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The Role of Neutral Atmospheric Dynamics in Cusp Density – 2nd Campaign

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14. ABSTRACT

This report covers research undertaken to verify and improve models of atmospheric density fluctuations in the regions of the magnetic cusp, where increased electromagnetic activity can correspond to a "cusp upwelling" which can double the atmospheric density at altitudes of up to 400km, relevant to satellite drag orbits.. The grant funded a field trip in January 2013 to Svalbard for a joint optical/radar experiment to augment the first case study from January 2012. Two Fabry-Perot interferometers measured the non-ionized component of the upper atmosphere, and independent measurements of the ionosphere were made using the European Incoherent Scatter Svalbard Radar. These observations were used to partially verify a mechanism proposed by Carlson et al in 2012 which proposed that depositing energy at high altitudes would require less energy to lift a shorter column of air to higher altitude (thus increasing the atmospheric density). Observations showed that large vertical winds in the cusp area did correspond to large ion temperatures (>2000K), and low vertical winds with low ion temperatures (<1000K); unable to measure horizontal plasma velocities due to an equipment constraint, the team inferred horizontal plasma flows (of greater than 2000 m/s) using these ion temperatures. Measurements on 12 Jan 2013 showed no cusp upswelling, while those on 14 Jan 2013 showed significant strong sustained upwelling winds, giving a useful contrast. Preliminary results from the first campaign appear to confirm the Carlson et al mechanism, while findings from the second campaign (this grant) confirm that it is necessary to have both soft particle precipitation and simultaneously fast plasma flow in order to provide frictional heating at a high enough altitude to lift the atmosphere at satellite altitudes.

15. SUBJECT TERMS

EOARD, atmospheric density, CHAMP satellite, Fabry-Perot

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The role of neutral atmospheric dynamics in cusp density – 2nd campaign

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Summary

This report will present observations from three field trips on Svalbard which were undertaken to test a mechanism that explains unexpected density enhancements seen by the CHAMP satellite. The CHAMP satellite observed up to double the surrounding atmospheric density in the region of the magnetic cusp at altitudes of 400km (*Lühr et al.*, 2004). This is a significant enough perturbation to be included in satellite drag models, and consequently inspired several modelling studies.

The proposed mechanism by *Carlson et al.* (2012) requires that soft particle precipitation increases the conductivity at 150-200km altitude and simultaneously there should be bursts of fast plasma convection to provide strong frictional heating. Heating at this high altitude means that it requires little energy to lift the rarefied gas above, and thereby bring denser air from below into the region passed through by CHAMP (~400km). The atmospheric drag increases at altitudes where satellites orbit as a consequence of upwelling,

The EOARD grant FA8655-13-1-3012 funded a field trip in January 2013 to Svalbard for a joint optical and radar experiment. This provided two case studies that test and augment the first case study from January 2012. The optical observations were provided by two University College London (UCL) Fabry-Perot Interferometers (FPIs) measuring the neutral (non-ionised) component of the upper atmosphere. Independent measurements of the ionosphere were made using the European Incoherent SCATter (EISCAT) Svalbard Radar (ESR). The radar time was won by competitive peer review from radar time awarded to the UK as part of its membership of the EISCAT consortium. Svalbard is currently the only site that passes under the magnetic cusp that is equipped with radar, optical and other suitable observational instrumentation. Further data have been sought out from the University of Oslo Meridian Scanning Photometer (MSP) and the SuperDARN coherent scatter radars and all are currently being analysed and interpreted, to be written up in a paper for submittal to the Journal of Geophysical Research (JGR). Our aim is to determine what are the conditions that caused upwelling on the nights of 22nd Jan 2012 (the first cusp upwelling experiment, reported in *Aruliah et al.*, 2014) and on the 14th January 2013; but not on the 12th January 2013. The first experiment appeared to confirm the *Carlson et al.* (2012) mechanism. The second and third experiments will be a test that we have correctly identified the mechanism. The second and third experiments also have the advantage of the radar beam scanning, which was not possible for the first owing to a broken driver motor.

