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Three-dimensional metal ion flow in the polar ionosphere simulated by a new ionospheric model

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Abstract—The temporal evolution of the three-dimensional metal ion flow (MIF) is crucial for polar sporadic E layer dynamics. Yet, until now it has not been studied in detail. Here, we present a new ionospheric model for metal ion dynamics, which incorporates electric fields and winds from a whole atmospheric model. We revealed the time-dependent three-dimensional MIFs in the polar ionosphere, driven by two-cell convective electric fields. The simulated MIFs closely matched observations reported in previous studies and were primarily caused by electric fields. For example, metal ions gather in the evening cell rather than the morning cell in the ionospheric *F* region owing to the morning divergence and evening convergence electric fields; the narrow latitudinal metal ion concentrations appear in the pre-midnight ionospheric *E* region owing to downward motions and vertical convergence of ions by electric fields. Our findings emphasize the critical role of electric fields in polar metal ion dynamics and provide valuable insights for interpreting past and future MIF observations in the polar ionosphere.

Keywords: Simulation / Polar ionosphere / Metal ion / Sporadic E

1 Introduction

Metal ions are ubiquitous in the planet's ionosphere (Kumar & Hanson, 1980; Grebowsky & Pharo, 1985; Molina-Cuberos et al., 2008), originating from metal atoms ablated from meteoroids (Plane et al., 2015). Metal ion distributions in Earth's ionosphere have been studied for decades (e.g., Gérard, 1976; Kumar & Hanson, 1980; Kopp, 1997; Feng et al., 2013; Chu & Yu, 2017; Huba et al., 2019). Metal ions are the primary source of sporadic E layers (EsLs) (Huuskonen et al., 1988), which form in the ionospheric *E* region. Advances in observational technology have recently drawn increased attention to the morphology of polar EsLs (e.g., McCrea et al., 2015; Chen et al., 2022; Wang et al., 2022). For example, the EISCAT_3D project has identified polar EsLs as a key target for observation (McCrea et al., 2015). These observations are expected to provide insights into the three-dimensional dynamics of EsLs in the polar ionosphere. A deeper understanding of metal ion flow and concentration is essential for interpreting past and future EsL observations in this region.

Ground-based and satellite-borne observational instruments have been used to investigate metal ion distributions in the ionospheric *E* and *F* regions (e.g., Gérard, 1976; Kumar & Hanson, 1980; Grebowsky & Pharo, 1985; Bedey & Watkins, 1998; Langowski et al., 2015; Chu & Yu, 2017). Kumar & Hanson (1980) reported that metal ions accumulate more in the evening than in the morning in the polar ionospheric *F* region. Furthermore, Grebowsky & Pharo (1985) demonstrated that, in the ionospheric *F* region, metal ions tend to accumulate in the day-side hemisphere. Bedey & Watkins (1998) identified a pre-midnight concentration of metal ions in the ionospheric *E* region. Bristow & Watkins (1993) observed zonally elongated regions of high ionization, which may consist of metal ions, in the ionospheric *E* region, using the incoherent scatter radar at Sondrestrom. Various characteristics of metal ion flow and concentration in the polar ionosphere have been revealed to date. However, no study has yet provided a comprehensive explanation for these metal ion flow and concentration patterns in the polar ionosphere.

Bedey & Watkins (1997) calculated the trajectories of metal ions under time-invariant electric fields, considering ion movement driven only by $\mathbf{E} \times \mathbf{B}$ drift and gravity. They described the following metal ion flow at high latitudes: metal ions in the day-side ionosphere ascend from the ionospheric *E* region to the

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F region owing to $\mathbf{E} \times \mathbf{B}$ drift and move meridionally toward the nightside ionosphere across the pole. In the nighttime ionosphere, electric fields generally drive a downward $\mathbf{E} \times \mathbf{B}$ drift, causing metal ions to descend into the pre-midnight ionospheric E region. Bedey & Watkins (1997) provided possible observational evidence of this metal ion flow, but the three-dimensional modeling of metal ions has not yet validated it. Note that Huba et al. (2019) mentioned that a similar high-latitude metal ion flow was observed in the SAMI3 simulation, although it was not explicitly shown in their paper.

Global and regional ionospheric models have been used to perform various three-dimensional simulations related to metal ions (Bristow & Watkins, 1994; Huba et al., 2019; Andoh et al., 2021; Wu et al., 2021; Aylett et al., 2025). Bristow & Watkins (1994) calculated metal ion distributions using a three-dimensional ionospheric model with convective electric fields derived from Heppner & Maynard (1987), but without winds. Their results showed that metal ions concentrate at latitudes of 70° – 80° when interplanetary magnetic fields (IMFs) are southward. However, the convective electric field pattern was fixed in their simulation. Moreover, Bristow & Watkins (1994) only investigated metal ion concentrations in the nighttime ionospheric E region at high latitudes. Other three-dimensional simulations of metal ion dynamics have not focused on metal ion flows or concentrations in the polar ionosphere (Huba et al., 2019; Andoh et al., 2021; Wu et al., 2021; Aylett et al., 2025). This is partially because the considerable variability in the convective electric fields and their interaction with neutral winds has caused difficulty in modeling metal ion dynamics in the polar ionosphere. It is important to recognize that Feng et al. (2013) have shown metal ion distributions in polar regions, but they did not simulate metal ion dynamics. Simulating metal ion dynamics is necessary to discuss the polar metal ion flows.

In this study, we aim to reveal the temporal evolution of the three-dimensional flow and concentration of metal ions in the polar ionosphere during summer when EsLs frequently occur (Bedey & Watkins, 1996; MacDougall et al., 2000). To achieve this, we extended the numerical model of Andoh et al. (2024) to develop a three-dimensional EsL model that resolves metal ion dynamics in the polar ionosphere. The model incorporates three-dimensional electric fields and winds calculated with a whole-atmosphere model using the Weimer model (Weimer, 2005; Tao et al., 2020). In this study, we focused on metal ion flow and concentration above the upper ionospheric E region to reveal how metal ions are supplied to the pre-midnight upper ionospheric E region where polar EsLs have frequently been observed (e.g., Bedey & Watkins, 1998; Voiculescu et al., 2006; Wang et al., 2022). We present a comprehensive three-dimensional description of metal ion flows and concentrations, which aligns with previous observations in the polar ionosphere, for the first time. In this study, when we refer simply to “cells,” we mean the vortices of the $\mathbf{E} \times \mathbf{B}$ drift in the evening and morning sectors, not the “two-cell convective electric fields.” When referring to the two-cell convective electric fields, we explicitly state them as such.

This study is entirely model-based, although our simulated results are generally consistent with satellite and ground-based observations in previous studies, as discussed later. Ideally, simulated results should be compared directly with observations to fully validate the findings. However, it should be noted that the

purpose of employing the model here is not to reproduce individual observations, but to provide a general overview of three-dimensional metal ion flows driven primarily by two-cell convective electric fields under quiet geomagnetic conditions in the polar ionosphere, where observational data remain sparse. The remainder of this paper is organized as follows: the next section describes the model used in this study, followed by the results and discussion, and finally, the summary and conclusions.

