

Manuscript angeo-2019-59: “Hybrid-Vlasov modelling of nightside auroral proton precipitation during southward interplanetary magnetic field conditions”
by M. Grandin et al.

Response to Reviewer #1

We thank the Reviewer for their careful analysis of our manuscript as well as their valuable comments and suggestions. Our responses to the comments are shown in blue, while the original text written by the Reviewer is shown in black.

This is interesting and important study of ion precipitations in the magnetotail. Authors use quite developed simulation tool to check the effect of fast plasma flows on formation of precipitating ion fluxes. The brief comparison of simulation results and published observational data shows a reasonable agreement. I believe this paper should be published in Angeo after Authors address several (quite minor) questions.

Introduction: there are several important references related to proton aurora investigations that may be included: 10.1029/2008JA013099, 10.1134/S001679321805016X, 10.1134/S0016793218040114

Thank you for suggesting those references, which have been added in the introduction.

– p. 2, l. 20: "Electromagnetic ion cyclotron (EMIC) waves are the prime candidate for such interactions (e.g., Erlandson and Ukhorskiy, 2001; Sakaguchi et al., 2008; **Popova et al., 2018**), but more recently, Xiao et al. (2014) suggested that fast magnetosonic waves, also known as equatorial noise, might interact with protons across a broad range of magnetic local times."

– p. 2, l. 25: "**On the dayside, it has been found that proton aurora flashes can be observed equatorwards from the cusp in relation with EMIC waves associated with plasma pressure pulses in the magnetosphere (Yahnina et al., 2008). More generally, EMIC waves can be responsible for auroral proton precipitation equatorwards of the proton oval forming long-lasting spots, arcs and flashes (Yahnin et al., 2018).**"

The Popova et al. (2018) reference was also added on p. 19, l. 11.

Page 7, eq. (8): this equation assumes that ion energy is conserved along the bounce trajectory, i.e. there is no field-aligned electric fields in the system. It would be useful to show 2D plot with the parallel electric field distribution and quickly discuss the weakness of this electric field effect on ion dynamics.

We have added Fig. S1 below to Supplementary Material, showing the parallel component of the electric field at the same time step and with a similar format as Fig. 3. This parallel component was averaged over 120 s, which corresponds roughly to one bounce period for 10 keV protons at $L = 9$ (virtual spacecraft S_1).

We have added the following discussion of this supplementary figure to the manuscript:

– p. 12, l. 29: "One assumption which is made during the derivation of the precipitating fluxes is that there are no field-aligned electric fields in the system (cf. eq. (8)). Figure S1 in the Supplementary Material shows the parallel component of the electric field at the same time step and with a similar format as Fig. 3. This parallel component was averaged over 120 s, which corresponds roughly to one bounce period for 10 keV protons at $L = 9$ (virtual spacecraft S_1). It can be seen that the parallel electric field between S_1 or S_2 and the inner boundary is of the order of 0.01 to 0.1 mV m $^{-1}$. When integrated along the field line between S_1 and the inner boundary, this corresponds to a potential difference of the order of 1 kV. In their discussion of the effect of potential drops in the auroral acceleration region on precipitating protons, Liang et al. (2013) estimate that for ions with energies $\gg 1$ keV the acceleration resulting from typical potential drops in the auroral acceleration region (~ 1 kV up to ~ 4 kV occasionally) can be neglected, which enables a reasonable mapping of auroral latitudes to the central plasma sheet. It therefore seems acceptable to neglect the effect of parallel electric fields when deriving the precipitating proton fluxes with the method described in section 2.2."

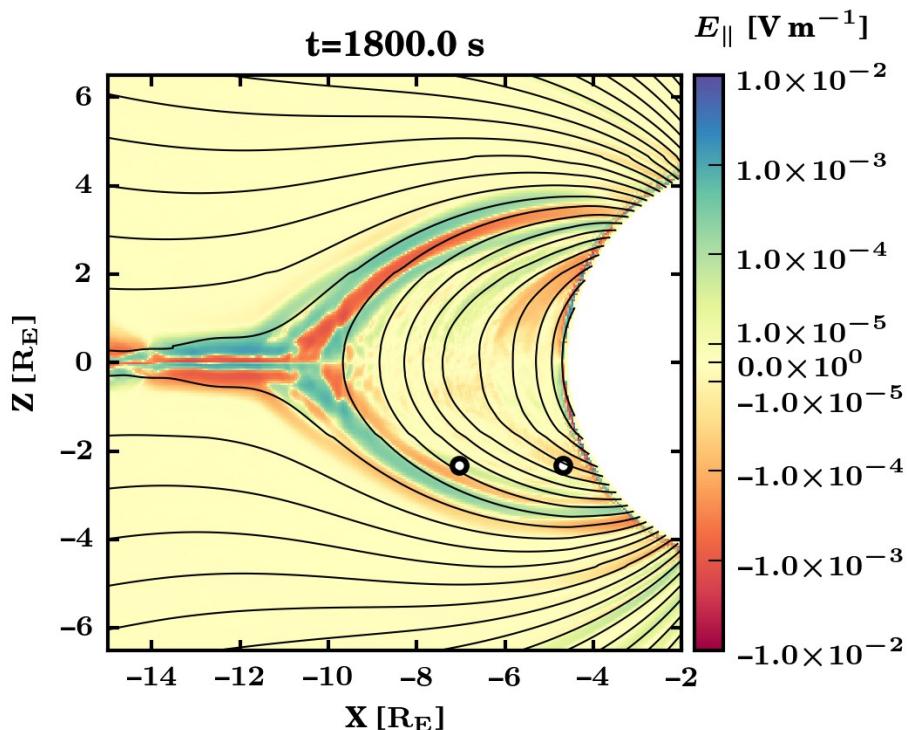


Figure S1. Simulated parallel component of the electric field in the nightside magnetosphere at $t = 1800$ s and averaged over 120 s. The Sun is located beyond the right boundary of the figure. The two black circles filled with white are virtual spacecraft S_1 and S_2 . $R_E = 6371$ km.

Page 8, Line 17: $<1^\circ$ of the loss-cone is an estimate based on nondisturbed magnetic field models. It would be useful to provide also a loss-cone estimate for magnetic field enhancements at the dipolarization front accompanied fast flows (where B_z is significantly larger than the magnetotail B_z)

This is a good point. We have added a short discussion as suggested in the revised manuscript:

– p. 9, l. 1: "In the **undisturbed** nightside equatorial plane, θ_{lc} takes values of a few degrees at most, and is smaller than 1° beyond $10 R_E$ (see, e.g., Sergeev and Tsyganenko, 1982). **In presence of a rather large dipolarisation front with, e.g., $B_0 \approx B_z = 30$ nT, assuming a mapping to auroral latitudes ($B_{sc} \sim 53\,000$ nT), eq. (11) gives $\theta_{lc} = 1.4^\circ$."**

Page 17, Lines 1-5: Previous models of pitch-angle scattering (e.g., Sergeev and Tsyganenko, 1982) were developed for the quiet time magnetotail current sheet, whereas in this paper Authors consider ion precipitation from the acceleration (fast plasma flow) region, what is closer to simulation results shown in 10.1029/2012JA018171, 10.1029/2012JA017677. Any relations to pitch-angle scattering on the magnetic field line curvature should be confirmed by corresponding estimates of the kappa parameter, e.g. kappa dependence on x and time would support Authors' conclusions.

Thank you for this suggestion. Below is a figure showing the value of the κ parameter along the x-axis between $-25 R_E$ and $-6 R_E$ (which corresponds to the regions of interest in our study) as a function of time from $t = 1000$ s until the end of the simulation, as in Fig. 5.

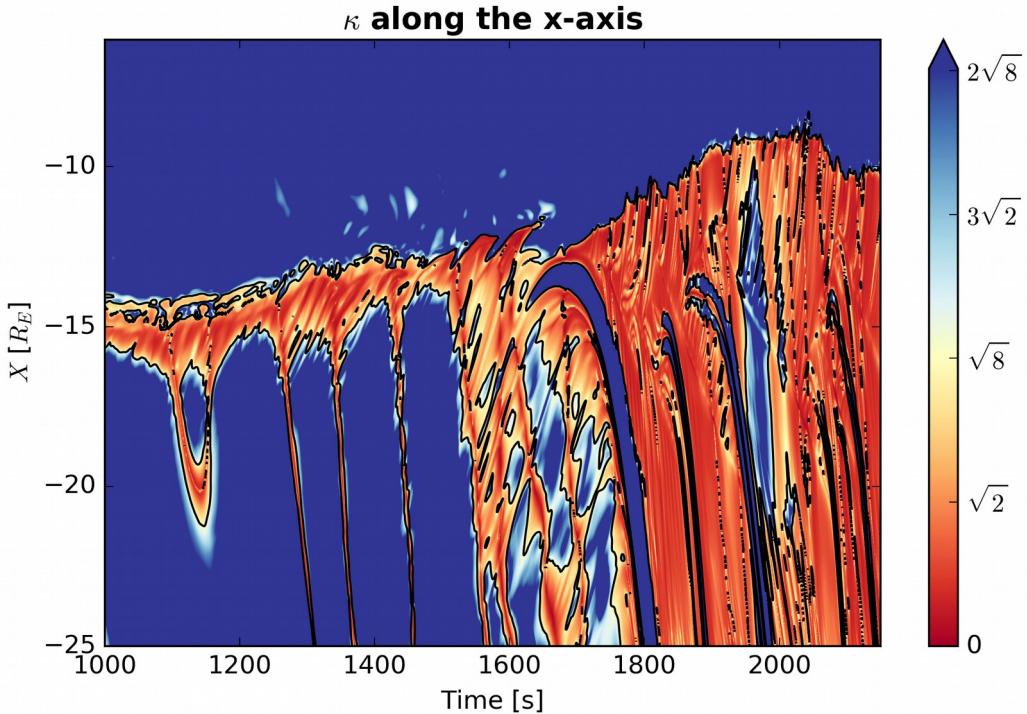


Figure S2. κ parameter along the x-axis between $-25 R_E$ and $-6 R_E$ as a function of time from $t = 1000$ s until the end of the simulation. The black contour shows the critical value $\sqrt{8}$ below which the criterion for particle pitch-angle scattering is verified (orange and red area).

Note: $\kappa = \sqrt{(R_c/r_L)}$, with R_c the curvature radius of the magnetic field and r_L the proton gyroradius (Sergeev et al., 1983).

We have added this figure in the Supplementary Material as Fig. S2, and we have added the following sentences to the Discussion:

– p. 19, l. 14: "In this study, however, the analysis of Fig. 7 suggests that the precipitating protons essentially come from the magnetotail and are hence precipitating due to pitch-angle scattering resulting from the small curvature radius of the magnetic field near the neutral sheet (Sergeev and Tsyganenko, 1982). **This is confirmed in Fig. S2 provided in Supplementary Material, which shows the value of the κ parameter (see Introduction) along the x-axis between $-25 R_E$ and $-6 R_E$ as a function of time from $t = 1000$ s until the end of the simulation, as in Fig. 5.** At the time of highest precipitating proton fluxes (i.e., after $t = 1800$ s) beyond $X \sim -10 R_E$ in the plasma sheet, κ exhibits mostly values below $\sqrt{8}$, hence fulfilling the Sergeev et al. (1983) criterion according to which protons get scattered into the loss cone on stretched field lines. While on the other hand it would prove interesting to estimate whether there is a non-negligible contribution to this precipitation from wave-particle interactions, this has to be left for a future study."

The two references suggested by the Reviewer have been discussed in the revised manuscript as follows:

– p. 20, l. 18: "In their study of BBF-associated proton precipitation with a MHD model, Ge et al. (2012) found that dipolarisation fronts led to precipitating proton enhancements into the ionosphere with integral energy fluxes of the order of $0.1 \mu\text{W m}^{-2}$. This corresponds to $6 \times 10^4 \text{ keV cm}^{-2} \text{ s}^{-1}$. Assuming a uniform flux along all downwards directions as a rough approximation (2π solid angle), this gives a directional integral energy flux of the order of $10^4 \text{ keV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$, which is roughly three orders of magnitude below values obtained with Vlasiator when the global magnetotail reconfiguration is taking place (cf. Fig. 7b). A likely explanation is that the MHD simulation has low ion temperature T_i values compared to our kinetic approach, leading to lower precipitation energy fluxes as these are proportional to $T_i \sqrt{T_i}$ in their approach (cf. eq. (1) in Ge et al., 2012). We note that the Vlasiator integral flux values are on the other hand in agreement with the test-particle simulation results presented in their companion paper (Zhou et al., 2012b) with integral energy fluxes of $0.2\text{--}1 \text{ mW m}^{-2}$ (equivalent to $2 \times 10^7\text{--}10^8 \text{ keV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ with the same reasoning as above), and with statistical patterns shown in Galand et al. (2001) ($\sim 0.1 \text{ mW m}^{-2}$). One strength of evaluating the proton precipitation parameters using a kinetic model is that not only integral energy fluxes can be calculated, but also differential fluxes, which may enable more detailed future studies of proton precipitation and its link to global magnetospheric dynamics. **Further, a test-particle approach is not fully self-consistent, in the sense that the electromagnetic fields affect the particle distributions but not vice versa. Therefore the test-particle approach does not fully describe, e.g., dynamics of reconnection-related precipitation.**"

– p. 20, l. 33: "The examination of precipitation bursts passing by virtual spacecraft S_1 between $t = 1920 \text{ s}$ and $t = 2080 \text{ s}$ suggests that these bursts are associated with dipolarising flux bundles originating from the vicinity of the stable X-line in the current sheet. **Field-aligned beams of plasma propagating earthwards associated to dipolarisation fronts have been observed and simulated not only in the central plasma sheet, but also in the plasma sheet boundary layer (PSBL) (Zhou et al., 2012a). In this Vlasiator run, there is unfortunately no cell located in the PSBL where the full VDF is saved at each time step to make a comparison with results from Zhou et al. (2012a), hence we focus on proton precipitation originating from the central plasma sheet.**"

There are two model features that require some explanations/discussions: Figure 3: what is a local temperature minimum around S_1 position? Temperatures earthward and tailward from S_1 are higher than in the S_1 location. Is there any analogy of such temperature minimum in the statistical spacecraft observations? As I know, the temperature profile along the magnetotail is generally monotonous (see, e.g., 10.1029/2008JA013849, 10.1002/2016JA023710.)

