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Recent Developments in Our Knowledge of Inner Magnetosphere-Ionosphere Convection

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Key Points:

- Subauroral convection is driven by complex interactions involving neutral winds, penetration electric fields, and polarization electric fields
- Key results on subauroral convection are summarized, with an emphasis on studies related to the SIMIC focus group of the NSF GEM program
- Modeling quiet geomagnetic conditions in conjunction with observations is necessary to understand the physics behind subauroral convection

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Abstract Plasma convection in the coupled inner magnetosphere-ionosphere is influenced by different factors such as neutral winds, penetration electric fields, and polarization electric fields. Several crucial insights about the dynamics in the region have been derived by interpreting observations in conjunction with numerical simulations, and recent expansion in ground- and space-based measurements in the region along with improvements in theoretical modeling has fueled renewed interest in the subject. In this paper we present a comprehensive review of the literature with an emphasis on studies since 2012 relevant to the National Science Foundation Geospace Environment Modeling program. We cover four specific areas: (1) the subauroral polarization stream, (2) penetration electric fields, (3) the disturbance dynamo, and (4) quiet time subauroral convection. We summarize new observations and resulting insights relevant to each of these topics and discuss various outstanding issues and unanswered questions.

1. Introduction

Determining the dynamics of the coupled magnetosphere-ionosphere region has been an active topic of research for several decades. The vast majority of studies have used data acquired at high latitudes (e.g., Heelis et al., 1982; Kim et al., 2013; Prikryl et al., 2013; Ruohoniemi & Baker, 1998) and at equatorial latitudes (e.g., Fejer & Scherliess, 1995; Fejer et al., 2007; Kelley et al., 1979). Efforts directed toward understanding plasma convection at midlatitudes have been limited, partly due to the lack of infrastructure in this region. Several factors such as the neutral winds (Blanc & Richmond, 1980; Rishbeth, 1971), polarization electric fields (Anderson et al., 1993; Galperin et al., 1974; Spiro et al., 1979), and penetration electric fields (PEFs; Blanc et al., 1977; Jaggi & Wolf, 1973) are expected to influence plasma flow at midlatitudes. During geomagnetically quiet conditions, it has commonly been assumed that neutral winds drive subauroral *F* region convection (Richmond et al., 1976; Rishbeth, 1971). This implied convection should be in the same direction as the neutral atmosphere, that is, eastward in the premidnight sector and westward in the postmidnight sector. During geomagnetic disturbances, strong westward directed flows driven by polarization electric fields have been reported in the subauroral region (Foster & Vo, 2002; Galperin et al., 1974; Spiro et al., 1979). In this paper, we review those studies that have examined inner magnetosphere-ionosphere convection under different geomagnetic conditions, with an emphasis on the studies related to the Storm-Time Inner Magnetosphere-Ionosphere Convection (SIMIC) focus group of the National Science Foundation (NSF) Geospace Environment Modeling (GEM) program (2012–2017).

Early studies used measurements from satellites (Heelis & Coley, 1992) and incoherent scatter radars (ISRs) (Buonsanto et al., 1993; Richmond et al., 1980) to derive average patterns of midlatitude ionospheric plasma drifts. Contrary to expectations, Heelis and Coley (1992) reported observations of westward flow at $\sim 55°$ magnetic latitude, throughout the nightside. These reports were further confirmed by Richmond et al. (1980) and Wand and Evans (1981) using electric field measurements from the ISRs. Finally, Buonsanto et al. (1993) and Buonsanto and Witasse (1991) derived average convection patterns for three seasons using Millstone Hill ISR measurements and found a predominantly westward flow in the nightside midlatitude region, with a strong seasonal dependence. This inconsistent behavior suggests that neutral winds may not be the dominant drivers of midlatitude ion convection and perhaps other factors such as PEFs can be important even during quiet geomagnetic conditions (Carpenter & Kirchhoff, 1975; Heelis & Coley, 1992; Wand & Evans, 1981). These early studies revealed the limitations in our understanding of quiet time subauroral convection by demonstrating that neutral winds cannot completely explain the observed patterns.

Overshielding/undershielding electric fields are an additional factor reported to influence midlatitude convection, especially during the early phases of geomagnetic storms (Blanc & Richmond, 1980; Huang et al., 2006; Maruyama et al., 2005; Nishida, 1968). Under geomagnetically steady conditions, the inner magnetosphere is thought to be shielded from the cross-tail electric field by a dusk-dawn-directed shielding electric field, generated due to charge separation associated with region-2 field-aligned currents (FACs; e.g., Jaggi & Wolf, 1973; Kelley et al., 1979, 2003; Wolf et al., 2007). However, during periods of large and rapid fluctuations of the interplanetary magnetic field (e.g., during the early phase of a geomagnetic storm) the shielding balance should be perturbed, resulting in either undershielding or overshielding of the inner magnetosphere (Jaggi & Wolf, 1973; Maruyama et al., 2005; Maruyama & Nakamura, 2007; Sazykin, 2000). In short, when interplanetary magnetic field B_Z suddenly turns southward (northward), the cross-tail electric field should increase (decrease) rapidly whereas the shielding electric field takes time to readjust, resulting in undershielding (overshielding) of the inner magnetosphere. When the inner magnetosphere is undershielded convection electric fields *penetrate* to the subauroral latitudes, and such electric fields are commonly referred to as PEFs and are expected to have time scales ranging from a few minutes to a few hours (Huang et al., 2006; Wolf et al., 2007). These shielding electric fields are typically thought to dominate during the early phases of a geomagnetic storm (Maruyama et al., 2005).

