Impacts of Subauroral Polarization Streams on Storm-Enhanced Density and Tongue of Ionization

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Abstract

The influences of subauroral polarization streams (SAPS) on storm-enhanced density (SED) and tongue of ionization (TOI), an important topic in the field of magnetosphere-ionosphere-thermosphere coupling, however, remain undetermined. The Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIEGCM) with/without an empirical SAPS model has been used to investigate the impacts of SAPS on SED and TOI. The modeled TEC and ion drift velocities agree reasonably well with the observations of GNSS and DMSP satellites on 17 March 2013. The TIEGCM simulations show that SAPS can significantly affect the electron density of SED and TOI depending on the relative location of SAPS and SED. SAPS reduces the electron density at the eastward edge of SED where they are overlapped, and enhances SED at its westward edge. A term-by-term analysis of the O+ ion continuity equation in the F-region shows that the electron density depletions at the eastward edge of SED are mainly due to increased local plasma loss rates because of SAPS elevated plasma-neutral temperatures and O/N2 reduction because of thermosphere upwelling. The electron density enhancements in the westward edge of SED are mainly due to SAPS-induced westward plasma E×B transports and O/N2 increment because of thermospheric downwelling. Moreover, SAPS-induced electron depletions in the throat region weaken TOI as plasmas undergo anti-sunward convection into the polar cap.

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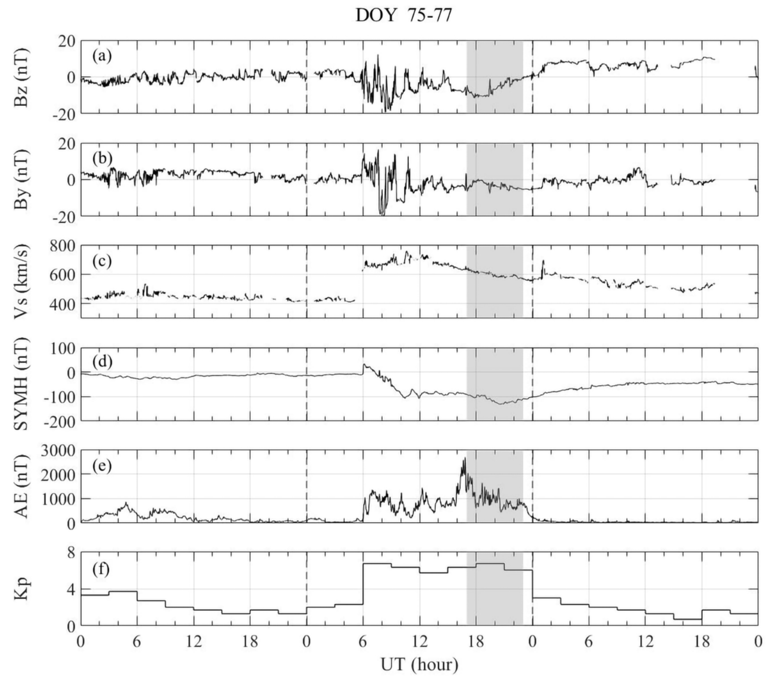
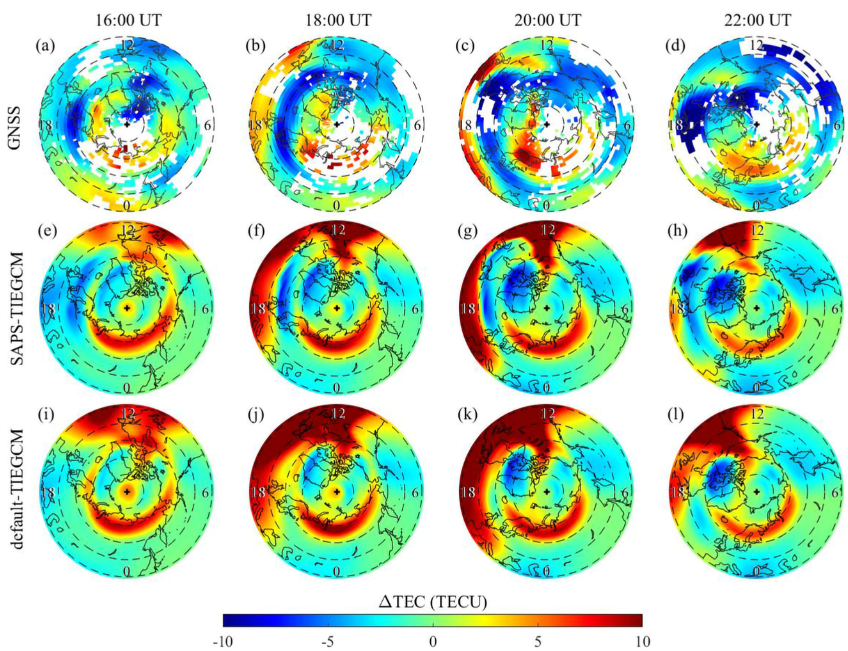
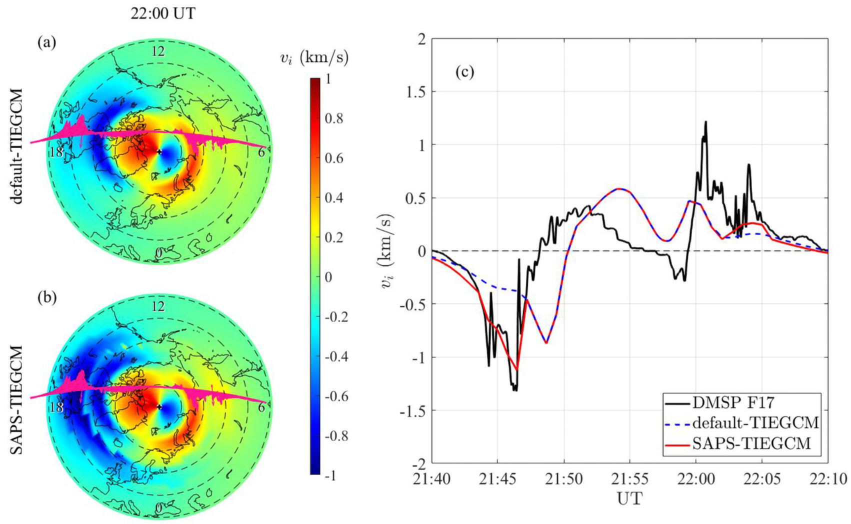
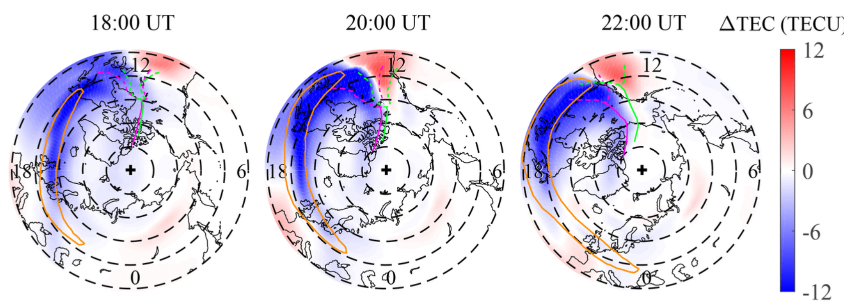

DOY 75-77
(a)
Bz (nT)
(b)
By (nT)
(c)
Vs (km/s)
(d)
SYMH (nT)
(e)
AE (nT)
(f)
Kp
UT (hour)


16:00 UT
18:00 UT
20:00 UT
22:00 UT
GNSS
SAPS-TIEGCM
default-TIEGCM
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(l)
ΔTEC (TECU)