2 Model description and setup

We developed a new ionospheric model for metal dynamics in the polar ionosphere. The model used the continuity and momentum equations of metal ions as described in Andoh et al. (2020, 2023):

$$\frac{\partial N_i}{\partial t} + \nabla \cdot (N_i \vec{V}_i) = P_i - L_i, \quad (1)$$

$$\begin{aligned} \vec{V}_i = & \frac{\zeta}{1 + \zeta^2} \frac{\vec{V}_n \times \vec{B}}{B} + \frac{\vec{V}_n \cdot \vec{B}}{1 + \zeta^2} \frac{\vec{B}}{B^2} + \frac{\zeta^2}{1 + \zeta^2} \vec{V}_n \\ & + \frac{1}{1 + \zeta^2} \frac{\vec{E} \times \vec{B}}{B^2} + \frac{q \vec{E} \cdot \vec{B}}{m_i v_{in} (1 + \zeta^2)} \frac{\vec{B}}{B^2} + \frac{\zeta}{1 + \zeta^2} \frac{\vec{E}}{B} \\ & + \frac{1}{1 + \zeta^2} \frac{\vec{F} \times \vec{B}}{q B^2} + \frac{\vec{F} \cdot \vec{B}}{m_i v_{in} (1 + \zeta^2)} \frac{\vec{B}}{B^2} + \frac{\zeta}{1 + \zeta^2} \frac{\vec{F}}{q B}, \end{aligned} \quad (2)$$

$$\vec{F} = -\frac{1}{N_i} \nabla (N_i k_B T_i) + m_i \vec{g}, \quad (3)$$

$$\vec{E} \cdot \vec{B} = \left(\frac{-1}{q N_e} \nabla (N_e k_B T_e) \right) \cdot \vec{B}, \quad (4)$$

where i , e , and n represent ions, electrons, and neutrals, respectively. N is the density, $\vec{V}$ is the velocity, P is the chemical production term, L is the chemical loss term, ζ is the ratio of ion–neutral collision frequency (v_{in}) to ion gyro-frequency (Ω_i), $\vec{B}$ is the geomagnetic fields; $\vec{E}$ is the electric fields, q is the elementary charge, m is the mass, k_B is the Boltzmann constant, T is the temperature, and $\vec{g}$ is the gravitational acceleration. The ambipolar diffusion was considered as shown in equation (4).

Fe^+ was used as a proxy for metal ions. The chemical processes for metal ions in the model were the same as those described by Andoh et al. (2024). Our model employed a spherical coordinate system, with a numerical domain spanning 40° – 87.5°N in latitude, 180°W – 180°E in longitude, and 85 – 310 km in altitude. The spatial resolution was 0.5° in longitude and latitude, and 0.5 – 2.0 km in altitude. The altitude grid spacing was set to 0.5 km between 85 and 140 km and gradually increased from 0.5 to 2.0 km above 140 km. For the boundary conditions, $\partial N / \partial t = 0$ was applied at the lower and upper boundaries as well as at the lower latitude boundary. At the higher latitude boundary, velocity values were obtained through

linear interpolation from inner grid data, and ion density was determined such that the ion density at 90° matched the average density of the outermost grid points.

The model incorporated various ionospheric and neutral parameters from external models. Neutral density and temperature were derived from the NRLMSISE-00 model (Picone et al., 2002). The Ap and F10.7 indices used in the NRLMSISE-00 model were obtained from the Data Analysis Center for Geomagnetism and Space Magnetism, Kyoto University¹ and National Research Council of Canada², respectively. The densities of O^+ , O_2^+ , and NO^+ , as well as neutral wind velocity and electric fields, were constrained by the Ground-to-Topside Model of Atmosphere and Ionosphere for Aeronomy (GAIA) (Jin et al., 2011). The upper boundary of our metal ion model was set to ~ 310 km, and below this altitude, the background ionospheric plasma consists primarily of O^+ , O_2^+ , and NO^+ (Schunk & Nagy, 2009). In this study, we used the GAIA simulation (Tao et al., 2020), coupled with the empirical high-latitude electric potential model (Weimer, 2005). The GAIA simulation is capable of modeling ion–neutral interactions in the polar ionosphere and has successfully reproduced a case involving severe space weather conditions caused by high-latitude ionospheric and thermospheric variations (Kataoka et al., 2022). The simulation employed a tilted dipole magnetic field, which was also adopted in our model. Tilted dipole magnetic fields generally provide a good approximation of geomagnetic fields in the northern high latitudes (Schunk & Nagy, 2009). The tilt angle and azimuth were calculated using the coefficients from the IGRF-13 model (Alken et al., 2021). The spline-interpolated data from the GAIA simulation were input into the EsL model every 10 min.

Polar EsLs frequently form in summer (Bedey & Watkins, 1996), making investigations of summertime metal ion flows particularly important. Therefore, we conducted EsL simulations for the summer months (June–August) from 2022 to 2024, for which the GAIA data were available. It should be noted that the purpose of this study is not to reproduce metal ion flows on a specific day, but rather to elucidate the typical patterns of metal ion flow and concentration in the polar ionosphere. To this end, we analyzed metal ion dynamics under conditions of two-cell convection in the Northern Hemisphere. The two-cell pattern is a common feature of electric fields in the polar ionosphere, especially on geomagnetic quiet days (Weimer, 1995, 2005). Hence, typical metal ion flows are expected to be driven by the two-cell electric fields. We defined two-cell convection as occurring when $|B_y|$ is less than 5 nT and B_z is negative for at least 80% of the day. Here, B_y and B_z represent the Y and Z components of the IMF in the GSM coordinate system, respectively, and were obtained from the DSCOVR 1-minute resolution data³. The selected simulation days were DOY 154, 158, and 160 for 2022, DOY 169 and 212 for 2023, and DOY 166, 204, 237, and 239 for 2024. Note that our criteria were conservative, and the two-cell patterns of electric fields occur on the other days. Each EsL simulation was run for 36 h, with the first 12 h discarded to remove initial transients.

3 Results and discussion

As an example, we present the simulation results for 18 June 2023 (DOY 169), when two-cell convective electric fields generally prevailed throughout the entire day. Note that similar metal ion distributions were observed when two-cell electric fields prevailed on the other simulated days. In other words, the present results can apply to three-dimensional metal ion flows driven by two-cell convective electric fields under geomagnetic quiet conditions. The Kp index is less than 3 in all the simulated days, according to the World Data Center for geomagnetism, Kyoto University. Figure 1 shows B_z (top plot) and B_y (bottom plot) variations on 18 June 2023 observed by DSCOVR. The horizontal dashed lines in each subplot denote -5 , 0 , and 5 nT. Although we do not consider the B_z magnitude criterion in this study, the absolute value of B_z is roughly within 5 nT.

Figure 2 shows horizontal distributions of the metal ion (Fe^+) density at 300 km altitude (first row), 200 km altitude (second row), and 120 km altitude (third row). Figure 3 shows horizontal distributions of the magnitude of the horizontal $\mathbf{E} \times \mathbf{B}$ drift at 300 km. The left and right columns of Figures 2 and 3 display each horizontal distribution at 6 UT and 18 UT, respectively. White streamlines indicate the direction of horizontal $\mathbf{E} \times \mathbf{B}$ drift, whereas yellow circles encircle the approximate locations of two-cell convection. Horizontal distributions of magnetic local time (MLT) are presented in the supplementary material as Figure S1 for reference. Hereafter, our analysis focuses on metal ion flow and concentration within the yellow circles, where two-cell convective electric fields appear.

