Model simulation of SAID intensification in the ionosphere under a current generator: the role of ion Pedersen transport

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Abstract. The sub-auroral ion drift (SAID) denotes a latitudinally narrow channel of fast westward ion drift in the sub-auroral region. The recently recognized sub-auroral optical phenomenon, the Strong Thermal Emission Velocity Enhancement (STEVE), is intrinsically related to intense SAIDs. Recently, we had developed a 2D time-dependent model to study the self-consistent variations of the ionosphere under intense SAID. The present study further advances the model to a current generator scenario of SAID. By assuming magnetospheric field-aligned current (FAC) inputs based on existing knowledge and observations, we model the self-consistent variations of the ionosphere, with focus on the dynamic changes of the plasma density, the Pedersen conductance, and the electric field. We can reproduce the self-consistent evolution of an intense SAID and its associated ionospheric dynamics such as extreme heating and depletion. We illustrate that the ion Pedersen drifts can cause dynamic density variations in the lower ionosphere. Positive feedback is found to exist between the self-consistent variations of the electric field and the conductance: the ion Pedersen transport associated with the electric field leads to density depletion in the lower ionosphere, thus reducing the Pedersen conductance and further enhancing the electric field there. We conclude that such positive feedback is key to the formation of intense SAID's in the ionosphere.

1. Introduction

The term Sub-Auroral Ion Drift (SAID) denotes a latitudinally narrow channel of fast westward ion drift in the sub-auroral region, often observed during geomagnetically disturbed intervals. Such phenomena were first reported and called "polarization jets" by Galperin et al. [1973]. Spiro et al. [1979] later called them SAID, a nomenclature still in use today. SAID's have been investigated in both ground and space-based observations (e.g., Anderson et al., 1991; 1993, 2001; Foster et al., 1994; Karlsson et a., 1998; Puhl-Quinn et al., 2007, Mishin; 2013; He et al., 2014; Archer et al., 2018). Motivated by the observations, numerous models have been constructted to study the ionospheric processes [e.g., Moffett et al., 1992; 1998; Heelis et al., 1993; Liang et al., 2021] and magnetospheric processes [Nishimura et al., 2020b; Wang et al. 2021] involved with SAID. SAID shares some similar properties with, yet differ in a few key aspects from, another sub-auroral flow phenomenon called the ”Sub-Auroral Polarisation Stream” (SAPS), which is usually weaker in flow magnitude and broader in latitudinal width than SAID [e.g., Foster and Burke, 2002; Mishin et al., 2017].

Recently, the recognition and observations of the Strong Thermal Emission Velocity Enhancement (STEVE) optical phenomena have further lifted interest in SAIDs. While the STEVE generation mechanism remains unclear to date, it is now well established that STEVE is collocated with intense SAID channels (MacDonald et al., 2018; Archer et al., 2019a; Nishimura et al., 2019; 2020a; Chu et al., 2019; Martinez et al., 2022). The STEVE-related SAID channels have larger flow speeds (in excess of 4 km/s), hotter electrons with temperatures up to 10^4 K, and density troughs deeper than 10^4 cm^{-3} in the F region. In this study, we will be more interested in those particularly intense SAID events related to STEVE, and investigate how such intense SAID's can form through ionospheric processes.

Several models have been proposed for the generation mechanisms of SAID, such as the voltage generator model [Southwood and Wolf, 1978; De Keyser et al., 1998; De Keyser, 1999; Burke et al., 2000], the current generator model [Karlsson et al., 1998; Anderssen et al., 1993; 2001], and the short circuit model (Mishin, 2013; Mishin et al., 2017). These candidate mechanisms differ in postulating which parameter, the electric field or the field-aligned current (FAC), is first established in the magnetospheric source region of SAID by certain local processes, while the second of these processes adjusts accordingly during the SAID evolution. In a current driver paradigm [e.g., Anderson et al., 2001], latitudinally-separated upward and downward FACs, presumably associated with electron precipitation and the pressure-gradient-driven Region-2 currents, respectively, are initially formed in the inner magnetosphere and imposed upon the ionosphere. Strong poleward electric fields appear in the sub-auroral low-conductance ionosphere, as the Pedersen current closes the upward-downward FAC loop, and maps to the magnetosphere. Such a current driver paradigm has been widely considered as the standard scenario of SAPS in a number of observations and numerical simulations [e.g., Zheng et al., 2008; Zou et al., 2012; Yu et al., 2015; 2017; Lin et al., 2019]. On the other hand, De Keyser [1999] and Mishin [2013] argued that radially outward SAID electric fields are first driven locally in the inner magnetosphere. The authors differed in the detailed magnetospheric mechanisms and processes underlying the formation of the SAID electric fields. To date, there is no adequate and overwhelming observational evidence to outright confirm or reject any of the afore-mentioned SAID mechanisms. It is even quite possible that different SAID events are led by different drivers, or that a mixture of different drivers may somehow co-exist in a SAID event [e.g., Figueiredo et al., 2004].

Notwithstanding the controversy about the driving mechanism for SAID, several observational facts regarding the FAC configuration associated with SAID have been well established:

(1) SAID is embedded in, and associated with, a moderate intensification of the Region-2 downward FAC [e.g., Anderson et al., 1993; 2001; Figueiredo et al., 2004; Puhl-Quinn et al., 2007; He et al., 2014; Mishin et al., 2017; Archer et al., 2019]. The source and mechanisms of the downward FAC related to SAID intensification are not fully determined to date, but have generally been considered to be related to the substorm ion injection. For example, via RCM-I simulation [Yang et al., 2019], Wang et al. [2021] found that consecutive bubble injections may lead to a strongly enhanced partial ring current and Region-2 FACs that are capable of driving intense SAID.

(2) SAID is equatorward of the electron plasma sheet precipitation boundary and yet is very close to it ($<1^0$ MLAT). The poleward tail of SAID is often found to barely extend into the electron precipitation region [He et al., 2004; Mishin, 2013; Mishin et al., 2017; Nishimura et al., 2020a]. This is also consistent with the optical observations in Yadav et al. [2021] who found STEVE to be adjacent to weak diffuse auroral emissions immediately poleward of STEVE. The plasma sheet electron precipitation naturally implies a source of upward FACs.

In all proposed mechanisms of SAID [e.g., De Keyser, 1999; Anderson et al., 2001; Mishin, 2013], there is a consensus that the ionosphere feedback must play a key role in the formation and evolution of SAID. The most rigorous way to examine the fine-scale evolution of the FAC and the electric field is a full electromagnetic (Alfvenic) approach [e.g., Sydorenko and Rankin, 2013; Tu et al., 2016]. That stated, in many practical studies, an electrostatic approach is often justifiable for solving electric fields and currents in the ionosphere, as long as the timescale of interest is longer than the Alfvenic transit time (see relevant discussions in St-Maurice et al. [1996]). In an electrostatic approach, the core link between the FAC and the electric field is the ionospheric conductance. The typically moderate downward FACs ($<\sim 1$ A/m^2) related to SAID, together with the very strong electric field, alludes to much reduced Pedersen conductance (Σ_P) inside the intense SAID channel at the level of ~ 0.1 S or even smaller (e.g., Karlsson et al., [1998]; Archer et al., [2018]). While it is true that strong plasma density depletion is often found within SAID in in-situ observations, the observations so far are all made in the upper F-region and/or topside ionosphere. Due to the small F-region ion-neutral collision frequency, the upper ionosphere is not likely to provide a major contribution to the height-integrated Σ_P. Even at night and in the absence of auroral precipitation, existing radar/rocket measurements typically reported electron densities on order of a few 10^3 cm^{-3} up to ~10^4 cm^{-3} in the nighttime subauroral E-region ionosphere [e.g., Chen and Harris, 1971; Strobel et al., 1974; Titheridge et al., 2000; Kim et al., 2020], which may still contribute to a major part of Σ_P there (see Section 2.2 later for a brief discussion of the possible ionization sources there). There is so far a lack of direct observations of the electron density under intense SAID in the lower ionosphere. The most recognized mechanism of density depletion in the upper ionosphere, namely a rapid conversion from O^+ to NO^+ ions under elevated electron/ion temperature [e.g., Schunk et al., 1976; Moffett et al., 1998], is presumably ineffective in the lower ionosphere where NO^+ is inherently dominant over O^+ owing to abundant molecular neutrals. Andersen et al. [1993; 2001] suggested one other contributing mechanism of interest, namely, that the enhanced ion Pedersen transport under SAID electric field may act to reduce the plasma density in the lower ionosphere and in turn the conductance. The role of ion Pedersen transport in the plasma density depletion in the lower ionosphere was first studied with a simple model by Banks and Yasuhara [1978], and later also addressed in deBoer et al. [2010] and Zettergren and Semeter [2012]. Recently, Liang et al. [2021] (hereafter referred to as LJ21) presented a comprehensive and dedicated study on the role of ion Pedersen transport in the dynamic variations of the lower ionosphere in a SAID channel. Using a 2D time-dependent model tailored to SAID conditions, LJ21 found that the transport effect of ion Pedersen drifts leads to strong density depletion and conductance drop in the lower ionosphere over a large portion of SAID.