22:00 UT
(a)
default-TIEGCM
(b)
SAPS-TIEGCM
v_i (km/s)
(c)
DMSP F17
default-TIEGCM
SAPS-TIEGCM
UT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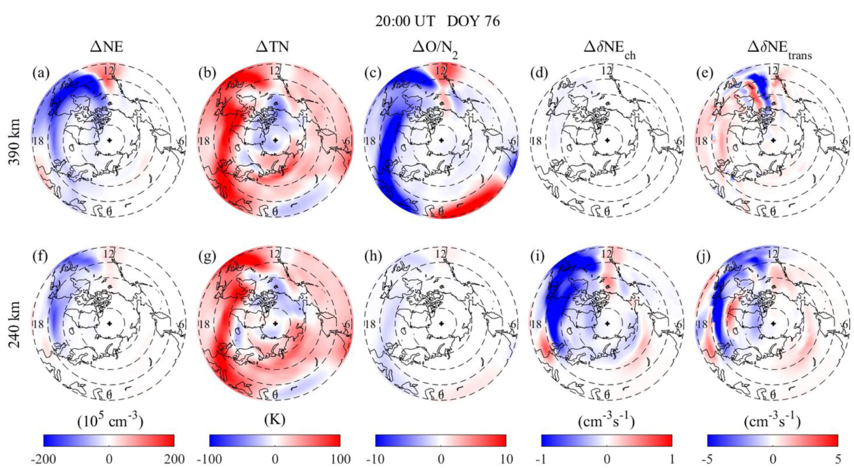
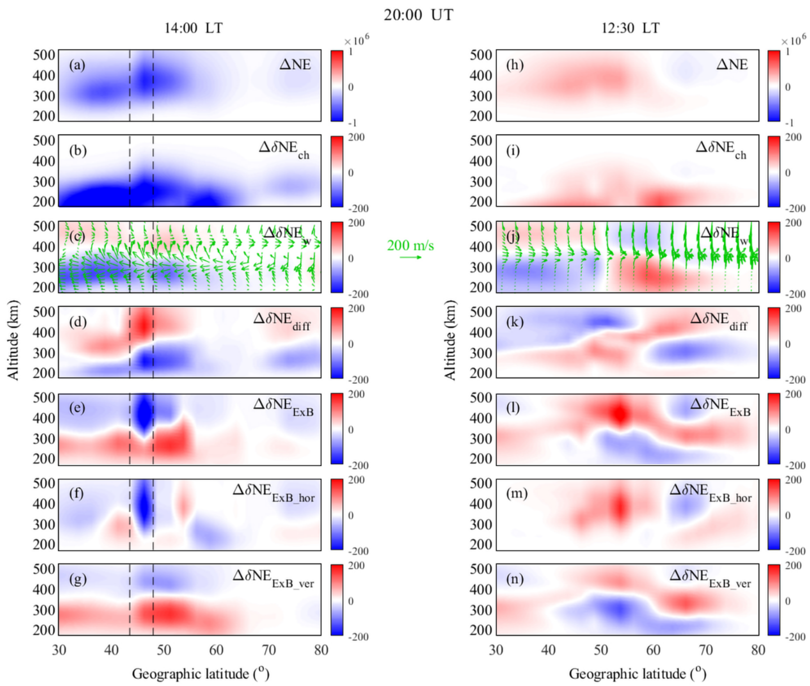
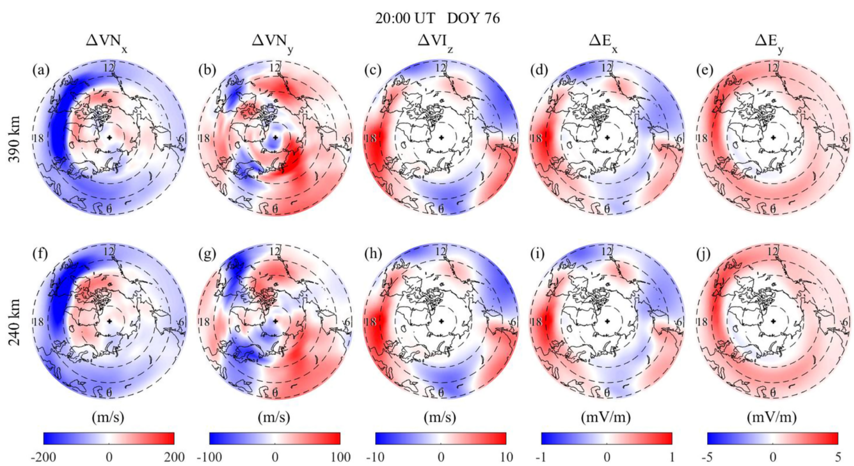
ΔTEC (TECU)


20:00 UT DOY 76
ΔNE
ΔTN
ΔO/N$_2$
ΔδNE$_{ch}$
ΔδNE$_{trans}$
390 km
240 km
(10^5 cm^{-3})
(K)
(cm^{-3}s^{-1})
(cm^{-3}s^{-1})


20:00 UT
14:00 LT
12:30 LT
(a) ΔNE
(b) ΔδNE_ch
(c) ΔδNE_w
(d) ΔδNE_diff
(e) ΔδNE_ExB
(f) ΔδNE_ExB_hor
(g) ΔδNE_ExB_ver
(h) ΔNE
(i) ΔδNE_ch
(j) ΔδNE_w
(k) ΔδNE_diff
(l) ΔδNE_ExB
(m) ΔδNE_ExB_hor
(n) ΔδNE_ExB_ver
200 m/s
Altitude (km)
Geographic latitude (°)


20:00 UT DOY 76
ΔVN_x
ΔVN_y
ΔVI_z
ΔE_x
ΔE_y
390 km
240 km
(m/s)
(m/s)
(m/s)
(mV/m)
(mV/m)

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Key Points:

- Subauroral polarization streams (SAPS) tend to move storm-enhanced density (SED)/tongue of ionization (TOI) westward.
- SAPS reduce the intensity of TOI.
- SED/TOI is affected by changing ionospheric loss rates and horizontal westward E×B transports.

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Abstract

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Plain Language Summary

Subauroral polarization streams (SAPS), storm-enhanced density (SED) and tongue of ionization (TOI) are prominent structures in subauroral and polar ionosphere during geomagnetic storm. The effects of SAPS on SED and TOI remains controversial. In this work, the simulated results from Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIEGCM) with and without SAPS empirical model are compared to understand the impacts of SAPS. The modeled results indicate that SAPS tend to move SED and thus TOI throat regions towards the morning side, and weaken TOI in the polar cap. Further analyses show that SAPS enhanced plasma and neutral temperatures lead to thermosphere upwelling/downwelling and thus weaken/intensify the eastward/westward edge of SED because of modified chemical reaction rates. In addition, the gradients of SAPS-induced westward E×B drift also transport additional plasma from eastside to westside of SED.

1. Introduction

Ionospheric subauroral polarization streams (SAPS) (Galperin et al., 1974; Karlsson et al., 1998; Smiddy et al., 1977; Spiro et al., 1979) refer to intense westward plasma flows driven by enhanced poleward electric fields in the dusk sector of the subauroral region. The term "SAPS" is proposed by Foster and Burke (2002a) to include subauroral westward plasma flows in a wider latitude region and narrower and more intense plasma jets (PJ) (Galperin et al., 1974) or subauroral ion drifts (SAID) (Anderson et al., 1993; Spiro et al., 1979). The average peak ion velocities of SAPS are larger than 500 m/s and located on the equatorward boundary of particle precipitation (Foster and Vo, 2002b). The occurrence of SAPS in ionosphere is related to the enhanced poleward electric fields in the duskside midlatitude trough region with low conductivities, probably caused by the mapping of magnetospheric electric field (Southwood and Wolf, 1978) or the field aligned current continuity (Anderson et al., 1993). The friction between high-speed SAPS and neutral atmosphere tends to heat the plasmas and deplete electron density and conductivity (Schunk et al., 1975), and this positive feedback effect strengthens the SAPS (Wolf et al., 2007). But some theoretical works show the electric fields are hard to penetrate the plasma and induce ion drift (Tu et al., 2008; Vasyliunas, 2001). The formation of SAPS electric fields related with magnetosphere-ionosphere-thermosphere (M-I-T) coupling remains a problem. Considering the morphological and physical characteristics of SAPS which can reflect the state of M-I-T coupling

(Goldstein et al., 2005; He et al., 2018; Horvath et al., 2020; Wang et al., 2012; Zhang et al., 2017; Zou et al., 2009), SAPS and related effects are interesting topics in M-I-T coupling studies.

In addition to SAPS, other prominent ionosphere structures exist in the subauroral latitude during geomagnetic storms. A significant electron density enhancement often occurs in the afternoon and dusk sector during a geomagnetic storm, called storm-enhanced density (SED) (Foster et al, 1993, 2007b, 2021; Liu et al., 2016a, 2016b; Zou et al., 2013, 2014). SED is related to the high-latitude convection and located at the equatorward edge of the middle latitude ionospheric electron density trough (Foster et al., 1993). The density enhancements of SED are localized with large density gradients at its boundaries to form ionospheric irregularities (Coster and Skone, 2009; Sun et al., 2013). SED often extends northwestward to higher latitudes and form a narrow plume. This plume can be further carried by the anti-sunward convection flows into the polar cap. The continuous high-density structure is termed the tongue of ionization (TOI) (Foster et al., 2005; Hosokawa et al., 2010; Liu et al., 2015), while the discrete structures are named patches (Moen et al., 2013). Therefore, TOI is influenced not only by the two-cell convective pattern, but also by the characteristics of SED located in the throat region of TOI. It should be noted that SED are not always accompanied by SAPS which can also be observed in quiet time (e.g., He et al., 2017; Kunduri et al., 2017; Lejosne and Mozer, 2017) and may be related to substorms (He et al., 2017). But when SAPS and SED occur together in a geomagnetic storm, considering that the occurrence of SED region often overlaps with that of SAPS, SAPS may influence the formation and development of SED structures, and thus the TOI structures (Foster and Rideout, 2007a).

