

JGR Space Physics

RESEARCH ARTICLE

10.1029/2024JA032415

Key Points:

- A new methodology for calculating the neutral wind response time to changes in ion convection is introduced
- The weighted windowed time-lagged correlation method is capable of resolving time-dependent responses of the neutral winds
- Comparison with previously derived neutral wind response times can shed insight on thermospheric drivers

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Citation:

Davidson, K., Zou, Y., Conde, M., & Bhatt, A. (2024). A new method for analyzing F-region neutral wind response to ion convection in the nightside auroral oval. *Journal of Geophysical Research: Space Physics*, 129, e2024JA032415. <https://doi.org/10.1029/2024JA032415>

Received 2 JAN 2024

Accepted 31 MAR 2024

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A New Method for Analyzing F-Region Neutral Wind Response to Ion Convection in the Nightside Auroral Oval

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Abstract High-latitude neutral winds have a number of drivers, both from solar and magnetospheric origins. Because of this, the neutral wind response to changes in ionospheric convection is not well understood. Previous calculations of response times resulted in a wide range of responses, from tens of minutes to hours. We present a new weighted windowed time-lagged correlation (weighted WTLC) method for calculating the neutral wind response time. This method provides a time evolution of the neutral wind response time and considers the effects of all thermospheric forces, while previous methods were only capable of one or the other. We use data from SDIs, ASIs, and PFISR to calculate the neutral wind response time using this new method in three case studies. The results are visually validated, and the weighted WTLC method was able to correctly calculate the neutral wind response time. The time evolution of the weighted WTLC time is then compared to previous neutral wind response time calculations in order to investigate the role of ion-drag on neutral winds. For the substorm event on 2013 Feb 28, we see a shorter response time from the weighted WTLC method, ranging from 0 to 15 min, than the e-folding time, ranging from 30 to 355 min. The relationship between the two calculation methods and their implications about the ion-drag force is discussed. Using the time-dependent feature of the weighted WTLC method, we observe the neutral wind response time decrease over the course of a substorm event, indicating ion-neutral coupling increased as the substorm progressed.

1. Introduction

High-latitude thermospheric winds are driven by both solar and magnetospheric forces due to magnetosphere-ionosphere-thermosphere (MIT) coupling. However, the efficiency and relative contributions of these drivers on thermospheric wind patterns are not well understood. On a global scale, F-region neutral winds are driven in a two-cell pattern by the Dungey plasma convection via ion-neutral collisions (Dungey, 1961). This flow consists of an anti-sunward flow over the poles with a sunward return flow in the auroral region. Solar EUV heats and expands the dayside thermosphere, resulting in a day-to-night pressure gradient that reinforces the anti-sunward flow and inhibits the return flow. In the northern hemisphere, the coriolis force acts in the westward direction, enhancing the dusk flow cell and suppressing the dawn flow cell (Killeen et al., 1988). Ion-neutral collisions also produce frictional heating, further altering the pressure gradient force. Advection and viscosity forces also influence the flow of neutral winds, although typically thought to be secondary forces compared to ion-drag and pressure (Killeen & Roble, 1988; Kosch et al., 2001; Thayer et al., 1995).

Due to the number of forces acting on the high-latitude thermosphere, the time-scale at which neutral winds respond to changes in ionospheric convection is not well understood. This response time-scale is an important quantity to study because it can represent the strength of ion-neutral coupling, which acts as a sink for the energy deposited in the high-latitude region from the magnetosphere. Previous calculations of the neutral wind response time have resulted in time-scales ranging from tens of minutes to hours (Killeen et al., 1984; Ponthieu et al., 1988; Kosch et al., 2001; Heelis et al., 2002; Aruliah & Griffin, 2001; Anderson et al., 2011; M. G. Conde et al., 2018; Zou et al., 2018; Joshi et al., 2015; Billett et al., 2019). The wide range of time-scales is the result of the different methods used to calculate the neutral wind response time. The two most notable calculation methods are the ion-drag time constant, or e-folding time, which is based on the assumption that ion-drag is the only driving force and the time-lagged correlation method, which considers the effects of all thermospheric drivers. Qualitative analysis methods have also been used for estimating the neutral wind response time.

Historically, simultaneous measurements of ionospheric and thermospheric parameters have been scarce. To overcome this limitation, Baron and Wand (1983) developed an ion-drag time constant using the assumption that

ion-drag is the most dominant force in the neutral momentum equation. This assumption resulted in an equation that only relied on the neutral density, plasma density, and collision frequency to estimate the time for neutral velocity to reach the ion velocity. They concluded that the time constant is inversely proportional to ion density, meaning higher ion density causes shorter response times, and vice versa, giving a range of 38 min for an ion density of $10^6/\text{cm}^3$ and 6.25 hr for an ion density of $10^5/\text{cm}^3$. Both Killeen et al. (1984) and Ponthieu et al. (1988) used ion and neutral densities measured by DE1 and DE2 satellites, along with collision frequencies calculated from formulae by Schunk and Nagy (1980), to obtain a time constant range from 1 to 3 hr Kosch et al. (2001) altered this ion-drag time constant (the e-folding time) to be dependent on just the observed neutral wind and plasma flow vectors. This altered method eliminates error caused by the calculation of the ion-neutral collision frequency. This study resulted in an average e-folding time of 1.8–3.3 hr for a geomagnetically active and quiet period, respectively. An alternative analysis was done by Heelis et al. (2002), where linear relationships between IMF and ion and neutral drifts were used to determine that ions respond to changes in solar wind driving in about 20 min, while neutrals respond in about 75 min. The 55 min time difference corresponds to the ion-neutral collision time.

With the recent expansion of ground based observations, high-latitude measurements of ionosphere and thermosphere parameters are now more readily available. The increase in observations has allowed additional neutral wind response time methodologies, such as qualitative analysis, to emerge. One example of this was by Aruliah and Griffin (2001), who used Fabry-Perot interferometers (FPIs) along with EISCAT radar measurements to qualitatively observe a neutral wind response time on the order of tens of minutes. Similarly, Anderson et al. (2011) and M. G. Conde et al. (2018) used Scanning Doppler Imagers (SDIs), which have a larger FOV than FPIs, to qualitatively estimate a neutral wind response time on the order of tens of minutes. Zou et al. (2018) used SDI and PFISR measurements to calculate the neutral wind response time by evaluating the time delay between the plasma flow and neutral wind at their maximum perturbations. This resulted in an average response time of around 20 min.

Finally, Joshi et al. (2015) introduced a time-lagged correlation method for calculating the neutral wind response time. In this method, a neutral wind time series is lagged against a plasma flow time series and a correlation coefficient is calculated at each lag step. The lag time at which the correlation between the two species is highest is taken to be the neutral wind response time. This resulted in a response time of 84 min during the main phase of a storm, and 0 min during the recovery phase of a storm once the two species were tightly coupled. Billett et al. (2019) also performed time-lagged correlation to find a neutral wind response time of around 75 min Billett et al. (2022) used the time-lagged correlation method at two different FPI sites to calculate the neutral wind response to a SAPS event, which resulted in a 0 min time delay for the FPI station closest to the SAPS event, and around a 2 hr delay for the FPI station further away. They attribute this difference to the time needed for the SAPS generated pressure gradient wavefront to propagate toward the FPI. The most recent neutral wind response calculation method was introduced by Kiene et al. (2018), who derived a coupling magnitude between the neutrals and the plasma by taking the vector projection between the winds and ion drifts. While this method doesn't explicitly result in a response time, it can be used to verify whether or not ion-drag is a dominant force, for example, if the coupling magnitude is large, and therefore if the e-folding time assumption is correct and can be used. In this study, an e-folding time estimate of 30 min was given.

Some studies have used the e-folding time in conjunction with other neutral wind response time calculations in order to investigate the efficiency of the ion-drag force. Zou et al. (2018) found that the e-folding time was longer than the observed neutral wind response time, which they attributed to the fact that other thermospheric forces prevent the neutrals from fully "catching up" to the plasma flow, halting at 20% of the flow perturbation. When they adjusted the e-folding time calculation to reflect this 20% difference, the calculated response times more similarly matched the observed response times. Additionally, Joshi et al. (2015) compared the time-lagged correlation response time to the e-folding time and found the lag time to be shorter than the e-folding time. They concluded that ion-drag alone cannot explain the neutral wind behavior, and other driving factors, such as Joule heating and associated transport, were at play. This type of analysis will be discussed further in Section 5.1.

