The Role of Neutral Winds in MIT Energy Transfer

A. M. Pepper[1] and S. R. Kaeppler[1]

1. Department of Physics and Astronomy, Clemson University, Clemson, SC, 29634

Abstract

The E-region ionosphere is the region where field-aligned currents terminate because of enhanced ion-neutral collisions enabling perpendicular closure currents. The closure of these currents enables energy to be dissipated through Joule heating. Thayer, 1998; Aikio et al., 2012; Cai et al., 2013; and Zahn et al., 2021; have shown that the neutral wind can play a significant role in enhancing or reducing energy dissipation. The observations presented were primarily derived from incoherent scatter radar observations that self-consistently calculated the neutral wind. Sangalli et al., 2009 presented one of the only case studies to quantify the impacts of the neutral winds on Joule heating using rocket-based observations. Since 2009, several other campaigns have derived neutral winds using the chemical tracer technique, and combined with observations from the Poker Flat Incoherent Scatter Radar (PFISR), there is a unique opportunity to quantify the impact of the neutral winds on the Joule heating over a range of magnetic local time sectors and geomagnetic activity levels. Direct TMA observations provide high-resolution (~1 km) neutral wind data that is notably independent of other measurement techniques.

In this investigation, we present results that combine PFISR data with in-situ data taken during five separate sounding rocket campaigns: Joule II, MIST, JETS, and INCAA. For each campaign, altitude-resolved neutral wind profiles have been determined via TMA observations which are triangulated using the line-of-sight projection method between 80-130 km. Where applicable, the impact of in-situ measured electric fields are compared with the impact PFISR-derived results have on energy exchange parameters. The Joule heating rate, including the effects of the neutral winds, are quantified during these experiments and the associated geomagnetic conditions. Our results assess the impact independently derived neutral winds have on Joule heating in the E-region spanning over multiple magnetic local time sectors and geomagnetic activity levels.

Motivation & Methods

- **Science Question: How does independently derived neutral winds impact energy transfer in the E-region during different MLT sectors and geomagnetic conditions?**
- To address the science question above, a total of four campaigns were considered. For each campaign in question, three selection criterion was met: The dispersal of TMA at E-region altitudes that was triangulated and processed into a neutral profile, the campaign must be at high latitudes with either low, medium, or high geomagnetic activity levels, and the campaigns must have coincident ground-based measurements for data verification. Two of the campaigns investigated can be viewed in Table 1.

Campaign	Date	MLT Sector	KP
Jets	3/2/2017 - 5:41 UT	Dusk	4.3
INCAA	4/7/2022 - 12:47 UT	Morning	2.0

- The Pedersen conductivity (conductance) was calculated using the equation below which is taken from Section 2.2 in Kelley, 2009. The ion-neutral collision frequency contained in this equation is calculated for both the resonant and non-resonant cases using section 4 in Shunk & Nagy, 2009. NRLMSIS-2.1 provides the neutral temperatures while PFISR provides both the plasma density and ion temperatures required. The ratio of the ion cyclotron frequency to the ion-neutral collision frequency (κ_i) is calculated with magnetic fields from IGRF and the aforementioned ion-neutral collision frequency.

$$\sigma_P = ne^2/[M\nu_{in}(1+\kappa_i^2)]$$

- The perpendicular ion drifts are estimated in the E-region with the methodology described in Heinselman and Nicolls, RS, 2008. The electric field estimated in the F-region used long pulse ISR data and is assumed to map vertically into the E-region. PFISR electric fields are compared against in-situ measurements. Both sources for electric fields are used to calculate passive energy deposition rate which is also integrated with respect to height.

$$q_j^E = \sigma_P \mathbf{E}_\perp^2 \qquad Q_j^E = \Sigma_P \mathbf{E}_\perp^2$$

- The vapor trail technique was used to provide measurements of the altitude resolved E-region neutral winds. The vapor trails of trimethylaluminum (TMA) were photographed and triangulated to obtain neutral velocity profiles utilizing the line-of-sight projection method providing profiles between 100-140 km. These neutral profiles are included in the calculation of the Joule heating rate which is also integrated with respect to height.

