Case Studies of Drivers of Ionospheric Upwellings

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Abstract
Electron precipitation is a phenomenon that occurs when highly energetic electrons are "rained" into the ionosphere through electromagnetic waves energisation, and as a result, ambipolar electric field is set up to accelerate particles such as O^+ to higher energy in order to cause an upwelling. Similarly, Joule heating, which points to neutral atmosphere heating, can also cause the neutral gas to upwell and as a result, pull up ions along the field lines. Analysis of the EISCAT Svalbard Radar (ESR) data in this work indicates periods when (i) ambipolar electric field is set up to drive ion upflow, (ii) Joule heating is responsible to the upwelling ions, and (iii) when both drivers combined to cause the energisation of the ion for upflow. The peak upwelling during the March 15, 2007 ambipolar-electric-field-driven event indicates enhanced ion flux of up to $1.0 \times 10^{14}\ m^{-2}\ s^{-1}$, covering up to the upper E-region. However, the September 11, 2007 event is Joule-heating-driven, and the heating is most effective in the F-region altitude, modifying the plasma pressure gradient and resulting in field-aligned ion acceleration. When strong electric field drives ion population through the neutral gas, friction heating occurs and an elevation of the plasma pressure gradient as a result. This is observed in the September 29, 2007 event, where both ambipolar electric field and the Joule heating are co-drivers, making the upwellings to cover long duration of up to 5 hours. Data from Cooperative UK Twin Located Auroral Sounding System (CUTLASS) indicates cusp signature for the dayside events.

***Keywords**:* Electron precipitation; Ambipolar electric field; Joule heating; Upflow

1. Introduction

The ionosphere is a region of the upper atmosphere that is rich in oxygen ions (O^+). Such an ionospheric plasma can flow into the magnetosphere under appropriate conditions of the coupling processes of the solar wind-magnetosphere-ionosphere system. Such flow of plasma originating from the ionosphere, mostly referred to in scientific literature as outflow or upflow, contributes to the average plasma density in the magnetosphere as ions upwell, in addition to influencing the magnetosphere's response to other external systems such as the solar wind and the

interplanetary magnetic field (IMF) [1-3]. According to Strangeway et al. [4] ions such as O^+ and NO^+ injected into the flux tube of the magnetosphere through upwelling processes from the ionosphere result in decreased Alfvén speed in the magnetospheric region, which affects how it relates to external influences. Ionospheric upwelling processes are driven, for example, by Joule heating at the onset of the upflow and the ambipolar electric field produced by solar radiation and electron precipitation [2,4-7]. Thus, the processes and dynamics that drive ionospheric upwelling are important for understanding the upper atmosphere and the near-earth plasma systems.

Wave modes are believed to be responsible for accelerating upwelling ions once they are above the atmosphere [8], yet much remains to be understood about the acceleration process. However the growth of the ambipolar electric field beyond a threshold as a result of increasing electron heating culminates in a substantial reduction of the upflowing flux [9]. It could also be inferred from [10,11] that in a collisionless space, inaccessibility regions in the velocity space could be created as the velocity vector of the particle changes direction and magnitude as a result of changes in the magnetic field or the various potential energies. They further explain that in the polar cap ionosphere, the force due to the ambipolar electric field for oxygen ions (O^+) to flow out is weaker than that due to gravity. In a nutshell, suprathermal energization is required to free the upwelling heavy ions from the strong magnetic field and gravitational pull of the planet into near-Earth space.

It was initially assumed that lighter ions, namely, H^+ and He^+ are the ones worthy of attention to outflow from the polar cap ([12] with references therein). The analysis of satellite data carried out by [13], was the first to report that heavy ions from the Earth's ionosphere are a major contributor to the magnetospheric plasma. Thereafter, notable researchers [14,15,16,17] had, through composition measurement from the Geostationary Earth Orbit Satellites (GEOS) 1 and 2, the Spacecraft Charging AT High Altitude (SCATHA) spacecraft, and the International Sun-Earth Explorer (ISEE 1), determined that O^+ fluxes are a notable ion in the magnetosphere.

As said earlier, the ambipolar electric field and Joule heating have been shown to be the main mechanisms responsible for the upflow of particles from the ionosphere. This can occur as a result of the ambipolar electric field, resulting from electron precipitation, and Joule heating from current closure in the ionosphere [4]. Electron precipitation is a phenomenon that occurs when highly energetic electrons are 'rained' into the ionosphere through energisation of electromagnetic waves and as a result an ambipolar electric field is established to accelerate particles such as O^+ to higher energy in order to cause an upwelling. On the other hand, Joule heating, which can occur as a result of frictional heating and low plasma density caused by the intensification of the ion temperature created by the perpendicular configuration of the electric field, can also cause the neutral gas to upwell and, as a result, to pull up ions along the field lines [12,18,19]. The main aim of this study is to study the ambipolar electric field and Joule heating, which drives ion upwelling from the Earth's ionosphere, which may end up in the magnetosphere. Previous works e.g. [2,5,6,20] have observed that the upwelling of ions in the upper atmosphere of the Earth is caused by ambipolar electric field or Joule heating, but the time of conjunction of both mechanisms is a gap in the literatures, which the present study intends to investigate. In this study, we used the International Polar Year (IPY) campaign data obtained by the ESR between March 2007 and February 2008, and focus on the flux threshold of 10 m^{-2} s^{-1} [14] following [12,18,21]. The long duration of the campaign would afford a period in which there is a joint contribution of both mechanisms driving the upflow.

2. Instrumentation and Data sources

The 42 m fixed and field aligned EISCAT Svalbard Radars (ESR) dish is the major source of data for this research. There are many experimental modes available for EISCAT common programmes based on the pointing direction(s) of the antenna in conjunction with the characteristic time spent in each direction. The common programmes available by Tjulin [22] are, inter alia, Common Programme 1, which employs a fixed transmitter that points along the field line, Common Programme 2, designed to use a 4-position scanning mode, Common Programme 3 which covers a range of 10° latitude in the F-region to about $74^{\circ}N$, Common Programme 4, which uses a low elevation scan to take measurements up to $80^{\circ}N$ and provides measurements for field-aligned and vertical observations. The Common Programme is commonly/frequently run from time to time for the purpose of long-term database for statistical studies. There are other special programmes run occasionally by the EISCAT community. One of such is the IPY (International Polar Year) mode, from which the data for the study are sourced. The reason for selecting the IPY 2007 campaign, which is the most recent, was to get better data coverage that runs concurrently for about 300 days.

The electron density, ion drift velocity, ion temperature, and electron temperature, which are the basic parameters of the ionosphere measured by the EISCAT Svarlbard Radar (ESR) were extracted from the Madrigal site. However, data for the power, line-of-sight velocity, and spectral width were sourced from the SuperDARN radar located in Finland, which operates in the high frequency (HF) band using the principle of coherent backscatter. Figure 1 shows that the field of view of CUTLASS radars covers a wide area, including the ESR facility, the area considered in the present study [23,24].

