Mesoscale F Region Neutral Winds Associated With Quasi-steady and Transient Nightside Auroral Forms

Ying Zou1,2, Yukitoshi Nishimura3,4, Larry Lyons4, Mark Conde5, Roger Varney6, Vassilis Angelopoulos2, and Stephen Mende8

1Department of Astronomy and Center for Space Physics, Boston University, Boston, MA, USA, 2Cooperative Programs for the Advancement of Earth System Science, University Corporation for Atmospheric Research, Boulder, CO, USA, 3Department of Electrical and Computer Engineering and Center for Space Sciences, Boston University, Boston, MA, USA, 4Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, CA, USA, 6Department of Physics, University of Alaska Fairbanks, Fairbanks, AK, USA, 5SRI International, Menlo Park, CA, USA, 7Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, CA, USA, 8Space Sciences Laboratory, University of California, Berkeley, CA, USA

Abstract

High-latitude neutral winds often circulate in a two-cell pattern as driven by large-scale auroral forcing. However, auroral forcing also occurs in various types of mesoscale forms (i.e., tens of kilometers in space and a few to tens of minutes in time) and contains more energy input over mesoscale than large scale. A question arises as to whether and how winds respond to the mesoscale forcing. We characterize F region winds associated with various types of auroral forms using scanning Doppler imagers, auroral imagers, and radars. The auroras examined include a quasi-steady east-west elongated arc, a quasi-steady Harang aurora, transient streamers, and a transient substorm westward traveling surge. We find that winds exhibit distinct spatial structures, appearing as channels, vortices, and reversals. Such structures are consistent with the structures of the plasma flows associated with the auroras. Winds exhibit a temporal evolution very similar to the plasma flows and reach maximum perturbations only ~20 min after the flows. The above results suggest that the thermosphere is closely coupled to the ionosphere/magnetosphere through the ion drag force. The ~20-min time scale can be partially explained by the strong ionization effect associated with the auroras and partially by the fact that the wind perturbations do not approach the flow perturbations but halt at ~20% possibly due to momentum forces other than the ion drag.

1. Introduction

High-latitude thermospheric winds are significantly influenced by forcing originating in the magnetosphere. Magnetospheric convection and currents drive plasma convection in the ionosphere, which drives neutral motion through ion-neutral collisions. Frictional heating during collisions modifies neutral pressure gradients, which also change neutral motion. Precipitating auroral particles collide with neutrals, providing another source of neutral heating. We refer to forcing arising from auroral precipitation and the associated electric field as auroral forcing in the current paper. On a large scale, the F region wind field is driven in a two-cell pattern by the Dungey cycle plasma convection (Dungey, 1961). Wind reversal boundaries closely correlate with the auroral oval location (Killeen et al., 1988). As geomagnetic activity increases, the latitudinal extent of wind cells and the wind speed increase (e.g., Förster et al., 2008; Killeen et al., 1995; McCormac et al., 1987). But these changes occur with a time delay on the order of hours (Heelis et al., 2002).

In addition to the large-scale convection, magnetospheric forcing contains spatially localized and temporally variable structures. For example, magnetospheric boundary layers, such as plasma sheet boundary layers, drive azimuthally elongated auroral arcs (Echim et al., 2009). Dawn-dusk asymmetry of plasma sheet content drives a clockwise rotating ionospheric convection, that is, Harang reversal (Erickson et al., 1991). Plasma sheet bursty bulk flows drive roughly north-south aligned auroral streamers (Gallardo-Lacour et al., 2014; Nakamura et al., 2001). Magnetospheric substorms drive westward propagating auroral vortices, that is, westward traveling surges (WTSS) (McPherron et al., 1973). These processes occur over a spatial range of tens to hundreds of kilometers in the ionosphere and evolve at a time scale of a few to tens of minutes, and are classified as mesoscale forcing. Compared with large-scale forcing, mesoscale forcing contains more intense precipitation and convection electric field and thus provides more energy input to neutrals. A question arises as to whether and how winds respond to the mesoscale auroral forcing.
While mesoscale auroral forcing has long been recognized to drive strong mesoscale winds in the $E$ region (Kosch et al., 2010; Walterscheid & Lyons, 1992; Walterscheid et al., 1985), its effect on the $F$ region winds has not been very well known. In the $F$ region ion-neutral collisions are viewed as being infrequent and the wind response time is perceived to be on the order of hours (Baron & Wand, 1983; Killeen et al., 1984; Kosch et al., 2001; Ponthieu et al., 1988), which would preclude wind from reacting to mesoscale forcing. However, observations indicate that mesoscale forcing may in fact be important in the $F$ region. $F$ region neutral winds have been found to be nonuniform over hundreds of kilometers (Aruliah & Griffin, 2001; Aruliah et al., 2005, 2004) using Fabry-Perot interferometers (FPIs). Conventional FPIs have a narrow field of view (FOV) of $4\sim 5$ km (at 250-km altitude) and are rotated through different azimuths to obtain 2-D wind distribution. Scanning Doppler imagers (SDIs) measure winds simultaneously over a wide FOV ($>1,000$ km; Conde & Nicolls, 2010) and serve as a better means of detecting mesoscale structures without the spatial-temporal ambiguity. SDI measurements show that local wind gradients are dominated by shears of zonal winds (Anderson et al., 2012b). The sheared winds have been associated with localized auroras, and when the auroras move, the sheared winds follow (Conde et al., 2001). Wind directions tend to align parallel to auroral arcs (Kosch, Anderson, Makarevich, et al., 2010), although the alignment is less prominent compared to $E$ region winds. Wind directions also agree with plasma convection directions down to scales like the Harang reversal (Kosch, Anderson, Yiu, et al., 2010).