As shown in the first and second rows of Figure 2, metal ion density decreases with increasing altitude in the ionospheric F region, and metal ion flows are observed in some narrow regions. In general, metal ions tend to move along (1) the outer edges of the morning and evening cells and (2) the boundary between the two cells. More metal ions are present on the day-side and along the periphery of the cells. Furthermore, more metal ions circulate inside the evening cell than in the morning cell. Within the evening cell, metal ion density depletion occurs at 70 – 80° N in the pre-midnight sector. Note that the above-mentioned metal ion flows can be seen at both 6 and 18 UT, although horizontal $\mathbf{E} \times \mathbf{B}$ drift was more prominent at 18 UT, as shown in Figure 3.

The metal ion concentration in the polar ionospheric F region was observed by satellites (Grebowsky & Brinton, 1978; Kumar & Hanson, 1980; Grebowsky & Pharo, 1985). Kumar & Hanson (1980) and Grebowsky & Pharo (1985) found that the Atmosphere Explorer satellites detected metal ions more frequently in the evening than in the morning at high latitudes, consistent with our metal ion distributions in the first and second rows of Figure 2. Grebowsky & Brinton (1978) and Grebowsky & Pharo (1985) reported that metal ions in the ionospheric F region moved in narrow flows, agreeing with our simulation. Grebowsky & Pharo (1985) showed metal ion distributions on latitude–longitude maps. Note that their observational data did not cover regions above 84° invariant latitude. In our simulation, localized increases and decreases in metal ion density generally appear at 65 – 80° invariant latitude on the day-side and at 60 – 70° invariant latitude on the night-side (Fig. 2),

¹ <http://wdc.kugi.kyoto-u.ac.jp/kp/index.html>.

² https://spaceweather.gc.ca/solar_flux_data/daily_flux_values/flux-table.txt.

³ <https://www.ngdc.noaa.gov/dscovr/data/>.

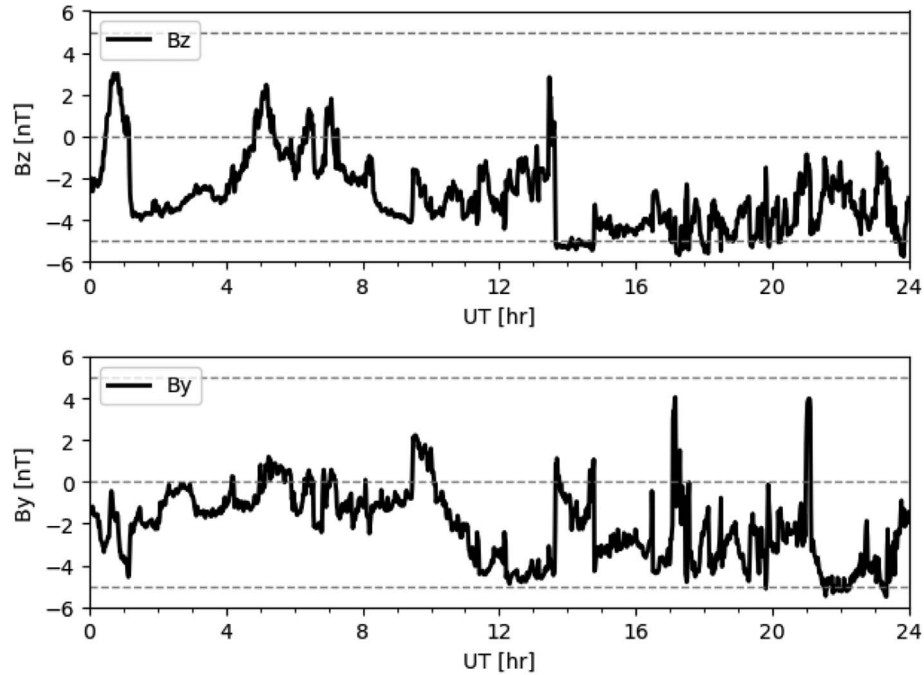


Figure 1. (Top panel) B_z and (bottom panel) B_y variations on 18 June 2023 (DOY 169) obtained from the DSCOVR 1-minute resolution data.

consistent with the observed metal ion distribution in Grebowsky & Pharo (1985). (The geographical distribution of invariant latitudes in our simulation is shown in Fig. S2 in the supplementary material.) Additionally, our simulation results show that metal ion density decreases with increasing altitude, which aligns with previous observational studies summarized in Kumar & Hanson (1980). Note that our simulation does not fully reproduce the metal ion flows reported in previous observations. This discrepancy may be due to variations in observed metal ion flows associated with geomagnetic activity, which are not addressed in this study. Nevertheless, the simulated metal ion flow in the ionospheric F region is generally consistent with satellite observations (Grebowsky & Brinton, 1978; Kumar & Hanson, 1980; Grebowsky & Pharo, 1985).

In the third row of Figure 2, within the yellow circles, metal ions are concentrated on the nightside of the cells, particularly before midnight. The increased metal ion concentration ($>10^{11} \text{ m}^{-3}$) in the ionospheric E region appears near regions where the metal ion density decreases in the ionospheric F region, as shown in the first and second rows of Figure 2. Notably, before midnight, metal ions ($>10^{11} \text{ m}^{-3}$) accumulate specifically in the reversal convection region, where the convection shifts between sunward and antisunward directions. This reversal convection occurs at 70–80°N in the pre-midnight sector. Consequently, metal ions tend to accumulate at 70–80°N in the pre-midnight ionospheric E region. This finding is consistent with the simulation by Bristow & Watkins (1994). In addition, the metal ion density is relatively low in the morning-side cells, especially at lower latitudes.

A high metal ion concentration in the ionospheric E region was observed in previous studies (Bedey & Watkins, 1998; MacDougall & Jayachandran, 2005; Chen et al., 2022). MacDougall & Jayachandran (2005) and Chen et al. (2022) reported that EsLs, which are highly dense metal ion layers, often formed

when the reversal convection passed over the observational site. Furthermore, using ionosonde data from Sondrestrom, Bedey & Watkins (1998) found that EsLs were frequently observed in the pre-midnight ionospheric E region. In our simulation, the metal ion density becomes relatively high ($>10^{11} \text{ m}^{-3}$) in the pre-midnight and the reversal convection regions, as shown in the third row of Figure 2. The region and time of this high metal ion concentration in the simulation are consistent with those in the previous studies (Bedey & Watkins, 1998; MacDougall & Jayachandran, 2005; Chen et al., 2022).

Figure 4 presents the vertical ion velocity (VIV; top panels) and the vertical $\mathbf{E} \times \mathbf{B}$ drift velocity (bottom panels) at an altitude of 300 km (positive values indicate upward motion), corresponding to the first-row plots in Figure 2. The yellow circles indicate the same as those in Figure 2. The top and bottom panels demonstrate that the $\mathbf{E} \times \mathbf{B}$ drift generally governs the vertical ion drift at 300 km altitude within the yellow circles. Upward VIV regions on the dayside include the dayside regions of high metal ion density at 200 and 300 km altitudes in Figure 2. Note that metal ions also move vertically owing to the $\mathbf{E} \times \mathbf{B}$ drift at 200 km altitude in the simulation. On the dayside, metal ions are transported vertically into the ionospheric F region by the $\mathbf{E} \times \mathbf{B}$ drift. Considering that the horizontal $\mathbf{E} \times \mathbf{B}$ drift is dominant in the ionospheric F region, ascending metal ions move from the dayside to the nightside along the boundary between convection cells, as shown by the streamlines in Figure 2. Subsequently, metal ions in the nightside ionospheric F region descend to lower altitudes owing to the downward $\mathbf{E} \times \mathbf{B}$ drift. We validated the metal ion transport mechanism proposed by Bedey & Watkins (1997) through a three-dimensional ionospheric simulation incorporating realistic winds and electric fields.