It should be noted that all of the above model studies were performed under the premise of externally imposed electric field profiles, and were thus more aligned to a voltage driver scenario. Therefore, we may state that, though still pending for direct observations, the role of ion Pedersen transport in the density and conductance depletion in the lower ionosphere has been reasonably established in model simulations only under the voltage generator scenario of SAID. It therefore remains that a full-fledged model study of SAID evolution under a current generator scenario, prescribed by the existing knowledge about the SAID-related FAC configuration is found lacking. Such a study needs to take into account the important dynamics in the lower ionosphere such as the electron anomalous heating and the ion Pedersen drift. From the perspective of simulation algorithm design, solving the continuity equations of the plasma density and currents in the ionosphere according to known electric field inputs is more straightforward and easily programmable. By contrast, solving those equations according to given FAC inputs is an inverse problem that is mathematically more difficult and requires more onerous numerical efforts. The difficulty is further augmented when the parallel electric fields are also considered (see Section 2.1 later in the text). This is not to say that the current driver scenario is a confirmed or the only viable SAID mechanism, but it nevertheless remains to be one of the major candidate mechanisms of SAID formation to date. It is thus highly desirable to examine the self-consistent variations of ionospheric conductance and electric fields while taking into account the role of ion Pedersen transport, under a current driver. Such a task is taken here for the first time to the authors' knowledge.

The rest of the paper is organized as follows. Section 2 describes the basic equations and our procedures to solve the electric field from given FAC inputs on top of the ionosphere. We present simulation results in Section 3 for a SAID run and a SAPS run, highlighting in the key role played by ion Pedersen transport in SAID intensification. We discuss a few implications of our results and future works in Section 4. Section 5 concludes this paper.

2. Procedures to solve E-field and other notes of the model

The model used in this study inherits from LJ21. In a nutshell, the LJ21 model is a 2D time-dependent auroral and ionospheric model with high temporal and latitudinal resolution. The model self-consistently calculates the plasma density and temperature changes of the ionosphere led by electron precipitation and/or associated with electric fields. To make the model suitable for SAID studies, it includes a number of key processes related to strong electric fields, such as the electron anomalous heating, the ion Pederson transport, the vibrational excitation of N_2 , and ambipolar diffusion. In the present study, most of the physical processes, the basic equations, the rate coefficients, and the numerical schemes are the same as in LJ 21, except that the model is now modified to account for a current driver scenario. One of the key challenges is how we solve the electric fields from given FAC inputs. In this section, we first describe the changes in the basic equations and procedures used to solve for the electric field in the new model. We also depict the ambient ionization sources besides electron precipitation. These sources govern the background/ initial conductance in our simulation. Throughout this paper, the magnetic latitude (MLAT) in our 2D model is defined as the invariant latitude of dipole field lines.

2.1 Basic equations and procedures to solve E-field from FAC inputs

Solving for electrostatic electric fields with conductivity gradients is a common problem in ionospheric studies. When the parallel electric field ($E_{//}$) is ignored, the problem can be greatly simplified to a 2D (latitude/longitude) Poisson equation of the electric potential or even a 1D equation of the electric field (if one dimension is assumed homogenous), which can be solved with given FAC input. However, when $E_{//}$ is taken into account, the resultant Poisson equation requires an upper boundary condition for the electric potential. In many existing studies, such an upper boundary condition is either considered as constant potential at a sufficiently high altitude [e.g., St-Maurice, 1996; Noel et al., 2000], or specified according to an externally imposed electric field profile [e.g., deBoer et al., 2010; Zettergren and Semeter, 2012]. These specifications are at odds with the current generator notion. Furthermore, the numerical implementation of a Poisson equation solver is not an easy task, typically involving the inversion of a massive sparse matrix. In the present study, we use a novel and numerically simpler method, based on a perturbation approach, to solve the electric field from FAC inputs under the current generator scenario. The presence of $E_{//}$ and the curved geomagnetic field geometry are considered in our approach. In designing the algorithm we take advantage of the facts that, (1) our model is 2D so that $E_\perp$ exists only in the meridional direction; (2) $E_{//}$ and its associated non-mapping component of $E_\perp$ are much smaller than the mapping component of $E_\perp$ for our research objective.

Following St-Maurice et al. [1996] and Noel et al. [2005], we break the FAC into a thermal response component and an externally driven one, namely, $\mathbf{j}_{//}=\mathbf{j}_{//}^{\text{th}}+\mathbf{j}_{//}^{\text{ext}}$. In our model, the perpendicular current and the downward FAC are deemed to be carried solely by ionospheric thermal electrons (labeled by a superscript '*th*', ignored for perpendicular currents). For the upward FAC component associated with electron precipitation, we denote by $\mathbf{j}_{//}^{\text{ext}}$ the part contributed by magnetospheric electron precipitation. The way we evaluate this suprathermal electron contribution $\mathbf{j}_{//}^{\text{ext}}$ is described in detail in the supplemantray material. For now, we are only concerned with the total FAC in the current continuity equation,

$\nabla \bullet \mathbf{j} = \nabla \bullet \left(\mathbf{j}_{\perp}+\mathbf{j}_{//}\right) = 0$ (1)

In a purely 2D model such as the one we use, the divergence of Hall currents is zero (no zonal conductivity gradients), so that the perpendicular current divergence comes from the divergence of ion-driven Pedersen currents, namely,

$\mathbf{j}_{\perp} = \sigma_P \mathbf{E}_{\perp}$ (2)

n which $E_{\perp}$ is the perpendicular E-field, and the Pederson conductivity is given by

$\sigma_P = \sum \frac{N_i e}{B} \frac{\kappa_i}{1+\kappa_i^2}$, (3)

where N_i denotes the ion density; B denotes the magnetic field magnitude, e denotes the electron charge, and $_i$ is the ion gyrofrequency to the ion-neutral collision frequency ratio. The sum is over all ion species. The ion drift associated with the pressure gradient is ignored in (2). While it is true that ion frictional heating can be very intense under SAID, one may infer from LJ21 - and will see in the simulation outcome in this study- that the intense T_i enhancement region is usually accompanied by significant density depletion. Even if we ignore the density change and assume $\nabla p_i \approx n_i k \nabla T_i$, using the approximate formula $T_i = T_n + \frac{\langle m_n \rangle}{3k} V_i^2$ [e.g., St-Maurice et al., 1999], which yields a reasonably good estimate of the ion frictional heating in the ionosphere, one can find that the ion pressure-gradient drift is smaller than the electric-field-driven drift by a factor of $\sim \frac{2\langle m_n \rangle}{3eB} \bullet \frac{V_{\text{iy}}}{L}$. Here $\langle m_n \rangle$ denotes the collision-frequency-weighted averaged neutral mass; V_{iy} and L denote the flow speed and the latitudinal scale width of the SAID of interest, respectively. With typical SAID parameters, it can be shown from this that the ion pressure-gradient drift is at least three orders of magnitude smaller than the electric-field-driven Pedersen transport.