Furthermore, there are indications that the $F$ region wind response time can be much shorter than the traditionally perceived few hour-long response time (Heeils et al., 2002). Aruliah and Griffin (2001) observed a rapid wind speed drop by 150 m/s and a rise within 40 min. Anderson et al. (2011) also reported that winds can be enhanced by 100 m/s within 20 min after an auroral appearance. The ionosphere density can dramatically ($>2\sim 3$ times) increase by particle precipitation (e.g., Marklund et al., 1982; Robinson & Mende, 1990). This combines with the strong electric field of auroral forms could potentially drive winds more efficiently than commonly believed.

The above studies indicate that there indeed is an important response of $F$ region winds to mesoscale auroral forcing. This motivates us to investigate spatial structures and temporal evolution of mesoscale $F$ region winds associated with various specific types of such forcing. Since different types of forcing have different spatial forms, they may drive winds of different properties. We focus on four types of auroral forms: east-west (E-W) elongated arcs, Harang auroras, streamers, and WTSs. E-W arcs and Harang auroras can at times persist $\geq1$ hr, and they allow studying winds under quasi-steady mesoscale forcing. WTSs and streamers often evolve rapidly on a time scale of tens of minutes or even minutes, but we select the relatively slowly evolving ones that persist $>20$ min for studying winds associated with transient mesoscale forcing without time aliasing. The 20-min requirement allows time for winds to show measurable responses (if any) so that the properties of the winds can be compared with those of the auroral forcing.

2. Instruments

We utilize simultaneous neutral wind, aurora, and plasma convection measurements from SDIs, imagers, and radars covering a common area over Alaska. The utilized SDI is located at Poker Flat (PKR, geographic 65.1°N, $\sim147.5$°E), and it observes Doppler shifts in 630.0-nm emissions (Conde & Nicolls, 2010; Conde & Smith, 1995, 1997, 1998). The observed Doppler shifts provide line-of-sight (LOS) velocities of winds at an altitude of 250 km over 1–2 hr in magnetic local time (MLT). The LOS velocities are inverted to horizontal wind vectors by assuming that vertical winds are constant across the FOV and that the zonal gradient of meridional winds is negligible (Conde & Smith, 1998). These assumptions are found to be reasonable even when wind has rapid temporal evolution or strong spatial gradients (Anderson et al., 2012a). The wind vectors have a spatial resolution of $\sim0.3^\circ$ in latitude near the zenith direction and $\sim1^\circ$ near the FOV edge, and a temporal resolution of 1–5 min.

We use the Time History of Events and Macroscale Interactions during Substorms all-sky imagers (ASIs; Mende et al., 2008) to measure auroras. The recorded auroral images are projected onto an altitude of 110 km. We mainly use the Fort Yukon (FYKN, geographic 66.6°N, $\sim145.2$°E) and Gakona stations (GAKO, 62.4°N, $\sim145.2$°E), which have large common FOVs with the PKR SDI. The ASIs have a FOV width of $\sim2$ hr in MLT and a spatial resolution of a few kilometers near the zenith direction. The data have a temporal resolution of 3 s.
We use Poker Flat Incoherent Scatter Radar (PFISR; 65.1°N, −147.5°E) to measure ionospheric convection and density within the SDI FOV. The long pulse mode data are used for F region LOS ion velocity, and the alternating code mode is used for density. LOS velocities in the F region ionosphere (>150 km) can be inverted to convection vectors by assuming that the velocity vectors are homogeneous in the east-west direction across the radar FOV (Heinselman & Nicolls, 2008). We mainly use the velocity vectors to determine the specific speed and the direction of the aurora-related plasma flows and how these parameters change over time. The vectors have a spatial resolution of 0.25° in latitude and have a temporal resolution of −1 min for the studied events. Original LOS velocities are presented in Figure S1 in the supporting information at representative time instants of the studied events. The small FOV of PFISR is somewhat limited in inferring the 2-D flow field. We use the knowledge that plasma flows around a given auroral form have a shear parallel to the auroral structure, as expected from the converging electric field surrounding an upward field-aligned current. This inference is in general consistent with PFISR observations as seen in section 3.

We require simultaneous operation of the SDI, ASIs, and PFISR. E-W arcs are identified as azimuthally extended (>2 hr in MLT) arcs and Harang auroras as hook-shaped features opening to the west (Nishimura et al., 2010). We select E-W arcs and Harang auroras that last ≥1 hr in order to be considered as quasi-steady aurora. WTSSs are identified as the westernmost part of the auroral surges and auroral streamers as north-south aligned or oblique arcs that propagate equatorward from the poleward portion of the auroral oval. We select WTSSs and streamers that maintain their vortex or equatorward propagating motion for ≥20 min, respectively. Data during the 2012–2013 winter months have been surveyed, and 4 to 10 events have been identified for each type of the auroral forms. Most of these auroral forms occurred in the premidnight sector, and the winds associated with each auroral type exhibit similar spatial and temporal characteristics. We focus on events with clear, isolated auroras located near the center of the SDI FOV in the premidnight sector and present representative wind perturbations below.

