarding blocks of the grid which have phase-space density below a pre-defined threshold, yet maintaining a buffer region around those cells in order to ensure physical behaviour at the edges of the velocity domain. The simulation state is propagated directly via the Vlasov equation, with fields solved on a regular Cartesian grid and closure provided by MHD Ohm’s law with the Hall and electron pressure gradient terms included.

A typical Vlasiator simulation models the global geomagnetic domain of the Earth, spanning tens to hundreds of Earth radii \( R_E = 6371 \text{ km} \) in each dimension with a spatial resolution of the order of the ion inertial length, and with an inner boundary positioned at roughly 5 Earth radii. The velocity grid is defined so to be able to discretize the inflowing solar wind. The Earth’s magnetic field is modeled at full strength, facilitating direct comparison with spacecraft observations. Sample simulation parametrizations can be found for example in Horaites et al. (2023) and Palmroth et al. (2023). Vlasiator runs are propagated on the order of hundreds to thousands of seconds, in order to facilitate self-consistent formation of the magnetospheric domain and its dynamics, but constrained by the availability of computational resources.
eVlasiator is an offshoot of Vlasiator which considers electrons as a kinetic population (Battarbee et al., 2021) instead of the usual ions. eVlasiator is not a standard full-kinetic plasma code, instead evaluating electron response to ion-scale structures and fields. What eVlasiator does provide is realistic electron VDFs evaluated for a single point in time from a larger Vlasiator simulation, such as presented in Alho et al. (2022) and validated against spacecraft observations. Since Alho et al. (2022), eVlasiator has been extended to work on 6D Vlasiator inputs, with the code available via Zenodo (Pfau-Kempf et al., 2022). Thus, eVlasiator can be used to infer kinetic electron VDFs along connected field lines, and thus also allowing the calculation of precipitating electron fluxes. Due to numerical constraints, eVlasiator utilizes a reduced mass ratio, for example \( m_p/m_e \approx 183.6 \) in Alho et al. (2022).

### 2.2 Simulating precipitating particle fluxes

In (e)Vlasiator, precipitating particle differential number fluxes are calculated in every ordinary space cell, at every output time step in the simulation. At a given position \( r \) in ordinary space, the precipitating electron differential number flux value at energy \( E \) is given by

\[
\mathcal{F}_e(E, r) = \frac{v^2}{m_e} \langle f_e(r, v, \theta, \phi) \rangle_{\theta_0}
\]

with \( v = \sqrt{2E/m_e} \) the corresponding electron speed, \( m_e \) the electron mass, \( f_e \) the electron phase-space density, \( \theta \) the pitch angle, \( \varphi \) the gyrophase angle, and \( \theta_0 \) the bounce loss cone angle, and where \( \langle . \rangle_{\theta_0} \) denotes averaging inside the loss cone. The full derivation of the version of Eq. (1) for proton fluxes can be found in Grandin et al. (2019). Subsequent studies investigating dayside and nightside auroral proton precipitation under various driving conditions are presented in Grandin et al. (2020, 2023) and Horaites et al. (2023).

In this study, we present for the first time precipitating electron fluxes obtained with eVlasiator. The Vlasiator run used as the basis for the eVlasiator simulation is the same as described in e.g. Palmroth et al. (2023), and the eVlasiator run is the first 3D-3V magnetospheric eVlasiator simulation. The Vlasiator simulation is driven by a solar wind of \( V_x = -750 \text{ km s}^{-1} \) with a density of \( n_p = 10^6 \text{ m}^{-3} \) and a temperature of 0.5MK. The inner boundary consists of stationary plasma at a radius of 4.7\( R_E \) and is modelled as a near-conducting sphere. The spatial mesh has a base resolution of 8000\( \text{ km} \) at the lowest refinement level, increasing up to 1000\( \text{ km} \) in regions of interest such as the magnetotail and the magnetopause. The ion velocity cell resolution is 40\( \text{ km s}^{-1} \). The Vlasiator simulation was propagated for a total of 1506 seconds. The eVlasiator run based on the final state of the magnetospheric Vlasiator simulation utilized a mass ratio of \( m_p/m_e = 40 \) and an electron velocity cell resolution of 128\( \text{ km s}^{-1} \), whilst maintaining the spatial resolution and fields of the Vlasiator simulation. Due to computational constraints, the eVlasiator simulation was run selectively on the inner magnetosphere only, spanning \( X \in [-20.1, 17.6] R_E \) and \( Y, Z \in [-20.1, +20.1] R_E \), and was propagated for a time extent of 1.4s. Figure 1 shows the Vlasiator and eVlasiator simulation domains and examples of electron velocity distributions in eVlasiator.
2.3 Construction of the auroral-electron forcing dataset

2.3.1 Mapping of the ionosphere grid to the eVlasiator simulation domain

To obtain the forcing dataset for WACC M consisting of precipitating electron fluxes at auroral energies (0.05–50 keV) as a function of magnetic local time (MLT) and geomagnetic latitude (MLAT), we first construct a MLT–MLAT grid at ionospheric altitudes, which we map to the magnetosphere. The procedure is similar to that presented in Grandin et al. (2023), with a notable difference to account for the specific setup of the eVlasiator run. It is described in detail in Appendix A.