First of all, something to note is that the shown temperature is the temperature of an isotropic plasma which would have the same total pressure as the simulated distribution, and thus does not represent the temperature of the bulk plasma but rather the measured effect of a combined bulk plasma and fast additional flow.

The local temperature minimum seen in Fig. 3 comes from the fact that hot plasma associated with the precipitating protons originates from the current sheet region, which leads to temperature enhancements propagating earthwards in terms of L shells. At the time step chosen for Fig. 3 (1800 s), a stream of hot ($T = 2 \times 10^7 \text{ K}$) plasma coming from the transition region is reaching S_1 , leading to a local enhancement of the proton temperature compared to its background value at S_1 .

It is difficult to compare our results to those shown in the two suggested references, as in 10.1029/2008JA013849 the statistical observations are obtained with slow flows ($V_\perp < 150 \text{ km/s}$) whereas in the situation shown in our Fig. 3 V_\perp is essentially greater than 200 km/s for $X < -7 R_E$. As for the T_i profile along the magnetotail shown in 10.1002/2016JA023710, it consists of only three points with X between $-10 R_E$ and $-30 R_E$, meaning that (i) the spatial resolution is too coarse

to capture such small-scale variations as that pointed in our Figure 3, and (ii) measurements at $X > -10 R_E$ are not available.

We therefore did not refer to the above two papers in the revised manuscript; however, we have added the following discussion on the plasma temperature shown in Fig. 3:

– p. 9, l. 20: "The main panel (a) shows the proton temperature in the nightside part of the noon-midnight plane at time step $t = 1800$ s, with magnetic field lines drawn in black. **It should be stressed that this temperature is that of an isotropic plasma which would have the same total pressure as the simulated distribution, thus it does not represent the temperature of the bulk plasma but rather the measured effect of a combined bulk plasma and potential fast additional flows. The effect of such a combination can be seen near S_1 , as a stream of hot ($T \approx 20$ MK) plasma coming from the transition region is reaching the virtual spacecraft, leading to a local enhancement of the proton temperature compared to its background value at S_1 .**"

Figure 4: some of shown distributions are definitely unstable (they contain ion beams with positive slabs along the parallel velocity direction). Thus, some discussion is needed to explain if these instabilities are too slow to influence ion distributions or they are simply suppressed in the numerical calculations.

Thank you for raising this issue. In Vlasiator, instabilities are resolved in the numerical calculations provided their wavelengths are larger than the grid resolution in ordinary space. According to Gary (1989, 10.1007/BF00196632; see especially Table II p. 385), there are several instabilities which can arise from interactions between a proton beam and a proton core population in a plasma.

The ion/ion right-hand resonant instability ("magnetosonic" or "fast MHD"), of much lower frequency than the ion gyrofrequency, can develop when the field-aligned drift velocity V_0 of the protons is greater than the Alfvén speed V_A , and when the ratio between beam (n_b) and core (n_c) densities is "very small". If we consider the distribution shown in Fig. 4a of our manuscript, we have $V_0 \sim 1000$ km/s, $V_A = 4379$ km/s, $n_b = 1.1e4$ m⁻³ and $n_c = 1.2e5$ m⁻³, i.e., $V_0/V_A \sim 0.2$ and $n_b/n_c = 8.6e-2$. Since the condition on the velocities is not fulfilled, it is unlikely that this instability grows at the location where the VDF is observed.

The ion/ion left-hand instability also requires $V_A < V_0$, and in addition it requires that the ion beam to be hot, i.e., with a thermal velocity greater than the beam drift velocity. This instability is therefore not expected to grow in the considered situation of Fig. 4a.

The ion/ion nonresonant instability ("firehose") can develop if $V_A \ll V_0$. Hence, it cannot grow in this situation either.

In conclusion, in the $V_A > V_0$ regime which characterises the plasma in the vicinity of virtual spacecraft S_1 and S_2 , we do not expect that the instabilities listed above can grow fast enough to significantly affect the ion distributions on the time scale needed for precipitating protons (i.e., essentially the field-aligned beam) to reach the inner boundary or even the ionosphere.

We have included a shorter version of this discussion in the revised manuscript as follows:

– p. 12, l. 1: "The crescent-shaped beam partly in the bounce loss cone shown in panel (a) is associated with a precipitating differential flux narrow in energies (panel e), peaking around 4–5 keV with values close to 10^4 proton cm⁻² s⁻¹ sr⁻¹ eV⁻¹. **Although this distribution is intrinsically unstable, the development of instabilities (magnetosonic, ion-ion left-hand, firehose) requires the conditions that the field-aligned drift velocity V_0 of the protons be greater than the Alfvén speed V_A , and that the ratio between beam (n_b) and core (n_c) densities be "very small" (Gary, 1991). While the distribution shown in panel (a) has $n_b/n_c = 0.086$, it exhibits $V_0 \sim 1000$ km s⁻¹ and $V_A = 4379$ km s⁻¹. Since the criterion on velocities is not verified, we do not expect that the instabilities listed above can grow fast enough to significantly affect the ion distributions on the time scale needed for precipitating protons (i.e., essentially the field-aligned beam) to reach the inner boundary or even the ionosphere.**"

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Response to Reviewer #2

We thank the Reviewer for their careful analysis of our manuscript as well as their constructive comments and suggestions. We provide our responses to the comments in blue, while the original text written by the Reviewer is shown in black.

The manuscript deals with the nightside proton precipitation, focusing on the perspective of the magnetosphere, by using Vlasior, a global kinetic hybrid simulation of the near-Earth environment. The authors found a good agreement in terms of differential number fluxes and energies, compared to the empirical Hardy model. The proton precipitations are observed as burst events and, in some cases, they can be traced back to the current sheet in the magnetotail and associated with depolarising flux bundles.

The paper brings interesting results and can be acceptable for publication after some clarifications.

1. In my opinion, the authors should justify the resolutions chosen for the simulation in terms of characteristic plasma quantities. In particular, in order to comment on the physical space resolution, what is the value for the ion inertial length? or Larmor radius? Since the proton precipitation is produced by the magnetic reconnection in the magnetotail, how thin is the current sheet? And, in a similar way, the authors should comment on the velocity space resolution. In this respect, what is the value for the Alfvén speed?

Thank you for this nice suggestion. We are indeed happy to provide these values and put them in perspective with the ordinary and velocity space resolutions. We can for instance provide such values in the solar wind (input) and in the transition region (at $X = -10 R_E$, $Y = Z = 0$) at $t = 1800$ s (Fig. 2).

Location	Solar wind	Transition region
– ion inertial length:	$\lambda_p = 228$ km	$\lambda_p = 906$ km
– ion Larmor radius:	$r_L = 214$ km	$r_L = 681$ km
– Alfvén speed:	$V_A = 109$ km/s	$V_A = 1596$ km/s

The ordinary space resolution of 300 km in this run is therefore sufficient to resolve most of the proton kinetics, as was confirmed in a dedicated study by Pfau-Kempf et al. (2018, 10.3389/fphy.2018.00044).

This discussion has been added to the revised manuscript as follows:

– p. 5, l. 6: "In the solar wind, the ion inertial length is $\lambda_p = 228$ km, and the proton Larmor radius is $r_L = 214$ km. A dedicated study by Pfau-Kempf et al. (2018) showed that the ordinary space resolution of 300 km is sufficient to resolve most of the proton kinetics in such conditions. Besides, the Alfvén speed is $V_A = 109$ km s⁻¹, which is significantly greater than the velocity space resolution of 30 km s⁻¹. Similarly, the ordinary space and velocity space resolutions are sufficient to resolve the ion kinetics in the transition region between stretched and dipole-like magnetic field lines in the magnetotail, where $\lambda_p = 906$ km, $r_L = 681$ km and $V_A = 1596$ km s⁻¹."

The plasma sheet thickness was evaluated during this same run by Juusola et al. (2018b, 10.5194/angeo-36-1027-2018) and is shown in Fig. 6 of their paper. In the region of interest for our study ($X > -20 R_E$), Juusola et al. find that the plasma sheet thickness essentially lies within 0.1–0.2 R_E (i.e., just a few simulation cells). This discussion has been added as follows:

– p. 6, l. 6: "Juusola et al. (2018b) studied the plasma sheet during this same run and evaluated its thickness to lie essentially within 0.1–0.2 R_E (i.e., just a few simulation cells) in the region of interest for our study ($X > -20 R_E$)."

2. In the inner boundary, protons are described with a static Maxwellian VDF. This means that here kinetic effects are neglected. However, the observed VDFs close to the inner boundary, for example in S2 (Fig.3), are strongly non Maxwellian during the precipitation. I am wondering if the imposed sharp change in the VDF could influence the results. Could the authors comment on this point?

The imposed static Maxwellian VDF at the inner boundary mostly affects the neighbouring cells through the calculation of translation and acceleration terms in the Vlasov equation. Since S₂ is located about 15 cells away from the inner boundary, its stencil used for acceleration and translation do not reach the inner boundary. Given that, in addition, the plasma flows from S₂ towards the inner boundary, potential diffusion effects are likely negligible in comparison with the bulk flow.

We have added a short discussion on this aspect as follows:

– p. 11, l. 3: "The imposed static Maxwellian VDF at the inner boundary can affect the neighbouring cells through the calculation of translation and acceleration terms in the Vlasov equation, but such effects vanish rapidly with distance to the boundary, and the plasma at S₂ is unlikely to be affected by the boundary condition."

3. One of the hypotheses used to evaluate the directional differential particle flux is that 'protons remain attached to a given magnetic flux tube'. However, during a magnetic reconnection event this is not exactly true. Although the locations in the magnetosphere are chosen far from the X-point, I am wondering if the change in the magnetic topology can have effects also at these points for the analysis.

Since the locations of virtual spacecraft S₁ and S₂ are on closed field lines which do not further reconnect and are convected earthwards, there is no risk that the precipitating protons observed at S₁ (or S₂) are affected by magnetic reconnection before they reach the ionosphere. Hence, there should be no concerns regarding the validity of the hypothesis that the plasma observed at the virtual spacecraft remains attached to its magnetic flux tube until precipitating protons reach the ionosphere.

We have mentioned this aspect in the following addition to the revised manuscript:

– p. 13, l. 4: "Furthermore, given the location of S₁ and S₂ on closed field lines which are being convected earthwards, there is no risk that the precipitating protons observed at S₁ (or S₂) are affected by processes such as magnetic reconnection before they reach the ionosphere."

4. During the phase 2, the orbit of the NASA-MMS mission was chosen to spend time on the night side of the Earth's magnetosphere. Did the authors check if there are any datasets able to support their results?

Comparing our results with MMS data would indeed be interesting; however, we feel that this task would be beyond the scope of the present study, whose main aim is twofold: (i) present the methodology to evaluate proton precipitation in Vlasior simulations, and (ii) discuss the nightside proton precipitation from a global perspective during a simulated event with southward IMF. A comparison of those results with observations could therefore be carried out in a follow-up study.

We hence mention this idea for future work as follows:

– p. 20, l. 3: "While direct comparison with particle data from spacecraft would be desirable, the fact that DMSP satellites, which are currently the main source of direct precipitating proton observations, are on Sun-synchronous orbits essentially near the dawn-dusk plane does not allow midnight-sector observations. In the nightside magnetosphere, comparison with data from the NASA Magnetospheric Multiscale (MMS) mission would prove interesting, but it is beyond the scope of the present study."

Hybrid-Vlasov modelling of nightside auroral proton precipitation during southward interplanetary magnetic field conditions

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Abstract. Particle precipitation plays a key role in the coupling of the terrestrial magnetosphere and ionosphere by modifying the upper atmospheric conductivity and chemistry, driving field-aligned currents, and producing aurora. Yet, quantitative observations of precipitating fluxes are limited, since ground-based instruments can only provide indirect measurements of precipitation while particle telescopes onboard spacecraft merely enable point-like in-situ observations with inherently coarse

5 time resolution above a given location. Further, orbit time scales generally prevent the analysis of whole events. On the other hand, global magnetospheric simulations can provide estimations of particle precipitation with a global view and higher time resolution. We present the first results of auroral (~ 1 –30 keV) proton precipitation estimation using the Vlasiator global hybrid-Vlasov model in a noon-midnight meridional plane simulation driven by steady solar wind with southward interplanetary magnetic field. We first calculate the bounce loss cone angle value at selected locations in the simulated nightside magnetosphere.