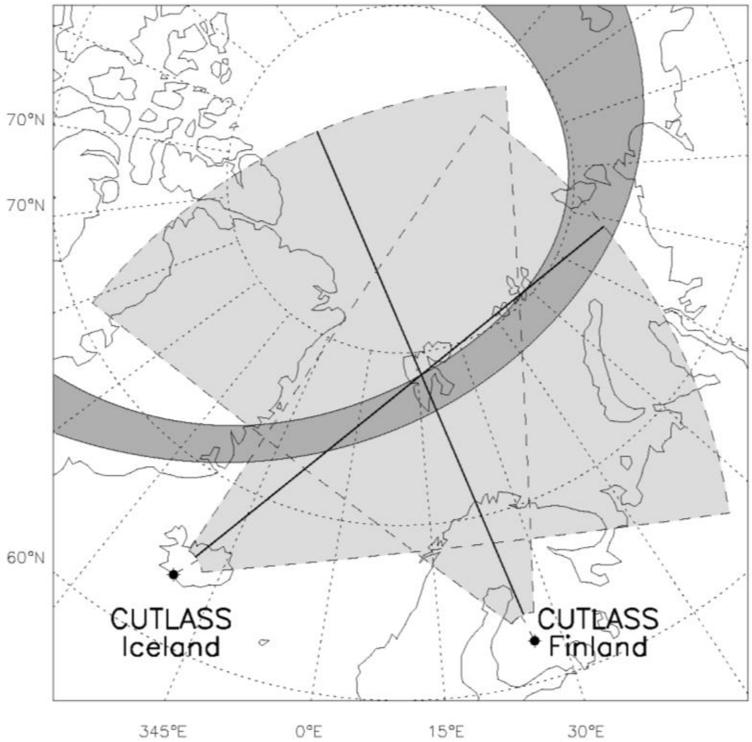

Figure 1: The fields of view of the Pykkvibær, Iceland and Hankasalmi, Finland CUTLASS radars over ESR.

3. Analysis of ESR parameter plot

This section shows the plots of some fundamental parameters of the ionosphere being measured by the EISCAT Svalbard Radars (ESR). The first four panels are the respective electron density (n_e), electron temperature (T_e), ion temperature (T_i), ion velocity (V_i), while the fifth panel is the derived ion flux (F_{ion}). The colour coded plots show variations in the above parameters with respect to altitude ranging from 100 km to around 500 km. It is worth mentioning that the positive values of the velocity from the ESR data represent an upward flow away from the radar.

Figure 2 shows the event on March 15, 2007, which began with a stable electron density in the E region (90 – 150 km; [25]) from 20:00 UT till around 21:20 UT. However, immediately after this time, intermittent intense electron precipitation down to the E region occurs until around 22:10 UT. At the same time, an enhancement follows from the electron precipitation, which would lead to the creation of an ambipolar electric field, setting up an increase in the ion scale height and ion upwelling as a result. Though, intermittent ion temperatures enhancement is indicated in the third panel, but the electron temperature appears to be the dominant driver of the upwelling ion flux. The peak upwelling around this period belongs to the high ion flux group[11] where $f_{ion} \geq 7.5 \times 10^{13}\ m^{-2}\ s^{-1}$. Archer et al. [26] and Xie et al. [27] had explained that the periods of elevated ion flow can lead to anisotropic ion temperature distribution, meaning that the ion is being heated preferentially in the direction perpendicular to the geomagnetic field compare to the parallel component of the ion temperature. Under such conditions and in the presence of the divergent geomagnetic field, the ions will experience an upward force, which [28], called the hydrodynamic mirror force. It can be inferred from the works of [6,29] that in the presence of an anisotropic ion-velocity distribution function which brings into play the magnetic mirror force, the conjunction of vertical upwelling of the neutral atmosphere and frictional heating of the ions will result in an adequate field-aligned velocity for the ions.

In Figure 3, an ESR indicates in the third panel a period of strong frictional heating between 21:30 UT and 22:30 UT and also between 23:10 UT and 23:30 UT. It is evident that the dominant mechanism for ion flux in these periods is the Joule heating as there is no indication of electron precipitation that can lead to an ambipolar electric field at the periods mentioned, yet an intense ion flux is indicated on the bottom panel of the figure. The strong elevation of the ion temperature, which is significantly enhanced through ion frictional heating, agrees with the existing theory that there is a clear relationship between large ion velocities and elevation of the ion temperature, as shown in the third and fourth panels [30]. The heating is most effective in the F-region (150 – 500 km; [25]) altitude, modifying the plasma pressure gradient and resulting in field-aligned ion acceleration.

Figure 4 shows a long duration of precipitation flux from 06:00 UT to 11:00 UT, driving an ambipolar electric field with a strong electron temperature. The Poynting flux also drives Joule dissipation through the current closure in the ionosphere, which gives rise to an intermittently enhanced ion temperature throughout the period. Free electron-ion pairs are produced when constituents of a neutral gas are photoionized in the atmosphere of planets. When the light energy exceeds the work function, it excites the ions and gives the photoelectrons kinetic energy above others because it is less massive. At higher altitudes, where the intensity of solar ionizing radiation is higher, the neutral gas density is lower, thereby having an effect on the production rate. However, the production rate is also a function of the solar zenith angle and attains its peak when the sun is overhead [31]. Figure 4 is a prenoon to local noon event at Svalbard, which is 2 hours ahead of UT, a period of decreasing solar zenith angle, when the production rate tends to maximum. Furthermore, one of the two major energy inputs into the ionosphere is electron precipitation. This is observed on the first panel of Figure 4, indicating that an ambipolar electric field is at play. Large currents circulating at the E region altitudes and intense $\mathbf{E}\times\mathbf{B}$ convection drifts greatly influence the ionosphere above the auroral and polar regions where the ESR is located. As plasmas moves through the neutral atmosphere in the E region, the electrons move under the effect of the $\mathbf{E}\times\mathbf{B}$ drift, whereas the ion, as a result of high ion-neutral collision frequency, undergoes substantial frictional heating [8,23]. The possible outcome of such frictional, or Joule heating, is an increase in the ion temperature, which under the influence of the field-aligned plasma pressure gradients will set up an upward motion of the ions. The expansion of the neutral atmosphere will also contribute to an increasing scale height of the upwelling ions. In consequence, extreme frictional heating transverse to the geomagnetic field can heat the ions preferentially in the transverse direction, subjecting the plasma to a mirroring force in the presence of divergent geomagnetic flux tubes with increasing altitude [8]. Heating results from ion-neutral friction arising from the Pedersen current that is being driven by an enhanced electric field. This leads to the Joule heating of the neutrals, causing an upwelling of the neutral gas that also drag ions up the field lines. The relative motion between the ions and the neutrals generates frictional heating which leads to the enhancement of the ion temperature [7,32], as shown in the second panel of Figure 4. Both ambipolar electric field and the Joule heating appear to be the co-drivers of the September 29, 2007 event.