$$q_j = \sigma_P(\mathbf{E}_\perp + \mathbf{U}_n \times \mathbf{B})^2 \qquad Q_j = \int \sigma_P(\mathbf{E}_\perp + \mathbf{U}_n \times \mathbf{B})^2 dz$$

- In order to accurately attribute the contribution of neutral wind to Joule heating, the percent difference between the passive energy deposition rate and the Joule heating rate is calculated for both campaigns using the equation below. For negative percent differences, the neutral wind effectively increases the rate of Joule heating and for positive percent differences, the Joule heating rate is decreased when neutral winds are included in the calculation.

$$\%\text{ diff} = \frac{q_j^E - q_j}{q_j} \times 100\%$$

Results

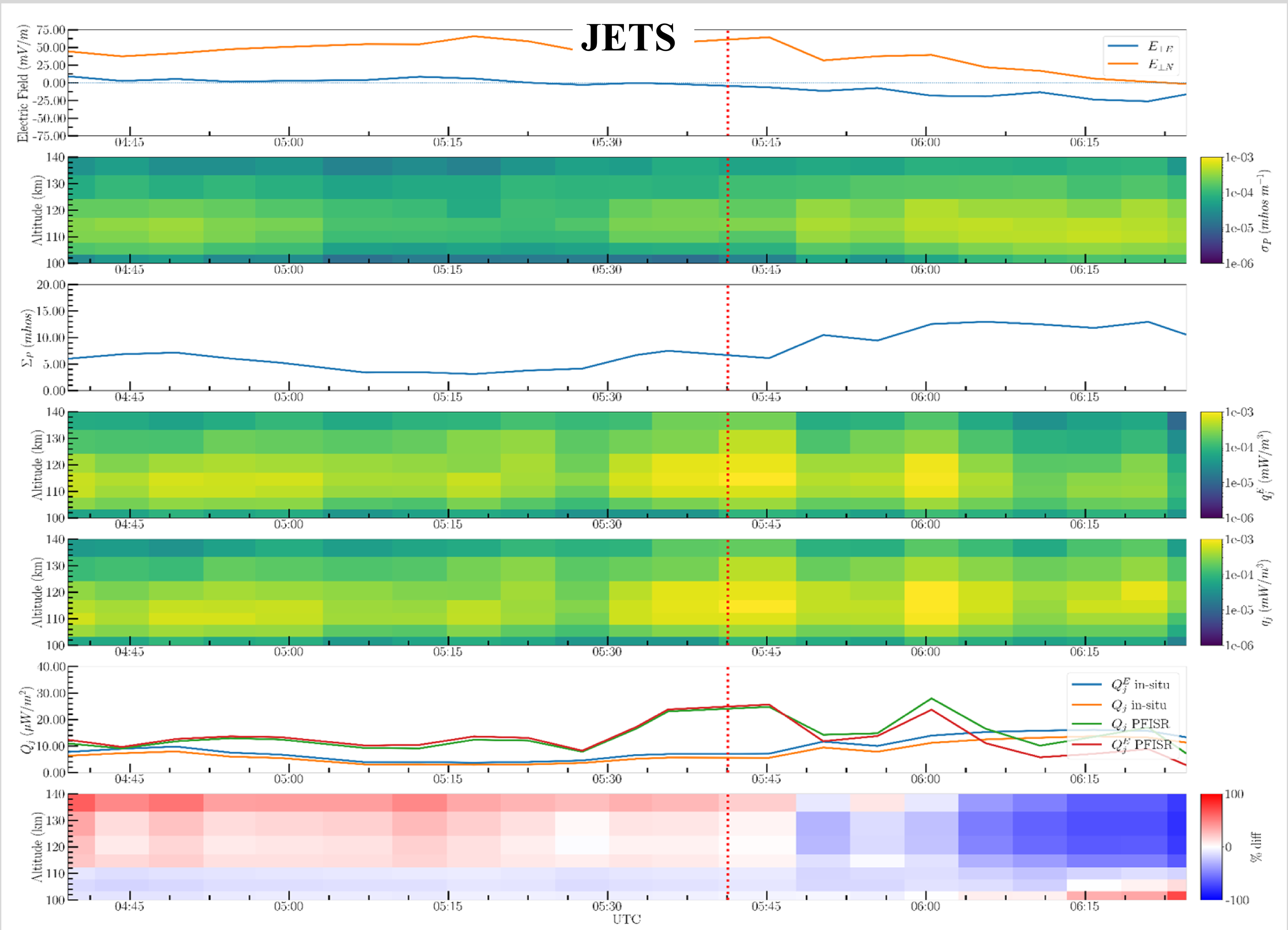

Figure 1: A summary figure depicting energy exchange parameters during the launch of Jets from Poker Flat Research Range on March 2nd, 2017, at 05:41 UT as indicated by the dashed red line corresponding to the dusk MLT sector. The influence of neutral wind is best seen in the 7th panel which shows that around (and before) launch when the electric field is strongest, the neutral wind acts to reduce the Joule heating rate at the higher altitudes. 30 minutes post launch, the waning electric field indicates that the neutral winds are beginning to drive the Joule heating rate which is seen as the percentage difference trends negative.