While it is beneficial to make the comparisons between various neutral wind response times and the e-folding time, it is important to note that the time-lagged correlation method only results in a single response time for the entire event. For example, Joshi et al. (2015) calculated the time-lagged correlation over an 8 hr period.

Ionospheric plasma convection can change dramatically over this period of time, and a single response time may not be sufficient to represent the neutral wind response time. Similarly, qualitative methods often only result in a single response time or estimated range of response times. Because of this, the time-lagged correlation method has only previously been used in the mid-latitude (Billett et al., 2022; Joshi et al., 2015) or polar (Billett et al., 2019) regions. However, the auroral region is highly variable and a nightly averaged coupling time would not be able to accurately represent the neutral wind response in this region (Kiene et al., 2018).

Therefore, we introduce a new methodology for calculating the neutral wind response time: the weighted windowed time-lagged correlation (Weighted WTLC) method. This method produces a time evolution of the neutral wind response time, eliminating the limitation of the nightly averaged response time produced by the time-lagged correlation analysis. This allows us to analyze how the neutral wind response time, and by proxy the ion-neutral coupling efficiency, changes throughout time. Additionally, this time-dependent response time can be compared to the e-folding time, which was already a time-dependent calculation of the neutral wind response time, in order to assess the efficiency of the ion-drag force.

In this study, we apply the weighted WTLC to substorm periods because substorms are associated with drastic changes in plasma convection, and possibly neutral winds. Magnetospheric substorms significantly alter plasma convection through reconfigurations of field aligned currents during each phase of the substorm. Nightside substorm convection patterns typically do not resemble the classic two-cell pattern due to a wide pre-midnight Harang reversal region (Gjerloev & Hoffman, 2001). Plasma convection is also intensified by the expansion of the auroral oval during the growth phase of the substorm (Bristow et al., 2001; Bristow & Jensen, 2007; Lewis et al., 1997; Provan et al., 2004). Additionally, positive By IMF causes the convection pattern to rotate clockwise, with rotation increasing with activity increasing (Crowley et al., 2006; Förster et al., 2006; Grocott & Milan, 2014). These substorm processes results in rapid changes in ionospheric plasma flow, on the order of hundreds to thousands of meters per second over intervals of 10–20 min (Sánchez et al., 1996). Increased particle precipitation also increase ion-neutral collisions, allowing neutral winds to be driven by these locally enhanced plasma flows. However, the efficiency of the ion-neutral coupling in the F-region during substorms is not well understood, resulting in a wide variation of the time-scale of neutral wind responses to these rapid changes in ionospheric plasma convection. Xu et al. (2019) observed sudden thermospheric wind variations within 30 min of substorm onset, in association with the abrupt substorm energy input. Cai et al. (2019) also observed wind accelerations that increased the wind speed by 100–300 m/s within 20–40 min during the expansion phase of a substorm. And Zou et al. (2021) showed that neutral winds begin to respond immediately after substorm onset and reach their new steady state within 1 hr of substorm onset. While these studies provide observational estimates of the neutral wind response time, a systematic and objective method calculating the neutral wind response time in the auroral F-region during substorms has not previously been done. This is primarily due to previous calculation methods' limitations as described above, exhibiting the need for a new response time calculation method capable of studying the highly active auroral region.

This paper describes the new weighted windowed time-lagged correlation method and applies the method to three substorm events in order to study the neutral wind response time-scale during substorms. Section 2 describes the instruments used and event selection criteria. Section 3 describes the new methodology, while Section 4 details the three events in which the new method is applied. The ability of the weighted WTLC to accurately calculate the neutral wind response time and the new method's limitations are discussed in Section 5.2. The paper is concluded with a summary in Section 6.

2. Instruments

2.1. Poker Flat Incoherent Scatter Radar

The Poker Flat Incoherent Scatter Radar (PFISR) (65.1°N, −147.5°E geographic) is an Advanced Modular Incoherent Scatter Radar (AMISR) and is used to measure ionospheric convection. We will employ long pulse mode for F-region (>150 km) line-of-sight ion velocity, which provides a FOV of 4° with a spatial resolution of 0.25°–0.5° and temporal resolution of 1–5 min. F-region LOS ion velocities can be inverted into convection vectors by assuming that the velocity vectors are homogeneous in the east-west direction across the radar FOV (Heinselman & Nicolls, 2008).

2.2. Scanning Doppler Imager

We utilize Scanning Doppler Imagers (SDIs) to obtain F-region thermosphere parameters (M. G. Conde & Nicolls, 2010; M. Conde & Smith, 1995, 1997, 1998). SDIs observe Doppler shifts in 630.0-nm emissions, then divides its observations into 115 subregions (zones), giving a spatial resolution 0.5° at the zenith and 1° near the FOV edge. The Doppler shifts of each region provide LOS velocities of winds at an altitude of 250 km over 1–2 hr in MLT. The LOS velocities are then inverted to horizontal wind vectors by assuming that vertical winds are constant across the FOV and that meridional winds are stationary in local time (M. Conde & Smith, 1998). The wind vectors have a temporal resolution of 1–5 min. For this study, we will be using data from the Poker Flat SDI (65.1°N , -147.4°E) in order to provide wind measurements around the same FOV as PFISR's ion measurements.

2.3. Time History of Events and Macroscale Interactions During Substorms All-Sky Imagers

The Time History of Events and Macroscale Interactions during Substorms all-sky imagers (THEMIS ASIs (Mende et al., 2008);) will be used to measure auroras. Images are recorded at a cadence of 3 s and projected onto an altitude of 110 km. We mainly use the Fort Yukon (FYKN; geographic 66.6°N , -145.2°E) and Gakona stations (GAKO, 62.4°N , -145.2°E), which have large common FOVs with the SDIs. The ASIs have a spatial resolution of a few kilometers near the zenith and a temporal resolution of 3 s.

2.4. Event Criteria

We require simultaneous operation of PFISR, the SDI and ASIs, as well as clear sky conditions (no cloud coverage) in the SDI and ASI's common FOV and relatively low error in the derived PFISR velocity vectors provided by AMISR. Substorm events were identified by using the Newell and Gjerloev (2011) substorm list provided by the SuperMAG website. Due to our data mainly being available at night, we primarily search for onsets that are in the nightside auroral oval, between 07:00UT and 14:00UT and 20–03 MLT, where 11UT corresponds to magnetic midnight in the Alaskan region. Additionally, we require that the substorms occurred near the observation sites. For example, we look for substorms whose growth phase or poleward expansion phase crosses over the latitudes our data covers. We also look for substorms whose onset time is at least 1 hr after and 3 hr before the end of our data timespan so we properly capture the effects of the substorm.

In order to make the best use of our new methodology, we require that the SDI has data available for at least 7–9 hr throughout the night, which is usually easily obtainable with the SDI's continuous operation mode. There are two reasons for length requirement: we aim to gather events that are 4–6 hr in length and we need data for 3 hr after the end of the event. The 3 hr post-event time allows us to lag the wind along the plasma velocity for 3 hr throughout the entire event, which is near the upper limit of previously calculated neutral wind response times during active periods (Heelis et al., 2002; Joshi et al., 2015; Killeen et al., 1984, 1988; Kosch et al., 2001). We use event times of 4–6 hr because this allows us to study the pre- and post-substorm quiet time along with the 3 hr substorm period. Studying the entire nighttime period often results in not enough SDI data to lag and too many features in the plasma data to match. We define a "feature" in the plasma data to be a sudden change (around ± 500 m/s in a 20 min time span) in flow as a response to a substorm.

3. Methodology

SDI data is obtained in the form of skymap, aligned geomagnetically, with zonal and meridional wind vectors at each viewing location of the SDI from the Monthly Data Archive maintained by UAF. To make keograms, or latitude versus time plots, of the zonal and meridional winds, data is binned by 1° latitude and a center slice is taken 2.5° east and west of the central magnetic longitude. The data is averaged over each latitude bin for smoothing. PFISR eastward/northward velocity vectors are obtained from MadrigalWeb in the form of keograms, aligned geomagnetically. Both the PFISR and SDI data are interpolated to a 5 min interval time-series, which is the average sampling time for both data -sets. This is done because SDI and PFISR have different recorded data times, and need to be interpolated to a common time interval in order to run our analysis. The PFISR data is then smoothed in time by taking a sliding 10 min (two data point) average. This is because the plasma can be highly variable due to the rapidly changing magnetospheric coupling (Murr & Hughes, 2001) and we are only interested in the large-scale responses to substorms. Finally, auroral keograms are obtained from the aurora-asi-lib python package developed by Shumko et al. (2022).

