AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2013GL058442

Key Points:

- *F* region Ti spikes occur in moderate conditions near the dusk plasmapause
- The spikes are related to small increases in magnetic activity
- Expansion of the convection enhances the friction between ions and neutrals

Correspondence to:
J.-P. St.-Maurice,
jp.stmaurice@usask.ca

Citation:
Goodwin, L., J.-P. St.-Maurice, P. Richards, M. Nicolls, and M. Hairston (2014), *F* region dusk ion temperature spikes at the equatorward edge of the high-latitude convection pattern, *Geophys. Res. Lett.*, *41*, 300–307, doi:10.1002/2013GL058442.

Received 23 OCT 2013
Accepted 13 DEC 2013
Accepted article online 16 DEC 2013
Published online 17 JAN 201

F region dusk ion temperature spikes at the equatorward edge of the high-latitude convection pattern

L. Goodwin[1], J.-P. St.-Maurice[1], P. Richards[2], M. Nicolls[3], and M. Hairston[4]

[1]Institute of Space and Atmospheric Studies, University of Saskatchewan, Saskatoon, Saskatchewan, Canada, [2]School of Physics, Astronomy and Computational Sciences (SPACS), George Mason University, Fairfax, Virginia, USA, [3]SRI International, Palo Alto, California, USA, [4]William B. Hanson Center, University of Texas at Dallas, Dallas, Texas, USA

Abstract Using Poker Flat Incoherent Scatter Radar data from the International Polar Year, we observed unexpected short-lived enhancements of a few 100 K in the *F* region ion temperature, or "T_i spikes", in conjunction with sharp *F* region plasma density drops near the dusk plasmapause. The geomagnetic conditions were moderately to weakly disturbed and the dusk spikes were often the largest T_i values recorded within the day. Taking various other observations into consideration, we conclude that the radar observed ion frictional heating events driven by large ion-neutral relative drifts caused by temporary intensifications in the convection pattern. The heating rate was enhanced through an increase in the size of the convection pattern, causing the neutrals just poleward of the dusk plasmapause to be moving antisunward while ions were moving sunward.

1. Introduction

Incoherent scatter radars (ISRs) are powerful tools in the study of ionospheric phenomena, which in turn relate to the larger issues of coupling between the ionosphere, the thermosphere, and the magnetosphere. We examine one facet of this coupling here by uncovering a new link between the interplanetary magnetic field and ion heating just poleward of the plasmapause, which is indicative in turn of a localized region of heretofore unexpected Joule heating.

With enough power, and special coded pulse sequences ISRs can provide simultaneous measurements of the plasma density, the ion and electron temperatures, and the line-of-sight velocity of the plasma, with a resolution as small as tens of seconds in time and fractions of kilometers in space. The main drawback is the requirement for high peak power and large aperture systems. As a result of the operational costs and complexity, compromises have to be struck with duty cycle and/or duration of experiments. Typically, experiments are of short durations, which can hide interesting morphological signatures. Alternatively, lower duty cycle and lower average power measurements can be used for long-duration experiments, albeit with reduced statistics and time resolution. This was done during the International Polar Year (IPY) in 2007, when the Poker Flat Incoherent Scatter Radar (PFISR) in Alaska provided a continuous set of ionospheric measurements at the expense of a 15 min long resolution [*Sojka et al.*, 2009]. Interspersed with these continuous observations were other higher-resolution campaigns. The low duty cycle scheme was so successful that PFISR has continued to use this IPY "background mode" when not running high duty cycle experiments.

The observations reported here revealed isolated strong ion temperature peaks in the 15 min resolution data. The events took place in the dusk sector during moderately disturbed conditions with the radar line-of-sight along the geomagnetic field direction. The brevity of the events meant that their repeated detection would have not been possible without the IPY background mode. Given (1) the moderate K_p of 1.5 to 2.5, (2) the location of the radar at 63.5° invariant latitude, and (3) the asymmetry of the auroral region, it is important to note that the radar was entering the auroral oval through the dusk sector around 6 to 8 UT before exiting it through the dawn sector roughly 12 h later.

In what follows we first describe our data set and the circumstances behind the *F* region T_i spikes. We then show that the spikes were caused by a temporary increase in the convection electric field and that the observations were on the equatorward boundary of the high-latitude convection region. We then discuss the origin of the spikes and why they were only seen when the radar was near the dusk plasmapause.