A majority of studies examining midlatitude dynamics have focused on disturbed geomagnetic conditions and reported observations of strong westward directed flows in the region equatorward of the auroral oval (Anderson et al., 1993; Spiro et al., 1979; Yeh et al., 1991). A number of terms such as polarization jets (PJ) (Galperin et al., 1974), subauroral ion drift (SAID; Anderson et al., 1993, 2001; Spiro et al., 1979), subauroral electric fields (Karlsson et al., 1998), and substorm associated radar auroral surges (Freeman et al., 1992) have been used to describe these flows. The term *subauroral polarization stream (SAPS)* was coined by Foster and Burke (2002) to encompass all these separately reported phenomena that exhibit a certain degree of similarity. SAPSs were defined as latitudinally broad regions ($3^\circ - 5^\circ$ wide) of enhanced westward flows observed in the nightside subauroral region (e.g., Yeh et al., 1991), while SAID/polarization jets are latitudinally narrow ($\sim 1^\circ$) channels of intense westward flows, often exceeding 1 km/s, which are embedded within the SAPS (Foster & Burke, 2002). SAPSs are thought to occur during the main and recovery phases of geomagnetic storms when a misalignment between the ion and electron Alfvén layers (Gussenhoven et al., 1987; Heinemann et al., 1989) generates strong poleward-directed electric field (Anderson et al., 1993; Foster & Burke, 2002). In addition, the enhanced electric fields lead to increased collision frequencies and ion recombination resulting in further decrease in conductivity (Schunk et al., 1976) producing a feedback effect that allows the electric fields to grow even more (Anderson et al., 1993, 2001). These early studies showed that SAPS was a prominent feature of the storm time subauroral region and different from PEFs (Huang et al., 2006). Finally, Wang et al. (2008) and Wang and Lühr (2011) used ion drift meter measurements from the Defense Meteorological Satellite Program (DMSP) to examine the influence of subauroral flux tube integrated conductivity on SAPS and found that lower conductivity is more favorable to their formation and for higher flux tube integrated conductivity SAPS moved to poleward latitudes and their velocities were suppressed.

The disturbance dynamo is the storm time version of the neutral wind dynamo, generating predominantly poleward electric field at the middle and low latitudes due to thermospheric circulation driven by auroral heating and the Coriolis force (Blanc & Richmond, 1980; Gonzales et al., 1978). A number of studies on midlatitude convection reported the effects of the disturbance dynamo using different observations such as satellites (Heelis & Coley, 1992) and incoherent scatter radars (Gonzales et al., 1978; Richmond et al., 1980). The disturbance dynamo develops over many hours and is typically thought to be dominant during the recovery phase of a geomagnetic storm (Blanc & Richmond, 1980; Maruyama et al., 2005). Although PEFs and the disturbance dynamo dominate at different phases of a geomagnetic storm, it has been a challenging task to determine their relative contributions just based on observations because of the similarities in electric fields generated by them (Fejer & Scherliess, 1995; Fejer et al., 2007). The importance of using first-principle models in conjunction with observations to understand the complex dynamics of PEFs and the disturbance dynamo was demonstrated by Maruyama et al. (2005) and Maruyama and Nakamura (2007).

2. Inner Magnetosphere-Ionosphere Convection: Recent Developments

The overall objective of the NSF GEM program is to make accurate predictions of geospace by developing physical understanding of the large-scale organization and dynamics from observations, theory, and increasingly realistic models. The GEM program's strategy to achieve this goal is by undertaking a series of focus groups, and one such focus group was SIMIC, active between 2012 and 2017. The aim of the SIMIC focus group was to utilize the augmentations to space- and ground-based infrastructure during the last solar cycle in conjunction with numerical advances in first-principle models, to synthesize a new understanding of how plasma distributions, convection electric fields, and current systems emerge and evolve in the inner magnetosphere and conjugate ionosphere, especially during geomagnetically disturbed periods. The new insights that emerged from the SIMIC effort can be summarized as follows:

Quiet Time Convection: The expansion of Super Dual Auroral Radar Network (SuperDARN) to midlatitudes combined with observations of electric fields in the inner magnetosphere by the Van Allen Probes have provided new opportunities to study quiet time convection in the subauroral region. Previous reports of westward flows (Heelis & Coley, 1992; Richmond et al., 1980) with a seasonal dependence (Buonsanto et al., 1993; Buonsanto & Witasse, 1991) throughout the nightside subauroral ionosphere were confirmed by Maimaiti et al. (2018) using over 2 years of midlatitude SuperDARN observations and by Lejosne and Mozer (2016) using direct current electric field measurements from the Van Allen Probes. To explain this pattern, Maimaiti et al. (2018) proposed that PEFs could be the dominant drivers in the premidnight sector, whereas the neutral wind dynamo might prevail in the postmidnight sector. Another important factor reported to influence subauroral convection is season (Buonsanto et al., 1993; Buonsanto & Witasse, 1991; Maimaiti et al., 2018). Plasma drifts in the subauroral region were found to reach a few tens of meters per second in magnitude, with the strongest and most spatially variable flows observed during winter (Maimaiti et al., 2018). In particular, Maimaiti et al. (2018) showed that near-midnight subauroral convection during winter was almost twice as strong compared to other seasons. Furthermore, a significant latitudinal gradient in flow velocity was observed during winter but was not as pronounced in other seasons. These recent studies suggest that quiet time subauroral convection is driven by complex interplay between PEFs and neutral winds, with season and local time determining the relative dominance of the drivers. To gain further insight, it is perhaps necessary to use first-principle models in conjunction with observations to determine the dynamics of quiet time subauroral convection. However, to date, modeling studies have focused almost exclusively on geomagnetic storms (e.g., Raeder et al., 2016; Yu et al., 2015).

The SAPS: SAPS is considered a prominent feature of the disturbed time subauroral convection and has been an important research theme in the recent literature (Clausen et al., 2012; Gallardo-Lacourt et al., 2017; Kunduri et al., 2012, 2017; Lejosne & Mozer, 2017; Lyons et al., 2015; Mishin et al., 2017; Wang, Lühr, et al., 2012). Using multisatellite observations, He et al. (2018) suggested that during severe geomagnetic storms SAPS flows appear near the dusk sector first and then expand toward the midnight sector, and large-scale structures associated with SAPS correspond closely with those of Region-2 FACs. Recent studies have revealed new insights into SAPS driving mechanisms, challenging the traditional paradigm. Specifically, Mishin et al. (2017) suggested current closure in the two-loop substorm current wedge (Kepko et al., 2015; Murphy et al., 2013) may be driving SAPS instead of the previously accepted current generator and voltage generator mechanisms. Furthermore, observations of SAPS during geomagnetically quiet conditions (Kunduri et al., 2017; Lejosne & Mozer, 2016) and with velocities as low as 150 m/s (Nagano et al., 2015) show that the electric fields associated with such low-speed SAPS events are almost an order of magnitude lower than the theoretically estimated threshold of 50 mV/m (Schunk et al., 1976) required to generate frictional heating, an important mechanism that is thought to sustain and enhance SAPS. These studies demonstrate the limitations in our current understanding of how SAPS is generated and the influences that modulate its dynamics. Lyons et al. (2015) and Gallardo-Lacourt et al. (2017) showed strong correlations between SAPS enhancements (SAID) and auroral streamers. They suggested that auroral streamers can intensify SAPS by enhancing the pressure gradients in ring current, and flow bursts in the plasma sheet can reach the inner magnetosphere and strengthen SAPS flows. Another important modulating influence on SAPS is the neutral wind, as discussed by Zhang et al. (2015). Contrary to the expected disturbance dynamo pattern, a poleward-directed meridional wind in the premidnight sector was observed by Zhang et al. (2015) during the 2015 St. Patrick's day storm. Using observations from the Millstone Hill ISR and Fabry-Perot interferometer in conjunction with first-principle models, Zhang et al. (2015) demonstrated that this anomalous behavior in wind was driven by SAPS. Specifically, SAPS drove a strong westward wind (~300 m/s) observed by multiple FPIs , due to ion drag, and Coriolis force effects on this westward neutral wind was thought to drive a poleward wind (reaching ∼100 m/s). The authors argued that such regional disturbances might counteract the influence of disturbance dynamo during geomagnetic storms. Finally, the important role played by SAPS in determining the dynamics of inner magnetosphere was further demonstrated by Lejosne et al. (2018). Previous studies showed that energetic electrons penetrate to lower L shells (L < 4) compared to ions (e.g., Reeves et al., 2016), inconsistent with the expected picture. In order to explain the differences between energetic electron and ion dynamics, Lejosne et al. (2018) suggested that SAPS could transfer potential energy to energetic electrons, resulting in their inward motion. Collectively, these new observations show that SAPS are more common features of the coupled inner magnetosphere-ionosphere region than previously realized and can have a significant influence on the dynamics of the inner magnetosphere.

The disturbance dynamo: During the later stages of a geomagnetic storm, the disturbance dynamo mechanism is thought to have a significant influence on convection at middle and low latitudes (Blanc & Richmond, 1980; Heelis & Coley, 1992; Maruyama et al., 2005; Maruyama & Nakamura, 2007). Using more than 5 years of data from the Hokkaido SuperDARN radar, Zou and Nishitani (2014) presented a comprehensive analysis of midlatitude convection (40° −50° magnetic latitude) during disturbed geomagnetic conditions and found that westward flows at midlatitudes intensified 5 hr after substorm onset, and the effect lasted for up to 20 hr, maximizing near 12 hr after onset. This intensification of flows and the associated time periods were consistent with the disturbance dynamo mechanism (Blanc & Richmond, 1980). Although there has been significant progress in characterizing subauroral convection during the last solar cycle, a comprehensive understanding of the complex interactions between the disturbance dynamo and PEFs and their relative influence on subauroral convection is yet to be developed. Maruyama et al. (2005) and Maruyama and Nakamura (2007) showed that PEFs dominate during the early stages of the storm, particularly on the dayside, whereas during the recovery phase PEFs are comparable to the disturbance dynamo on the nightside. Moreover, PEFs are known to change *F* region electron density, Pedersen conductivity, and ion drag and thereby modify the disturbance dynamo (Maruyama et al., 2005), further complicating the situation. These studies demonstrate the importance of comparing observations with first-principle models to separate the various driving influences of inner magnetosphere-ionosphere convection.