Special features in the ion flux which look like upgoing ions over the whole range of altitudes is seen in Figure 5 along the field lines. Existing literature [33,34], points out that these are the common signatures of TIDs (travelling-ionospheric disturbances) or other waves-like structures (e.g. gravity waves). The obvious signature of TIDs is the series of descending phase fronts, which are actually the signature of ascending waves. The signatures of TIDs are dominated by the ion velocities, and the occurrence is more frequent during the summer months than in the winter months [33]. The TIDs which are the ionospheric signatures of atmospheric gravity waves [35,36] are associated with energy and momentum transport from high to low latitudes and its signature might be clearer during solar minimum condition as the IPY 2007 campaign [33,34]. Atmospheric gravity waves are generally launched by Joule heating in the ionosphere and are traced to heating due to either enhanced particle precipitation or heating created along with nightside auroral activity [37-39]. Detailed analysis of TID signatures and its occurrence are left open for researchers to explore.

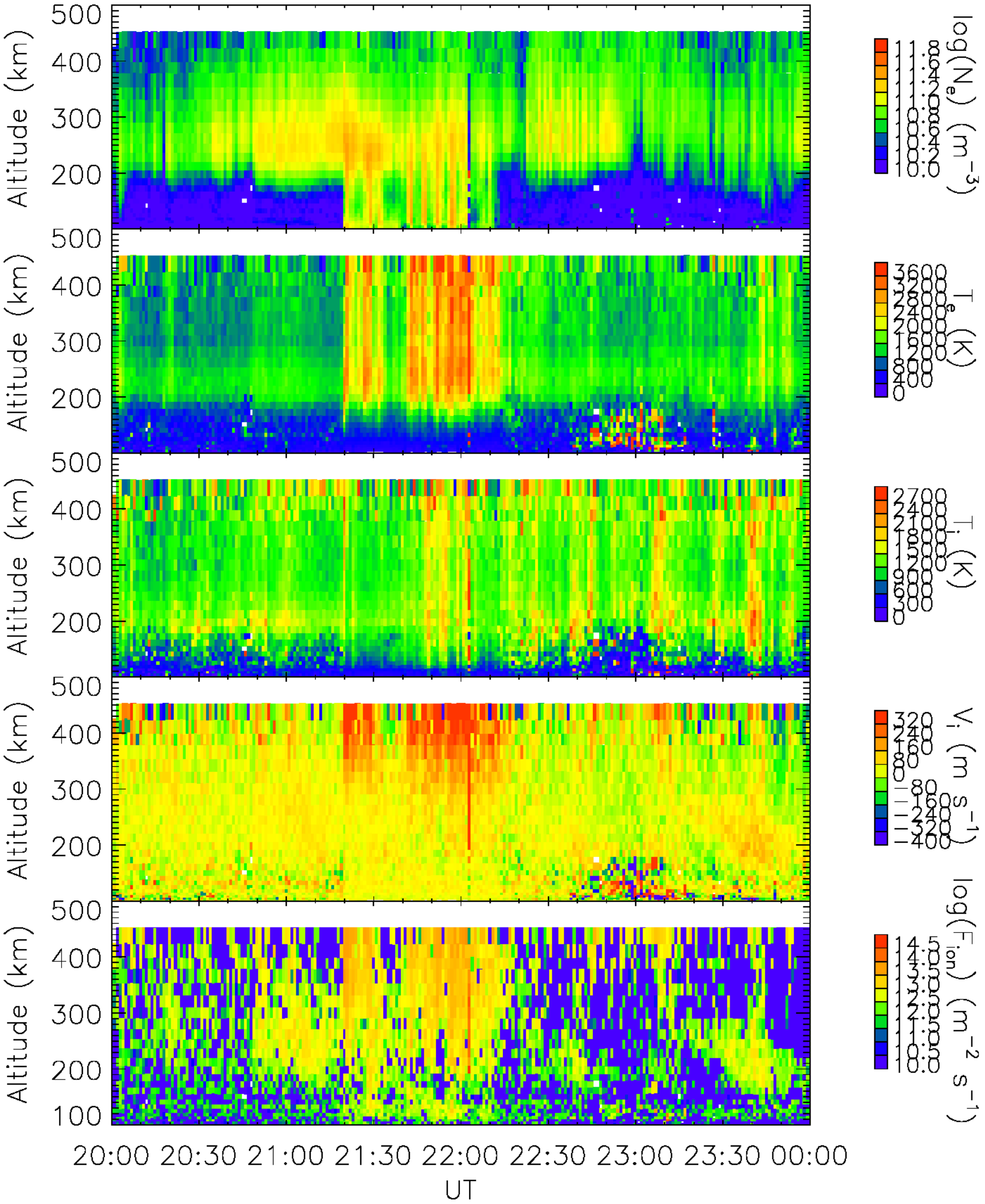

Figure 2: The ESR parameter plot for March 15, 2007 indicating ambipolar electric field as the main driver of the upwelling ions during the period.