It is worth highlighting that the obtained precipitating electron fluxes are the result of the physical processes described in the eVlasiator simulation. These do not include some of the important processes for auroral electron acceleration and pitch-angle scattering, such as inner-magnetospheric waves or field-aligned potential drops above the ionosphere. As a consequence, the precipitating fluxes extracted from the eVlasiator run are lower than in reality. For this reason, calibration with observational data has been performed as explained in the next section.
2.3.2 Calibration of the eVlasiator fluxes with DMSP observations

To calibrate the eVlasiator differential number fluxes with observations, we use two pairs of overpasses of Defense Meteorological Satellite Program (DMSP) spacecraft during similar driving conditions. Each pair contains a polar cusp overpass in the northern hemisphere (NH) and a nightside oval overpass in the southern hemisphere (SH). The dates of the events are 1 August 2011 (06:00–07:30 UT) and 10 October 2015 (05:30–06:30 UT). We use measurements from the Special Sensor J (SSJ) instrument (Redmon et al., 2017), which provides particle counts within a field of view spanning $4^\circ \times 90^\circ$ in the observation plane (Hardy et al., 2008). Precipitating electron differential number fluxes are collected in 19 logarithmically spaced energy bins between 30 eV and 30 keV. For the first (second) event, SSJ measurements from the DMSP-F16 (F17) and DMSP-F18 (F17) spacecraft are considered. These two events were previously used for precipitating proton flux comparison between Vlasiator and observations in Grandin et al. (2023).

A detailed description of the eVlasiator flux calibration based on the DMSP observations is given in Appendix B. In summary, we apply an energy-dependent correction factor to the eVlasiator fluxes in the polar cusp and in the nightside auroral oval. There is one such correcting function for the cusp fluxes, $\alpha_{\text{day}}(E)$, and another one for the nightside fluxes, $\alpha_{\text{night}}(E)$. We first calculate the ratio between the measured differential number fluxes by DMSP/SSJ and those obtained with eVlasiator, along the DMSP orbit, separately for the dayside and nightside overpasses. Then, for a given electron energy, we examine the distribution of the obtained ratios, and retain a certain quantile for which we fit a polynomial function (as a function of energy). Which quantile we retain is determined such that the ratio between the integrated energy fluxes is close to one (see Appendix B4 for details). We have determined that the 61st (67th) quantile optimally fulfils this condition for the dayside (nightside) ratios.

2.4 Whole Atmosphere Community Climate Model

The Whole Atmosphere Community Climate Model (WACCM) is a global 3-D chemistry-climate model that covers the altitude range from the surface up to about 140 km. The model incorporates various physical processes and interactions within the atmosphere, including dynamics, chemistry, radiation, and their interactions with the Earth’s surface and external forcings such as solar radiation and greenhouse gases (Marsh et al., 2013; Gettelman et al., 2019). Here, we use WACCM-D, a variant of WACCM that enhances standard parameterizations of HO$_x$ and NO$_x$ production by incorporating a comprehensive ionospheric chemistry. This alteration aims to better replicate the observed impacts of energetic particle precipitation on the composition of the mesosphere and upper stratosphere (Verronen et al., 2016; Andersson et al., 2016). We conducted specified dynamics simulations (SD) where horizontal winds, temperature, pressure, surface stress and heat fluxes are adjusted to 3 hourly Modern-Era Retrospective Analysis for Research and Applications (MERRA-2) reanalysis data (Molod et al., 2015). The model is constrained by the reanalysis data up to about 50 km while the dynamics are free-running at altitudes above. We use version 6 of the model with a latitude × longitude resolution of $0.95^\circ \times 1.25^\circ$.

As a default, WACCM input of solar and geomagnetic forcing is taken as recommended for the Coupled Model Intercomparison Project Phase 6 (Matthes et al., 2017). In addition to total and spectral irradiance, this data set also includes atmospheric
ionization rates due to solar protons, medium-energy electrons, and galactic cosmic rays. The auroral electron precipitation, however, is driven by the geomagnetic $K_p$ index, and represented by a Maxwellian energy distribution and a characteristic energy of 2 keV (Roble and Ridley, 1987). Further, to account for the impact of electron forcing above its altitude range, WACCM makes use of the three-dimensional nitric oxide empirical model (NOEM) to set NO at the model upper boundary. NOEM is driven by $K_p$, day of year, and solar 10.7 cm radio flux (Marsh et al., 2004).

### 2.4.1 Atmospheric ionization rates

Using the eVlasiator electron energy–flux spectra, we calculated corresponding forcing for our WACCM atmospheric simulations. In WACCM-D, ionization by EPP drives the initial production rates of ions and neutrals due to particle impact ionization, dissociative ionization, and secondary electron dissociation (Verronen et al., 2016, Table 1). These rates are incorporated in the WACCM ion and neutral chemistry scheme, connecting EPP forcing to the $NO_x$ and ozone concentrations.