Modeling efforts: A majority of the modeling efforts during the last solar cycle were focused on SAPS observations during geomagnetic storms, especially the St. Patrick's day storms in 2013 and 2015 (Huba et al., 2017; Krall et al., 2017; Raeder et al., 2016; Yu et al., 2015). For example, Yu et al. (2015) modeled SAPS on 17 March 2013 using ring current-atmosphere interactions model with self-consistent magnetic field and Block Adaptive Tree Solarwind-Roe-Upwind Scheme and captured a SAPS feature at subauroral latitudes, but the SAPS velocities were underestimated, and its location was deeper than in actual observations. Raeder et al. (2016) modeled the same event using Open Geospace General Circulation Model, Coupled Thermosphere Ionosphere Model, and Rice Convection Model and found better *overall* agreement with observations in terms of SAPS location and velocity; they attributed the improvement (compared to Yu et al., 2015) to the contribution of ionospheric feedback in the trough. The influence of SAPS on thermospheric winds was analyzed using the Thermosphere Ionosphere Electrodynamics General Circulation Model by Wang, Talaat, et al. (2012) who showed that SAPS drive westward thermospheric winds due to joule heating and ion drag, similar to the observations presented in Zhang et al. (2015). Furthermore, Wang et al. (2018) used the global ionosphere and thermosphere model to demonstrate that during SAPS intervals westward winds are enhanced at dusk and the influence of SAPS on neutral winds varies with universal time. This dependence has been attributed to the influence of solar illumination (which in turn varies with universal time) on ion drag. Collectively, these studies highlight several important aspects of magnetosphere-ionosphere-thermosphere coupling in SAPS and demonstrate the utility of first-principle models in understanding the physics behind different phenomena. However, looking forward, it is necessary to model a wider range of geomagnetic conditions (rather than limiting our focus to geomagnetic storms) to develop a more comprehensive picture of the full spectrum of behavior in the coupled inner magnetosphere-ionosphere-thermosphere system.

3. Conclusions and Still-Open Questions

Over the past 10 years a significant increase in observations at midlatitudes and improvement in modeling techniques have advanced our understanding of the dynamics of inner magnetosphere convection. New self-consistent models have demonstrated the importance of active ionospheric feedback in driving/enhancing SAPS, and the traditional paradigm of SAPS was challenged by new observations. Several unresolved questions still remain:

1. What are the drivers of SAPS under different geomagnetic conditions? The *traditional paradigm* proposes SAPS to be a manifestation of an active magnetosphere-ionosphere feedback process whereby Region-2 FACs close across the midlatitude trough, eliciting chemical changes that further reduce ionospheric conductivity while increasing the electric field in a manner that maintains current continuity. However, recent studies (Kunduri et al., 2017, 2018; Lejosne & Mozer, 2017; Mishin et al., 2017) show SAPS can also occur during periods of geomagnetic quiet, which cannot be explained by the traditional paradigm. To help improve our understanding of SAPS, it is necessary to determine the extent to which the traditional paradigm is valid under different geomagnetic conditions and to determine the role of different factors in driving SAPS flows that were overlooked in previous studies. Specifically, data from different ground-based resources such as Millstone Hill ISR, SuperDARN, and space-based resources such as DMSP, Swarm, and AMPERE should be collectively analyzed to develop a statistical characterization of SAPS and determine the role of different factors such as the region-2 FACs, substorm current wedge, and undershielding in driving and controlling them.
2. What is the role of PEFs and neutral winds in driving quiet time convection? Measurements provided by the midlatitude SuperDARN radars and the Van Allen Probes show that the quiet time convection is predominantly westward throughout the nightside subauroral ionosphere. To explain these observations, recent studies (Maimaiti et al., 2018) suggested the possibility that PEFs could be the dominant drivers of convection in the dusk sector and neutral winds dominate in the dawn sector. However, the persistent penetration of high-latitude electric field into the subauroral region has not been fully tested yet and needs to be validated using first-principle models in combination with observations. It is therefore necessary to model subauroral ionospheric convection during geomagnetically quiet conditions and to compare the results with longitudinally extended observations from SuperDARN and Millstone Hill ISR, to determine the relative contributions of PEFs and neutral winds in driving quiet time subauroral convection.
3. What is the role of ionospheric conductivity and local time effects in modulating the drivers of subauroral convection such as PEFs, the neutral winds/disturbance dynamo, and the substorm current wedge? Two major factors that influence ionospheric convection are conductivity and local time. However, only a few studies (Sazykin, 2000; Senior & Blanc, 1984; Wang et al., 2008; Wang & Lühr, 2011) discuss their role in modulating subauroral convection, and we do not yet have a comprehensive understanding. For example, ionospheric feedback from the midlatitude trough (a region of low ionospheric conductivity) is thought to play an important role in driving and sustaining SAPS flows. However, new observations of low-velocity SAPS (Kunduri et al., 2017, 2018; Nagano et al., 2015) suggest that electric fields observed during these events are almost an order of magnitude lower than the theoretically estimated threshold necessary to generate frictional heating in the trough. Measurements from Millstone Hill ISR and GPS TEC can be used to determine the magnitude of electric fields necessary to produce frictional heating in the trough. Longitudinally distributed electric field measurements could be combined with conductivity information from ISRs and DMSP to develop a statistical characterization of the dependence of PEFs on conductivity and local time.