3. Observations

3.1. Mesoscale Wind Associated With a Quasi-Steady E-W Arc

Figure 1 presents F region neutral wind before and during an E-W arc brightening in the premidnight sector (magnetic midnight around 1100 UT) on 1 March 2012. The red arrows represent horizontal velocity vectors of neutral wind and the cyan arrows represent the velocity vectors of plasma flow. The velocity scales are shown on the top right of Figure 1a, different scales being selected for the flow and the wind for this event. Before the E-W arc occurred (Figure 1a), only some very faint auroras were visible at 67–68° magnetic latitude (MLAT). The wind speed was <50 m/s below 66° MLAT, increased with latitude between 66° and 68° MLAT and reached >150 m/s in the westward direction above 68° MLAT. This wind shear was likely due to the wind at >66° MLAT being dragged by the westward plasma convection within the duskside auroral oval via ion-neutral collision.

As the arc brightened at 67–68° MLAT, the plasma flow near and just equatorward of it became substantially enhanced in the westward direction (Figure 1b). This is expected as E-W arcs in the premidnight sector are known to be associated with enhanced poleward electric field and enhanced westward plasma flow (illustrated by the dashed cyan arrow) just equatorward of the arcs (e.g., Aikio et al., 2002). The wind was also enhanced in the westward direction around and just equatorward of the arc, as expected from acceleration by the flow. This wind reached ~300 m/s as the auroral forcing continued (Figures 1c and 1d). This speed was larger than the wind poleward and far equatorward of the arc, suggesting that a fast and latitudinally narrow wind channel had formed around the arc latitude. This event suggests that the wind field associated with E-W arcs can develop latitudinally narrow, but longitudinally extended, channels of fast wind.

Figures 2a–2e present the time evolution of the auroral activity, the plasma flow, and the neutral wind along the central longitude of the imager FOVs of the Figure 1 event. The flow is divided into the northward and the eastward component in Figures 2b and 2d, respectively. The total flow vectors are superimposed on each component. The wind measurements are presented in the same way in Figures 2c and 2e. The vertical dashed lines mark the times corresponding to Figures 1a–1d. The E-W arc emerged at 0524 UT and stayed quasi-steady for ~1 hr (Figure 2a). In association with the arc, the plasma flow (observed near and equatorward
of the arc) promptly increased to $>\sim 1,000$ m/s in the westward direction (Figure 2b). The change in the neutral wind speed was less sharp, but it started roughly simultaneously with the plasma flow (Figure 2c). The wind was most strongly enhanced at and just equatorward of the arc latitude, resulting in a strong westward wind channel $\sim 3^\circ$ wide in magnetic latitude. The enhanced wind did not show any signature of propagation from the edge of the FOV and should thus be locally driven. It should be noted that we classify the auroral arc and the associated forcing as quasi-steady because of their prolonged presence. But the magnitude of forcing can still have detailed variations. For example, the arc here exhibited variations in brightness by hundreds of count/s and location by 1–2$^\circ$ in latitude, and the enhanced plasma flow fluctuated by hundreds of meter per second over time. These variations may possibly be important for understanding wind dynamics as discussed in section 4. The north-south velocity was a minor component throughout the interval of our interest (Figures 2d and 2e).

We quantify how rapidly the wind responded to the auroral forcing by using time delays between the plasma flow and the neutral wind of their maximum perturbations. The maximum perturbation is defined as the first local peak of the eastward velocity component. As will be seen later, the eastward component is the major component of the perturbation associated with the auroras studied in this paper. A precise determination of the maximum perturbation is subject to measurement errors, and the uncertainty is given by those data points whose error bars overlap with that of the maximum perturbation. We use only data points before the maximum perturbation, because the perturbation can stay elevated for some time after reaching the maximum. The measurement errors of the PFISR flow measurements are available in

Figure 1. (a–d) Snapshots showing auroras (gray scale), neutral wind (red arrows), and plasma flow (cyan arrows) before and during the presence of an E-W arc in the altitude adjusted corrected geomagnetic coordinates. The red arrows represent the horizontal velocity vectors of neutral wind (extending from each dot), and the cyan arrows represent the velocity vectors of plasma flow (extending from the radar central meridian). The arrow directions give the velocity direction, and the arrow length gives the velocity magnitude. The dashed cyan arrow represents the expected enhancements in flows associated with the auroral arc.
the PFISR data product, and we use 20 m/s as the error of SDI wind measurements (Dhadly et al., 2015). Figure 2f shows a comparison of the eastward velocity component of the plasma flow and the neutral wind at 67.3° MLAT (still along the central longitude of their common FOVs). This latitude is selected because the wind speed peaked around this latitude, and simultaneous measurements of plasma and neutrals were available (as marked by the dotted magenta lines in Figures 2b–2e). Other latitudes give similar results (Figure S2).