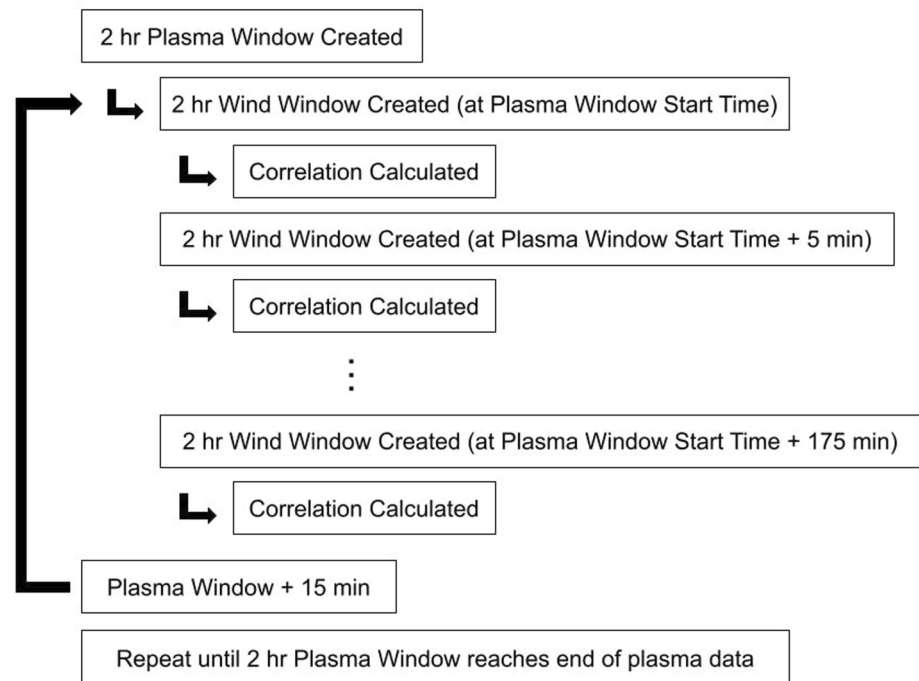


Figure 1. Flow chart of the windowed time-lagged correlation (WTLC) method.

In order to perform our analyses, we select a time-series of the neutrals and ions from single latitude, within 1° latitude of each other. This latitudinal difference is acceptable for observing temporal differences in the time-series, since the SDI have a spatial error of around 1° in latitude from our binning process. These time series are used for the analysis of the neutral wind response times. An example of the resulting keograms and time-series plots can be seen in Figure 2, with 2 (c–e) showing zonal velocities and 2 (h–j) showing meridional velocities. This figure will be explained in detail in Section 4. It should be noted that the meridional velocities show little variation during the substorm, with the majority of the response occurring in the zonal direction. Therefore, we focus our analysis on the zonal winds for this study.

We first perform a windowed time-lagged correlation calculation that results in a time-dependent neutral wind response time by sectioning the plasma time-series into sliding 2 hr windows and performing the time-lagged correlation calculation on each window. The method proceeds as follows. First we define our start and end time of the substorm event and the plasma and neutral time-series are created as described in Section 3, with 3 hr being added to the end time of the wind time-series. Our plasma correlation windows are 2 hr in length, starting at our event start time and sliding every 15 min. We require that all of our correlation windows remain the same length, which means our correlation windows will end 2 hr before the end of the event. For example, for an event time of 06:00UT–12:00UT, this will result in 16 plasma correlation windows (06:00UT, 06:15UT, 06:30UT, ... 09:45UT, 10:00UT). For each plasma correlation window, we perform our time-lagged correlation calculation. This is done by creating a wind correlation window with the same length and start time as the current plasma correlation window. Then, the wind correlation window is stepped forward in time by one time step (equating to one data point) until a 3 hr time lag has been reached. The correlation between the plasma window and the lagged wind windows are calculated at each lag step. The lag time that resulted in the highest correlation between the two time-series is then deemed our neutral wind response time. In order to assure that this time lag is representative of ion-neutral coupling, we only consider windows with a correlation coefficient greater than 0.4. This process results in a time-lagged neutral wind response time for each 2 hr plasma window. In other words, we have a neutral wind response time every 15 min throughout our event. A flow chart of the windowed time-lagged correlation method is provided in Figure 1.

This windowed time-lagged correlation (WTLC) analysis allows us to maintain the observational basis of the time-lagged correlation method, while now providing a neutral wind response time every 15 min. The time-

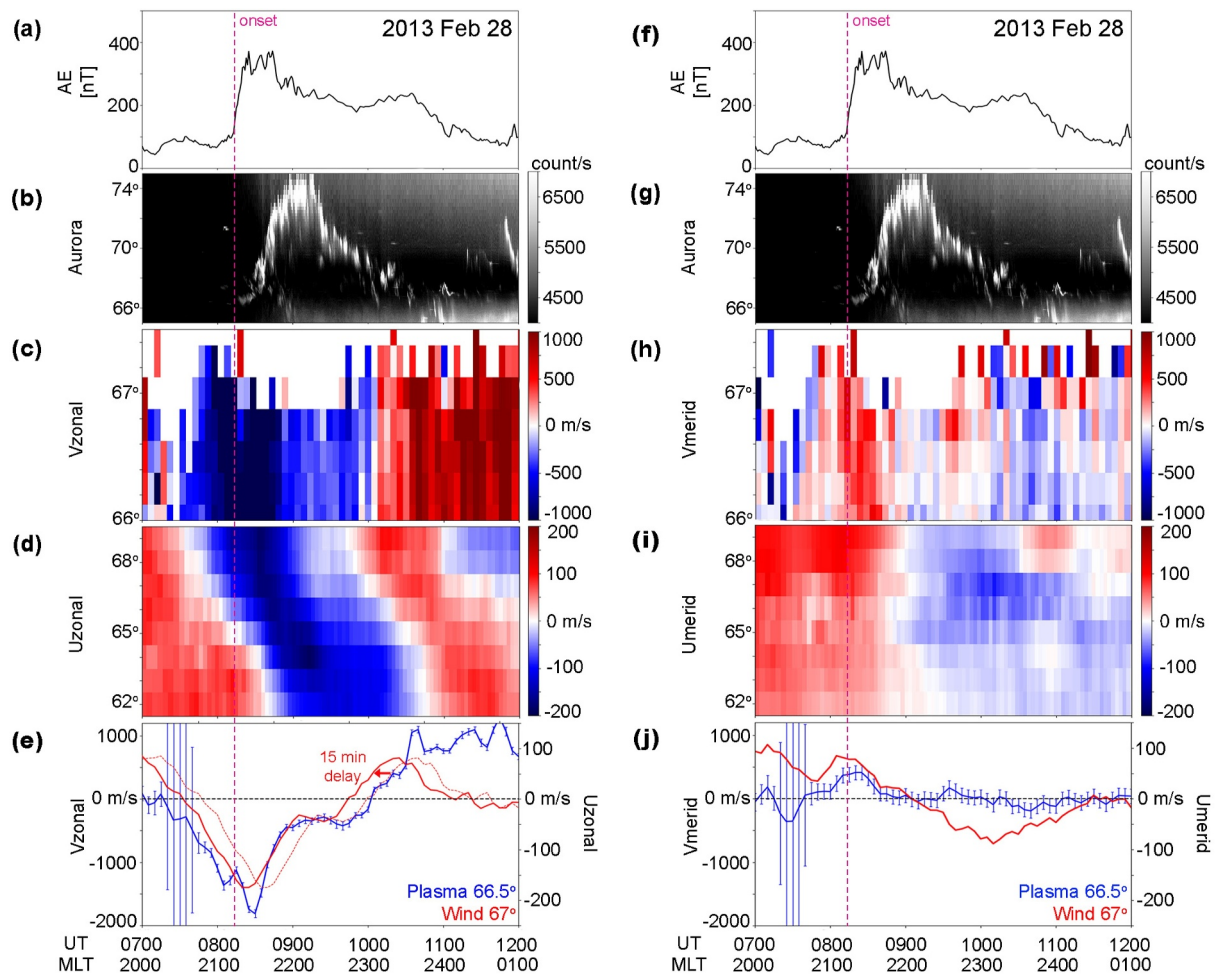


Figure 2. (a–d) Time series of the auroral electrojet (AE) index, auroral activity, eastward plasma flow, and eastward neutral wind on 28 February 2013. (e) Time series of the eastward plasma flow (solid blue line) at 66.5° and eastward neutral wind (dashed red line) at 67°, with a time delayed eastward neutral wind (solid red line) according to the full correlation time lag (f–j) Time series of the AE index, auroral activity, northward plasma flow, northward neutral wind, and single latitude velocities. The latitude on the Y-axis is magnetic latitude. Substorm onset is indicated by magenta dashed lines.

dependency of the WTLC method allows us to study how the neutral wind response evolves during events. However, because of the short correlation window and the fact that the correlation calculation only considers the shape of the time series, and not the magnitude, the WTLC can often result in high correlations for periods of time that are not related. For example, a steady eastward flow can have a high correlation with a steady westward flow, simply because the two species have a similar shape. This presents itself as multiple peaks in the WTLC.