Measurements of multiple parameters such as ionospheric convection, FACs, conductivity, and neutral winds are necessary to answer some of these questions. Different sources such as AMPERE, SuperDARN (expansion across China), GPS TEC, Exploration of energization and Radiation in Geospace, Millstone Hill ISR, Van Allen Probes, Swarm, and China Seismo-Electromagnetic Satellite have been providing some of these measurements. Finally, the upcoming Ionospheric Connection Explorer and Global-scale Observations of the Limb and Disk missions will provide exciting new opportunities to investigate magnetosphere-ionosphere-thermosphere coupling and help determine the role of neutral winds in driving quiet time subauroral convection.

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References

Anderson, P. C., Carpenter, D. L., Tsuruda, K., Mukai, T., & Rich, F. J. (2001). Multisatellite observations of rapid subauroral ion drifts (SAID). *Journal of Geophysical Research*, *106*(A12), 29,585–29,599. https://doi.org/10.1029/2001JA000128

Anderson, P. C., Hanson, W. B., Heelis, R. A., Craven, J. D., Baker, D. N., & Frank, L. A. (1993). A proposed production model of rapid subauroral ion drifts and their relationship to substorm evolution. *Journal of Geophysical Research*, *98*(A4), 6069–6078. https://doi.org/10.1029/92JA01975

Blanc, M., Amayenc, P., Bauer, P., & Taieb, C. (1977). Electric field induced drifts from the French Incoherent Scatter Facility. *Journal of Geophysical Research*, *82*(1), 87–97. https://doi.org/10.1029/JA082i001p00087

Blanc, M., & Richmond, A. (1980). The ionospheric disturbance dynamo. *Journal of Geophysical Research*, *85*(A4), 1669–1686. https://doi.org/10.1029/JA085iA04p01669

Buonsanto, M. J., Hagan, M. E., Salah, J. E., & Fejer, B. G. (1993). Solar cycle and seasonal variations in *F* region electrodynamics at Millstone Hill. *Journal of Geophysical Research*, *98*(A9), 15,677–15,683. https://doi.org/10.1029/93JA01187

Buonsanto, M. J., & Witasse, O. G. (1991). An updated climatology of thermospheric neutral winds and *F* region ion drifts above Millstone Hill. *Journal of Geophysical Research*, *104*(A11), 24,675–24,687. https://doi.org/10.1029/1999JA900345

Carpenter, L. A., & Kirchhoff, V. W. J. H. (1975). Comparison of high-latitude and mid-latitude ionospheric electric fields. *Journal of Geophysical Research*, *80*(13), 1810–1814. https://doi.org/10.1029/JA080i013p01810

Clausen, L. B. N., Baker, J. B. H., Ruohoniemi, J. M., Greenwald, R. A., Thomas, E. G., Shepherd, S. G., et al. (2012). Large-scale observations of a subauroral polarization stream by midlatitude superdarn radars: Instantaneous longitudinal velocity variations. *Journal of Geophysical Research*, *117*, A05306. https://doi.org/10.1029/2011JA017232

Fejer, B. G., Jensen, J. W., Kikuchi, T., Abdu, M. A., & Chau, J. L. (2007). Equatorial ionospheric electric fields during the November 2004 magnetic storm. *Journal of Geophysical Research*, *112*, A10304. https://doi.org/10.1029/2007JA012376

Fejer, B. G., & Scherliess, L. (1995). Time dependent response of equatorial ionospheric electric fields to magnetospheric disturbances. *Geophysical Research Letters*, *22*(7), 851–854. https://doi.org/10.1029/95GL00390

Foster, J. C., & Burke, W. J. (2002). SAPS: A new categorization for sub-auroral electric fields. *Eos, Transactions American Geophysical Union*, *83*(36), 393–394. https://doi.org/10.1029/2002EO000289

Foster, J. C., & Vo, H. B. (2002). Average characteristics and activity dependence of the subauroral polarization stream. *Journal of Geophysical Research*, *107*(A12), 1475. https://doi.org/10.1029/2002JA009409

Freeman, M. P., Southwood, D. J., Lester, M., Yeoman, T. K., & Reeves, G. D. (1992). Substorm-associated radar auroral surges. *Journal of Geophysical Research*, *97*(A8), 12,173–12,185. https://doi.org/10.1029/92JA00697

Gallardo-Lacourt, B., Nishimura, Y., Lyons, L. R., Mishin, E. V., Ruohoniemi, J. M., Donovan, E. F., et al. (2017). Influence of auroral streamers on rapid evolution of ionospheric SAPS flows. *Journal of Geophysical Research: Space Physics*, *122*, 12,406–12,420. https://doi.org/10.1002/2017JA024198

Galperin, Y., Ponomarev, V., & Zosimova, A. (1974). Plasma convection in the polar ionosphere. *Annales Geophysicae*, *30*, 1–7.