The atmospheric ionization rates were calculated at magnetic latitudes between 63° and 88° in both hemispheres with one degree spacing. A half-an-hour temporal resolution was used for the magnetic local time throughout the day. Electron energy range from 50 eV to 50 keV was considered with 32 individual grid points. We made use of the method of parameterized electron impact ionization by Fang et al. (2010). Atmosphere for the calculation was calculated using the NRLMSIS-00 model by Picone et al. (2002). This is the same method that was used to create electron ionization rates for the Coupled Model Intercomparison Project Phase 6 (van de Kamp et al., 2016; Matthes et al., 2017). Here, however, the electron flux data are not from a proxy model based on satellite observations but from the eVlasiator magnetospheric simulations. Figure 2 shows an example of eVlasiator spectra and corresponding atmospheric ionization rates. Large differences in fluxes at different geomagnetic latitudes result in a similarly large range of ionization. According to the spectral energy range (electron energies <50 keV), the bulk ionization is restricted to altitudes above 90 km.

### 2.4.2 WACCM simulation setup and output

All WACCM simulations were set up using the recommended CMIP6 solar and geomagnetic forcing (Matthes et al., 2017). WACCM-D was run from January 2005 to June 2006 in order to cover both southern and northern hemispheric winters. In this study, we consider daily average outputs of the ionization rates, as well as $NO_x$ and ozone concentrations.

In order to better implement the eVlasiator derived ionization rates, we input the forcing on a magnetic local time dependent grid. For this purpose, we created a modification for WACCM, which enables $MLAT \times MLT$ ionization forcing and turns off the $K_p$ index driven parameterized aurora, in order to fully replace WACCM’s default aurora with eVlasiator (Häkkilä, 2024). In addition to geomagnetic latitude, support for $L$-shell $\times$ MLT grids is also included, as well as a version that does not turn off the $K_p$ aurora. The MLT-dependency code requires daily forcing files, but supports multiple time steps per daily file.

Two WACCM-D simulations were performed using the MLT-dependent ionization input. First, a simulation with the eVlasiator-derived ionization rates as input in WACCM-D on a $MLAT \times MLT$ grid of $1^\circ \times 0.5h$ resolution (VLAS). For each day of the simulation we use the same ionization data, since only one time step was available from the eVlasiator output. The second MLT-dependent run was a reference simulation, with the ionization from auroral electrons set to 0 at all gridpoints. This way
the REF run has no auroral input and no $K_p$-driven parameterized aurora. We also performed simulations using WACCM’s parameterized Kp-driven aurora, to use as comparisons against the eVlasiator auroral forcing. Since the VLAS run was performed using the same data every day, we use a fixed $K_p$ value for the comparison runs. We performed 6 separate WACCM-D runs, each with a different, fixed $K_p$ index value from 0 to 5 (KP0–KP5), but we present here only the runs KP1 and KP2, since those most closely correspond to the level of ionization found in the eVlasiator aurora, as well as the KP0 and KP5 runs in order to give a range of the $K_p$-driven aurora. To ensure comparability, the $K_p$ indices were also fixed for the MLT-dependent simulations, as $K_p$ affects the background levels of NO$_x$ in the model through NOEM. The $K_p$ value was fixed to 0 for the REF run to create minimal conditions for comparisons. For VLAS, we considered the DMSP overpasses used for the calibration of the eVlasiator electron fluxes, which took place during $K_p$ index values around 2 and 3, for 1 August 2011 and 10 October 2015, respectively. We used the fixed the $K_p$ index 2 for the VLAS run. All the WACCM-D simulations presented here and their differences are given in Table 1.

Table 1. The WACCM-D simulation runs and differences in their setups.

<table>
<thead>
<tr>
<th>simulation</th>
<th>description</th>
<th>aurora</th>
<th>$K_p$ index (fixed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>REF</td>
<td>Reference run with no aurora</td>
<td>none</td>
<td>0</td>
</tr>
<tr>
<td>KP0</td>
<td>Default WACCM-D run with fixed $K_p = 0$</td>
<td>parameterized</td>
<td>0</td>
</tr>
<tr>
<td>KP1</td>
<td>Default WACCM-D run with fixed $K_p = 1$</td>
<td>parameterized</td>
<td>1</td>
</tr>
<tr>
<td>VLAS</td>
<td>Main run with eVlasiator aurora</td>
<td>eVlasiator</td>
<td>2</td>
</tr>
<tr>
<td>KP2</td>
<td>Default WACCM-D run with fixed $K_p = 2$</td>
<td>parameterized</td>
<td>2</td>
</tr>
<tr>
<td>KP5</td>
<td>Default WACCM-D run with fixed $K_p = 5$</td>
<td>parameterized</td>
<td>5</td>
</tr>
</tbody>
</table>
Figure 3. Polar view of integrated parameters of auroral electron precipitation in the eVlasiator run, after calibration with DMSP/SSJ observations (see Sect. 2.3.2). (a–b) Precipitating electron integrated energy flux in the northern and southern hemispheres. (c–d) Mean precipitating electron energy in the northern and southern hemisphere. In each panel, the radial coordinate is geomagnetic latitude, and the angular coordinate is magnetic local time.