Instead of manually identifying which peak is correct, we weight the WTLC by the time-lagged correlation analysis of the entire event, resulting in the Weighted WTLC. This allows for the consideration of the behaviors of the two species before and after any given window, which eliminates any mismatches in the WTLC. In the next section, we apply the weighted WTLC method to three events to show the efficiency and capabilities of the new technique.

4. Observations

4.1. 2013 February 28

The first substorm event occurred on 2013 February 28. Substorm onset was at 08:13UT at 1.53 MLT and 68.5° magnetic latitude according to the SuperMAG substorm list. At the time of substorm onset, our observations are around 21 MLT and range from 62 to 69° MLAT and 66–67.5° MLAT for the SDI and PFISR, respectively. While our observations are around 4 hr MLT away from onset, substorms are typically a few hours width in MLT

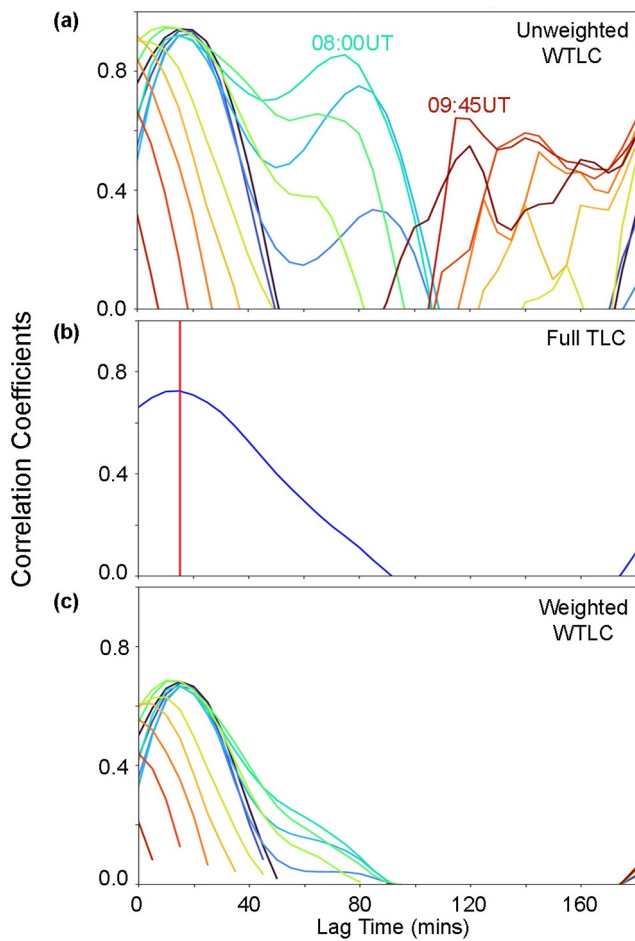


Figure 3. (a–c) Correlation coefficient versus lag time plots of the unweighted windowed time-lagged correlation, full time-lagged correlation, and weighted windowed time-lagged correlation methods, respectively, on 28 February 2013.

rate than the plasma, then plateaued into a steady westward flow from around 09:15UT–09:45UT and finally accelerated into an eastward flow. Again, this pattern begins at 68° MLAT and expanded equatorward with a delay.

The time-series was chosen at 66.5° and bin 66.5–67.5° for the plasma and wind, respectively. These latitudes were chosen because it allowed for low error data from PFISR, while being within the range of particle precipitation we see from the auroral keogram. The zonal time-series is plotted in Figure 2e, with plasma plotted as a solid blue line with error bars provided by PFISR data output, and wind plotted as a dashed red line. The time-series exhibits the same behavior of plasma and winds as described above, with a westward acceleration shortly before substorm onset, eastward acceleration and plateau after substorm onset, and then continuation of the eastward acceleration into eastward flows.

Figure 3a shows the WTLC for the event on 2013 February 28. The response times are highly variable, with peaks ranging from 0 min to 180 min. The dark blue curves have single peaks focused around 15 min. The light blue and green curves have multiple peaks, one around 15 min and another around 75 min. The red and orange curves also have multiple peaks, at 0 min, around 120–140 min, and then at 180 min. This variation in the response times shows the need for a time-dependent neutral wind response time. The full time-lagged correlation, shown in Figure 3b, peaks at 15 min and quickly declines from there. To assess the physical meaning of this 15 min time-lag, we plot the wind time-series at a 15 min delay to the plasma time-series in Figure 1e, presented as a solid red line. It can readily be seen that this 15 min response time is an appropriate match to the plasma time-series in the

(Reeves et al., 1990), therefore placing our observations at the westward edge of the substorm. Figure 2 presents an overview of this event, including the AE index, aurora signatures, eastward plasma and wind keograms, and a time-series plot of the plasma and wind velocity. Poleward expansion of the aurora is seen by the FYKN ASI station at the time of substorm onset (Figure 2b), with the equatorward edge of the auroral oval being observed at 66° MLAT.

Although the PFISR FOV (66°–67.5° MLAT) was at a lower latitude than the substorm onset given by Newell and Gjerloev (2011), our ASI data indicates substorm activity as low as 66° MLAT. Additionally, we see strong westward flows, reaching close to $-2,000$ m/s, around the substorm onset (Figure 2c). This can be attributed to the enhancement of the large scale two-cell convection pattern associated with a high-latitude substorm (Grocott et al., 2009), where in this event we are seeing an enhanced westward dusk cell. This westward acceleration began about an hour before substorm onset, with the plasma flow reaching its maximum speed around 15 min after substorm onset. At this point, the plasma experienced an eastward acceleration at 08:30UT, indicating that either the dusk convection cell is weakening or our observations are moving out of the dusk convection cell both from a contraction of the cell during the recovery phase of the substorm and moving toward magnetic midnight at around 11:00UT. The plasma plateaued into a steady westward flow from 08:45UT–09:45UT, where it then accelerated to an eastward flow associated with the dawn convection cell. This eastward convection occurred before magnetic midnight due to a rotation of the two-cell convection pattern with the presence of +By IMF.

The SDI data also show a response to the substorm (Figure 2d) that is similar to the plasma flow. Winds around 68° MLAT turned westward around 30 min before substorm onset, reaching its maximum westward speed of around -175 m/s 30 min after substorm onset. This westward acceleration expanded equatorward, which can either be attributed to advection from higher latitudes or lower latitude coupling between the ions and neutrals. The latitudinal extent of ion-neutral coupling during substorms are not well understood, and without larger FOV observations of ionosphere parameters this issue is out of the scope of this study. Winds accelerated eastward at 08:45UT, at a slower

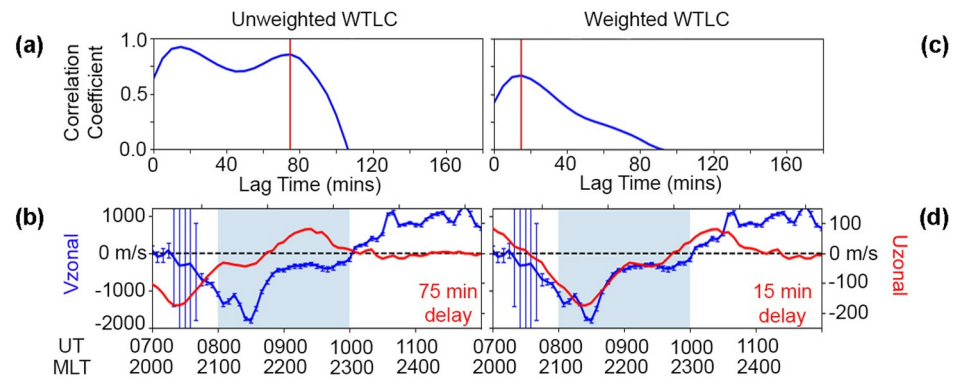


Figure 4. (a),(c) Unweighted and Weighted Windowed Time-Lagged Correlation of the 08:00UT window on 28 February 2013, respectively (b),(d) Time series of the eastward plasma flow at 67° , with a time delayed eastward neutral wind at 66° according to the unweighted and weighted WTLC time, respectively.

beginning of the event, from around 07:00UT to 09:30UT, but then is too delayed from 09:30UT onward, causing the winds to no longer match the plasma. This, in addition to the variation in response times seen in the WTLC, solidifies the conclusion that ion-neutral coupling, and therefore the neutral wind response time, is a non-static variable and cannot be accurately represented by a single nightly averaged time.