Gonzales, C. A., Kelley, M. C., Carpenter, L. A., & Holzworth, R. H. (1978). Evidence for a magnetospheric effect on mid-latitude electric fields. *Journal of Geophysical Research*, *83*(A9), 4397–4399. https://doi.org/10.1029/JA083iA09p04397

Gussenhoven, M. S., Hardy, D. A., & Heinemann, N. (1987). The equatorward boundary of auroral ion precipitation. *Journal of Geophysical Research*, *92*(A4), 3273–3283. https://doi.org/10.1029/JA092iA04p03273

He, F., Zhang, X., Wang, W., Liu, L., Ren, Z., Yue, X., et al. (2018). Large-scale structure of subauroral polarization streams during the main phase of a severe geomagnetic storm. *Journal of Geophysical Research: Space Physics*, *123*, 2964–2973. https://doi.org/10.1002/2018JA025234

Heelis, R. A., & Coley, W. R. (1992). East-west ion drifts at mid-latitudes observed by Dynamics Explorer 2. *Journal of Geophysical Research*, *97*(A12), 19,461–19,469. https://doi.org/10.1029/92JA01840

Heelis, R. A., Lowell, J. K., & Spiro, R. W. (1982). A model of the high-latitude ionospheric convection pattern. *Journal of Geophysical Research*, *87*(A8), 6339–6345. https://doi.org/10.1029/JA087iA08p06339

Heinemann, N. C., Gussenhoven, M. S., Hardy, D. A., Rich, F. J., & Yeh, H.-C. (1989). Electron/ion precipitation differences in relation to region 2 field-aligned currents. *Journal of Geophysical Research*, *94*(A10), 13,593–13,600. https://doi.org/10.1029/JA094iA10p13593

Huang, C., Sazykin, I., Spiro, R., Goldstein, J., Crowley, G., & Ruohoniemi, J. M. (2006). Storm-time penetration electric fields and their effects. *Eos, Transactions American Geophysical Union*, *87*(13), 131–131. https://doi.org/10.1029/2006EO130005

Huba, J. D., Sazykin, S., & Coster, A. (2017). SAMI3-RCM simulation of the 17 March 2015 geomagnetic storm. *Journal of Geophysical Research: Space Physics*, *122*, 1246–1257. https://doi.org/10.1002/2016JA023341

Jaggi, R. K., & Wolf, R. A. (1973). Self-consistent calculation of the motion of a sheet of ions in the magnetosphere. *Journal of Geophysical Research*, *78*(16), 2852–2866. https://doi.org/10.1029/JA078i016p02852

Karlsson, T., Marklund, G. T., Blomberg, L. G., & Malkki, A. (1998). Subauroral electric fields observed by the Freja satellite: A statistical study. *Journal of Geophysical Research*, *103*(A3), 4327–4341. https://doi.org/10.1029/97JA00333

Kelley, M. C., Fejer, B. G., & Gonzales, C. A. (1979). An explanation for anomalous equatorial ionospheric electric fields associated with a northward turning of the interplanetary magnetic field. *Geophysical Research Letters*, *6*(4), 301–304. https://doi.org/10.1029/GL006i004p00301

Kelley, M. C., Makela, J. J., Chau, J. L., & Nicolls, M. J. (2003). Penetration of the solar wind electric field into the magnetosphere/ionosphere system. *Geophysical Research Letters*, *30*(4), 1158. https://doi.org/10.1029/2002GL016321

Kepko, L., McPherron, R. L., Amm, O., Apatenkov, S., Baumjohann, W., Birn, J., et al. (2015). Substorm current wedge revisited. *Space Science Reviews*, *190*(1), 1–46. https://doi.org/10.1007/s11214-014-0124-9

Kim, H., Cai, X., Clauer, C. R., Kunduri, B. S. R., Matzka, J., Stolle, C., & Weimer, D. R. (2013). Geomagnetic response to solar wind dynamic pressure impulse events at high-latitude conjugate points. *Journal of Geophysical Research: Space Physics*, *118*, 6055–6071. https://doi.org/10.1002/jgra.50555

Krall, J., Huba, J. D., & Sazykin, S. (2017). Erosion of the plasmasphere during a storm. *Journal of Geophysical Research: Space Physics*, *122*, 9320–9328. https://doi.org/10.1002/2017JA024450

Kunduri, B. S. R., Baker, J. B. H., Ruohoniemi, J. M., Clausen, L. B. N., Grocott, A., Thomas, E. G., et al. (2012). An examination of inter-hemispheric conjugacy in a subauroral polarization stream. *Journal of Geophysical Research*, *117*, A08225. https://doi.org/10.1029/2012JA017784