Figure 5 presents the meridional ion velocity (MIV) with the meridional $\mathbf{E} \times \mathbf{B}$ drift velocity subtracted (top panels) and the

Metal Ion Density

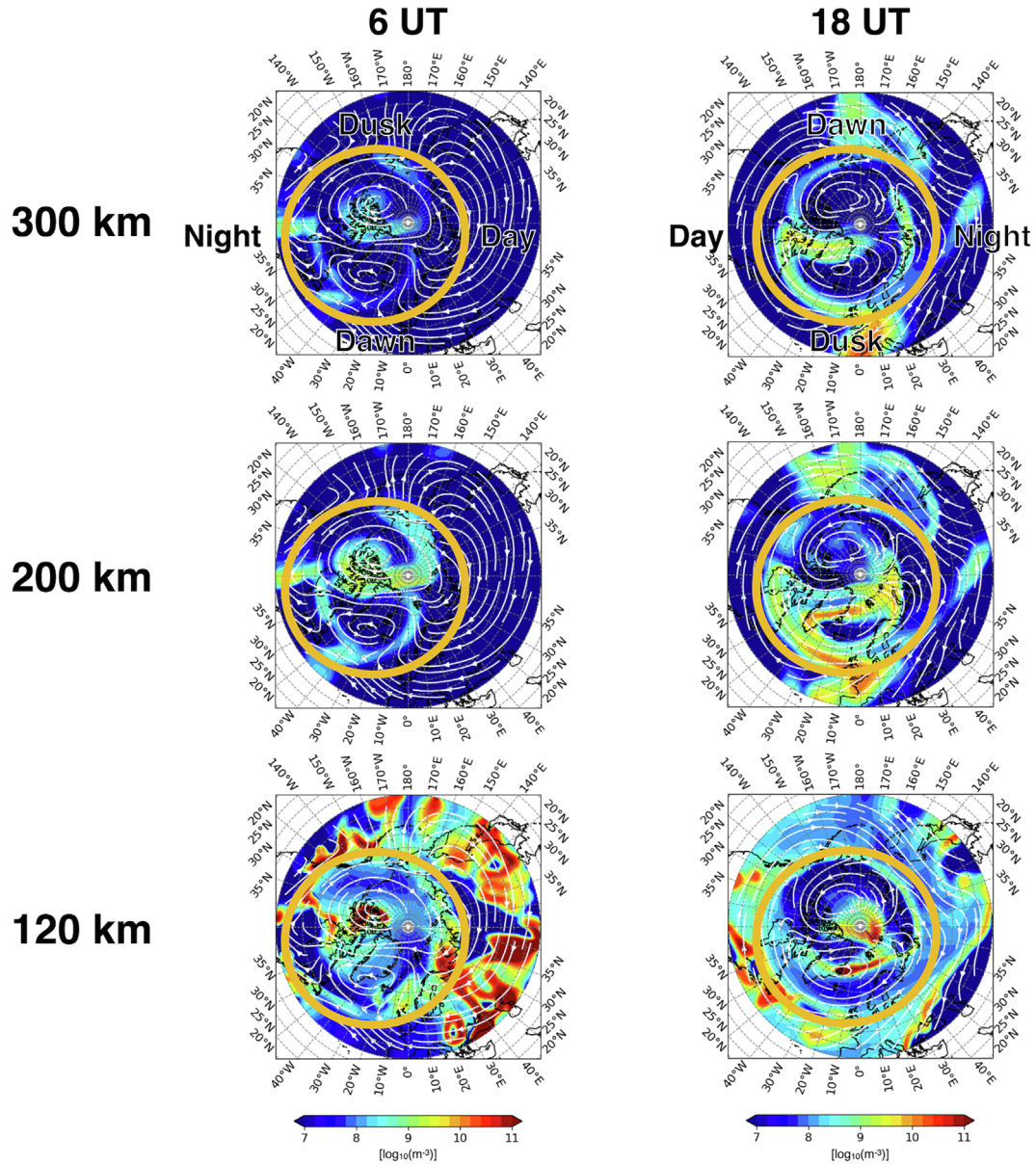


Figure 2. Horizontal distributions of Fe^+ at (first row) 300 km, (second row) 200 km, and (third row) 120 km altitudes. The left and right columns show these at 6 and 18 UT, respectively. White streamlines show the horizontal $\mathbf{E} \times \mathbf{B}$ drift direction, and yellow circles denote the approximate locations of two-cell convection.

meridional Pedersen drift velocity (bottom panels) at an altitude of 200 km (positive values indicate southward motion), corresponding to the second-row plots in Figure 2. Note that the Pedersen drift is the movement in the $\mathbf{E}_\perp$ direction, corresponding to the sixth term on the right-hand side of equation (2). The residual MIV in the top panels of Figure 5, which is not caused by the meridional $\mathbf{E} \times \mathbf{B}$ drift, indicates that ions move into the evening cell and out of the morning cell from the outer sides of the evening and morning cells. This metal ion flow explains why metal ions appear in the evening cell rather than in the morning cell. The top and bottom panels of Figure 5

demonstrate that the meridional Pedersen drift drives this metal ion flow. In our simulation, the metal ion flow driven by the meridional Pedersen drift appeared in the lower ionospheric F region and the upper ionospheric E region, where $v_{in} \leq \Omega_i$. The meridional Pedersen drift is responsible for the asymmetry in the metal ion distribution between the two cells. Note that although the meridional $\mathbf{E} \times \mathbf{B}$ drift is dominant in the ionospheric F region, it only governs ion circulation within each cell.

Figure 6 presents the VIV (top panels) and the vertical Pedersen drift velocity (bottom panels) at an altitude of 120 km (positive values indicate upward motion), corresponding to the

Magnitude of $E \times B/B^2$

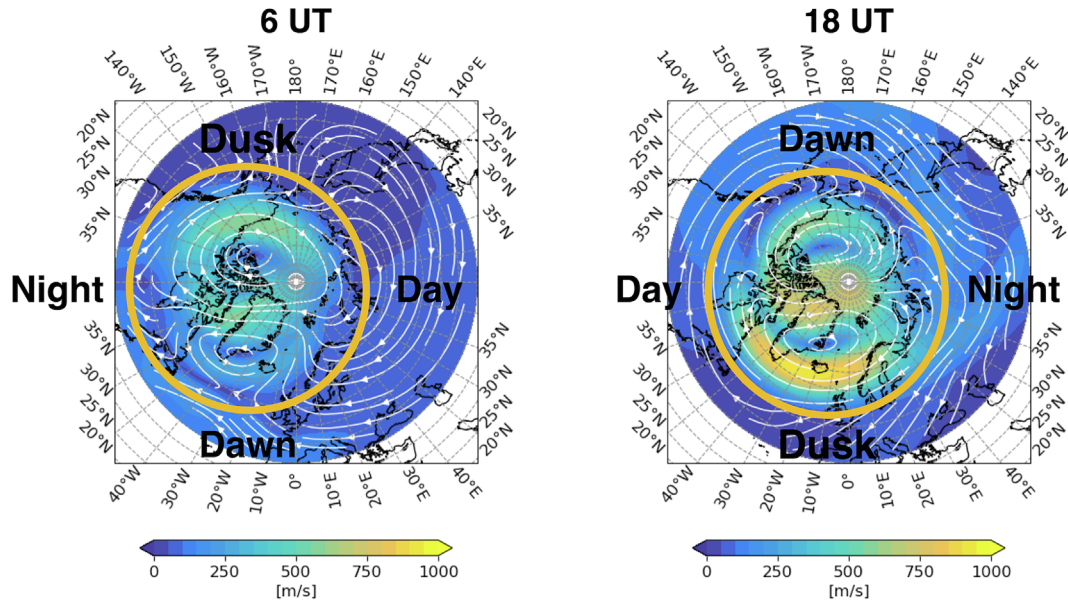


Figure 3. Horizontal distributions of the magnitude of the horizontal $E \times B$ drift. The left and right columns show these at 6 and 18 UT, respectively. White streamlines and yellow circles are as in Figure 2.