The multiple peaks in the WTLC are caused by the fact that the correlation windows are short, and only consider the shape of the time-series within that window. For example, in this event there are two periods of eastward acceleration, one that causes the flow to be steady near 0 m/s, but still westward, and another that causes the flow to turn eastward. The correlation calculation can result in a high correlation between the first acceleration and the second acceleration, even if they are driven separately. In order to disregard these secondary correlations, we perform the weighting calculation between the WTLC and full time-lagged correlation curve. Figure 3c shows the resulting weighted WTLC. The secondary peaks in the green, light blue, red and orange curves have been eliminated from the multiplication of the WTLC with the full time-lagged correlation, leaving only one neutral wind response time per window.

In order to validate the weighted WTLC method, we plot the time delays of the unweighted WTLC and the weighted WTLC and manually inspect the match between the plasma series and delayed wind series. The unweighted and weighted WTLC and corresponding delays of the 08:00UT window on 2013 February 28 is shown in Figure 4. The time-lagged correlation of this window resulted in a peak at 15 min and at 75 min. Because this window includes our substorm onset, it's important to be able to distinguish between the two response times, which makes the difference between whether or not neutral winds are capable of responding rapidly to ionospheric convection during substorms. Although the correlation is higher at a 15 min delay, the correlation is still significant at 75 min (~ 0.8). Therefore, we use 75 min as the time delay in Figure 4b in order to investigate its accuracy. This 75 min time delay results in a poor physical match between the plasma and delayed wind series. In the beginning of the window, at 08:00UT plasma time, the wind plateaued and near 0 m/s while the plasma is undergoing significant acceleration changes around 08:15UT. Additionally, while the plasma is plateaued and remaining steady in the westward direction starting around 08:45UT, the wind is accelerating in the eastward direction. Again, this high correlation between the two species is caused by the fact that the correlation calculation only considers the shape or acceleration of the time-series, not the magnitude. In this case, the calculation matched the eastward acceleration of the plasma at 08:30UT to the eastward acceleration of the neutrals at 09:45UT. So although a 75 min delay has a high correlation, it is not physically meaningful as the plasma and winds are undergoing separate processes at that time.

The resulting weighted WTLC eliminates the peak at 75 min, leaving just the peak at 15 min (Figure 4c). The resulting plasma and delayed wind series in Figure 4d shows a fairly good match. Both the plasma and the wind reach their maximum westward speeds of around $-2,000$ and -175 m/s, respectively, at the same time around 08:30UT. Additionally, each species shifts from westward acceleration to eastward acceleration at 08:30UT and plateau at around -400 and -50 m/s at 08:45UT. The only discrepancy is that the wind resumes its eastward acceleration slightly before the plasma at the end of the window, at 09:30UT plasma time instead of 09:45UT.

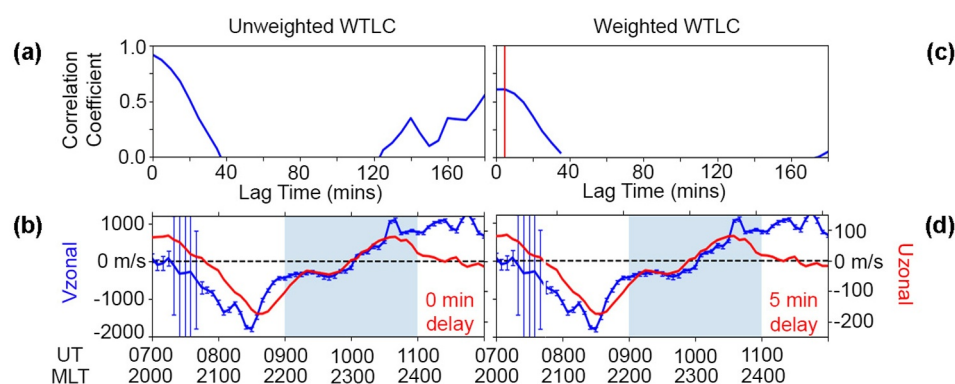


Figure 5. Same as Figures 4, 09:00UT window on 28 February 2013.

This is most likely due to the fact that the wind's plateau is shorter than the plasma's, so a perfect match at the beginning of the plateau would result in a mismatch at the end of the plateau.

This method oftentimes results in unweighted and weighted WTLC times that are the same or very similar, within 15 min of each other. This usually occurs when the unweighted WTLC time is close to the full TLC time. An example of this can be seen in Figure 5, which shows the time delays of the unweighted and weighted WTLC for the 09:00UT window on 2013 February 28. The unweighted WTLC results in a time delay of 0 min, while the weighted WTLC results in a time delay of 5 min. Because our data is interpolated to 5 min intervals, this means that the unweighted WTLC and weighted WTLC are only one data point away from each other, which is not a significant enough difference to determine which result is better. Figures 5b and 5d show that the resulting plasma and delayed wind series plot are very similar to one another. For the purposes of validating the weighted WTLC method, we consider cases like these to be in favor of the weighted WTLC and take the difference to be the error in the method.

4.2. 2013 January 26

Figure 6 presents an overview of a substorm event that occurred on 2013 January 26. The figure is the same as Figure 2, except we exclude the meridional panel and add the full time-lagged correlation plot. This event contained two substorms very close to one another one at 08:34UT (21.46MLT, 65.45°MLAT) and another at 09:05UT (23.87MLT, 67.47°MLAT). At these times, our observations are around 21.5MLT and 22MLT, respectively, allowing for good observations of the effects of the substorm on the plasma flow and winds. Substorm expansion is seen in the FYKN auroral data (Figure 5b) around 08:30UT, expanding from ~63°–73° MLAT. Precipitation then moves equatorward around 09:00UT. Bright moonlight inhibits our view of any auroral features from around 09:30–11:30UT and 63°–67° MLAT.

Initially, plasma had a strong westward flow associated with an enhanced dusk convection cell, reaching speeds of around $-1,000$ m/s (Figure 6d). Shortly before the first substorm onset, plasma flow abruptly turned eastward across the entire PFISR FOV, to a speed of around 400 m/s. The flow remained eastward above 67° MLAT, and returned to a stagnant below 67° MLAT. Following the second substorm onset, plasma accelerated eastward across the entire FOV again, this time reaching speeds of over $1,000$ m/s. The return to stagnant flow and reacceleration occurred again around 10:00UT and 10:30UT, respectively.

