Impact of Flow Bursts in the Auroral Zone on the Ionosphere and Thermosphere

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Abstract High-latitude ionospheric plasma flows often contain embedded localized velocity enhancements with associated plasma density structures. Localized strong flows are significant energy sources to the thermosphere that are not contained in present empirical models of plasma convection. In this study, Global Ionosphere-Thermosphere model, a nonhydrostatic model with flexible resolution, has been utilized to evaluate the influence of such localized strong enhancements of forcing on the global dynamics of the upper atmosphere. Specifically, three idealized configurations of flow burst have been examined, one flow burst with the typical spatial scale seen in the auroral zone, two neighboring flow bursts with the same spatial scale, and one flow burst with doubled spatial scale. The comparison between the cases with and without the flow burst illustrates that one regular-sized flow burst at midnight can cause the neutral density to increase by 5% and the horizontal wind to increase by ~30 m/s at 300 km altitude. The associated enhancement in the electron precipitation can increase total electron content by 15% (1 TECU) during the first 15 min. Two simultaneous flow bursts can cause a rich wave structure with multiple wavelengths in traveling atmospheric disturbances due to wave-wave interactions. A flow burst with doubled spatial size can increase the impact on the ionosphere/thermosphere by 2 times or even more. The outcome of this study illustrates substantial local and nonlocal responses of the ionosphere-thermosphere system to the mesoscale energy and momentum inputs from the magnetosphere.

1. Introduction

Determining the importance and effects of energy deposition, dissipation, and momentum exchange at different spatial and temporal scales is a critical question in the study of the ionosphere-thermosphere (I-T) system. Plasma motions driven by a large-scale two-cell convection pattern (Heelis et al., 1982; Weimer & flexible, 1996) are frequently described by an almost uniform antisunward flow in the center of the polar cap region. However, ion convection flows may often contain embedded localized velocity enhancements, many with elevated plasma number density. A recent significant change in our understanding of the I-T system is the frequent driving by dynamic mesoscale structures (100–500 km), including subauroral polarization electric fields (SAPS), and flow bursts within the cusp, polar cap, and auroral oval. For example, storm-enhanced density and plumes are found to be associated with strong SAPS (Foster et al., 2002), and a premidnight poleward surge in neutral winds has been reported following the large westward winds in a SAPS event (Zhang et al., 2015). Also, the Joule heating and particle precipitation deposited in the cusp are strongly related to the persistent and localized neutral density enhancements around the cusp region (Carlson et al., 2012; Deng et al., 2013). Localized flow channels have been found to be common features within the nightside aurora using the Super Dual Auroral Radar Network (SuperDARN) radar and all-sky imager observations (Gallardo-Lacourt et al., 2014) and within the polar cap using airglow patches and the SuperDARN radar (Zou et al., 2015). The structures with the polar cap region have been found to be important for energy input to the I-T system (Huang et al., 2014). Studies such as these indicate that mesoscale structures play a critical role in overall plasma dynamics within the ionosphere, interacting with the large-scale quasi-static electrodynamic structures, which is more directly driven by interaction with the solar wind. Various properties of mesoscale features have been recognized in different data sets. The statistical properties of mesoscale plasma flows in the nightside high-latitude ionosphere have been characterized using
Nine years of SuperDARN line-of-sight velocity data from the stations at Rankin Inlet and Saskatoon (Gabrielse et al., 2018). Results showed that the typical width of a characteristic equatorward flow perturbation is ∼180 km in the polar cap and ∼140–150 km in the auroral oval and that the mesoscale flows tend to follow the large-scale background convection. Meanwhile, ion drift measurements from the Defense Meteorological Satellite Program (DMSP) F17 satellite were utilized to identify mesoscale flow perturbations with spatial scale sizes between 100 and 500 km in the high-latitude ionosphere (Chen & Heelis, 2018). By appropriately filtering the global signatures of convection from the DMSP satellite observations, the scale sizes, magnitude, and spatial distribution of these mesoscale features were determined. The data analysis suggests that flow perturbation locations strongly depend on the interplanetary magnetic field (IMF) orientation as does their occurrence frequency. The perturbation flow speed is almost independent of their scale size and underlying convection speed, but the largest speeds (>1,000 m/s) are preferentially seen at scale sizes between 200 and 300 km.