10 Then, using the velocity distribution function representation of the proton population at those selected points, we study the population inside the loss cone. This enables the estimation of differential precipitating number fluxes as would be measured by a particle detector onboard a low-Earth-orbiting spacecraft. The obtained differential flux values are in agreement with a well-established empirical model in the midnight sector, as are also the integral energy flux and mean precipitating energy. We discuss the time evolution of the precipitation parameters derived in this manner in the global context of nightside magnetospheric activity in this simulation, and we find in particular that precipitation bursts of < 1 min duration can be self-consistently and unambiguously associated with dipolarising flux bundles generated by tail reconnection. We also find that the transition region seems to partly regulate the transmission of precipitating protons to the inner magnetosphere, suggesting it has an active role in regulating ionospheric precipitation.

Copyright statement.

20 1 Introduction

The terrestrial atmosphere and ionosphere are known to be affected by the precipitation of particles coming from the magnetosphere and the solar wind. Precipitating protons in the keV energy range produce diffuse auroral emission, principally in the

auroral oval and in the cusp region (Hardy et al., 1989). Some emission lines are only produced during proton aurora, namely the H_{α} and H_{β} lines (at 656.3 nm and 486.1 nm, respectively), and the Lyman- α line at 121.7 nm (Lummerzheim et al., 2001). It is hence possible to distinguish aurora related to proton precipitation from the aurora produced by electron precipitation.

Contrary to precipitating electrons which may be significantly affected by parallel electric fields in the auroral acceleration region (e.g., Lin and Hoffman, 1982), the acceleration (or deceleration) of auroral-energy precipitating protons by parallel electric fields resulting from a field-aligned potential drop is negligible (Liang et al., 2013). This enables a mapping of the proton aurora in the ionosphere to the magnetospheric region from which the particles originate. Frey et al. (2003) used this property to produce evidence of continuous magnetic reconnection at the magnetopause, as a proton aurora spot was observed to persist for several hours in the cusp region.

Within the auroral region, proton precipitation maximises in the pre-midnight sector in terms of total energy flux, but the mean precipitating energy peaks in the evening sector near 18 magnetic local time (MLT), where it can exceed 20 keV (Galand et al., 2001). The most common form of nightside proton aurora is a diffuse arc equatorwards from the electron aurora in the pre-midnight sector (Hardy et al., 1989). In addition, Nomura et al. (2016) have presented recent observations of pulsating proton aurora patches in the evening sector.

On the nightside, precipitating protons mostly originate from the central plasma sheet (e.g., Eather, 1967; Gilson et al., 2012; Spanswick et al., 2017). **Proton precipitation is most commonly associated to two mechanisms.** First, pitch-angle scattering into the bounce loss cone can take place in regions where the magnetic field curvature radius R_c is within the same order of magnitude as the gyroradius r_L of particles, as can be the case near the neutral sheet (Tsyganenko, 1982; Sergeev and Tsyganenko, 1982). This criterion has been formalised as $0 < \kappa \leq \sqrt{8}$, with $\kappa = \sqrt{R_c/r_L}$ (Sergeev et al., 1983). Second, loss-cone scattering of protons can be due to wave–particle interactions. Electromagnetic ion cyclotron (EMIC) waves are the prime candidate for such interactions (e.g., Erlandson and Ukhorskiy, 2001; Sakaguchi et al., 2008; Popova et al., 2018), but more recently, Xiao et al. (2014) suggested that fast magnetosonic waves, also known as equatorial noise, might interact with protons across a broad range of magnetic local times. It has been found, for instance, that pulsating proton aurora can be produced by non-linear interactions with EMIC waves, which show as Pc1 pulsations in ground-based magnetometers (Ozaki et al., 2016). **On the dayside, it has been found that proton aurora flashes can be observed equatorwards from the cusp in relation with EMIC waves associated with plasma pressure pulses in the magnetosphere (Yahnina et al., 2008). More generally, EMIC waves can be responsible for auroral proton precipitation equatorwards of the proton oval forming long-lasting spots, arcs and flashes (Yahnin et al., 2018). Besides pitch-angle scattering associated with the κ parameter and with EMIC waves, protons may precipitate because of configurational changes and magnetic reconnection (Mende et al., 2002).**

Observations of proton precipitation can be achieved from space using particle detectors onboard spacecraft or from the ground using optical instruments or radars. Low-Earth-orbit (LEO) satellites comprising particle detectors, such as those of the Defense Meteorological Satellite Programme (DMSP) or NOAA 6, have been gathering electron and proton data in the keV energy range for several decades (Galand, 2001). Other spacecraft, such as the NASA Thermosphere Ionosphere Mesosphere 35 Energetics and Dynamics (TIMED) or Imager for Magnetosphere-to-Aurora Global Exploration (IMAGE), have been measur-

ing auroral emission from space, in particular the hydrogen lines in the ultraviolet range (e.g., Zhang et al., 2005; Frey et al., 2002; Hubert et al., 2003).

From the ground, optical instruments such as meridian scanning photometers or all-sky imagers can be used to monitor proton precipitation by measuring the auroral emission at the hydrogen lines. Recently, two Forty-Eight Sixty-One (FESO) meridian scanning photometers, designed to observe the second hydrogen Balmer line (486.1 nm), have been deployed in Canada to provide observations of the proton aurora with enhanced sensitivity and sample rates (Unick et al., 2017). Ground-based optical instruments can be used in conjunction with satellite observations (e.g., Donovan et al., 2008). Besides, since energetic proton precipitation produces ionisation enhancements in the *E* region of the ionosphere, ionospheric radars such as incoherent scatter radars can provide indirect observations of proton precipitation (e.g., Lyons et al., 2010).

In numerical studies, two aspects of proton precipitation can be distinguished. First, empirical models describing precipitation fluxes and locations have been developed. One example of these is the Hardy model (Hardy et al., 1989, 1991) which provides the average precipitation patterns as a function of the K_p index obtained by compiling two years of DMSP spacecraft data. This statistical model describes proton precipitation in a spatial grid containing 30 bins in corrected geomagnetic latitude above 50° and 48 bins in MLT, at seven levels of geomagnetic activity from $K_p = 0$ to $K_p \geq 6$. The model gives the proton precipitation differential number flux in the 20 DMSP energy channels (from 30 eV to 30 keV with regular spacing in logarithmic scale) as well as the integral number flux, the integral energy flux and the mean precipitating energy. The Hardy model has been used as an input in a number of ionospheric models, e.g., Transcar and IPIM (Blelly et al., 2005; Marchaudon and Blelly, 2015). More recently, the OVATION Prime model (Newell et al., 2014), derived from a combination of DMSP particle data and global ultraviolet imager (GUVI) data from the TIMED spacecraft, has been developed and includes proton precipitation. However, due to the lack of DMSP satellites orbiting in the postmidnight sector, the magnetic local time (MLT) sectors comprised between 00:15 and 03:30 MLT are described using a linear interpolation.

Second, models based on first principles focus essentially on ionospheric effects of precipitating ions, such as the linear transport model described in Basu et al. (2001). In such approaches, precipitating fluxes are taken as model inputs, and the transport code provides ion production rates and auroral emission intensity profiles in the ionosphere. From a magnetospheric point of view, while simulations of electron precipitation have been achieved with various models (e.g., Palmroth et al., 2006; Raeder et al., 2008), attempts to model proton precipitation are scarce. A few magnetohydrodynamics (MHD) models have addressed the issue of relating particle precipitation characteristics to the magnetotail dynamics (Gilson et al., 2012; Ge et al., 2012, see below); however, currently no global kinetic simulations of the near-Earth environment have undertaken this task.

One obvious aspect through which proton precipitation and magnetotail dynamics can be tied is the relationship between auroral streamers and bursty bulk flows (BBFs). Bursty bulk flows are fast plasma flows propagating in the magnetotail along the Sun–Earth direction, either earthwards or away from the Earth (Angelopoulos et al., 1992, 1994). They are also characterised by an enhanced B_z (northward component of magnetic field) and reduced plasma pressure (e.g., Ohtani et al., 2004). A given BBF may embed several dipolarising flux bundles (DFBs), which are themselves coherent magnetic structures exhibiting a B_z increase by up to a few tens of nanoteslas (Liu et al., 2013) and may play a role in particle energisation in the magnetotail (Runov et al., 2017). Auroral streamers are thin auroral structures oriented in the north–south direction (e.g., Nishimura et al.,

2011). They have been associated with BBFs based on observational evidence combining spacecraft data with ground-based auroral imager, magnetometer and coherent scatter radar data (e.g., Fairfield et al., 1999; Nakamura et al., 2001a, b; Amm and Kauristie, 2002; Sergeev et al., 2004; Gallardo-Lacourt et al., 2014). On modelling aspects, Ge et al. (2012) reproduced proton precipitation enhancements associated with approaching BBFs with a global MHD model and found good agreement 5 with spacecraft and ground-based auroral observations.

In this paper, we present an overview of nightside proton precipitation in a global magnetospheric hybrid-Vlasov simulation under southward interplanetary magnetic field (IMF) conditions, using the Vlasiator model (von Alfthan et al., 2014; Palmroth et al., 2018). Contrary to previous work in which the main focus was on the ionosphere, we here look at precipitation from the perspective of the magnetosphere and unambiguously tie the precipitation characteristics to the self-consistent simulation 10 results. In particular, following the study by Juusola et al. (2018a) investigating flow bursts inside a BBF in the same Vlasiator run, we examine how proton precipitation can be related to dipolarising flux bundles. Section 2 describes the Vlasiator model as well as the methods developed to estimate proton precipitation from its outputs. Section 3 presents the results of the study, i.e., the features of nightside proton precipitation in the simulation under southward IMF. Section 4 discusses those results, and sect. 5 summarises the main conclusions.

15 2 Methods

2.1 Vlasiator

This study relies on numerical simulations using Vlasiator, a global hybrid-Vlasov model of the near-Earth plasma environment (von Alfthan et al., 2014; Palmroth et al., 2018). In the hybrid-Vlasov approach, protons are described as velocity distribution functions (VDFs) in a grid of the phase space (ordinary space and velocity space), whereas electrons are treated as a massless, 20 charge-neutralising fluid. The time evolution of the VDFs is obtained by solving the Vlasov equation, and closure of the system is achieved with Ohm's law including the Hall term (Palmroth et al., 2018).

The simulation run used in this study is a 2D-3V (two-dimensional in ordinary space, three-dimensional in velocity space) simulation in the noon-midnight meridional plane of the magnetosphere, i.e., XZ in the geocentric solar magnetospheric (GSM) coordinate system. The origin of the simulation domain is set in the Earth's centre. The simulation box in ordinary 25 space spans from $X = -94R_E$ (Earth radii, $1R_E = 6371$ km) on the nightside to $X = +47R_E$ on the dayside, and is comprised between boundaries at $Z = \pm 57R_E$ in the north-south direction, with a grid resolution of 300 km. The inner boundary of the magnetospheric domain lies at $\sim 4.7R_E$ from the center of the Earth. In each cell of the ordinary space, a velocity grid extends between ± 4020 km s $^{-1}$ with a resolution of 30 km s $^{-1}$ in V_X , V_Y , and V_Z . A sparsity threshold is implemented in Vlasiator, below which phase-space density values are discarded to limit the computational load of the simulation. In the run used in this 30 study, the sparsity threshold is set to 10^{-15} m $^{-6}$ s 3 .