Similar to the previous event, the SDI data also experienced westward winds associated with the dusk cell that expanded equatorward in time. Westward winds started above 65° MLAT at speeds of around -250 m/s, and by 07:30UT westward winds have reached as low as 62° MLAT, reaching a minimum speed at that latitude of around -250 m/s. At the first eastward plasma acceleration, the winds around the PFISR latitude (66° – 68° MLAT) abruptly accelerated eastward to a stagnant wind of around 0 m/s. At the second plasma acceleration, winds turned from stagnant wind to eastward winds of around 50 m/s. This time, the eastward winds reach lower latitudes, down to 64° MLAT. Finally, at the third eastward plasma acceleration, winds accelerated to a stronger eastward wind of around 200 m/s, extending down to latitudes of 62° MLAT. The eastward winds are stronger at the PFISR latitudes, and weakening as they move equatorward. In this event, the winds experienced the same accelerations

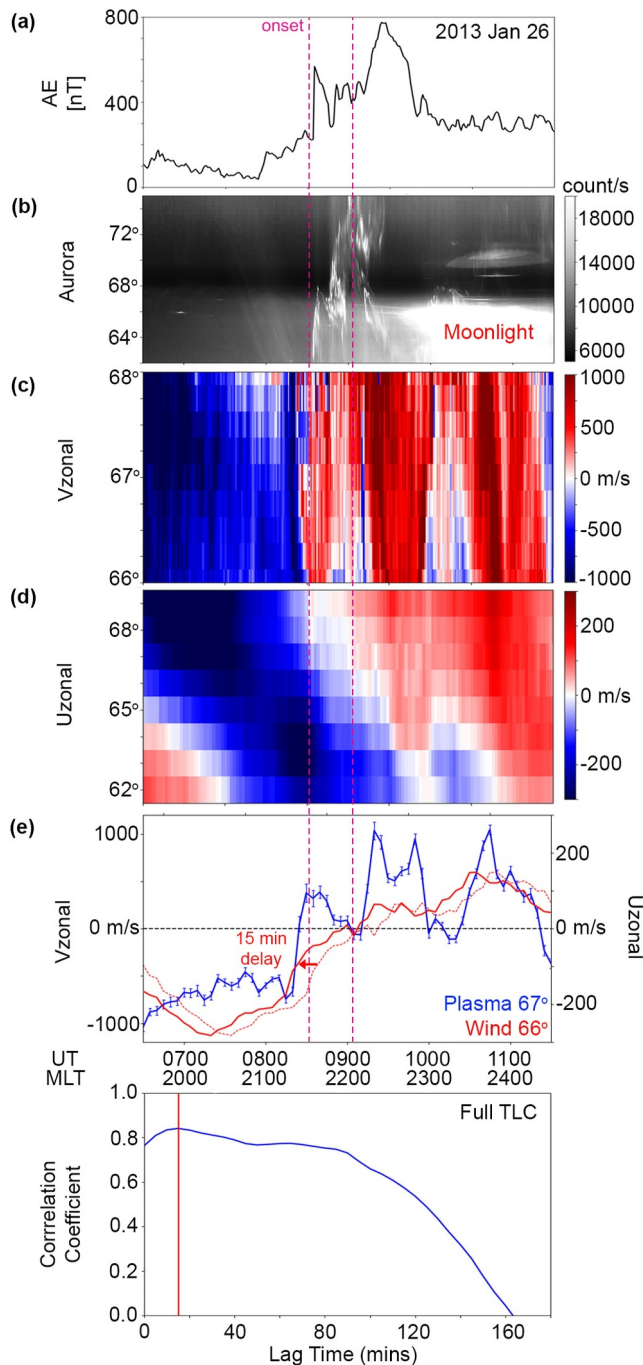


Figure 6. (a–d) Time series of the auroral electrojet (AE) index, auroral activity, eastward plasma flow, and eastward neutral wind on 26 January 2013. (e) Time series of the eastward plasma flow (solid blue line) at 67° and eastward neutral wind (dashed red line) at 66°, with a time delayed eastward neutral wind (solid red line) according to the full correlation time lag. The latitude on the Y-axis is magnetic latitude. Substorm onsets are indicated by magenta dashed lines.

as the plasma, indicating tight coupling between the two species. These accelerations expanded equatorward with time in the winds, again either due to advection or coupling with the plasma at latitudes not visible in the PFISR FOV.

The time series is plotted at 67° and bin 65.5–66.5° MLAT for the plasma flow and neutral wind, respectively, in Figure 6e. The plasma is plotted in a solid blue line, and the winds as a dashed red line. The plasma and neutrals follow the same pattern as described above, with three sudden eastward accelerations in the plasma and the winds. Here, we can also see winds began slowly accelerating eastward around 07:30UT, but experienced a stronger acceleration with the presence of the first substorm around 08:30UT. The full time-lagged correlation, shown in Figures 6f and is not as sharp as the one for the 2013 February 28 event, but still as a significant drop of correlation after around 80 min. Again, the time delay of the full time-lagged correlation calculation is plotted with the plasma and wind time series in Figure 6e. This 15 min delay resulted in an appropriate match for the first two eastward accelerations, but resulted in a poor match for the last eastward acceleration at 10:15UT.

The time delays of the unweighted and weighted WTLC for the 07:15UT window on 2013 January 26 are presented in Figure 7. The unweighted WTLC resulted in a time delay of 130 min. This results in a poor match between the plasma and delayed wind series. In the beginning of the window, the plasma velocity is steady in the westward direction, while the wind is steady in the eastward direction. While both the plasma and wind experience an eastward acceleration around the same time at 08:15UT plasma time, it is clear from the overall trend of the data that this is not the appropriate match. In addition to the two species flowing in opposite directions in the beginning of the window, this time delay causes the two species to be poorly matched after the window, with winds accelerating westward toward 0 m/s while the plasma is experiencing multiple eastward accelerations. Because of the drop-off in correlation in the full TLC, the resulting weighted WTLC has a peak at 10 min, eliminating the secondary peak seen in the unweighted WTLC. The time delay from the weighted WTLC results in a good match between the plasma and delayed wind series, with the plasma and wind both flowing westward before suddenly accelerating eastward at 08:15UT. Due to the particle precipitation present at these latitudes seen in the FYKN auroral data, it is reasonable to believe that the two species are tightly coupled via increased ion-neutral collisions and therefore have a short lag time, like the one provided by the weighted WTLC.

4.3. 2013 February 20

Figure 8 presents an overview of a substorm event that occurred on 2013 February 20. This event consisted of two substorms, one at 09:42UT (23.77MLT, 69.85°MLAT) and another at 10:05UT (22.43MLT, 70.87°MLAT). At these times, our observations were around 22.75MLT and 23MLT, respectively, which are similar to the substorm onset MLT's. The onset MLAT's given by Newell and Gjerloev (2011) are higher than our observation MLAT's, however the growth phase of the substorm can be seen in the FYKN auroral data in Figure 8b expanding equatorward to around 66°.

The growth phase of substorms are associated with a strong ion-drag effect in the eastward electrojet region (Cai et al., 2019), making this an appropriate event to study even though our FOV lands below the given substorm onset MLAT's. The summary of the event is shown from 07:00 – 13:00UT, but the analysis is performed only from 08:00 – 13:00UT due to higher error in the plasma data before 08:00UT. The

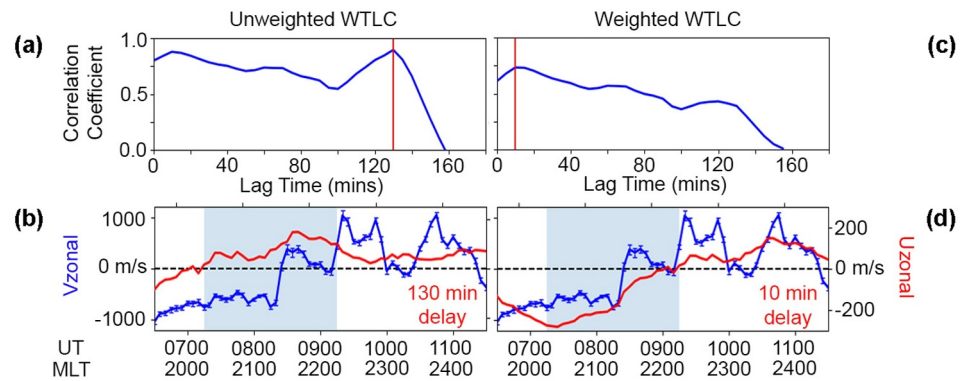


Figure 7. Same as Figures 4, 07:15UT window on 26 January 2013.

analysis was performed both including/excluding the 07:00UT hr and results were not drastically changed by omitting this data.

The FYKN auroral keogram in Figure 8b shows the growth phase expanding equatorward from around 08:15UT and 69° MLAT to around 09:45UT and 66° MLAT. Substorm onset then began at 09:45UT, expanding poleward to around 72° MLAT. Highly variable particle precipitation is seen following substorm onset. The PFISR data has a limited FOV from 07:00–10:00UT, with a high error in the data above 66.5° MLAT. Regardless, westward plasma flow is seen in the PFISR data from 07:00–10:00UT, with speeds reaching around -800 m/s. The plasma slowly accelerated eastward, having smaller fluctuations between eastward and westward accelerations while maintaining an overall eastward trend. These fluctuations occur on a time-scale of around 20 min.