third-row plots in Figure 2. The yellow circles indicate the same as those in Figure 2. As shown in the top and bottom panels, the VIV distribution within the cells corresponds to the vertical Pedersen drift distribution at 120 km altitude. In the top panels, VIV is upward and downward in the morning and evening cells near the boundary between the two cells, and downward and upward in other areas of the morning and evening cells, respectively. Upward VIV is more prevalent in the evening cell than in the morning cell. Consequently, (1) metal ions tend to stagnate at higher altitudes (above 120 km) in the evening cell but not in the morning cell, and (2) in the evening cell, metal ions can descend to lower altitudes only in a limited region near the boundary between the cells in the pre-midnight sector, where VIV is downward. Comparing the third row in Figure 2 with the top row in Figure 6, we observe that the metal ion density increases in the nighttime ionospheric E region within areas where VIV is downward. Thus, the downward Pedersen drift plays a key role in the distribution of metal ions in the polar ionospheric E region. Note that metal ions do not accumulate in the downward VIV region of the morning-side cell, indicating that fewer metal ions descend from the ionospheric F region in this area. This is due to the evening–morning asymmetry in the metal ion distribution.

Bedey & Watkins (1997) predicted that metal ions precipitate into narrow regions in the nighttime ionospheric E region. They proposed that this metal ion precipitation is driven solely by the $E \times B$ drift and gravity. According to Bedey & Watkins (1997), metal ions stop ascending at similar altitudes owing to gravity, form narrow altitudinal streams, and consequently precipitate into confined regions in the ionospheric E region. Our simulations are partially consistent with the metal ion flow proposed by Bedey & Watkins (1997); however, the formation mechanism of narrow metal ion concentrations in the ionospheric E region is not consistent. Comparing the third row in

Figure 2 with the top row in Figure 6, we observe that the narrow metal ion concentrations are located near the boundary between the upward and downward VIV regions in the pre-midnight sector. At this boundary, the direction of the electric field generally shifts geomagnetically northwestward, considering the $E \times B$ and Pedersen drift directions (the electric field directions are shown in Fig. S3 in the supplementary material for clarity). Geomagnetically northwestward electric fields are particularly effective at vertically concentrating metal ions (Nygrén et al., 1984). Hence, the narrow regions of highly dense metal ions result from vertical ion convergence induced by the geomagnetically northwestward electric fields in the pre-midnight sector.

Using a time-independent ionospheric model, Bristow & Watkins (1994) conducted three-dimensional simulations of metal ions and demonstrated nighttime metal ion concentrations in the ionospheric E region. Their simulated results were broadly consistent with nighttime metal ion concentrations observed as EsLs by ionosondes. However, Bristow & Watkins (1994) were unable to reproduce the narrow metal ion concentrations in the ionospheric E region, which have a latitudinal extent of approximately 2° , as observed by Bristow & Watkins (1993). In contrast, our simulation successfully reproduces narrow metal ion concentrations in the ionospheric E region, with a latitudinal extent of $\leq 2^\circ$, as shown in Figure 2. This result highlights the potential of our model to fully reveal the three-dimensional morphology of high-latitude EsLs, which remains an area for future research. Studies using our model would be highly beneficial for understanding the three-dimensional dynamics of high-latitude EsLs in both past and future observations. We emphasize that this is the first study to reveal “time-varying” three-dimensional metal ion flows in the polar ionosphere using a physics-based three-dimensional ionospheric model.

We used winds and electric fields obtained from the GAIA model. The GAIA model incorporates the ion–neutral drag

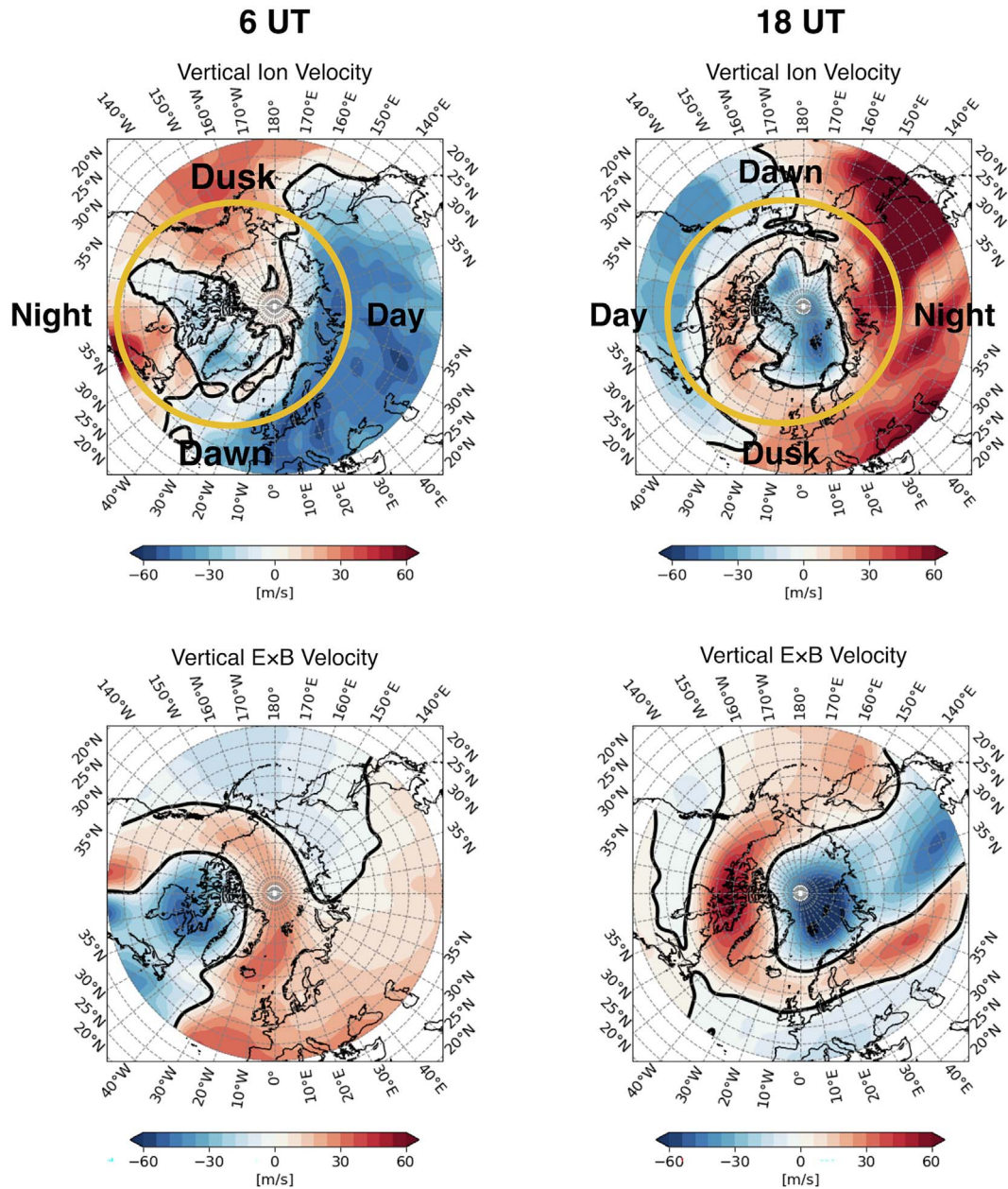


Figure 4. (Top plots) VIV and (bottom plots) vertical $E \times B$ drift velocity at 300 km altitude (upward positive), corresponding to the top plots in Figure 2. Yellow circles are as in Figure 2.