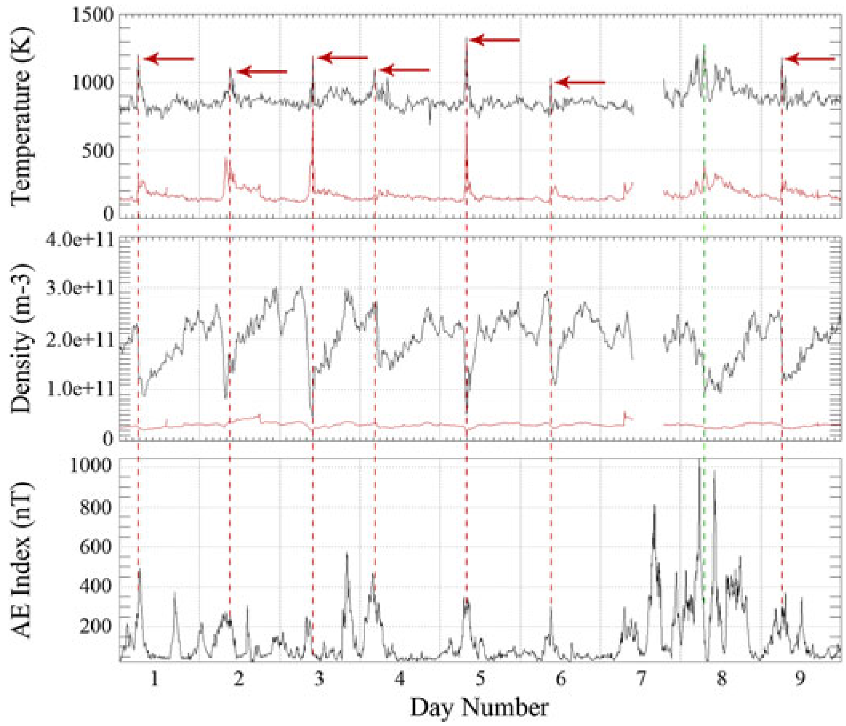

Figure 1. (top) T_i at 275 km from 27 June 2007 (day 1) to 5 July 2007, as a function of UT. Arrows indicate spikes. (middle) n_e at 275 km. (bottom) *AE* index as a function of time. Dashed lines indicate the T_i enhancement times. A green rather than red line was used for 4 July because a definite spike event could not be determined unambiguously on that day. Error bars (multiplied by 10 to facilitate their display) are also shown for T_i and n_e through the red traces in the top and middle panels.

2. The Observation of T_i Spikes by PFISR

Figure 1 provides an unusual example of repeated "T_i spikes" characterized by a risetime often equal to the 15 min integration time and lasting for 30 to 45 min. They occurred on an almost daily basis for the nine consecutive days interval, starting on 27 June 2007. The observations were taken along the geomagnetic field (azimuth −154° east of north, elevation 77.5°) using long pulse data with a 35 km resolution. Short pulse data with a 4.5 km resolution from an alternating-coded pulse were also available for higher spatial resolution, but these data had larger uncertainties and were only needed below 200 km, where plasma parameters change over smaller distances. In the low duty cycle (1%) used during the bulk of the IPY, results were processed with a 15 min integration time. The T_i analysis assumed O^+ to be by far the dominant ion at 275 km, which was likely an overestimation for high latitudes. However, even if the O^+ to NO^+ density ratio had been as little as a factor of 3, the ion temperature would have been underestimated by less than ≈10%.

Figure 1 (top) shows how T_i and the plasma density, n_e, (middle) were changing as a function of time at 275 km altitude. Figure 1 (middle), together with the vertical dashed lines, indicates that every T_i spike occurred in the immediate vicinity of a steep decrease in the *F* region electron density. The error bars for each parameter are also displayed. Figure 1 (bottom) is discussed later.

We also used convection maps inferred from the Super Dual Auroral Radar Network (SuperDARN) HF radar data [*Ruohoniemi and Baker*, 1998] to determine the PFISR radar position relative to the high-latitude convection pattern for the days shown in Figure 1. One typical example is provided in Figure 2 for 27 June just before the T_i spike was observed. It shows that PFISR was clearly near the dusk equatorward boundary of the sunward ion convection region.