The SDI data again follows a similar trend to the previous two events. Winds accelerated westward with the westward convection cell at high latitudes, and then expanded equatorward with time. Winds reach a minimum westward speed of around -200 m/s at 09:00UT above 68° MLAT, while winds did not turn westward until near 10:00UT at 62° MLAT, only reaching a minimum speed of around -50 m/s. Winds slowly accelerated eastward starting around 10:00UT at the higher latitudes, and turned eastward around 10:45UT and accelerated to a maximum speed of around 150 m/s. Winds turned fully eastward around 11:00UT at the lower latitudes. The rapid fluctuations of the PFISR keogram is not seen in the SDI keogram. This is likely due to the fact that while winds have been shown to respond to changes in the ionospheric convection on a time-scale of tens of minutes, the changes in the convection should be sustained in order to facilitate this response.

The time series is plotted at 66° MLAT and bin 65.5 – 66.5° MLAT for the plasma and wind, shown as a solid blue and dashed red line in Figure 8e, respectively. The fluctuations in the PFISR data is much more apparent in this figure, with the data switching from westward to eastward accelerations around every 20 min, maintaining an overall eastward trend. The most significant change in the data is seen shortly after the first substorm onset, at 09:45UT. The plasma flow experiences a sudden eastward acceleration, moving the plasma flow from around -800 m/s to near 0 m/s. The SDI data shows a smooth eastward acceleration from westward to eastward winds throughout the course of the event, with the winds shifting to eastward acceleration just before 10:00UT, around 15 min after substorm onset. Because of the relatively slow eastward accelerations from both the plasma and the wind, the full time-lagged correlation remains highly correlated throughout the event, seen in Figure 8f. The correlation does not drop below 0.6 until after 140 min time lag. In this case, the resulting time-delay of 50 min, plotted as a solid red line in Figure 8e, improperly matches the initial eastward accelerations of the two species. If we only consider the long term trends in the plasma data, then we can consider the sudden eastward acceleration of plasma at 09:45UT to be when the plasma turns from westward to eastward acceleration. Then, the 50 min time delay places the eastward turning of the wind at around 09:00UT plasma time, 45 min before the eastward turning of the plasma. However, after this initial eastward turning of the two species, starting at around 10:00UT, the time-delayed wind matches the plasma well. While the previous events have shown that more than a single time-delay is needed to describe the neutral wind response time, this is more so a result of the fact that the eastward acceleration of the wind is occurring slowly throughout the entire event, so that any time-delay would create a high correlation with the plasma's slow eastward accelerations.

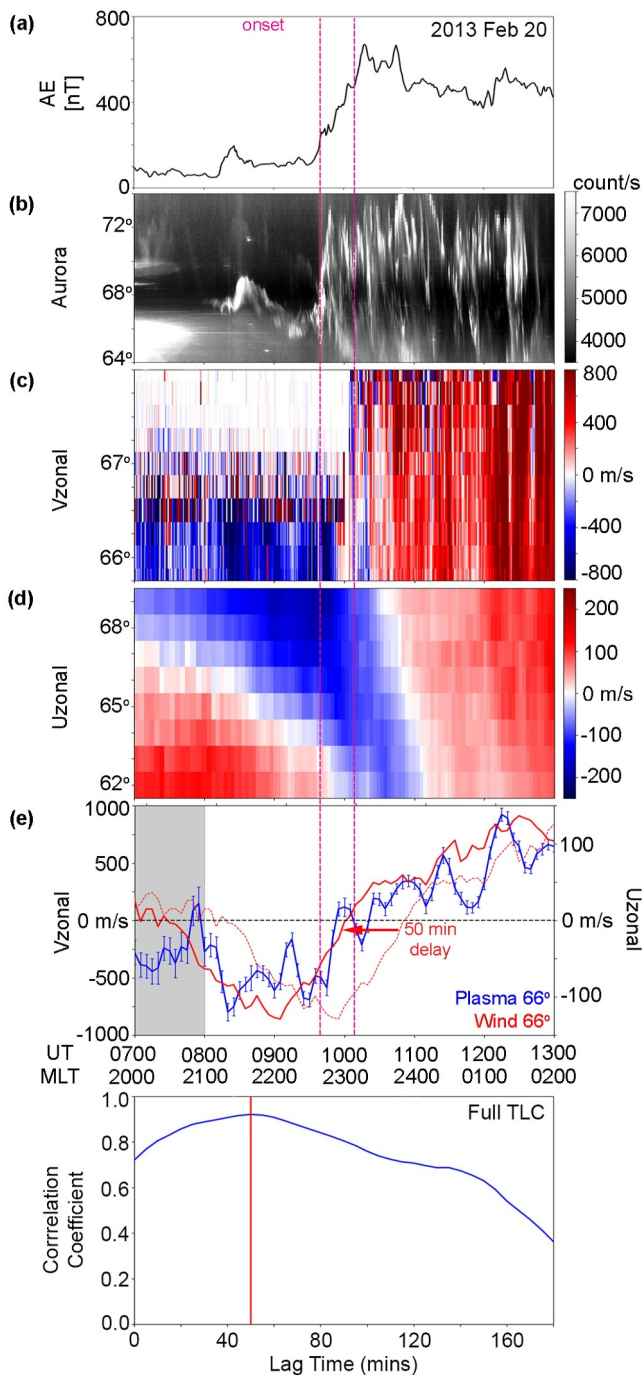


Figure 8. Same as Figure 6 for the 20 February 2013 event.

time depends on the magnitude of both the ions and the neutrals, which is varying greatly throughout the event, while the lag time is just dependent on the direction of acceleration of both species.

In addition to differing trends between the two response times, the magnitude of each are also very different. The e-folding time has a minimum value of 30 min and a maximum value of 355 min, while the weighted WTLC time has a minimum value of 0 min and a maximum value of 15 min. According to our theoretical analysis, this would indicate that there are significant thermospheric forces on top of ion-drag since the observed weighted WTLC response time is much shorter than the ion-drag based e-folding time. This result is different than previous

Because of the plateaued full time-lagged correlation curve, there is not much change in the curves when the WTLC is weighted. An example of this can be seen in Figure 9, showing the time delays of the unweighted and weighted WTLC for the 09:30UT window on 2013 February 20. Both the unweighted WTLC and the weighted WTLC result in the same neutral wind response time. Additionally, both curves show long plateaus, with the weighted WTLC plateau being less extreme than the unweighted WTLC, suggesting a wide range of acceptable time lags. Again, the 50 min time delay does not accurately match the initial eastward acceleration of the plasma and the wind, with wind acceleration now occurring 45 min before the plasma acceleration. This result is to be expected when the eastward acceleration is slow and is barely discernible compared to the highly variable plasma, causing the correlation calculation to have no notable features to match. In cases where the full time-lagged correlation is a plateau and the weighted WTLC still results in multiple peaks, the neutral wind response time can still be selected manually by visual inspection.

5. Discussion

5.1. Comparison of Weighted WTLC and E-Folding Time

The new weighted WTLC method provides a time-dependent neutral wind response time that can be used that in order to study how neutral wind response evolves throughout substorm events. This can also be compared to the e-folding time, which already provided a time evolution of the neutral wind response time. The e-folding time, derived by (Baron & Wand, 1983), is given by:

$$\tau = \frac{\mathbf{V} - \mathbf{U}}{\partial \mathbf{U} / \partial t} \quad (1)$$

The e-folding time is dependent on the assumption that ion-drag is the only acting force, even though neutral winds also have a dependence on horizontal advection, pressure gradient, coriolis and other forces. On the other hand, the weighted WTLC time is an observation based method, that includes the effects of all neutral wind drivers. In theory, the two methods can be compared in order to assess the efficiency of ion-drag as a neutral driver. For example, if the e-folding time is significantly different than the lag time, this would be an indication that forces other than ion-drag are contributing.

