Meso-scale observations of Joule heating near an auroral arc and ion-neutral collision frequency in the polar cap E-region

M.J. Kosch[1], I. Yiu[2], C. Anderson[3], T. Tsuda[4], Y. Ogawa[5], S. Nozawa[6], A. Aruliah[7], V.Howells[8], L.J. Baddeley[9], I.W. McCrea[10], J.A. Wild[11]

1) Physics Dept., Lancaster University, Lancaster, UK, m.kosch@lancaster.ac.uk.
2) Dept. Physics and Astronomy, University College London, London, UK, iris@star.ucl.ac.uk.
3) Geophysical Institute, University of Alaska, Fairbanks, Alaska, ceanderson3@alaska.edu.
4) Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya, Japan, ttsuda@stelab.nagoya-u.ac.jp.
5) National Institute of Polar Research, Tokyo, Japan, yogawa@nipr.ac.jp.
6) Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya, Japan, nozawa@stelab.nagoya-u.ac.jp.
7) Dept. Physics and Astronomy, University College London, London, UK, anasuya@star.ucl.ac.uk.
8) Space Science and Technology Dept., Rutherford Appleton Laboratory, Didcot, UK, vikki.howells@stfc.ac.uk.
9) UNIS, Longyearbyen, Svalbard, Lisa.Baddeley@unis.no.
10) Space Science and Technology Dept., Rutherford Appleton Laboratory, Didcot, UK, ian.mccrea@stfc.ac.uk.
11) Physics Dept., Lancaster University, Lancaster, UK, j.wild@lancaster.ac.uk.

Abstract

We report on the first meso-scale combined ionospheric and thermospheric observations, partly in the vicinity of an auroral arc, from Svalbard in the polar cap on 2 February 2010. The EISCAT Svalbard radar employed a novel scanning mode in order to obtain F- and E-region ion flows over an annular region centred on the radar. Simultaneously, a co-located Scanning Doppler Imager observed the E-region neutral winds and temperatures around 110 km altitude using the 557.7 nm auroral optical emission. Combining the ion and neutral data permits the E-region Joule heating to be estimated with an azimuthal spatial resolution of ~64 km at a radius of ~163 km from the radar. The spatial distribution of Joule heating shows significant meso-scale variation. The ion-neutral collision frequency is measured in the E-region by combining all the data over the entire field of view with only weak aurora present. The estimated ion-neutral collision frequency at ~113 km altitude is in good agreement with the MSIS atmospheric model.

1. Introduction

At high latitudes, magnetosphere-ionosphere coupling is achieved through large-scale field-aligned current (FAC) systems [1]. In the pre-magnetic midnight dusk sector, downward FACs flow equatorward of the upward return currents, and vice versa in the post-magnetic midnight dawn sector. The large-scale morphology of the FACs is controlled by the interplanetary magnetic field (IMF) B_z and B_y components. For B_z negative the statistical strength of the FAC is controlled by the amplitude of B_z. For B_z positive, the FAC strength weakens and breaks up into multiple zones. These currents close via poleward (equatorward) ionospheric Pedersen currents in the dusk (dawn) sector and dissipate energy via Joule heating, which is largely an E-region phenomenon in the ionosphere.

Ionospheric Joule heating is an important energy sink for the magnetosphere [2], accounting for ~55 – 60% of the global energy budget [3] and is usually greater than the energy dissipated from particle precipitation. Unfortunately, it is difficult to monitor the global ionospheric electric field and Pedersen conductance simultaneously, which is why global Joule heating is often parameterized using geomagnetic indices. Height-integrated ionospheric Joule heating is typically <30 mW/m^2, although peak values can be much greater than this [4].

The spatial scales of structures in the ionospheric auroral plasma can vary from the whole auroral oval down to the Debye length limit. In particular, auroral arcs may be 100s to even 1000s of km geomagnetic east-west aligned but the average optical width of steady-state auroral arcs is only 18 ± 9 km [5]. Auroral precipitation is associated with upward FACs and local changes in ionospheric conductivity. The upward FAC must return via an equivalent downward FAC in order to satisfy current continuity, connecting in the ionosphere via Pedersen currents and dissipating energy in the form of Joule heating. The closing downward current normally appears equatorward (poleward) of the auroral arc in the dusk (dawn) sector, consistent with the large-scale ionospheric electric field