The position of PFISR relative to the convection pattern explains why the *F* region density undergoes a sudden drop a short time before the T_i spikes. The plasma observed just before the spikes is corotating with the earth, i.e., moving antisunward, gradually entering a region of higher solar zenith angles. However, a few moments later, the radar observes sunward moving plasma coming from the nightside. The *F* region plasma carried by the convection undergoes decay due to elevated solar zenith angles or nighttime conditions prevailing after the plasma has convected through darker conditions. One possibility is that after having

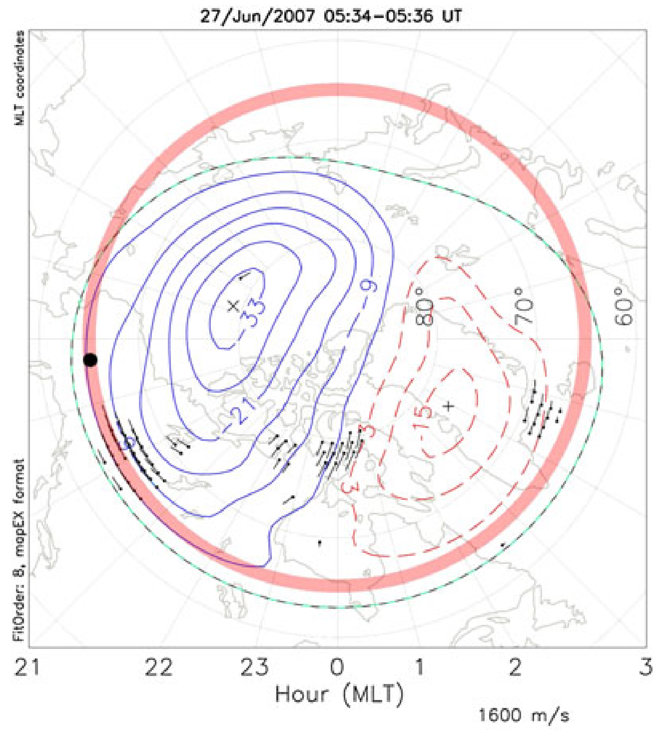

Figure 2. PFISR position (black dot on red circle) relative to the convection cell pattern reconstructed from the SuperDARN data. The position is given just before the onset of the 27 June 2007, T_i spike.

convected over the polar cap, the plasma moved to lower latitudes where there was no sunlight, prior to returning to lower solar zenith angle regions as it approached the dusk sector. Another possibility is that the plasma corotated at first but after reaching a region of darkness or of high solar zenith angles, got caught in a sunward convection owing to a growth in the size of the convection pattern. Either way, the sharp density changes have to be a signature of the boundary between plasmas with very different histories, which we consider a very good indicator of the high-latitude convection boundary, or the plasmapause. The presence of a clear boundary requires the absence of large changes in the plasmapause position, explaining the connection with the relatively quiet conditions.

3. The Electric Field Origin of the T_i Spikes

3.1. Epoch Study Results From the IPY

We produced an epoch study with $t = 0$ at the peak of the spikes. The data came from 15 min integration times and comprised T_i spike events found on 25 different days during the IPY. The events had the signatures displayed in Figure 1, namely, sharp T_i maxima appearing within 1.5 h of a precipitous drop in the 275 km plasma density after a clear density plateau. All the events were found to be in the dusk sector, with the bulk within the interval 4 to 9 UT. The epoch results are displayed in Figure 3.

Figure 3a shows the evolution of T_i against altitude and epoch time. It shows that the rise in T_i around the spikes was steeper than the decline, with the overall period of elevated ion temperatures lasting approximately 1.5 h. Furthermore, the plasma density drop normally preceded the T_i spikes, if only for a brief moment (Figure 3c). We also produced an epoch plot of T_e (not shown), which showed nothing of interest. Furthermore, for the 9 day interval shown in Figure 1 we reanalyzed the data using a 5 min integration time. The results (not shown) showed that in spite of added noise, the T_i peaks had a tendency to rise at a faster rate, were showing added structure, and had sharper peaks (by up to 150K) than seen through the 15 min integration time used to produce Figures 1 and 3. The 30 to 45 min event duration was not affected.