3 Results

3.1 Auroral electron precipitation

3.1.1 Auroral electron fluxes from eVlasiator

Figure 3 shows the integrated parameters of the auroral electron precipitation forcing dataset obtained from eVlasiator, after the calibration with DMSP/SSJ observations (see Sect. 2.3.2). Each panel gives the data as a function of geomagnetic latitude (radial coordinate) and MLT (angular coordinate). Figures 3a and 3b show the precipitating electron integrated energy flux in the
northern and southern hemispheres, respectively. We can identify the cusp region on the dayside, between 70° and 80° MLAT and within 9–15 MLT, with flux magnitudes on the order of \(10^8\) keV cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\). On the nightside, the integrated energy flux peaks in the pre-midnight sector and within 65–70° MLAT, reaching magnitudes on the order of \(10^9\) keV cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\). The forcing is very symmetrical on the nightside, whereas slight differences can be noted in the polar cusps – these results are similar to those obtained for auroral proton precipitation and discussed in Grandin et al. (2023). Figures 3c and 3d present the mean precipitating electron energy. Values are below 1 keV on the dayside and reach up to 5 keV on the nightside.

### 3.1.2 Ionisation rates from WACCM-D

![Figure 4](https://example.com/figure4.png)

**Figure 4.** Vertically integrated auroral ionization rates, as output from WACCM-D on geographic coordinates for the northern hemisphere (geographic latitude > 50°N), 1 Jan 2006. (a) VLAS, (b) KP0, (c) KP1, (d) KP2 (e) KP5.

Comparisons of the ionization rates from eVlasiator and the \(K_p\) parameterization are shown in Figs. 4–5 for the northern hemisphere. The vertically integrated ionization rates in Fig. 4 show the full auroral oval. While the eVlasiator-derived auroral ionization rates roughly match the location of the \(K_p\)-driven ionization rates, the oval is much more sharply defined than the parameterized auroral precipitation. The sharpness can also be seen in the latitudinal extent of the aurora in Fig. 5, which shows the logarithm of the ionization rates at longitude 90°E for the VLAS and KP2 runs. The auroral ionization rates peak at roughly the same latitude, but the \(K_p\) parameterization has a much wider latitudinal spread. This difference in extent results from the limitation in the latitudinal coverage made possible by the used eVlasiator run, as the cutoff latitude of 63° MLAT corresponds to the mapping of the innermost considered locations in the magnetospheric domain (4.8 \(R_E\); see Appendix A). In future runs...
with an inner boundary closer to the Earth’s surface, this sharp cutoff near the auroral oval’s equatorward boundary could be avoided. The eVlasiator ionization rates also have a slight secondary peak on the poleward side, while the $K_p$ parameterization clearly only has one peak.

The eVlasiator auroral ionization forcing reaches deeper into the atmosphere down to around $0.01 \text{ hPa}$ ($\sim80\text{ km}$), while the $K_p$ parameterization stops at around $5 \times 10^{-4} \text{ hPa}$ ($\sim95\text{ km}$), the lower boundary of the parameterization. Though the eVlasiator ionization rates are negligible at the $0.01 \text{ hPa}$ level, the tapering off of the aurora towards lower altitudes is more gradual compared to the $K_p$ parameterization.

### 3.2 Atmospheric impact

Figure 6 shows the polar cap-averaged (geographic latitude > 60°), altitude-integrated NO$_x$ response in the auroral runs relative to the REF run with no auroral electron forcing. For both SH and NH we clearly see the NO$_x$ impact during the winter season for all the auroral forcing scenarios. The effect is naturally strongest in the thermosphere, where the auroral electrons have a direct impact, with the eVlasiator auroral precipitation causing a NO$_x$ increase of up to 200% in the SH lower thermosphere ($\sim85$–125 km). The descent of the produced NO$_x$ can also clearly be seen in the mesosphere ($\sim50$–85 km) and upper stratosphere ($\sim25$–50 km). The descent is seen in the lag when comparing the peak occurrence times, as the strongest SH thermospheric, mesospheric, and stratospheric NO$_x$ impacts occur in June, July, and August, respectively. The impact also grows weaker during the descent, since the background levels of NO$_x$ are higher at lower altitudes, and not all the produced NO$_x$ descends.
Figure 6. Auroral impact on NO\(_x\) concentrations: Polar cap (geographic latitude > 60°) averages of the integrated (a–b) lower thermosphere, (c–d) mesosphere, and (e–f) upper stratosphere for the (a, c, e) SH and (b, d, f) NH winters. Relative difference of the auroral precipitation simulation runs (colours) compared to the REF run with no auroral electron forcing. Lower thermosphere integrated from \(3 \times 10^{-3}\) hPa to \(1 \times 10^{-5}\) hPa (~85–125 km), mesosphere from 1 hPa to \(3 \times 10^{-3}\) hPa (~50–85 km), and upper stratosphere from 30 hPa to 1 hPa (~25–50 km).
Comparing the $K_p$-driven auroral precipitation runs, there is a clear scaling effect: the NO$_x$ impact grows stronger with increasing $K_p$. Even in the KP0 case the SH lower thermospheric NO$_x$ is increased by more than 90%, with KP5 reaching an increase of 680% in the SH. The eVlasiator aurora run (VLAS) corresponds to the KP1 and KP2 simulations in terms of the NO$_x$ impact, often coming closer to the KP1 scenario. This is despite the eVlasiator electron fluxes being calibrated using DMSP observations during $K_p$ index values of $\sim$2–3, and the $K_p$ index being fixed to 2 for the VLAS WACCM-D simulation.