Many observations from satellites and incoherent scattering radar revealed that the location of SAPS coincided with middle latitude ionospheric F region plasma density trough (e.g., Anderson et al., 1993; Foster et al., 2007b; Spiro et al., 1979). To simulate SAPS effects, Sellek et al. (1991) and Moffett et al. (1992) imposed an extra high-speed westward ion drift at subauroral latitudes, and Pintér et al. (2006)

imposed a poleward electric field in pre-midnight sector at 50-60° magnetic latitude into the Sheffield Coupled Thermosphere-Ionosphere-Plasmasphere (CTIP) model. Their results showed that the friction between the rapid plasma flow and thermosphere can enhance the ion temperature, elevating recombination rates and decreasing plasma densities in F region. Some researchers thus considered the density depletions induced by SAPS against the formation of SED (e.g., Fuller-Rowell, 2011). However, a different viewpoint was thought the strong sunward ion flux carried by SAPS to be a source of SED (Foster et al., 2007b; Erickson et al., 2011; Park et al., 2012). SAPS was also considered to have a close association with SED plume and plasmasphere erosion (Foster et al., 2007b; Horvath et al., 2009). Horvath et al. (2014) showed that SAPS electric field could enhance the process of plasmaspheric erosion and provide a continuous supply of high-density SED plume plasma to develop and maintain SEDs during the main phase. Lu et al. (2020) compared TIEGCM model and GNSS TEC to confirm that SAPS contribute to form SED plume at the equatorward and westward edge of the SAPS channel.

To sum up, there is still no clear explanation for the contradiction between SAPS causing reduced density and contributing to SED. The dominate mechanism of the interaction between SAPS and SED are not fully understood in typical storm events. These impair our understanding of subauroral electrodynamics and dynamics and even the related M-I-T coupling processes during geomagnetic disturbed conditions. The impacts of SAPS can alter the SED edges with high-density gradients associated with irregularity production and scintillation (Basu et al., 2007; Foster and Rideout, 2005). Their interaction can thus disrupt the civilian and military electromagnetic signals in subauroral region.

In this work, the impacts of SAPS flow on SED and TOI have been investigated by comparing the results between TIEGCM with and without SAPS empirical model. Then the contribution of each physical mechanism is explored using term-by-term analysis method.

2. Model and Data

The NCAR Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIEGCM) is a first-principles three-dimensional model, which self-consistently solves the continuity, momentum and energy equations for ion and neutral species. TIEGCM is driven by solar EUV and UV parameterized by $F_{10.7}$ solar index (Richards et al., 1994), particle precipitation (Roble and Ridley, 1987) obtained from 3-hour Kp index, high-latitudes convection electric fields provided by Heelis model (Heelis et al., 1982) or Weimer model (Weimer, 2005), and diurnal and semidiurnal migrating/non-migrating tides (Hagan and Forbes, 2002, 2003) specified by the Global Scale Wave Model (GSWM). The high-resolution TIEGCM used in this study is 2.5° in latitude and longitude and one quarter of a scale height in the vertical pressure coordinate ranging from ~97 to ~600 km.

In this work, the SAPS effects are introduced into TIEGCM by imposing the SAPS ion drift velocity into the subauroral region at all altitudes, referring to as SAPS-TIEGCM. In the following part, TIEGCM without SAPS imposed is named as default-TIEGCM. In SAPS-TIEGCM model, the 3-hour Kp index is used to drive empirical SAPS model and high-latitude Heelis model, including convection and auroral particle precipitation pattern. SAPS model is called for the grid points within 10° equatorward from the auroral precipitation boundary at each time step. The calculated horizontal ion drift velocities are added to the ion velocities obtained from default-TIEGCM as the modification of SAPS. Then the modified E×B drift is substituted into the self-consistent I-T system. The same model has also been used in the researches of the ionosphere-thermosphere response to SAPS (Wang et al., 2012; Zhang et al., 2021a, 2021b, 2022). For the purpose of analyzing the effects of SAPS on SED and TOI, the results from default-TIEGCM and SAPS-TIEGCM are compared in this work.

The solar wind parameters, interplanetary magnetic field, and geomagnetic activity index are obtained from the OMNI database. MIT's Madrigal database provides the global ionospheric TEC data, which is the vertical height integral of electron density with 1°×1° horizontal resolution every 5 min distributed over locations where GPS data is available (Rideout et al., 2006). In this work, a median filtering for TEC is used to reduce its noise. The ion drift velocities are observed by ion drift meters of DMSP satellites (Rich et al., 1994). The horizontal cross-track ion drift velocity is projected to zonal direction to compare with the simulated results.

3. Results

3.1. Interplanetary solar wind and geomagnetic activity conditions

The geomagnetic storms significantly perturbed the geospace system during the St. Patrick's Days of 17 March 2013 (Li et al., 2014; Foster et al., 2014a, 2014b; Liu et al., 2016b; Zhang et al., 2017). Figure 1 shows the temporal variations of interplanetary magnetic field (IMF) B_z and B_y components in GSM coordinates, solar wind velocity V_s, the symmetric ring current (SYM-H) index, the AE index, and the Kp index during DOY 75-77 (Mar 16-18), 2013. The shaded region at 1700-2300 UT on DOY 76 is the interval of the SED and TOI.

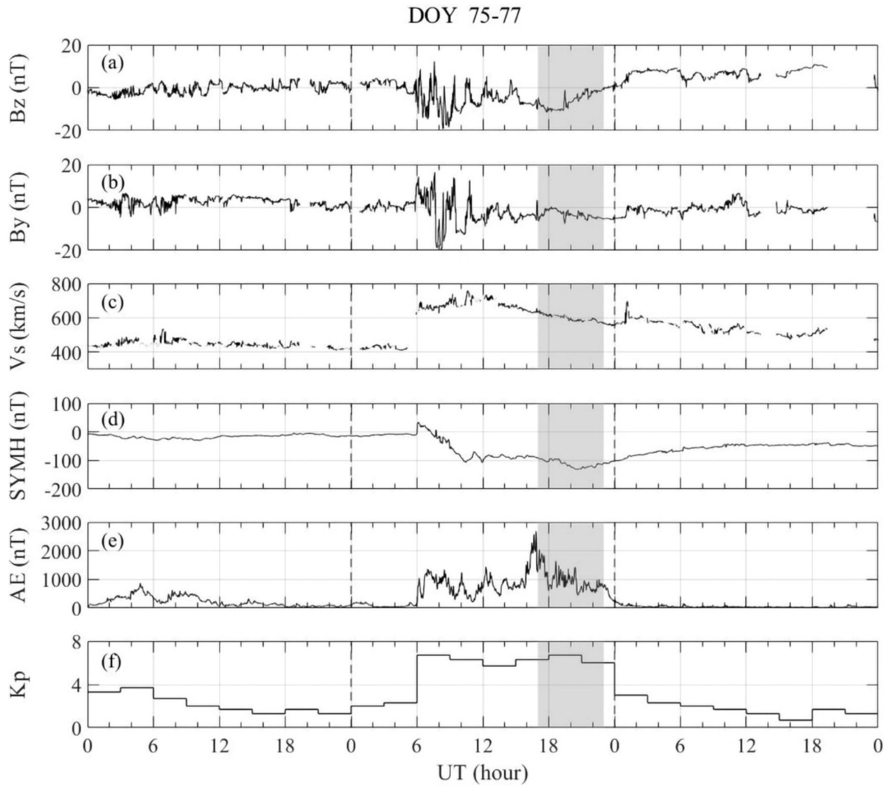

Figure 1. (a,b) IMF B_z, B_y, (c) solar wind velocity V_s, (d,e,f) SYM-H, AE, and Kp index from DOY 75 to 77 (March 16 to 18), 2013. The shaded regions denote the interval of SED and TOI.

On DOY 76 a strong disturbance of IMF and a sudden enhancement in the solar wind velocity approximately at 0600 UT indicate an interplanetary disturbance arriving the magnetosphere. In the subsequent geomagnetic storm, the SYM-H index reaches the minimum values of -100 nT and -132 nT at ~1000 UT and ~2000 UT, respectively. The AE index increases to a maximum value of 2689 nT at 1648 UT in the main phase of storm. SED and TOI were observed at 1700-2300 UT, which locates at the later main phase and early recovery phase of the geomagnetic storm as reported in previous studies (Ferdousi et al., 2019; Lin et al., 2019; Liu et al., 2016b; Yu et al., 2015).