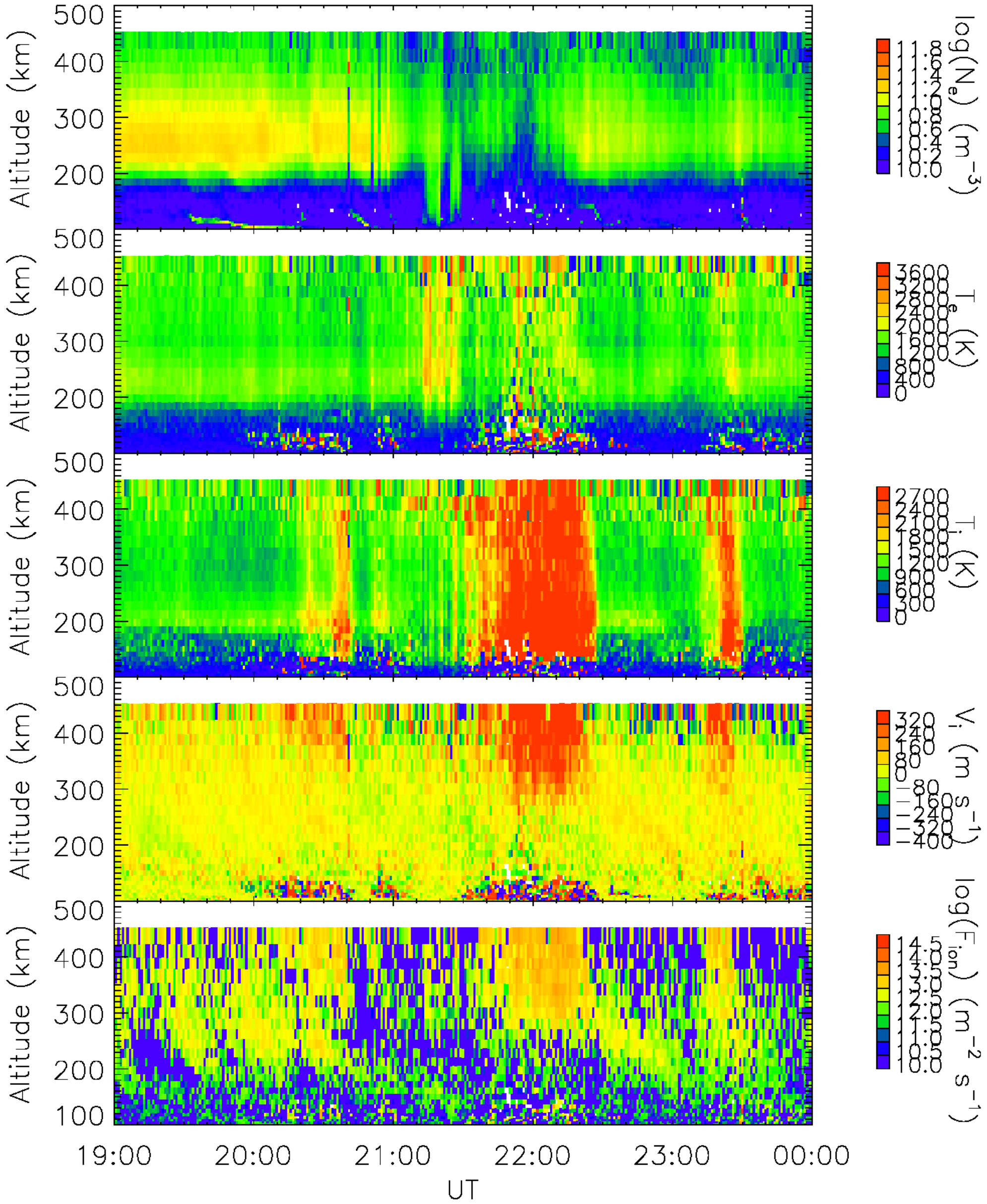

Figure 3: The ESR parameter plot for September 11, 2007 indicating Joule heating as the main driver of the upwelling ions during the period.

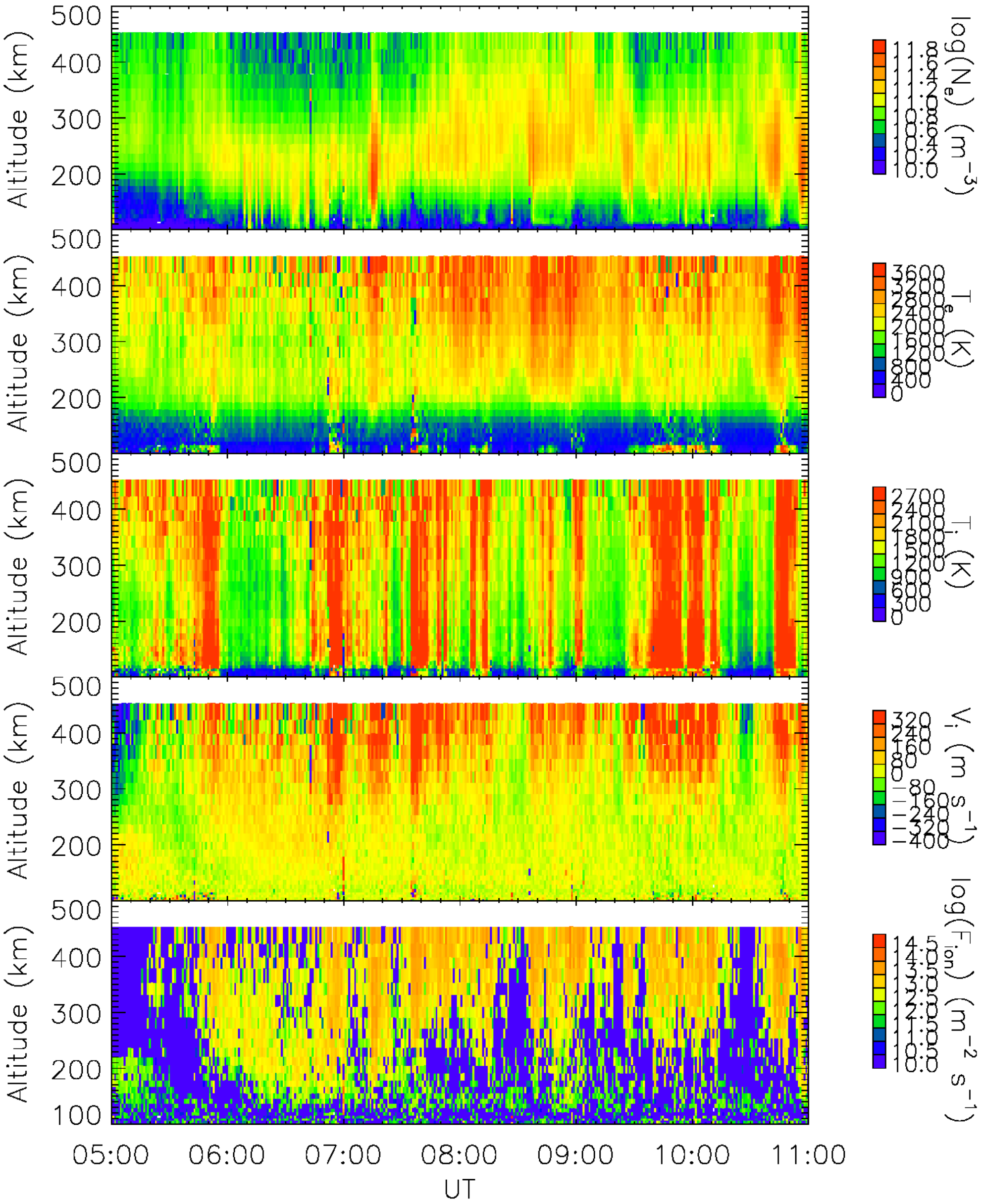

Figure 4: The ESR parameter plot for September 29, 2007 showing Joule heating and ambipolar electric field as the contributors to the upwelling during the period.