The near-Earth environment is driven by incoming solar wind from the $+X$ wall of the simulation domain. The solar wind population consists of protons characterised by Maxwellian VDFs with a number density of 1 cm $^{-3}$, a temperature of 500 kK, a bulk velocity of -750 km s $^{-1}$ along the X axis, a dynamic pressure of about 0.9 nPa, and carrying a purely

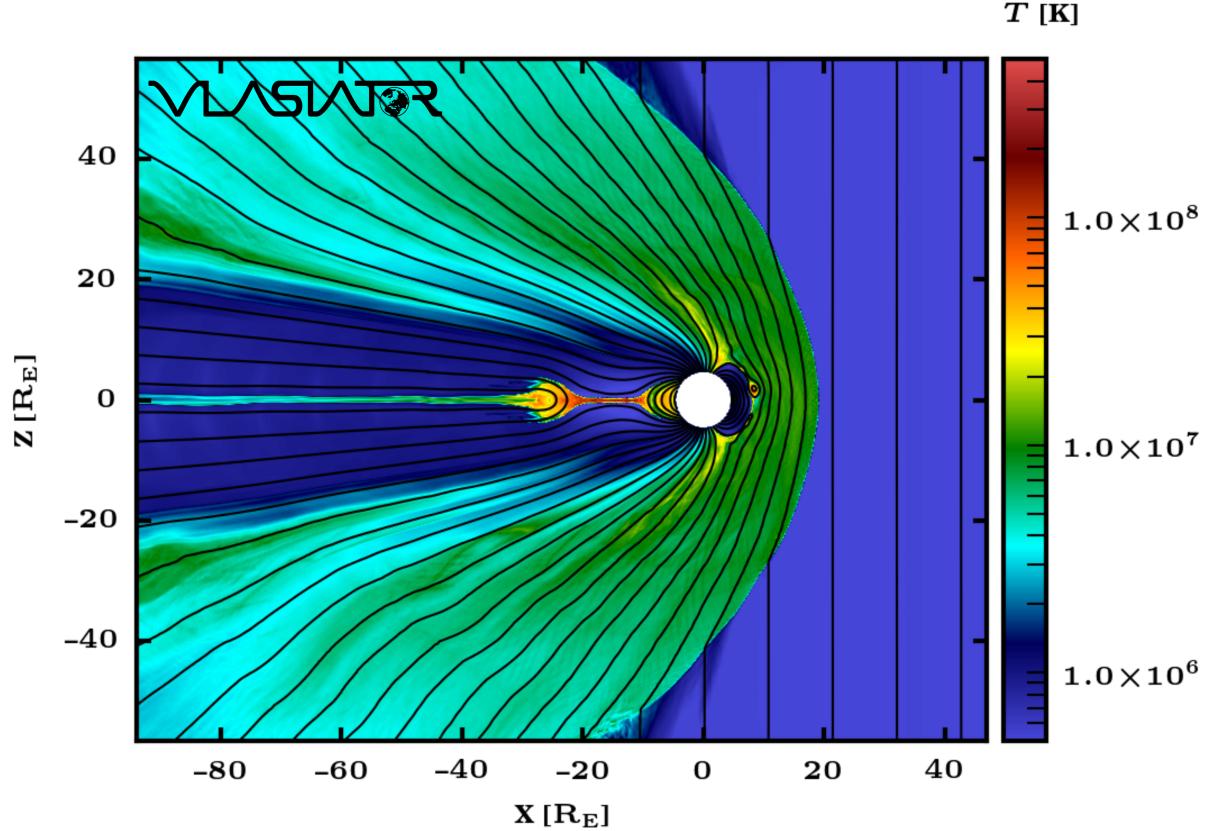


Figure 1. Simulated plasma temperature in the entire simulation domain, at $t = 1800$ s. The white area corresponds to near-Earth space located inside the inner boundary at $4.7 R_E$. Black lines represent magnetic field lines.

southward interplanetary magnetic field (IMF) with a magnitude of 5 nT. Other boundary conditions are as follows: von Neumann condition for the $-X$ and $\pm Z$ walls, periodic conditions in the out-of-plane direction ($\pm Y$), whereas the inner boundary is a perfectly conducting cylinder with a static Maxwellian VDF for protons. Finally, the geomagnetic field is given by a 2D line dipole along the Z axis, centred at the origin, and scaled to obtain a realistic magnetopause standoff distance 5 (Daldorff et al., 2014).

In the solar wind, the ion inertial length is $\lambda_p = 228$ km, and the proton Larmor radius is $r_L = 214$ km. A dedicated study by Pfau-Kempf et al. (2018) showed that the ordinary space resolution of 300 km is sufficient to resolve most of the proton kinetics in such conditions. Besides, the Alfvén speed is $V_A = 109$ km s $^{-1}$, which is significantly greater than the velocity space resolution of 30 km s $^{-1}$. Similarly, the ordinary space and velocity space resolutions are sufficient to 10 resolve the ion kinetics in the transition region between stretched and dipole-like magnetic field lines in the magnetotail, where $\lambda_p = 906$ km, $r_L = 681$ km and $V_A = 1596$ km s $^{-1}$.

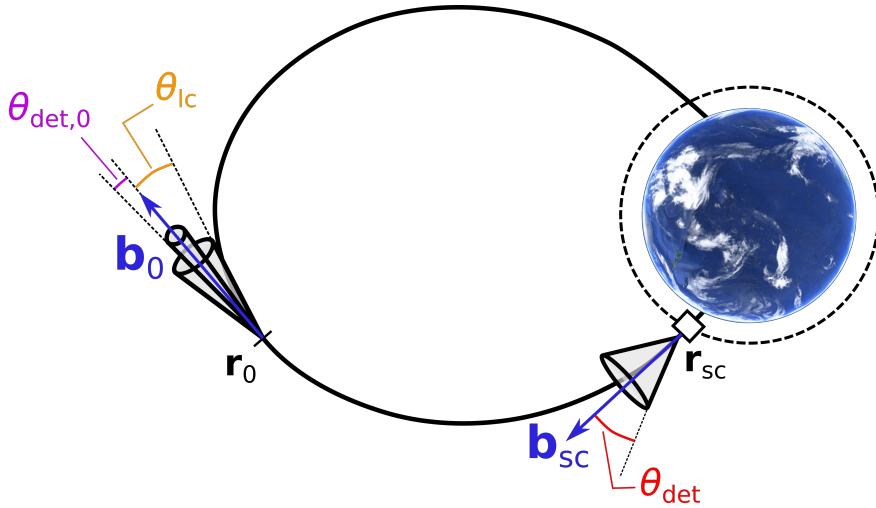


Figure 2. Geometry used in the derivation of directional differential flux of precipitating protons.

Figure 1 gives an overview of the simulated area at a time step ($t = 1800$ s) when nightside reconnection is taking place. The plotted parameter is the plasma temperature, and the black lines correspond to magnetic field lines. The incoming solar wind at 500 kK with southward IMF can be seen on the right-hand side of the figure, and the major geospace regions (bow shock, magnetosheath, dayside magnetopause, polar cusps, magnetotail lobes, plasma sheet) can be identified. A plasmoid is forming in the nightside magnetosphere (Palmroth et al., 2017), whose signature is visible between $X = -30R_E$ and $X = -20R_E$.
 5 **Juusola et al. (2018b) studied the plasma sheet during this same run and evaluated its thickness to lie essentially within 0.1–0.2 R_E (i.e., just a few simulation cells) in the region of interest for our study ($X > -20R_E$).**

This simulation run was previously used in several studies focusing on various phenomena and regions in the near-Earth space, such as dayside magnetopause reconnection (Hoilijoki et al., 2017), ion acceleration in the magnetosheath (Jarvinen et al., 2018), magnetotail reconnection (Palmroth et al., 2017; Juusola et al., 2018a), and magnetotail current sheet flapping (Juusola et al., 2018b). In each of these studies, the presented results showed good correspondence with earlier findings. Here, this run will be used to characterise nightside auroral proton precipitation in the simulation by making use of the VDF description of the proton population.

2.2 Precipitation spectra calculation

15 Figure 2 illustrates the definitions of angles and vectors used in this section. The configuration is shown for particles precipitating in the southern hemisphere to be consistent with the results shown in the rest of the paper. For particles precipitating in the northern hemisphere, the configuration is symmetrical.

At a given three-dimensional location \mathbf{r} of the ordinary space, the differential intensity \mathcal{J} (more generally called directional differential flux) of protons at energy E for the direction along unit vector \mathbf{u} is related to the velocity distribution function f

by (see 6.4.1. in Baumjohann and Treumann, 1997)

$$\mathcal{J}(E, \mathbf{u}, \mathbf{r}) = \frac{v^2}{m_p} f(\mathbf{r}, v, \mathbf{u}), \quad (1)$$

where m_p is the proton mass and $v = \sqrt{2E/m_p}$ is the velocity magnitude. \mathcal{J} , when expressed in SI units, is given in particles $\text{m}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{J}^{-1}$.

5 Particle detectors onboard spacecraft estimate \mathcal{J} by taking the average of the incoming particle flux in a given energy channel over the detector's surface S_{det} and viewing angle Ω_{det} , which can be written

$$\hat{\mathcal{J}}(E, \mathbf{n}_{\text{det}}, \mathbf{r}_{\text{sc}}) = \frac{1}{\int_{S_{\text{det}}} \int_{\Omega_{\text{det}}} \mathbf{u}' \cdot \mathbf{n}_{\text{det}} d\Omega dS} \int_{S_{\text{det}}} \int_{\Omega_{\text{det}}} \frac{v^2}{m_p} f(\mathbf{r}_{\text{sc}}, v, \mathbf{u}') \mathbf{u}' \cdot \mathbf{n}_{\text{det}} d\Omega dS, \quad (2)$$

where \mathbf{u}' is the unit vector of a given velocity direction inside Ω_{det} , \mathbf{n}_{det} is the unit vector normal to the detector's surface, and \mathbf{r}_{sc} is the location of the spacecraft, for instance near the top of the ionosphere. Strictly speaking, $\hat{\mathcal{J}}$ is a differential 10 intensity measured within a fixed solid angle and detector area. In practice, telescopes onboard spacecraft generally collect particles within a cone with an opening angle θ_{det} of the order of 15° (e.g., Rodger et al., 2010). Assuming that the directional differential flux is uniform over the detector's surface and that \mathbf{n}_{det} is aligned with the local geomagnetic field direction \mathbf{b}_{sc} (i.e., the telescope measures precipitating particles), and expressing the velocity distribution function in spherical coordinates (v, θ, φ) in the local magnetic frame, one gets

$$15 \quad \hat{\mathcal{J}}(E, \mathbf{b}_{\text{sc}}, \mathbf{r}_{\text{sc}}) = \frac{1}{\int_0^{2\pi} \int_0^{\theta_{\text{det}}} \cos \theta \sin \theta d\theta d\varphi} \int_0^{2\pi} \int_0^{\theta_{\text{det}}} \frac{v^2}{m_p} f(\mathbf{r}_{\text{sc}}, v, \theta, \varphi) \cos \theta \sin \theta d\theta d\varphi, \quad (3)$$

or, by defining $\mu = \cos \theta$,

$$\begin{aligned} \hat{\mathcal{J}}(E, \mathbf{b}_{\text{sc}}, \mathbf{r}_{\text{sc}}) &= \frac{v^2}{m_p} \frac{1}{\int_0^{2\pi} \int_{\mu_{\text{det}}}^1 \mu d\mu d\varphi} \int_0^{2\pi} \int_0^1 f(\mathbf{r}_{\text{sc}}, v, \mu, \varphi) \mu d\mu d\varphi \\ &= \frac{v^2}{m_p} \frac{2}{2\pi(1 - \mu_{\text{det}}^2)} \int_0^{2\pi} \int_0^1 f(\mathbf{r}_{\text{sc}}, v, \mu, \varphi) \mu d\mu d\varphi \end{aligned} \quad (4)$$

with $\mu_{\text{det}} = \cos \theta_{\text{det}}$. In the symmetrical configuration where the spacecraft observes precipitating particles in the northern 20 hemisphere, \mathbf{n}_{det} is aligned with $-\mathbf{b}_{\text{sc}}$, but angle definitions remain the same.

As a first-order approximation, protons remain attached to a given magnetic flux tube; one can hence trace particles backwards in time out to the magnetosphere, following magnetic field lines. Assuming smooth quasilinear propagation, for a given particle of pitch angle θ , the quantity $\sin^2 \theta / B$ is conserved along the trajectory. Let \mathbf{r}_0 be a location in the magnetosphere mapping to the spacecraft in terms of magnetic field topology. For particles travelling between \mathbf{r}_0 and \mathbf{r}_{sc} , we have

$$25 \quad \frac{\sin^2 \theta_0}{B_0} = \frac{\sin^2 \theta}{B_{\text{sc}}}, \quad (5)$$

where B_0 and θ_0 correspond to the magnetic field magnitude and the particle pitch angle at \mathbf{r}_0 , respectively, and B_{sc} and θ correspond to the same parameters at \mathbf{r}_{sc} . This can also be written

$$\frac{1 - \mu_0^2}{B_0} = \frac{1 - \mu^2}{B_{\text{sc}}}, \quad (6)$$

with $\mu_0 = \cos \theta_0$. By differentiating eq. (6), one gets

$$5 \quad \mu d\mu = \frac{B_{\text{sc}}}{B_0} \mu_0 d\mu_0. \quad (7)$$

According to Liouville's theorem, $f(\mathbf{r}, v, \mu, \varphi)$ is conserved along the trajectories of the system, i.e., in the absence of potential fields

$$f(\mathbf{r}_{\text{sc}}, v, \mu, \varphi) = f(\mathbf{r}_0, v, \mu_0, \varphi_0). \quad (8)$$

Using eq. (8), and then equations (6) and (7), yields from eq. (4)

$$10 \quad \begin{aligned} \hat{\mathcal{J}}(E, \mathbf{b}_{\text{sc}}, \mathbf{r}_{\text{sc}}) &= \frac{v^2}{m_p} \frac{2}{2\pi(1 - \mu_{\text{det}}^2)} \int_0^{2\pi} \int_{\mu_{\text{det}}}^1 f(\mathbf{r}_{\text{sc}}, v, \mu, \varphi) \mu d\mu d\varphi \\ \hat{\mathcal{J}}(E, \mathbf{b}_{\text{sc}}, \mathbf{r}_{\text{sc}}) &= \frac{v^2}{m_p} \frac{2}{2\pi(1 - \mu_{\text{det}}^2)} \int_0^{2\pi} \int_{\mu_{\text{det}}}^1 f(\mathbf{r}_0, v, \mu_0, \varphi_0) \mu d\mu d\varphi \\ \hat{\mathcal{J}}(E, \mathbf{b}_{\text{sc}}, \mathbf{r}_{\text{sc}}) &= \frac{v^2}{m_p} \frac{2}{2\pi(1 - \mu_{\text{det},0}^2)} \frac{B_{\text{sc}}}{B_0} \int_0^{2\pi} \int_{\mu_{\text{det},0}}^1 f(\mathbf{r}_0, v, \mu_0, \varphi_0) \frac{B_{\text{sc}}}{B_0} \mu_0 d\mu_0 d\varphi_0 \\ \hat{\mathcal{J}}(E, \mathbf{b}_{\text{sc}}, \mathbf{r}_{\text{sc}}) &= \frac{v^2}{m_p} \frac{1}{\int_0^{2\pi} \int_{\mu_{\text{det},0}}^1 \mu_0 d\mu_0 d\varphi_0} \int_0^{2\pi} \int_{\mu_{\text{det},0}}^1 f(\mathbf{r}_0, v, \mu_0, \varphi_0) \mu_0 d\mu_0 d\varphi_0 \end{aligned} \quad (9)$$

$$\hat{\mathcal{J}}(E, \mathbf{b}_{\text{sc}}, \mathbf{r}_{\text{sc}}) = \hat{\mathcal{J}}(E, \mathbf{b}_0, \mathbf{r}_0),$$

15 where \mathbf{b}_0 is the unit vector with the direction of the local magnetic field at \mathbf{r}_0 , and

$$\mu_{\text{det},0} = \sqrt{1 - \frac{B_0}{B_{\text{sc}}}(1 - \mu_{\text{det}}^2)}. \quad (10)$$

In other words, the directional differential particle flux observed by the telescope onboard the spacecraft can be estimated by averaging the relevant subset of the particle VDF at a chosen conjugate location in the magnetosphere. The angular boundaries of the averaged phase space domain are obtained by scaling the viewing angle of the detector to $\theta_{\text{det},0} = \arccos \mu_{\text{det},0}$ based

20 on the ratio of magnetic field magnitudes at the spacecraft and at the conjugate location in the magnetosphere where the VDF is analysed (cf. eq. (10)).