The nightside auroral oval is often dominated by mesoscale auroral forms, including auroral poleward boundary intensifications (PBIs; Lyons et al., 2009) and their equatorward extension (auroral streamers; Zesta et al., 2000). Mesoscale flow bursts associated with auroral streamers in the nightside auroral zone have been investigated using ion flow observations from SuperDARN radars and auroral images from the Time History of Events and Macroscale Interactions during Substorms (THEMIS) ground-based all-sky imager array (Gallardo-Lacourt et al., 2014). It was found that flow bursts and streamers are invariably correlated in all the 135 events they studied, and the flow bursts are often directed equatorward and appear simultaneously with the streamers.

The mesoscale structures in aurora and plasma flow are sufficiently large and common that they can be significant mesoscale momentum and energy sources to the thermosphere, and these are not contained in the present empirical models of plasma convection and particle precipitation (Fuller-Rowell & Evans, 1987; Weimer & flexible, 1996). Such localized momentum and energy inputs can significantly impact the thermospheric density and temperature (Carlson et al., Deng et al., 2013). For example, the all-sky imaging and GPS total electron count (TEC) observations show traveling ionospheric disturbances (TIDs) with magnitude of 0.3 TECU driven by auroral oval flow bursts (Lyons et al., 2019). However, those localized and bursty ionospheric signatures and their influence on the upper atmosphere are not considered in global I-T modeling. In this study, we have specified mesoscale flow bursts in the nightside auroral zone in Global Ionosphere-Thermosphere model (GITM) simulations according to the ground-based and satellites observations to quantify their roles in energy and momentum exchange between the ionosphere and the thermosphere. Three different configurations of flow burst have been applied to the GITM simulations to examine the dependence on the spatial size and the number of flow burst. As a result, this study will improve our understanding of I-T system responses to mesoscale energy and momentum inputs.

2. Methodology

The GITM is a three-dimensional spherical code that models the Earth’s thermosphere and ionosphere system using a stretched grid in latitude and altitude (Ridley et al., 2006). It solves for the neutral and ion densities, velocities, and temperatures self-consistently. The most significant differences between GITM and other upper-atmospheric models are the nonhydrostatic solver and the flexible resolution. GITM does not assume a hydrostatic balance in the vertical direction; instead, it solves the vertical momentum equation for neutral species. Relaxing the hydrostatic approximation allows significant vertical winds and acoustic waves to form due to nongravitational forces (Deng et al., 2008a; Deng & Ridley, 2014). Meanwhile, the resolution of GITM is flexible since stretched grids in latitude and altitude are possible and the number of grid points in each direction can be specified. GITM can also be run both globally and regionally. An altitude grid rather than a pressure grid is used for the vertical direction in GITM, which also uses an altitude-dependent gravitational acceleration (Deng et al., 2008b). The nonhydrostatic solver and flexible resolution in GITM makes it an excellent candidate to simulate the transient and mesoscale phenomena, since the system can be more easily deviated from hydrostatic equilibrium over short periods within mesoscale events (Deng et al., 2008a).