3.2. Implications From the Ion Energy Balance

To understand the origin of the T_i spikes we now consider the ion energy balance. In the F region the ion-neutral collision frequency is so large that advection and conduction of heat and viscous heating can be

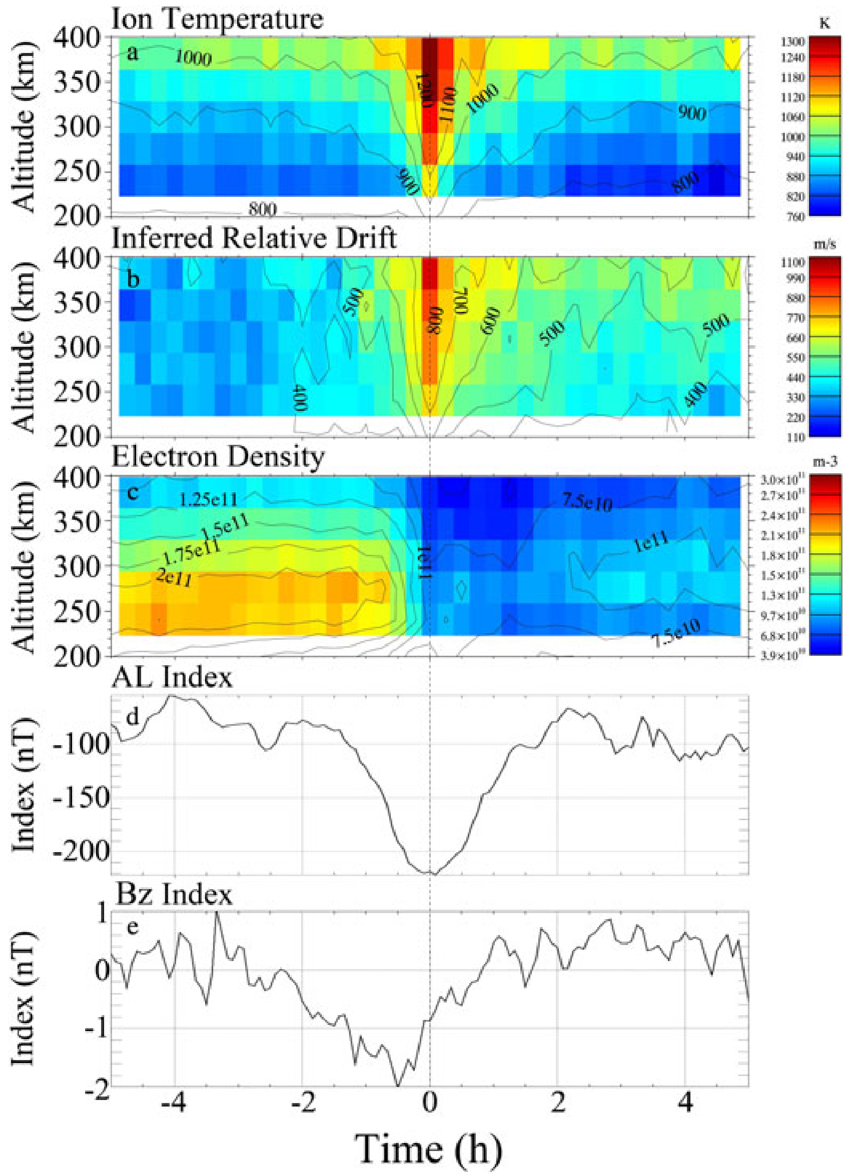

Figure 3. Epoch studies of 25 events of the type shown in Figure 1 using 15 min integration times. The zero epoch time matches when a T_i spike reached its peak. (a) T_i. (b) Inferred ion-neutral relative drift, after subtracting 100 K from the Mass Spectrometer Incoherent Scatter (MSIS) neutral temperature. (c) n_e. (d) *AL* index. (e) IMF B_z from the OMNI database.

neglected. The remaining terms are frictional heating due to ion-neutral collisions plus heat exchange with neutrals and electrons. This yields the following leading order result [*St.-Maurice and Hanson*, 1984]:

$$T_i \approx \frac{\frac{m_n}{3k_b}(\mathbf{V_i} - \mathbf{V}_n)^2 + T_n + \frac{m_i+m_n}{m_i}\frac{\nu_{ie}}{\nu_{in}}T_e}{1 + \frac{m_i+m_n}{m_i}\frac{\nu_{ie}}{\nu_{in}}} \tag{1}$$

where m_i and m_n are the ion and neutral masses, T_n and T_e are the neutral and electron temperatures, ν_{ie} and ν_{in} and the ion-neutral and ion-electron collision frequencies, k_b is the Boltzmann constant, and $\mathbf{V}_i$ and $\mathbf{V}_n$ are the ion and neutral velocities. The heat exchange with electrons is not very significant in the lower *F* region, but we included it, as it was easy to compute since n_e and T_e were both available from observations.