Under a dipole geomagnetic field, it proves necessary to use a dipole coordinate system (, ,) so as to be able to deal properly with directions perpendicular to and parallel to the geomagnetic field. How do deal with this orthogonal coordinate system is described in e.g., [Orens et al, 1979]. This means that equation (1) is now written in the following form for our 2D geometry:

$\nabla \bullet \mathbf{j} = \frac{1}{h_1 h_2 h_3} \bullet \left[\frac{\partial}{\partial \chi}\left(h_1 h_3 j_{\perp}\right) + \frac{\partial}{\partial \mu}\left(h_2 h_3 j_{//}\right)\right] = 0$ (4)

where h_1, h_2, and h_3 are the metric coefficients corresponding to the (field-aligned), (meridional perpendicular), and (azimuthal) coordinates, respectively, meaning that

$h_1 = \frac{r^3}{R_E^2\sqrt{1+3\cos^2\theta}}$; $h_2 = \frac{R_E \sin^3\theta}{\sqrt{1+3\cos^2\theta}}$; $h_3 = rsin\theta$ (5)

In these equations, r and describe the radial distance (to the Earth's center) and the co-latitude with respect to the dipole axis. For the narrow-width SAID structure ($<1^0$ MLAT) of interest, the latitudinal change of the metric coefficients is negligible compared to that of the conductivity and E-field. We thus ignore the perpendicular derivatives of the metric coefficients, but we still consider the change of the metric coefficients along a field line, meaning that $E_\perp$ and $j_{//}$ would map along the field line accordingly. Using the relation $\frac{h_2 h_3}{h_1} = const$ along a field line, equation (4) can be simplified to take the form,

$\nabla_\perp(\sigma_i E_\perp) + \frac{\partial}{h_1 \partial s}\left(h_1 j_{//}\right) = 0$ (6)

in which

$$\nabla_\perp = \frac{1}{h_2 \partial\chi} \quad ; \quad \nabla_{//} = \frac{\partial}{\partial s} = \frac{1}{h_1 \partial\mu}$$

are the gradient operators along the perpendicular and field-aligned directions respectively. From (6) we have,

$j_{//}(s) = -\frac{\int_0^s h_1(s')\nabla_\perp(\sigma_P E_\perp)ds'}{h_1(s)}$ (7)

For our current generator model, the FAC is imposed at an upper boundary of the F-region ionosphere, and we have

$j_{//}^{\mathrm{top}} = -\frac{\int_0^{s_{\mathrm{top}}} h_1(s)\nabla_\perp(\sigma_P E_\perp)\mathrm{ds}}{h_1(s_{\mathrm{top}})}$ (8)

in which the superscript/subscript '*top*' denotes the values at the upper boundary.

The approach we use to solve for $E_\perp$ from (8) is described as follows: in a nutshell, we separate the perpendicular E-field into mapping and non-mapping components. In a zeroth-order approximation, we ignore the presence of the parallel electric field $\mathrm{E}_{//}$. Under such a condition, the field line is an equipotential, and $E_\perp$ maps along the field line according to $E_{\perp M} \bullet h_2 = const$. The subscript '*M*' here denotes the mapping component of the electric field. As a result, and based on equation (8), after some algebra we obtain the following equation for the zeroth-order solution of $E_{\perp top}^M$,

$j_{//}^{\mathrm{top}} = -\nabla_\perp^{\mathrm{top}}\left[\widetilde{\Sigma}_P \bullet E_{\perp M}^{\mathrm{top}}\right]$ (9)

where the operator

$$\nabla_{\perp}^{\mathrm{top}} = \frac{h_2 \nabla_{\perp}}{h_2(s_{\mathrm{top}})}$$

denotes that the derivative is evaluated at the upper boundary altitude, and

$\widetilde{\Sigma}_P = \int_0^{s_{\mathrm{top}}} M \bullet \sigma_P \mathrm{ds}$ (10)

$$M(s) = \frac{h_2\left(s_{\mathrm{top}}\right)}{h_3\left(s_{\mathrm{top}}\right)} \bullet \frac{h_3(s)}{h_2(s)} = \frac{\sqrt{4-3\cos^2\Lambda \bullet \frac{r}{R_E}}}{\sqrt{4-3\cos^2\Lambda \bullet \frac{r_{\mathrm{top}}}{R_E}}}$$

where Λ is the invariant latitude of the field line. Equation (10) is basically equivalent to the well-known form $j_{//} = -\nabla_{\perp}(\Sigma_p E_{\perp})$ and the conventional definition of Σ_{P}, except for a modification, M(s), led by the curved geometry of the dipolar field line. A similar modification of Σ_{P} was involved in the studies of ionospheric electrodynamics at low latitudes [e.g., Haerendel et al., 1992]. For the high-latitude ionosphere, the conventional form of equation $j_{//} = -\nabla_{\perp}(\Sigma_p E_{\perp})$ would suffice in most practical applications, since M(s) is fairly close to unity over the ionospheric altitudes of interest. In this study, since our research target is the subauroral ionosphere, we retain the modification factor and adopt equations (9) and (10). Throughout this paper, when we mention the "Pedersen conductivity" ($_{\mathrm{p}}$), we refer to the definition in (3). When we use the "Pedersen conductance" (Σ_{P}, or sometimes conductance in abbreviation) in order to comply with the conventional nomenclature in literature, we actually mean the generalized definition from equation (10), namely a field-line-integral with the modification factor M(s) considered.

When $E_{\perp M}^{\mathrm{top}}(x)$ is obtained from (9) for a given $j_{//}^{\mathrm{top}}(x)$ profile at the upper boundary, where x denotes the invariant MLAT of a field line, the E-field is mapped along the field line according to

$E_{\perp M}(x,s) = E_{\perp M}^{\mathrm{top}}(x) \bullet \frac{h_2(s_{\mathrm{top}})}{h_2(s)} = E_{\perp M}^{\mathrm{top}}(x) \bullet \left(\frac{r_{\mathrm{top}}}{r}\right)^{3/2} \bullet \frac{\sqrt{4-3\cos^2\Lambda \bullet \frac{r}{R_E}}}{\sqrt{4-3\cos^2\Lambda \bullet \frac{r_{\mathrm{top}}}{R_E}}}$ (11)

This zeroth-order $E_{\perp M}(x,s)$ is the dominant part of the overall perpendicular E-field, and usually offers a very good approximation in the upper F-region. For a more accurate refinement, we consider the modification from the presence of the parallel electric field (see LJ21 for derivation),

$\mathbf{E}_{//} = \frac{\mathbf{j}_{//}^{\mathrm{th}}}{\sigma_{//}} - \frac{\nabla_{//} p_e}{N_e e} - \frac{m_e v_{\mathrm{en}}}{N_e e} \sum N_i u_{i//}$, (12)

where $\mathbf{j}_{//}^{\mathrm{th}}$ is the FAC carried by the ionospheric thermal electrons. $\sigma_{//}$ is the parallel conductivity. N_e and p_{e} denote the ionospheric electron density and pressure, respectively. N_i and $\mathrm{u}_{\mathrm{i}//}$ denote the density and field-aligned drift of ions, respectively. $_{\mathrm{en}}$ is the electron-neutral collision frequency. In the presence of electron precipitation, the overall FAC in the ionosphere contains mixed contributions from the suprathermal electron precipitation (labeled by $\mathbf{j}_{//}^{\mathrm{ext}}$) as well as from ionospheric thermal electrons, e.g., $\mathbf{j}_{//} = \mathbf{j}_{//}^{\mathrm{ext}} + \mathbf{j}_{//}^{\mathrm{th}}$ [e.g., Cattel et al., 1979; St-Maurice et al., 1996; Noel et al., 2005]. The current continuity equation (1) and its direct deduction equation (8) do not discriminate the current carriers, but in some processes only the thermal electron motion is relevant (such as in equation 12), so that the profile of $j_{//}^{\mathrm{ext}}$ along a field line needs to be evaluated and subtracted in the electron precipitation region. In this study, we evaluate $j_{//}^{\mathrm{ext}}$ using an empirical model proposed by Maeda & Aikin [1968] based on a Monte-Carlo transport simulation (see more details in supplementary material). Note that $j_{//}^{\mathrm{ext}}$ is relevant only in the upward FAC and electron precipitation region; the downward FAC is deemed as carried solely by ionospheric thermal electrons in our model. For the zeroth-order $\mathrm{E}_{//}$ in (12), we calculate the $j_{//}$ distribution along field lines and over latitudes from equation (7) according to the zeroth-order $E_{\perp M}(x, s)$, and subtract the suprathermal electron contribution $\mathbf{j}_{//}^{\mathrm{ext}}$ if applicable. In the presence of $E_{//}$, a non-mapping component of the perpendicular E-field ($E_{\perp N}$) arises. Under the electrostatic approximation $\nabla \times \mathbf{E} = 0$,

$\frac{\partial(h_2\,\mathrm{E}_{\perp N})}{\partial s} = h_2 \nabla_\perp E_{//}$, or

$\delta E_{\perp N}(s) = -\frac{\int_s^\infty h_2 \nabla_\perp E_{//} ds'}{h_2(s)}$ (13)

In practice, the upper limit of the field-line integral in (13) can be set a sufficiently high altitude where $E_{//}$ virtually vanishes. As pointed out in deBoer et al. [2010], and confirmed in our numerical tests, $E_{//}$ becomes very small in the upper ionosphere, so that the solution of the electric field is insensitive to the actual location of the upper integral boundary, as long as such a boundary is above ~500 km. In the runs presented in this paper, we set the upper limit of the integral in (13) at 600 km altitude.