3.2 Comparisons of TEC and ion horizontal drift velocities

Figure 2 shows the polar view of absolute TEC difference (ΔTEC) in the Northern Hemisphere between storm (DOY 76) and quiet (DOY 75) times from GNSS, SAPS-TIEGCM, and default-TIEGCM during 1600-2200 UT. In the snapshot of Figures 2a-d, a GNSS-observed TEC enhancement forms below 50°N around the duskside at 1600-2000 UT, and ΔTEC recovers gradually during 2000-2200 UT. An obvious SED plume with an intensity of ~5 TECU appears at 1300-1400 LT at 2000 UT. The modeled SED in ΔTEC also occurs at the throat region at 1300-1400 LT, with an overestimated magnitude of ~6 TECU (Figures 2e-h). The overestimation of dayside TEC is perhaps owing to the underestimated Joule Heating, and the resultant smaller loss rate, or excess soft particle precipitation (Liu et al., 2016b). Both in the observations and results from SAPS-TIEGCM (Figures 2a-h), a TEC depletion appears at geographic latitudes of 50-70°N in the dusk sector, with an intensity of ~-6 TECU. Previous studies have disclosed that the trough of ΔTEC due to SAPS extends sunward and tended to cut off the TOI structure (Horvath et al., 2016; Zheng et al., 2008). Compared with the results from default-TIEGCM (Figures 2i-l), the trough structures at dusk of subauroral latitudes simulated by SAPS-TIEGCM (Figures 2e-h) are more aligned with the observations (Figures 2a-d) in a strong SAPS case. Considering the only modification in SAPS-TIEGCM is the additional ion drift velocity, thus the differences between modeled TEC by SAPS-TIEGCM and default-TIEGCM are caused by SAPS directly or indirectly.

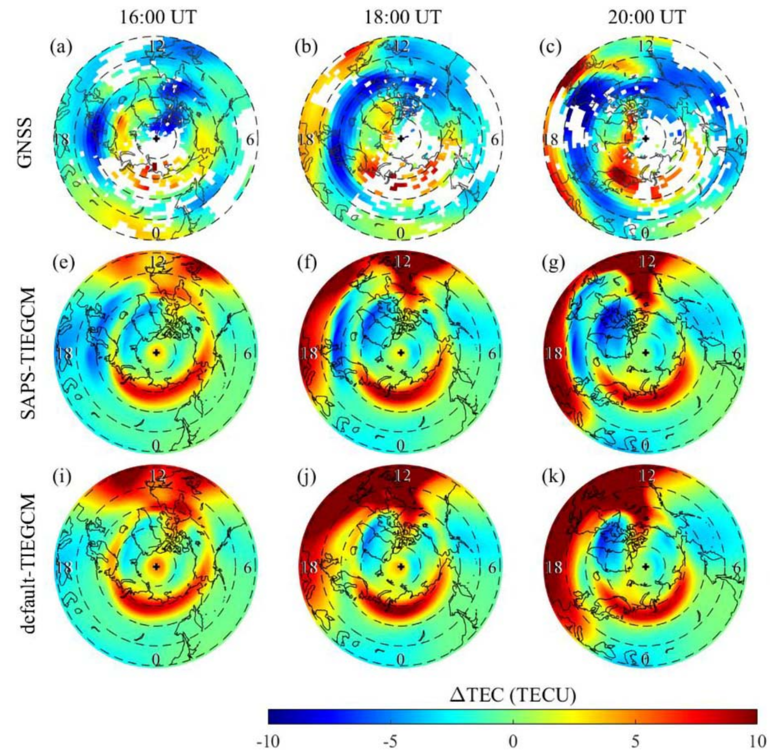

Figure 2. Absolute TEC difference in the Northern Hemisphere between storm time (DOY 76) and quiet time (DOY 75) from GNSS (a-d), SAPS-TIEGCM (e-h) and default-TIEGCM (i-l), respectively. The dotted circles are geographic 10° apart with the outer circle at 40°N.

Figures 3a and 3b show the modeled eastward ion drift velocities from default-TIEGCM and SAPS-TIEGCM on pressure level 2.0 (~300 km) at 2200 UT, respectively. The observed cross-track velocities from DMSP F17 at 2140-2210 UT are overlapped. The detailed profiles of simulations and observation on DMSP trajectory are shown in Figure 3c. Since the magnetic field lines at high-latitudes are nearly vertical, the simulated horizontal ion drift velocities on ~300 km are considered to be approximately equal to the measurements of DMSP satellite on ~830 km. An obvious two-cell plasma convection is presented in Figure 3a. The differences between the modeled ion velocities from default-TIEGCM and SAPS-TIEGCM are mainly located in the dusk subauroral region in Figures 3a and 3b. Comparing with Figure 3a, Figure 3b shows a stronger westward ion drift with a peak velocity of over 1000 m/s located at ~50° in dusk sector at 2200 UT. The detailed profile in Figure 3c indicates that the simulated SAPS-induced westward flow velocity is ~1100 m/s at the equatorward of the high-latitude evening convection, and it is consisted with the DMSP observations in magnitude. The simulation results underestimate the size of the convection pattern calculated by empirical Heelis model driven by 3-hour Kp, and it makes the simulated convection velocity peak in both dusk and dawn shrink to higher latitude. However, considering the better simulated results of TEC and SAPS velocity from SAPS-TIEGCM than that from default-TIEGCM (Figures 2 and 3), SAPS-TIEGCM model can be used to analyze the dynamics and electrodynamics processes induced by SAPS qualitatively (Wang et al., 2012; Wu et al., 2019; Zhang et al., 2021a).

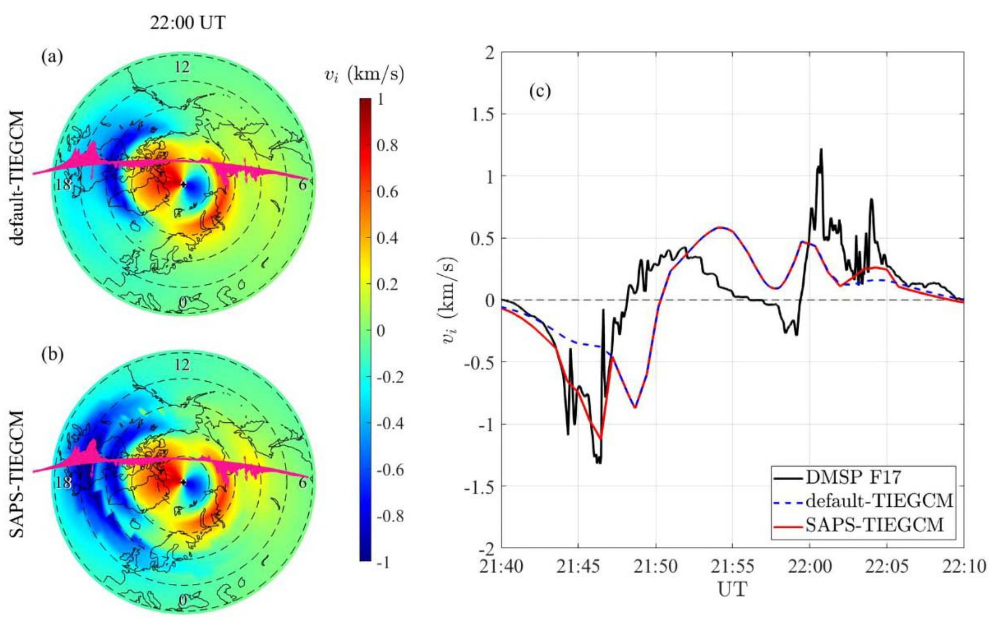

Figure 3. (a,b) Polar view of eastward ion drift velocities on pressure level 2.0 (~300 km) in the Northern Hemisphere at 2200 UT on DOY 76 (Mar. 17, 2013) from default-TIEGCM and SAPS-TIEGCM. Overlapping magenta arrows show DMSP F17 cross-track ion velocities during 2140-2210 UT. (c) Detailed eastward ion drift velocities on the track of DMSP satellite.

3.3 Effects of SAPS on SED and TOI

Figure 4 illustrates the absolute TEC difference between TIEGCM with and without SAPS model. The locations of SAPS channel are shown as the orange lines, which are the contour lines where the ion westward velocity difference between SAPS-TIEGCM and TIEGCM exceeds 200 m/s. The contour lines of SED and the peak of TOI with and without SAPS effects are respectively painted green and purple. In Figure 4, TEC depletions locate around SAPS channel with a TEC reduce of ~12 TECU, while a TEC enhancement of ~6 TECU appears at the westward edge of SAPS channel. These SAPS-induced variations cause the westward movement of SED and TOI peak, which is more obvious (~10° longitude) in Figures 4b and 4c. It indicates that the values of SED/TOI westward shift increase with the development and persistence of SAPS.