During the period of this award, a paper by *Aruliah et al.* (submitted in 2013) reported the first cusp upwelling experiment in January 2012, also funded by an earlier EOARD grant. The paper is currently undergoing the refereeing process. The results of the 2012 and 2013 cusp upwelling experiments were used as part of a 3 year grant proposal to the UK Natural Environment Research Council (NERC) for a modelling and experimental study to improve the modelling of the lower thermosphere. This proposal went through to the final selection, but we heard recently that it was not funded. Over the last few years it has been realized by the atmospheric community that the middle atmosphere plays a valuable role in coupling the lower atmosphere, where weather and climate are, with the upper atmosphere, which is strongly influenced by solar variability and the solar wind, i.e. Space Weather. Investigating the cusp upwelling mechanism was one of the coupling mechanisms used in our NERC proposal and is a motivation in addition to improving satellite drag modelling.

Introduction

In January 2012 and January 2013 the Atmospheric Physics Laboratory at UCL carried out a first and second experimental campaign to investigate an unexpected phenomenon observed by the CHAMP satellite. *Lühr et al.* (2004) reported that the CHAMP satellite observed a localized region of increased atmospheric density nearly every time it passed over the magnetic cusps. The two regions of enhanced density had a horizontal extent of a few hundred kilometres. Although this is a relatively small part of a complete polar orbit, the densities could be up to double the surrounding region, and are repeated systematically in every orbit. Consequently this is a significant enough perturbation to be included in satellite drag models, and special workshop sessions were convened and several modeling studies were carried out to determine a mechanism.

The density enhancement is caused by denser air from below being lifted into the increasingly rarefied air above. A conventional modelling simulation required 110 times the typical measured values of ion-frictional heating in the cusp (*Demars and Schunk*, 2007). The unrealistically large heating value was required because the heat source was positioned in the E-region at around 120 km altitude, which meant lifting a column of gas that was a few hundreds of kilometres tall to create the observed density enhancement at the CHAMP altitude of 400 km. Then *Clemmons et al.* (2008) presented observations from the Streak satellite (in a highly elliptical orbit) that showed density *depletions* of the thermosphere at altitudes of 250 km. This appeared to contradict the CHAMP observations, so *Clemmons et al.* proposed that heating occurred at an altitude above Streak, caused by soft particle precipitation. Recently *Deng et al* (2013) systematically introduced ions, electrons and Poynting flux heating to drive their model, but could not reproduce a sufficiently large density enhancement to match CHAMP. However, they were able to produce vertical winds of 100 ms^{-1} which is consistent with our FPI observations. This is because their model is one of only two upper atmosphere models that assume non-hydrostatic equilibrium. All other upper atmosphere models use the simplification of hydrostatic equilibrium, which has the consequence that large vertical winds are not allowed. Our own UCL Coupled Middle Atmosphere Thermosphere model (CMAT2), which assumes hydrostatic equilibrium, was able to produce vertical winds of only a few tens of ms^{-1} when we modelled the Carlson mechanism (*Carlson et al.*, 2012). This is illustrated in Figure 1 which is taken from this paper. Figure 1a shows a contour plot of the density above 80km altitude, and over a latitudinal range 60°-90°N. The density enhancement is confined to the cusp region between 70°-80°N. Arrows indicating the flow of gas are overlaid on the plot. Figure 1b shows that the response to heating is rapid and the duration of the density enhancement is a few tens of minutes.