Since the total $E_\perp$ must satisfy equation (8), we obtain the following equation for the first-order modification to the mapping component of $E_\perp$

$\nabla_\perp^{\mathrm{top}} \left(\widetilde{\Sigma}_P \bullet\ \mathrm{E}_{\perp M}^{\mathrm{top}} \right) = -\frac{\int_0^{s_{\mathrm{top}}} h_1 \nabla_\perp (\sigma_P\, \mathrm{E}_{\perp N}) \mathrm{ds}}{h_1(s_{\mathrm{top}})}$. (14)

After solving $\mathrm{E}_{\perp M}^{\mathrm{top}}$ from the above equation, we again map it along field lines according to (11). The total modified perpendicular electric field is,

$E_\perp = E_{\perp M} + \delta E_{\perp M} + \delta E_{\perp N}$. (15)

This modified E-field satisfies equation (8). Substituting (15) into (7), we compute again the $j_{//}$ distribution along field lines and derive the first-order modification of $\mathrm{E}_{//}$ using equation (12). We can then calculate again the second-order modification of the non-mapping and mapping components of $E_\perp$ following equations (13)-(15). Via numerical tests we find that the second-order modification of $E_\perp$ would suffice for the solution of E-fields with satisfactory precision over the simulation area of interest.

The conductivity is determined by the ion densities, whose variations in the lower ionosphere are intrinsically related to the E-field via the ion Pedersen transport. In our numerical algorithm, at each timestep of the plasma density, the calculations of the E-field and densities are iterated. We first use the ion densities and in turn p from the previous timestep to solve the E-fields, and then use these E-fields in the continuity equation to solve the ion densities at the current timestep. We then use the newly obtained densities to re-compute the p and the E-fields. The iteration repeats until convergent solutions of the densities of all major ions ($NO^+/O2^+/O^+$) and the E-field are reached, in practice defined by the relative difference between successive iterations becomes smaller than $1x10^{-5}$, over the entire latitudinal/altitudinal region of simulation at each timestep.

2.2 Background ionization and conductance.

Characteristic of the sub-auroral region, the electron precipitation is very weak in a main portion of our simulation area except near the poleward end (see Section 3.1 and Figure 1). However, it is important to note that, even in the absence of electron precipitation, certain weak ionization sources can still be present and are considered in our model. In the nightside sub-auroral region, some recognized weak yet nonzero sources of ionization include (see, e.g., Chen and Harris, 1971; Strobel et al., 1974; 1980; Titheridge, 2000; Solomon et al., 2020):

(a) The geocorona scattering of Hydrogen (Lyman- 121.6 nm and Lyman- 102.6 nm) and Helium (He I 58.4 nm and HE II 30.4 nm) lines. These geocorona fluxes may depend on a number of parameters such as the solar flux and the exospheric neutral density [e.g., Østgaard et al., 2003]. It is not our intent in this study to provide a detailed and accurate modeling of the geocorona fluxes. Instead, for our research purpose we are content with an approximate estimate of the background ionization level. Our modeling of these geocorona scattered lines adopts the same specification embedded in the current version of the GLOW and TIEGCM models for the nightside background ionization. More specifically, the incident Lyman- flux upon the ionosphere is assumed to be $5 \times 10^9 \bullet [1 + 0.002 \bullet (F_{10.7} - 65)]$ photons/cm^2/s, in which $F_{10.7}$ is the daily solar F10.7 flux, while the Lyman- , He I, and He II geocorona fluxes are assumed to be $1.5 \times 10^7,\ 1.5 \times 10^6,\ and\ 1.5 \times 10^6$ photons/cm^2/s, respectively.

(b) EUV light from the stars and galactic sources. Strobel et al. [1980] used the Smithsonian Astrophysical Observatory Star Catalog and summed O and B stars to obtain the starlight fluxes, but the detailed starlight flux spectra were not given in their paper. Instead, Strobel et al. [1980] presented the calculated production rates of O_2^+ ions led by the starlight. Starlight fluxes feature seasonal and latitudinal dependence; the resulting O_2^+ production rates at 120 km altitude range between ~0.5-2.7 cm^{-3}s^{-1} in Strobel et al. [1980]'s calculation. Again, we are content with an approximate estimate of the background ionization led by starlight for our research purpose. We thus use an approach similar to that in Titheridge [2000]: we assume a flat incident starlight flux spectrum of

1×10^6 photons/cm^2/s/nm over the 91.1-105 nm wavelength range (wavelengths $<$ 91.1 nm are strongly absorbed by the interstellar medium). Such a flux level is compatible with realistic observations of the stellar radiation over 91.1-105 nm band by STP satellite [Opal and Weller, 1984], and is found to yield ~1.1 cm^{-3}s^{-1} O_2^+ production rates at 120 km height in our model, comparable to the model results in Strobel et al. [1980].

(c) The interhemispherically transported photoelectrons if the conjugate hemisphere is sunlit. In our model, the solar flux spectrum is based on the EUVAC model parametrized by $F_{10.7}$ [Richards et al., 1994]. The production of photoelectrons is calculated accordingly in the conjugate sunlit ionosphere. For the transport of conjugate photoelectrons, we use the simplified approach by Solomon et al. [2020]: the interhemispherically transported photoelectrons are assumed to be equal to the upgoing photoelectrons from the sunlit hemisphere.

The computation of the above ionization sources involves the generation and transport of photoelectrons. Our model inherits such a module from the GLOW model [Solomon et al., 1998; 2017; 2020]. The relevant absorption/ionization/excitation cross sections involved in the calculation are also the same as those contained in the GLOW model. The above background ionization sources presumably feature much larger spatial and temporal scales than SAID of interest in this study. Their ionization rates are precalculated for the specific date/time/location of the run and then deemed constant over latitudes and during the elapsed times of our simulation.

The E-and F-region conductance is computed in our model according to density variations solved from the continuity equation. The D-region conductance is, however, not contained in our model, since our model ignores the electron Pedersen drift and has a lower boundary at 90 km. Even in the nightside subauroral latitudes without solar EUV fluxes and auroral electron precipitation, the D-region ionosphere may still be subject to ionization sources such as the galactic cosmic rays (Jackman et al., 2015). In this study, we resort to the WACCM-D model (Verronen et al., 2016, and in coutersy of Dr. Christopher Cully) to obtain the D-region electron density profile and in turn the conductance. We then attach this D-region conductance as a constant add-on to the total ionospheric conductance in solving for the electric field.

Albeit not without uncertainties, the modeling of the ambient ionization sources as depicted above may give us a reasonable estimate of the approximate level of the background ionization. In our runs, they in total contribute ~0.3 S Pedersen conductance in the absence of electron precipitation and without the transport effect. A similar estimate of the nightside background Σ_P was achieved in Ridley et al. [2004]. In their SAID simulation, Wang et al. [2021] adopted a ~0.4 S subauroral Σ_P, as inferred from the IRI model. Zheng et al. [2008] used 0.3 S as the minimum value in constructing the trough conductance profile in their SAPS simulation runs. Yu et al. [2017] applied Σ_P ~0.5 S in the mid-latitude region in their SAPS simulation. The initial Σ_P value in our run is thus compatible with these existing model simulations of SAID/SAPS. However, it is important to note that, unlike in our study, none of the above existing simulations consider the subsequent variations of the sub-auroral conductance under the SAID/SAPS dynamics in the ionosphere.