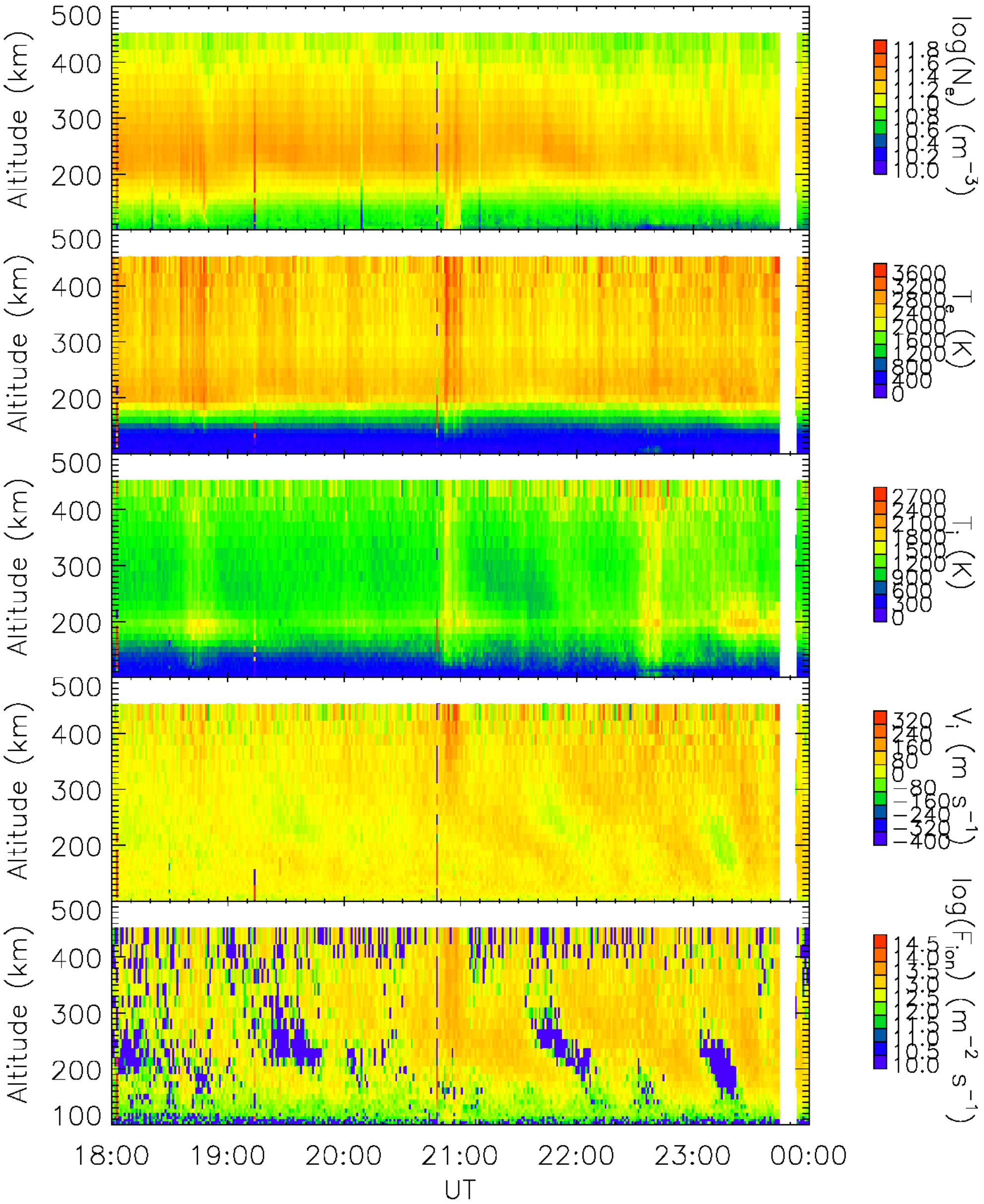

Figure 5: The ESR parameter plot for June 29, 2007 showing the signatures of descending phase front of ascending waves.

4. Analysis of SuperDARN parameter plot

The data from the CUTLASS (Cooperative UK Twin Located Auroral Sounding System) Finland radar of the SuperDARN family of radars are investigated in this section. In contrast to the ISRs such as EISCAT, these radars operate in the high frequency (HF) band using the principle of coherent backscatter when the radar signal encounters the plasma irregularities in the ionosphere along geomagnetic field lines perpendicularly. It has sixteen (16) radar beams covering wide range field-of-view of which beam 9 passes through the ESR facility [40]. The plots in this section consist of three panels representing power, line-of-sight velocity and spectral width respectively.

Figures 6 - 9 show events in March 15, 2007, September 11, 2007, September 29, 2007, and June 29, 2007 respectively. The CUTLASS Finland radar indicates paucity of data during the periods, especially on Figures 6 and 7. At the ESR magnetic latitude ($75.18^{\circ}N$), the radar indicates on the second panel of Figure 8, a high flow, away from the radar from 07:00 UT until 08:00 UT and thereafter, intermittent high flow for the rest of the period. The third panel on Figure 8 indicates a mixture of moderate and high spectral width during the same time interval. The high flows indicate a cusp signature for the dayside event with probably an asymmetry in the cusp position due to the fluctuating flow.

The few data available for the nightside event at the ESR magnetic latitude is presented in Figure 9. It indicates fluctuations from low to moderate irregularities in the power spectrum, and the backscatter at the magnetic latitude is predominantly ground scatter. Other nightside events show a paucity of data at the ESR latitude.