978-1-4244-6051-9/11/$26.00 ©2011 IEEE

associated with ionospheric convection [6], although this is not always the case. Normally, the local arc-induced ionospheric electric field enhances the large-scale convection electric field. However, the downward current is carried by cold ionospheric electrons propagating upward, which leaves a region typically less than 100 km wide adjacent to the auroral arc where a plasma depletion of 20 to 70% (average 45%) may occur within a minute, though it typically takes 5 min to develop [7]. The plasma depletion results in a similar decrease in Pedersen conductivity. Hence, in order to satisfy current continuity, intense horizontal ionospheric electric fields, possibly exceeding 100 mV/m, pointing into the auroral arc can develop in a narrow region, possibly less than 45 km wide, on the equatorward (poleward) side of auroral arcs in the dusk (dawn) sector [7]. Radar and rocket studies have all found that strong Joule heating occurred near the boundaries of auroral arcs, but was weak within the aurora itself [8].

Including electric field variability always increases the estimated Joule heating rate compared to using averaged electric fields [9]. Using temporally and spatially averaged electric fields can result in 20 – 65% [2] underestimation of the total Joule heating, respectively. In addition, ignoring the F-region neutral wind when estimating the ionospheric electric field may result in an error of up to 60% in the F-layer Joule heating calculation [10]. [11] found that the F-region neutral wind dynamo was on average 50% of the magnetospheric electric field and contributed an average 41% of in-situ Joule heating. A similar study has not been done in the E-layer, although the maximum in ionospheric Joule heating occurred around 110 – 130 km altitude. Of course, the E-region neutral winds can substantially affect the transfer of energy from the magnetosphere into the ionosphere. ~30-35% of the total energy entering the ionosphere goes into accelerating the E-region neutral wind and the rest into Joule heating [12]. However, the E-region neutral wind effect is height dependent and the neutral winds can also act as a dynamo releasing energy into the thermosphere. Meso-scale neutral winds in the upper E-region (>128 km) can be dramatically changed by the appearance of auroral arcs [13]. Neutral winds within ~50 km of an auroral arc could rotate their direction by ~90^o within 7 – 16 min in the height range ~130 – 200 km. This was attributed to ion drag as a result of the enhanced electric field and plasma density associated with auroral precipitation, which is consistent with [14] who found that ion drag became an important force above 107 and 118 km in the auroral oval and polar cap, respectively.

The solar minimum period of cycle 23/24 recently ended has experienced solar and geomagnetic activity at their lowest point for a century [15]. Deep solar minima are associated with atmospheric cooling and therefore contraction [15, 16]. Satellite observations of the ionosphere and the thermosphere [16] at 400 km altitude show that both were cooler and less dense in 2008 than at any other time since the beginning of the space age. In particular, [16] found that the global average thermospheric mass density to be 10-30% lower than expected. Since estimates of anthropogenic forcing and long term climatological trends cannot account for most of the density change **[**16**]**, the main driver appears to be solar EUV.

2. Experiment and data

Simultaneous E-region observations of neutral wind and ion flow in the vicinity of an auroral arc have been undertaken using a Scanning Doppler Imager (SCANDI) and the EISCAT Svalbard Radar (ESR), both located at 78.2^o N, 16.0^o E in the polar cap near Longyearbyen on Svalbard. SCANDI observed 557.7 nm in the E-region with 7 min integration. The ESR 360-degree azimuth scan, which was executed for two zenith angles sequentially, took 17.8 min to complete. An unfiltered all-sky colour camera recorded optical images of the sky every 3 min. using 2 min. integration. We analyse an almost-stationary aurora for 23:36 – 23:54 UT on 2 February 2010. We also investigate geomagnetically quiet periods before (23:12 – 23:30 UT on 2/2/2010) and after (00:36 – 00:54 UT on 3/2/2010, hereafter labelled 24:36 – 24:54 UT) the aurora appeared. 23:12 – 23:30 UT had no aurora present. 24:36 – 24:54 UT had some quiet aurora present near the south-east horizon. Geomagnetic conditions were moderately active with K_p = 3 – 4 in the period of interest. The IMF data from the ACE satellite in GSM coordinates, adjusted by 48 min to account for the solar wind speed of ~520 km/s, gives B_z in the range -5.9 to +2.8 nT, B_y in the range -2.2 to -6.0 nT and B_x in the range +0.1 to +4.6 nT throughout the period of interest. SuperDARN global ionospheric convection shows Longyearbyen under a weakly developed dawn convection cell, consistent with B_z mostly positive and B_y negative. Inverting the plasma density profiles obtained from the ESR field-aligned 42m dish gave the effective 557.7 nm emission altitude to be in the range 105 – 117 km with an average of 110.5 km during the periods of interest.

