Ion heating in the polar cap under northwards IMF Bz

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Key Points:

- Ion temperature enhancements are frequently observed in the noon sector of the polar cap under IMF north conditions
- Current models driven by large-scale convection and precipitation fail to produce the observed ion temperature enhancements
- Mesoscale flows and precipitation structures may be critical to account for ion heating in the polar cap

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Abstract

Joule heating deposits a significant amount of energy into the high-latitude ionosphere and is an important factor in many magnetosphere-ionosphere-thermosphere coupling processes. Although the interplanetary magnetic field (IMF) is known to impact the Joule heating pattern across the entire polar cap ionosphere, it is less clear how it influences specific localized heating events. We consider the relationship between localized temperature enhancements in polar cap measured with the Resolute Bay Incoherent Scatter Radar-North (RISR-N) and the orientation of the IMF. Based on analysis of 10 years of data, RISR-N most commonly observes ion heating in the noon sector under northwards IMF B_z. We interpret heating events in that sector as being primarily driven by electric fields associated with lobe reconnection. We attempt to model two of the observed temperature enhancements with a data-driven first principles regional model of ionospheric plasma transport and dynamics, but fail to fully reproduce the ion temperature enhancements. However, evaluating the ion energy equation using the locally measured ion velocities reproduces the observed ion temperature enhancements. This result indicates that current techniques for estimating global electric fields are not adequately capturing mesoscale electric fields in the polar cap, and this can result in underestimation of the energy deposition into the ionosphere and thermosphere.

1 Introduction

Joule heating in the polar cap F-region ionosphere is a significant factor in magnetosphere-ionosphere coupling. Magnetic reconnection between the interplanetary magnetic field (IMF) and the Earth's magnetosphere drives strong plasma convection across the entire polar region (Dungey, 1961). A relative velocity between ionized species and neutral species increases collisions between the two and heats both the plasma and neutral populations (Thayer et al., 1995; Fujii et al., 1999; Thayer & Semeter, 2004; Aikio et al., 2012). Plasma temperature enhancements have been connected to ion upflow, which contributes to the outflow of ionospheric plasma into the magnetosphere (Wahlund et al., 1992; Skjæveland et al., 2011). Ion outflow from the polar ionosphere has been identified as a significant source of cold-ion transport into the ring current and plasma sheet (Peterson et al., 2009; Li et al., 2013), resulting in mass loading of the magnetosphere (Moore & Horwitz, 2007; Li et al., 2012).

Joule heating is most significant in the cusp and auroral regions at high latitudes (Foster & St.-Maurice, 1983; Olsson et al., 2004; Aikio & Selkälä, 2009), however, it has been identified as the dominate form of energy input into the polar cap, particularly during active periods (Lu et al., 2016). Joule heating is estimated to be responsible for 50%-60% of the global storm-time energy budget (Tanskanen et al., 2002; Østgaard et al., 2002; Knipp et al., 1998). The IMF orientation can also impact Joule heating at high latitudes, in addition to broader ion transport processes (McHarg et al., 2005; Howarth & Yau, 2008; Yau et al., 2012; Cai et al., 2014). Extensive statistical surveys of the entire high-latitude region have resulted in empirical models of Joule heating patterns parameterized by IMF conditions and geomagnetic indices (Chun et al., 2002; Palmroth et al., 2005; X. X. Zhang et al., 2005), however, these are mostly useful to gain insight on the average large-scale behavior and are not designed to predict localized heating events.

Time-varying magnetic reconnection at the mangetopause can drive heating events in the ionosphere (Moen et al., 2004; Lockwood et al., 2005). In particular, northwards IMF moves the reconnection point from close to the sun-earth line to the lobe of the magnetosphere, which significantly changes the ionospheric convection pattern (Burke et al., 1979; Cowley, 1983). The resulting pattern often has three or more cells and is highly asymmetric (particularly if there is also a strong IMF By component) (Reiff & Heelis, 1994; Förster, Haaland, et al., 2008; Cousins & Shepherd, 2010; Thomas & Sheperd, 2018). These patterns can cause strong flow channels in the dayside polar cap, which may be responsible for significant localized Joule heating events.

This study will examine the relationship between the IMF orientation and localized ion temperature enhancements in the polar cap ionosphere. In addition to a statistical analysis of ion temperature, we will attempt to model several observed Joule heating events to gain more insight as to what geophysical parameters and processes contribute to localized heating in the polar cap.

2 Methodology

2.1 RISR-N

The Resolute Bay Incoherent Scatter Radar - North (RISR-N) is an Advanced Modular Incoherent Scatter Radar (AMISR) located deep within the northern polar cap (Kelly & Heinselman, 2009; Bahcivan et al., 2010). At 82°N magnetic latitude (74.7°N, 94.9°W geodetic) with a boresight directed roughly towards the magnetic pole, RISR-N is ideally located to observe open field line plasma dynamics. By employing electronic beam steering, RISR-N can quickly cycle through multiple look directions within its field of view to measure electron density, ion and electron temperature, and line-of-sight plasma velocity in a 3D volume in the ionosphere. RISR-N first began collecting science data in 2009 and operated roughly 5-10 days per month between 2009-2018. In September 2018, a new smaller generator was installed at the site (in addition to the main generator) to power the radar, which allows much more flexibility in scheduling operations and observation time. One advantage of this has been several month-long periods of almost continuous low duty cycle radar operations since the beginning of 2019.

This study focuses on F-region dynamics so only long pulse data are presented. The standard AMISR processing routine gates the lag product array into autocorrelation functions, and determines the plasma parameters within each range gate through nonlinear least squares fitting of the autocorrelation functions. This analysis assumes the fitted parameters are slowly varying in range over the pulse length and in time over the integration period. Most standard modes have a range resolution between 49-72 km and a minimum integration period of 1-3 minutes. The data-model comparisons shown later in this study use special Topside modes, which are optimized for observing dynamics in the topside F-region. These topside modes use only 5 beam positions in order to increase the number of samples in each beam compared to more typical RISR-N modes using 11 to 52 beam positions. The topside modes interleave long pulses of different lengths, although this manuscript will only discuss parameters derived from the 480 μs pulses (72 km range spreading) using the standard AMISR processing.

