Mid-Latitude Neutral Wind Responses to Sub-Auroral Polarization Streams

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Abstract. We investigate the response of the mid-latitude thermospheric neutral winds to a sub-auroral polarization stream (SAPS) event. Using red-line (F-region) airglow data from two Fabry-Perot interferometers (FPIs), and F-region ionospheric flow velocities from four Super Dual Auroral Radar Network (SuperDARN) radars, the drivers behind changes seen in the neutral winds are explored within the context of the larger SAPS structure. Different, although strong, neutral wind responses

5 to the SAPS are seen at the two FPI sites, even though they are relatively close geographically. We attribute the wind differences to the varying balance of pressure gradient, ion-drag, and Coriolis forces, which ultimately depend on proximity to the SAPS. At the FPI site equatorward of the SAPS, pressure-gradient and Coriolis forces drive the winds equatorward and then westward. At the FPI site co-located with the SAPS, ion-drag is strong and results in the winds surging westward, before turning eastward when becoming influenced by dawnside sunward plasma convection drifts.

1 Introduction

Thermospheric neutral winds are highly susceptible to ionospheric dynamics at Earth. This is particularly true in the high-latitude regions, where strong plasma drifts driven by coupling to the magnetosphere and the solar wind are often present. The study of ion-neutral coupling is very important in the field of space weather, as it directly relates to how energy from the solar wind is deposited into the upper atmosphere. It has also been a challenge, however, as measurements of the neutral wind can

15 be difficult to obtain on large scales. Analysis of neutral winds in the context of geomagnetic activity has thus often relied on measurements within limited regions, statistics, and modelling (Meriwether, 2006; Billett and McWilliams, 2021).

At geomagnetic mid-latitudes ($\sim$30-60°), disturbance winds (i.e., deviations from quiet-time diurnal and seasonal variations) are commonly observed during times of high geomagnetic activity. These events occur when typically high-latitude (>60°) ionospheric dynamics impinge on lower latitudes, such as when the polar cap expands or during substorms (Cowley and

20 Lockwood, 1992; Walach and Grocott, 2019). The winds at these locations are primarily disturbed by a combination of 3 forces: the pressure gradient force from thermospheric expansion due to Joule heating, the ion-drag force due to collisions with fast

moving plasma, and the rotational Coriolis force, which acts in response to winds generated by the previous forces. A common feature of mid-latitude storm-time winds, in response to higher latitude activity for example, is a pressure-gradient-driven equatorward surge followed by a westward Coriolis-driven-turning (e.g., Makela et al., 2014). By contrast, neutrals in the direct

25   vicinity of ionospheric drifts are driven strongly by ion-drag, which acts in the direction of the drifts (Deng and Ridley, 2006). The Coriolis force can additionally act on ion-drag driven winds, turning them poleward if they are initially flowing westward (Zhang et al., 2015). The balance of forces driving disturbance winds is thus quite complicated and highly dependent on factors such as geographic location and proximity to the ionospheric disturbance. Altitude within the thermosphere/ionosphere system is also a factor, as the ion-neutral collision frequency is a function of the neutral and electron densities (Billett et al., 2020b).

30   Sub-auroral polarization steams (SAPS; Foster and Burke, 2002) are an ionospheric phenomenon unique to mid-latitudes. They are characterised by channels of strong westward plasma drifts slightly equatorward of the nightside auroral oval, a few degrees of latitude wide. SAPS are notably separate from the high-latitude plasma convection, but still strongly correlated with the occurrence and strength of geomagnetic storms (Huang and Foster, 2007). They are driven by poleward directed electric fields thought to be produced in the low-conductivity trough region in response to charge separation in the magnetospheric ring

35   current (Southwood and Wolf, 1978). Sub-auroral ion drifts (SAID), latitudinally narrow ($\sim 1°$) and very fast (several $\mathrm{km\,s^{-1}}$) plasma flow channels, are also sometimes seen embedded within SAPS (Anderson et al., 2001).

In this study, we present observations of F-region neutral winds from two mid-latitude Fabry-Perot Interferometers (FPIs) located in the continental USA, in conjunction with a SAPS event observed by high-frequency (HF) radars in the Super Dual Auroral Radar Network (SuperDARN). The event presented is very unique, in that the SAPS were observed independently

40   across the fields-of-view (FOVs) of 4 mid-latitude SuperDARN radars and that the FPIFPIss both observed strong, but quite different, neutral wind responses. We examine the potential drivers behind the behaviour of the FPI winds, whilst taking into account the larger-scale context of the ionospheric plasma, provided by the SuperDARN radars.

2   Data

Plasma velocity data in this study is primarily obtained from four mid-latitude radars that are part of the SuperDARN (Green-

45   wald et al., 1995; Chisham et al., 2007; Nishitani et al., 2019). SuperDARN radars measure the line-of-sight (LOS) doppler velocity of ionospheric magnetic field-aligned irregularities from a backscattered HF signal. The FOVs of the four Super-DARN radars used for LOS plasma velocities in this study, located at Fort Hays West, Fort Hays East, Blackstone and Wallops in the continental USA, are shown in Figure 1. The FOVs of the radars encompass a large swath of the geomagnetic mid-latitudes across North America (below $60°$ Altitude-adjusted corrected geomagnetic (AACGM; Shepherd, 2014) latitude), a