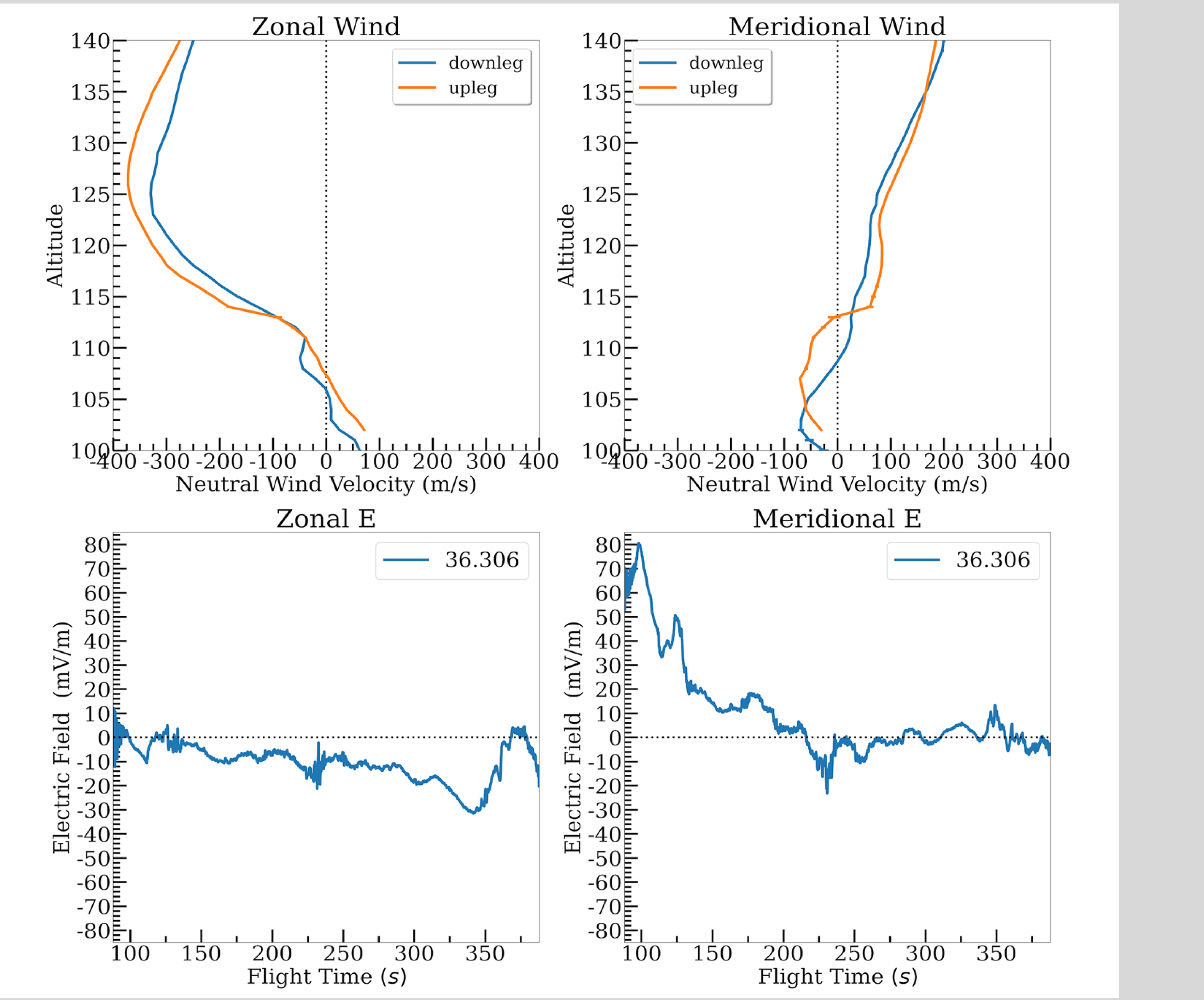

Figure 2: The zonal and meridional wind components from the neutral profile triangulated from the Jets campaign depicted in geomagnetic coordinates shown above the in-situ measured electric field. The high geomagnetic activity level and enhanced electric fields indicative of strong Lorentz forcing facilitate the strong zonal neutral wind component that reaches a magnitude of almost 400 m/s in this coordinate system. The electric fields measured in-situ early in the flight show agreement with the PFISR calculated fields.