2.2 IPWM

The Ionosphere/Polar Wind model (IPWM) is a 3D plasma transport model designed for high latitudes (Varney et al., 2015, 2016). It solves the 8-moment equations for the parallel transport of H^+, He^+, $O^+\left({}^4S\right)$, and electrons. Photochemistry for the species N^+, NO^+, N_2^+, O_2^+, $O^+\left({}^2D\right)$, and $O^+\left({}^2P\right)$ is also included. The model includes a kinetic electron solver, but it has been disabled for the simulations done in this study. Details on the parallel transport and chemistry schemes can be found in Varney et al. (2014) and a description of perpendicular transport is available in Varney et al. (2015). IPWM assumes no neutral winds, but the density and temperature of neutral species are takes from the Naval Research Laboratory's Mass Spectrometer Incoherent Scatter Radar Extended (NRLMSISE-00) empirical model (Picone et al., 2002). NRLMSISE-00 is driven by the F10.7 solar radio flux, a proxy for solar extreme ultraviolet radiation, and the Ap geomagnetic index. The solar EUV spectra is provided by a high-resolution solar EUV irradiance model for aeronomic calculations (HEUVAC) (Richards et al., 2006) and the model calculates production and heating from precipitation with the empirical relationships found in Fang et al. (2008).

IPWM uses a nonorthogonal magnetic-centered dipole Eulerian grid. The grid is constructed from surfaces of constant L shell, MLT, and altitude. The lower boundary is set at 97 km by chemical equilibrium while the upper boundary is open at 8400 km. The equatorward boundary (set at L=4) is treated as a hard wall with no transport from lower latitudes. All simulations shown in this paper use spatial resolution of 2° in dipole magnetic latitude and output parameters at a temporal resolution of 1 minute.

IPWM requires high-latitude energetic particle precipitation and electrostatic potential patterns as inputs. Past work with IPWM has always used magnetospheric simulations to set these inputs (Varney et al., 2016). In contrast, in this work, simulations will be driven by precipitation patterns derived from the Ovation Prime empirical model (Newell et al., 2009). Ovation Prime outputs the number flux and average energy of monoenergetic and broadband precipitation for a requested magnetic latitude and MLT at high latitudes. The model is based on data from the DMSP SSJ/4 electrostatic analyzers (Hardy et al., 1984, 2008) and is parameterized by solar wind conditions.

This study considers two independent sources of the high-latitude electrostatic potential: SuperDARN and AMPERE. The Super Dual Auroral Radar Network (SuperDARN) consists of about 30 ground-based high-frequency coherent-scatter radars at mid-, high-, and polar latitudes (Greenwald et al., 1995; Chisham et al., 2007). Each radar makes independent line-of-sight measurements of the plasma velocity, but convection maps covering the entire polar region can be created by combining all measurements from a particular time with climatological models of convection patters based on geophysical parameters such as the IMF and dipole tilt angle (Greenwald et al., 1995; Cousins & Shepherd, 2010; Thomas & Sheperd, 2018). The Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE) uses magnetic field data from the Iridium satellites to derive the global Birkeland current distributions (Waters et al., 2001;

Anderson et al., 2014). The Iridium Communications constellation consists of around 70 near-polar orbiting satellites, each carrying engineering magnetometers. Cross-track magnetic field perturbations can be inverted to determine field-aligned currents (Anderson et al., 2000; Waters et al., 2001). From AMPERE current distributions, it is possible to derive the electrostatic potential by assuming constant conductance across the polar cap (Richmond & Kamide, 1988; Cousins et al., 2015). Because SuperDARN and AMPERE electrostatic potential maps are based on two independent data sources and involve different assumptions, there can be significant differences between the two (Cousins et al., 2015). It is challenging to determine which is more accurate for any given period, so two IPWM simulations were run for each event discussed in this paper, one driven by SuperDARN potential patterns and one by AMPERE.

3 Results

3.1 Statistical Analysis of Ion Temperature Enhancements

We performed a statistical analysis of ion temperature over the entire RISR-N database in order to determine which conditions most commonly produced ion heating. The database consists of all 5-minute-integrated long-pulse data collected by RISR-N between January 2010 and February 2020. For each experiment, we filter out points where the AMISR fitting procedure is expected to have failed or where the ion temperature error exceeds 1000 K. Failed fits are detected by checking if the exit code from the Levenberg-Marquardt algorithm, which performs the nonlinear least-squares fitting, does not indicate successful convergence, or if the normalized chi-squared statistic is less than 0.1 or greater than 10. Then we extract the median ion temperature between 300–400 km altitude in the highest elevation beam within the grating lobe limit of the radar's field-of-view. Above 300 km, the AMISR fitting procedure assumes the ion composition is entirely O^+. For experiments where the database does not include 5-minute-integrated files, we post-integrate 1-minute data to 5 minutes by taking an error weighted average in time after the initial "failed fit" filter, then removing any points where the resulting weighted ion temperature error is greater than 1000 K before finding the median temperature between 300-400 km altitude. After extracting the median F-region ion temperature for every long-pulse experiment, we bin these data by MLT (0.8 hour bins) and the IMF clock angle (12° bins) using one-hour resolution OMNI data and calculate the average temperature in each bin. The results are plotted in Figure 1a. Note that the IMF clock angle is de-

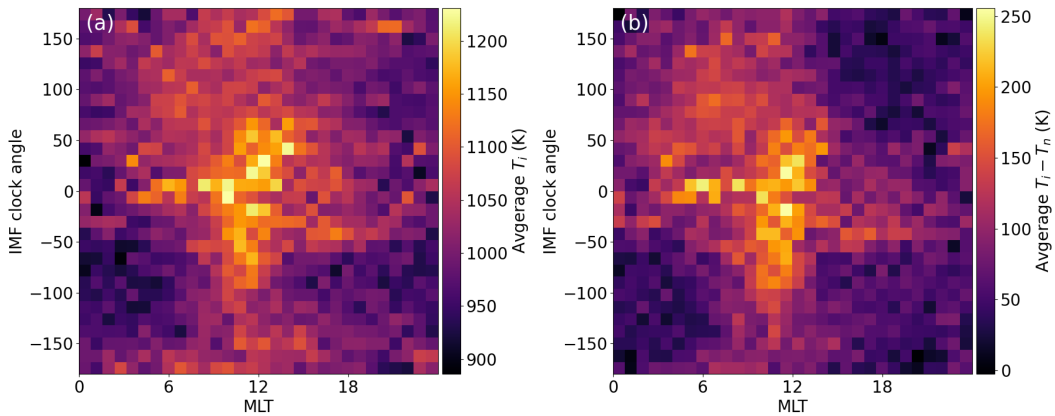

Figure 1. a) Average ion temperature observed by RISR-N per MLT sector and IMF clock angle (θ_c), and b) Average ion temperature minus NRLMSISE-00 neutral temperature per MLT sector and IMF clock angle. A clock angle of zero indicates northwards IMF.

fined as $\theta_c = \arctan By/Bz$ such that $\theta_c = 0°$ corresponds to the IMF directed northwards. In order to detrend diurnal, seasonal, and solar cycle variations in the neutral atmosphere, we have also computed the average of $(T_i - T_n)$ using neutral temperatures, T_n, from NRLMSISE-00 (Picone et al., 2002).