GITM simulations for this study are initialized from the Mass Spectrometer Incoherent Scatter model (Hedin, 1983, 1987, 1991) of the neutral atmosphere, and international reference ionosphere model (Bilitza, 2001; Rawer et al., 1978) for the ionosphere with static neutrals. The International Geomagnetic Reference Field magnetic field represented in the APEX coordinate system (Richmond, 1995) is used. GITM can be
coupled to a large number of models of the high-latitude ionospheric drivers. In this study, we use Weimer and flexible (1996) and Fuller-Rowell and Evans (1987) empirical models to specify the electric potential and particle precipitation patterns, respectively, for the idealized conditions. A solar extreme ultraviolet flux model (SERF2) (Tobiska, 1991) has been used to specify the solar extreme ultraviolet irradiance. The inputs into GITM include F10.7, hemispheric power (HP), IMF, and solar wind conditions. The F10.7 index is used to specify the solar ionization and absorption of the atmosphere to the solar irradiation. The HP index is utilized to drive the Fuller-Rowell and Evans (1987) empirical model, which specifies the particle precipitation patterns for GITM. For the case we studied, the HP is equal to 30 GW, and the corresponding average electron energy and flux are 4 keV and 3 mW/m², respectively. The IMF and solar wind conditions drive the Weimer and flexible (1996) model, which specifies the electric potential patterns for GITM. For this particular study, the IMF and solar wind conditions are IMF $B_y = 0$, $B_z = −5$ nT, and $V_x = 400$ km/s and the time is winter solstice. Therefore, the background ion convection around midnight in the auroral zone is mainly in the equatorward direction.

In order to emphasize the influence of a flow burst on the ionosphere/thermosphere, the difference field between the cases with and without a flow burst are shown in all figures. To specify a flow burst in GITM, a perturbation electric potential has been added on top of the background electric potential from the Weimer empirical model. The perturbation potential has two Gaussian distributions in longitude (a negative and a positive potential cell) and a Gaussian distribution in latitude. The electric field is calculated through $E = −AU$ and the plasma drift velocity is decided by the ion momentum equation (Ridley et al., 2006). Above 150 km altitude, $V_i = (E \times B)/B^2$. The perturbation of ion drift in the meridional direction shown in Figure 1 is comparable with the equatorward flow channel in the extreme case (Chen & Heelis, 2018; Lyons et al., 2010). The size of the flow burst pattern is $\sim 200$ km in longitude (the width of equatorward ion flow is $\sim 100$ km and the returning flows on each side is $\sim 50$ km) and 400 km in latitude, as a typical flow channel width in observations (Chen & Heelis, 2018; Gabrielse et al., 2018). To avoid artificial perturbation of electric field at the boundary of the flow burst pattern, we control the shape of the Gaussian distribution through changing the standard deviation and make sure that the perturbation of electric potential goes to zero before reaching the boundary. The observed values of flow bursts from both DMSP (Chen & Heelis, 2018) and SuperDARN (Gallardo-Lacourt et al., 2014; Gabrielse et al., 2018) are related to $V_i$ and $V_i = (E \times B)/B^2 = −(AU \times B)/B^2$. In order to match the observed maximum equatorward flow channel velocity ($\sim 1,000$ m/s) (Chen & Heelis, 2018; Lyons et al., 2010) with the size of $\sim 100$ km, the peak value of the corresponding perturbation in electric potential is close to 2,000 volts. In this way, the resulting perturbation of $V_i$ in GITM simulation is comparable with the observed value of $V_i$ from DMSP and SuperDARN. The specification of the forcing is to mimic the observations of ion drift, which is relatively simple and needs to be improved for precise event studies. Nevertheless, this work is serving as a mechanism study about the influence of mesoscale structures in the electrodynamics on the I-T system, and this simplified specification should be sufficient for this purpose. The accompanying electron precipitation flux is doubled (Gallardo-Lacourt et al., 2014) in the center of the flow burst pattern, overlapping with the equatorward ion flow burst. In this simple representation the electron precipitation is displaced slightly from its expected location ($\sim 50$ km westward of the equatorward flow channel) across the gradient in the plasma flow, but we expect this effect to be small compared to the impact on the thermosphere of the flow itself. In order to resolve the narrow longitudinal structure of plasma flow, the resolution of GITM has been set up as 0.5° in longitude × 2° in latitude. The flow burst lasts for 15 min which represent the upper bound of lifetime of a flow burst according to the statistical studies (Chen & Heelis, 2018; Gabrielse et al., 2018). After 15 min, the enhancement of both convection and particle precipitation is turned off and the electrodynamic forcing goes back to the background large-scale specification.
Figure 2. (top) Difference fields for vertical neutral wind (color contour) and horizontal neutral wind (vector) between the simulations with and without flow burst. (bottom) The same as in the top panel except for the color contour for neutral density (Rho). T = 0 is the onset of flow burst.