For particles located at \mathbf{r}_0 to reach a spacecraft at the top of the ionosphere at ~ 800 km altitude, their pitch angles must be within the bounce loss cone, whose opening angle is determined by

$$\theta_{\text{lc}} = \arcsin \sqrt{\frac{B_0}{B_{\text{sc}}}}. \quad (11)$$

In the **undisturbed** nightside equatorial plane, θ_{lc} takes values of a few degrees at most, and is smaller than 1° beyond $10 R_E$ (see, e.g., Sergeev and Tsyganenko, 1982). **In presence of a rather large dipolarisation front with, e.g., $B_0 \simeq B_z = 30$ nT, assuming a mapping to auroral latitudes ($B_{sc} \sim 53\,000$ nT), eq. (11) gives $\theta_{lc} = 1.4^\circ$.** In Vlasiator, knowing the VDF at a given location in the magnetosphere, one can calculate the bounce loss cone angle value and, at a given velocity magnitude v (i.e., at a given energy), average the phase-space density inside the loss cone to evaluate $\tilde{\mathcal{J}}(E, \mathbf{b}_0, \mathbf{r}_0)$. It should be noted that, with this approach, the obtained directional differential precipitating flux corresponds to the one which would be measured by a telescope onboard a spacecraft at the topside ionosphere with a viewing angle $\Omega_{det} = 2\pi$ sr (cf. eq. (2)).

In practice, the methodology to estimate differential precipitating proton fluxes at \mathbf{r}_0 is as follows. First, the loss cone angle θ_{lc} is calculated. This is achieved by following the magnetic field line from \mathbf{r}_0 to the inner boundary of the simulation domain, at about $4.7 R_E$, and then extrapolate the magnetic field to the top of the ionosphere using the line dipole approximation. The ratio of the magnetic field magnitudes at \mathbf{r}_0 and at the mapped region in the topside ionosphere enables the calculation of the bounce loss cone angle using eq. (11). Second, we estimate the differential precipitating flux by calculating

$$\tilde{\mathcal{J}}(E, \mathbf{b}_0, \mathbf{r}_0) = \frac{v^2}{m_p} \langle f(\mathbf{r}_0, v, \theta, \varphi) \rangle_{\theta < \theta_0 = \theta_{lc}}, \quad (12)$$

where $\langle f(\mathbf{r}_0, v, \theta, \varphi) \rangle_{\theta < \theta_0}$ is the average value of the phase-space density at speed v inside the bounce loss cone. This approximation of eq. (9) is reasonable since θ_0 is very small and hence we have $\mu_0 = \cos \theta_{lc} \approx 1$ inside the integral.

2.3 Examples of differential precipitating proton fluxes with Vlasiator

In the simulation used in this study, full velocity distributions of protons are saved every 50 simulation cells in the X and Z direction due to limitations in the file sizes. Therefore, the estimation of the differential precipitating proton flux based on eq. (12) can be applied only in a few selected locations in the nightside magnetosphere. Figure 3 shows examples of velocity distributions observed at two virtual spacecraft S_1 and S_2 that are used in this study. The main panel (a) shows the proton temperature in the nightside part of the noon-midnight plane at time step $t = 1800$ s, with magnetic field lines drawn in black. **It should be stressed that this temperature is that of an isotropic plasma which would have the same total pressure as the simulated distribution, thus it does not represent the temperature of the bulk plasma but rather the measured effect of a combined bulk plasma and potential fast additional flows. The effect of such a combination can be seen near S_1 , as a stream of hot ($T \approx 20$ MK) plasma coming from the transition region is reaching the virtual spacecraft, leading to a local enhancement of the proton temperature compared to its background value at S_1 .** The white area corresponds to the region of the geospace located earthwards from the inner boundary at $\sim 4.7 R_E$. Black arrows indicate the magnetic field direction at the virtual spacecraft. Panels (b) and (c) show slices of the velocity distributions at S_1 and S_2 , respectively, in the plane defined by the local magnetic field direction \mathbf{v}_B and the local electric field direction $\mathbf{v}_{B \times V}$ (approximately aligned with the Y direction, i.e., into the simulation plane). The grid spacing is 1000 km/s. The velocity distribution at S_1 consists of a core population centred near the origin and a crescent-shaped beam at about 1000 km/s. It corresponds to the superposition of a cold plasma with a low bulk velocity in the magnetic field direction with a more energetic population travelling earthwards. The velocity distribution at S_2 is nearly Maxwellian with a broad loss cone in the magnetic field direction (this loss cone will

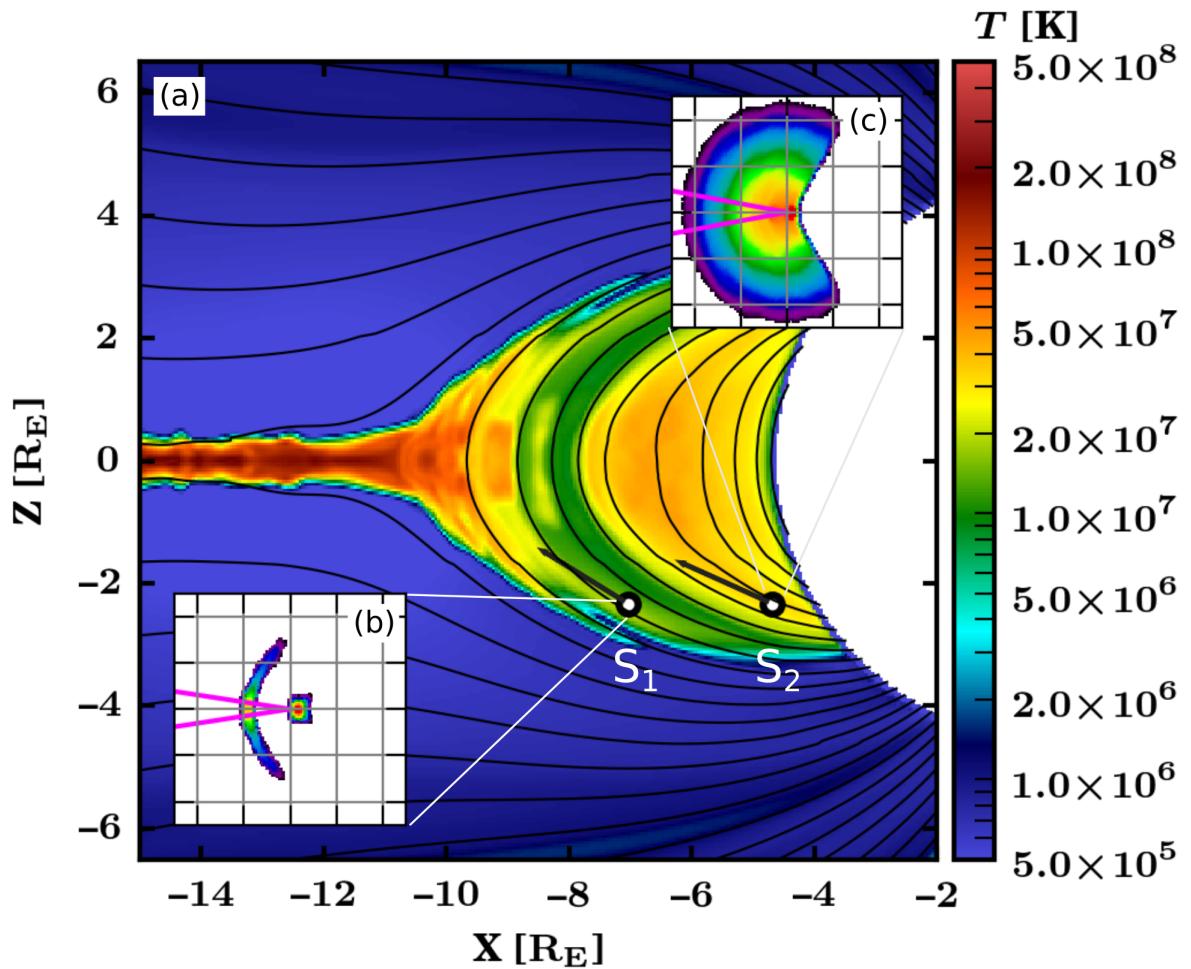


Figure 3. (a) Simulated plasma temperature in the nightside magnetosphere at $t = 1800$ s. The Sun is located beyond the right boundary of the figure. The two black circles filled with white are virtual spacecraft S_1 and S_2 . The arrows indicate the magnetic field directions at S_1 and S_2 . (b) Velocity distribution function of protons at S_1 in the $(v_{\parallel}, v_{B \times V})$ plane. The grid spacing is 1000 km/s. The magenta lines indicate the boundaries of the bounce loss cone. (c) Same for protons at S_2 .

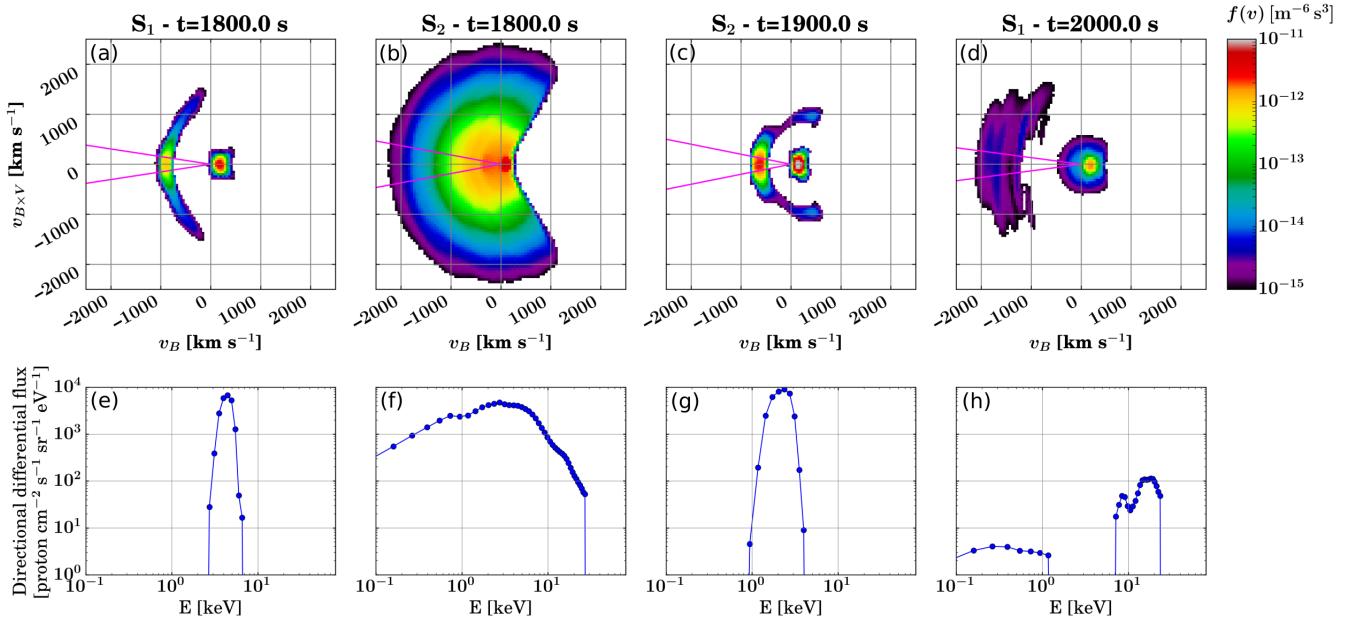


Figure 4. (top) Examples of proton velocity distribution slices in the local magnetic frame at virtual spacecraft S_1 and S_2 at various time steps of the simulation. The bounce loss cone is shown with magenta lines. (bottom) Corresponding directional differential precipitating fluxes obtained with the presented method.

be discussed below). The width of the distribution, centred near the origin, indicates that it corresponds to a hotter plasma (in comparison with the one at S_1) nearly at rest in the local magnetic frame, with protons having velocities up to about 2000 km/s. **The imposed static Maxwellian VDF at the inner boundary can affect the neighbouring cells through the calculation of translation and acceleration terms in the Vlasov equation, but such effects vanish rapidly with distance to the boundary, and the plasma at S_2 is unlikely to be affected by the boundary condition.**

The contrast between the velocity distributions at S_1 and S_2 is reflected in the plasma temperature, which is 15 MK at S_1 and 32 MK at S_2 . In panels (b) and (c), the bounce loss cone is indicated with pink lines. As can be seen in the two examples, the loss cone is not empty, and hence a directional differential flux of precipitating protons can be derived using eq. (12). We note that the empty part of the phase space in panel (c) is due to the presence of the inner boundary. Indeed, the inner boundary absorbs incoming protons, and particles bouncing back from a mirror point earthwards from the inner boundary in the southern hemisphere are therefore absent at virtual spacecraft S_2 in the simulation. This feature does not have consequences in our study, since the relevant part of the velocity distribution function is the one located inside the bounce loss cone.