2.3 Additional notes about the model.

The intense SAID is intrinsically related to very high electron and ion temperatures. In our modeling efforts, high prudence has been exercised in checking the validity of the empirical formulas of reaction rates at higher temperature. We carefully examined all reaction rate formulas and their source publications for their range of validity. Our general strategy was explained in LJ21 and is briefly re-addressed here. (a) If there are several reported empirical formulas with different validity ranges of temperature, we choose to adopt the one with the highest upper temperature bound and/or that converged toward the highest temperature. (b) Some empirical rate formulas are found to become stable toward high temperature, even beyond the labeled upper temperature limit. In some cases, the authors of those empirical formulas expect them to be applicable to higher temperatures. For example, in Sheehan and St-Maurice [2004], the marked upper T_e limit of the NO^+ + e recombination rate formula is 5000 K, but the authors stated that "this rate might reasonably be extended up to 10,000 K." (d) Occasionally, when the original data are available in a publication, we re-fit the reaction rates based on the published data, to achieve a better fitting to the higher temperature range than in the original publication (e.g., the reaction $N(^2D, {}^2P)$+e, as discussed in more detail in supplementary material). (d) If none of the above situations apply, for rate formulas that are not convergent beyond the given upper temperature limit, when the simulated temperature is exceedingly high, we shall use the rate value at the upper temperature limit of the formula.

One noteworthy complement to the LJ21 rate coefficients is that we have renewed the rates for the dissociative recombination between O^+ and N_2. The reaction rate used LJ21 is from St-Maurice and Laneville [1998], which remains valid for an effective ion temperature up to ~30,000 K. In LJ21, the peak SAID velocity is set at about 4 km/s so that the effective temperature stays below 30,000 K. However, in the present study the SAID flow speed exceeds 6 km/s, and the effective temperature can be beyond 30,000 K. Since the O^+ and N_2 reaction is one of the most import chemical processes leading to the plasma density depletion (see reaction R1 and detailed explanation later in section 3.2), it is desirable for the reaction rate to be more accurate under high temperature for our research purpose. In this regard, we have extended the empirical reaction rates up to an effective temperature of 70,000 K. The data source and the detailed procedure for achieving such an extension are given in the supplementary material.

3. Simulation

3.1 FAC and electron precipitation configuration

The specification of the FAC input in our model is based upon a number of existing in-situ observations of SAID/STEVE. SAID/STEVE is found to be embedded in a downward FAC region with magnitude < ~1 A/m2, but it is in close vicinity to the plasma sheet electron precipitation (<1^0 MLAT, see e.g., He et al., 2014, Puhl-Quinn et al., 2007, He et al., 2014; Mishin et al., 2017; Nishimura et al., 2020a). There is observational evidence that STEVE is located amid a region of rather weak yet increasing (toward high latitudes) electron precipitation [Gallardo-Lacourt et al., 2018a; LJ21]. DMSP satellite measurements repeatedly indicated that the electron precipitation fluxes rise sharply at the poleward potion of SAID, and typically reach the order of ~10^{11} eV/cm^2/s/sr within 1^0 deg poleward of SAID --- such a flux level was either explicitly presented (e.g., Figure 7 in Nishimura et al. [2020] and Figure 1 in He et al. [2014]) or can be inferred from observed electron flux spectrograms [e.g., Puhl-Quinn et al., 2007, Mishin et al., 2017]. Note that 10^{11} eV/cm^2/s/sr directional flux would imply ~0.5 erg/cm^2/s in terms of total precipitation flux assuming isotropicity, a level adopted in our model specification. Such a precipitation flux level would lead to optical auroras below the visual threshold and yet be detectable by a high-sensitivity camera under ideal ambient light condition. This would potentially account for the optical observations in Yadav et al. [2021] that STEVE is located next to a region of weak diffuse emissions immediately poleward of it. Besides the increase in the total precipitation flux, it is also often observed that the energy range of the precipitation is elevated toward higher latitudes [e.g., He et al., 2014, Nishimura et al., 2019; 2020a]. THEMIS in-situ observations also indicated that the magnetospheric root of STEVE/SAID is situated in a transition from the plasmapause into the electron plasma, and that both the total flux and the energy range of precipitating electrons increase with radial distance across the magnetospheric SAID structure [Chu et al., 2019; Nishimura et al., 2019]. The potential existence of the low-energy electron precipitation (<~500 eV) in SAID/STEVE and its possible underlying mechanism was also discussed by Mishin et al. [2019].

The above information is assimilated in our specification of the electron precipitation flux across SAID. The precipitation energy flux spectrum is assumed to be Maxwellian,

$$\Psi(\mathcal{E}) = \frac{Q}{2\mathcal{E}_c^3} \cdot \mathcal{E} \cdot \exp(-\frac{\mathcal{E}}{\mathcal{E}_c}) \ . \ (16)$$

The total energy flux Q and the characteristic energy $\mathcal{E}_c$ are assumed to change with the latitude via

$$Q(x) = \frac{Q_{\max}\bullet\left[1+tanh\left(\frac{x-d_1}{d_2}\right)\right]}{2} \ (17)$$

$$\mathcal{E}_c(x) = \mathcal{E}_0 + \frac{\mathcal{E}_1\bullet\left[1+tanh\left(\frac{x-d_1}{d_2}\right)\right]}{2} \ (18)$$

in which x denotes the relative MLAT. x=0 is set as the midpoint of our simulation area and, as can be seen in the following simulation results, roughly corresponds to the peak latitude of the downward FAC and SAID. The precipitation flux is ~0 at the equatorward portion of our simulation area and rises to the level of $Q_{\max}$ at diffuse auroral latitudes. In runs in this paper, the following parameters are chosen: $Q_{\max}$=0.5 erg/cm^2/s; $\mathcal{E}_0$= 100 eV; $\mathcal{E}_1$= 2 keV; d$_1$=0.45^0 MLAT, d$_2$=0.2^0 MLAT. The precipitating electrons are imposed at 800 km altitude, and their transport in the ionosphere, including ionization/excitation of neutrals and production of secondary electrons, is computed in our model.

The FAC input in our model is constituted by the sum of upward and downward FACs. The upward FAC incident upon the topside ionosphere is carried by the electron precipitation from the magnetosphere, which is depicted by the above equations (16)-(18) in our model. The FAC carried by the precipitating electrons is given by,

$$j_{//}^{\mathrm{up}}(x) = e \bullet \int_0^{\infty} \Psi(\mathcal{E}) d\mathcal{E} = \frac{\mathrm{Qe}}{2\mathcal{E}_c} \quad (19)$$

The downward FAC is deemed driven by the pressure-gradient current in the ring current region associated with substorm ion injections [e.g., Mishin, 2013; Yu et al., 2015; 2017; Wang et al., 2021]. Since existing observation indicated that SAID/STEVE is situated in a region void of proton auroral precipitation [McDonald, 2018; Gallardo-Lacourt et al., 2018a; Liang et al., 2019; Nishimura et al., 2020a], it is reasonable to deem that the downward FAC is carried by upflowing ionospheric electrons. This downward FAC component is assumed to have a latitudinal profile at the topside ionosphere in our model,

$$j_{//}^{\mathrm{down}} = \begin{cases} 0 & x < -d_0 \\ J_{\max}\cos^2\left(\frac{\mathrm{x}}{2d_0}\right) & -d_0 < x < d_0 \\ 0 & x > d_0 \end{cases} \quad (20)$$

There is partial co-existence of the electron precipitation and upgoing ionospheric electrons in the interface between the upward and downward FAC components, and the actual FAC intensity is the sum of the two components. The input FAC profile corresponding to the above depiction and parameters is plotted in Figure 1. J$_{\max}$ =0.53 A/m2, and d$_0$=0.65^0 MLAT are used in the following run. These parameters are so chosen that the total FAC would feature a downward peak of 0.5 A/m2 and a half width of 0.6^0 MLAT at 500 km altitude, consistent with the typical values observed by Swarm satellites for intense SAID/STEVE events [e.g., Archer et al. 2018; 2019; Nishimura et al., 2019].