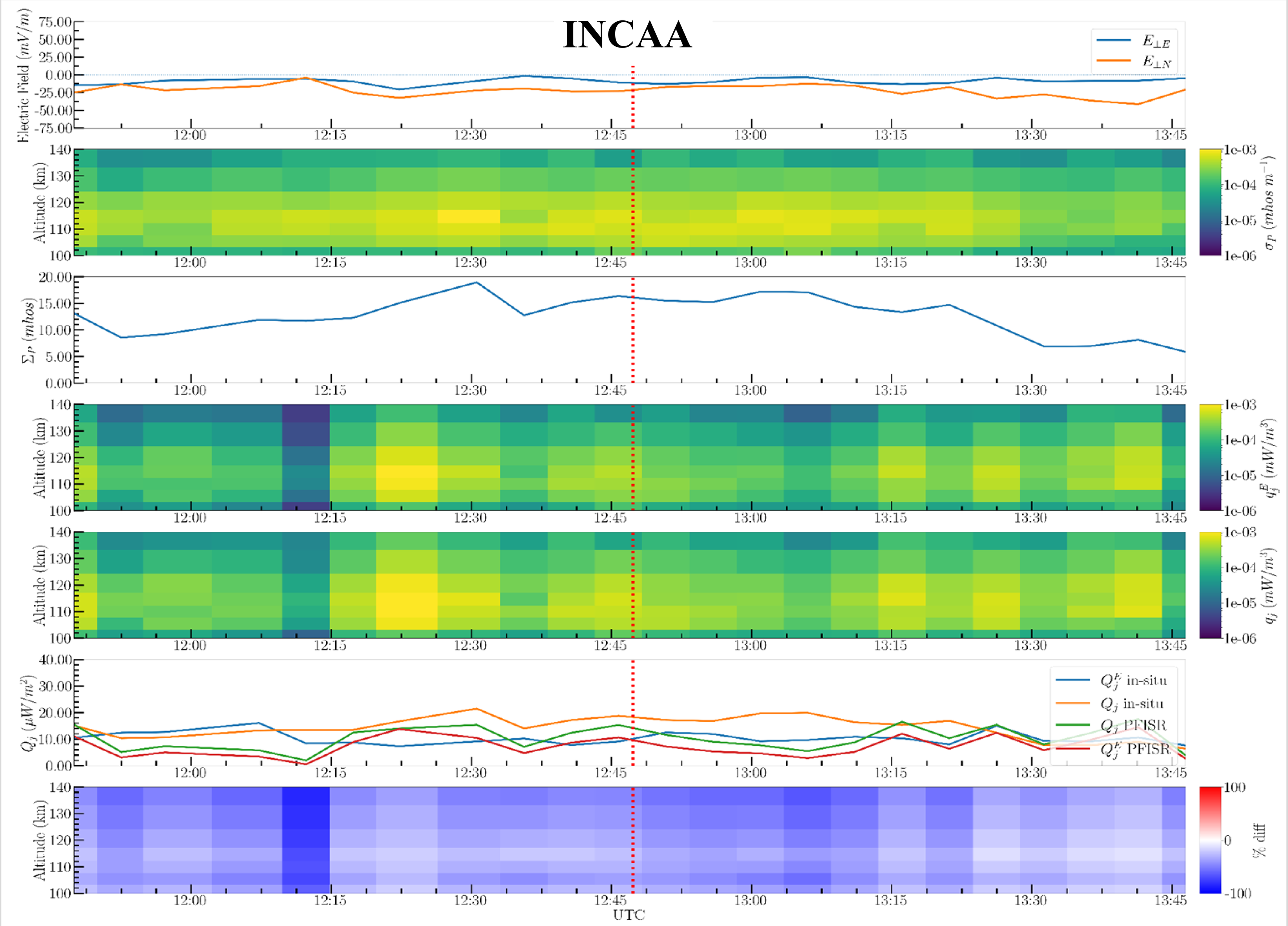

Figure 3: A summary figure depicting energy exchange parameters during the launch of INCAA from Poker Flat Research Range on April 7th, 2022 at 12:47 UT as indicated by the dashed red line corresponding to the dawn MLT sector. The influence of neutral wind during this campaign results in increases in the Joule heating rate at all altitudes that is consistent with the level of geomagnetic activity. Without a substantial electric field, the Joule heating rate is driven primarily by the neutral wind and illustrates how the Joule heating rate is often underestimated in periods of weak geomagnetic activity when neutral profiles are not considered.