The e-folding time, along with a fit using the Savitzky-Golay filter, is plotted for the entire event, and the peak lag time at the midpoint of each 2 hr plasma window versus time is shown in Figure 10. E-folding time increases to a maximum before substorm onset at 08:13UT, then decreases before increasing again around 09:30UT, and plateauing at the end of the event. The lag time remains constant for the first hour of the event, and then decreases to 0 min at the end of the event. In this case, the e-folding time is much more variable than the lag times. This is most likely due to the fact that the e-folding

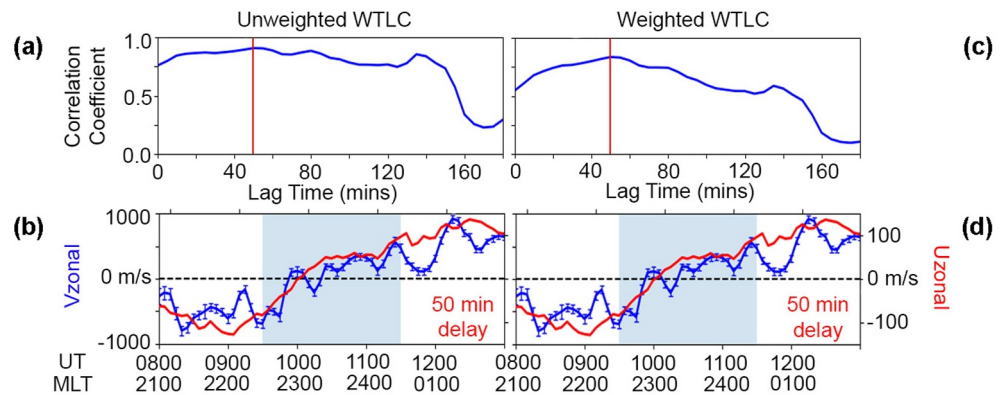


Figure 9. Same as Figures 4 and 09:30UT window on 20 Feb 2013.

conclusions that ion-drag is a dominant force during periods with substantial particle precipitation (Killeen & Roble, 1988; Kosch et al., 2001; Thayer et al., 1995), like we see in the auroral keogram. However, a conclusion about the efficacy of the ion-drag force may be more complex than a simple comparison between the two response times. For example, as Kiene et al. (2018) pointed out, the e-folding time could grow to be very large when the coupling reaches a steady state. That is, when the winds are changing slowly compared to the magnitude of the plasma, Equation 1 consists of a large numerator and a very small denominator, resulting in a large response time. Considering the nature of the ions and neutrals, the $\partial U/\partial t$ term will usually be small relative to the magnitude of the plasma flow, like in the 2013 February 28 event where the plasma is almost 13x greater than the neutrals at some times. In this case, the large e-folding time may be more influenced by the magnitude difference between the two species, rather than being representative of the strength of the ion-drag force. Therefore, the e-folding time being much larger than the weighted WTLC time may not be a good indication of the influence of the ion-drag force on the neutrals. The e-folding time could more accurately be described as a representative response time if ion-drag was the only acting force, instead of a measure of the neutral wind response time itself, since we know that even if ion-drag is a dominant force, other thermospheric forces will always be present. In this case, we cannot draw conclusions about the ion-drag force from the comparison of our weighted WTLC time to the e-folding time. We do, however, believe the shorter 0–15 weighted WTLC time to be accurate due to the visual inspections of the time lags shown in Figures 4 and 5 and the recent observational response time studies showing a similar timescale (Aruliah & Griffin, 2001; Anderson et al., 2011; M. G. Conde et al., 2018; Zou et al., 2018).

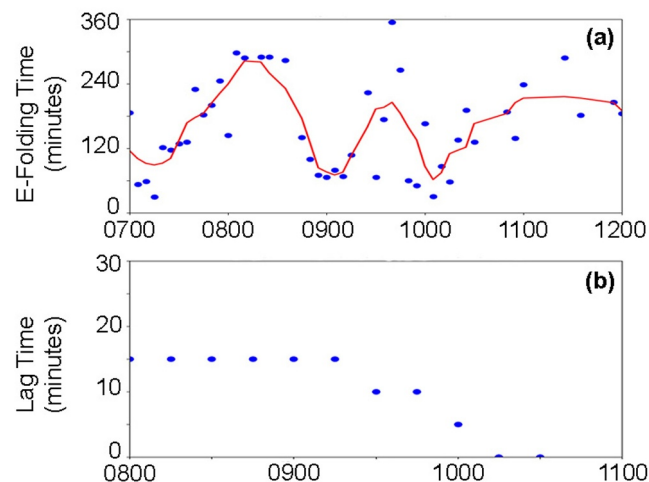


Figure 10. Neutral wind response times versus UT for the 2013 February 28 event. (a) E-folding time calculated using Equation 1. (b) Weighted WTLC times at the midpoint of each 2 hr window.

Further studies are needed in order to investigate the relationship between the e-folding time and the ion-drag force, and how these compare to the weighted WTLC time.

5.2. Efficiency and Limitations of the Weighted WTLC Time

For the events shown here, the weighted WTLC outperformed the unweighted WTLC, giving a better match between the two species 100% of the time in windows where the two lag times weren't equal or within 15 min of each other. Additionally, around two thirds of the window's lag times either remained unchanged or stayed within 15 min after applying the weighting calculation. We consider this to be a successful result, since the goal of the weighting calculation is not to significantly alter the WTLC results, but just to eliminate double peaks caused by false coupling matches in the calculation.

In order to validate the time evolution of the weighted WTLC time, we can again look at the time series plot in Figure 2e. As we noted before, a 15 min time lag provides a good visual match for the beginning of the event, then we see the species become tightly coupled by the end of the event with no time lag needed to provide a good match between the two species. This trend can easily be seen in our weighted WTLC time in Figure 10b, with the 15 min time lag decreasing to 0 min by the end of the event. Thus, our weighted WTLC response times were able to accurately represent the response of the neutral wind to changes in the plasma flow, which decreased during the substorm event.

The weighted WTLC method does have a few limitations. Mainly, there needs to be a sustained, sudden change in plasma flow that is discernible from any small scale fluctuations. For example, the event on 2013 February 20 showed slow, long-term plasma accelerations with embedded variable small-scale accelerations. This makes it difficult for our correlation calculation to provide any reliable results, since there are no discernible features to correlate. Additionally, due to lagging the wind along the plasma, the available wind data must be quite long, with the desired length around 8 hr. This limits our events to the winter and equinox months that have longer nights and therefore more data.

6. Summary

We presented a new methodology for calculating F-region neutral wind response times during substorms. The neutral wind's response to changes in plasma convection during substorm periods is not well understood due to the debated influence of ion-neutral collisions on winds. Additionally, this response has previously been difficult to study due to limitations in calculation methods. While the e-folding time provided a time-evolution of the neutral wind response time, it made the assumption that ion-drag was the only driving force. Conversely, the time-lagged correlation coefficient is observation based, thus considering all drivers of the neutral winds, but resulted in a single response time, insufficient for studying the highly active F-region auroral zone. The new weighted windowed time-lagged correlation method allows us to maintain the consideration of all drivers, while re-introducing the time-dependency of the neutral wind response time. These response times ranged between 0 and 85 min across our three events.

We utilized this method in three case studies in order to showcase its capabilities and limitations. For the events shown here, the weighted WTLC method was able to accurately calculate the neutral wind response time, validated by visual inspection and comparisons of other neutral wind response calculations. In order for this method to be used, the plasma must exhibit a sudden but sustained change in flow. This provides the method with a discernible feature to correlate with the wind data. Additionally, it is desirable to have a continuously long period of data, which limits this method to be used on winter and equinox months. A comparison of the e-folding time and the new weighted WTLC time was also discussed. The e-folding time was longer than the weighted WTLC time by an order of hours at some points, suggesting that ion-drag alone cannot explain the neutral wind's response to changes in ion convection, but further investigation is needed to make any conclusions about the thermospheric forcing based on the response time calculations. The weighted WTLC time showed the ion-neutral coupling time decreasing over time, indicating ion-neutral coupling grew stronger as the substorm event progressed. This result displays the scientific capabilities of the weighted WTLC method, which allows us to investigate both how the neutral wind response changes over time and the influence of ion-neutral coupling.

Data Availability Statement

The THEMIS mission data are available from <https://themis.ssl.berkeley.edu/index.shtml>. PFISR operations data are available from <https://amisr.com/database> or <https://isr.sri.com/madrigal>. SDI data are available from http://sdi_server.gi.alaska.edu/sdiweb/index.asp.

Acknowledgments

This work was supported by NASA Grant 80NSSC21K1859. We acknowledge NASA contract NAS5-02099 and V. Angelopoulos for use of data from the THEMIS Mission. Specifically: S. Mende and E. Donovan for use of the ASI data, the CSA for logistical support in fielding and data retrieval from the GBO stations, and NSF for support of GIMNAST through grant AGS-1004736. We acknowledge Poker Flat Incoherent Scatter Radar which is a major facility funded by the National Science Foundation through cooperative agreement AGS-1840962 to SRI International. We acknowledge the SuperMAG collaborators (<https://supermag.jhuapl.edu/info/?page%3Dacknowledgement>). We acknowledge Stephen Lesage for providing a Python package for reading SDI data.

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