One other external input to our model is the magnetospheric electron heat flow, which provides the upper boundary condition to solve the electron temperature. To date, there is no direct measurement of the heat flow associated with SAID, but it is generally conceived that strong magnetospheric heat flows are operational in causing the extremely high *Te* (up to ~ 10^4 K) in the upper ionosphere within intense SAID/STEVE [e.g., Moffett et al., 1998; LJ21]. During geomagnetically disturbed times, cold plasmaspheric electrons can be heated via Coulomb collisions with ring current and become suprathermal. These suprathermal plasmaspheric electrons may bring strong heat flow into the topside ionosphere and lead to much enhanced T_e in the upper ionosphere [e.g., Rees and Roble, 1975; *Fok et al.*, 1993]. Conceptually, the heat flow level is contingent upon two populations, the ring current energetic ions, and the plasmaspheric cold electrons. It is instructive to note that the source mechanisms of the downward FAC and the heat flow may both be related to the ring current ion injections. Guided by the above notions, we assume that the plasmaspheric heat flow input follows the profile shape of the downward portion of the FAC, with an ambient quiet value of 2×10^9 eV/cm^2/s [Fallen and Watkins, 2013] and a peak value of 2.6×10^{10} eV/cm^2/s at the peak of the Region-2 downward FAC. In the upward FAC portion which is inside the plasma sheet, the cold electron density presumably drops, and we assume that the electron heat flow retreats to the ambient value.

3.2 Simulation runs of SAID

Our simulation run goes through two steps. The first step is to achieve an initial chemical-diffusion equilibrium status of the ionosphere. This is done without the downward FAC, but with the ambient ionization sources depicted in Section 2.2 and the electron precipitation given by equations (16)-(19). We start from the IRI-2016 model with location/date/time that are appropriate for the 10 April 2018 STEVE event [Gillies et al., 2019]. Realistic solar and geomagnetic parameters for that event are used for the IRI model. The same parameter set is used in other external models, such as NRLMSISE-00 and WACCM-D, involved in our simulation. A constant weak westward flow (150 m/s evaluated at 500 km altitude), deemed a part of the quiescent global convection system, is imposed at the equatorward edge of the simulation area and constitutes the equatorward boundary condition in solving equation (9). The upper boundary heat flow is fixed at the ambient quiet level. We run our model to a quasi-steady-state, in practice defined as when the relative change of the electron density and the E-field between successive timesteps becomes smaller than $1\text{x}10^{-5}$ throughout the simulation area. Such a quasi-steady-state solution will then be used as the initial/ambient condition of the subsequent run with downward FAC and SAID evolution. At that stage we impose the downward FAC and the extra heat flow at t=0, and trace the time evolution of the plasma temperature, density, and E-field afterward. The latitudinal grid resolution of the simulation run is 0.02^0 MLAT, while the simulation timestep is 0.1 sec, though in all following presentation and movies the results are binned into 1-sec cadences.

Movies showing the simulation outcome of the spatial-temporal evolution of the electron/ion temperature (T_e, T_i), the plasma density (N_e), and the ExB convective flow (V_y), are given in supplementary material. In all following presentations, V_y is evaluated at 500 km altitude to facilitate a direct comparison with the Swarm satellite measurements [e.g., McDonald et al., 2018; Archer et al., 2019]. Figures 2-4 shows the latitude-altitude distributions of T_e, T_i, and N_e, at elapsed times t=0, 30s, 1 min, 3 min, 6 min, and 10 min. It should be noted that the height profile presented in all movies and figures actually represents the altitudinal distribution along a magnetic field line. The imposed FAC configuration and the V_y profile at each elapsed time is also plotted for reference, from which one may visualize the development of a narrow intense flow structure, i.e., SAID, with time. Many of the known or expected features of SAID are reproduced in the simulation. For example, the T_e enhancement in the E-region ionosphere led by the anomalous heating, the *Te* enhancement in the F-region resulting from the heat flow and the electron frictional heating in the presence of FAC, the intense T_i enhancement over broad altitudes due to ion frictional heating, and the plasma density depletion in both the upper and lower ionosphere.

In this study we shall be more focused on the variations of the density, the conductance, and the plasma flow. Upon imposing the downward FAC, a SAID *Vy* structure starts to develop. The rising electric field drives the ion Pedersen drift in the lower ionosphere. As one can see from Figure 4 or the supplementary movie, N_e in the lower ionosphere first starts to show a decrease in the equatorward side of SAID. This variation is led by the transport term $\nabla \cdot \left(N_i \mathbf{u}_{\mathrm{pi}}\right)$ in the continuity equation. More specifically, $N_i \nabla \cdot \mathbf{u}_{\mathrm{pi}}$ and $\mathbf{u}_{\mathrm{pi}} \bullet \nabla N_i$ are both depletion terms in the equatorward side of SAID. With growing density variations, the $\mathbf{u}_{\mathrm{pi}} \bullet \nabla N_i$ term then drives the density depletion into the poleward portion of SAID (except at the very poleward edge of SAID where the $N_i \nabla \cdot \mathbf{u}_{\mathrm{pi}}$ term leads to a pileup). The ion Pedersen drift pushes the plasma upward, as has to be expected from the $\mathbf{u}_{\mathrm{pi}}$ direction under the tilted field-line geometry.

Above 200 km, the density variations are driven by a fundamentally different processes, for example, the well-recognized mechanism of plasma depletion due to the conversion from O^+ to NO^+ ions via the reaction,

$O^+ + N_2 \rightarrow NO^+ + N$, (R1)

This reaction rate increases rapidly with enhanced ion temperature and electron temperature [St-Maurice and Laneville; 1998, Moffet et al., 1998], causing NO^+ to replace O^+ to become the major ion species in the F-region under strong SAID. Since NO^+ has a faster recombination rate than O^+ , the plasma density decreases accordingly. However, since the NO+ recombination timescale needs at least a few minutes (and even longer with decreasing N_e) under elevated T_e, the most pronounced density drop in the upper F-region lags the most rapid development of SAID by a couple of minutes.

To better distinguish the respective role of each term in the density continuity equation, we present in Figure 5 the altitude profiles of the Pedersen transport term $-\nabla \cdot \left(N_i \mathbf{u}_{\mathrm{pi}}\right)$, the term related to chemical processes (production minus loss) including electron impact ionization, and the term pertaining to the ambipolar diffusion transport $-\nabla \cdot \left(N_i \mathbf{u}_{i//}\right)$, averaged around the SAID peak at t=30s, 1min, 3min, and 5 min. We have summed over ion species for the above terms. Positive (negative) values indicate a source (sink) in the continuity equation. As one can see, the Pedersen transport term is the dominant sink in the lower ionosphere (<200 km). After t~3 min, the Pedersen transport term remains to be the dominant sink in the lower F-region (~160-190 km), but decreases in magnitude in the E-region due to the already much-reduced density there and also partly because the E-region ionosphere has been approaching a transport-chemical quasi-equilibrium by then. By contrast, the chemical term and the ambipolar diffusion term are both acting as important sinks in the upper ionosphere (above 200 km). This is consistent with the previous findings that chemical reactions (e.g., R1) under enhanced electric field and ion upflows constitute the two main mechanisms contributing to the density depletion in the upper F-region [e.g., Schunk et al., 1976; Andersen et al., 1991; 1993].

The dynamic variations of the plasma density naturally lead to corresponding variations in the conductance. The latitudinal profiles of Σ_P at several elapsed times are demonstrated in Figure 6. Readers are referred to supplementary movie to watch the full time evolution of the Pedersen conductance. Note that we have presented the total conductance as well as separated into values integrated over two different height ranges, namely, 90-190 km and 190-500 km. This provides a useful tool to distinguish the rather different contributions from the lower ionosphere and the upper ionosphere. There is a persistent reduction of Σ_P and a continuing increase of V_y with time in the downward FAC region. The overall sequence corroborates the proposed scenario in Anderson et al. [1993; 2001] under a current generator: decreasing Σ_P leads to the enhancement of the perpendicular E-field. The increasing E-field, via its resultant ion Pedersen transport and heating, acts to further deplete the plasma density and thus further reduce the conductance. Such a positive feedback results in a strong intensification of the E-field, forming an intense SAID. Compared to the geometry of FAC and electron precipitation, the intense SAID structure is mainly within the downward FAC region. Yet, its poleward descending edge overlaps with the slope of rapidly rising electron precipitation, consistent with the existing observations [e.g., He et al., 2004; Mishin, 2013; Mishin et al., 2017; Nishimura et al., 2020a]. The rising electron precipitation partly cancels the downward FAC and, more importantly, the resulting conductance enhancement acts to suppress the flow magnitude, contributing to the descending slope of SAID.