Figure 1a shows that on average, RISR-N observes higher ion temperatures in the noon sector, particularly when the IMF has a significant northwards component ($\theta_c = 0°$). Furthermore, Figure 1b demonstrates that this pattern persists even after subtracting NRLMSISE-00 neutral temperature. At 12 MLT, RISR-N is located just polewards of the cusp (B. Zhang et al., 2013). This region often experiences fast plasma flows, particularly under northwards IMF conditions when magnetic reconnection occurs in the lobe of the magnetosphere driving 4-cell or asymmetric convection patterns in the ionosphere. It should be clarified that these are flows in the polar cap and not associated with the bursty reconnection flows that occur in the cusp (Prikryl et al., 2002; Provan et al., 2002; Farugia et al., 2004). The elevated average ion temperature observed under these conditions may be due to an increased likelihood of RISR-N observing a Joule heating event due to fast sunward flows in the plasma driven by lobe reconnection.

The database contains several large heating events at local times away from 12 MLT, many of which are directly related to large geomagnetic storms. Most of these storm events, however, end up being statistical outliers in their particular MLT and IMF clock angle bin. Note that our analysis only sorts by IMF clock angle, and not IMF magnitude. The few storm events with very large IMF magnitude and southwards clock angle do show elevated ion temperatures, but the relatively rarity of those events results in them not significantly contributing to the averages in Figure 1. The enhancement at 12 MLT and $\theta_c = 0°$ in Figure 1 indicates that heating events under those conditions are very common and are not confined to geomagnetic storm times.

3.2 Modeling Joule Heating Events with IPWM

We chose two particularly large ion heating events observed by RISR-N for detailed case studies: one in May 2014 and another in April 2016. The May 2014 event has been previously discussed by Shen et al. (2016), and it was also a large ion upflow event observed by the enhanced Polar Outflow Probe (e-POP). Both of these events occurred during IMF northwards conditions and both were observed using topside modes at RISR-N. These events both have ion temperatures significantly higher than the average ion temperatures in Figure 1, but neither is as extreme as the September 2014 event previously discussed by Clauer et al. (2016). We modeled both of these events using convection patterns from both SuperDARN and AMPERE, for a total of four simulations. Animations of all full runs are provided in the supplementary materials.

Figure 2 summarizes the heating observations made during the May 2014 event and the two simulations of this event. Figures 2c shows ion temperature measured in the RISR-N beam closest to vertical (80° elevation), and the upper two panels show the ion temperature along the field line in the model grid cell closest to Resolute Bay. The data are presented in UT, and at RISR-N MLT = UT-6, such that noon is 18 UT. The RISR-N measurements in Figure 2c show two strong ion temperature enhancements on May 30, 2014, a broad one around 21 UT and a shorter but more intense one right before 22 UT. Figure 3 is a snapshot of the SuperDARN electric potential (left) and Ovation Prime monoenergetic precipitation average energy and flux (center) used to drive IPWM, as well as the output ion temperature from IPWM at 300 km. All panels are in the native IPWM dipole grid with grey dashed lines showing dipole colatitude 10° and 20° off the pole. The location of RISR-N at each time is indicated with the black tripod. Figure 4 has the same format as Figure 3, but is shown for a time during the second observed ion temperature enhancement right before 22 UT. For both time periods, the IMF has a strong northward component which restructured the ionospheric convection to produce a reverse convection cell near RISR-N. During the first observed heating period around 21

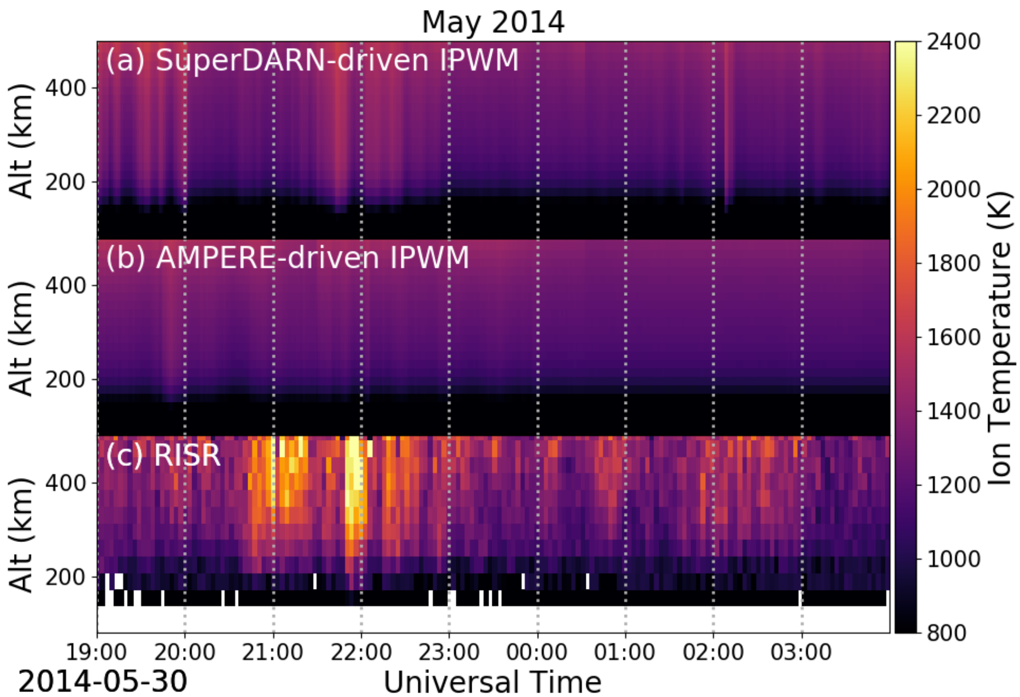

Figure 2. Modeled and observed ion temperature over Resolute Bay from May 30, 2014 19:00 UT to May 31, 2014 4:00 UT. Panel a shows the temperature modeled by IPWM driven by Ovation Prime precipitation and SuperDARN electric potential maps. Panel b shows the temperature modeled by IPWM driven by Ovation Prime precipitation and AMPERE electric potential maps. Panel c shows the ion temperature measured by RISR-N along the highest elevation beam.