50   region which is almost always "sub-auroral", depending on geomagnetic activity level. Due to the geometry of HF propagation through the ionosphere and the requirement that the signal be perpendicular to the geomagnetic field lines for Bragg reflection to occur, measurements beyond slant rages of $\sim 800\,\mathrm{km}$ are typically considered to be located at F-region altitudes (Thomas and Shepherd, 2018). Although, far range echoes may still potentially be from E-region scatter depending on factors that can affect ionospheric conductivity gradients, such as seasonal or diurnal trends (Chisham and Pinnock, 2002). The spatio-temporal
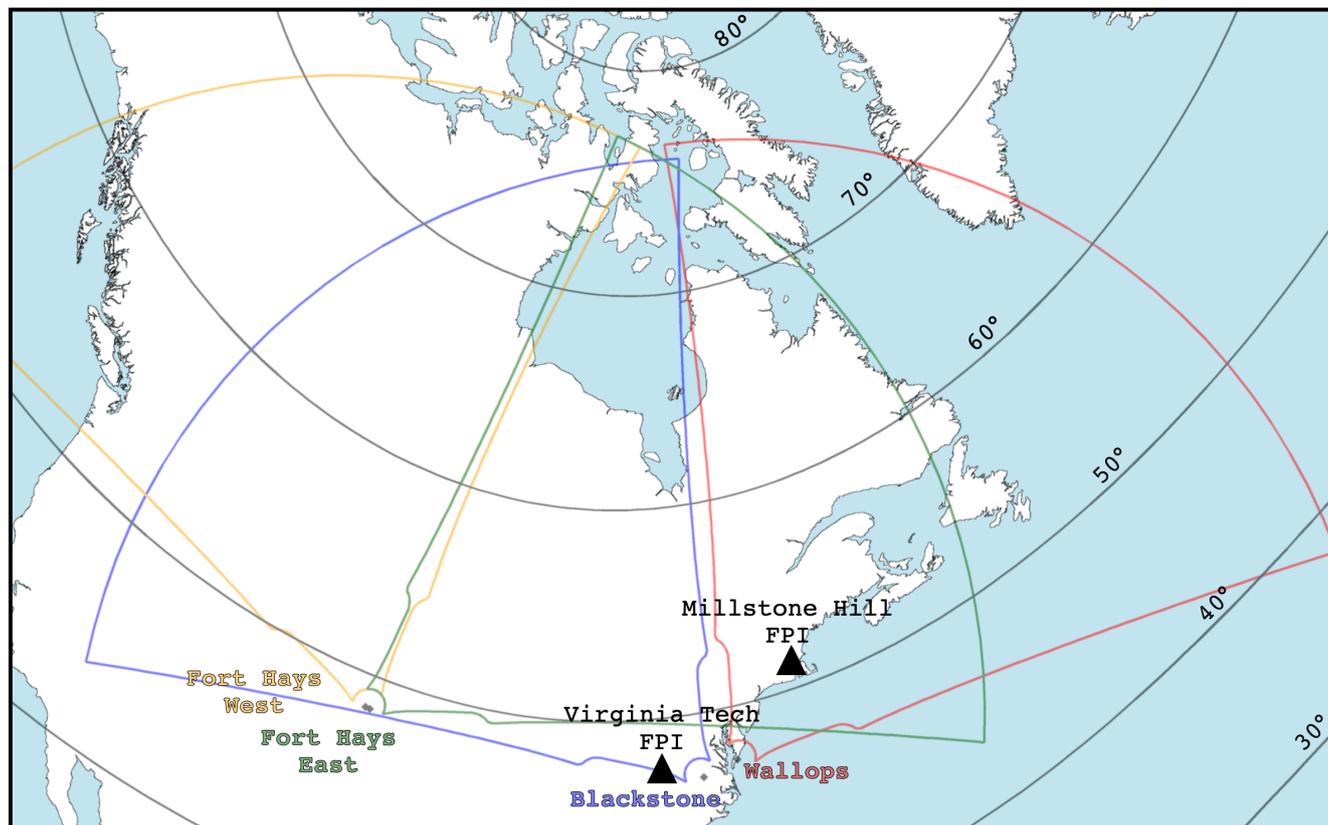
Figure 1. The fields of view of the Fort Hays West, Fort Hays East, Blackstone and Wallops SuperDARN radars, up to range gate 75 (each gate being 45 km wide). Also shown are the locations of two FPIs (black triangles), one at Millstone Hill Geospace Facility and the other at Virginia Tech (November 2013). Black lines indicate parallels of constant AACGM latitude.

resolution of the radars depends on the scan mode employed, but typically (which is the case in this study), a 1-minute scan time with 45 km range gates is used. The mid-latitude SuperDARN radars are excellent at making observations of SAPS due to their wide FOVs and fast sampling rates, and have been used in several previous studies for plasma velocity information (e.g. Oksavik et al., 2006; Kataoka et al., 2007; Clausen et al., 2012; Kunduri et al., 2018)

In addition to SuperDARN radar LOS velocity measurements, we also utilise the 'map potential' technique whereby velocities from all available radars in the northern hemisphere are combined to generate a fitted pattern of the high-latitude electric potential, otherwise known as a convection pattern (Ruohoniemi and Baker, 1998). In short, a global electric potential (Φ) best fit to the SuperDARN radar LOS velocities is derived, where the parameters are associated with each other through the relations $\mathbf{v} = \frac{\mathbf{E} \times \mathbf{B}}{B^2}$ and $\mathbf{E} = -\nabla \Phi$. $\mathbf{E}$, $\mathbf{B}$ and $\mathbf{v}$ are the electric field, magnetic field and convection velocity, respectively. Best-fit plasma velocities can then be obtained at an arbitrary location within the bounds of the convection pattern, which are used later in the manuscript to obtain the average velocity over a specific spatial area coinciding with the SAPS region. The fitted SuperDARN

electric potential (where equipotentials are equivalent to plasma velocity streamlines) is a hemispheric spherical harmonic fit, resulting in velocities at a certain location being inherently coupled to data gathered elsewhere in the hemisphere. Although, because the data coverage for the four aforementioned radars is good for the event described in this study, the SAPS region of interest is well constrained by the fit and thus will capture changes in the SAPS velocity. A caveat of using the SuperDARN

70 fitted plasma velocities is that plasma drifts associated with SAPS will be fitted together with drifts associated with the large scale ionospheric convection pattern. This will potentially result in an underestimation of the fitted SAPS velocity, because SAPS at mid-latitudes and the large scale convection at higher latitudes are driven by inherently different processes, causing them to be decoupled. We minimise this source of error by later averaging the fitted velocities in the sub-auroral region only, but cannot fully eliminate it.

75 Also shown in Figure 1 are the locations of the FPIs used in this study (black triangles), situated at the Millstone Hill Geospace Facility (MH; Kerr et al., 2017; Kerr, 2022) and Virginia Tech university campus (VTI; Makela et al., 2011, 2012; Harding et al., 2014). Both FPIs observe the 'red-line' 630 nm $O(^1D)$ nightglow/auroral emission, which is used to estimate the neutral wind LOS Doppler velocity in four cardinal directions (North, South, East and West, geographically) at a zenith of $\sim 45°$. Clear and dark skies are required for good data, which were both the case during the event presented in this study.

80 To obtain horizontal winds from the LOS Doppler velocities, it is assumed that both the vertical wind is negligible and that it remains constant across the FPI FOV, thus allowing for the wind to be resolved in the horizontal plane. Finally, the horizontal wind components are transformed from a geographic coordinate system to an AACGM coordinate system using the 2D rotation matrix transformation:

$$\mathbf{v}' = R\mathbf{v} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} v_{zonal} \\ v_{meridional} \end{bmatrix} \tag{1}$$

85 where $\mathbf{v}$ and $\mathbf{v}'$ are the original and transformed wind vectors, respectively. R is the rotation matrix given by the left set of square brackets, where θ is the angle subtended by the great circle lines connecting the location of the FPI to the geographic and AACGM poles. The rotation into a magnetic reference frame requires pairing a meridional ($v_{meridional}$; North or South) measurement with a zonal (v_{zonal}; East or West) one. This is because the FPI measures the wind sequentially in the four cardinal directions, and a complete vector is required to carry out the transformation. For clarity, all mentions of latitude/longitude and