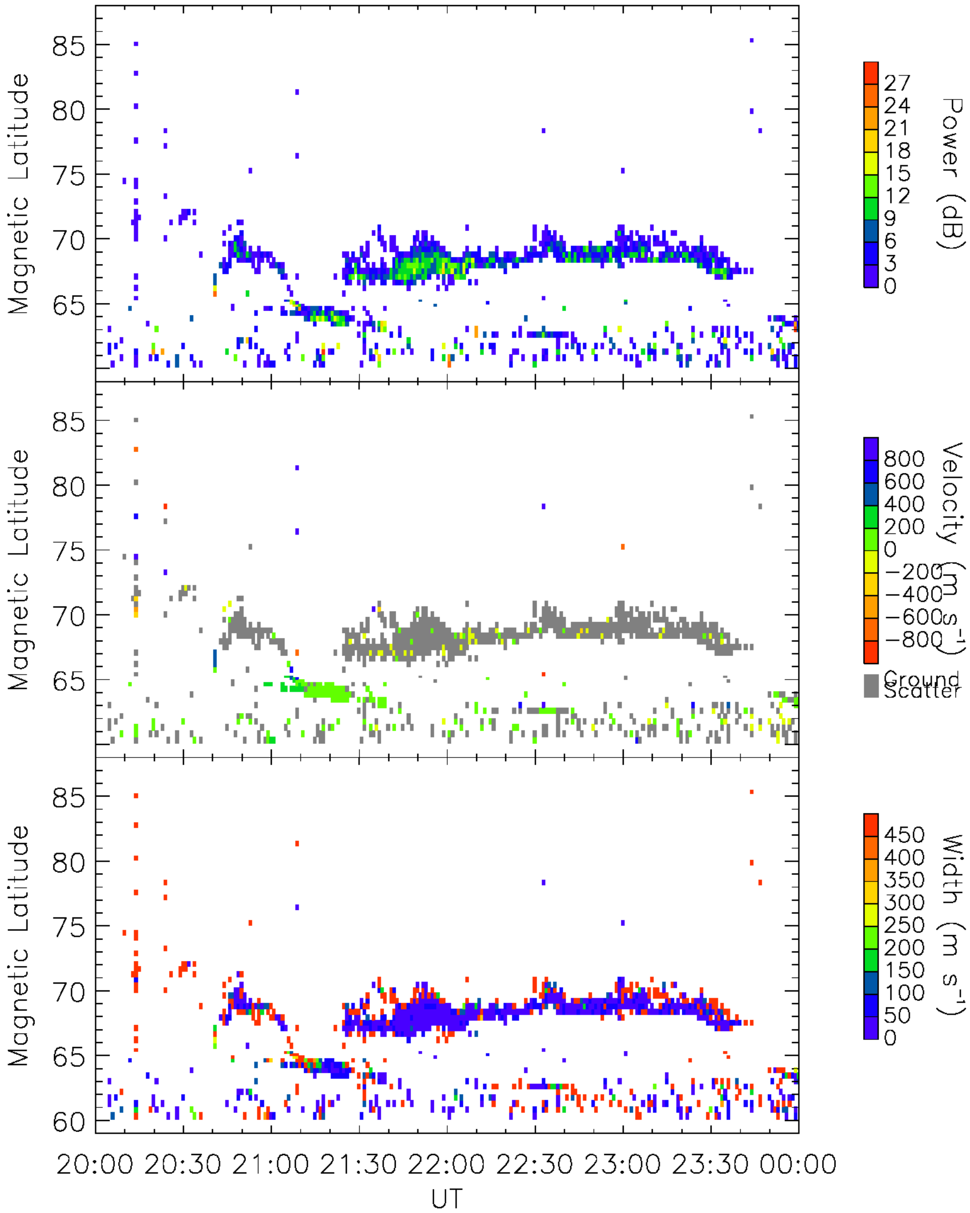

Figure 6: The SuperDARN parameter plot for March 15, 2007.

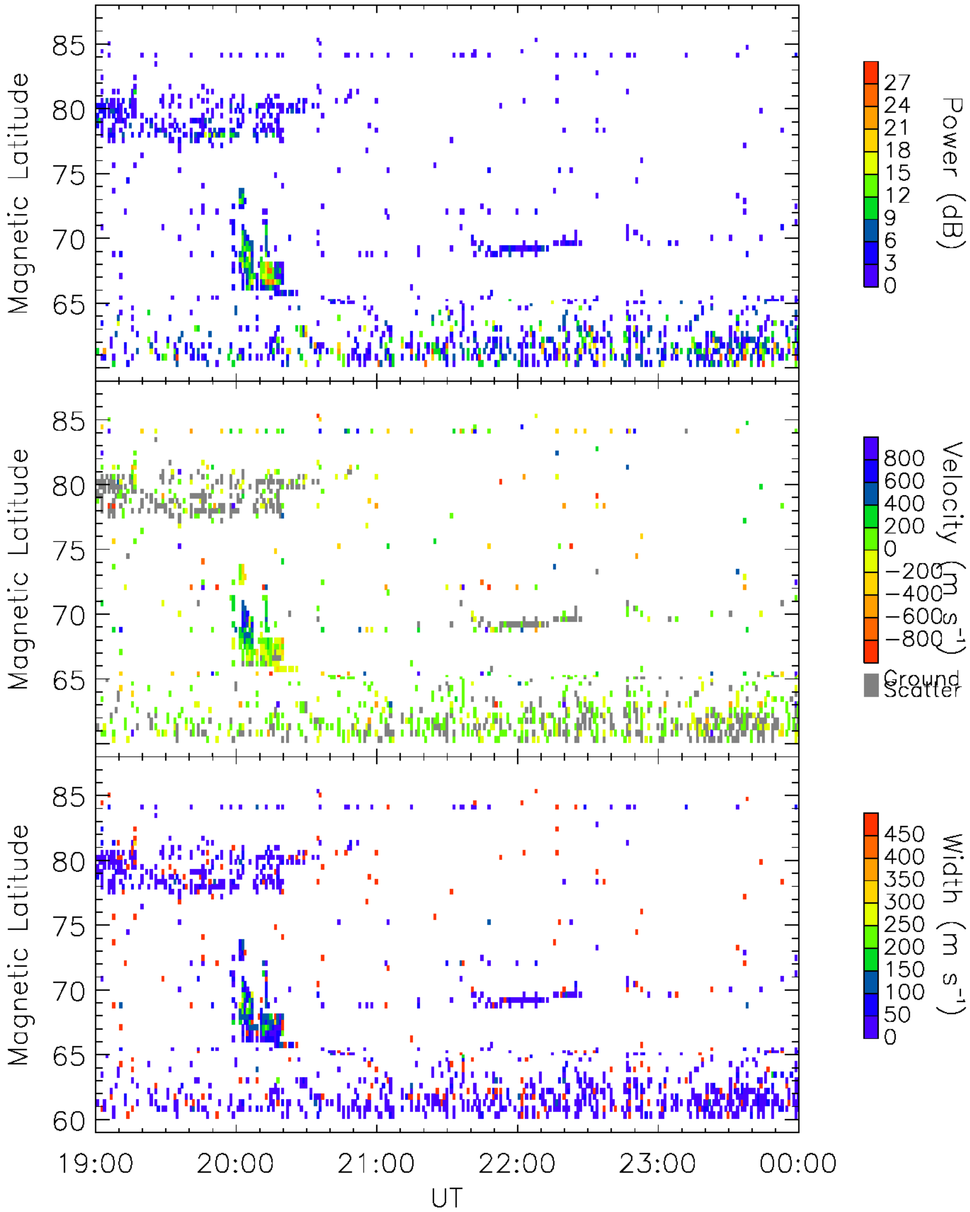

Figure 7: The SuperDARN parameter plot for September 11, 2007.