UT (Figure 3), this reverse convection from SuperDARN is very weak, and IPWM did not produce any significant ion temperature enhancement. During the second period right before 22 UT (Figure 4), the SuperDARN reverse convection cell is more pronounced, and IPWM does generate some temperature enhancement. Nonetheless, this ion temperature enhancement is still substantially less than that measured by RISR-N.

Figure 5 summarizes the heating observations made during the April 2016 event and the two simulations of this event in the same format as Figure 2. The RISR-N observations in Figure 5c show two distinct heating events: a short one on April 21, 2016 around 19 UT and a much more extended event on April 22, 2016 between 17-20 UT. Neither SuperDARN-driven (Figure 5a) nor AMPERE-driven (Figure 5b) IPWM reproduced the short temperature enhancement on April 21, 2016, however both showed some evidence of enhanced ion temperatures during the longer heating event on the next day.

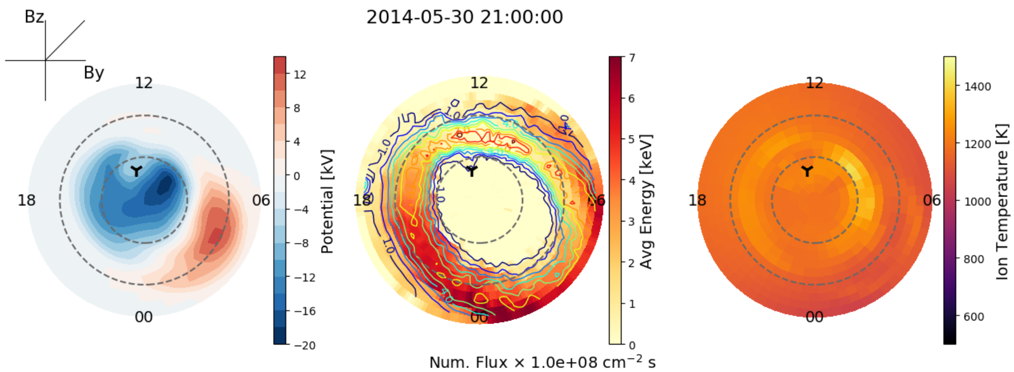

Figure 3. Snapshot of SuperDARN-driven IPWM run on May 30, 2014 at 21:00 UT. The left plot shows the electric potential used to drive IPWM at this time. The middle plot show the average energy (background color) and number flux (overlayed line contours) of the input monoenergetic particle precipitation from Ovation Prime. The right panel shows the modeled ion temperatures at 300 km. All panels are in the IPWM magnetic latitude/MLT grid. The two dashed grey circles indicate magnetic latitude 10° and 20° from the pole. The black tripod shows the location of RISR-N in each panel. IMF clock angle at this time is indicated in the top left corner.

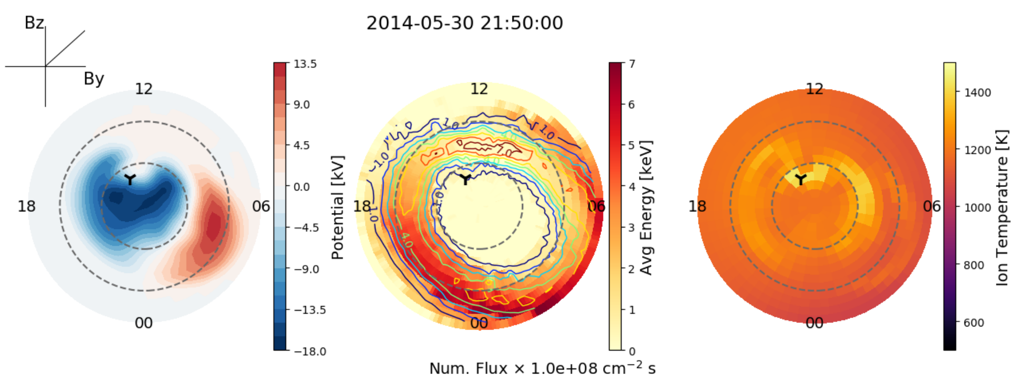

Figure 4. Snapshot of SuperDARN-driven IPWM run on May 30, 2014 at 21:50 UT. Figure format is the same as Figure 3.

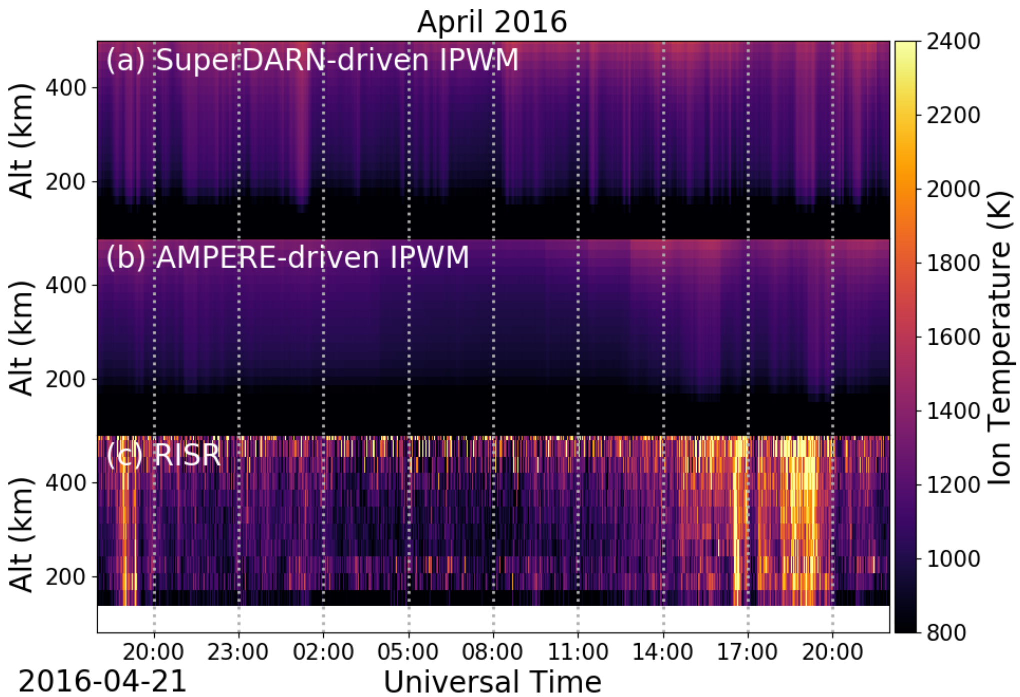

Figure 5. Modeled and observed ion temperature over Resolute Bay from April 21, 2016 18:00 UT to April 22, 2016 22:00 UT. Figure format same as Figure 2.