90 zonal/meridional velocities going forward refer to those in an AACGM reference frame. The integration time in each cardinal direction for the MH data is 3 minutes and the average fit uncertainty for the 136 LOS measurements used in this study is $0.9\,\mathrm{ms}^{-1}$. Meridional and zonal wind uncertainties sum the North/South and East/West LOS errors respectively, producing an average velocity uncertainty of $1.8\,\mathrm{ms}^{-1}$ at MH. At VTI the integration time is dynamic (up to 300s) achieving an average LOS uncertainty of $8.6\,\mathrm{ms}^{-1}$ for the 204 LOS measurements used here. The corresponding average uncertainty for the meridional

95 and zonal velocities at VTI is $17.1\,\mathrm{ms}^{-1}$

3 Results and Discussion

3.1 Case Study: November 9th 2013

An overview of a SAPS event is shown in Figure 2. The disturbance storm time (Dst) index for the event is shown in Figure 2[a], which indicates that the "main phase" of geomagnetic storm began at ∼03:30 UT on November 9th 2013 and ended at ∼09:00 UT the same day (grey shaded region). The peak Dst minimum was -80 nT, which would classify the event as a "moderate" storm (Loewe and Prölss, 1997). The interplanetary magnetic field (IMF) B_z component (GSM coordinates) is shown in Figure 2[b], which stays almost entirely negative from ∼02:00 UT onwards on November 9th.

Also shown in Figure 2 are range-time-velocity plots along specific beams of four mid-latitude SuperDARN radars: Fort Hays West, Fort Hays East, Blackstone and Wallops. There is a diagram at the bottom of Figure 2 showing the relevant beam geometries in AACGM coordinates. The zonal (east-west) looking beams with the most ionospheric backscatter were chosen. Fort Hays West beam 10 and Blackstone beam 8 point westward, whilst Fort Hays East beam 7 and Wallops beam 6 point eastward. There were radar operating mode changes to using a different frequency at 00:00 UT on November 9th for Wallops and Blackstone, which caused a change in the propagation path of the radar beam and an apparent "shift" in ground scatter location at those times. Similar mode changes occurred at Fort Hays East (01:00 UT) and at Fort Hays West (02:00 UT). The changes act to modify the HF beam propagation through the ionosphere, causing it to refract and hit the ground/ionosphere at different range gates.

At the beginning of the geomagnetic storm main phase (03:30-06:00 UT), North America was located in the pre-midnight dusk sector and all radars observed westward ionospheric flow enhancements, between range gates 15 and 45. Based on the radar beam geometry, these ranges vary between 50 and 60 degrees geomagnetic latitude. The westward flows are most prominent in the Fort Hays West and East observations (Figure 2[c] and [d]), where they reach approximately $300 ms^{-1}$. Before the storm, at around 02:00 UT, strong flows at far ranges/higher-latitudes (range gates >60, 65-70° geomagnetic latitude) were observed by the Fort Hays West and East radars. The high latitude flows appear detached from those seen at a lower latitude later on, which could indicate the distinction between high-latitude convection and SAPS. Additional low-latitude westward plasma flows can be seen from 07:00 UT till roughly the end of the storm main phase, which are strongest in the Blackstone data (Figure 2[e]). From ∼11:00 UT, eastward flows are seen by both Fort Hays East and West, which could be observation of the dawnside ionospheric convection return flow.

Meridional and zonal neutral wind velocity data from the VTI and MH FPIs are shown as red lines in Figure 3, which are averaged from the north/south and east/west FPI look directions, respectively. The blue lines with diamonds are the "quiet-time" neutral wind velocities obtained from the Horizontal Wind Model 2014 (HWM14; Drob et al., 2015) at the location of the FPIs, using an Ap index of 0 as geomagnetic activity input. We classify the difference between the FPI data and the HWM14 quiet-time curve as the disturbance neutral wind, i.e. the deviation from normal (non-geomagnetically enhanced) diurnal variations.