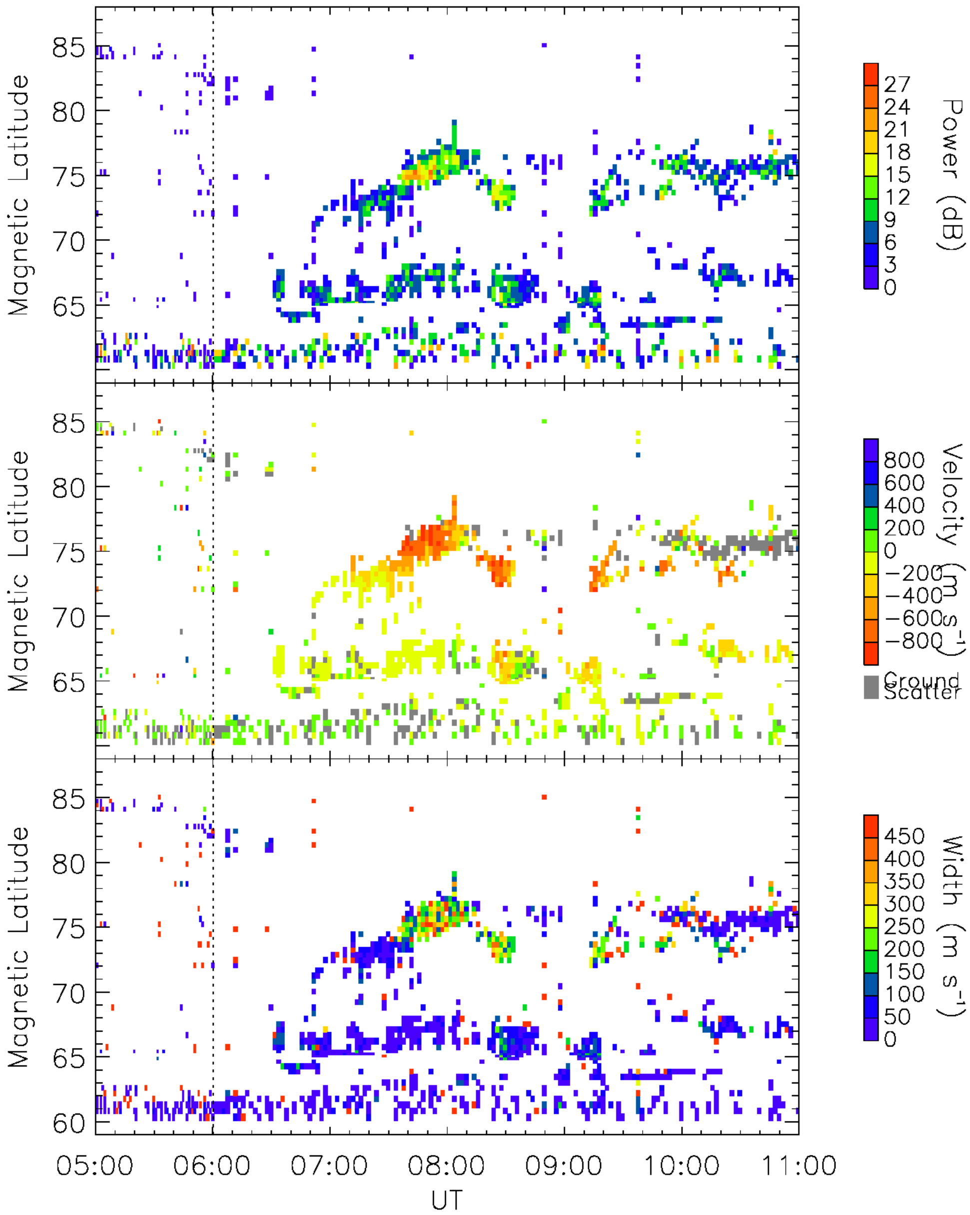

Figure 8: The SuperDARN parameter plot for September 29, 2007.

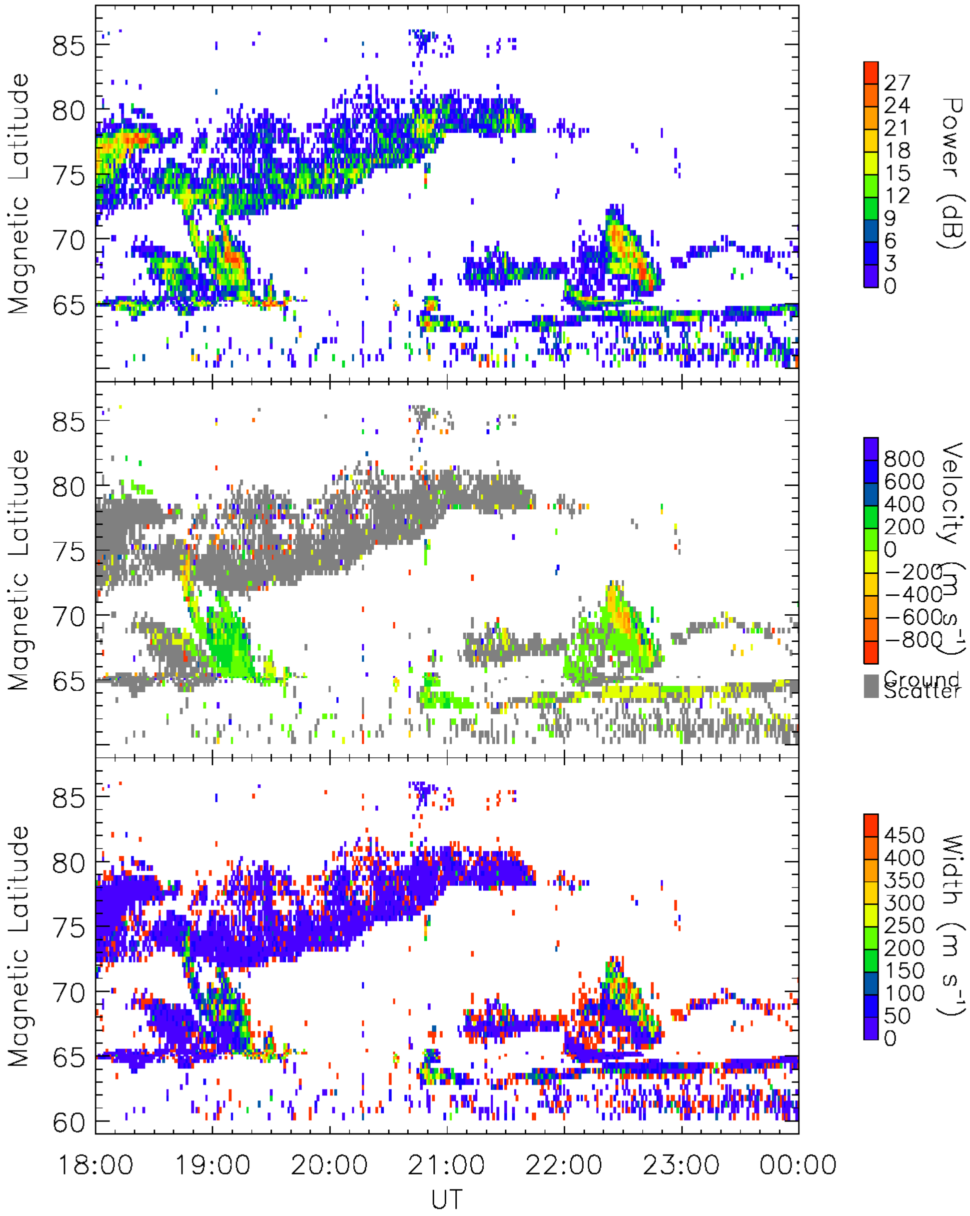

Figure 9: The SuperDARN parameter plot for June 29, 2007.

5. Conclusions

This work looked at the case studies of drivers of ion upwellings from the Earth's upper atmosphere during the IPY 2007campaign at a time of deep minimum in solar activity. Four events were studied, which occurred on March 15, 2007, September 11, 2007, September 29, 2007, and June 29, 2007. The ion fluxes are calculated for these events and the following conclusions are arrived at.

ESR indicates both ambipolar electric field and Joule heating as the drivers of the upwellings, with fluxes exceeding $7.5 \times 10^{13}\ m^{-2}\ s^{-1}$

Precipitation of electron down to the E-region leads to the creation of an ambipolar electric field, setting up an increase in the ion scale height and ion upwelling as a result, while heating is most effective in the F-region altitude, modifying the plasma pressure gradient and resulting in field-aligned ion acceleration.

Ambipolar electric field is the main mechanisms during the March 15, 2007 event, while the Poynting flux giving rise to Joule heating through the current closure in the ionosphere drives the September 11, 2007 event.