The geometry of the experiment has the low zenith angle annulus in the F-region vertically above the high zenith angle annulus in the E-region, which coincides with the middle annulus of E-region neutral winds from SCANDI. The magnetic field inclination over Svalbard is only ~8^{o}, i.e. effectively vertical. For the height range 105 – 115 km, the E-region ESR data at 56^{o} zenith angle covers a radial distance of 156 – 170 km, whereas the SCANDI sector at 45 – 60^{o} zenith angle covers 110 – 190 km. We denote the effective radial distance of the combined data as 163 km. This gives an azimuthal distance of 64 km for the 22.5^{o} sectors. The F-region ESR data at 30^{o} zenith angle intersects the middle annulus SCANDI sector boundaries at 190 – 329 km altitude, which conveniently allows integration over 200 – 300 km in the F-layer to obtain a good estimate of the ionospheric electric field. The E-region ESR data at 56^{o} zenith angle is used to obtain the Pedersen conductance for the Joule heating calculation.

For 24:36 – 24:54 UT we estimate the effective 557.7 nm altitude was 112.8 ± 0.8 km. By combining the ESR and SCANDI data of E-region ion and neutral flow as well as F-region electric field, the ion-neutral collision frequency is estimated to be in the range 424 – 450 Hz (average 438 Hz) with an uncertainty of 36% (±79 Hz). The average uncertainty in the F-region ion flow is 19%, and in the E-region ion and neutral flow uncertainties are 16% and 29%, respectively.

3. Results and Discussion

The neutral temperature data shows a maximum variation of 22% around the analysis annulus for both 23:36 – 23:54 and 24:36 – 24:54 UT, indicating that the effective height variation of the 557.7 nm emission over 360^{o} was probably low and reasonably well constrained within one scale height (±5 km) of 110 km altitude.

The main point here is the variability of the Joule heating. At 23:12 – 23:30, 23:36 – 23:54 and 24:36 – 24:54 UT, Joule heating varies by 308%, 90% and 269%, respectively, over 360^{o} with respect to the average. This variation is large compared to the average measurement uncertainty of 35.8%. Bearing in mind that it takes 30 s to scan two neighbouring sectors, the largest change in Joule heating between any pair of neighbouring sectors is 278%, 47% and 201% with respect to the average, for the three time intervals respectively. It is clear that current ionosphere-thermosphere models cannot replicate this variability due to their low spatial and temporal resolution (e.g. CTIP, 2^{o} latitude, 18^{o} longitude, 72 min). The consequence of this is illustrated by the total power dissipated in our analysis annulus, covering 110 to 190 km radius. The total area covered by the annulus is 7.54 x 10^{10} m^2 and by each 22.5^{o} sector is 4.71 x 10^9 m^2. Using the average electric field and Pedersen conductance, the total power dissipated is 4.16 x 10^7, 3.05 x 10^8 and 5.82 x 10^7 W for each time interval, respectively. However, if we integrate the power dissipated in each sector, giving the same total area, then the total power dissipated is 4.74 x 10^7, 3.12 x 10^8 and 6.10 x 10^7 W for each time interval, respectively. This means that the total power dissipated, when integrated over smaller sectors, results in a 13.9%, 2.3% and 4.8% increase for each time interval, respectively. It seems clear that large-scale spatial averaging results in the underestimation of energy dissipation, which is consistent with previous findings.

The measured ion-neutral collision frequency has an average value of 438 Hz, whereas using the MSIS model predicts 471 Hz at 112.8 km altitude, a discrepancy of 33 Hz which is within the measurement uncertainty (±79 Hz). The predicted ion-neutral collision frequency varies rapidly with altitude in the E-region, changing by almost an order of magnitude within one scale height (~10 km). To get good agreement, our altitude estimate of the 557.7 nm emission would have to be ~113.2 km, which is entirely feasible given our measurement uncertainty of ± 0.8 km. The ±79 Hz uncertainty in the ion-neutral collision frequency estimate corresponds to a height range of about 1 km around 113 km, i.e. much less than one scale height. Since our height estimate is 112.8 ± 0.8 km, it appears that our observational estimate of the E-region ion-neutral collision frequency is good agreement with that derived from MSIS.