The VTI (Figure 3[a] and [b]) meridional velocity closely follows the quiet time curve before 02:00 UT, whilst the zonal velocity is offset by around $50 \, ms^{-1}$ westward (but follows a similar trend). Before the storm at MH (Figure 3[c] and [d]),
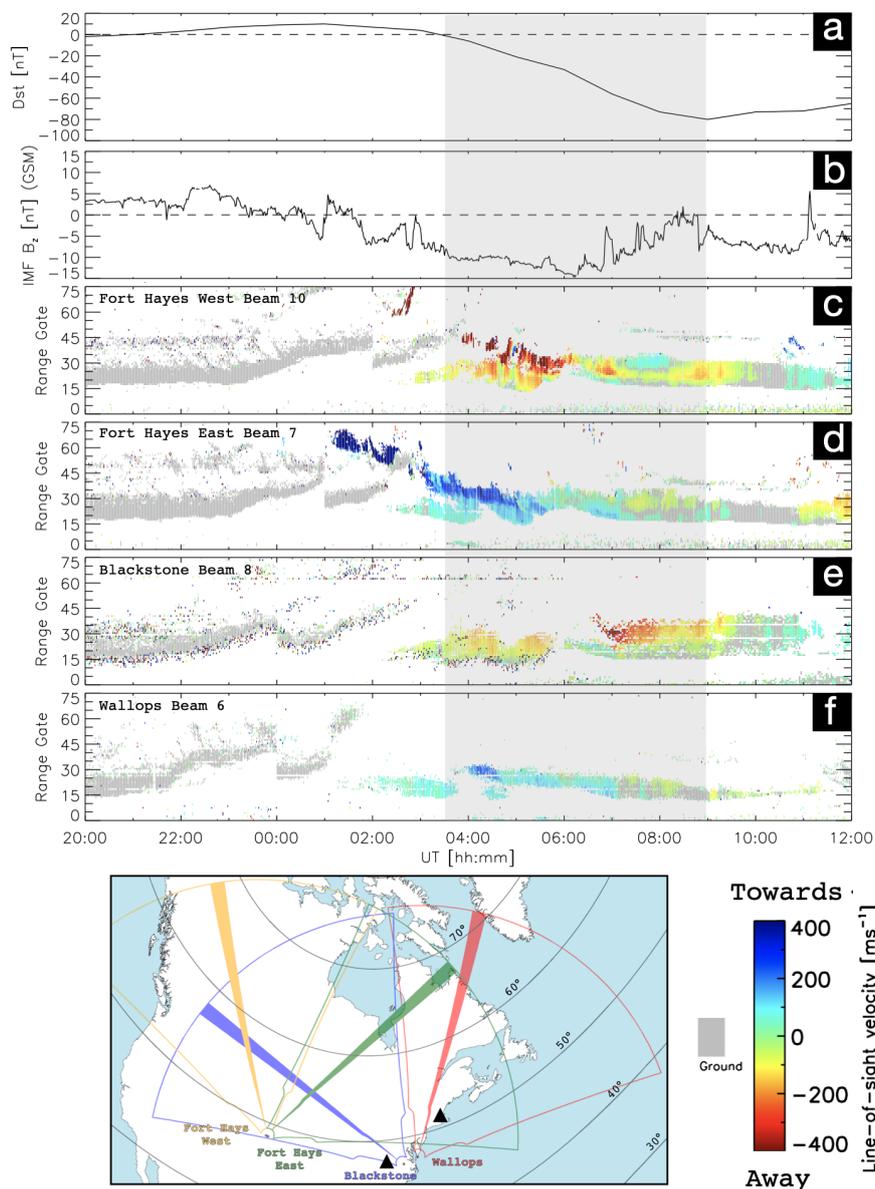
Figure 2. SAPS event overview, starting at the 20:00 on November 8th and ending at 12:00 November 9th, 2013. [a] Disturbance storm time (Dst) index. [b]: IMF B_z in geocentric solar magnetospheric coordinates (GSM). [c,d,e,f]: Range-time plots of the LOS plasma velocity from beams 10, 7, 8 and 6 of the Fort Hays West, Fort Hays East, Blackstone and Wallops SuperDARN radars, respectively. Blue indicates plasma moving towards the radar site, whilst red means away. Grey indicates data that has been flagged as ground scatter. The diagram at the bottom shows the orientations of the chosen beams for [c,d,e,f]. The grey shaded region is the geomagnetic storm "main phase", as dictated by the Dst index.
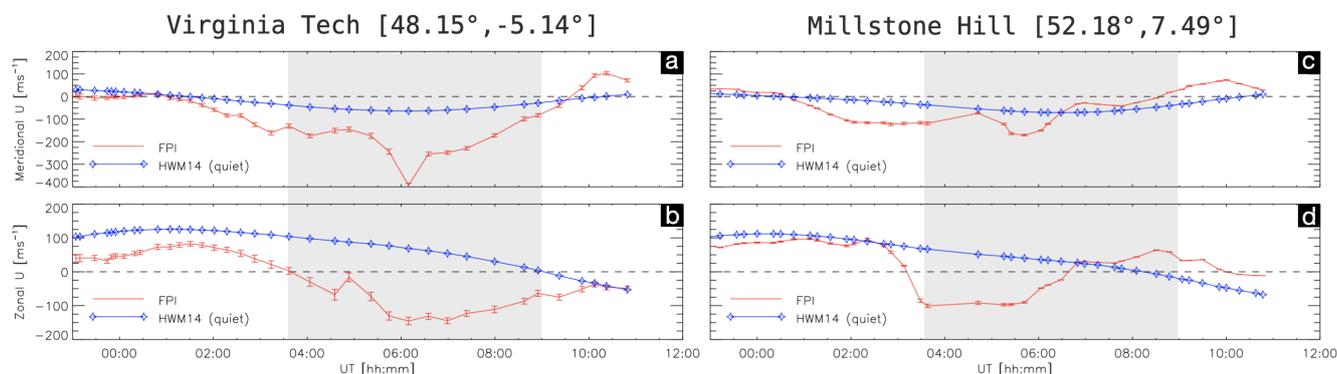
Figure 3. Timeseries of neutral wind zonal [a,c] and meridional [b,d] velocities, at the locations of the VTI [a,b] and MH [c,d] FPIs starting at the 20:00 on November 8th and ending at 12:00 November 9th, 2013. Red lines are velocities from the FPIs with error bar uncertainties, whilst blue lines with diamonds are the quiet-time curve from the HWM14. The grey shaded region is the geomagnetic storm main phase, also shown in Figure 2. Positive values are poleward and eastward for the meridional and zonal data, respectively.

130   the zonal winds closely follow the quiet-time curve, whilst the meridional winds become disturbed by around $100\,\mathrm{ms}^{-1}$ equatorward at 02:00 UT. Both FPIs observed significant disturbance winds slightly before and during the storm main phase: the peak disturbance meridional and zonal velocities were $330\,\mathrm{ms}^{-1}$ equatorward and $215\,\mathrm{ms}^{-1}$ westward at VTI, whilst they were $100\,\mathrm{ms}^{-1}$ equatorward and $165\,\mathrm{ms}^{-1}$ westward at MH. After the storm main phase, winds observed at both FPIs returned approximately to quiet-time velocities, however, the data recordings ended at 11:00 when the skies were no longer dark enough

135   for the FPI to work.

The large wind excursions equatorward and westward, as seen by the VTI FPI, are commonly seen disturbance wind features (e.g. Yagi and Dyson, 1985; Fejer et al., 2002; Makela et al., 2014; Sivla and McCreadie, 2014; Joshi et al., 2015). Energy is deposited into the ionosphere-thermosphere system via either high-latitude convection or SAPS, which then drives the thermospheric heating and an equatorward pressure gradient force (Rishbeth et al., 1987). A westward wind then develops

140   due to a westward directed Coriolis force on the equatorward winds. At the MH FPI, there is much smaller equatorward wind disturbance, but a much more sudden westward wind enhancement. This could mean that that MH measured winds are directly in the path of the westward plasma flows seen in Figure 2, thus experiencing the ion-drag force westward, in a manner similar to the strong ion-neutral coupling seen at higher latitudes (e.g. Förster et al., 2008; Billett et al., 2020a). Westward mid-latitude winds directly driven by SAPS ion-drag have also been seen by Zhang et al. (2015), which could additionally explain the

145   decrease in equatorward wind velocity at MH during the storm main phase (as the Coriolis force would act poleward).