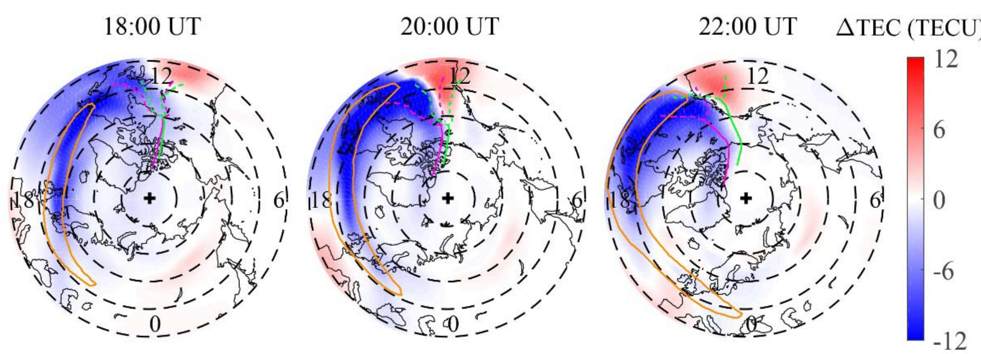

Figure 4. Absolute TEC difference between SAPS-TIEGCM and TIEGCM on DOY 76. The orange lines denote the locations of SAPS. The dashed and solid lines indicate the locations of SED and TOI peak, while the purple and green lines are for TIEGCM and SAPS-TIEGCM respectively.

SAPS-induced local TEC reduce along its flow channel has been reported by Schunk et al. (1975), Foster et al. (2002a), and Wang et al. (2012). It is worth noting that the electron density depletions on the westward edge of SAPS are more significant than that on its eastward edge. As the enhanced westward transports are determined by the gradients of increased westward ion drift velocities, the heated plasmas move from dusk to post-noon and tend to accumulate at the westward edge of SAPS. The stacked heated plasmas with higher loss rates thus tend to reduce more electron density at westside of SAPS along its channel. SAPS can thus reduce TEC in eastward edge of SED region and throat region of TOI. Subsequently, the effects of reducing electron density diffuse at the westward edge of SAPS and enter the polar cap with sunward return convection to weaken the peak of TOI. However, in the noon sector where SAPS no longer have high drift velocities, a promotion of TEC appears at the westward edge of SAPS channel. Therefore, the impacts of SAPS on SED and TOI manifest as moving them westward, and the movement is more significant with the development of SAPS during 1800-2200 UT.

3.4 Term analysis during SAPS affecting SED/TOI

To investigate the SAPS-induced electron density disturbances, a term analysis of O^+ continuity equation has been performed in default-TIEGCM and SAPS-TIEGCM, following the method using in previous studies (e.g., Buonsanto et al., 1995; Lei et al., 2008; Liu et al., 2016; and Zhang et al., 2021c). The O^+ continuity equation is expressed as follow

$$\frac{\partial N_{\mathrm{O}^+}}{\partial t} = q_{\mathrm{O}^+} - \beta N_{\mathrm{O}^+} - \nabla \cdot (N_{\mathrm{O}^+}\boldsymbol{V}),$$

where N_{O^+}, q_{O^+}, β, and $\boldsymbol{V}$ are the density, chemical production, loss coefficient, and velocity of O^+, respectively. The factors affecting change rate of O^+ density include chemical terms (production and loss) and transport terms which consist of neutral wind transport, electric field transport, and ambipolar diffusion. As O^+ is the major ion species in the F region, the change rate of O^+ density can almost represent the change rate of electron density. Thus, the change rate of electron density, $\delta\mathrm{NE}$, can be described as

$$\delta\mathrm{NE} = \delta\mathrm{NE}_{\mathrm{ch}} + \delta\mathrm{NE}_{\mathrm{w}} + \delta\mathrm{NE}_{\mathrm{E\times B}} + \delta\mathrm{NE}_{\mathrm{diff}},$$

where $\delta\mathrm{NE}_{\mathrm{ch}}$, $\delta\mathrm{NE}_{\mathrm{w}}$, $\delta\mathrm{NE}_{\mathrm{E\times B}}$ and $\delta\mathrm{NE}_{\mathrm{diff}}$ are the change rate of electron density induced by chemical processes, neutral wind transport, electric field transport, and ambipolar diffusion, respectively. To compare the relative contributions between these different terms during SAPS affecting SED and TOI, the absolute difference for electron density, neutral temperature, thermospheric composition, chemical and transport terms between SAPS-TIEGCM and default-TIEGCM at 240 km and 390 km are depicted in Figure 5.

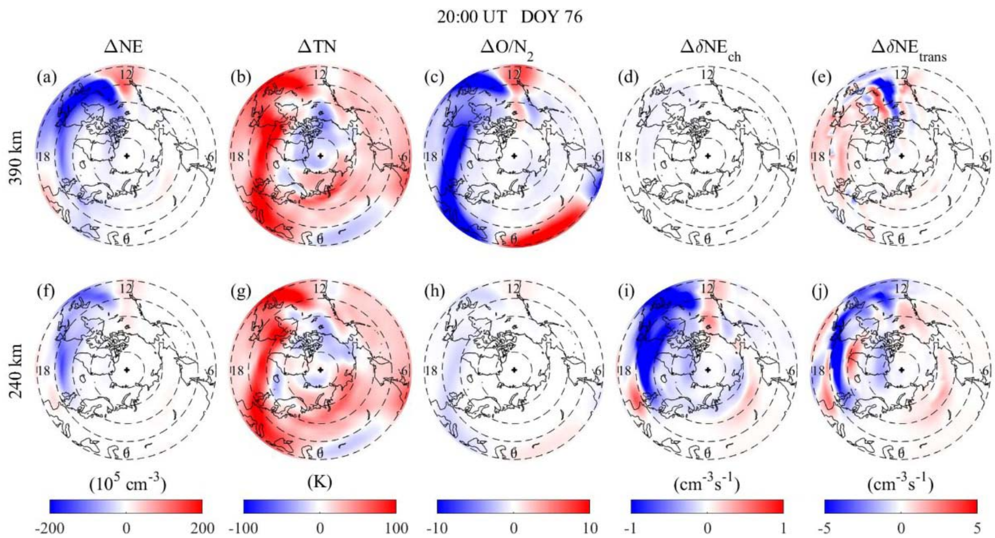

Figure 5. The absolute difference between SAPS-TIEGCM and default-TIEGCM for (a,f) electron density ($\Delta\mathrm{NE}$), (b,g) neutral temperature ($\Delta\mathrm{TN}$), (c,h) thermospheric composition ($\Delta\mathrm{O/N_2}$), electron density change rate induced by (d,i) chemical processes ($\Delta\delta\mathrm{NE_{ch}}$), and (e,j) transport processes ($\Delta\delta\mathrm{NE_{trans}}$) at 390 and 240 km at 2000 UT.

The simulated F_2 layer peak height (h_mF_2) is ~340 km on average. In Figure 5a, the variation of electron density is significant above h_mF_2. On one hand, the violent frictions between high-speed plasmas and background atmosphere lead to the increases of duskside thermospheric temperature in Figures 5b and 5g, and the increased neutral and plasma temperatures can cause the enhanced recombination rates in Figure 5d and 5i as reported in previous studies (e.g., Foster et al., 2002b; Moffett et al., 1992; Schunk et al., 1975). On the other hand, the local heating in the SAPS region can induce the changes of thermospheric composition in topside F-region as shown in Figure 5c. The O/N_2 decreases at dusk sector and increases at noon, which indicates that there are upwelling around SAPS channel and downwelling at the westward edge of SAPS. The upward neutral winds lead to a decrease in O/N_2 owing to the uplifting molecular rich air from lower altitudes, and the upwelling with high recombination rate contributes to electron depletion, while the downwelling does the opposite. Wang et al. (2012) also exhibit that SAPS can result in upwelling owing to local Joule heating in the SAPS region and downwelling owing to neutral wind convergent flow away from the SAPS region. Figures 5e and 5j exhibit that SAPS-induced transport processes increase the electron density in the topside ionosphere and decrease the electron density in the bottomside along SAPS channel. The directions of ion vertical transport in SAPS channel roughly consist with neutral winds indicated by Figure 5c. Therefore, the heated plasmas and the upwelling of thermosphere contribute to the increased chemical loss rate in dusk, while the downwelling contribute to the decrease in loss rate at noon.