While the VLAS impact does occasionally reach the KP2 level, with the NH mesospheric and upper stratospheric responses being very similar between the two simulations, it is possible that the parameterization is overestimating the auroral electron forcing at low $K_p$ values.

The strongest impacts are consistently seen in the southern hemisphere. The differences between the hemispheres can be explained by the instability of the polar vortex in the NH, as well as the sudden stratospheric warming (SSW) that occurred in mid-January 2006 (Manney et al., 2008; Butler et al., 2015). This is likely the cause of the double peaks in the NO$_x$ impact in the NH, since the anomalous dynamical conditions due to SSW result in higher NO$_x$ levels also in the REF simulation, so the relative differences are smaller during the SSW. Later in the winter strong downward transport resumed and caused a sharp increase of NO$_x$ in the mesosphere (Randall et al., 2009), which is also seen in our simulations.

For more details on the spatial distribution of the auroral precipitation NO$_x$ impact, Fig. 7 shows the REF wintertime averages in both hemispheres, and the increase in the VLAS simulation relative to REF. From the REF number densities we see that there is a difference in the NO$_x$ vertical profiles between the hemispheres. In the north, NO$_x$ has a polar peak at thermospheric altitudes, but in the south the peak is located lower, in the mesosphere. The occurrence of a solar proton event in mid-May 2005 likely contributes to the SH peak, as the proton precipitation penetrates to mesospheric altitudes. The increased NO$_x$ production and the longer chemical lifetime in the winter pole allows NO$_x$ to accumulate in the SH mesosphere. In the NH the SSW may also be leading to disruption in the vertical transport of NO$_x$ so that a greater proportion of produced NO$_x$ stays in the thermosphere rather than being transported downward.

In the SH the NO$_x$ is rather symmetrically distributed around the pole. Since the southern polar vortex is very stable, and there is no auroral precipitation, the NO$_x$ production in the thermosphere is driven by solar radiation. On the other hand, in the NH the peaks and troughs are distributed off-pole, and there are shifts in spatial location between the altitude layers. This is caused by the less stable nature of the NH polar vortex. The SSW that occurred during the 2005–2006 NH winter likely adds to the effect.

In the VLAS run, NO$_x$ is clearly increased throughout the thermosphere and mesosphere, and not just in the auroral oval latitudes, as NO$_x$ is transported from the production region. In the upper stratosphere, the impact is confined inside the polar vortex latitudes with little impact outside it. The SH lower thermosphere does show the effect of the electron precipitation within the auroral oval, with the strongest NO$_x$ responses reaching over 200%, corresponding to Fig. 6a. The NH thermospheric NO$_x$ response in much weaker than the SH, and the auroral oval pattern can only be distinguished on the North American longitude sector. The weaker response and its longitude distribution can overall be explained by the higher REF levels of NO$_x$ in the NH and the location of the NH thermospheric NO$_x$ peak over the Eurasian longitude sector, respectively.
Figure 7. (a–f) Altitude integrated REF NO$_x$ number densities and (g–l) the relative NO$_x$ impact of the VLAS simulation compared to REF, for (a–c, g–i) SH and (d–f, j–l) NH polar regions (geographic latitude > 50$^\circ$). Both the concentrations and relative differences are averaged over the winter seasons (Jun–Aug 2005 for SH, Dec 2005–Feb 2006 for NH). The atmospheric layers – (a, d, g, j) lower thermosphere, (b, e, h, k) mesosphere, and (c, f, i, l) upper stratosphere – correspond to Fig. 6.

In the mesosphere, the relative auroral precipitation impact is stronger in the NH, again explained by the difference in the REF background levels. This corresponds well to the mesospheric VLAS impacts in Fig. 6c–d. Stratospheric impacts show again the differences in the REF NO$_x$ number densities. The SH shows clearly the impact centred around the pole, since the NO$_x$ produced by the auroral precipitation descends within the polar vortex from thermospheric altitudes to the stratosphere. In the NH the VLAS auroral electron impact in the stratosphere has a more irregular form, and it is located off-pole, showing the less stable polar vortex.