To assess the neutral winds in context with the enhanced plasma velocities, Figure 4 shows a series of nightside-only polar plots from just before till the end of the storm main phase, with the SuperDARN and FPI disturbance data overlain. The plots are in a AACGM latitude-magnetic local time coordinate system and show the radar/FPI locations moving from the pre-midnight to post-midnight MLT sector. The equatorward boundary of the auroral oval is also drawn as a red circle, which was
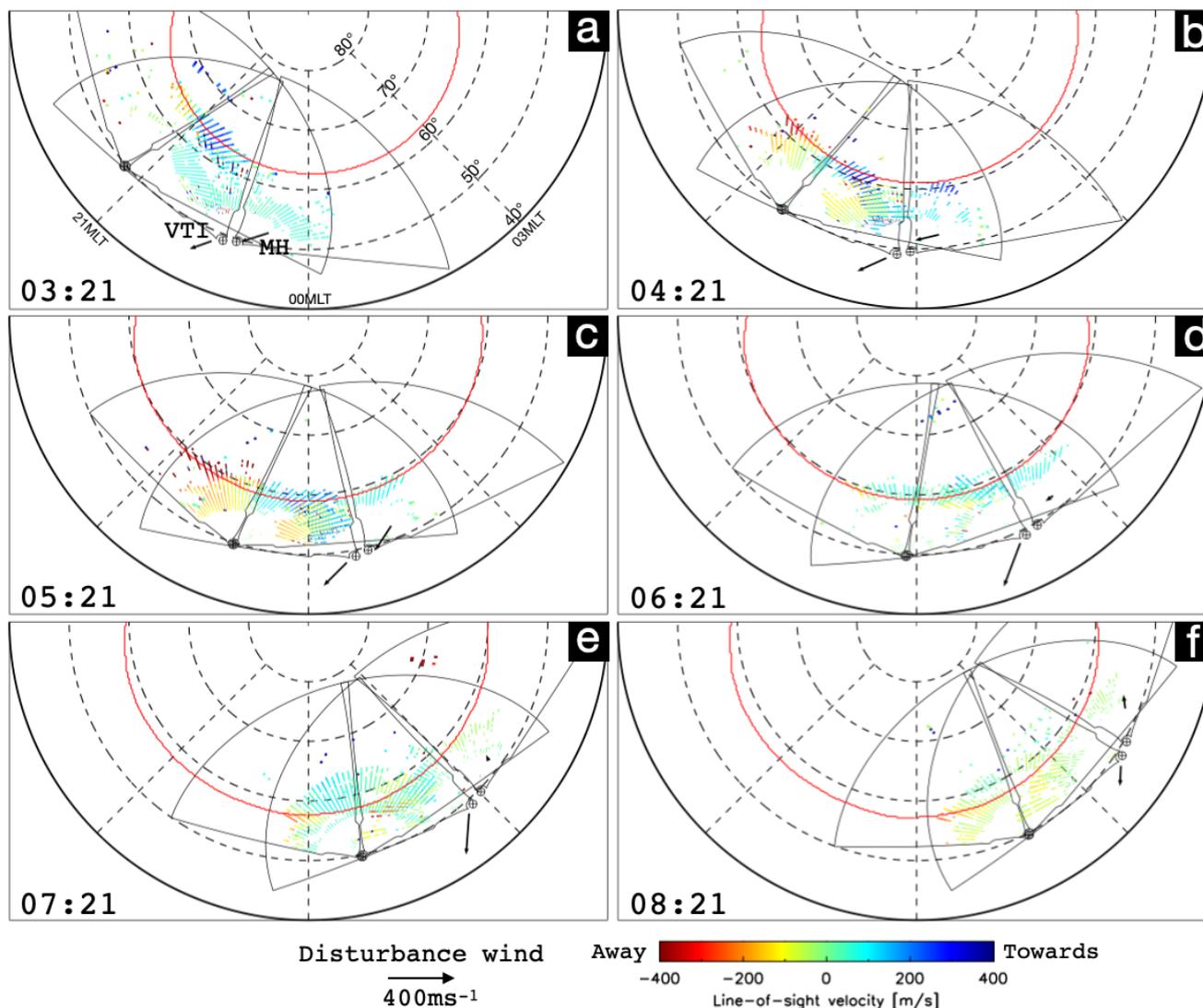
Figure 4. Nightside polar plots of plasma velocity data from four SuperDARN radars, as well as disturbance neutral wind velocity vectors from the VTI and MH FPIs (black arrows) for times on November 9th, 2013. The red circle is the approximate location of the auroral oval lower-latitude boundary, derived from SSUSI data onboard whichever DMSP satellite (F-16, F-17 or F18) last crossed the pole. Six times are shown 1 hour apart each, the coordinate system is AACGM latitude-magnetic local time and the concentric dashed lines separate 10° of latitude. Data in each SuperDARN radar beam has been made thinner to help show which radar it was measured by, and thus the LOS direction. The VTI FPI is the arrow with a base at a slightly lower latitude, compared to the MH FPI.

150   derived from the previous polar pass of the Spectral Sensor Ultraviolet Spectrographic Imager (SSUSI; Paxton et al., 2002; Ding et al., 2017) instrument onboard the Defence Meteorological Satellite Program (DMSP) F-16, F-17 and F18 satellites.

The SSUSI equatorward auroral oval boundary gives an indication of which SuperDARN detected flows are "sub-auroral", and thus potentially SAPS. Throughout the times shown in Figure 4, the equatorward auroral oval boundary consistently expands to lower latitudes. This is an indication of polar cap expansion and follows from the consistently southward IMF B_z during
155 those times (Figure 2b). The auroral oval typically expands during geomagnetic storms (Craven and Frank, 1987), and is offset from the high-latitude convection by a few degrees of latitude (Imber et al., 2013).

Based on the SSUSI equatorward auroral oval boundaries, there is clear indication that a large portion of the SuperDARN measured plasma flows are sub-auroral and westward orientated. These flows are most intense in Figure 4[b] and [c] (04:21 and 05:21), where all the radars measure sub-auroral westward plasma flows on the order of 200-400 ms^{-1}. Based on statistics
160 of SuperDARN data from the Hokkaido East radar, Nagano et al. (2015) notes that the lower velocity limit of SAPS which distinguishes them from mid-latitude F-region ionospheric echoes is between 150 and 200 ms^{-1}. We therefore classify the measured sub-auroral flows during this event as relatively low-magnitude SAPS. There does not appear to be high-velocity SAID embedded within the SAPS. Near the end of the storm main phase (Figure 4[f], 08:21), the equatorward auroral oval boundary is at 57° latitude (at midnight MLT), and the SAPS have mostly subsided to 100 ms^{-1} or less. The SAPS velocity
165 decrease is expected as the radar FOVs move into to the post-midnight dawn sector, as fast SAPS are usually longitudinally constrained to pre-midnight local times (Clausen et al., 2012; Landry and Anderson, 2018; Zhang et al., 2021). We note that although plasma flows were not observed by the SuperDARN radars directly over MH, that does not necessarily mean no flows exists there. This is due to backscatter only being possible where the radar signals hit ionospheric irregularities perpendicularly. Due to a lack of coverage, we also cannot entirely rule out the potential for plasma flows above VTI.

170 The disturbance neutral wind vectors (measured winds from the FPIs with the quiet-time curve from the HWM14 subtracted) are also shown in Figure 4. Between 03:21 and 05:21, when the SAPS flows are most intense, both FPIs observe wind disturbances south-westward. At 06:21, the VTI FPI (lower latitude arrow) observes a large equatorward disturbance, whilst the MH disturbance winds (higher latitude arrow) decrease to near quiet-time levels. Assuming the wind disturbances at VTI and MH are due to the aforementioned pressure gradient forces and ion-drag, respectively, then the differences between them
175 could possibly be due to their location with respect to the SAPS. As the VTI measurement is at a consistently lower latitude than the SAPS, then the large equatorward enhancement at 06:21 could be due to the delay in the pressure gradient force wave front propagation from higher latitudes, generated by heating from earlier SAPS. The disturbance winds measured at MH, conversely, do not appear to be strongly delayed in their response to the SAPS subsiding. As the MH winds are at a latitude closer to that of the SAPS, they may be more directly susceptible to ion-drag forcing from the plasma. Indeed, previous studies
180 have shown that ion-drag is likely the dominant force acting on the neutrals within the SAPS region, versus pressure gradient or Coriolis forces (Ferdousi et al., 2019; Zou et al., 2022). There is still a delay between plasma acceleration/deceleration becoming apparent in the neutral winds, but it would be a function of the ion-neutral collision frequency and usually varies significantly (Billett et al., 2019; Aa et al., 2021).