To present the temporal development of SAID in a more succinct way, we plot in Figure 7 the time evolution of the peak V_y magnitude and the half-peak latitudinal width of the SAID structure. The half-peak width is calculated according to where V_y falls to half of the maximum, with interpolation between grids to determine the half-peak latitude. During the SAID evolution, the peak V_y rises from ~1.5 km/s to ~7 km/s, while the half-peak width decreases from ~0.53 to ~0.35^0 MLAT. A narrow intense SAID is thus formed. Note that the peak velocity appears to become constant after ~7.5 min. This duration is imposed by the limit of the azimuthal extension of the SAID structure, which we shall discuss in more details in the next section. The bottom panel of Figure 7 shows the time evolution of the Pedersen conductance at the peak latitude of SAID. To distinguish the contribution from different regions of the ionosphere, we present the conductance integrated over 90-190 km and that over 190-500 km altitudes. The delimitation altitude (190 km) is based on the inference (see

Figure 5) that ion Pedersen transport dominates the contribution of the density variations below this altitude throughout the interval of interest. While the conductance in both altitude ranges shows a consistently decreasing trend over time, the contribution from the lower ionosphere remains larger than that from the upper ionosphere. Thus the steepest rise of V_y during the first ~3 min is clearly due to the significant conductance drop in the lower ionosphere, since the change in the upper region is much less prominent during this interval. As afore-analyzed, the conductance depletion in the lower ionosphere is primarily driven by the ion Pedersen transport. After ~4 min, the decrease of lower ionospheric conductance slows down, while the upper ionospheric conductance goes through an expediated decrease, due to the above-depicted chemical processes and the upflow evacuation. We recall that these chemical processes and upflow evacuation become significant largely because of the preceding strong V_y intensification driven by the ion Pedersen transport, which has boosted the heating and upflows in the upper ionosphere. In the end, V_y continues to rise after ~4 min, buts at a rate slower than that in earlier minutes. In summary: a number of processes contributes to the density/conductance reduction and in turn, in a feedback fashion, to the SAID intensification. The density depletion in the lower ionosphere led by the ion Pedersen transport initiates the process and is responsible for the most significant rise of SAID speed in the first couple of minutes. After that, when *Vy* is already strongly enhanced and the effect of the ion Pedersen transport in the lower ionosphere gradually tappers off, the chemical processes and the upflow evacuation in the upper ionosphere may take up the baton and continue to cause the decrease of conductance and the increase of V_y.

To further clarify the role of ion Pedersen transport, we also ran a test simulation in which the ion Pedersen drift was artificially turned off. All other model specifications and parameters remained unchanged. It should be recalled that the dismissal of ion Pedersen transport under a SAID situation is scientifically problematic and not self-consistent, but just serves here as a numerical reference to highlight the unique role of ion Pedersen transport in density variations. A movie showing the simulation outcome of the spatial-temporal evolution of N_e and V_y in this new run is given in supplementary material in the same format as in the previous run. Figure 8 shows the peak speed and half-width of the SAID V_y, as well as the change of the conductance at the peak latitude, using the same procedures as in Figure 7. Note, however, that the Y-axis scales here are different from those in Figure 7, since the variations in this run are much smaller. It can easily be seen from Figure 8 that there is little intensification of SAID in the absence of Pedersen ion transport, so that the V_y structure remains fairly stable. While the chemical process described by reaction (R1) still operates --- but not as effective as in the previous run since V_y is never intensified --- and leads to a small density/conductance decrease in the upper ionosphere, it is counterbalanced by a tiny increase of conductance in the lower ionosphere, which is caused by the slowly increasing N_e in the E-region ionosphere within SAID (see supplementary movie), owing to smaller recombination rates in the presence of electron heating while the ionization source does not change. This result is consistent with the simulation results of Noel et al. [2005], Milikh et al. [2006], and Liu et al. [2016], which all predicted an increase of the plasma density and conductivity in the anomalous electron heating (AEH) region under strong E-field conditions. However, none of the three studies cited here considered the ion Pedersen drift effect. For the SAID of our interest, when the ion Pedersen drift and the narrow width of the SAID channel are considered, the ion Pedersen transport effect dominates over the chemical recombination process in terms of its contributions to density variations in the lower ionosphere (see Figure 5), and drives the density/conductance depletion over the SAID region. The dramatic difference between the two runs unambiguously indicates the crucial role of the ion Pedersen transport in the formation of intense SAID.

3.3 Comparison to a SAPS run

Compared to SAID, there is more consensus that the SAPS formation conforms to a current generator scenario, which typically involves the Region-2 downward FAC and the electron-precipitation-related upward FAC [e.g., Zheng et al., 2008; Zou et al., 2012; Yu et al., 2015; 2017; Lin et al., 2019]. One important difference with SAID is the spatial scales of the FACs, which are much wider than those of SAID. For instance, upon comparing SAID and SAPS events, Nishimura et al. [2020a] found that both the region-2 downward FAC and the ascending slope of the electron precipitation (upward FAC) are distributed in much larger latitudinal width for SAPS events than those for SAID/STEVE events. With this in mind, we now present another run in this subsection to simulate the SAPS evolution and contrast it with the SAID evolution.

In this new run, the Region-2 downward FAC has a broader latitudinal width with a weaker peak density, and the ascending slope of the electron precipitation and upward FAC toward higher latitude is more gradual. More specifically, we assume the same functional form as equations (16) to (20), but with new parameters $d_0=2.8^0$ MLAT, $j_{\max}=0.07$ A/m2, $d_1=1.8^0$ MLAT, and $d_2=0.8$ MLAT. The parameters $\Psi_{\max}$, $\mathcal{E}_0$ and $\mathcal{E}_1$ remain the same as in the previous run. The configuration of the electron precipitation and the FACs for the new run are given in Figure 9a, where the bottom panel shows the V_y profile at t=0, 5 min, and 10 min. In Figure 9b, we plot the time evolution of the peak V_y magnitude and the half-peak width of the V_y structure, as well as the Pedersen conductance of the new run. As one can see, the V_y magnitude increases much more slowly than that in the previous run; it begins from ~900 m/s and saturates at ~1.2 km/s after t~10 min. The half-peak width of the flow structure decreases slightly from ~2^0 to ~1.9^0 MLAT. The Pedersen conductance shows a moderate decrease in the lower ionosphere and an even tinier change in the upper ionosphere. We thus infer that the ion Pedersen transport still moderately contributes to the conductance variations in the SAPS run, but that is much less effective than that in the SAID run. The key difference between SAPS and SAID is rooted in the fact that the flow structure in SAPS is distributed over a much wider latitudinal scale and thus features much smaller flow gradients, which suppresses much of the Pedersen transport effect. The comparison highlights the influence of the latitudinal scale width of the flow structure on the ion Pedersen transport and in turn on the depth of density/conductance depletion. A direct deduction of this result is that the SAID peak velocity is expected to show a tendency to be anti-correlated with the latitudinal width of SAID, which was indeed unveiled in the statistics in Karlsson et al. [1998].