Figure 4 shows four examples of velocity distributions at virtual spacecraft S_1 and S_2 during the simulation run (panels a–d) and the associated precipitating proton differential fluxes obtained using the method described in section 2.2 (panels e–h). The velocity distributions are slices in the plane defined by the magnetic field direction, v_B , and the electric field direction, $v_{B \times V}$. Panels (a) and (b) are the distributions at $t = 1800.0$ s at virtual spacecraft S_1 and S_2 , respectively, shown in Fig. 3.

The crescent-shaped beam partly in the bounce loss cone shown in panel (a) is associated with a precipitating differential flux narrow in energies (panel e), peaking around 4–5 keV with values close to 10^4 proton $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{eV}^{-1}$. **Although this distribution is intrinsically unstable, the development of instabilities (magnetosonic, ion-ion left-hand, firehose) requires the conditions that the field-aligned drift velocity V_0 of the protons be greater than the Alfvén speed V_A , and that the ratio between beam (n_b) and core (n_c) densities be “very small” (Gary, 1991).** While the distribution shown in panel (a) has $n_b/n_c = 0.086$, it exhibits $V_0 \sim 1000 \text{ km s}^{-1}$ and $V_A = 4379 \text{ km s}^{-1}$. Since the criterion on velocities is not verified, we do not expect that the instabilities listed above can grow fast enough to significantly affect the ion distributions on the time scale needed for precipitating protons (i.e., essentially the field-aligned beam) to reach the inner boundary or even the ionosphere.

In contrast with the distribution with a crescent-shaped beam shown in panel (a), the hot, nearly-Maxwellian velocity distribution inside the loss cone at S_2 (panel b) is associated to a broad precipitation spectrum (panel f), with energies of precipitating protons ranging from below 100 eV to nearly 30 keV. The peak differential flux values are of the order of 4000 proton $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{eV}^{-1}$, at energies of 2–5 keV. The sharp cutoff taking place at ~ 25 keV in panel (f) is due to the sparsity threshold, set to $10^{-15} \text{ m}^{-6} \text{s}^3$ in this run, hence corresponding to the lower limit of the colour axis in panels a–d.

Panel (c) shows a velocity distribution relatively similar to panel (a) but was obtained at virtual spacecraft S_2 with a delay of 100 s, indicating that the region with narrow-beam precipitation moved earthwards. The corresponding differential flux in panel (g) is centred around 2–3 keV, i.e., slightly lower than in panel (e), while peak flux values are almost the same with nearly 10^4 proton $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{eV}^{-1}$. The last velocity distribution, in panel (d), was taken at S_1 200 s after the one from panel (a). The core population is broader and is partly inside the bounce loss cone, leading to a low flux of low-energy (0.1–1 keV) proton precipitation as can be seen in panel (h). A beam of low phase-space density with a complex structure partly fills the loss cone at velocities of 1300–2100 km/s, which shows in the precipitating spectrum as two peaks, at about 8 keV and 15 keV, with flux values two orders of magnitude lower than in panel (a). These four selected examples suggest that at virtual spacecraft S_1 and S_2 one can observe a variety of precipitating fluxes during the Vlasiator simulation. If compared to observations, these differential fluxes are within the same order of magnitude as the NOAA 6 proton energy spectra shown in Basu et al. (2001) in terms of peak energy (1–10 keV) and slightly higher in terms of flux values (10^2 – 10^3 $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{eV}^{-1}$). Observations from the DMSP 12 spacecraft reported in Lummerzheim et al. (2001) indicate mean precipitating energy of the order of 10 keV and flux values around 10^3 $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{eV}^{-1}$. These values were however obtained in the evening MLT sector, where proton precipitation exhibits statistically harder energy spectra than in the midnight sector (Galand et al., 2001).

One assumption which is made during the derivation of the precipitating fluxes is that there are no field-aligned electric fields in the system (cf. eq. (8)). Figure S1 in the Supplementary Material shows the parallel component of the electric field at the same time step and with a similar format as Fig. 3. This parallel component was averaged over 120 s, which corresponds roughly to one bounce period for 10 keV protons at $L = 9$ (virtual spacecraft S_1). It can be seen that the parallel electric field between S_1 or S_2 and the inner boundary is of the order of 0.01 to 0.1 mV m^{-1} . When integrated along the field line between S_1 and the inner boundary, this corresponds to a potential difference of the order of 1 kV. In their discussion of the effect of potential drops in the auroral acceleration region on precipitating protons,

Liang et al. (2013) estimate that for ions with energies $\gg 1$ keV the acceleration resulting from typical potential drops in the auroral acceleration region (~ 1 kV up to ~ 4 kV occasionally) can be neglected, which enables a reasonable mapping of auroral latitudes to the central plasma sheet. It therefore seems acceptable to neglect the effect of parallel electric fields when deriving the precipitating proton fluxes with the method described in section 2.2. Furthermore, 5 given the location of S_1 and S_2 on closed field lines which are being convected earthwards, there is no risk that the precipitating protons observed at S_1 (or S_2) are affected by processes such as magnetic reconnection before they reach the ionosphere.

3 Results

3.1 Nightside proton precipitation

10 An overview of the dynamics of the nightside magnetosphere from $t = 1000$ s until the end of the simulation at $t = 2150$ s is provided with supplementary animation S1. Figure 5 shows the time evolution of the proton precipitation at virtual spacecraft S_1 and S_2 during this time interval. Panels (a) and (b) show the precipitating proton differential flux (colour scale) as well as the mean precipitating energy (black line) as a function of time, while panels (c) and (d) show the integral energy flux. It can be seen that, at virtual spacecraft S_1 , broad-energy proton precipitation above 1 keV starts around $t = 1360$ s, as the 15 magnetic field line observed by S_1 is becoming slightly stretched. The energetic tail of the proton precipitation spectrum reaches up to 20 keV and the mean precipitating energy fluctuates between 2 and 5 keV until $t \approx 1750$ s, i.e., about 90 s after the global magnetotail reconfiguration is initiated by the dominant X-line near $X = -13R_E$. Around $t = 1750$ s, the precipitation becomes narrower in energy and, after $t = 1850$ s, the mean precipitating energy increases from 4 keV to 20 keV, while fluxes decrease by almost two orders of magnitude. This corresponds to the times during which the nightside reconnection speeds 20 up and S_1 observes magnetic field lines becoming more dipolar. Between $t = 1900$ s and $t = 1925$ s, S_1 does not observe any precipitation, as the virtual spacecraft is momentarily observing lobe-type plasma and the local loss cone is empty, but precipitation resumes with high energy (10–20 keV) and relatively low differential flux values ($\sim 10^2 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ eV}^{-1}$) after $t = 1925$ s, as S_1 is magnetically connected to the transition region. A low-energy (< 1 keV) precipitating population appears between $t = 1990$ s and $t = 2040$ s, presumably associated with heating of the core plasma. At the end of the simulation, 25 the precipitating mean energy decreases while differential flux values are enhanced to $\sim 10^3 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ eV}^{-1}$. The integral energy flux remains within $1\text{--}6 \times 10^7 \text{ keV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ during the broad-energy precipitation phase, but then drops between 10^6 and $10^7 \text{ keV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ during the phase when field lines passing by S_1 become dipolar ($t = 1800\text{--}1900$ s). When precipitation observations from S_1 resume ($t \approx 1930$ s), the integral energy flux remains close to $10^7 \text{ keV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ before briefly increasing to reach $10^8 \text{ keV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ and abruptly decreasing around $10^6 \text{ keV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ until the end 30 of the simulation. Those integral energy flux values are in agreement with the Hardy model, according to which the nightside maximum total energy flux ranges between about 4×10^7 and $2 \times 10^8 \text{ keV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$, depending on the Kp index value (Hardy et al., 1989).

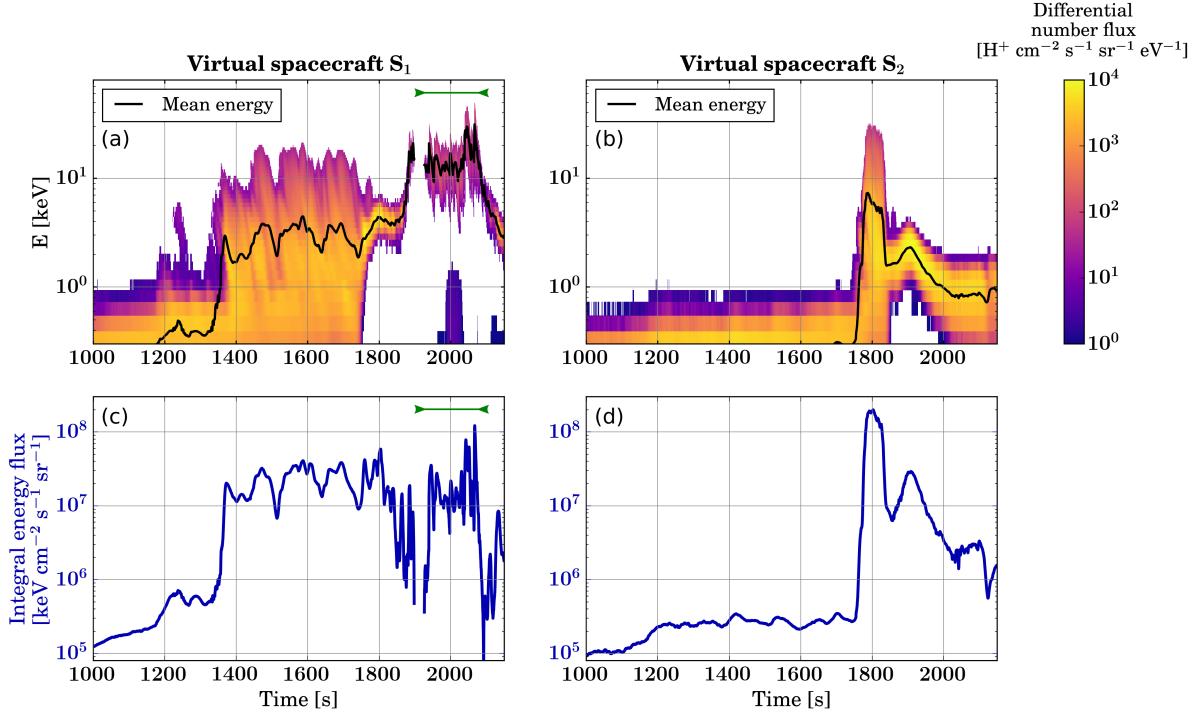


Figure 5. (a) Differential number flux of precipitating protons observed at virtual spacecraft S_1 as a function of time during the simulation. The black line indicates the mean precipitating energy as a function of time. (b) Same but at virtual spacecraft S_2 . (c) Integral energy flux associated with proton precipitation as a function of time, at virtual spacecraft S_1 . (d) Same but at virtual spacecraft S_2 . The green segments in panels (a) and (c) indicate the time interval with precipitation associated with dipolarising flux bundles presented later.

At virtual spacecraft S_2 (panels b and d), proton precipitation above 1 keV appears around $t = 1760$ s in the simulation, corresponding roughly to the time when the broad-energy precipitation at S_1 becomes narrower in energy. For about one minute, broad-energy precipitation with up to 30 keV protons and with a mean energy of 6–7 keV is observed, leading to integral flux values reaching $2 \times 10^8 \text{ keV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. The precipitating energy spectrum then becomes narrower and centred around 2 keV (during $t = 1850$ –1900 s) and gradually broadens again until the end of the simulation, when the mean precipitating energy decreases below 1 keV.