In addition to single vector wind measurements from the MH and VTI FPIs, horizontal wind fields from the North American
185 Thermosphere Ionosphere Observing Network (NATION; Makela et al., 2012) of FPIs were available for the night of event. The full process by which the horizontal wind field is derived is described by Harding et al. (2015), however in short, a

regularization-based technique is employed to fit the measured neutral winds from NATION FPIs to the smoothest possible structure. During storm-times however, and indeed as shown by the VTI and MH measurements in Figure 3, the neutral winds become inherently structured due to sharp ion-drag and pressure gradients. Similarly to the VTI and MH data, an

190 assumption is also made that the vertical wind is negligible and constant across the fitting region, which is probably inaccurate and contributes to the uncertainty of the wind field. When compounded with an average uncertainty of $\sim$20 ms^{-1} for each NATION FPI during this event, the uncertainty in the derived wind field becomes significant (potentially around 100 ms^{-1} in some regions). However, the field is still useful to obtain a general idea of the mesoscale neutral wind direction across North America, appreciating that the uncertainty during this event is probably too high to resolve wind structures between the FPI

195 locations. We therefore include a video of the NATION derived wind in supplementary material S1, between 23:30 UT on the 8th and 11 UT on the 9th of November, 2013. The coordinate system in S1 is geographic and black dots indicate FOV observation directions from 5 NATION FPIs, projected to an altitude of 250 km (corresponding to the red-line emission). For context, the geographic coordinates (lat/lon) of MH and VTI are 43.5°N/71.3°W and 38.2°N/80.6°W respectively. MH is out of bounds of the axis shown. The SSUSI auroral boundary shown in Figure 4 reaches a lower geographic latitude limit of

200 around 48°, thus we consider the entire wind field shown in S1 as sub-auroral.

The entire NATION wind field in S1 shows strong equatorward winds from around 03 UT to 07:30 UT, in agreement with the equatorward disturbance wind enhancements seen by VTI Figures 3 and 4, soon after the occurrence of SAPS. Between 06:30 UT and 09:30 UT, there is also a notable westward component of the lower-latitude (below 40°) winds, which is consistent with the VTI measured westward winds (geomagnetically) within a similar region. As mentioned previously, this westward

205 turning of the lower-latitude winds is may be due to a westward-acting Coriolis force on the previously equatorward flows, which were pressure gradient driven from the higher-latitude SAPS. From 09:30 UT the NATION winds become poleward, which also occurs in the geomagnetic north direction for the VTI and MH winds in Figure 3. In summary, the general wind direction in the smoothed NATION wind field is consistent with VTI and MH measured winds during the SAPS event shown.

3.2 Cross-correlation of Neutral Wind and SAPS Flow

210 We empirically examine the VTI and MH neutral wind response to the 9th November 2013 SAPS event by carrying out a cross-correlation analysis. Cross-correlation in this context involves lagging the disturbance wind timeseries against that for the plasma drift, and seeing which pair of lagged timeseries has the highest correlation. The lag with the highest correlation could be considered the "delay" of the disturbance wind to plasma drift variations, depending on the shape of the correlation curve, and give a potential insight into the processes driving the winds. To do this, however, a plasma velocity timeseries within

215 the SAPS region is required which can then be compared to the VTI and MH wind measurements.

To obtain the plasma timeseries, we average the zonal and meridional components of the fitted SuperDARN plasma convection velocity, within a region bound by 50 to 60° AACGM latitude and -25.14 to 27.49° AACGM longitude ($\pm$20° longitude each side of the FPI locations). As mentioned in Section 2, obtaining an average SAPS velocity from the SuperDARN fitted data product likely results in a source of error, due to the fit coupling to high-latitude convection which is separate from SAPS.

220 For the purposes of cross-correlation, however, averaging in this way would still extract the SAPS velocity trend. For example,
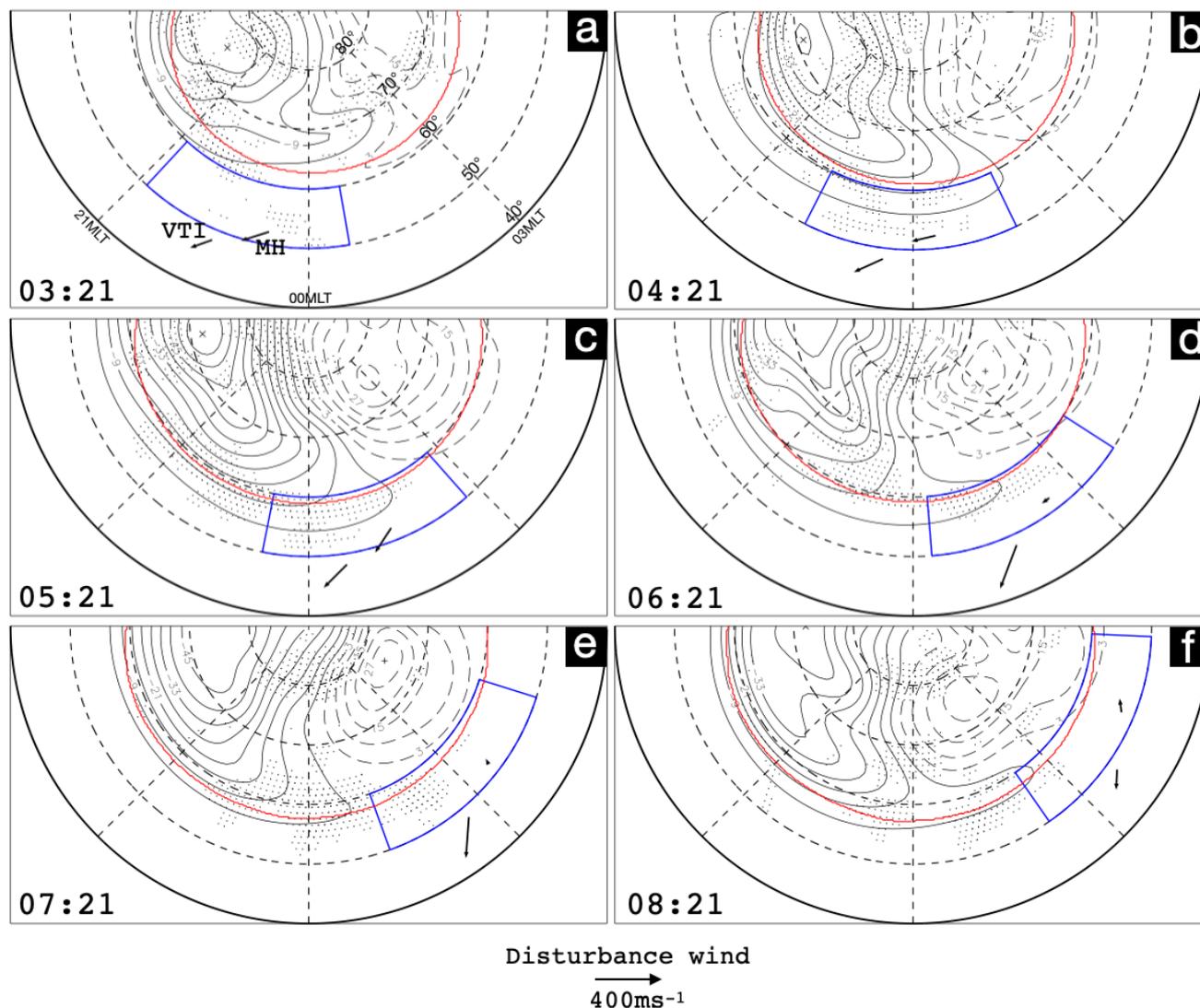
Figure 5. Polar plots in the same format as Figure 4, except with the SuperDARN global fitted electric potential contours (in kV) instead of the radar LOS data. Black dots are the locations of SuperDARN radar LOS data which contributed to the fit. The blue box is the region over which the fitted plasma velocity was averaged for the purpose of cross-correlation, results of which are shown in Figure 6.