Figure 2. (a–e) Evolution of the auroral activity, the eastward plasma flow and neutral wind, and the northward plasma flow and neutral wind as a function of time and latitude at the FOV central longitude. Overlaid in Figures 2b and 2d are the same total flow vectors downsampled to a temporal resolution of 5–6 min. Overlaid in Figures 2c and 2e are the same wind vectors downsampled to a temporal resolution of 5–6 min. (f) Comparison of the eastward velocity component of the plasma flow (black) and the neutral wind (red) at 67.3° MLAT. The time when the flow/wind reached its maximum perturbation is shaded in black/red.
The flow had gradual and small amplitude variations before 0513 UT, likely associated with the weak auroral activity preceding the E-W arc. From 0513 UT the flow started to accelerate rapidly westward and at 0531 UT it reached its maximum velocity. The time of maximum perturbation considering the measurement errors is associated with an uncertainty range of 0528–0531 UT. Following the maximum perturbation, the flow experienced a second peak at 0555 UT after which the flow perturbation decreased to ~900 m/s until 0630 UT, the end of the time interval of our interest. The initial wind response occurred roughly simultaneously with the flow although a definitive determination of the initial response is obscured by the background variations that were always present. The maximum wind perturbation occurred at 0553 UT and is associated with an uncertainty range of 0546–0554 UT (shaded in red). The wind maximum perturbation is therefore 22, or 15–26 min if considering the uncertainties, delayed relative to the flow. The wind experienced a second peak at ~0610 UT (also seen in other latitudes in Figure S2a) after which the wind perturbation decayed. This wind evolution trend is very similar to, although smoother than, the flow. Between the initial and the maximum perturbations, the plasma gained 950 m/s in the westward component of the velocity. The neutrals gained 180 m/s, which is 19% of that of the plasma. Such a difference between the plasma and the neutral velocity is likely due to the balance with momentum sources other than the ion drag force as discussed in section 4. Mannucci et al. (2018) discussed that the difference can be expressed as a relative momentum exchange between ions and neutrals (denoted as the electric field in the ion rest frame).

3.2. Mesoscale Wind Associated With a Quasi-Steady Harang Aurora

Figure 3 presents neutral wind associated with a Harang aurora on 17 March 2013. Before the Harang aurora occurred (Figure 3a), the bright discrete auroras were limited to >70° MLAT. Diffuse and faint auroral emissions extended down to ~66° MLAT (also seen in Figure 4a). The bright spot circled in black at 66° MLAT to the west of the center of the imager FOV was due to moonlight contamination. The plasma flow collocated with the diffuse auroras was directed westward, but it decreased in magnitude toward low latitudes,
indicating that the radar was located near the equatorward edge of the auroral oval. The wind at the aurora latitude had a southwest velocity of ~50 m/s, and those below the auroras were near zero. A hook-shaped aurora emerged at >67° MLAT as a Harang aurora (Figure 3b). The aurora was part of the Harang reversal, which developed across 20–01 MLT. The extension of the Harang to ~20-hr MLT, away from the magnetic midnight, was likely due to the elevated geomagnetic activity (Kp = 7). Nielsen and Greenwald (1979) suggested that as geomagnetic activity increases the Harang is displaced toward early MLTs. The plasma flow showed a clockwise shear around the Harang aurora. This is consistent with the 2-D plasma flow pattern inferred from the shape of the Harang aurora, rotating clockwise from southeastward to southward and to westward direction (dashed cyan arrow). The wind >67° MLAT started to rotate toward

Figure 4. (a–e) Evolution of the auroral activity, the eastward plasma flow and neutral wind, and the northward plasma flow and neutral wind. (f) Comparison of the eastward velocity component of the plasma flow (black) and the neutral wind (red) at 68° MLAT.
the southeast, possibly driven by the southeast flow. The wind at 65°–67° MLAT increased slightly in the southward direction and that <65° MLAT remained small.

As the Harang aurora continued (Figure 3c), the clockwise shear in the plasma flow persisted. While at this moment the measured flow was not part of the enhanced flow to the west of the auroral structure, the sense of the flow rotation was consistent with that of the enhanced flow (dashed cyan arrow). The neutral wind around the aurora became increasingly large in the southeast direction, while that equatorward of the aurora remained weak. This wind shear became progressively pronounced over time, and its location shifted equatorward as the Harang aurora moved equatorward (Figure 3d). The wind eventually evolved into a clockwise vortex, the shape being similar to that of the Harang aurora. However, the wind vectors were not exactly parallel to the aurora structure but turned their directions less sharply than the structure or the plasma flow. This may imply that the wind shear was partially sustained by pressure gradient and the Coriolis force in addition to the ion drag. The pressure gradient term is expected to be directed away from the auroral structure and the Coriolis force directed perpendicular to the wind vectors toward the wind vortex/auroral hook center.