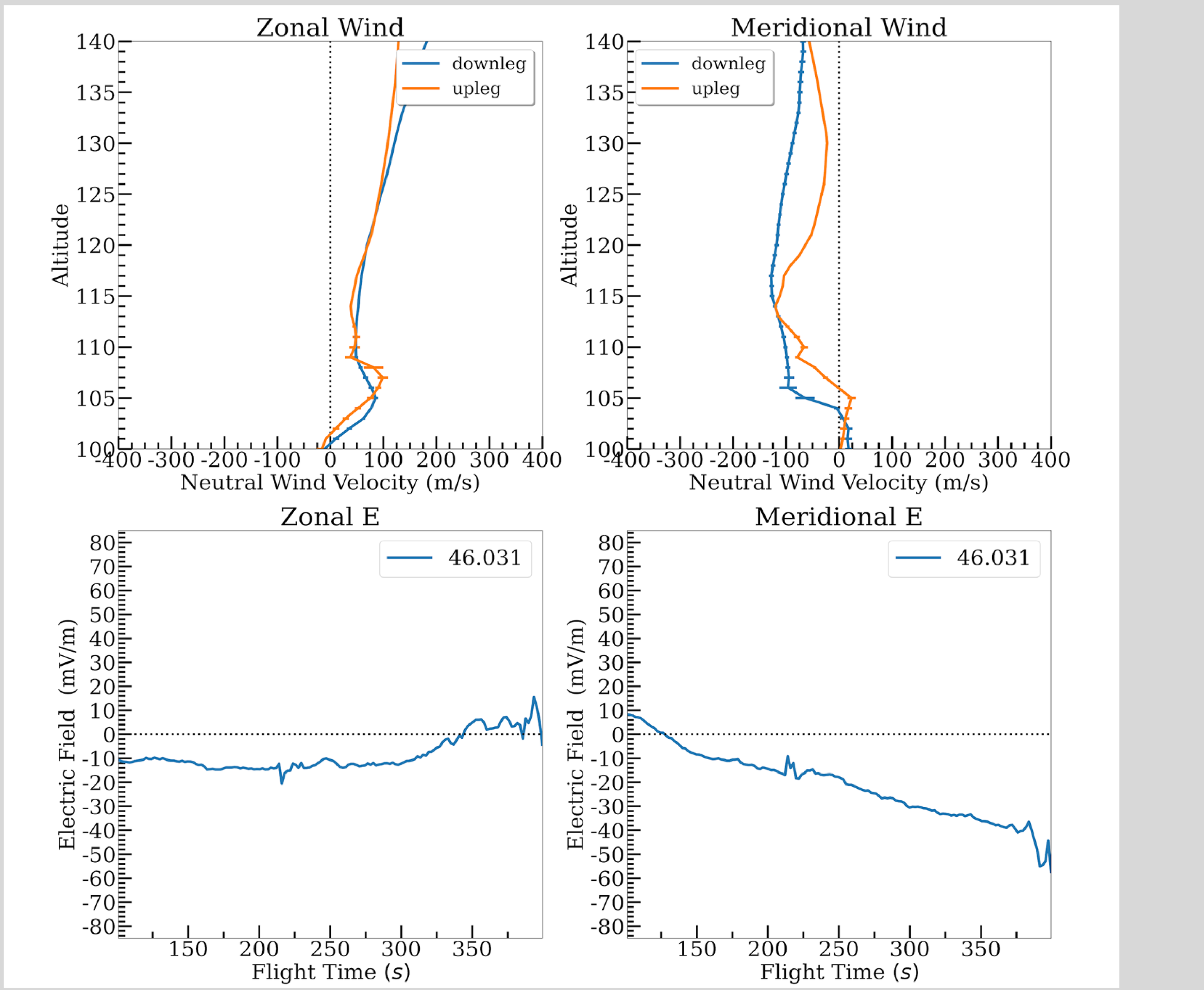

Figure 4: A four panel figure showing the neutral profile created following data collection and triangulation during the INCAA campaign above the in-situ measured electric fields. The error bars are associated with the measurement error that is dependent upon the miss distance found during the process of creating the profile. The modest electric fields and morning sector time of launch does not provide a sufficient balance of forcing to keep the neutrals in the acceleration channel or enough Lorentzian force to accelerate them.

Summary

- For each campaign depicted, we quantify the response of energy exchange parameters to independently derived neutral winds which is dependent upon the MLT sector and geomagnetic activity level. In agreement with the statistical results from Zhan et al., 2021, during low geomagnetic activity levels neutral winds tend to increase the rate of Joule heating in comparison to the passive energy deposition rate by 28% at E-region heights as shown in Figure 3. In more active times, neutral winds reduce the Joule heating rate at higher altitudes on the dusk side of the auroral oval (lower altitudes in the morning sector) to compensate for the primary driver of Joule heating during this forcing regime, the electric field. This is especially true for the Jets campaign as shown in figure 1 which was found to have an average reduction of 26% between 110-140 km during the enhanced geomagnetic activity prior to launch.
- Using independently derived neutral wind profiles provides a high degree of precision to the calculations presented. The agreement between the PFISR based and in-situ based calculations allow for high resolution investigations both temporally and spatially.
- **The differences in the ion and neutral forcing for these MLT sectors and geomagnetic activity levels directly impacts the dissipation of energy in the E-region ionosphere.**

Acknowledgements: We thank R. Pfaff (PI of Jets) for providing neutral wind profiles and guidance essential in this study. We also acknowledge NASA grant #80NSSC19K0810 for funding.