effect in the polar ionosphere, and the simulated neutral winds sometimes reach 300–400 m/s, which cannot be explained without considering ion–neutral drag. These strong winds were generally neglected in previous studies of metal ion flows (e.g., Bedey & Watkins, 1997). In Figures 4–6, the differences between the top and bottom plots are primarily attributed to neutral winds. Figure 7 shows wind-driven VIV at 300 km, MIV at 200 km, and VIV at 120 km altitude from the top to the bottom panels. Wind-driven ion velocities in the top, middle, and bottom panels correspond to Figures 4, 5, and 6, respectively. The overall ion velocity distribution within the cells (yellow circles) resembles the electric-field-driven ion velocity better than the wind-driven one. Thus, electric fields play a more dominant role than neutral winds in controlling metal ion dynamics.

However, the effect of winds in the ionospheric F region is not negligible, as seen by comparing Figures 4–6 and 7. Neutral winds can modify the strength of metal ion flows in the F region, depending on the relative magnitude of wind-driven ion velocities, even though electric fields primarily determine the overall flow patterns.

We examined three-dimensional metal ion flows driven by two-cell convective electric fields at high latitudes. However, convective electric fields do not always exhibit a two-cell structure owing to varying IMF and magnetospheric conditions (Schunk & Nagy, 2009). For example, when the IMF is directed northward, the number of convection cells increases beyond two (Weimer, 2005). The occurrence of polar EsLs is known to depend on the IMF direction (Voiculescu et al., 2006), possibly

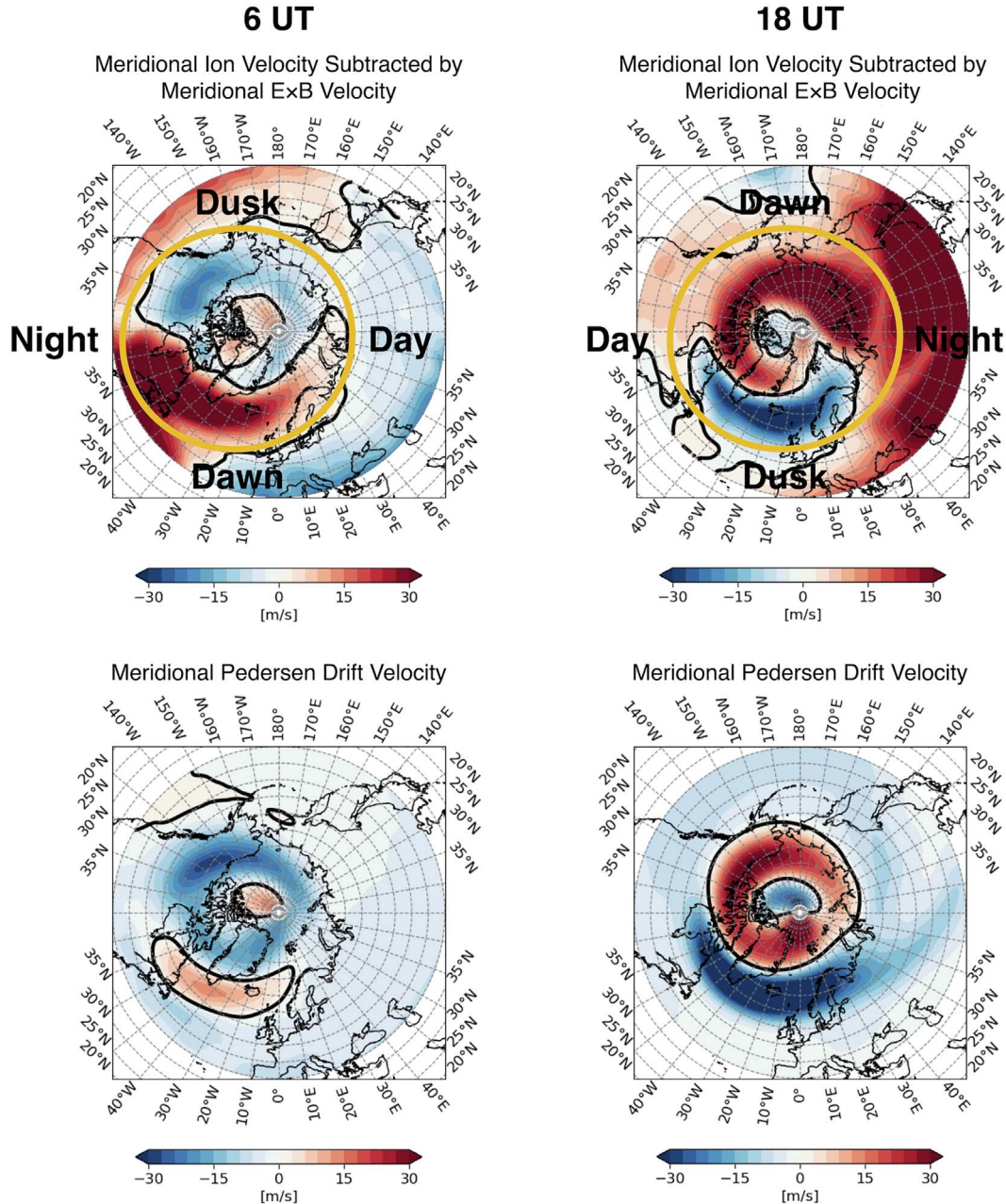


Figure 5. (Top plots) MIV subtracted by meridional $E \times B$ drift velocity and (bottom plots) meridional Pedersen drift velocity at 200 km altitude (southward positive), corresponding to the second-row plots in Figure 2. Yellow circles are as in Figure 2.

owing to differences in three-dimensional metal ion flows. Investigating the geomagnetic activity dependence of metal ion flows should be an important topic. Further simulations using our model will clarify the relationship between the IMF and metal ion flows and, consequently, the IMF dependence of EsL occurrences in the polar ionosphere.

4 Summary and Conclusions

We studied the three-dimensional flows of metal ions driven by two-cell convective electric fields in the polar ionosphere using a new ionospheric model. In general, the simulated metal

ion flows explained the previously observed metal ion concentrations in the polar ionosphere. For the first time, we revealed the time-varying three-dimensional metal ion flow in the polar ionosphere under winds and electric fields. Our findings showed that two-cell electric fields are primarily responsible for the three-dimensional metal ion flows in the polar ionosphere.