During this longer event, the IMF was northwards, but also had a significant By component, resulting in multi-celled and highly asymmetric convection patterns. A small temperature enhancement is seen in the vicinity of RISR-N in SuperDARN-driven IPWM at 19 UT (Figure 5a). As seen in Figure 6, this corresponds to a small region of dayside sunwards convection. A similar temperature enhancement is seen slightly later in the AMPERE-driven IPWM at around 19:30 UT (Figure 5b). In this case, the IMF is pointed almost entirely in the positive y direction, resulting in strong dawnward convection over RISR-N. It is important to note however that neither the SuperDARN-driven nor AMPERE-driven IPWM produced the duration or amplitude of the ion temperature enhancement observed in the RISR-N data.

4 Discussion

In the simulations shown in Section 3.2, IPWM is driven with measured convection patterns from either SuperDARN or AMPERE, yet strongly underestimate the observed ion temperature enhancements. This suggests that there are either fundamental

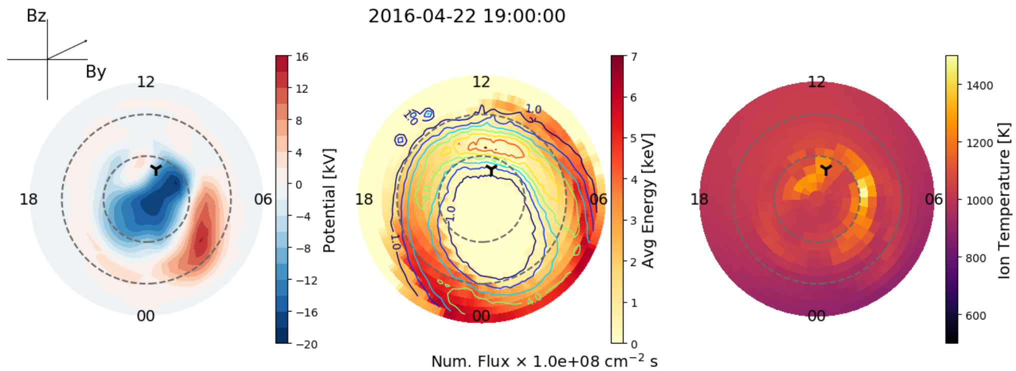

Figure 6. Snapshot of SuperDARN-driven IPWM run on April 22, 2016 at 19:00 UT. Figure format is the same as Figure 3.

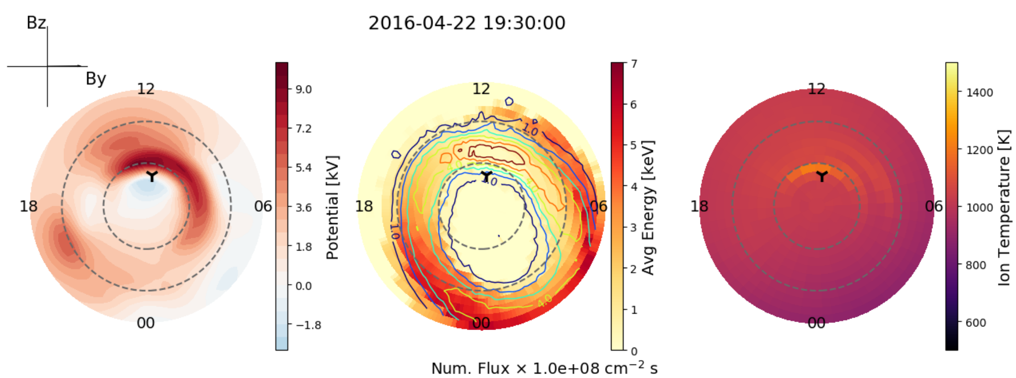

Figure 7. Snapshot of AMPERE-driven IPWM run on April 22, 2016 at 19:30 UT. Figure format is the same as Figure 3.

physics that are not being captured by IPWM or that the observation-based drivers do not adequately capture all important scales. In the F-region, Equation 1 is a reasonable approximation of the ion energy equation (St.-Maurice & Hanson, 1982).

$$T_i = T_n + \frac{m_n}{3k_B}\left|\vec{V_i} - \vec{V_n}\right|^2 \tag{1}$$

Here, T_i and T_n are the ion and neutral temperatures, respectively, m_n is the average mass of the neutral species, k_B is Boltzmann's constant, and $\vec{V_i}$ and $\vec{V_n}$ are the ion and neutral velocities, respectively. Although this expression describes frictional heating, Joule heating rates are equivalent to frictional heating rates under F-region assumptions (Thayer & Semeter, 2004). To first order in the F-region, the ion temperature is predominantly determined by the ion-neutral velocity difference.

Although both SuperDARN and AMPERE create data-derived convection patterns, neither system provides convection measurements with sufficient spatial resolution characterize small and meso-scale flows across the entire polar cap. It is possible that small and meso-scale flows are a significant source of heating in the polar cap ionosphere, contributing to the substantial temperature enhancements shown in Figures 2 and 5. Chen and Heelis (2018) tabulated a significant number of mesoscale (100-500 km) flow perturbations over the background convection and concluded they were an additional source of frictional heating. In order to assess the importance of meso-scale fast flows in our two events, we examined the local velocity observations from RISR-N. RISR-N line-of-sight velocity measurements from different beams can be inverted to derive the vector $\vec{E} \times \vec{B}$ plasma drift velocity by assuming the flow field varies slowly over the RISR-N field-of-view (Heinselman & Nicolls, 2008). In both events, RISR-N locally observed faster ion velocities than predicted by either the SuperDARN or AMPERE global patterns.