Figure 4 presents the time evolution of the Harang aurora event. The Harang aurora started at 0640 UT and persisted for ~1 hr (Figure 4a). It was associated with a southeast enhancement in the plasma flow and the neutral wind (Figures 4b–4e). The flow enhancement occurred in two steps for the studied event: the eastward flow component first increased to ~200 m/s during 0648–0710 UT and then rose to >400 m/s during 0710–0721 UT (Figure 4b). The wind enhancement also occurred in two steps. The eastward wind component first increased to ~50 m/s and then >150 m/s (Figure 4c). The two-step evolution seems to be associated with the evolution of the Harang aurora where the optical intensity (e.g., the poleward portion of the hook) and the plasma flow increased during the period of 0710–0725 UT.

The wind showed a sharp latitudinal shear, which was centered at 67° MLAT at 0650 UT, moved equatorward with time, and reached 63° MLAT around 0705 UT (Figures 4c and 4e). This shear separated the wind collocated with the Harang aurora from the wind located equatorward as seen in the 2-D snapshots, and the motion of the shear was very similar to the equatorward motion of the Harang aurora (Figure 4a, delineated by the yellow dotted line). The motion is much faster than the wind velocity (a speed of 100 m/s in the southwest direction in Figure 4e would only result in a propagation of 1.2° in 20 min), suggesting that the sheared wind was driven locally.

Figure 4f shows a comparison of the plasma flow and the neutral wind speed in the eastward direction at 68° MLAT. The flow started to increase at 0637 UT and reached its maximum velocity at 0719 UT. The timing of the flow reaching the maximum perturbation lies within 0717–0719 UT. The flow maintained its large velocity for 2 min and then decelerated, in association with the disappearance of Harang aurora. The wind started to increase nearly simultaneously with the flow and reached maximum perturbation at 0725 or 0720–0726 UT considering the observational uncertainties. The wind measurements in this event had relatively low temporal resolution (3 min) and this has also contributed to the uncertainty range of the time reaching the maximum perturbation. The wind decelerated from 0729 UT, imitating the flow evolution trend. The wind evolution was thus 6 or 1–9 min delayed relative to that of the flow. Such a time scale is much shorter than the typically perceived ~1- to 2-hr-long response time constant (Killeen et al., 1984; Kosch et al., 2001; Ponthieu et al., 1988). The prompt responses to auroras are likely due to the strong ionization effect of the auroras (see discussion in section 4). The total eastward velocity gain was 1,600 and 380 m/s for the plasma flow and the neutral wind, respectively, the gain of neutrals being 24% of that of plasma.

### 3.3. Mesoscale Wind Associated With Transient Auroral Streamers

Figure 5 presents neutral wind associated with auroral streamers on 10 October 2012. Before the streamers occurred, the auroral oval was filled with patchy auroral structures propagating westward. The wind was directed eastward poleward of the most intense aurora and rotated to southwestward equatorward of the auroral oval. This pattern changed as the streamers appeared. Streamers are north-south aligned or oblique arcs that propagate equatorward from the poleward portion of the auroral oval, and they are known to be associated with channels of fast southward plasma flow adjacent to, and aligned with, the streamers (e.g., Gallardo-Lacourt et al., 2014). The streamers in this event extended southeastward with time, and they should therefore be associated with fast southeast directed flows (illustrated by the dashed cyan arrow). This would introduce an obliquely oriented ion drag force to the otherwise east-west directed forcing background (e.g.,
sunward plasma convection and day-night temperature difference). Interestingly, the wind field well responded to this ion drag. As the streamer extended to 67° MLAT (Figure 5b), the wind at 67° MLAT just to the east of the streamer intensified in the southeast direction. The wind <67° MLAT had little change until a few minutes later when the streamer extended to 65° MLAT (Figure 5c). At that time, the wind at 65° MLAT intensified. This streamer disappeared but a second, although somewhat faint, streamer occurred. The second streamer extended all the way to 63° MLAT (Figure 5d), and upon its arrival, the wind at 63° MLAT started to intensify. The wind was strongest just to the east of the streamer, where the streamer-related plasma flow channel tends to be located. This event suggests that the wind field associated with auroral streamers is composed of channels of fast wind that are aligned with and propagate together with the streamers.

Figure 6 shows the time evolution of this event. The streamers started at 0855 UT and continued until 0925 UT. The plasma flow showed an increase in the southeast direction, the same direction as the orientation of the streamers. Despite the transient nature of the streamers, the neutral wind exhibited an evolution surprisingly similar to the streamer and the associated flow. The wind was enhanced in the southeast direction, with the eastward component about twice as large as the southward component, consistent with the oblique streamer orientation. The enhancement started from high latitudes and progressed to low latitudes (very clearly seen in Figure 6c). The progression speed is very similar to the streamer propagation speed, indicating that the enhanced wind was locally driven by the streamers, rather than propagating from elsewhere. As a function of magnetic longitude (not shown), the velocities were spatially strongest near the central FOV just eastward of the streamers and had a width of 8° in magnetic longitude, which was twice that of the streamer width. The difference between the wind perturbation and the auroral width is likely associated with the flow channel width rather than mapping uncertainties as they both were measured near the zenith.
The plasma flow showed a sharp and brief increase in the westward direction during 0850–0859 UT in association with a rapidly westward propagating auroral structure. This flow increase, however, lacked clear correspondences in the wind. We attribute the reason partially to the short duration of the flow increase (only 10 min long) and partially to the weaker ion-neutral coupling associated with the faint auroral patches than with the streamers (see discussion in section 4).