3. Results and Discussion

3.1. One Regular-Sized Flow Burst at Midnight

As shown in Figure 1, one flow burst has been added in the aurora zone close to local midnight. The central location of the flow burst is [2330 LT, 65° Lat] in the geographic coordinates. The spatial extent of the equatorward flow in longitude is 100 km and there are poleward returning flows each of 50 km in spatial extent each side. The setup is consistent with Gallardo-Lacourt et al. (2014) and the statistical results based on DMSP and SuperDARN observations (Chen & Heelis, 2018; Gabrielse et al., 2018). While observed less frequently, evidence has been found for two poleward flows to the east and west of the equatorward flow, giving a three-flow structure as illustrated in Gallardo-Lacourt et al. (2014), and the coverage limitations can account for the reason that the poleward flows are observed less often in their study. To focus on the structure of the flow burst, the difference field of ion drift in the meridional direction (positive is north) between the cases with and without the flow burst is shown in Figure 1. In the center of the flow burst, the equatorward ion drift increases by more than 1,000 m/s and the returning poleward flow on two sides is ∼400 m/s, which is comparable to the background large-scale ion drift convection speed. The 900 m/s equatorward flow speed and 15-min life time are larger than the average values for a flow burst but are still within the range of commonly observed values (2–15 min; Chen & Heelis, 2018; Gabrielse et al., 2018; Sergeev et al., 2004). The particle precipitation flux in the center of the flow burst (overlapping with the equatorward ion drift flow) has been doubled without changing the average energy of the precipitating particles.

Figure 2 shows the perturbation in the neutral wind and the neutral density at 5, 15, and 30 min. We pick those three times because 5 min is roughly the length of time needed for an acoustic wave to propagate to 300 km altitude (Deng et al., 2008a), 15 min is the lifetime of the flow burst we add in, and 30 min represents the time without flow burst when the perturbation is mainly related to traveling atmospheric disturbances (TADs) propagating out of the source region after the forcing has been turned off. In the top panel, the vector shows the difference in the horizontal wind and the color contour shows the difference in the vertical wind. The horizontal wind perturbation can reach 30 m/s and propagates out as a TAD even after the flow burst has been turned off at 15 min. The phase speed is ∼800 m/s, which is close to the sound speed at the altitudes displayed. A clear dawn-dusk asymmetry can be identified in the horizontal wind disturbance.
In general, the duskside has larger perturbation with a more complex structure than the dawnside, which may be related to the difference in the Coriolis force at these locations. The vertical wind is upward with magnitude 20 m/s at 300 km altitude at 5 min. However, after the flow burst has been turned off at 15 min, the vertical wind is mainly downward and the perturbation also propagates outward in concert with the perturbation in the horizontal wind. The vertical wind also shows a dawn-dusk asymmetry, with larger perturbation on the duskside than the dawnside. In the bottom panel of Figure 2, the color contour shows the percentage difference in the neutral density at 300 km altitude between the cases with and without the flow burst. After the flow burst is active for 5 min, the neutral density enhancement can reach 5%. The neutral density variation remains positive until the flow burst is turned off at 15 min. A strong negative neutral density perturbation with a magnitude of 4–5% appears at 30 min. Actually, the Joule heating is more than doubled at the center of the flow burst at 15 min due to the enhancement of $V'_{e}$. The neutral density perturbation is primarily driven by the atmosphere upwelling associated with the Joule heating increase and the corresponding gravity waves propagating out of the source region.

In order to separate the effect of ion velocity perturbation and electron precipitation, an additional GITM run has been done with the electron precipitation increase only. The resulting perturbations (not shown) in neutral density (<1%) and horizontal neutral wind (<10 m/s) at 300 km altitude is much smaller than those values (5% and 30 m/s) in the case with both velocity perturbation and electron precipitation. This indicates that the ion velocity perturbation plays a major role in disturbing the thermosphere at 300 km altitude.