The three-dimensional metal ion flow in the polar ionosphere is summarized in Figure 8. Figure 8a shows a schematic diagram of the three-dimensional metal ion flow between the upper ionospheric E region and the ionospheric F region. Blue and orange ovals denote the morning and evening cells, respectively. Important metal ion flows in the polar ionosphere are labeled 1–5. In Figure 8b, the vertical directions of ion motions

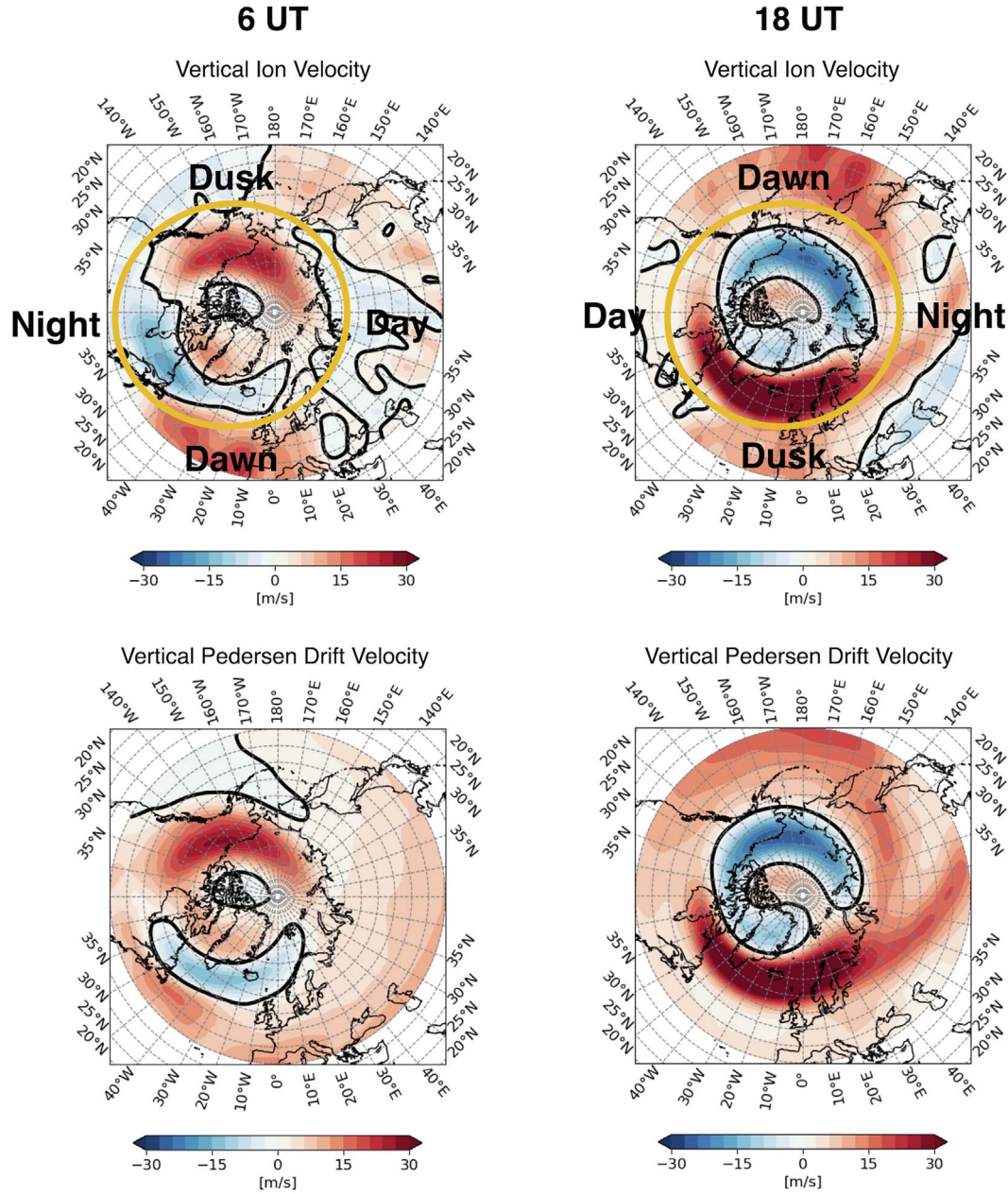


Figure 6. (Top plots) VIV and (bottom plots) vertical Pedersen drift velocity at 120 km altitude (upward positive), corresponding to the third-row plots in Figure 2. Yellow circles are as in Figure 2.

driven by the $\mathbf{E} \times \mathbf{B}$ drift and Pedersen drift are shown in the top and bottom plots, respectively. The black and white areas indicate the downward and upward VIV regions driven by electric fields, respectively. Note that the $\mathbf{E} \times \mathbf{B}$ and Pedersen drifts are dominant in the ionospheric F and E regions, respectively.

Metal ion flow 1 refers to the upward movement of ions from the upper ionospheric E region to the F region on the day-side. It is driven by upward Pedersen drift in the ionospheric E region and by upward $\mathbf{E} \times \mathbf{B}$ drift in the ionospheric F region (see the white areas on the dayside in Fig. 8b). The metal ions ascending into the ionospheric F region circulate driven by the horizontal $\mathbf{E} \times \mathbf{B}$ drift. Eventually, the metal ions gather into horizontal streams at the boundary of two cells and flow from

the dayside to nightside ionosphere across the pole, a process referred to as Metal ion flow 2. During this flow, the vertical $\mathbf{E} \times \mathbf{B}$ drift direction gradually shifts from upward to downward (Fig. 8b). Consequently, the metal ions moving to the nightside ionosphere start descending into the lower ionospheric F region, which constitutes Metal ion flow 3. As the metal ions descend to lower altitudes, the horizontal Pedersen drift becomes significant, affecting their horizontal motion. This constitutes Metal ion flow 4. In Metal ion flow 4, the horizontal Pedersen drift causes divergence of metal ions from the morning cell and convergence into the evening cell. As a result, the metal ion density increases in the evening cell relative to the morning cell, particularly in the upper E region and the bottomside F region. Thus,