While the 2D simulation setup with a scaled line dipole does not enable a direct mapping of the virtual spacecraft locations in terms of geomagnetic latitudes or even L values, it appears clearly that the properties and the dynamics of proton precipitation are very different at S_1 and S_2 . From the geometry, S_1 maps to higher geomagnetic latitudes than S_2 , and the analysis of Fig. 5 suggests that S_1 represents well geomagnetic latitudes usually mapping to the auroral oval, while S_2 would correspond to slightly lower latitudes where the proton auroral arc can be observed around the onset of ionospheric substorms, after drifting equatorwards during the growth phase (Liu et al., 2007). Indeed, precipitation is observed at S_1 before the global

magnetotail reconfiguration due to reconnection is initiated (around $t = 1660$ s; Palmroth et al. (2017)), which suggests that S_1 maps to geomagnetic latitudes where aurora is visible during the growth phase of substorms. On the other hand, proton precipitation is only observed at S_2 around the time when the first particles accelerated earthwards following the global magnetotail reconfiguration reach the inner magnetosphere.

5 3.2 Flow bursts and precipitation

In what follows, we will focus on the proton precipitation associated with dipolarising flux bundles by considering virtual spacecraft S_1 between $t = 1920$ s and $t = 2080$ s. During this time span, S_1 is on magnetic field lines mapping to the transition region near $X = -9R_E$, as can be seen in supplementary animation S2. Juusola et al. (2018a) showed that, during this time period, sustained tail reconnection is taking place at a dominant X-line drifting from $X \approx -14R_E$ to $X \approx -18R_E$ and is 10 associated with fast earthward flows on the earthward side of the X-line.

Figure 6 is a snapshot of supplementary animation S2 at $t = 1945$ s. The colour-coded parameter is the x -component of the plasma bulk velocity, V_x . The location of virtual spacecraft S_1 is indicated with a red and white circle. Eight plus signs of various colours indicate locations of additional virtual spacecraft which will be used in the following to track the field-aligned component of the plasma bulk velocity. These virtual spacecraft are arranged in such a way that one can follow the 15 bulk properties of the plasma between S_1 and the current sheet through the transition region. As can be seen in the figure, they are not located on a same field line, but rather along the region of positive V_x , which corresponds to the path followed by precipitating protons as field lines are being convected earthwards. Full velocity distributions are not available at those points due to limitations in the file sizes. The spacecraft indicated with an orange plus sign, which is the furthest in the current sheet, will be called S_0 .

20 Figure 7 shows the precipitation flux observed at S_1 between $t = 1920$ s and $t = 2080$ s, corresponding to the time interval marked with a green line in panels (a) and (c) of Fig. 5. Panel (a) of Fig. 7 shows the differential number flux of precipitating protons (colour scale) and the mean precipitating energy (black line). One can visually identify successive bursts of precipitating protons at energies ranging between about 5 keV and 50 keV. The energy dispersion of precipitating protons is visible, as within a given precipitation burst the highest energies are observed first and the lowest energies are observed last. This is 25 also visible in the time variations of the mean precipitating energy. Between $t = 1985$ s and $t = 2035$ s, a low-energy (< 1 keV) population of precipitating protons is observed in addition to the ~ 10 keV precipitation, but with fluxes lower than the main precipitating population around 10 keV by almost two orders of magnitude. The differential flux of the main precipitating proton population at 5–50 keV has values around $10^2 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ eV}^{-1}$, which is relatively low compared to flux values at other times in the simulation that can reach $10^4 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ eV}^{-1}$ (cf. Fig. 5a). Panel (b) shows the integral energy flux 30 (blue line) alongside the component of the plasma bulk velocity at S_1 parallel to the magnetic field (red line), V_{\parallel} . Signatures of the precipitation bursts seen in panel (a) can be identified in both the integral energy flux and the plasma parallel bulk velocity. This suggests that the parallel bulk velocity can be used as a proxy for precipitating protons in this context.

In panel (c), the time series of the plasma parallel bulk velocity at the virtual spacecraft shown in Fig. 6 are indicated with a colour code consistent with that of the symbols indicating virtual spacecraft locations. The thick red line corresponds to the

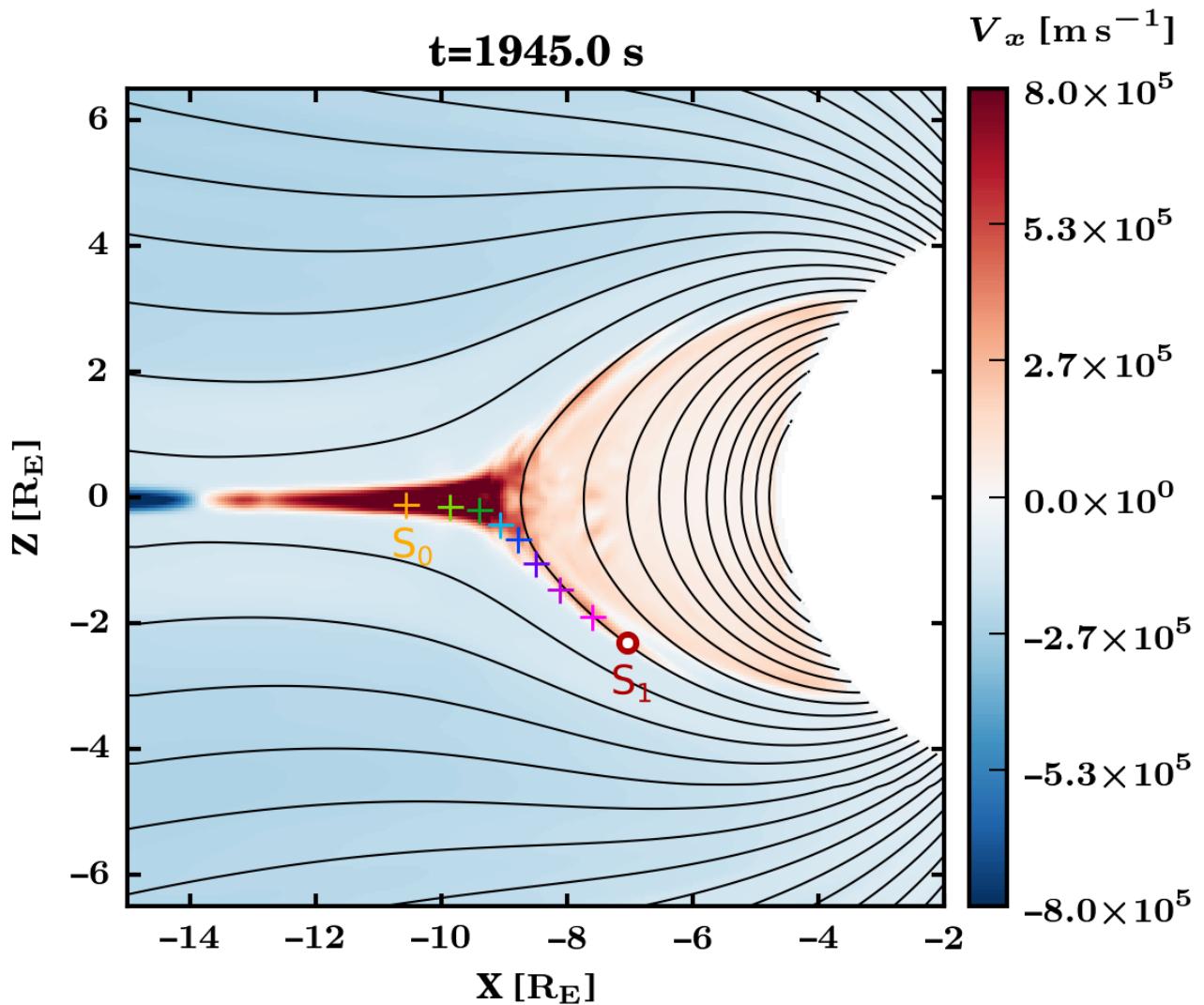


Figure 6. x -component of the plasma bulk velocity in the nightside part of the simulation plane at $t = 1945.0$ s. The red circle indicates the location of virtual spacecraft S_1 , and the eight coloured plus signs show additional virtual spacecraft for which the parallel velocity components are shown in Fig. 7. Black lines represent magnetic field lines.

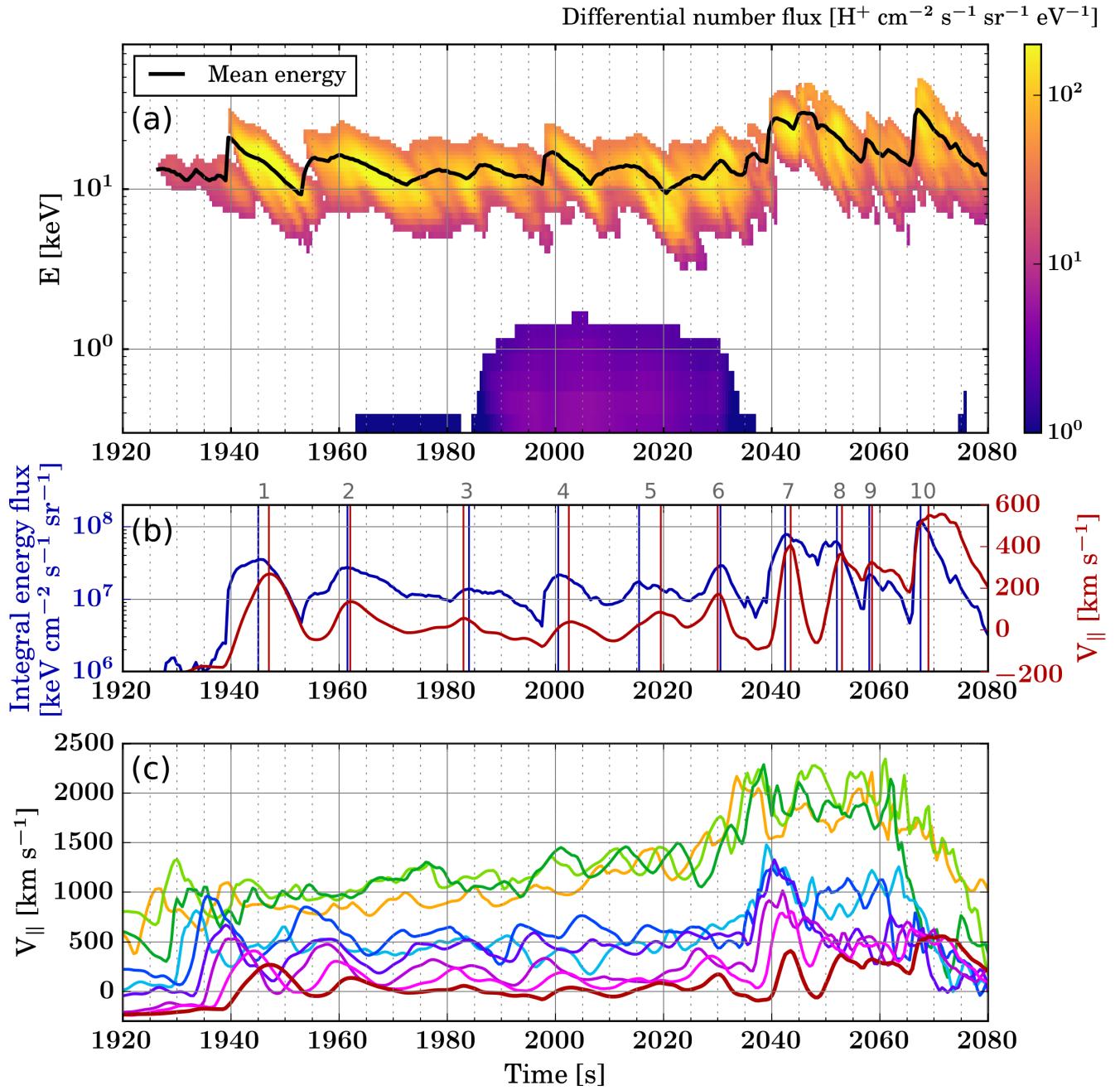


Figure 7. (a) Differential number flux of precipitating protons observed at virtual spacecraft S_1 between $t = 1920$ s and $t = 2080$ s. The black line indicates the mean precipitating energy as a function of time. (b) Blue line: Integral energy flux associated with proton precipitation as a function of time at virtual spacecraft S_1 . Red line: Parallel component of the plasma bulk velocity at S_1 . The vertical lines indicate the times associated with peak values for these two parameters, and the numbers in grey above the panel identify the precipitation bursts discussed in the text. (c) Parallel component of the plasma bulk velocity at S_1 and at the virtual spacecraft indicated with plus signs in Fig. 6, with a consistent colour code.

Table 1. Times of peak integral energy flux and plasma bulk parallel velocities at S_1 and S_0 for the main bursts of proton precipitation. In the last column, X indicates whenever a given precipitation burst observed at S_1 could not be traced back to S_0 .

Burst number	Time of integral flux peak [s]	Time of $S_1 V_{\parallel}$ peak [s]	Time of $S_0 V_{\parallel}$ peak
1	1945.0	1947.0	1926.5
2	1961.5	1962.0	1939.0
3	1984.0	1983.0	X
4	2000.5	2002.5	1985.0
5	2015.5	2019.5	1996.5
6	2030.5	2030.0	X
7	2042.5	2043.5	2033.5
8	2052.0	2053.0	X
9	2058.0	2058.5	X
10	2067.5	2069.0	2056.0

parallel velocity at S_1 , i.e., shows the same data as the red line in panel (b). A given fluctuation in the parallel velocity at S_1 can be traced back in time and tailwards by visually identifying its corresponding signature at successive tailward virtual spacecraft. For instance, the parallel velocity enhancement peaking at S_1 around $t = 1947$ s is consistent with parallel velocity enhancements visible at each of the virtual spacecraft, from the magenta one which is the closest to S_1 till the orange one 5 (S_0) which is the deepest in the current sheet, peaking around $t = 1927$ s. This suggests that some dipolarising flux bundles, which are identified through short-lived enhancements in $V_x \approx V_{\parallel}$ in the current sheet, directly lead to proton precipitation into the ionosphere in the regions mapped to the current sheet. However, not all the V_{\parallel} enhancements at S_1 can be related to V_x 10 enhancements in the current sheet. For instance, the V_{\parallel} peak at S_1 around $t = 2030$ s cannot be traced back to a specific V_{\parallel} peak at S_0 .