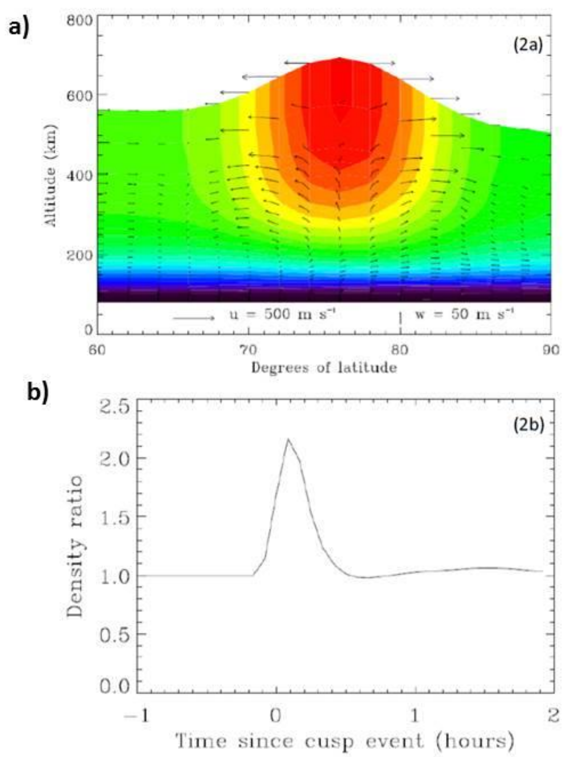


Figure 1: CMAT2 simulation of observations of cusp density by the CHAMP satellite at 400 km. a) Cusp upwelling shown by arrows representing the flow of gas; and the doubling of density shown by the colour contour plot over a latitudinal range of 60°-90°N. b) The variation with time of the modelled ratio of the cusp density with respect to the surrounding region. (Figure taken from Carlson et al., 2012)

Carlson et al. (2012) independently proposed that depositing energy at a higher altitude would require less energy to lift a shorter column of air above. We were able to demonstrate that this mechanism allowed us to produce the doubling of density using realistic levels of energy in CMAT2. The form of the heating energy was discussed but not specified in the model simulation. In *Aruliah et al.* (2014) the Carlson mechanism was developed further by providing experimental support from the first cusp campaign in January 2012. In order to produce the necessary conditions it was proposed that particle precipitation enhance the conductivity of the ionosphere in the altitude region 180-200km, and importantly, there should be simultaneously fast plasma flows to create high frictional heating. This accounted for why CHAMP observed the density enhancements consistently at the magnetic cusps, since the cusps provided both these conditions: soft particle precipitation and flux transfer events, which are both characteristic features of the cusp. The aim of the cusp upwelling experiments were to test the mechanism using simultaneous measurements of the thermosphere and ionosphere by using the two FPIs and two ESR radar dishes on Svalbard.

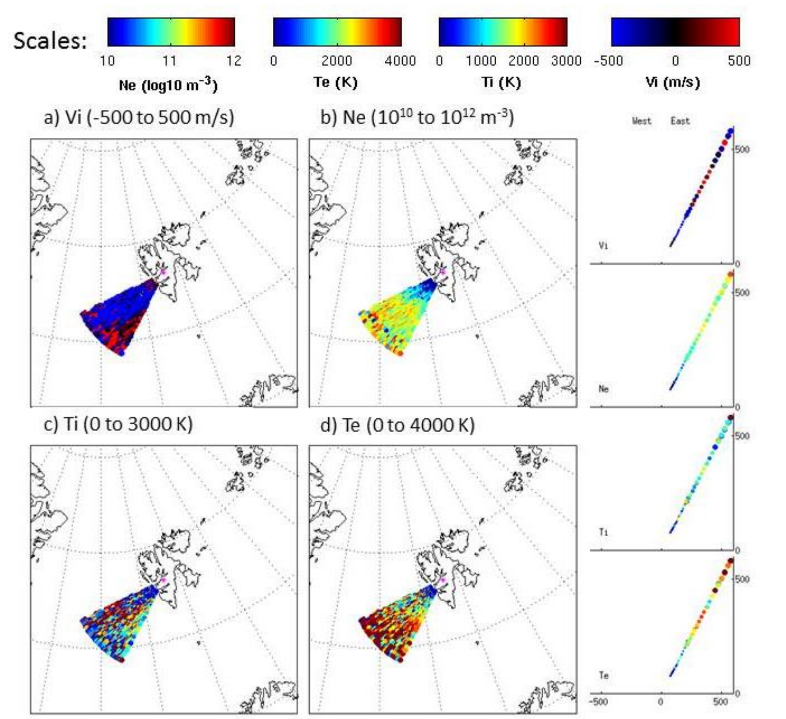
Methods, Assumptions, and Procedures

The second cusp upwelling campaign covered the new moon period from 6th to 14th January 2013. It involved Dr Anasuya Aruliah (UCL) and Dr Ian McWhirter (electro-optical engineering consultant, and honorary Fellow of UCL). We were joined on Svalbard by our collaborators, Dr Herb Carlson (University of Utah) and Dr Kjellmar Oksavik (University of Bergen, Denmark), who were not supported by the EOARD grant.