Comparing the eastward component of the wind velocities with the flow velocities at the same latitude (Figure 6f), we find that the wind showed an acceleration from 0900 UT, essentially simultaneously with the aurora and the plasma flow. (The variations before 0900 UT were of small magnitude and are likely due to the nonquiet auroral activity preceding the streamer.) The wind reached the maximum

Figure 6. (a–e) Evolution of the auroral activity, the eastward plasma flow and neutral wind, the northward plasma flow and neutral wind. (f) Comparison of the eastward velocity component of the plasma flow (black) and the neutral wind (red) at 67.3° MLAT.
perturbation at 0915 or 0907–0916 UT if considering the observational uncertainties. After reaching the maximum perturbation, the wind velocity remained elevated with a gradual falloff. The wind response is 14 or 5–15 min later than the flow, which again indicates a rapid response. The uncertainty range of the wind response is asymmetric because the wind evolved more slowly and had a larger uncertainty in time of reaching its maximum perturbation than did the flow. For interested readers, we have compared the southward component of the wind and the flow in Figure S2 and a similar relation has been found. The total eastward velocity gain was 730 m/s (discarding the velocity change during 0850–0859 UT) and 150 m/s for the plasma flow and the neutral wind, respectively, the gain of neutrals being 21% of that of plasma.

3.4. Mesoscale Wind Associated With a Transient WTS

Figure 7 presents neutral wind associated with a WTS on 10 October 2012. Before the WTS approached the Alaska longitudes (Figure 7a), the auroras mostly consisted of E-W arcs centered at 65–66° MLAT. The wind field was directed westward, with the strongest velocity near the arc latitude similar to what we saw in section 3.1. As the WTS approached from the east, the plasma flow redirected to the east (Figures 7b and 7c). This is consistent with a clockwise flow vortex pattern at the leading edge of the WTS (magenta arrow in Figure 7c; Oppennooth et al., 1983). Similarly, the initially westward directed neutral wind at >66° MLAT decreased to zero (Figure 7b) and then increased in the eastward direction (Figure 7c). This resulted in a sharp wind reversal at 66° MLAT between the wind at the same latitude as the WTS and that equatorward. As the WTS propagated across the FOV, the eastward directed flow and wind turned westward with a small poleward component (Figure 7d). This event suggests that the wind pattern ahead of WTSs consists of a wind reversal while the pattern inside WTSs constitutes westward wind.

Figure 8 shows the time evolution of the WTS event. While the WTS did not arrive until 0540 UT, the flow and the wind ahead of the WTS started to change 40 min before the arrival of the WTS. The flow started to
accelerate eastward after 0500 UT, reached >200 m/s at 0517 UT, and remained quasi-steady for ~20 min until turning westward again in association with pass of the WTS. This flow variation, although in total only 40 min long, was closely followed by the wind. The wind at the same latitude as the flow started to accelerate nearly simultaneously with the flow and reached maximum perturbation only 11 or 3–15 min later than the flow. The eastward velocity gain was 1,150 and 190 m/s for the plasma flow and the neutral wind, respectively, the gain of neutrals being 17% of that of plasma.

As the WTS passed across the FOVs, the flow redirected westward at 0540 UT and reached 500 m/s in the westward direction at 0542 UT. The wind again responded instantaneously to the flow and reached maximum westward speed only 10 or 7–13 min later than the flow. The westward velocity gain was 970 and

Figure 8. (a–e) Evolution of the auroral activity, the eastward plasma flow and neutral wind, and the northward plasma flow and neutral wind. (f) Comparison of the eastward velocity component of the plasma flow (black) and the neutral wind (red) at 67° MLAT.
180 m/s for the plasma flow and the neutral wind, respectively, the gain of neutrals being 19% of that of plasma.

4. Discussion

The events above show that wind fields have large spatial gradients and rapid temporal evolution around auroral forms. In particular, the winds reached the maximum perturbations only <~20 min later than the plasma flows, much faster than the time scales reported in the literature (Heelis et al., 2002; Killeen et al., 1984; Kosch et al., 2001). We examine whether an efficient ion-neutral coupling can explain such wind behavior, since the wind evolution is tightly related to the flow evolution.

Assuming that the wind is at a steady state before the auroral forcing starts to operate, the state is described as follows:

\[
\rho_n \frac{\partial V_n}{\partial t} = -\rho_n (V_n \nabla) V_n + \rho_n \nu_{ni} (V_{io} - V_n) - \nabla P - \rho_n f_{coriolis} = 0
\]  

(1)

where \(\rho_n\) is the neutral mass density, \(V_n\) and \(V_i\) are the neutral and ion velocities, \(\nu_{ni}\) is the neutral-ion collision frequency, \(P\) is the neutral pressure, and \(f_{coriolis}\) is the Coriolis force. Subscript \(o\) denotes the initial state, which was presumably steady. Associated with the auroral forcing, the plasma flow abruptly increases to \(V_{aurora}\), and the wind starts to evolve according to

\[
\rho_n \frac{\partial V_n}{\partial t} = -\rho_n (V_n \nabla) V_n + \rho_n \nu_{ni} (V_{aurora} - V_n) - \nabla P - \rho_n f_{coriolis}
\]  