It follows from (1) that the T_i spikes could be due to spikes in T_e, T_n, m_n, or $|\mathbf{V}_i - \mathbf{V}_n|$. We can rule out T_e, which observations showed was clearly not spiky. Also if there were spikes in T_n or m_n they had to be related to a sharp increase in Joule heating, which would have meant a spike in $|\mathbf{V}_i - \mathbf{V}_n|$ to start with. In addition, there is no documented case of sudden neutral temperature or mass increase over narrow portions of the

F region. This has been shown from small-scale numerical model calculations [e.g., *St-Maurice and Schunk*, 1981; *Fuller-Rowell*, 1984; *Chang and St.-Maurice*, 1991]. This leaves a spike in the relative ion-neutral drift as the most likely culprit. Still, larger-scale changes in T_n and m_n had to be present. They were estimated using the empirical MSIS model [*Hedin*, 1987]. One issue with the use of MSIS is that it produced T_n values that were often greater than T_i, contrary to physical expectations. To remedy this shortcoming we had to decrease the T_n model values by 100 K in order for T_i to stay greater or equal to T_n most of the time. This correction is relatively large, probably owing to the exceptionally quiet solar conditions that prevailed during the IPY.

Shown in Figure 3b are the values recovered from equation (1) for $|\mathbf{V}_i - \mathbf{V}_n|$ using the observed T_e, the model m_n values and the modified T_n model values. While the magnitude of the individual spikes varied from day to day, the important point is that the average magnitude implied relative drifts of the order of 800 m/s resulting if we use the 15 min integration times. The relative drift goes up to 1000 m/s when we use the smaller subset with the more accurate 5 min integration, where the spikes are found to be narrower and sharper than indicated by the 15 min integration.

It should be clear that the bulk of the increase in the magnitude of $|\mathbf{V}_i - \mathbf{V}_n|$ was due to $\mathbf{V}_i$, that is, to a surge in the plasma $\mathbf{E} \times \mathbf{B}$ drift. This conclusion has to be reached because the neutral winds cannot develop spikes, and certainly not multiple spikes of the kind seen in the 5 min integrations, in time or space. Furthermore, if and when the neutral winds change appreciably and quickly, it's because of a large ion drag effect, namely, a "spike" in the ion drift to start with [e.g., *St-Maurice and Schunk*, 1981; *Fuller-Rowell*, 1984; *Chang and St.-Maurice*, 1991].

4. Questions Raised by the Morphology of the Spikes

4.1. Are the T_i Spikes Localized in Time or in Space?

Figure 3a shows that the T_i spikes were the largest temperatures recorded within an 8 h span. They were also often the largest temperatures recorded on a given day (e.g., Figure 1). They were found in the dusk sector, just poleward of the plasmapause. This indicates that the spikes were localized in space. However, it turns out that they were also related to a larger-scale phenomenon of a relatively brief duration. A first argument supporting this notion comes from the few rare instances for which the radar was used to infer electric fields during higher-resolution campaigns using multiple beams looking poleward of its location. Reliable electric fields were recovered at positions 2° of latitude to the north and beyond. At the times of the T_i spikes, the following clearly stood out when electric field observations were made: (1) for every observed T_i spike, there was a corresponding northward electric field spike to the north of the radar with drift magnitudes peaking between 600 and 800 m/s; (2) not all electric field spikes to the north of the radar were associated with a T_i spike seen at the latitude of the radar. A simple explanation for the second feature is that the radar was sometimes equatorward of the convection region. More importantly, the first feature indicates that the spikes were associated with large scale changes in the electric field: While T_i at the latitude of the radar was going through a peak in 15 min or less, the radar was traveling across equipotentials (as indicated by a 23° angle of the drift with respect to a circle of geographic latitude, and consistent with Figure 2) by less than 1° in latitude, even though the associated observed spikes in the electric field were 2° to the north and beyond.