The optical observations were provided by two FPIs belonging to University College London (UCL) which measured the winds and temperatures of the neutral (non-ionised) component of the upper thermosphere. The radar observations were provided by the European Incoherent SCATter (EISCAT) Svalbard Radar (ESR) to measure independently the temperatures, electron density and plasma velocities of the ionosphere. Svalbard is currently the only site with radar, optical and other suitable observational instrumentation that passes under the magnetic cusp. Signatures of the cusp can appear within 1-2 hours on either side of magnetic noon, which for Svalbard is around 09 UT. Radar time was booked for a few 6-hour periods covering 06-12UT. Two of the periods of radar experiments were successful: 06-12UT on the 12th and 06-12UT on the 14th November 2013. On these dates the geomagnetic conditions and weather were both favourable, and the radar was able to scan the radar beam, although more slowly than our optimum requirement owing to problems with the drive motor.

During our first cusp upwelling experiment in January 2012 (also funded by EOARD) the drive motor of the ESR broke during high winds, which meant that it was no longer possible to scan the radar beam, and we were limited to a fixed beam of ionospheric measurements along the magnetic field line, which points nearly vertical. The range of the radar measurements were from 90-600 km altitude. However, the *Carlson* mechanism required measurements of horizontal plasma flow speeds, so as a proxy we used the radar's ion temperature measurements to represent the kinetic energy of the plasma being converted into thermal energy of the ions. We reapplied to EOARD for a second cusp upwelling campaign in anticipation of a full beam swinging capability in the coming January 2013. However, there were funding limitations on the EISCAT radars and issues of procurement of the drive motor parts which meant that only a limited beam scanning facility was possible in January 2013. This was about twenty times slower (1.5° in 18 seconds for our campaign compared with the normal speed of 1.5° per second). An illustrative example of the 32m dish radar beam-swinging observations is shown in Figure 2: a) line-of-sight ion velocities; b) electron densities; c) ion temperatures and d) electron temperatures. The right hand column of Figure 2 shows the corresponding near vertical field-aligned fixed beam observations of the 42m radar dish for these same four ionospheric parameters.

Figure 2 : ESR 32m dish fan plots on 14 Jan 2013 10:06:17 – 10:10:14 UT



The UCL FPIs on Svalbard are a narrow field FPI and an all-sky FPI called the Scanning Doppler Imager (SCANDI, *Aruliah et al.*, 2010). The FPIs observed the 630nm airglow and auroral emissions of the upper atmosphere. This emission occurs in a layer that lies at an altitude of about 240km which is in a region called the upper thermosphere. By measuring the Doppler shift and Doppler broadening of the emission line, we are able to calculate the line-of-sight neutral gas wind speeds and neutral gas temperatures, respectively. Thus a ground-based instrument is able to probe winds and temperatures of the upper thermosphere. The narrow field FPI was set up to observe the vertical component of the neutral wind at a high time resolution of 30 seconds. The narrow field FPI observing cycle consisted of 3 consecutive observations in the zenith direction, followed by a set of anticlockwise observations to the north-east, north-west, south-west, south-east plus a calibration lamp observation to monitor the instrument temperature. The azimuthal look directions are close to the directions of the geomagnetic east, north, west and south. The lower time resolution set of horizontal neutral wind measurements provided a context to the vertical neutral winds in the geomagnetic meridional and zonal directions. The ionosphere is driven by the magnetospheric dynamo, which follows the Earth's magnetic field lines; hence the choice of geomagnetic coordinates. The SCANDI provided all-sky observations of the neutral wind speeds, neutral temperature and intensity of the 630nm emission.