Kunduri, B. S. R., Baker, J. B. H., Ruohoniemi, J. M., Nishitani, N., Oksavik, K., Erickson, P. J., et al. (2018). A new empirical model of the subauroral polarization stream. *Journal of Geophysical Research: Space Physics*, *123*. https://doi.org/10.1029/2018JA025690

Kunduri, B. S. R., Baker, J. B. H., Ruohoniemi, J. M., Thomas, E. G., Shepherd, S. G., & Sterne, K. T. (2017). Statistical characterization of the large-scale structure of the subauroral polarization stream. *Journal of Geophysical Research: Space Physics*, *122*, 6035–6048. https://doi.org/10.1002/2017JA024131

Lejosne, S., Kunduri, B. S. R., Mozer, F. S., & Turner, D. L. (2018). Energetic electron injections deep into the inner magnetosphere. A result of the subauroral polarization stream (SAPS) potential drop. *Geophysical Research Letters*, *45*, 3811–3819. https://doi.org/10.1029/2018GL077969

Lejosne, S., & Mozer, F. S. (2016). Typical values of the electric drift $E \times B/B^2$ in the inner radiation belt and slot region as determined from Van Allen Probe measurements. *Journal of Geophysical Research: Space Physics*, *121*, 12,014–12,024. https://doi.org/10.1002/2016JA023613

Lejosne, S., & Mozer, F. S. (2017). Subauroral polarization streams (SAPS) duration as determined from Van Allen Probe successive electric drift measurements. *Geophysical Research Letters*, *44*, 9134–9141. https://doi.org/10.1002/2017GL074985

Lyons, L. R., Nishimura, Y., Gallardo-Lacourt, B., Nicolls, M. J., Chen, S., Hampton, D. L., et al. (2015). Azimuthal flow bursts in the inner plasma sheet and possible connection with SAPS and plasma sheet earthward flow bursts. *Journal of Geophysical Research: Space Physics*, *120*, 5009–5021. https://doi.org/10.1002/2015JA021023

Maimaiti, M., Ruohoniemi, J. M., Baker, J. B. H., & Ribeiro, A. J. (2018). Statistical study of nightside quiet time midlatitude ionospheric convection. *Journal of Geophysical Research: Space Physics*, *123*, 2228–2240. https://doi.org/10.1002/2017JA024903

Maruyama, T., & Nakamura, M. (2007). Conditions for intense ionospheric storms expanding to lower midlatitudes. *Journal of Geophysical Research*, *112*, A05310. https://doi.org/10.1029/2006JA012226

Maruyama, N., Richmond, A. D., Fuller-Rowell, T. J., Codrescu, M. V., Sazykin, S., Toffoletto, F. R., et al. (2005). Interaction between direct penetration and disturbance dynamo electric fields in the storm-time equatorial ionosphere. *Geophysical Research Letters*, *32*, L17105. https://doi.org/10.1029/2005GL023763

Mishin, E., Nishimura, Y., & Foster, J. (2017). SAPS/SAID revisited: A causal relation to the substorm current wedge. *Journal of Geophysical Research: Space Physics*, *122*, 8516–8535. https://doi.org/10.1002/2017JA024263

Murphy, K. R., Mann, I. R., Rae, I. J., Waters, C. L., Frey, H. U., Kale, A., et al. (2013). The detailed spatial structure of field-aligned currents comprising the substorm current wedge. *Journal of Geophysical Research: Space Physics*, *118*, 7714–7727. https://doi.org/10.1002/2013JA018979

Nagano, H., Nishitani, N., & Hori, T. (2015). Occurrence characteristics and lowest speed limit of subauroral polarization stream (SAPS) observed by the superDARN Hokkaido East radar. *Earth, Planets and Space*, *67*(1), 126. https://doi.org/10.1186/s40623-015-0299-7

Nishida, A. (1968). Coherence of geomagnetic DP 2 fluctuations with interplanetary magnetic variations. *Journal of Geophysical Research*, *73*(17), 5549–5559. https://doi.org/10.1029/JA073i017p05549

Prikryl, P., Ghoddousi-Fard, R., Kunduri, B. S. R., Thomas, E. G., Coster, A. J., Jayachandran, P. T., et al. (2013). GPS phase scintillation and proxy index at high latitudes during a moderate geomagnetic storm. *Annales Geophysicae*, *31*(5), 805–816. https://doi.org/10.5194/angeo-31-805-2013

Raeder, J., Cramer, W. D., Jensen, J., Fuller-Rowell, T., Maruyama, N., Toffoletto, F., & Vo, H. (2016). Sub-auroral polarization streams: A complex interaction between the magnetosphere, ionosphere, and thermosphere. *Journal of Physics: Conference Series*, *767*(1), 12021.