A second point favoring a global temporal effect on top of a localized one is based on Figures 3e and 1 (bottom), which show that the T_i spikes were associated with a minimum in the *AL* index (and a maximum in the *AE* index). The *AL* and *AE* indices measure the intensity of electric currents around the auroral regions. Since the radar showed little in the way of precipitation during the days involved (consistent with weak activity) we can infer that the increase in the *AE* index was associated with an increase in the overall electric field strength of the high-latitude convection pattern more than with an increase in the *E* region electron density. Figure 3e shows weak 1 to 3 h long negative excursions in the *z* component of the Interplanetary Magnetic Field (IMF B_z) near the bow shock occurring, on average, 30 min before *AL* reached a minimum, thereby pointing to a likely origin for the weak episodic periods of activity.

On a more anecdotal note, Defense Meteorological Satellite Program (DMSP) data from four satellites were retrieved for some of the dates on which the T_i spikes and accompanying *AE*/*AL* oscillations were obtained. The reliable data coverage was limited to the sunlit higher latitudes owing to depleted O^+ densities elsewhere at the orbiting height for the quiet conditions prevailing in 2007. For the orbits closest to the *AE* maxima, the high-latitude convection was stronger than for the orbits before or after. For summer data (half of our data set), the DMSP orbits were also distinctly sunward of the radar observations when PFISR was in the dusk sector. It should also be noted that at least for these locations, the convection showed no sign of local enhancements near the plasmapause, consistent with the sunlit conditions and our current understanding of SAPS (subauroral polarization streams).

Taken together, the simultaneous intensification in the *AE* index, the handful of radar electric field observations, and the DMSP observations were all consistent with the T_i spikes being associated with brief (1 to 2 h) periods of enhancement in the global convection pattern. The spikes were observed when the strength of the *AE*/*AL* index and of the few recorded electric fields were maximizing (within ± 20 min of the recorded peaks in *AE* in particular).

4.2. Why Were the Spikes Occurring Only Near the Plasmapause in the Dusk Sector?

It might seem easy at first to dismiss the location of the spikes as an effect of data preselection on our part. However, recall that in Figure 1 the T_i spikes were the largest temperatures recorded over a 24 h period. Furthermore, there were other episodes of comparable enhancements in the *AE* index without obvious T_i enhancements, even though the radar was clearly inside the high-latitude convection region. For these episodes only modest enhancements in T_i were recorded (examples can be seen in Figure 1). We should add that, by contrast, during actual magnetic storms and/or with large substorms and large *AE* peaks, for example on 4 July 2007, T_i spikes were indeed recorded anywhere the radar happened to be when the electric field became very strong, as long as the radar was inside the region of high-latitude convection.

We conclude that the region just poleward of the dusk plasmapause favored the occurrence of T_i spikes. Two factors could have been involved to locally create this phenomenon. The first possibility is that the electric field was systematically stronger near the plasmapause when the overall convection pattern was intensifying. Electric field strengths of the order of 40 mV/m or more and the location would be consistent with SAPS [*Foster and Burke*, 2002]. The lack of major storm activity and the evening location could also indicate that narrower and more intense 2° wide SAIDs (subauroral ion drifts) were behind the observations [*Spiro et al.*, 1979; *Wang et al.*, 2008; *Wang and Lühr*, 2011; *Smiddy et al.*, 1977]. Taken at face value, and with the absence of spikes when the radar was deeper into the high-latitude convection region, this would indicate that the SAIDs were of the order of 40 mV/m while the rest of the convection region registered fields not much stronger than 30 mV/m, given the lack of strong frictional heating everywhere else. One problem with this interpretation is that many of the spikes occurred in summer and covered the time interval 15 to 21 magnetic local time (MLT), whereas SAIDs are typically seen in winter around 21 MLT, that is, away from sunlit conditions. Another problem is that on the few occasions for which there were radar electric field observations to the north of PFISR the electric fields were already of the order of 40 mV/m, which should have been enough to create T_i spikes. This suggests that another factor was at play.