Figure 3 shows the perturbation in the electron density at 120 km altitude and in the TEC. As shown in the top panel, the electron density at 120 km increases by almost 50% at 5 min due to the enhanced particle pre-
cipitation flux. However, the electron density disturbance quickly decays when the flow burst and particle precipitation enhancement are turned off at 15 min. It is difficult to identify a noticeable variation in electron density at 30 and 50 min. The TEC perturbation at 5 min is close to 15% (~1 TECU), and goes down to 1–2% (~0.1 TECU) at 30 and 50 min.

Figure 3 illustrates that the electron density responds quite differently before 15 min and after, which can be explained as the consequence of the particle precipitation enhancement and the interaction between TADs and TIDs. Before 15 min, when there is a significant particle precipitation enhancement in the center of flow burst, the E region ion density increases significantly due to the augmented ionization. But the E region ionosphere is close to a chemical equilibrium and the electron density enhancement quickly decays when the enhanced particle precipitation is removed after 15 min. Following the period of the flow burst, the ion density can be strongly influenced by TADs through ion-neutral coupling and exhibits a wave structure, called a TID (Balthazor & Moffett, 1997; Hocke & Schlegel, 1996). TADs are neutral density changes associated with wave features due to the dissipation of energy from particle and Joule heating. Manifestations of TADs in various ionospheric parameters are more commonly observed and referred to as TIDs. While a TAD can be clearly identified in Figure 2, the accompanying TID signal with a magnitude of ~2% can barely visualized after 15 min in Figure 3, which may due to the relatively small neutral density perturbation (5%). However, the signal of TIDs in TEC becomes much clearer when the size of the flow burst is doubled, as shown in section 3.3.

**3.2. Two Simultaneous Flow Bursts**

According to the auroral imaging from Polar UVI instrument (Sergeev et al., 2004), there is a high probability for multiple flow bursts to happen simultaneously in the auroral zone. Therefore, we examined the ionosphere/thermosphere response to two flow bursts separated by 15° in longitude or 1 hr in LT, as shown in Figure 4. Compared with the flow burst shown in Figure 1, an additional flow burst has been added at 2230 LT and 65° Lat. The size and magnitude of both flow bursts are each the same as the one shown in Figure 1.

The top panel of Figure 5 shows the perturbation in neutral density and horizontal neutral winds at 300 km altitude. At 5 min, the disturbance in neutral density and neutral winds is similar to that caused by two individual and independent flow bursts. However, at 15 min, the neutral density enhancement is slightly
larger than that caused by a single flow burst shown in Figure 2, which may be due to the influence of TADs that propagate from the neighboring flow burst. At 30 and 50 min when the flow bursts are no longer active, the neutral density perturbation presents more mesoscale structures than that in the single flow-burst case shown in Figure 2. Meanwhile, the horizontal neutral wind perturbation shown in vector representation presents a rich wave structure with multiple wavelengths produced by the interaction of waves trigged by the two different flow bursts. The bottom panel of Figure 5 shows the percentage difference in TEC, which is similar to Figure 3 except that there are two peaks produced by particle precipitation instead of one at 5 and 15 min. As before the wave signatures in TEC percentage difference at 30 and 50 min are too small to be visualized.

3.3. One Double-Sized Flow Burst

Both ground-based radar observations (Gabrielse et al., 2018) and DMSP satellite observations (Chen & Heelis, 2018) show that the typical scale size of ion flow bursts is 100–200 km and can be up to 400 km. In order to examine the dependence of I-T perturbations on the spatial size of a flow burst, we doubled the spatial size of flow burst shown in Figure 1 in both longitude and latitude. As shown in Figure 6, the extent of this equatorward ion flow is 200 km in longitude. However, the maximum ion drift speed (933 m/s) and the lifetime of flow burst (15 min) are the same as those for a single flow burst in section 3.1.