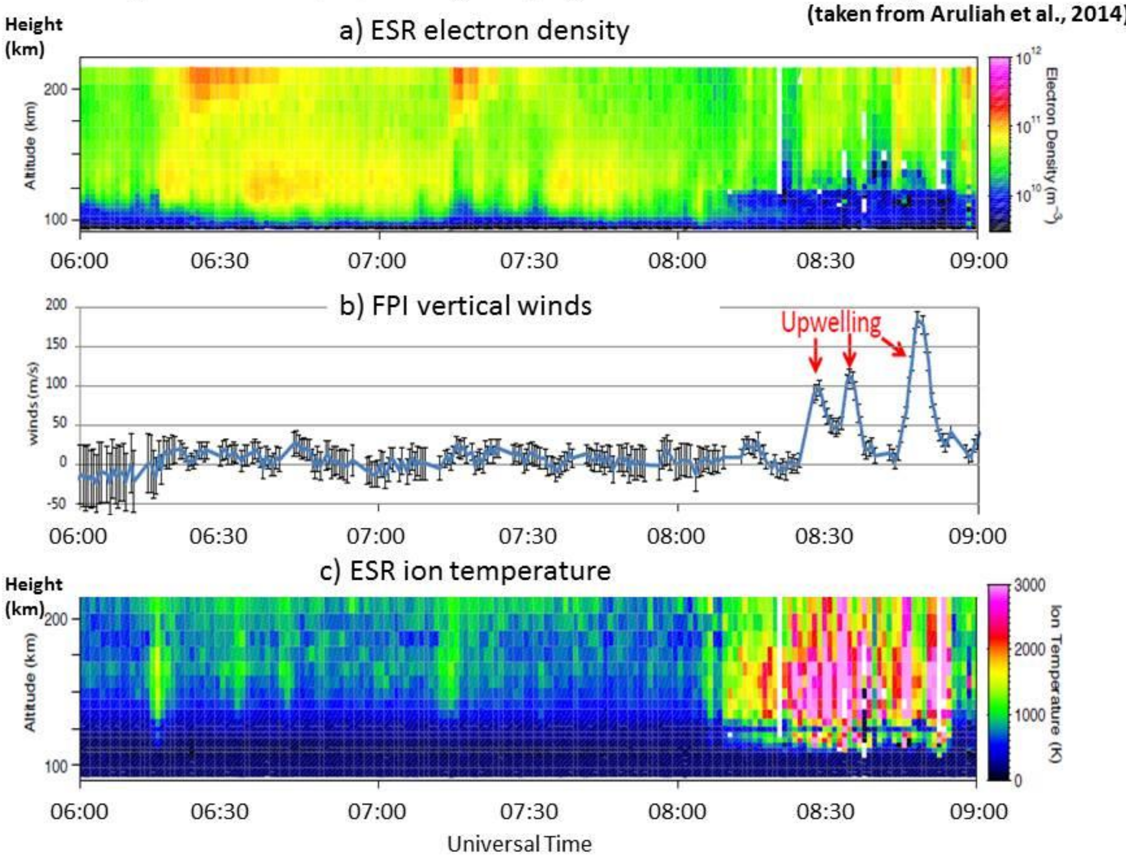
We have also called on supporting observations from the University of Oslo Meridian Scanning Photometer (MSP) from Prof Joran Moen, and SuperDARN coherent scatter measurements of plasma velocities from Dr Adrian Grocott (University of Leicester). The MSP can be used to identify the location of the magnetic cusp by comparing the airglow emissions at 630nm with 558nm. The SuperDARN radar can give a very large-scale view (thousands of kilometres) of the plasma flows over the polar region. We will also refine the original CMAT2 model simulation in the light of our improved understanding of the upwelling mechanism. The simulation used for Carlson et al. (2012) did not specify what caused the heating, but only that the heating should be in the altitude region 180-200km. Our next simulations will explicitly define the height profile of the conductivity and frictional heating in the model (*Spain et al.*, 2013).

Results and Discussion

Figure 3 is taken from *Aruliah et al.* (2014) and shows the period 06-09UT on 22nd January 2012 observed during the first cusp upwelling campaign. There was an extended period of strong upward neutral winds observed by the narrow field FPI between 08:22-11:19 UT. Figure 3b homes in on the period 06-09 UT to show three distinct peaks of vertical winds of 112 ms^{-1} at 08:29 UT; 127 ms^{-1} at 08:35 UT and 199 ms^{-1} at 08:48 UT. Figure 3b also shows that between 06-08:20 UT the vertical winds remained small and close to a zero value. The fixed beam 42m ESR radar measurements of electron density and ion temperature are shown in the Figure 3a and 3c. The scale bar on the right of each panel indicates the size of each parameter, by using colours ranging from blue (low values) to red (high values).