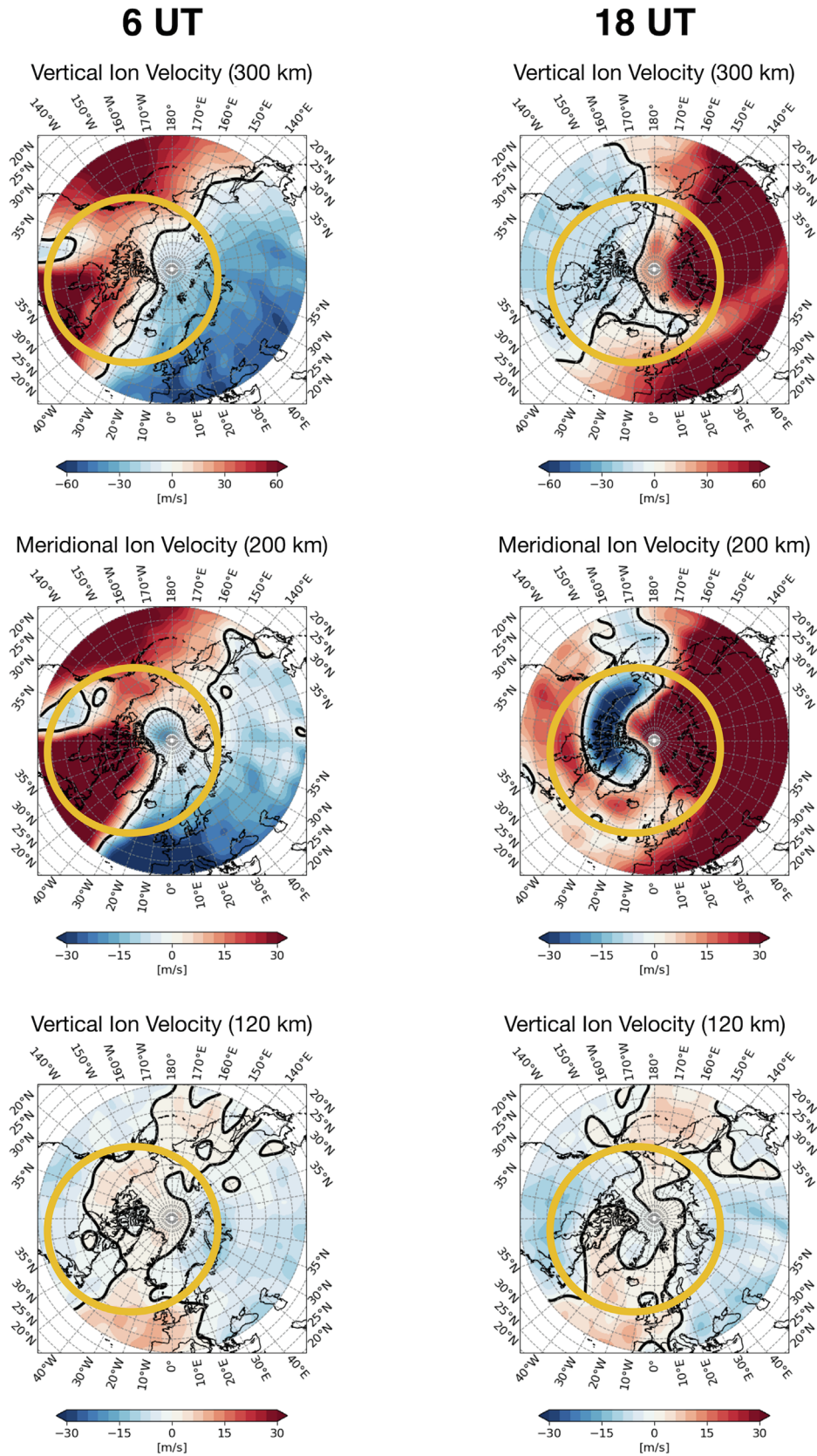


Figure 7. Wind-driven VIV at 300 km, MIV at 200 km, and VIV at 120 km altitude from the top to bottom panels. Wind-driven ion velocities in the top, middle, and bottom panels correspond to [Figures 4, 5, and 6](#), respectively.

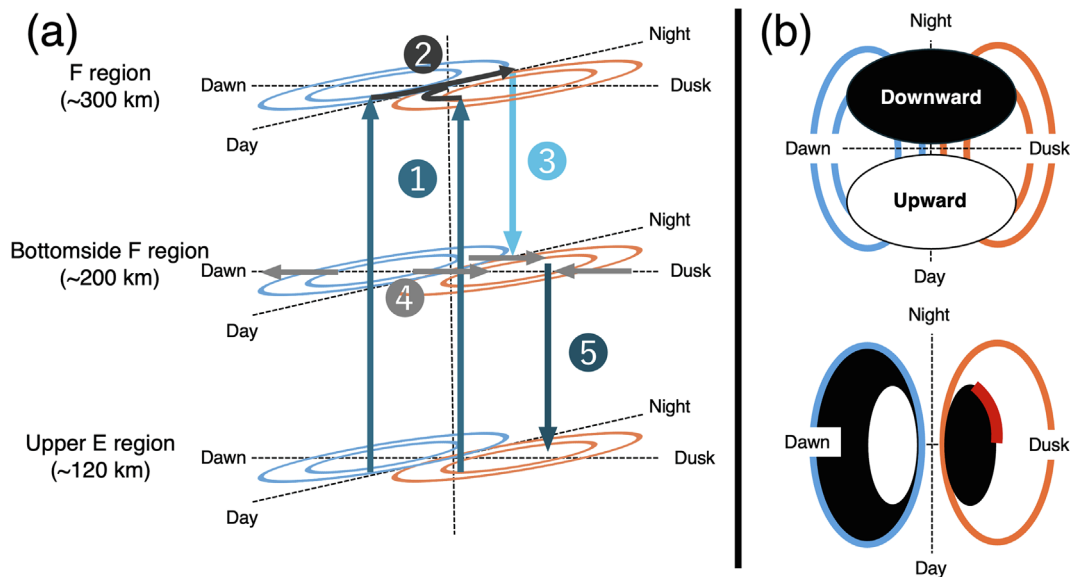


Figure 8. Schematic figures of (a) the three-dimensional metal ion flow in the polar ionosphere and (b) the vertical ion movements in the $E \times B$ (top plot) and Pedersen (bottom plot) directions. Blue and orange ellipses represent morning and evening cells of electric fields, respectively. The red line in the bottom plot of Figure 8b indicates the region where metal ions can accumulate in the ionospheric E region.

the metal ions in Metal ion flow 3 tend to accumulate in the nightside of the evening cell. Note that Metal ion flow 4 can affect ion movements during Metal ion flow 1. The metal ions in Metal ion flow 3 can further descend into the E region, but only near the boundary between the two circulation cells (see the black region within the evening cell in the bottom part of Fig. 8b). This process corresponds to Metal ion flow 5. Ultimately, the descending metal ions converge vertically and result in a region of high ion density, particularly where the electric field shifts northwestward (marked by the red line in Fig. 8b) in the northern polar ionosphere. The red line generally lies over the reversal of the electric field convection.

Overall, our results provide new insights into the metal ion flows and concentrations in the polar ionosphere. The three-dimensional metal ion flows are expected to significantly affect the occurrence and intensity of EsLs in the polar ionosphere. Thus, the present results are also important for EsL studies in the polar ionosphere. Our simulated results enable (1) synthesis and extension of the understanding obtained from past measurements, (2) identification of spatial and temporal patterns that are difficult to capture given the limited coverage of observations, and (3) provision of physically consistent estimates that can guide and motivate future observational studies. Thus, they can complement existing measurements and advance scientific understanding by offering testable predictions and bridging observational gaps. In conclusion, this study significantly advances our understanding of metal ion physics in this region.

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Data availability statement

Ap and F10.7 indices are from the Data Analysis Center for Geomagnetism and Space Magnetism, Kyoto University (<http://wdc.kugi.kyoto-u.ac.jp/kp/index.html>) and National Research Council of Canada (https://spaceweather.gc.ca/solar_flux_data/daily_flux_values/fluxtable.txt), respectively. One-minute resolution DSCOVR data were obtained from <https://www.ngdc.noaa.gov/dscovr/data/>. The simulation data presented in this study are currently available upon request to the corresponding author and will be made open access in the future at https://gaia-web.nict.go.jp/data_e.html.

Supplementary material

Figure S1: Geographical distribution of magnetic local time in this study. White lines indicate the boundaries of each MLT hour. The yellow circles represent the approximate locations of the two cells in this study.

Figure S2: Geographical distribution of invariant latitudes in this study.

Figure S3: Directions of geomagnetic electric fields in the simulation at 120 km altitude and (upper plots) 6 UT and (lower plots) 18 UT. The left and right columns show directions of geomagnetic eastward and northward electric fields, respectively. Red and blue regions indicate eastward and westward (northward and southward) in the left column (right column).

The supplementary materials of this article are available at <https://www.swsc-journal.org/10.1051/swsc/2025056/olm>.

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