the fitted westward velocity will still enhance and subside in response to the underlying data at that location from the four mid-latitude SuperDARN radars. In short, this means that changes in the convection pattern velocity at the location of the SAPS should still be representative of SAPS variations assuming the radar data coverage is good. The SuperDARN derived electric potential fit, as well as the averaging region (blue box) just described, are shown in Figure 5 for the same times shown in Figure 4. Black dots indicate where radar data has contributed to the fit.

225

At 03:21 UT (Figure 5[a]), there exists a two-cell convection pattern of which the equatorward edge is within a few degrees latitude of the auroral oval boundary. Soon after however, and shown in the panels from 04:21-06:21 UT, the contours expand significantly further equatorward of the oval. Plasma convection during this time is still two-cell, with anti-sunward flow over the pole and return flows on the dawn and dusk sides, but the dusk cell is elongated onto the dawn side near midnight MLT. The elongation of the dusk cell is a typical signature of SAPS flow in the global SuperDARN convection patterns, as westward flow directly post-midnight usually best-fits to the dusk cell instead of the dawn in an apparent enhancement of the Harang discontinuity (Bristow et al., 2001; Zou et al., 2009, 2012). In the 07:21 UT and 08:21 UT panels, the auroral oval boundary is expanded to a similar latitude as the convection pattern boundary and the averaging region is far on the dawn side.

Looking at the disturbance winds from VTI and MH in context with the convection pattern in Figure 5, we see that MH winds (higher latitude arrow) are consistently closer to the convection contours than those measured by VTI. This can help explain why the MH winds are more impacted in the zonal direction compared to meridional (Figure 3[c] and [d]), and also their eastward turning to align with the dawn side convection return flow (07:21 and 08:21 UT panels). Due to pressure gradients from solar heating, in addition to Coriolis forces tending to oppose the eastward ion-drag direction, winds on the dawn side are typically anti-sunward orientated (Förster et al., 2008). Eastward/sunward winds measured by the MH FPI thus imply a particularly strong ion-drag force.

A cross-correlation analysis is carried out by shifting ("lagging") the neutral wind disturbance timeseries backwards, in 5-minute intervals, up to 180 minutes. At each step, the Pearson correlation (r) coefficient is calculated against the magnitude of the average plasma velocity timeseries (from the fitted SuperDARN convection velocities), which is fixed in time. The correlation window used for the neutral wind is between 02:00 and 10:00 UT on 9th November 2013, and the wind components from VTI and MH are cross-correlated separately. Lagging wind data backwards in this way assumes that the plasma velocity magnitude is driving the wind disturbances, and not vice versa. Winds themselves may drive ion-drift (i.e., via the disturbance dynamo or neutral wind flywheel effects; Blanc and Richmond, 1980; Deng et al., 1991), but this would be unrelated to the SAPS drift seen before the winds themselves became enhanced. The cross-correlation results are shown in Figure 6, where an $r = 1$ indicates perfect correlation and $r = -1$ is perfect anti-correlation.