Figure 3: 1st Cusp Upwelling campaign: 06-09UT on 22 January 2012

(taken from Aruliah et al., 2014)



It can be seen that at the times of large vertical winds there were also high ion temperatures greater than 2000 K, while the period of low vertical winds was also a time of low ion temperatures less than 1000 K. The ion temperatures can be related to the speed of the plasma as shown by *St Maurice and Hanson* (1982) using the assumption that ion temperature rises due to frictional heating from the passage of ions through the neutral gas. Since we did not have the beam-swinging capability, we used the ion temperatures as a proxy for the horizontal plasma velocities and inferred horizontal plasma flows of greater than 2000 ms^{-1}, using the St Maurice and Hanson relationship.

At the time of the large vertical winds after 08:20 UT we saw low electron densities (less than 10^{10} m^{-3}) below 120 km altitude and higher electron densities (greater than $3x10^{10}$ m^{-3}) above 120 km altitude (Figure 3a). In contrast, between 06:15-07:45 UT, there were sustained bursts of high electron density when densities ten times stronger were observed in the E-region (around 120 km) and above 180 km altitude. However, the ion temperature remained low during this period (Figure 3c), which implied little frictional heating and small plasma velocities, and no significant upwelling was measured by the narrow field FPI (Figure 3b). We have interpreted Figure 3 as showing that energetic particles dumping energy in the E-region between 06:15-07:45 UT were insufficiently energetic to lift the column of air above the E-region. In this same period the two large bursts of energetic particle precipitation that occurred above 180 km altitude were also insufficient to lift the column of air above this altitude, despite having far less mass to lift. It was only when large plasma flows were indicated by the high ion temperatures after 08:15 UT, augmented by a reasonable electron density above 120 km, that significant upwelling was seen by the FPI.

The 2nd campaign provided two further case studies to test the Carlson mechanism. Figure 4 shows the period 06-12 UT on 12th January 2013 in the same format as Figure 3. The electron densities measured by the radar below 200 km altitude (shown in Figure 4a) were low throughout this period (below $3x10^{10}$ m^{-3}) and ion temperatures were below 700 K (Figure 4c). This indicated low electrical conductivity, low frictional heating and small plasma velocities. The FPI vertical winds were small, consistent with these conditions. The average vertical winds hovered around zero, and the wind error bars were large because the 630nm emission intensity was weak resulting in a small signal to noise ratio. At altitudes above 200 km the electron density was quite high, reaching $2x10^{11}$ m^{3}. These electrons were directly transferring their kinetic energy to the surrounding gas close to the altitude sampled by the 630 nm emission. Yet the energy deposited was insufficient to lift the gas. The scanning measurements of the 32 m dish ESR showed horizontal plasma vectors with magnitudes less than 500 ms^{-1}. The ion temperatures between 200-300 km altitude were less than 1000 K, which was close to the ambient temperature of the surrounding neutral gas, and indicated that there was too little frictional heating to cause upwelling.

The observations of the period 06-12 UT on 14th January 2013 shown in Figure 5 provide a valuable comparison with Figure 4. The electron densities in the region below 200 km altitude were only slightly higher than on the 12th January 2013, but above 200 km altitude there were bursts of high electron densities of around $2x10^{11}$ m^{-3}. Despite the bursts, there was only a single period of upwelling between 09:30-10:15 UT. Inspection of the ion temperatures (Figure 5c) during the upwelling show 3 brief periods (09:33 UT, 09:45 UT and 10:05 UT) when the ion temperature rose sharply to over 2300 K for the altitude range 200-250 km. There were similar bursts of high ion temperatures between 11:20-11:40 UT and the beginning of a second upwelling was seen by the FPI in Figure 5b. However, at an earlier period, between 07:20-07:40 UT when bursts of high ion temperature were observed by the ESR, there was no corresponding upwelling observed by the FPI. The electron densities during this period of no upwelling were similar to the upwelling period too. This inconsistency indicates the complexity of the mechanism.