The upper stratospheric ozone responses to the auroral electron forcing scenarios are shown in Fig. 8. The O$_3$ impact is much weaker than NO$_x$, and comparing the KP5 SH results from Fig. 6, and Fig. 8, we see that a NO$_x$ increase of over 600% in the lower thermosphere leads to an increase of around 35% NO$_x$ in the upper stratosphere, corresponding to a reduction in upper
Upper stratospheric ozone response to auroral electron forcing: daily relative difference in vertically integrated ozone number densities from the auroral precipitation simulation runs (colours) compared to the REF run with no auroral precipitation. Polar cap averages (geographic latitude > 60°) for (a) SH and (b) NH winters. stratospheric O$_3$ by only 2.5 %. Similarly for the VLAS run, we see an increase of up to 200 % in the lower thermospheric NO$_x$, which results in a decrease of around 0.7 % in upper stratospheric ozone. As with NO$_x$, the ozone impact is stronger in the SH, and the NH upper stratospheric impact is less than 0.8 % even in the KP5 case when compared to no auroral electron forcing.

### 4 Discussion

Our results demonstrate a successful interfacing of magnetospheric and atmospheric simulations. We are able to produce realistic auroral electron precipitation fluxes from eVlasiator, and they have been applied as auroral electron forcing in the WACC model. The simulated electron fluxes produce atmospheric impacts comparable to WACC’s current auroral electron parameterization, but with enhanced information on energy and spatial distribution. Thus this work presents the potential for future studies on the interaction between the solar wind and the atmosphere, e.g., for the study of the atmospheric impacts of magnetospheric substorms. Eventually, atmospheric forcing could be driven directly by solar wind parameters instead of...
proxy-based parameterizations built on limited magnetospheric electron flux data. In the future, this would also make way for near-real-time predictions of the atmospheric response. First steps towards this include the production of time-dependent auroral electron precipitation forcing from the magnetospheric simulations, on an extended temporal scale more useful to long-term atmospheric simulations.

Our results also indicate that the current parameterization of aurora may be overestimating the auroral forcing, at least at low $K_p$ index values. Further studies are needed to ascertain the correct level of auroral electron forcing, including eVlasiator simulations of the auroral electron fluxes during periods of higher $K_p$ indices. Satellite observations of NO$_x$ species could be used to study the accurate levels of NO$_x$ production that should result from auroral electrons. In addition, electrons at energies beyond the auroral range (>50 keV) should also be considered, e.g. through the inclusion of reconnection and radiation belt processes in future versions of Vlasiator. This could aid in bridging the gap between auroral and medium-energy electrons.

Limitations of the magnetospheric models should also be considered. As pointed out in Sect. 2.3.1, eVlasiator does not model all sources of precipitating auroral electrons, an therefore underestimated the total precipitating fluxes. We have mitigated the effect of this underestimation in this study by using the DMSP observations to calibrate the electron fluxes. The latitudinal extent of the eVlasiator-derived auroral precipitation is also limited compared to the $K_p$ parameterization, arising from the distance of the eVlasiator run’s inner boundary from the surface of the Earth. We have not considered this limitation in the interpretation of the atmospheric impacts of the precipitation. Auroral ionization rates for future eVlasiator simulations with a less sharp cutoff on the equatorward side of the auroral oval will therefore likely provide an enhancement in the NO$_x$ response, and, as seen in Fig. 7, the NO$_x$ impact is not limited to the auroral oval region.

5 Conclusions

In this study we have demonstrated for the first time a novel approach to investigating the role of auroral electron precipitation in the MLTI. We used eVlasiator to simulate electron precipitation fluxes at auroral energies (50 eV–50 keV) that were scaled using satellite observations to account for deficiencies in the magnetospheric model. Ionization rates derived from the electron fluxes were then used as input in WACCM-D in order to analyze the atmospheric NO$_x$ and ozone impacts of the auroral electron precipitation. We found the strongest response in the SH polar lower thermosphere, where the eVlasiator-derived auroral precipitation increased NO$_x$ concentrations up to 200 %. In the mesosphere there was an increase of more than 50 % in NO$_x$ in both hemispheres. The auroral precipitation response can also be seen in the upper stratosphere, where we see a NO$_x$ increase of around 7 %, which corresponds to a peak decrease of 0.7 % in upper stratospheric ozone.

As comparison to the eVlasiator-derived auroral precipitation we used WACCM’s parameterization of auroral electron forcing, which is driven by the $K_p$ index. Overall, the electron precipitation from eVlasiator is similar to the parameterized auroral electron forcing in location and impact, although there are some clear differences. The latitudinal extent of the eVlasiator auroral electron precipitation is partially limited, and the ionization rates are somewhat weaker than the parameterization, even with the satellite observation-based scaling of the electron fluxes. On the other hand eVlasiator provides more detailed energy...
and spatial distributions of the auroral electron precipitation, with ionization forcing reaching deeper into the atmosphere, down to 80 km compared to around 95 km in the parameterization.