4. Conclusion

Using a novel dish scan mode on the EISCAT Svalbard radar, combined with all-sky E-region neutral wind observations from a scanning Doppler imager, we have made meso-scale observations of ion and neutral flow, partly in the vicinity of an auroral arc, within the polar cap at ~110 km altitude. We show that Joule heating can vary by >100% within 64 km horizontal distance. It is clear that current ionosphere-thermosphere general circulation models are far from realising such meso-scale variability, which probably accounts for at least part of their underestimation of the ionosphere-magnetosphere energy coupling budget. We also perform the first estimate of the E-region ion-neutral collision frequency at 112.8 (±0.8) km altitude by combining E- and F-region ion flow with E-region neutral flow data. Our result is in good agreement with the ion-neutral frequency derived from the MSIS atmospheric model.

5. References

1. Kosch, M. J., and E. Nielsen (2001), Coherent radar estimates of high latitude field-aligned currents: statistical averages, *Adv. Space Res.*, 27(6-7), 1239-1244.

2. Rodger, A. S., et al. (2001), The variability of Joule heating, and its effects on the ionosphere and thermosphere, *Ann. Geophys.*, 19, 773-781.

3. Tanskanen, E., et al. (2002), Substorm energy budget during low and high solar activity: 1997 and 1999 compared, *J. Geophys. Res.*, 107, 1086, doi:10.1029/2001JA900153.

4. Kosch, M. J., and E. Nielsen (1995), Coherent radar estimates of average high-latitude ionospheric Joule heating, *J. Geophys. Res.*, 100, 12201-12215.

5. Knudsen, D. J., et al. (2001), Width and structure of mesoscale optical auroral arcs, *Geophys. Res. Let.*, 28, 705-708.

6. Lewis, R. V., et al. (1994), The electrodynamics of a drifting auroral arc, *Ann. Geophys.*, 12, 478-480.

7. Doe, R. A., et al. (1995), Electrodynamic model for the formation of auroral ionospheric cavities, *J. Geophys. Res.*, 100, 9683-9696.

8. McCrea, I. W., et al. (1991), On the identification and occurrence of ion frictional heating events in the high-latitude ionosphere, *J. Atmos. Terr. Phys.*, 53, 587-597.

9. Codrescu, M. V., et al. (1995), On the importance of E-field variability for Joule heating in the high-latitude thermosphere, *Geophys. Res. Lett.*, 22, 2393-2396.

10. Cierpka, K., et al. (2000), Ion-Neutral Coupling in the High-Latitude F-Layer from Incoherent Scatter and Fabry-Perot Interferometer Measurements, *Ann. Geophys.*, 18, 1145-1153.

11. Aruliah, A. L., et al (2004), First tristatic studies of meso-scale ion-neutral dynamics and energetics in the high-latitude upper atmosphere using collocated FPIs and EISCAT radar, *Geophys. Res. Lett.*, 31, L03802, doi:10.1029/2003GL018469.

12. Fujii, R., et al. (1999), Statistical characteristic of electromagnetic energy transfer between magnetosphere, the ionosphere, and the thermosphere, *J. Geophys. Res.*, 104, 2357-2365.

13. Kosch, M. J., et al. (2010), First E-region observations of meso-scale neutral wind interaction with auroral precipitation, *J. Geophys. Res.*, 115, A02303, doi:10.1029/2009JA014697.

14. Nozawa, S., et al. (2005), Mean winds, tides, and quasi-2 day wave in the polar lower thermosphere observed in European Incoherent Scatter (EISCAT) 8 day run data in November 2003, *J. Geophys. Res.*, 110, A12309, doi:10.1029/2005JA011128.

15. Russell, C. T., et al. (2010), How unprecedented a solar minimum?, *Rev. Geophys.*, 48, RG2004, doi:10.1029/2009RG000316.

16. Emmert, J. T., et al. (2010), Record-low thermospheric density during the 2008 solar minimum, *Geophys. Res. Lett.*, 37, L12102, doi:10.1029/2010GL043671.