Figure 4: 2nd Cusp Upwelling campaign: 06-12UT on 12 January 2013

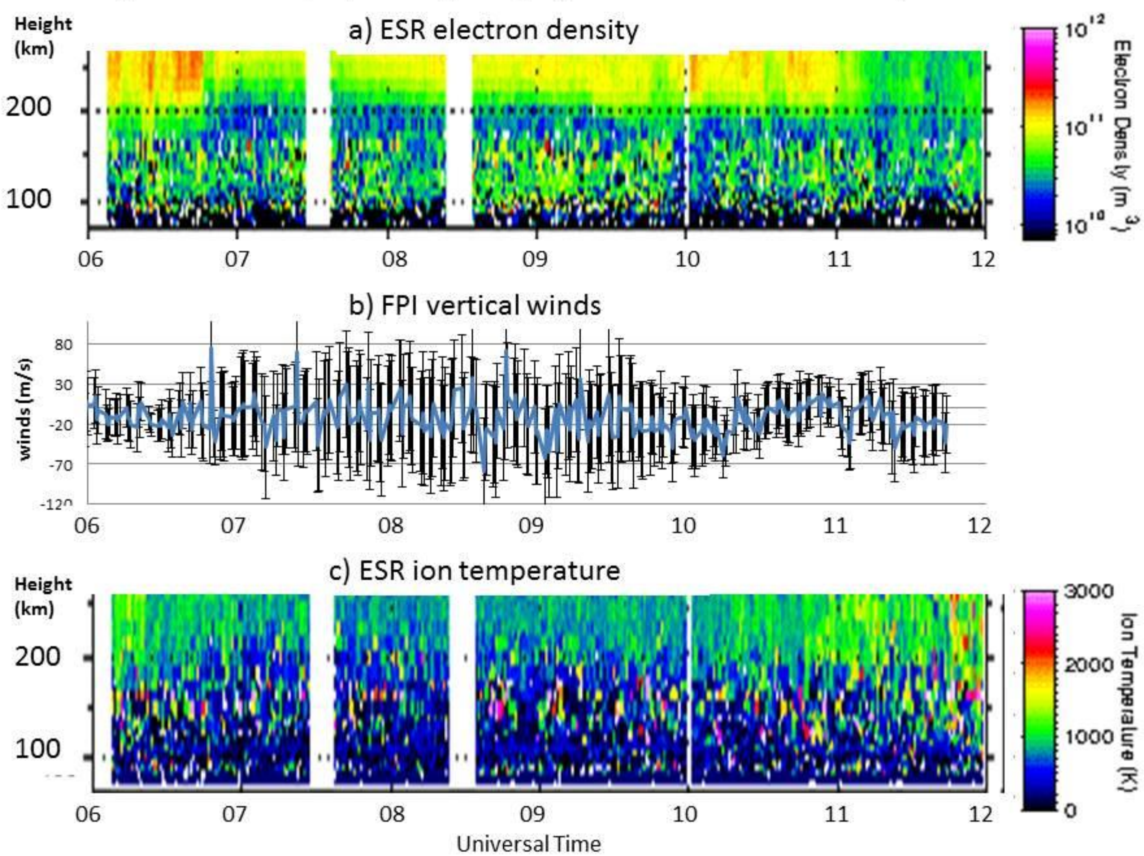
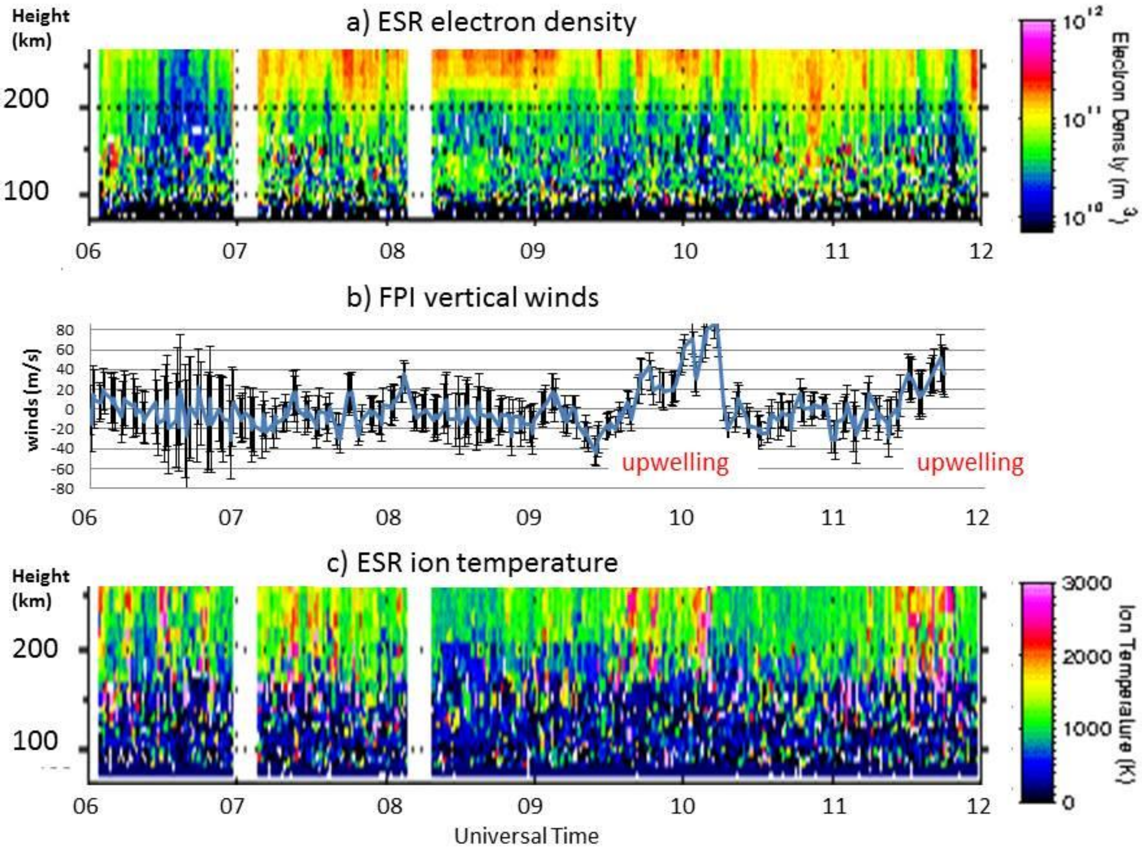