The only other mechanism that we could think of for the privileged location of spikes involves the neutral wind as follows: equatorward of the plasmapause where the ion drift is normally weak and antisunward, the neutrals also moved antisunward with a speed of the order of 200 to 300 m/s [e.g., *Fuller-Rowell et al.*, 2008]. However, when the magnetic activity, weak as it was, was picking up, the whole convection region expanded, with the plasmapause moving equatorward, as observed during substorms by, e.g., *Goldstein* [2007]. The SuperDARN data, when available, also show somewhat broader and stronger convection regions near dusk at the *AE* peaks. An immediate result of the equatorward motion of the plasmapause was that the ions would have been moving sunward at, say, 600 m/s in a region where the neutrals were still moving antisunward at, say, 200 m/s, for a total relative drift of the order of 800 m/s, enough to explain the magnitude of the T_i spikes. However, poleward of this region, namely, after a long enough exposure to ion drag, the neutrals are known to start moving sunward [*St–Maurice and Hanson*, 1982; *Fuller-Rowell and Rees*, 1981]. This would mean that the relative drift would be less than 400 m/s poleward of the plasmapause, too small to produce ion temperature enhancements in excess of 100 K. The sudden increase in T_i at the onset and its subsequent gradual decrease are consistent, in other words, with a gradual rotation of the neutral wind with increasing latitude; a substantial rotation is expected in the evening sector, but not the morning sector, owing to the role played by the Coriolis force [*Fuller-Rowell and Rees*, 1981].

5. Summary and Conclusion

During the IPY we uncovered 25 days during which there were isolated T_i spikes in the dusk sector just poleward of the plasmapause. Our reconstruction of the events starts with, on average, 1 to 3 h long −2 nT excursions in the IMF B_z. These excursions did not trigger magnetic storms, with excursions in the *SYM-H* index all smaller than 10 nT in magnitude (not shown). The negative IMF B_z excursions triggered a few 100 nT responses in the *AE*/*AL* indices, 1 to 3 h in duration, approximately 30 min later. Associated with these *AE*/*AL* enhancements, the convection electric fields became stronger and expanded equatorward. The few electric fields retrieved during the events indicated that their strengths were of the order of 40 mV/m 2° north of the radar. As such, a 40 mV/m field should have been able to produce observable T_i enhancements of the order of a few 100 K above the background. However, we only observed the enhancements in the form of short-lived spikes less than 1 h in duration and always only near the boundary of the ion sunward convection at dusk.

The most likely explanation for a lack of T_i spikes poleward of the convection boundary but of strong spikes at the convection boundary is that neutrals strongly affected T_i through its dependence on $(\mathbf{V}_i - \mathbf{V}_n)^2$ in the *F* region. At the equatorward edge of the expanded convection boundary, the sunward ion convection had no time to give the neutrals a sunward component through frictional drag. However, according to separate model and observational studies, at higher latitudes the neutrals do acquire a substantial sunward component if exposed for long enough to sunward ion drag in the dusk sector. This means a much higher T_i just poleward of the plasmapause than further poleward, and a higher probability of detecting a large T_i just after the radar has passed through the plasmapause 30 min after the negative IMF B_z excursions. From this perspective, the duration of the heating events also had to be shorter than the *AE*/*AL* excursions since the hot T_i regions typically had to take place while an *AE* event was already in progress when the radar was passing through the plasmapause.

It remains possible that the electric fields were stronger near the plasmapause , i.e., SAID like, although the morphology did not look quite right for that. Besides, the electric fields a bit to the north of the radar, when measured, were of the order of 40 mV/m, implying that SAIDs would have not been necessary to explain the T_i spikes: with neutral winds of the order of 200 to 300 m/s flowing antisunward at the radar latitude, there already was more than enough relative drift to make sense of the observations with rather uniform fields of 30 to 40 mV/m. The more important question answered by the neutral wind contribution is actually an explanation as to why T_i was not going through a substantial enhancement when the electric field poleward of the convection boundary should have been strong enough on its own to produce a large T_i.

Our work indicates that when the IMF B_z undergoes small short-lived excursions, substorm-like *AE* excursions are triggered without magnetic storms. Furthermore, the *F* region T_i provides a sensitive way to study overall electric field strengths once the convection electric fields are of the order of 40 mV/m or greater. It would be of interest to study the correspondence between the IMF, *AE* and *AL*, and T_i under more strongly driven conditions when T_i enhancements would not be limited to the dusk sector near the plasmapause.