10 Table 1 gives the peak times of the integral energy flux, plasma bulk parallel velocity at S_1 and plasma bulk parallel velocity at S_0 for the ten main precipitating flux enhancements between $t = 1920$ s and $t = 2080$ s. These times correspond to those of local maxima of each parameter, as indicated with vertical lines in panel (b) of Fig. 7 for the integral energy flux and the parallel velocity at S_1 . For the four precipitation bursts observed at S_1 which could not be traced back to S_0 in the current sheet, the time of $S_0 V_{\parallel}$ peak is replaced with an X in the last column. In all cases but one, the peak times for the integral energy flux 15 and V_{\parallel} at S_1 are the same within 2 s; the exception is burst number 5 for which the triple peak in flux is associated with a single broad peak in V_{\parallel} , with 4 s difference in the times of local maxima.

15 In the four cases where a precipitation burst cannot be directly linked to a DFB passing by S_0 , the signatures are lost between the cyan and blue spacecraft (burst number 3), between the blue and indigo spacecraft (burst number 6), between the indigo and purple spacecraft (burst number 8), and between the light and dark green spacecraft (burst number 9). These virtual spacecraft 20 are located in the transition region, which suggests that the transition region can act like a buffer for DFBs, either directly

transmitting them and leading to bursts of precipitating protons, or releasing precipitating particles with no direct correlation with an incoming DFB from the tail.

4 Discussion

This paper presents the first unambiguous investigations of the global terrestrial magnetic field dynamics and its effects on proton precipitation in the midnight sector using a global hybrid-Vlasov model of the near-Earth environment, Vlasiator. Mende et al. (2002) listed four possible causes for particles to precipitate: (i) injection of particles on closed geomagnetic field lines, (ii) interaction of particles with electric fields, in particular waves, (iii) compression of the magnetic flux tube, and (iv) scattering on stretched magnetic field lines. All these causes can be studied using Vlasiator, except for some of the wave-particle interactions, as waves may not all be resolved by the model. It is known that proton precipitation can result from interactions with electromagnetic ion cyclotron (EMIC) waves (Erlandson and Ukhorskiy, 2001; Sakaguchi et al., 2008; Popova et al., 2018) as well as magnetosonic waves (Xiao et al., 2014). While magnetosonic waves are well resolved in Vlasiator, it is unclear whether this is also the case for EMIC waves, as their expected spatial scale is close to the ordinary-space grid resolution in the current runs. Wave-particle interactions are expected to be particularly important in the case of loss-cone scattering of trapped particles, i.e., ring current protons in the case of auroral proton precipitation. In this study, however, the analysis of Fig. 7 suggests that the precipitating protons essentially come from the magnetotail and are hence precipitating due to pitch-angle scattering resulting from the small curvature radius of the magnetic field near the neutral sheet (Sergeev and Tsyganenko, 1982). **This is confirmed in Fig. S2 provided in Supplementary Material, which shows the value of the κ parameter (see Introduction) along the x -axis between $-25R_E$ and $-6R_E$ as a function of time from $t = 1000$ s until the end of the simulation, as in Fig. 5. At the time of highest precipitating proton fluxes (i.e., after $t = 1800$ s) beyond $X \sim -10R_E$ in the plasma sheet, κ exhibits mostly values below $\sqrt{8}$, hence fulfilling the Sergeev et al. (1983) criterion according to which protons get scattered into the loss cone on stretched field lines.** While on the other hand it would prove interesting to estimate whether there is a non-negligible contribution to this precipitation from wave-particle interactions, this has to be left for a future study.

One limitation coming from the simulation set-up is related to the fact that the simulation run used in this study is 2D in ordinary space, which besides preventing a 3D description of the tail plasma requires using a line dipole instead of a point dipole for the geomagnetic field. The line dipole is scaled to reproduce a realistic dayside magnetopause stand-off distance, but it implies that geomagnetic field line equations have the form $r(\theta) = C \cos \theta$ in polar coordinates, with C a constant and θ the latitude, instead of $r(\theta) = C \cos^2 \theta$ in the case of a centre dipole. This means that it is not possible to map L values with geomagnetic latitudes at ionospheric altitudes in this run; hence, we cannot assess how virtual spacecraft S_1 and S_2 are mapped to the ionosphere in terms of geomagnetic latitude. Such a discussion will be possible once 3D-3V Vlasiator runs are available. However, this 2D set-up still allows us to investigate the connection between tail dynamics, such as dipolarisation fronts, and precipitation.

Despite those limitations, the precipitating proton fluxes (differential number flux and integral energy flux) observed at the two selected locations (virtual spacecraft S_1 and S_2) are in agreement with predictions from the Hardy model (Hardy et al., 1989, 1991) in the midnight MLT sector and for active geomagnetic conditions ($K_p > 3$). While direct comparison with particle data from spacecraft would be desirable, the fact that DMSP satellites, which are currently the main source of 5 direct precipitating proton observations, are on Sun-synchronous orbits essentially near the dawn-dusk plane does not allow midnight-sector observations. **In the nightside magnetosphere, comparison with data from the NASA Magnetospheric Multiscale (MMS) mission would prove interesting, but it is beyond the scope of the present study.**

While velocity distributions are not saved in every simulation cell in Vlasiator runs, results suggest that the parallel component of the plasma bulk velocity can be used to at least qualitatively describe the integral energy flux of precipitating protons 10 (cf. Fig. 7b). The idea that a beam superimposed to the core plasma population could lead to observable effects in the VDF first and second moments (bulk velocity and temperature) was brought forward by Parks et al. (2013), who showed that the apparent slowing down and temperature increase of the solar wind associated with nonlinear structures are due to the presence of a beam of particles propagating in opposite direction and with greater energy than the core solar wind population. In our 15 case, precipitating proton beams along the magnetic field direction affect the parallel component of the plasma bulk velocity in an analogous manner. Future work could therefore include deriving a proxy for proton precipitation relying on plasma bulk parameters, which are saved in every simulation cells, to quantitatively estimate the precipitation parameters such as the integral energy flux or mean energy.

In their study of BBF-associated proton precipitation with a MHD model, Ge et al. (2012) found that dipolarisation fronts led to precipitating proton enhancements into the ionosphere with integral energy fluxes of the order of $0.1 \mu\text{W m}^{-2}$. This 20 corresponds to $6 \times 10^4 \text{ keV cm}^{-2} \text{ s}^{-1}$. Assuming a uniform flux along all downwards directions as a rough approximation (2π solid angle), this gives a directional integral energy flux of the order of $10^4 \text{ keV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$, which is roughly three orders of magnitude below values obtained with Vlasiator when the global magnetotail reconfiguration is taking place (cf. Fig. 7b). A likely explanation is that the MHD simulation has low ion temperature T_i values compared to our kinetic approach, leading to lower precipitation energy fluxes as these are proportional to $T_i \sqrt{T_i}$ in their approach (cf. eq. (1) in Ge et al., 2012). 25 We note that the Vlasiator integral flux values are on the other hand in agreement with **the test-particle simulation results presented in their companion paper (Zhou et al., 2012b) with integral energy fluxes of $0.2\text{--}1 \text{ mW m}^{-2}$ (equivalent to $2 \times 10^7\text{--}10^8 \text{ keV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ with the same reasoning as above), and with statistical patterns shown in Galand et al. (2001) ($\sim 0.1 \text{ mW m}^{-2}$)**. One strength of evaluating the proton precipitation parameters using a kinetic model is that not only 30 integral energy fluxes can be calculated, but also differential fluxes, which may enable more detailed future studies of proton precipitation and its link to global magnetospheric dynamics. **Further, a test-particle approach is not fully self-consistent, in the sense that the electromagnetic fields affect the particle distributions but not vice versa. Therefore the test-particle approach does not fully describe, e.g., dynamics of reconnection-related precipitation.**

The examination of precipitation bursts passing by virtual spacecraft S_1 between $t = 1920\text{s}$ and $t = 2080\text{s}$ suggests that these bursts are associated with dipolarising flux bundles originating from the vicinity of the stable X-line in the current sheet. 35 **Field-aligned beams of plasma propagating earthwards associated to dipolarisation fronts have been observed and**

simulated not only in the central plasma sheet, but also in the plasma sheet boundary layer (PSBL) (Zhou et al., 2012a). In this Vlasior run, there is unfortunately no cell located in the PSBL where the full VDF is saved at each time step to make a comparison with results from Zhou et al. (2012a), hence we focus on proton precipitation originating from the central plasma sheet. Dipolarisation front signatures in the B_z component of the current-sheet plasma can be identified 5 in Fig. 6 of Juusola et al. (2018a) during the studied time interval (written as $t = 32:00$ – $34:40$ in their figure). While there are not enough precipitation bursts at S_1 in the studied time period to carry out a statistical analysis of their properties (integral flux enhancement and parallel velocity enhancement at S_1 , v_x enhancement at S_0), it can be noted that there does not seem to be a one-to-one correlation between the magnitude of the v_{\parallel} enhancement at S_1 and the possibility to trace it back to S_0 . This suggests that the transition region, corresponding to the location in the magnetotail where tail-like geomagnetic field 10 lines become more dipolar (near $X = -10.5 R_E$ in Fig. 3), plays a role in regulating these bursts. It is known that fast flows associated with BBFs can bounce when reaching the inner magnetosphere (e.g., Ohtani et al., 2009; Juusola et al., 2013; Nakamura et al., 2013) and may even exhibit multiple overshoots and oscillations around their equilibrium position (Panov et al., 2010). Our results further indicate that contrary to a frequent assumption, the transition region may be more than just a passive mediator between the plasma sheet and the ionosphere. DFBs could perhaps themselves experience some form of 15 bouncing near the transition region, which could explain the regulation of the studied proton precipitation bursts.

Auroral activations concurrent with BBFs have been widely studied (e.g., Nakamura et al., 2001a; Sergeev et al., 2004; Gallardo-Lacourt et al., 2014). However, the time scales that are involved in such processes are of the order of up to 10 min, in contrast to the short-lived DFBs and associated proton precipitation bursts (< 1 min duration) studied here. In terms of auroral emissions observed from the ground, it must be noted that the precipitation bursts observed at S_1 might actually lead 20 to more weakly modulated emissions than can be inferred from the integral energy flux variations at the virtual spacecraft, as the energy dispersion of precipitating protons tends to smooth the integral energy flux as particles get closer to Earth. This warrants future studies involving ground-based optical observations of proton aurora at high enough cadence (a few seconds at most) to investigate whether DFB-related proton aurora signatures can be seen from the ground. If not, this would imply that global **ion-kinetic** magnetospheric simulations, supplemented by data from spacecraft orbiting in the magnetosphere, might 25 be the only tool to investigate the active role played by the transition region in regulating the precipitation of auroral protons to the nightside ionosphere.

5 Conclusions

This paper presents the first evaluations of auroral (\sim 1–30 keV) proton precipitation from a global hybrid-Vlasov magnetospheric model, Vlasior. The simulation run considered here corresponds to relatively fast solar wind (750 km s^{-1}) with purely 30 southward IMF of moderate magnitude ($|\mathbf{B}| = |B_z| = 5 \text{ nT}$).

The evaluation of the differential number flux of precipitating protons at a given location in the nightside magnetosphere is achieved by averaging the velocity distribution function inside the bounce loss cone within energy bins. The integral energy

flux of precipitation as well as the mean precipitating energy are also calculated from the differential number flux. The main results of this study can be summarised as follows.

1. From this first case study, we find that Vlasiator reproduces auroral proton precipitation with realistic differential number fluxes and energies, when compared to the Hardy model.
- 5 2. During a selected time interval when a single X-line dominates the tail reconnection in the simulation, proton precipitation observed at a virtual spacecraft in the inner magnetosphere occurs in a bursty manner. In this situation, the integral precipitating energy flux exhibits variations mostly similar to the parallel component of the plasma bulk velocity at the virtual spacecraft. This suggests that the integral energy flux can qualitatively be described with the local parallel velocity at locations for which full velocity distributions are not saved in the Vlasiator run.
- 10 3. Finally, it is found that proton precipitation bursts can in some cases be traced back to the current sheet and are associated with dipolarising flux bundles. However, not all precipitation bursts correspond to a definite DFB, which suggests that the transition region plays a role in regulating auroral proton precipitation associated with DFBs during BBFs.

Code availability. Vlasiator is an open source code released under the GPLv2 license. The code is available at <http://github.com/fmihpc/vlasiator>.

Author contributions. MG carried out most of the analysis and prepared the manuscript. YP-K participated in running the simulation and 15 development of the analysis methods. UG and MB participated in the development of the analysis methods. All co-authors helped in the interpretation of the results, read the manuscript and commented on it.

Competing interests. The authors declare that they have no conflict of interest.

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