Figure 5: 2nd Cusp Upwelling campaign: 06-12UT on 14 January 2013



Conclusions

The EOARD grant funded a field trip to Svalbard to carry out a joint optical and radar campaign in January 2013. The cusp observations of the 12th January 2013 provided an example when no upwelling of the thermosphere was observed, which was an extremely useful contrast with the 14th January 2013 when strong, sustained, upwelling winds were observed by the narrow field FPI. The data are currently being analysed and interpreted, to be written up in a paper for submittal to the *Journal of Geophysical Research* (JGR). Our aim is to determine what were the conditions that caused a period of around 3 hours of sustained vertical winds, reaching a maximum of 200 ms^{-1}, on the night of 22nd Jan 2012 (the first cusp upwelling campaign reported in *Aruliah et al.*, 2014) and 40 minutes of upwelling winds, reaching 90 ms^{-1}, on the 14th January 2013; but no upwelling on the 12th January 2013. The first campaign appeared to confirm the *Carlson et al.* (2012) mechanism. The two cusp observations of the second campaign will be used to probe and test the details of the mechanism. Our initial findings from the second campaign confirm that it is necessary to have both soft particle precipitation and simultaneously fast plasma flow in order to provide frictional heating at a high enough altitude to lift the atmosphere at satellite altitudes. However, the 14th January 2013 observations demonstrate that interpretation of the behaviour of the upper atmosphere is complex and requires a careful dismantling of the data, with the help of model studies. This we will undertake in the coming year in collaboration with our colleagues.

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List of Symbols, Abbreviations, and Acronyms

CHAMP	CHAllenging Minisatellite Payload
EISCAT	European Incoherent SCATter radar consortium
ESR	EISCAT Svalbard Radar
FPIs	Fabry-Perot Interferometers
JGR	Journal of Geophysical Research
MSP	Meridian Scanning Photometer
NERC	Natural Environment Research Council
SCANDI	Scanning Doppler Imager
UCL	University College London