Both ambipolar electric field and Joule heating are the driver of the September 29, 2007 event. The event duration covered when both mechanisms are at play appears to be longer in this study than when each mechanism singly drives the upwelling. This assertion is left open for further research.

Descending phase fronts are prevalent in the ion flux along the field lines during the June 29, 2007 event. This is the signature of ascending waves commonly referred to as TIDs (travelling ionospheric disturbances).

The CUTLASS Finland radar indicates cusp signature for the dayside events that occurred on September 29, 2007.

References

1 A Glocer, G Tóth, T Gombosi, and D Welling *Journal of Geophysical Research* **114** (2009)

2 E A Kronberg, M Ashour-Abdalla, I Dandouras, D C Delcourt, E E Grigorenko, L M Kistler, I V Kuzichev, J Liao, R Maggiolo, H V Malova, K G Orlova, V Peroomian, D R Shklyar, Y Y Shprits, D T Welling, and L M Zelenyi *Space Science Reviews* **184** 173 (2014).

3 K H Pham, W Lotko, R H Varney, B Zhang, and J Liu *Journal of Geophysical Research. Space Physics* **126** (2021).

4 R J Strangeway, R E Ergun, Y -j. Su, C W Carlson, and R C Elphic *Journal of Geophysical Research* **110** (2005).

5 A W Yau and M André *Space Science Reviews* **80** 1 (1997).

6 P A Fernandes, K A Lynch, M Zettergren, D L Hampton, T A Bekkeng, I J Cohen, M Conde, L E Fisher, P Horak, M R Lessard and R J Miceli *Journal of Geophysical Research: Space Physics* **121** 1587 (2016).

7 S C Buchert, Y Ogawa, R Fujii, and A P Van Eyken *Annales Geophysicae* **22** 889 (2004).

8 B Hultqvist G Paschmann, and R Treumann *Magnetospheric plasma sources and losses : final report of the ISSI study project on source and loss processes of magnetospheric plasma* **6** (1999).

9 T E Moore, M -c. Fok, and K Garcia-Sage *Journal of Atmospheric and Solar-Terrestrial Physics* **115–116** 59 (2014).

10 G V Khazanov, M W Liemohn, E N Krivorutsky, and T E Moore *Journal of Geophysical Research* **103** 6871 (1998).

11 H Saleem and S A Shan *Review of Modern Plasma Physics* **4** 3 (2020)

12 T W David, D M Wright, S E Milan, S W H Cowley, J A Davies, and I McCrea *Journal of Geophysical Research. Space Physics* **123** 2192 (2018).

13 E G Shelley, R G Johnson, and R D Sharp *Journal of Geophysical Research* **77** 6104 (1972).

14 J H Waite, T Nagai, J F E Johnson, C R Chappell, J L Burch, T L Killeen, P B Hays, G R Carignan, W K Peterson, and E G Shelley *Journal of Geophysical Research* **90** 1619 (1985).

15 W K Peterson, T Abe, H Fukunishi, M J Greffen, H Hayakawa, Y Kasahara, I Kimura, A Matsuoka, T Mukai, T Nagatsuma, K Tsuruda, B A Whalen, and A W Yau *Journal of Geophysical Research* **99** 23257 (1994).

16 D V Chugunin, M V Klimenko, A A Chernyshov, V V Klimenko, A A Il'yasov and R Y Luk'yanova *Geomagnetism and Aeronomy* **58** 50 (2018).

17 C A Maldonado, P A Resendiz Lira, G L Delzanno, B A Larsen, D B Reisenfeld and V Coffey *Frontiers in Astronomy and Space Sciences* **9** 1005845 (2023).

18 J E Wahlund, H J Opgenoorth, I Häggström, K J Winser, and G O L Jones *Journal of Geophysical Research* **97** 3019 (1992).

19 M J Kosch, Y Ogawa, M T Rietveld, S Nozawa, and R Fujii *Journal of Geophysical Research* **115** A12 (2010).

20 K Li, M André, A Eriksson, Y Wei, J Cui, and S Haaland *Frontiers in Physics* **9** 743316 (2021).

21 T W David C M Michael, D Wright, A T Talabi, and A E Ajetunmobi *Annales Geophysicae* **42**, 349 (2024)

22 A Tjulin EISCAT experiments. *EISCAT Scientific Association,* (2017).

23 S E Milan, T K Yeoman, M Lester, E C Thomas, and T B Jones *Annales Geophysicae* **15** 703 (1997).

24 D M Wright, T K Yeoman, L J Baddeley, J A Davies, R Dhillon, M Lester, S E Milan, and E E Woodfield *Annales Geophysicae* **22** 169 (2004).

25 W Xu, R A Marshall, J Bortnik and J W. Bonnell *Journal of Geophysical Research: Space Physics* **126** e2021JA029288 (2021).

26 W E Archer, D J Knudsen, J K Burchill, M R Patrick, and J P St.-Maurice *Geophysical Research Letters* **42** 981 (2015).

27 Y Xie, R Wang, S Wang, X Li, X Gao, and S Lu *Journal of Geophysical Research: Space Physics* **128** e2023JA031737 (2023).

28 K Suvanto, M Lockwood, and T J Fuller-Rowell *Journal of Geophysical Research* **94** 1347 (1989).

29 K J Winser, G O L Jones, and P J S Williams *Journal of Atmospheric and Terrestrial Physics* **50** 379 (1988).

30 J P St.-Maurice, and W B Hanson *Journal of Geophysical Research-Space Physics*, **87** 7580 (1982).

31 R W Schunk and A F Nagy *Ionospheres: Physics, Plasma Physics, and Chemistry: Cambridge Atmospheric and Space Science Series. Cambridge University Press* (2009)

32 Å Skjæveland, J Moen and H C Carlson *Journal of Geophysical Research: Space Physics* **119**, 6876 (2014)

33 A Vlasov, K Kauristie, M Van De Kamp, J -p. Luntama, and A Pogoreltsev *Annales Geophysicae* **29** 2101 (2011).

34 G Crowley and F S Rodrigues *Radio Science* **47** RS0L22 (2012).

35 C Y Huang, J F Helmboldt, J Park, T R Pedersen, and R.Willemann *Reviews of Geophysics* **57** 78 (2019).

36 C Borries, A A Ferreira, G Nykiel, and R A Borges *Journal of Atmospheric and Solar-Terrestrial Physics* **247** 106069 (2023).

37 S T Moges, R O Sherstyukov, A Kozlovsky, T Ulich and M Lester *Journal of Geophysical Research: Space Physics* **129** e2023JA031694 (2024)

38 G Lu, A D Richmond, H Lühr and L Paxton *Journal of Geophysical Research: Space Physics* **121** 7108 (2016).

39 P Prikryl, R G Gillies, D R Themens, J M Weygand, E G Thomas and S Chakraborty *Annales Geophysicae* **40** 619 (2022).

40 T K Yeoman, D Yu Klimushkin, and P N Mager *Annales Geophysicae* **28** 1499 (2010).