We also considered the possible role of neutral winds. The IPWM simulations in this work ignore the background neutral wind field, effectively assuming the neutral species are stationary with respect to the plasma. A nonzero neutral wind will reduce the heating rate if the neutral motion is aligned with the ion motion and enhance it if it opposes it, so neglecting the neutral wind should not result in a systematic underestimation of the ion temperature in all cases. Strong plasma velocity can drag the neutral atmosphere into a similar pattern through ion-neutral collisions (Richmond et al., 2003; Emmert et al., 2006; Förster, Rentz, et al., 2008). Billett et al. (2019) estimated the neutral wind response time to a change in plasma convection at high latitudes to be roughly 75–90 minutes, depending on the strength of the event. During the heating event shown in May 2014, the IMF moved steadily from southwards to northwards about 2 hours before the event was observed while in the April 2016 event, the IMF was strongly northwards for several hours before the heating event, but then moved southwards at the end of the observed heating period. In the May 2014 event, it is possible that differences between the neutral atmosphere motion and the plasma motion enhanced Joule heating. This is less likely in the April 2016 event due to the extended period of consistent IMF before the event began.

In order to test the consistency of the RISR-N observed temperature enhancements with the locally-measured $\vec{V}_i$, we have evaluated Equation 1 using the RISR-N locally-measured $\vec{V}_i$ and empirical models for T_n and $\vec{V}_n$. The neutral temperatures use Naval Research Laboratory's Mass Spectrometer Incoherent Scatter Radar Extended (NRLMSISE-00) emprical model (Picone et al., 2002), and the neutral winds use the High-latitude Thermospheric Wind Model (HL-TWiM) (Dhadly et al., 2019). HL-TWiM is an empirical model of F-region neutral winds based on several decades of high-latitude ground- and space-based measurements, including Fabry-Perot Interferometer measurements from an instrument at the Resolute Bay Observatory, colocated with RISR-N.

In general, the ion temperature calculated from Equation 1 with accurate mesoscale flows matches the measured temperature enhancements substantially better than the IPWM runs shown in Figures 2 and 5. Figure 8a shows the geodetic eastwards components of the RISR-N ion velocity (V_i, green) and the HL-TWiM neutral velocity (V_n, purple) at 300 km over Resolute Bay for the May 2014 event. Likewise, Figure 8b shows the geodetic northwards components of these velocities. The green lines in Figures 8c and 9c show the ion temperature calculated with Equation 1 neglecting the neutral wind ($\vec{V}_n = 0$) while the purple lines are the same calculation using neutral winds from HL-TWiM. The black line in Figure 8c is the percent difference between the ion temperatures calculated with and without accounting for neutral wind, with positive values (blue) indicating the background neutral winds enhance T_i and negative values (red) indicating they diminish T_i. Figure 8d shows the full temperature profile calculated over Resolute Bay with the RISR-N $\vec{V}_i$ and HL-TWiM $\vec{V}_n$, and Figures 8e shows the T_i profiles directly measured by RISR-N. Figure 9 shows the same calculations for the April 2016 event in the same format as 8.

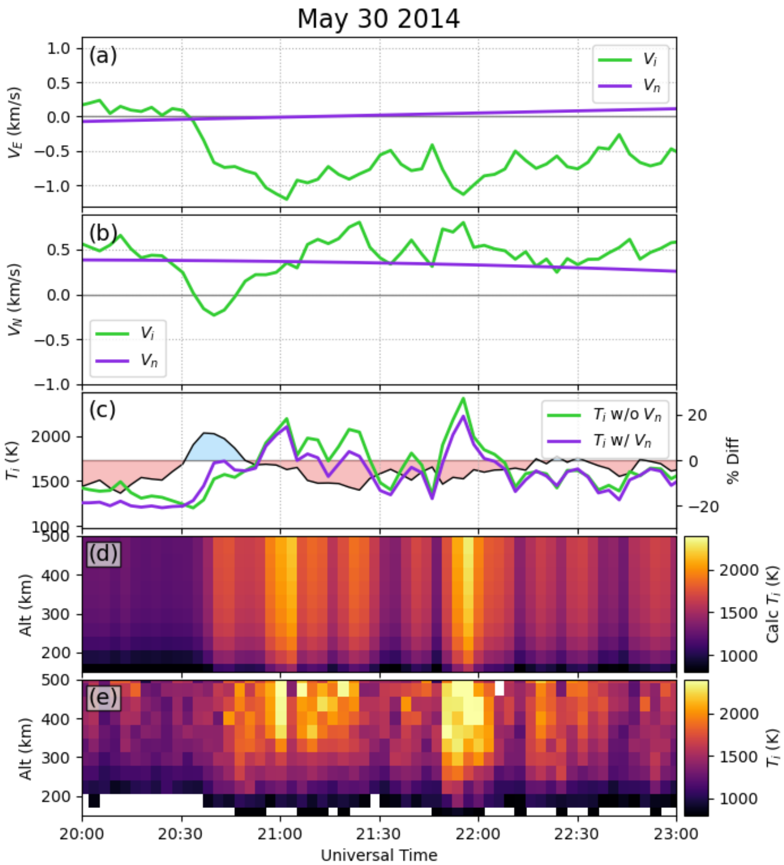

Figure 8. Comparison of the ion temperature calculated from RISR-N parameters with Equation 1 with the actual observed ion temperature for the May 2014 heating event. Panels a and b show the geodetic northwards and geodetic eastwards (respectively) components of the ion drift (V_i, green) and neutral wind (V_n, purple) at 300 km. The ion drift is the $\vec{E} \times \vec{B}$ plasma drift velocity reconstructed from all AMISR LoS velocity measurements while the netural winds are from HL-TWiM. Panel c shows the ion temperature calculated with Equation 1 at 300 km neglecting (green) and including (purple) the neutral winds, as well as the percent difference between the two (right hand axis). Panel d shows the full temperature profile calculated with Equation 1 using the RISR-N resolved ion velocities and HL-TWiM neutral winds. Panel e is the actual ion temperature directly measured by RISR-N.