As the variations of plasma transport shown in Figures 5e and 5j are complex around the westward edge of SAPS, Figure 6 shows the detailed latitude-altitude profiles for electron density and electron density change rate induced by chemical and transport processes in SED region with reduced electron density (1400 LT) and enhanced electron density (1230 LT) at 2000 UT. The absolute differences of neutral winds between SAPS-TIEGCM and default-TIEGCM are shown in Figures 6c and 6j. Since the influences of SAPS on meridional winds are much greater than that on vertical winds, the amplitudes of vertical winds are magnified 10 times for a better visibility. The simulated SAPS was driven by 3-hour Kp index which reached more than 6 at 0600 UT and lasted for 18 hours as shown in Figure 1f, so the SAPS were obviously activated at 0600 UT. At 2000 UT, SAPS significantly enhance the upward and equatorward winds in a wide range in Figure 6c as reported by Wang et al. (2012). In SAPS channel (at 1400 LT), the enhanced upward winds with velocities of ~20 m/s tend to increase the electron density above h_mF_2 and reduce it below h_mF_2 in Figure 6c, and the uplifting of thermosphere with a high recombination rate combined with local heating cause the high loss rate in Figure 6b. Meanwhile, SAPS induce weaker downward and poleward winds with velocities of ~5 m/s at its westward edge in Figure 6j, leading to the low loss rate as shown in Figure 6i. However, because the downwelling is so weak at 1230 LT, the dominant westward wind transports still cause the electron density increase above h_mF_2 and decrease below h_mF_2 as the same tendency in SAPS channel at subauroral latitudes in Figure 6j. The SAPS-induced subauroral vertical ambipolar diffusions driven by local Joule heating are consistent with the vertical winds to transport plasma from bottomside of F-region to its topside at 1400 LT, and do the opposite at 1230 LT. The heated plasmas are cooled adiabatically and descend at SAPS equatorward and westward edges (Wang et al., 2012). Moreover, Figure 6f shows that the horizontal electron transport reduces electron density at eastside SED (1400 LT), and enhances density at its westside (1230 LT), which implies that the plasmas are deposited on the westward edge of SAPS and contribute to westside SED. Compared with the weak downwelling leading to the thermospheric composition changes, the horizonal E×B transports should be the main reason for the SAPS-enhanced westside SED.

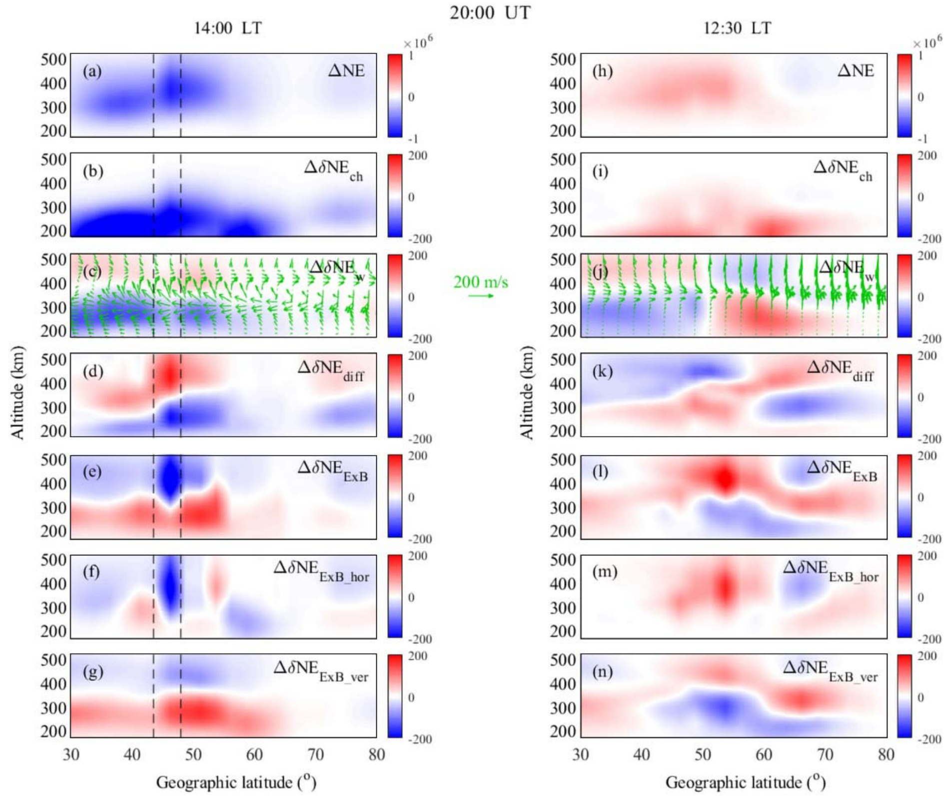

Figure 6. Geographic latitude-altitude profiles of the absolute difference between SAPS-TIEGCM and default-TIEGCM for (a,h) electron density and electron density change rate induced by (b,i) chemical processes, (c,j) neutral winds, (d,k) ambipolar diffusion, (e,l) electric fields, (f,m) horizontal component of electric fields ($\Delta\delta \mathrm{NE}_{\mathrm{E\times B\_hor}}$) and (g,n) vertical component of electric fields ($\Delta\delta \mathrm{NE}_{\mathrm{E\times B\_ver}}$) at 1400 LT and 1230 LT at 2000 UT. The regions between two dashed lines denote the SAPS channel. The green arrows denote SAPS-induced neutral wind disturbances.

4. Discussion

SAPS can affect SED by local heating and ion drag to induce chemical and dynamic processes. Moreover, Figure 6 (e-g and l-n) exhibits that SAPS can also modulate electron density by changing electrodynamic processes, which imply that SAPS can cause electric field variations. The SAPS-induced changes in horizonal neutral winds, ion vertical velocities, and horizonal electric fields are shown in

Figure 7.

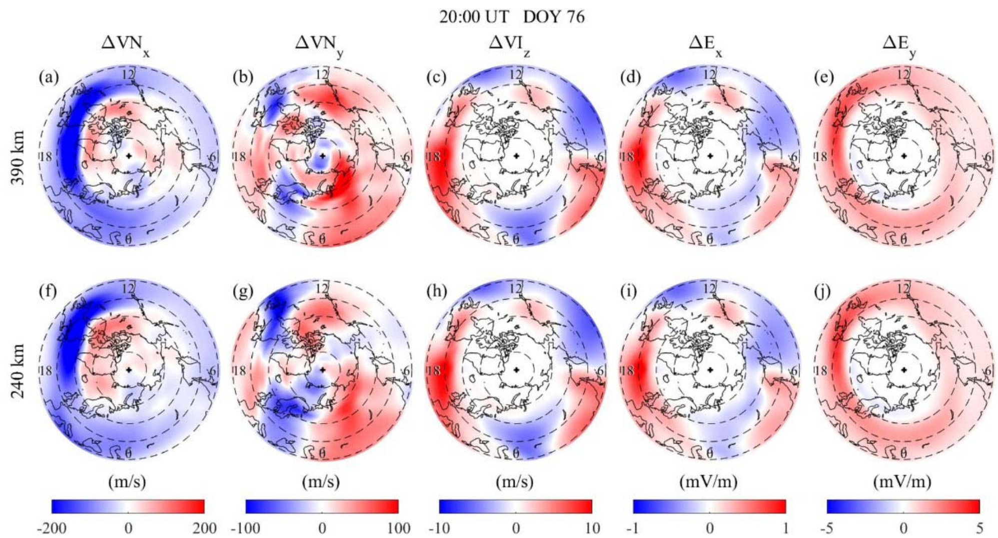

Figure 7. The absolute differences between SAPS-TIEGCM and default-TIEGCM for (a,f) eastward winds ($\Delta \mathrm{VN}_x$), (b,g) northward winds ($\Delta \mathrm{VN}_y$), (c,h) upward ion E ×B drift velocity ($\Delta \mathrm{VI}_z$), (d,i) eastward electric field ($\Delta \mathrm{E}_x$), and (e,j) northward electric field ($\Delta \mathrm{E}_y$) at 240 and 390 km at 2000 UT.

Westward SAPS can enhance the local westward neutral winds by ion-neutral collision in Figures 7a and 7f as reported in the literature (e.g., Miller et al., 1990; Reddy and Mayr, 1998; Wang et al., 2012). The enhanced westward winds combined with the downward component of geomagnetic field can promote poleward polarization electric fields through the dynamo process as Figures 7e and 7j. As the peak velocity of the modeled SAPS is only ~300 m/s, $\Delta \mathrm{E}_y$ is just below 5 mV/m. Banafsheh et al. (2019) also shows that the neutral wind dynamo effect can increase the ion westward drift by 20% using a MIT coupling model RCM-CTIPe. The enhanced westward E×B transport at westward edge of SAPS redistributes electron density from eastside of SED to its westside as shown in Figures 6f and 6m.