As a next step, in order to validate the accuracy of the model results, a specific simulation could be made for comparisons with satellite observations. For this, time-dependent auroral electron precipitation data from eVlasiator would be needed in order to model the variability of auroral electron impact in the atmosphere. For example, we should study impacts during the different phases of substorms. For the future, this work makes way for a more complete description of auroral electron forcing in atmospheric simulations and, eventually, for the detailed study of solar wind – atmosphere interaction.

**Code and data availability.** The Vlasiator code is open-source under GPL-2, indexed through Zenodo (Pfau-Kempf et al., 2024), and available through GitHub. The eVlasiator release used for this study is similarly available at Pfau-Kempf et al. (2022). The Vlasiator simulation data used for this study consists of several terabytes of data, and is thus not made available online, but the authors accept data requests. The reduced output of the eVlasiator simulation consisting of precipitating electron differential number flux data is available at Finnish Meteorological Institute Research Data repository METIS (Grandin, 2024).

The DMSP/SSJ precipitating particle fluxes are openly available and were retrieved from http://cedar.openmadrigal.org/.

The WACC-M-D simulation data analysed in this paper are available at Finnish Meteorological Institute Research Data repository METIS (Häkkilä and Szelag, 2024). The WACC-M modification enabling MLT-dependent ionization input is indexed via Zenodo (Häkkilä, 2024), and publicly available on GitHub at https://github.com/hakkila/waccm_iprmlt.

**Appendix A: Detailed description of the mapping between the ionosphere grid and the eVlasiator simulation domain**

To produce an auroral-electron forcing dataset for WACC-M-D, we need to map the fluxes obtained with eVlasiator to ionospheric altitudes. The procedure detailed below is illustrated in Fig. A1.

Magnetic field lines (in magenta) are traced between the ionosphere (at an altitude of 110 km; points A_i) and the inner boundary of the simulation domain from seed points placed every 1° in MLAT and 0.5 h in MLT. Since the magnetic field inside the inner boundary only consists of the Earth dipole and has no perturbed field term, we construct a more realistic mapping by superposing two magnetic field components. The internal contributions to the geomagnetic field are described by a simple point dipole to match the geomagnetic field description used in Vlasiator. The Tsyganenko 2001 (T01; Tsyganenko, 2002a, b) model is used to describe the external field contributions, with the solar wind conditions of the Vlasiator run (see Sect. 2.1), at a date when the geomagnetic dipole was almost perpendicular to the ecliptic plane (11 March 2020, 21:40 UT), and assuming a Dst value of $-30$ nT. The Python versions of T01 and Earth dipole field implemented in the geopack library (Tian, 2023) were used for this mapping of atmospheric altitudes to 4.8 $R_E$, i.e. just beyond the inner boundary (points B_i). From each grid point, we follow the geomagnetic field line obtained by combining the un tilted dipole model for internal contributions with the T01 model for external contributions. Up to this step, the procedure is the same as described in more detail in Grandin et al. (2023).
Within the 1.4 s of the eVlasiator run, electrons scattered into the bounce loss cone in the plasma sheet do not have time to reach the inner boundary of the simulation domain. To account for this, we extend the mapping of the MLT–MLAT grid further into the eVlasiator simulation domain so as to reach the magnetospheric regions where precipitating electrons originate. To ensure better self-consistency, we use the magnetic field lines from the Vlasiator file (in red) to extend the mapping outwards for another 7.5 $R_E$, or until reaching the equatorial plane.

Finally, along each field line thus obtained and for each electron energy bin, the maximum value of the precipitation differential flux between the inner boundary (points B$_1$, B$_2$) and either the other end of the traced field line (point C$_2$) or the equatorial plane (point C$_1$) is retained. This therefore ensures that precipitating electrons which may not have had time to reach the inner boundary by the end of the electron simulation are taken into account, and gives a conservative high value for the differential number flux.
Appendix B: Detailed description of the calibration of eVlasiator electron fluxes with DMSP/SSJ observations

B1 Comparison of eVlasiator fluxes along the DMSP orbits

Figures B1 and B2 show the comparison of eVlasiator precipitating electron fluxes with DMSP/SSJ measurements during the two events with similar driving conditions as in the Vlasiator run (8 Aug 2011 and 10 Oct 2015). The top panels show the global view of eVlasiator integrated energy fluxes in both hemispheres, on top of which DMSP/SSJ integrated energy fluxes along the spacecraft’s orbits are overlaid. The middle panels enable the comparison of differential number fluxes of precipitating electrons. One can see in particular that overall eVlasiator spectra have a cutoff at high energies, indicating that the high-energy component is often missing compared to DMSP/SSJ observations.

The bottom panels show the ratio between the differential number fluxes measured by DMSP/SSJ and obtained with eVlasiator are displayed, along the satellites’ orbits. Green regions correspond to eVlasiator underestimating the electron precipitation, whereas purple regions correspond to eVlasiator overestimating it, when considering a given event and location along the orbit.
Figure B2. Comparison of eVlasiator and DMSP/SSJ observations during the 10 Oct 2015 overpasses. Same format as in Fig. B1.