As shown in the top panel of Figure 7, the neutral density and horizontal neutral wind perturbations become much stronger than those caused by a regular-sized flow burst. The neutral density can increase by 8% at 5 min and still shows a clear enhancement in some regions even at 30 and 50 min. Although Figures 2 and 7 show a similar TAD pattern, the magnitude of the horizontal neutral wind perturbation is up to 100 m/s in Figure 7, which is more than double the perturbation shown in Figure 2. The middle and bottom panels of Figure 7 show the corresponding change in TEC and electron density at 300 km. When the size of flow burst increases, the maximum TEC enhancement is close to 30% at 5 min, most likely due to the enlarged region with enhanced particle precipitation. The electron density at 300 km altitude actually decreases inside the flow burst, which may be explained as the consequence of the atmospheric heating and the increase in the chemical loss rate. At 30 and 50 min, both TEC and electron density at 300 km show a clear signal of TIDs propagating equatorward from the source region. The magnitude can be ~5% in TEC (0.3 TECU) and ~20% in electron density at 300 km altitude, which show a remarkable consistency with the magnitude of TIDs that appear to be driven by auroral oval flow bursts (Lyons et al., 2019).

4. Conclusion

Mesoscale flow bursts associated with enhanced electron precipitation have often been observed to be embedded in the large-scale high-latitude ionospheric convection pattern. The fast flow bursts can reach more than 1,000 m/s with scale sizes of 100–300 km and lifetimes of ~15 min. Such localized strong flows are significant mesoscale momentum and energy sources to the thermosphere that are not contained in present empirical models for electrodynamics in the high latitudes. To evaluate the influence of localized strong enhancements of forcing in the auroral zone on the global dynamics of the I-T system, GITM has been run with resolution of 0.5° Lon × 2° Lat. Specifically, the change of neutral velocity, neutral density, TEC, and electron density for three idealized configurations of flow bursts has been examined closely by comparing the cases with and without the flow burst. Our results reveal that a single flow burst with equatorward flow speed of ~900 m/s over a spatial extent of 100 km in longitude and 400 km in latitude can cause the neutral density and the magnitude of the horizontal wind to increase by 5% and 30 m/s, respectively, at 300 km altitude. A strong dawn-dusk asymmetry can be identified in the perturbation pattern in both neutral density and neutral wind, which may be related to the contribution from the Coriolis force. TEC increases by 15% (~1 TECU) during the first 15 min are produced by the enhancement of electron precipitation associated with the flow burst. A wave structure associated with flow burst persists after the flow event ceases. When two simultaneous neighboring flow bursts are present, a rich spectrum of perturbations persists due to the wave-wave interaction from the two sources. A flow burst with doubled spatial size can increase the impact

![Figure 6. The same as Figure 1, except that the size is doubled in both longitude and latitude.](Image)
on the ionosphere/thermosphere by 2 times or even more. In this case the magnitude of the atmospheric perturbations increases significantly and the TADs produce corresponding significant perturbations in the plasma density that also persist after the flow burst ceases.

Our results indicate that multiple flow burst can strongly increase the mesoscale structures in the I-T perturbation and wider flow bursts can have a more significant influence on I-T. While TID events have been reported in different observations associated with geomagnetic activity changes, our simulations illustrate possible ways that flow bursts can trigger and contribute to the TID events. Certainly, more detailed model-data comparisons for different sizes and distributions of flow bursts should be proved to be interesting in the future for determining the characteristics of flow bursts that are important for TIDs. Such studies should strongly improve our understanding of the I-T response to the locally applied mesoscale energy and momentum inputs from the magnetosphere and how they are redistributed globally by propagating disturbances.

Figure 7. (top) Difference fields for neutral density (color contour) and horizontal neutral wind (vector) between the simulations with and without double-sized flow burst. (middle) Percentage difference of total electron content (TEC) integrated from 100 to 600 km. (bottom) Percentage difference of electron density at 300 km altitude.
Acknowledgments
This research at the University of Texas at Arlington was supported by NASA through Grant NNX14AD46G and AFOSR through Awards FA9550-16-1-0059 and FA9559-16-1-0364. Research at UCLA has been supported by NSF Grant 1401822 and AFOSRFA9559-16-1-0364. The model outputs are available on this website (http://doi.org/10.5281/zenodo.2555518).

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