(2)

The observations suggest that the wind evolution was very similar to the flow, as expected from being predominantly driven by the ion drag. We therefore assume that the momentum advection, pressure gradient, and Coriolis force do not vary significantly from the initial state. Combining (1) and (2) results in

\[
\frac{\partial V_n}{\partial t} = \nu_{ni} (V_{aurora} - V_n) - \nu_{ni} (V_{io} - V_n)
\]  

(3)

\[
V_n - V_{no} = \left( V_{aurora} - V_{io} \right) + \frac{V_{aurora} - V_{io}}{\nu_{ni}} (V_{io} - V_{no}) \left( 1 - e^{-\nu_{ni}t} \right)
\]  

(4)

The above equation suggests that the wind perturbation does not exponentially approach the flow perturbation. Instead, it approaches a velocity that additionally depends on the difference between the flow and the wind at the initial state and the collision frequencies with and without the presence of auroral forms. The e-folding time taken for the neutrals to approach such a velocity is (Baron & Wand, 1983)

\[
\tau_{ni} = \frac{1}{\nu_{ni}} = \frac{\rho_n}{\rho_i \nu_{ni}}
\]  

(5)

where \(\tau_{ni}\) is the e-folding time, \(\nu_{ni}\) is the ion-neutral collision frequency, and \(\rho_i\) is the ion mass density. We can determine the magnitude of the time constant by obtaining the plasma density, ion composition, and ion-neutral collision frequency from the PFISR measurements and the neutral density from the Mass Spectrometer and Incoherent Scatter model-00 (Picone et al., 2002). We expect that most of the uncertainty of \(\tau\) comes from the ion composition coming from the PFISR measurements and the neutral density from the Mass Spectrometer and Incoherent Scatter model. The ion composition is calculated based on Richards and Voglozin (2011) where the calculation may have uncertainties up to 30%. The uncertainty of the neutral density in our studied events cannot be easily quantified. We use the streamer and the Harang aurora events shown as examples to calculate the ion-neutral coupling time and to compare with the observed response time because the auroras in these two events extended into the PFISR zenith.

Figures 9a and 9b present the auroral activity and the electron density of the streamer event. The electron density was measured along the zenith direction as a function of altitude at 65.5° MLAT (Figure 9b). We mark this latitude as the white line in Figure 9a and the time when the streamer activity extended to this latitude as the orange bar below Figure 9a. The altitudinal profile of the calculated ion-neutral coupling time constant is
presented in Figure 9c. When no auroral streamers but only diffuse auroras were present at 65.5° MLAT, the F region plasma density was \( \sim 1 \times 10^{11} \text{ m}^{-3} \) and the time constant was \( \sim 120 \text{ min} \) at 250 km. This time constant was similar to the time constants reported by Killeen et al. (1984) and Kosch et al. (2001). Winds with such time constant cannot follow transient flow variations like the one preceding the streamer (0850–0859 UT). Instead, they need a prolonged forcing to show any sizeable perturbation. When the streamer activity commenced and extended to 65.5° MLAT, the F region density increased to \( \sim 2.0 \times 10^{11} \text{ m}^{-3} \) and the time constant dropped to \( \sim 60 \text{ min} \). Such a drop in the time scale indicates that the ionization associated with the streamers can facilitate ion-neutral coupling to a strong level. When the streamer activity faded, the density and the time constant returned to their initial values.

Figures 9d–9f present the Harang aurora event. Associated with the Harang aurora, the F region plasma density increased from \( \sim 1 \times 10^{11} \) to \( \sim 6 \times 10^{11} \text{ m}^{-3} \) and the time constant decreased from \( \sim 200 \text{ to } \sim 30 \text{ min} \). The 30-min time constant is half of that of the streamer event. Whether the difference can be attributed to the type of the auroral forms is an interesting question, but this would require a thorough investigation of whether and how the ionization depends on the type of the auroras. It is also possible that the ionization is associated with geomagnetic condition, where stronger ionization occurs under more active conditions. The Harang aurora occurred when \( Kp = 7 \)– while the streamer \( Kp = 2 \). Nevertheless, the strong coupling only occurred locally around the auroral forms and during the auroras’ presence and can be missed if observations only focus on the large-scale wind distribution/evolution. Similarly, if modeling does not include precipitation consistently with plasma flows, the ion-neutral coupling time scale stays long and the fast wind response cannot be reproduced. Thus, a coherent treatment of precipitation and plasma flows is critical for accurately understanding ion-neutral coupling. (Strictly speaking, plasma flows are expected to be enhanced adjacent to the auroral ionization region, but PFISR velocity vectors do not have a sufficiently high resolution to differentiate the displacement. It is also possible that the dynamic motion of the auroras can cause the ionization at F region to spread wider than the instantaneous auroral width.)