The cross-correlation curves for the VTI disturbance winds (Figure 6[a]) all have well defined peaks at high correlation values (indicated by the dashed vertical lines). The lags with the highest r are also fairly close: 105 mins for the zonal component and 125 mins for the meridional and magnitude components. This implies that enhancement of the disturbance winds at VTI lags that of the SAPS drift by roughly two hours, in agreement with the large meridional enhancements seen in Figure 4[d] and [e] even though the bulk of the SAPS occurred between panels [a], [b] and [c]. As mentioned earlier, we attribute this lag to the time taken for the pressure gradient force wavefront, driven by SAPS heating, to propagate equatorward to the region observed by the VTI FPI. Once the pressure gradient force begins to act on the neutrals, there is then additional time for the velocity of the wind to fully change. The $\sim$2 hour full response time of the VTI measured winds thus includes propagation of the pressure force to a lower latitude and the momentum change of the winds. A similar lagged equatorward propagation of disturbance wind enhancements can be seen in Figure 3 of Makela et al. (2014) (for the vertical wind component), which also appears to be on the order of a couple of hours across $\sim$6° of latitude.
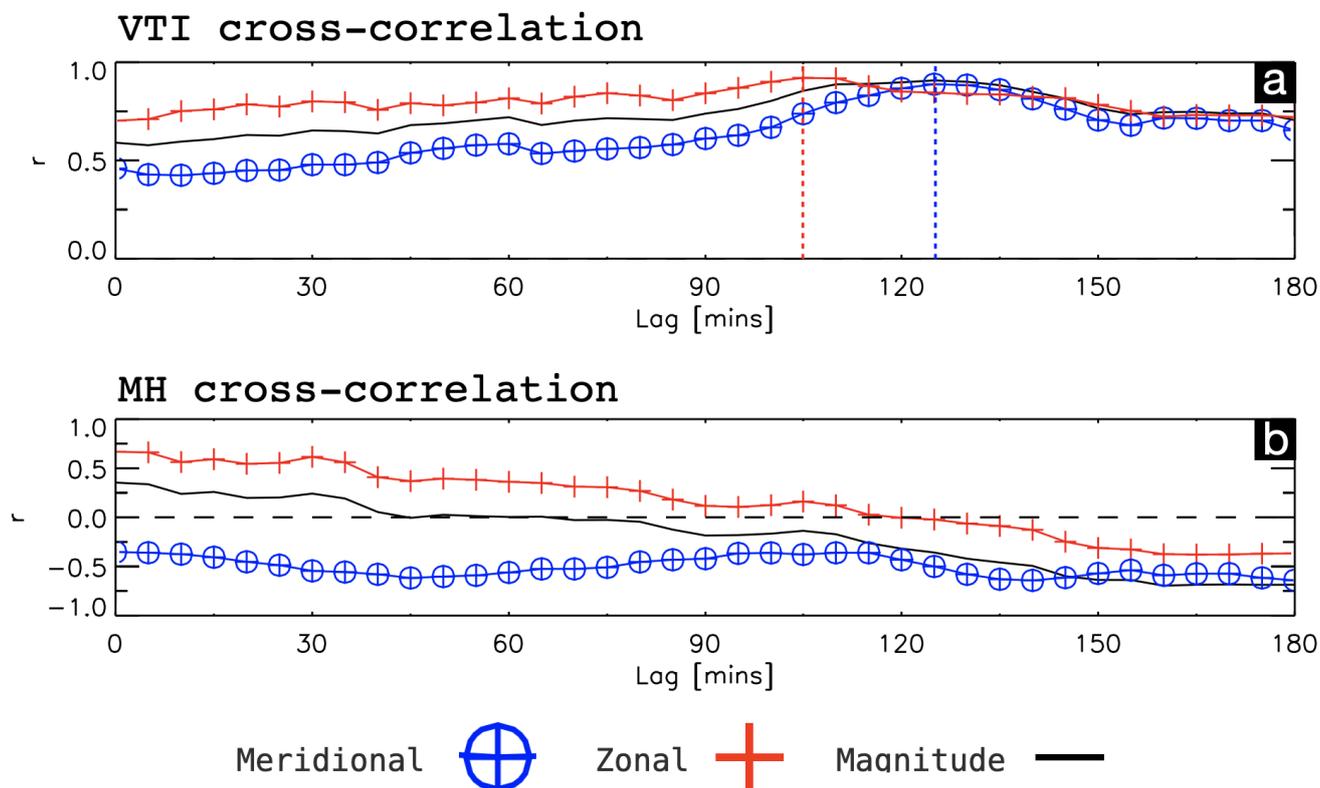
Figure 6. Cross-correlation results from the meridional (blue circle-crosses), zonal (red crosses) and magnitude (black line) disturbance winds from [a] VTI and [b] MH. Winds are lagged backwards up to 180 minutes in 5-minute steps, against the average plasma drift magnitude within the region shown in Figure 5. Vertical dashed lines in [a] indicate the lags with the highest *r*-values for the meridional and zonal components.

At MH (Figure 6[b]), the correlation of the zonal disturbance wind is highest when there is no lag and steadily decreases up to a lag of 180 mins. By contrast, the MH meridional correlation curve shows no well defined peaks or troughs throughout all lags. We interpret this as the zonal disturbance wind being closely coupled with the SAPS drift, whilst the meridional wind is mostly not consistently affected. This agrees with the winds at MH being strongly affected by ion-drag forcing because of a closer proximity to the SAPS and high-latitude convection, compared to VTI (e.g. Figure 5[b]-[f]). In a force term analysis by Ferdousi et al. (2019), it was found that ion-drag was indeed dominant in the SAPS region versus the Coriolis and pressure gradient forces. In global simulations by Wang et al. (2012), a similarly strong ion-drag effect was seen.

4 Conclusions

We have presented neutral wind measurements from two mid-latitude FPIs, which showed significant disturbances in response
to a sub-auroral polarisation stream (SAPS) event observed by mid-latitude SuperDARN radars. The two FPIs, located at
Virginia Tech (VTI) and Millstone Hill (MH) observe a significantly different response, which could be explained by their
proximity to the SAPS itself:

– Large equatorward and westward disturbance winds were observed at the VTI FPI, which was consistently located
   equatorward of the SAPS region. We propose that the observations were driven by the pressure gradient force and
   subsequent Coriolis force, due to SAPS heating at higher latitudes.

– The VTI disturbance wind was delayed from the SAPS by roughly 2 hours, indicative of the time taken for the pressure
   gradient force wave front to propagate equatorward from the SAPS region to the FPI location.

– Strong westward winds were observed at the MH FPI almost immediately in response to the SAPS. As the MH FPI was
   located much closer to the SAPS region than VTI, we propose that the MH observed winds were driven strongly by
   ion-drag from the westward SAPS drift.

Our results illustrate the degree of neutral wind variability at mid-latitudes in response to the impingement of high-latitude
ionospheric flows. Although the VTI and MH FPIs are fairly close geographically, the disturbance winds measured by each
vary significantly during a single geomagnetic event. It is thus important when analysing disturbance neutral wind data to
be attentive to mesoscale ionospheric events, such as SAPS, which can have wide reaching effects on the thermosphere. We
also highlight the diagnostic potential of direct thermospheric wind measurements in conjunction with SuperDARN observed
ionospheric flows. The mid-latitude expansion of the SuperDARN within the last decade, in particular, has greatly enhanced
options for the multi-instrument studies of mesoscale ion-neutral coupling mechanisms equatorward of the auroral zones.

Code and data availability. The authors acknowledge the use of data from SuperDARN, an international project made possible by the
national funding agencies of Australia, Canada, China, France, Italy, Japan, South Africa, Norway, the United Kingdom and the United
States of America. Fitted SuperDARN data can be downloaded from Globus, instructions of which are provided here: https://superdarn.
ca/data-products. Raw SuperDARN data with DOI's can be accessed via: https://www.frdr-dfdr.ca/repo/collection/superdarn. Fabry-Perot
Interferometer data from both the Millstone Hill and Virginia Tech sites was obtained from the Madrigal Millstone Hill data repository at
http://millstonehill.haystack.mit.edu/index.html. The NATION wind fields were obtained from https://airglow.ece.illinois.edu/Data/Calendar.
Disturbance storm time (Dst) index data was accessed from https://wdc.kugi.kyoto-u.ac.jp/dstdir/. IMF data was accessed from the OMNI
dataset at https://omniweb.gsfc.nasa.gov/ow_min.html. DMSP SSUSI auroral boundary data was accessed from https://spdf.gsfc.nasa.gov/
pub/data/dmsp/. The HWM14 Fortran software was obtained from the supporting information of Drob et al. (2015). SuperDARN data in this
study was processed using the Radar Software Toolkit (RST), version 4.6: https://zenodo.org/record/5156752.

Author contributions. This manuscript was written by DDB, who also carried out the event analysis. KAM, ATC and JMR aided in result interpretation for the SuperDARN data. RBK and JJM aided in interpretation of the FPI data. SK, MAM and JR carry out ongoing software and engineering maintenance for the MH FPI.

Competing interests. The authors declare no competing interests.

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