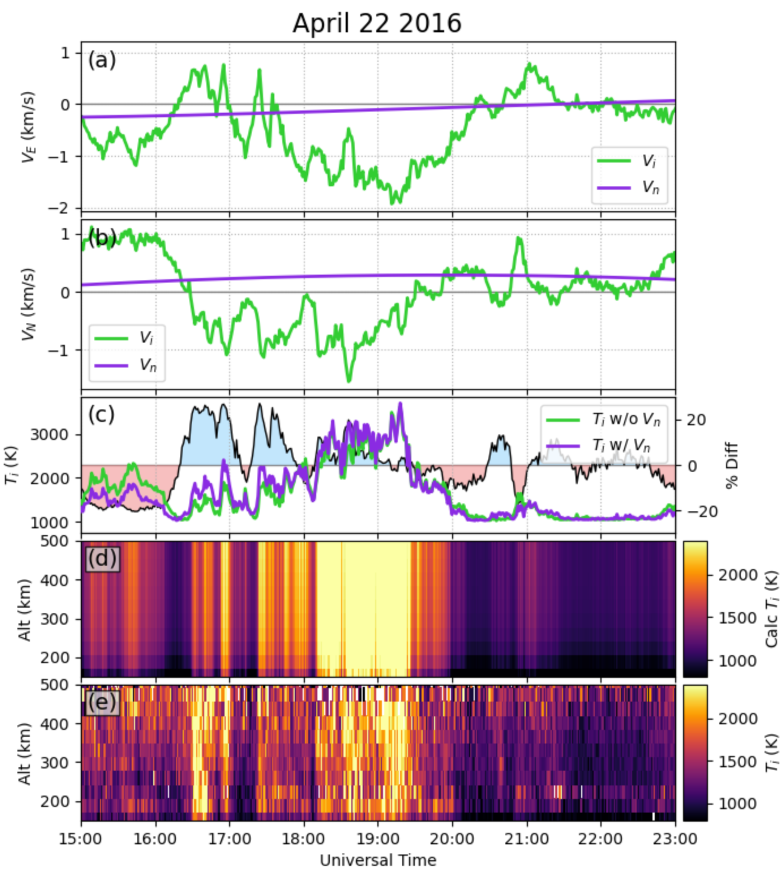

Figure 9. Comparison of calculated ion temperatures and observed ion temperatures for the April 2016 heating event. Figure format same as Figure 8

The neutral wind effects are generally of secondary importance compared to the magnitude of the ion drifts. For most of the May 30 heating event (except for a small period after 20:30 UT), neutral winds reduce the expected T_i by a small amount, generally less than 10%. The April 22 2016 heating event on the other hand has two distinct periods between 16:00–18:00 UT where neutral winds enhance T_i by over 20%. Neutral winds do not appear to significantly alter T_i during the main heating period on April 22 2016 (18:00–19:30 UT).

The underestimation of the ion temperatures in the IPWM simulations can be largely explained by the underestimation of the input ion velocities. IPWM is solving a much more complex ion energy equation than Equation 1, which includes heat conduction along the field lines and ion-electron heating. Nonetheless, we can verify that Equation 1 is a reasonable approximation for the F-region solutions in IPWM. Figure 10 shows the comparison of the IPWM results with the ion temperatures calculated from Equation 1 using the SuperDARN and AMPERE velocities directly for the May 2014 event. Like IPWM, this calculation uses NRLMSISE-00 for the neutral temperature and ignores the neutral winds. Figures 10a shows the ion temperatures from IPWM, similar to Figures 2a, but focused on the same time periods shown in Figures 8. Figures 10b shows the ion temperature calculated from Equation 1 with the SuperDARN $\vec{V}_i$ and neglecting $\vec{V}_n$. Panels c and d of Figure 10 are analogous to panels a and b, but use the AMPERE convection patterns. Figure 11 shows the same calculations for the April 2016 events in the same format as Figure 10. The strong similarities between the T_i profiles from IPWM and calculated from Equation 1 in Figures 10 and 11 confirm that Equation 1 is a suitable approximation of the full IPWM energy equation solution in the F-region. Neither the SuperDARN nor the AMPERE T_i profiles match the T_i profiles RISR-N measured during these heating events though (Figures 8e and 9e). This is a strong indicator mesoscale flow channels RISR-N observed during these heating events are critical to these extreme heating event.

The IPWM simulations presented in this study are relatively low resolution. Nonetheless, Equation 1 is an entirely local calculation that does not require gradients of any parameters. The calculations shown in Figures 10 and 11 confirm that IPWM agrees with this local equation. We have also confirmed that the velocities in the IPWM after grid interpolations retain approximately the same magnitudes as the velocities directly from

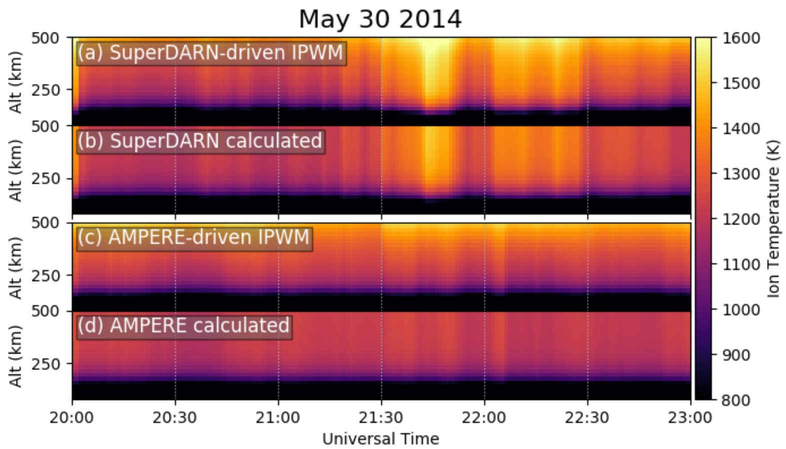

Figure 10. Comparision of ion temperatures produced by IPWM and those calculated with Equation 1 for the May 2014 heating event. Panels a and b are the ion temperature profiles from IPWM and Equation 1, respectively, using ion velocities from SuperDARN. Panels c and d are the ion temperature profiles from IPWM and Equation 1, respectively, using ion velocities from AMPERE.

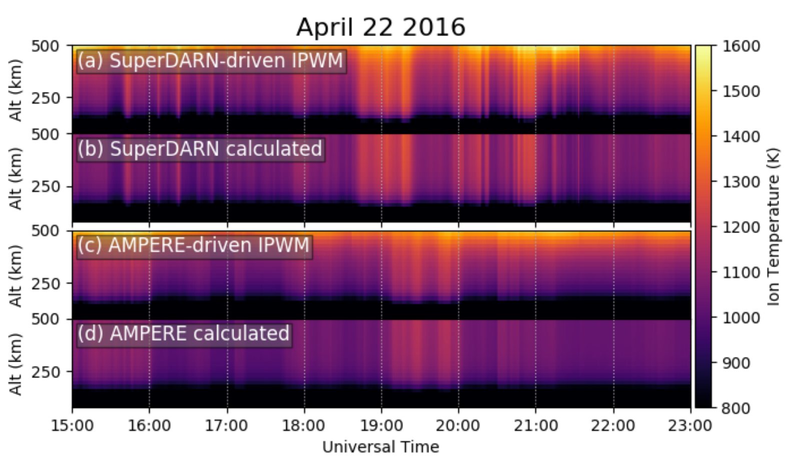

Figure 11. Comparision of ion temperatures produced by IPWM and those calculated with Equation 1 for the May 2014 heating event. Figure format is the same as Figure 10.