The ratios typically range between 0.001 and 1000, highlighting the need for a calibration of the eVlasiator fluxes so that they might be more realistic. It is clear from those bottom panels that the correction to be applied to eVlasiator fluxes must be different on the dayside and on the nightside, and that it must be energy-dependent. Below we detail how the corrected eVlasiator fluxes were determined and we justify the choices made in developing the method.

B2 Selection of regions of interest to be corrected

In order to avoid increasing the precipitating electron fluxes outside of the auroral oval (e.g. in the polar cap or in the flanks, where eVlasiator fluxes might be contaminated by boundary effects), we restrict the correction to the cusp and nightside oval regions, as indicated with magenta contours in Fig. B3a–b. Besides, extremely low eVlasiator flux values (< 0.01 el cm$^{-2}$ s$^{-1}$ sr$^{-1}$ eV$^{-1}$) are masked too.

Since the dayside overpasses include measurements outside the hence delimited cusp, we discard observations made outside of the cusp for the calibration procedure. The masked data are shown in grey in Fig. B3c,e.
Since we want to obtain correction coefficients for the eVlasiator fluxes as a function of electron energy, we need to find a suitable metrics to derive such coefficients based on the ratios between DMSP and eVlasiator fluxes along the DMSP orbits. A quick inspection of Fig. B3e–f reveals that using the mean value of the ratio at a given energy would not provide a robust estimate of the needed correction, since for instance at 1 keV on the nightside values range from $10^3$ (start of the orbit) to $<1$ el cm$^{-2}$ s$^{-1}$ sr$^{-1}$ eV$^{-1}$ (middle of the orbit), which would result in a mean value skewed to the high values and not necessarily representative of the needed correction coefficient at 1 keV. This is because the eVlasiator fluxes drop off quickly at the high-energy end of their spectra, due to the sparse velocity space description (Palmroth et al., 2018). Therefore, instead of using the mean, we use a quantile value as the metrics to determine the energy-dependent correction coefficients (one set for cusp fluxes, one set for nightside fluxes).

Figure B4 shows results obtained when considering median (50th quantile) values. We see that the median values of the ratios (blue lines) can be fitted with a third-order polynomial for the cusp and with a second-order polynomial for the nightside (red curves), when considering energies and ratios in logarithmic scale. We can then correct the eVlasiator fluxes by multiplying...
B4 Adjustment based on the integrated energy fluxes

The median-based corrections presented above lead to an enhancement of the eVlasiator fluxes in a way which gives priority to increasing the energies needing it the most to better resemble observations. However, this increase is still insufficient. Indeed, if we consider the ratio of the corrected eVlasiator and DMSP integrated energy fluxes along the satellite orbits, we find that its 90th quantile values are 0.18 in the cusp and 0.24 in the nightside oval, which means that the corrected eVlasiator fluxes are still 4–5 times lower than in observations using this metrics.

Therefore, we have adopted the following strategy to obtain corrected eVlasiator fluxes providing a good match with DMSP/SSJ measurements in terms of integrated energy flux: instead of taking median values of the DMSP/eVlasiator ratios to determine the analytical expression of the energy-dependent correction coefficients, we find the optimal quantiles of these ratios such that the integrated energy fluxes match as closely as possible between corrected eVlasiator fluxes and observations.

We found that selecting the 61st (cusp) and 67th (nightside) quantiles of the DMSP/eVlasiator differential flux ratios along the orbits give the best results, with corrected eVlasiator precipitation being on par with DMSP/SSJ observations in terms of integrated energy fluxes. The corresponding correction coefficients are given in Fig. B5.

Those coefficients were therefore retained for the eVlasiator flux correction, and produced the corrected fluxes shown in Fig. 3.
**Figure B5.** Same as Fig. B4 but using the 61st quantile of the DMSP/eVlasiator flux ratios for the cusp and the 67th quantile for the nightside fluxes.

**Author contributions.** MB and MA developed the eVlasiator approach, with LK extending it to support 3D spatial meshes. MA ran the eVlasiator simulation presented in this work. MG developed the particle precipitation approach of Vlasiator, applied it to the eVlasiator data, implemented the ionospheric mapping and calibration approaches presented in the appendices and used in this study, and wrote the corresponding sections of the manuscript. MP is the Vlasiator PI, and she participated in conceptualisation of the study, and supervised the Vlasiator portion of the study. TH, MES, NK, and PTV participated in planning the WACCM-D simulations. TH carried out the WACCM-D simulations with support from MES. PTV produced the ionization rates used in WACCM-D from the eVlasiator electron fluxes. TH analyzed the WACCM-D data and led the writing of the paper, with all co-authors participating in discussions and providing feedback on the manuscript.

**Competing interests.** At least one of the (co-)authors is a member of the editorial board of Annales Geophysicae.

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The scientific colour maps batlow and lajolla (Crameri, 2023) are used in this study to prevent visual distortion of the data and exclusion of readers with colour-vision deficiencies (Crameri et al., 2020).

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