However, the \( \sim 60 \text{ min} \) (for the streamer event) or \( \sim 30 \text{ min} \) (for the Harang event) time constant is still longer than the observed response time (\( [5, 15] \text{ min} \) for the streamer and \( [1–9] \text{ min} \) for the Harang aurora). This could be due to uncertainties associated with the ion composition, the plasma density (as the radar beam may have missed the strongest ionization), the ion-neutral collision frequency, or their combinations. Another probable reason may arise from possible other forces that prevent the observed wind perturbations from advancing to their new steady state predicted by equation (4). Instead, wind perturbations halt at 20%
of the flow perturbation. For the streamer event, \((V_{\text{aurora}} - V_i) = 730 \text{ m/s}, \frac{\nu_{ni}}{C_0} = 0.5, (V_{io} - V_{no}) = -360 \text{ m/s},\) and \(\nu_{ni} = 1/60 \text{ (min}^{-1}\text{)}. The wind evolution expressed in (4) becomes

\[
V_n - V_{no} = 550 \left(1 - e^{-\frac{t}{\tau_{ni}}}\right) \text{ (m/s)}
\]  

The time it takes to reach a wind perturbation of 150 m/s (i.e., the maximum wind perturbation observed in section 3.3) is

\[
t = -\frac{\ln(1 - 150/550)}{\nu_{ni}} = 0.32\tau_{ni}
\]  

which gives a response time of \(\sim 19\) min, comparable to the observation. For the Harang aurora event, \((V_{\text{aurora}} - V_i) = 1,600 \text{ m/s}, \frac{\nu_{ni}}{C_0} = 0.85, (V_{io} - V_{no}) = -820 \text{ m/s},\) and \(\nu_{ni} = 1/30 \text{ (min}^{-1}\text{)}. The wind evolution expressed in (4) becomes

\[
V_n - V_{no} = 900 \left(1 - e^{-\frac{t}{\tau_{ni}}}\right) \text{ (m/s)}
\]  

The time it takes to reach a wind perturbation of 380 m/s (i.e., the maximum wind perturbation observed in section 3.2) is

\[
t = -\frac{\ln(1 - 380/900)}{\nu_{ni}} = 0.55\tau_{ni}
\]  

which gives a response time of \(\sim 16\) min, closer to the observational result than 30-min time constant. The 20% relative magnitude of the wind perturbation to the flow perturbation is common for the few events studied here, and it could be partially due to the variable nature of the auroral forms and plasma flow on mesoscale. For example, even during the long-lasting E-W arc and Harang aurora, the auroral brightness and the flow speed and direction can vary considerably over a few to tens of minutes, well shorter than the e-folding time. Effects by the momentum advection, pressure gradient, Coriolis, and viscosity may also possibly limit the growth of the wind perturbation. Therefore the e-folding time constant describes a hypothetical state that is unlikely reachable for winds at mesoscale and may not be applied directly to realistic wind evolution.

Winds associated with auroral forms are of great importance. The combined effect of the enhanced ion-neutral collisions and the enhanced plasma flows can drive F region winds to a large speed at mesoscales. The enhanced plasma flow velocity increases the magnitude of momentum change of neutrals upon ion-neutral collisions, and the enhanced collisions increase the rate of momentum change. For the streamer-related wind, we consider two conditions where auroras only introduced enhanced collisions versus where auroras only introduced enhanced flows. The magnitude of the resultant ion drag force in the former condition was about twice as large as the latter condition. The mesoscale wind speed often deviates from the large-scale background winds by 200–300 m/s and should thus have a significant contribution to transport of momentum and energy of the high-latitude thermosphere. These winds can also feed back to the auroral forcing, since large-scale winds are known to have large influences on ionospheric electrodynamics and the M-I coupling efficiency (Lu et al., 1995) and mesoscale winds have larger speed and more dynamic variation than large-scale ones (Lyons & Walterscheid, 1986).

5. Summary

While auroral forcing has been acknowledged to affect neutral winds in the E-region, its effects in the F region have not been very well explored. We have identified and determined characteristics of mesoscale F region winds associated with various types of auroral forms/ionospheric flows. The examined auroras include E-W arcs, Harang auroras, substorm WTS, and streamers, all being common and representative in the nightside auroral oval under various geomagnetic conditions.

Winds exhibit distinct spatial distributions. The wind field consists of latitudinally narrow channels of fast winds around E-W arcs, clockwise wind vortices around Harang auroras, longitudinally narrow and
propagating channels of fast winds around streamers, and reversed winds ahead of WTSs. Such distributions are consistent with the distributions of the plasma flows associated with the auroral forms. Winds exhibit a temporal evolution very similar to the plasma flows and reach maximum perturbations only \( <\sim -20 \) min lagged behind the plasma flows. Such a time lag is similar to the findings of Aruliah and Griffin (2001) and Anderson et al. (2011). The prompt response can be partially explained by the strong ionization effect associated with the auroral forms and partially by the fact that the wind perturbations cannot approach the flow perturbations but halt at \( \sim 20\% \) of the flow perturbations. The results suggest that neutral winds are more structured and responsive than commonly perceived and that the thermosphere is closely coupled to the ionosphere/magnetosphere at mesoscale. The results have provided observational properties that can be used for future modeling studies in evaluating the M-I-T interaction at mesoscale.

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