On the other hand, SAPS-driven meridional winds are more complicated due to the geomagnetic inclination, LT, and UT by changing the pressure gradient, ion drag, the Coriolis force, and the centrifugal force (Ferdousi et al., 2019; Wang et al., 2012; Zhang et al., 2021a) as shown in Figures 7b and 7g. The meridional wind dynamo process cause the changes in zonal polarization electric field as shown in Figures 7d and 7i, which results in the vertical E×B drifts as shown in Figures 7c and 7h. Wang et al. (2012) disclose that the adiabatic thermal expansion of heated plasma may lead to an upward ambipolar diffusion combined with the upwelling of the thermosphere in SAPS channel. Our results show that vertical E×B drifts induced by the dynamo processes of meridional winds are consisted with ambipolar diffusion to enhance the upward transports in SAPS channel and the downward transports at westward edge of the flow channel.

Overall, the dynamic effects of SAPS in ionosphere-thermosphere system drive not only the changes in plasma chemical processes and thermospheric composition, but also the dynamics and electrodynamics of plasmas to redistribute the electron density in SED and TOI region. The SAPS-induced horizonal transports tends to directly move SED westward, while the vertical transports alter the electron density in SED by affecting plasma temperature via adiabatic compression or expansion processes. Our results prove that the influences of SAPS on SED and TOI depend on their relative locations. SAPS decrease the electron densities in SED and TOI throat region overlapped with SAPS channel, and increase the electron densities in SED located at SAPS westward edge. Therefore, SAPS may be a part of the reason for forming SED at afternoon sector (Evans et al., 1983, Foster et al., 2006; and Pirog et al., 2009). Meanwhile, there is no contradiction between that SAPS weaken SED by reducing electron density along its channel (Fuller-Rowell, 2011) and that SAPS promote SED formation through zonal transport (Foster et al., 2007b).

5. Summary

By imposing a non-self-consistent empirical SAPS model into TIEGCM model, this work investigates the subsequent ionosphere-thermosphere response caused by high-speed westward plasma flow. Simulated results show that SAPS can significantly impact on the location and strength of SED and TOI by modulating local electron density. The TEC depletion appears in SED region and throat region of TOI overlapped with SAPS channel, while a TEC raise appears at the westward edge of SAPS. As a result, SED and the throat of TOI are forced to shift westward, and the influences of SAPS enter the polar cap with convection to weaken the intensity of TOI.

A term analysis for O^+ to confirm that the major mechanisms in the influences of SAPS on SED and TOI are the variations of ionospheric loss rates and dynamic and electrodynamic transports. In SED and throat of TOI overlapped with high-speed SAPS, the electron density decreases in three ways. (1) The heated plasma by ion-neutral atmosphere friction raises the local loss rate; (2) The upwelling of the thermosphere induced by upward ambipolar diffusion of heated plasma reduce O/N_2 to increase the loss rate; (3) the horizonal E×B transport moves plasma westward out of flow channel. In sunward SED region, SAPS enhance the electron density in two ways. (1) The downwelling driven by adiabatic thermal cooling increases O/N_2 to reduce the loss rate; (2) the plasma transported to the westward edge of SAPS is stacked near noon.

Using SAPS-TIEGCM, this work exhibits the detailed impacts of SAPS on SED and TOI and the physical mechanisms. But due to the differences in SAPS intensity between the results from empirical SAPS model and actual observations, the conclusions in this work are qualitative to some extent.

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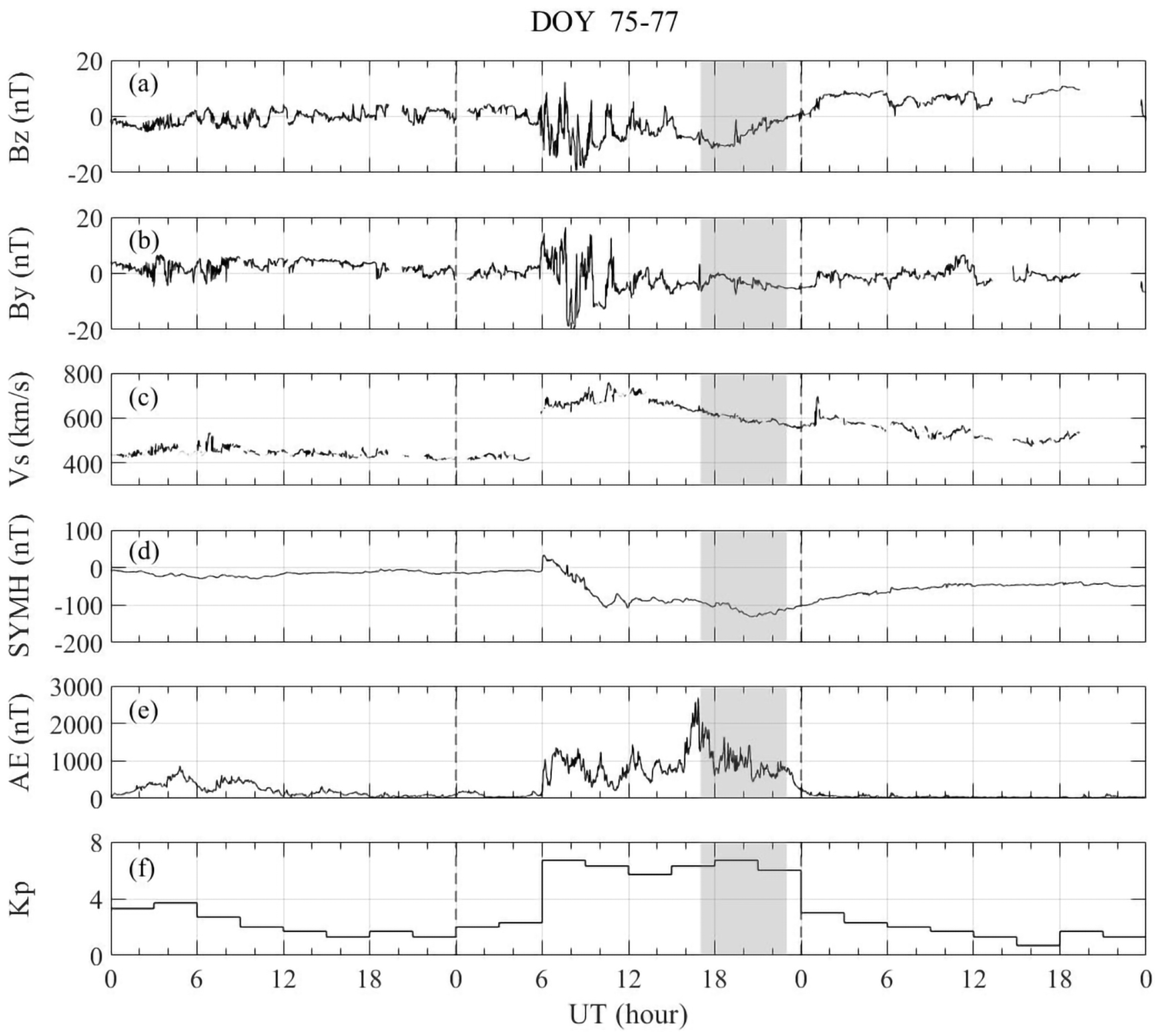
Figure 1.



DOY 75-77
Bz (nT)
(a)
By (nT)
(b)
Vs (km/s)
(c)
SYMH (nT)
(d)
AE (nT)
(e)
Kp
(f)
UT (hour)

Figure 2.

16:00 UT
18:00 UT
20:00 UT
22:00 UT
GNSS
SAPS-TIEGCM
default-TIEGCM
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(l)
12
18
6
0
ΔTEC (TECU)
-10
-5
0
5
10

Figure 3.