SuperDARN and AMPERE. Therefore, IPWM simulations at higher resolutions are not expected to produce significantly different results for the ion temperatures.

Previous studies have shown good agreement between the SuperDARN and RISR-N line-of-sight velocities (i.e. Koustov et al., 2016); however, there have rarely been comparisons specifically of strong flow events (≥ 1 km/s) like the ones that drove the heating events shown in Figures 8 and 9. Furthermore, both the SuperDARN and AMPERE electric potential patterns that were fed into IPWM are designed to be global-scale maps that show dynamics across the entire polar cap, and may struggle to reproduce extremely localized structures like the ones observed by RISR-N during these heating events.

In addition to subgrid flows, small-scale precipitation structures may also be import to localized heating events. Precipitation can modify the ionospheric conductivity profile, altering how effective Joule heating is at different altitudes. Ovation Prime is a purely empirical model, meaning that unlike the SuperDARN and AMPERE convection data sets that were used, it does not assimilate real measurements from a particular time so spectral characteristics are based exclusively off of historical statistics. In our simulations, RISR-N is consistently poleward large precipitating fluxes in the cusp and in a region where Ovation Prime predicts very little precipitation. The highly structured and dynamic nature of the polar cap in general presents a significant challenge to statistical models, but it is difficult to quantify the uncertainty between the model output and the true precipitation patterns. Northwards IMF conditions, such as those examined in this study, have been associated with sun-aligned arcs, which are known to contain mesoscale precipitation features (L. Zhu et al., 1997). Mesoscale precipitation features of scales not captured by Ovation Prime do impact Joule heating in the auroral zone (Kosch et al., 2011; Q. Zhu et al., 2018), but more research is required to determine if they have a similar effect in the polar cap.

Finally, the thermodynamic ion temperature is the second moment of the full 3D ion distribution function, whereas monostatic incoherent scatter radars can only measure the 1D marginal ion distribution function along the radar's line of sight (Akbari et al., 2017). Standard AMISR fitting assumes an isotropic Maxwellian distributions of both electrons and ions, in which case the 1D line of sight temperatures are the same as the full 3D ion distribution function. This assumption starts to break down under strong relative ion-neutral drift, which can cause the distribution function to migrate from the assumed isotropic distribution towards an anisotropic bi-Maxwellian or toroidal distribution (St.-Maurice & Shunk, 1977; St.-Maurice & Schunk, 1979). For a bi-Maxwellian distribution with different parallel and perpendicular ion temperatures, $T_{\parallel i}$ and $T_{\perp i}$, the ISR spectrum measured along a line of sight at an angle α away from the magnetic field will be identical to the ISR spectrum from an isotropic Maxwellian with effective temperature (Raman et al., 1981)

$$T_{1D} = T_{\parallel i} \cos^2 \alpha + T_{\perp i} \sin^2 \alpha, \tag{2}$$

which is generally different from the thermodynamic ion temperature for a bi-Maxwellian

$$T_i = \frac{1}{3} T_{\parallel i} + \frac{2}{3} T_{\perp i}. \tag{3}$$

For torodial ion distribution functions the ISR theory is far more complex, but the modifications to the spectral shape are only detectable at angles significantly far away from parallel to the magnetic field (Winser et al., 1989; Akbari et al., 2017). For the heating events shown in this study which are characterized by strong V_i flows, anisotropic plasma distributions are a reasonable concern. All data-model comparisons in this study employed high elevation beams with a small aspect angle with respect to the near-vertical magnetic field in the polar cap. Therefore, the measured ion temperatures presented in this work are essentially measurements of the parallel ion temperatures. For either bi-Maxwellian or torodial distributions that form due to frictional heating, the parallel temperature is expected to be less than the thermodynamic temperature, so the ion temperatures shown in Figures 2 and 5 can be thought of as a lower limit to the thermodynamic temperature (Akbari et al., 2017). This makes the fact that the modeled temperatures were significantly lower than the observed (lower limit) temperatures all the more significant.

5 Conclusion

Joule heating is a significant factor in magnetosphere-ionosphere-thermosphere coupling and energy deposition in the polar cap ionosphere. Using a decade of RISR-N data, we performed a statistical analysis of the conditions under which temperature enhancements were most likely to occur, then attempted to model two notable events with IPWM. On average, the highest ion temperatures were observed under IMF Bz north conditions when the radar was in the noon sector. This is likely due to lobe reconnection driving fast sunwards flows polewards of the cusp. Data-driven IPWM simulations reproduced some localized heating, but neither the timing nor the magnitude of the temperature enhancements produced by the model matched the dramatic heating events observed in RISR-N data. Calculations using the locally measured ion velocities, however, were able to explain the observations. Furthermore, neutral wind effects are only of secondary importance given the typical magnitudes of the neutral wind velocities compared to the fast ion drifts observed in the polar cap ($>$ 2 km/s). These results demonstrate that lobe reconnection can produce highly localized fast ion drifts that are very effective at producing frictional heating, and these localized drifts are not well resolved by current global electric field mapping techniques. More work is required to determine the origin of mesoscale structures in the polar cap and their impact on energy deposition.

Acknowledgments

This work is supported by NSF Grant AGS-1452191. Additionally, it is based upon work supported by the Resolute Bay Observatory which is a major facility funded by the National Science Foundation through cooperative agreement AGS-1840962 to SRI International. RISR-N data is available through the SRI International ISR Database at `https://amisr.com/database/`. The resolvedvelocities code which is used to generated the $\vec{E}\times\vec{B}$ plasma drift velocities from AMISR data is publicly available at `http://doi.org/10.5281/zenodo.4451504`. The 5-minute-integrated RISR-N database used for the statistical study, specific RISR-N data files used in the event studies, IPWM input and configuration files, and scripts for generating the results and plots shown in this paper have also been made publicly available (`https://doi.org/10.5281/zenodo.4453389`). IPWM output are available at `https://doi.org/10.5281/zenodo.4451249`, `http://doi.org/10.5281/zenodo.4452793`, `http://doi.org/10.5281/zenodo.4453485`, and `http://doi.org/10.5281/zenodo.4453495`. The analysis code is also available in a configured Resen bucket (Bhatt et al., 2020), also at `https://doi.org/10.5281/zenodo.4453389`. OMNI data was retrieved through spacepy (Morley et al., 2011).

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