Reeves, G. D., Friedel, R. H. W., Larsen, B. A., Skoug, R. M., Funsten, H. O., Claudepierre, S. G., et al. (2016). Energy-dependent dynamics of keV to MeV electrons in the inner zone, outer zone, and slot regions. *Journal of Geophysical Research: Space Physics*, *121*, 397–412. https://doi.org/10.1002/2015JA021569

Richmond, A. D., Blanc, M., Emery, B. A., Wand, R. H., Fejer, B. G., Woodman, R. F., et al. (1980). An empirical model of quiet-day ionospheric electric fields at middle and low latitudes. *Journal of Geophysical Research*, *85*(A9), 4658–4664. https://doi.org/10.1029/JA085iA09p04658

Richmond, A. D., Matsushita, S., & Tarpley, J. D. (1976). On the production mechanism of electric currents and fields in the ionosphere. *Journal of Geophysical Research*, *81*(4), 547–555. https://doi.org/10.1029/JA081i004p00547

Rishbeth, H. (1971). The F-layer dynamo. *Planetary and Space Science*, *19*(2), 263–267. https://doi.org/10.1016/0032-0633(71)90205-4

Ruohoniemi, J. M., & Baker, K. B. (1998). Large-scale imaging of high-latitude convection with super dual auroral radar network HF radar observations. *Journal of Geophysical Research*, *103*(A9), 20,797–20,811. https://doi.org/10.1029/98JA01288

Sazykin, S. (2000). Theoretical studies of penetration of magnetospheric electric fields to the ionosphere (PhD thesis), Utah State University.

Schunk, R. W., Banks, P. M., & Raitt, W. J. (1976). Effects of electric fields and other processes upon the nighttime high-latitude F layer. *Journal of Geophysical Research*, *81*(19), 3271–3282. https://doi.org/10.1029/JA081i019p03271

Senior, C., & Blanc, M. (1984). On the control of magnetospheric convection by the spatial distribution of ionospheric conductivities. *Journal of Geophysical Research*, *89*(A1), 261–284. https://doi.org/10.1029/JA089iA01p00261

Spiro, R. W., Heelis, R. A., & Hanson, W. B. (1979). Rapid subauroral ion drifts observed by Atmosphere Explorer C. *Geophysical Research Letters*, *6*(8), 657–660. https://doi.org/10.1029/GL006i008p00657

Wand, R. H., & Evans, J. V. (1981). Seasonal and magnetic activity variations of ionospheric electric fields over Millstone Hill. *Journal of Geophysical Research*, *86*(A1), 103–118. https://doi.org/10.1029/JA086iA01p00103

Wang, H., & Lühr, H. (2011). The efficiency of mechanisms driving subauroral polarization streams (SAPS). *Annales Geophysicae*, *29*(7), 1277–1286. https://doi.org/10.5194/angeo-29-1277-2011

Wang, H., Lühr, H., & Ma, S. Y. (2012). The relation between subauroral polarization streams, westward ion fluxes, and zonal wind: Seasonal and hemispheric variations. *Journal of Geophysical Research*, *117*, A04323. https://doi.org/10.1029/2011JA017378

Wang, H., Ridley, A. J., Lühr, H., Liemohn, M. W., & Ma, S. Y. (2008). Statistical study of the subauroral polarization stream: Its dependence on the cross-polar cap potential and subauroral conductance. *Journal of Geophysical Research*, *113*, A12311. https://doi.org/10.1029/2008JA013529

Wang, W., Talaat, E. R., Burns, A. G., Emery, B., Hsieh, S.-Y., Lei, J., & Xu, J. (2012). Thermosphere and ionosphere response to subauroral polarization streams (SAPS): Model simulations. *Journal of Geophysical Research*, *117*, A07301. https://doi.org/10.1029/2012JA017656

Wang, H., Zhang, K., Zheng, Z., & Ridley, A. J. (2018). The effect of subauroral polarization streams on the mid-latitude thermospheric disturbance neutral winds: A universal time effect. *Annales Geophysicae*, *36*(2), 509–525. https://doi.org/10.5194/angeo-36-509-2018

Wolf, R., Spiro, R., Sazykin, S., & Toffoletto, F. (2007). How the Earth's inner magnetosphere works: An evolving picture. *Journal of Atmospheric and Solar-Terrestrial Physics*, *69*(3), 288–302. https://doi.org/10.1016/j.jastp.2006.07.026

Yeh, H.-C., Foster, J. C., Rich, F. J., & Swider, W. (1991). Storm time electric field penetration observed at mid-latitude. *Journal of Geophysical Research*, *96*(A4), 5707–5721. https://doi.org/10.1029/90JA02751

Yu, Y., Jordanova, V., Zou, S., Heelis, R., Ruohoniemi, M., & Wygant, J. (2015). Modeling subauroral polarization streams during the 17 March 2013 storm. *Journal of Geophysical Research: Space Physics*, *120*, 1738–1750. https://doi.org/10.1002/2014JA020371

Zhang, S.-R., Erickson, P. J., Foster, J. C., Holt, J. M., Coster, A. J., Makela, J. J., et al. (2015). Thermospheric poleward wind surge at midlatitudes during great storm intervals. *Geophysical Research Letters*, *42*, 5132–5140. https://doi.org/10.1002/2015GL064836

Zou, Y., & Nishitani, N. (2014). Study of mid-latitude ionospheric convection during quiet and disturbed periods using the superDARN Hokkaido radar. *Advances in Space Research*, *54*(3), 473–480. https://doi.org/10.1016/j.asr.2014.01.011