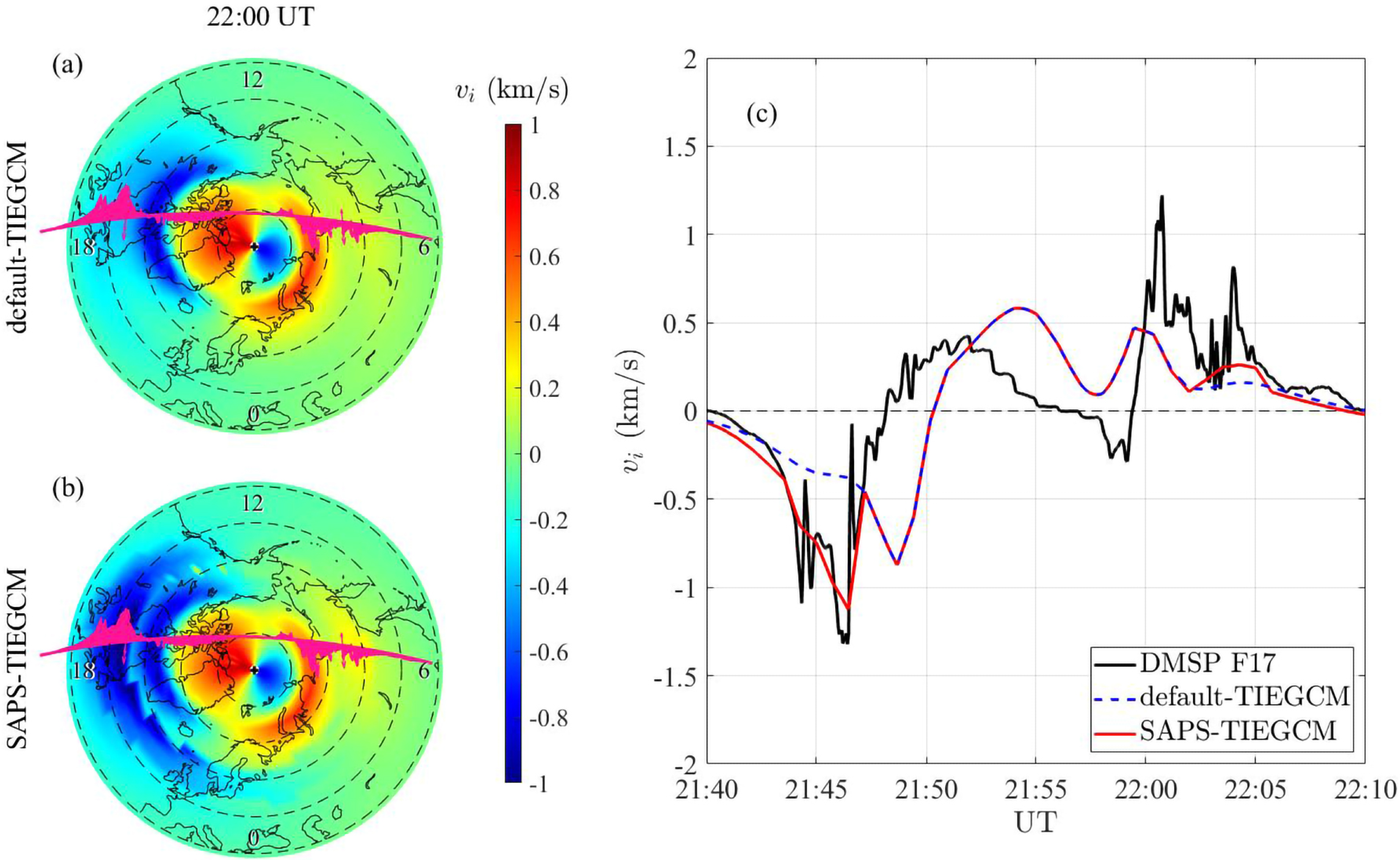

22:00 UT
(a)
(b)
(c)
default-TIEGCM
SAPS-TIEGCM
12
18
6
0
v_i (km/s)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
21:40
21:45
21:50
21:55
22:00
22:05
22:10
UT
DMSP F17
default-TIEGCM
SAPS-TIEGCM

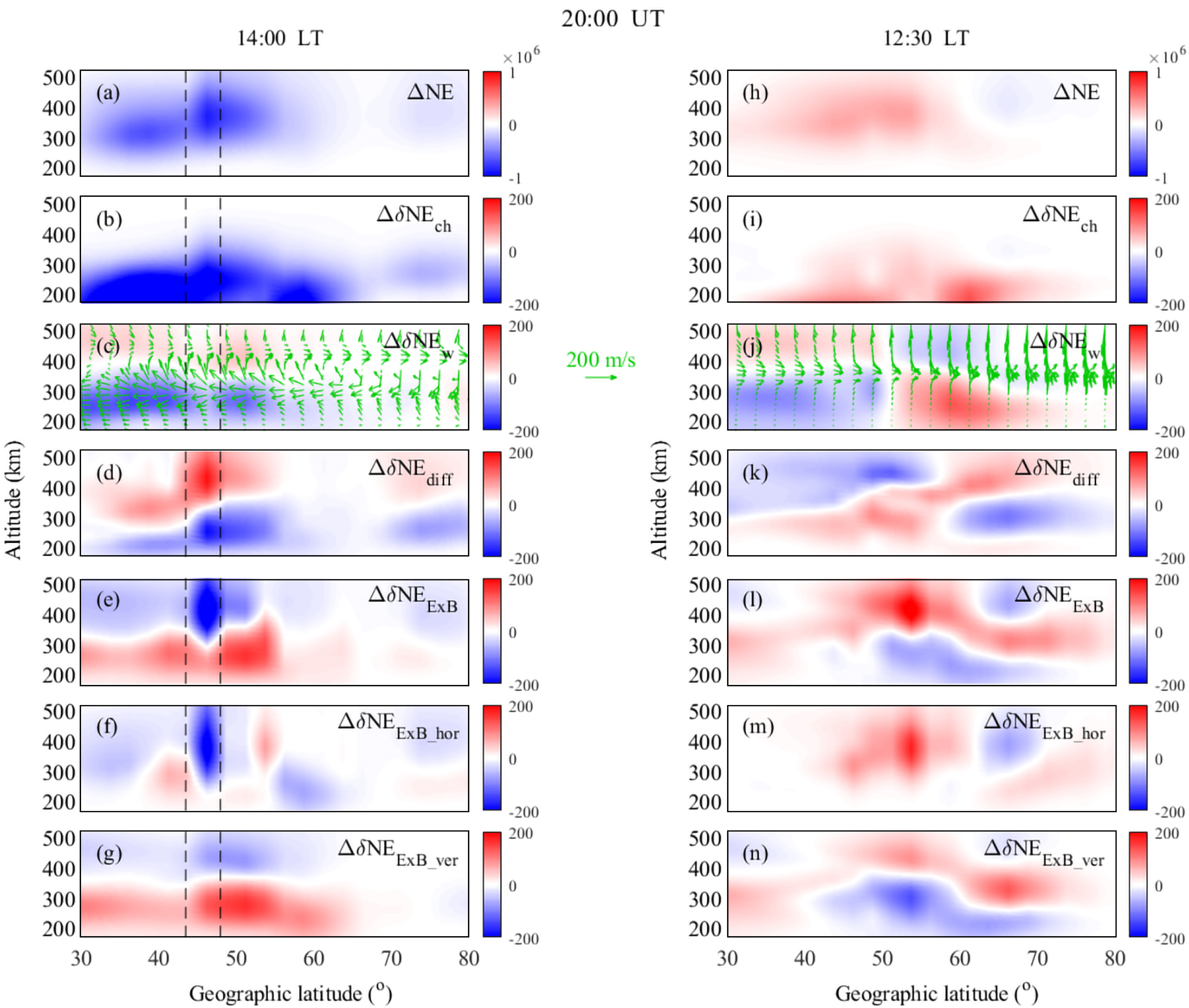
Figure 4.


18:00 UT
20:00 UT
22:00 UT
ΔTEC (TECU)
12
18
6
0
12
18
6
0
12
18
6
0
12
6
0
-6
-12

Figure 5.

20:00 UT DOY 76
ΔNE
ΔTN
$\Delta O/N_2$
$\Delta\delta NE_{ch}$
$\Delta\delta NE_{trans}$
390 km
240 km
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
12
18
6
0
$(10^5\ cm^{-3})$
(K)
$(cm^{-3}s^{-1})$
$(cm^{-3}s^{-1})$
-200
0
200
-100
0
100
-10
0
10
-1
0
1
-5
0
5

Figure 6.



20:00 UT
14:00 LT
12:30 LT
(a) ΔNE
(b) ΔδNE_ch
(c) ΔδNE_w
(d) ΔδNE_diff
(e) ΔδNE_ExB
(f) ΔδNE_ExB_hor
(g) ΔδNE_ExB_ver
(h) ΔNE
(i) ΔδNE_ch
(j) ΔδNE_w
(k) ΔδNE_diff
(l) ΔδNE_ExB
(m) ΔδNE_ExB_hor
(n) ΔδNE_ExB_ver
200 m/s
×10^6
Altitude (km)
Geographic latitude (°)

Figure 7.


20:00 UT DOY 76
ΔVN_x
ΔVN_y
ΔVI_z
ΔE_x
ΔE_y
390 km
240 km
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
12
18
6
0
(m/s)
(m/s)
(m/s)
(mV/m)
(mV/m)
-200 0 200
-100 0 100
-10 0 10
-1 0 1
-5 0 5