Acknowledgments
PFISR is operated by SRI International on behalf of the U.S. National Science Foundation under NSF Cooperative Agreement AGS-1133009. We thank S. Chen for having reprocessed the radar data with a shorter integration time. P.G.R. was supported by NSF grant 1048350 to George Mason University. J.P.S.M. and L.G. were supported by NSERC and the Canada Research Chair program. The OMNI data were obtained from the GSFC/SPDF OMNIWeb interface at http://omniweb.gsfc.nasa.gov.

The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

References

Chang, C., and J.-P. St.-Maurice (1991), Two-dimensional high-latitude thermospheric modeling: A comparison between moderate and extremely disturbed conditions, *Can. J. Phys.*, *69*(8–9), 1007–1031.

Foster, J., and W. Burke (2002), SAPS: A new categorization for sub-auroral electric fields, *Eos, Trans. AGU*, *83*(36), 393–394.

Fuller-Rowell, T. (1984), A two-dimensional, high-resolution, nested-grid model of the thermosphere: 1. Neutral response to an electric field "spike", *J. Geophys. Res.*, *89*, 2971–2990.

Fuller-Rowell, T. J., and D. Rees (1981), A three-dimensional, time-dependent simulation of the global dynamical response of the thermosphere to a geomagnetic substorm, *J. Atmos. Terr. Phys.*, *43*(7), 701–721.

Fuller-Rowell, T. J., A. D. Richmond, and N. Maruyama (2008), Global modeling of storm-time thermospheric dynamics and electrodynamics, in *Midlatitude Ionospheric Dynamics and Disturbances, Geophys. Monogr. Ser.,* vol. 181, edited by P. M. Kintner Jr. et al., pp. 187, AGU, Washington, D. C.

Goldstein, J. (2007), Plasmasphere response: Tutorial and review of recent imaging results, in *Solar Dynamics and Its Effects on the Heliosphere and Earth*, edited by D. N. Baker et al., pp. 203–213, Springer, New York.

Hedin, A. E. (1987), MSIS-86 thermospheric model, *J. Geophys. Res.*, *92*, 4649–4662.

Ruohoniemi, J., and K. Baker (1998), Large-scale imaging of high-latitude convection with Super Dual Auroral Radar Network HF radar observations, *J. Geophys. Res.*, *103*, 20,797–20,811.

Smiddy, M., M. C. Kelley, W. Burke, F. Rich, R. Sagalyn, B. Shuman, R. Hays, and S. Lai (1977), Intense poleward-directed electric fields near the ionospheric projection of the plasmapause, *Geophys. Res. Lett.*, *4*(11), 543–546.

Sojka, J., M. J. Nicolls, C. J. Heinselman, and J. D. Kelly (2009), The PFISR IPY observations of ionospheric climate and weather, *J. Atmos. Sol. Terr. Phys.*, *71*(6-7), 771–785.

Spiro, R., R. Heelis, and W. Hanson (1979), Rapid subauroral ion drifts observed by Atmosphere Explorer C, *Geophys. Res. Lett.*, *6*(8), 657–660.

St-Maurice, J.-P., and W. Hanson (1982), Ion frictional heating at high latitudes and its possible use for an in situ determination of neutral thermospheric winds and temperatures, *J. Geophys. Res.*, *87*, 7580–7602.

St.-Maurice, J.-P., and W. Hanson (1984), A statistical study of *F* region ion temperatures at high latitudes based on Atmosphere Explorer C data, *J. Geophys. Res.*, *89*, 987–996.

St-Maurice, J.-P., and R. Schunk (1981), Ion-neutral momentum coupling near discrete high-latitude ionospheric features, *J. Geophys. Res.*, *86*, 11,299–11,321.

Wang, H., and H. Lühr (2011), The efficiency of mechanisms driving subauroral polarization streams (SAPS), *Ann. Geophys.*, *29*, 1277–1286.

Wang, H., A. J. Ridley, H. Lühr, M. W. Liemohn, and S. Y. Ma (2008), Statistical study of the subauroral polarization stream: Its dependence on the cross–polar cap potential and subauroral conductance, *J. Geophys. Res.*, *113*, A12311, doi:10.1029/2008JA013529.