4. Discussion

This study advances the previous LJ21 model to a current generator scenario of SAID. Assuming magnetospheric FAC inputs based on existing knowledge and observations, we have modeled the self-consistent variations of the ionosphere, with focus on the dynamic changes of the plasma density, the Pedersen conductance, and the electric field. We have demonstrated that with a moderate downward FAC input with intensity readily achievable in realistic observations, we are able to reproduce the self-consistent evolution of an intense SAID together with the associated ionospheric dynamics, its extreme heating and density depletion. We noted that a positive feedback exists between the self-consistent variations of the electric field and the conductance [e.g., Anderson et al., 2001], leading to the formation of intense SAID. In particular, we have illustrated that ion Pedersen transport causes dynamic density variations in the lower ionosphere which, in turn, plays a crucial role in the conductance reduction and the E-field intensification. Since LJ21 already demonstrated the role of ion Pedersen transport in the density/conductance variations in the lower ionosphere under an external imposed E-field, which is more aligned to a voltage driver scenario, we are in a position to state that the dynamic variation of the plasma density and the conductance led by the ion Pedersen transport constitutes one of the key processes of SAID evolution in the ionosphere, regardless of the exact driver mechanism of SAID in the magnetosphere. On the other hand, we also simulated the evolution of SAPS under a similar scenario and found that the much broader latitudinal scale of SAPS makes the ion Pedersen transport much less effective, which in turn limits the velocity enhancement of a SAPS. While direct observations of the lower ionospheric variations under SAID are still lacking to date, we expect that some of our model results may be validated by the upcoming EISCAT3D data.

This present study has focused on the ionospheric electrodynamics of SAID, and we have assumed non-varying FAC inputs from the magnetosphere. There is little doubt that the intensified ionospheric electric fields might be conveyed back to the magnetosphere and change the plasma dynamics there, and in turn may modify the currents in the magnetosphere. For example, the inertial currents associated with the strong electric field variations might lead to nontrivial changes in the magnetospheric current system [Yang et al., 2019]. Therefore, in reality, the evolution of SAID would likely involve a complicated two-way feedback interplay between the magnetosphere and the ionosphere. In the future, it would therefore be desirable to couple our model so some magnetospheric models (e.g., Wang et al. 2021) so as to obtain a more comprehensive picture of the SAID generation and its self-consistent evolution in both the magnetosphere and the ionosphere.

Our model being 2D, we have neglected azimuthal variations. Any realistic SAID structure certainly has a finite azimuthal extension, and such a finite azimuthal width may limit the length of time that new plasma fed into the SAID channel by the ambient global convection can undergo SAID intensification. In our model, this finite azimuthal extension of SAID is qualitatively considered by introducing an upper limit of the elapsed time of the simulation: we cease to trace the temporal variation at a given latitude when $\int V_y dt > L_y$ is reached at this latitude, in which Ly is the azimuthal extension of SAID. The ionospheric parameters at such a latitude are then held constant after that epoch. In the presented run, Ly= 2000 km is assumed, which is inferred from the existing optical observations of the azimuthal extension of STEVE [Gallardo-Lacourt et al., 2018b; Nishimura et al., 2020b]. However, it is to be expected that the azimuthal spanning of SAID may differ from case to case. Furthermore, in terms of practical in-situ observations, the actual SAID intensification time between the new plasma's SAID entry and its detection by the satellite is contingent upon the relative azimuthal location of the satellite in the SAID segment. This may constitute one of the reasons for the substantial variability of SAID speeds in realistic observations [e.g., Karlsson et al., 1998; Figueiredo et al., 2004; Archer et al., 2019]. There are certainly other reasons for the variability of SAID speeds, for example, in relation to the intensity and scale width of the downward FAC structure, and the initial background conductance.

In this study, we have assumed that the electron precipitation and upward FAC in the poleward adjacency of SAID stem from the plasma sheet electrons, e.g., diffuse aurora-like. At times, detached electron precipitation structure and a narrow peak of upward FAC were observed immediately poleward of SAID in some SAID/STEVE events, and were proposed to be related to the so-called "Picket Fence" phenomenon [e.g., Nishimura et al., 2019]. Picket Fences are located in close proximity of STEVEs, apparently near their poleward edge [Gillies et al., 2020; Semeter et al., 2020]. Mishin et al. [2019] suggested that the Picket Fence is related to structured suprathermal (<500 eV) electron precipitation from the turbulent plasmapause. However, so far it is still not clear whether the electron precipitation associated with the Picket Fence stems from the magnetosphere or is locally accelerated in the ionosphere [Mende et al., 2019; Semeter et al., 2020]. The complication regarding the Picket Fence and its related FAC structure are not considered in the current paper, and will be left for future studies.

Our model is based on an electrostatic approach. Two key simplifications in our model are $\nabla \times \mathbf{E} = 0$ and the steady-state balance of the plasma momentum equation. It is true that an electromagnetic approach is more rigorous in examining the dynamic M-I coupling and the fine-scale evolution of the FAC and the electric field in the form of waves. Such electromagnetic models of M-I coupling were developed, for example, to study the ion upflows associated with electron precipitation by Sydorenko and Rankin [2013], and to study the cross-polar cap dynamic responses of the ionosphere to imposed magnetospheric convection by Tu and Song [2016]. However, for a number of reasons their models may not be directly applicable to the SAID phenomenon of interest here. A full electromagnetic model specifically tailored for SAID is left for future efforts. In our simulation results, the rise time of V_y is a couple of minutes, presumably longer than the Alfvenic timescale. We thus speculate that, the essential physical processes unveiled in the present study would remain operational, and our achieved level of the SAID E-field intensification would not be qualitatively changed by an electromagnetic approach.

5. Conclusion

In this study, we have extended our previous LJ21 model to a current generator scenario of SAID. Using magnetospheric FAC inputs based on existing knowledge and observations, we simulated the self-consistent variations of the ionosphere and the temporal evolution of the SAID structure. We were able to reproduce the development of an intense SAID and its associated ionospheric dynamics and associated as extreme heating and plasma depletions. A positive feedback was found to exist between the self-consistent variations of the electric field and the conductance, with a strong electric field driving strong density depletions in the ionosphere in the downward FAC region, reducing the Pedersen conductance and further enhancing the electric field there. A central role was shown to be played by the ion Pedersen transport as a cause of density depletions in the lower ionosphere in the downward FAC region. These strong depletions were shown to strongly reduce the conductance and to trigger a large intensification in the perpendicular E-field, resulting in an intense SAID.

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Figure Captions.

Figure 1. Top panel shows the FAC profiles (upward/downward components, and total) used in our SAID run. The middle and bottom panels show the profiles of the total energy flux and the characteristic energy of electron precipitation imposed on the ionosphere.

Figure 2. Simulation outcome of altitude-MLAT profile of Te and the concurrent development of SAID Vy at six elapsed times. The latitudinal profiles of the

FAC input (black) and the electron precipitation flux (orange) are plotted on top for reference.

Figure 3. Same as Figure 3 but for Ti.

Figure 4. Same as Figure 3 but for Ne.

Figure 5. Altitudinal profile of the terms contributing to density variations, including the Pedersen transport (black), the ambipolar diffusion (green), and the chemical production/loss (red), at (a) t=30 s; (b) t=1 min; (c) t=3 min; and (d) t=5 min.

Figure 6. Latitudinal profiles of Σ_P and concurrent development of Vy at six elapsed times. Σ_P integrated over two height ranges (90-190 km, and 190-500 km) are presented to help distinguish the contribution from the lower/upper ionosphere. The latitudinal profiles of the FAC input (black) and the electron precipitation flux (orange) are plotted on top for reference.

Figure 7. The top two panels show the time evolution of the peak Vy magnitude and the half-peak latitudinal width of the SAID structure, respectively. The bottom panel shows the time evolution of Σ_P integrated over 90-190 km and that over 190-500 km altitudes at the peak-Vy latitude. The occasional "discontinuity" in the bottom panel is due to the slight swing of the peak-Vy grid point where we sample the conductance.

Figure 8. Same as Figure 7 but for the run with ion Pedersen drift turned off. Note that the Y-axis ranges in this Figure are different from that in Figure 7, since the variations in this run are much smaller.

Figure 9. (a) FAC profiles (upward/downward components, and total) used in the SAPS run. (b) profile of the total energy flux of electron precipitation; (c) profile of characteristic energy of electron precipitation; (d) profile of Vy flows at t=0, 5min, and 10 min; (e) time evolution of the peak Vy magnitude of SAPS; (f) time evolution of the half-peak latitudinal width of the SAPS; (g) the time evolution of Σ_P integrated over 90-190 km and that over 190-500 km altitudes at the peak-Vy latitude.