*Planet. Space Sci.*, Vol. 38, No. 9, pp. 1187–1201, 1990
Printed in Great Britain.

0032–0633/90 \$3.00+0.00
Pergamon Press plc

# A STATISTICAL STUDY OF LARGE FIELD-ALIGNED FLOWS OF THERMAL IONS AT HIGH-LATITUDES

J. G. KEATING, F. J. MULLIGAN and D. B. DOYLE
Department of experimental Physics, St Patrick's College, Maynooth, Co. Kildare, Ireland

and

K. J. WINSER and M. LOCKWOOD
Rutherford Appleton Laboratory, Chilton, Didcot, Oxford OX11 0QX, U.K.

(*Received in final form* 18 *May* 1990)

**Abstract**—A number of case studies of large, transient, field-aligned ion flows in the topside ionosphere at high-latitudes have been reported, showing that these events occur during periods of frictional heating and/or intense particle precipitation. This study examines the frequency of occurrence of such events for the altitude range 200–500 km, based on 3 years of incoherent scatter data. Correlations of the upgoing ion flux at 400 km with ion and electron temperatures at lower altitudes are presented, together with a discussion of possible mechanisms for the production of such large flows. The influence of low-altitude electron precipitation on the production of these events is also considered.

## INTRODUCTION

Ion flows from the high-latitude ionosphere into the magnetosphere divide into two main categories. The first is the "classical" polar wind which is predicted to consist of low energy ($<1$ eV), light ($H^+$ and $He^+$) ions with fluxes of about $10^{12}$ m$^{-2}$ s$^{-1}$. However, in recent years observations have revealed significant fluxes of heavier (principally $O^+$) and more energetic ions (ranging from $\sim 1$ eV up to several tens of kiloelectron volts) emanating from the ionosphere. In fact, upward flowing ions with energies ranging up to several kiloelectron volts are observed as a common feature of the high-altitude, high-latitude ionosphere. Spacecraft observations show that conical ion distributions, indicating transverse acceleration of ions to energies in the range 5–100 eV, are more widespread and occur at lower altitudes, and at lower energies than ion beam distributions (Klumpar, 1979; Gorney *et al.*, 1981). Ungstrup *et al.* (1979) using ISIS data in the height range 1400–3000 km, found that conics, in general, were a common feature in the winter hemisphere, and occurred with a 50% probability around local midnight at the lowest altitudes. However, such distributions are generally observed in regions of net downward field-aligned current (where the dominant carrier is upgoing, cold ionospheric electrons), which typically extend from about 22:00 to 10:00 L.T. Similar acceleration processes have been observed as low as 400–500 km using rocket measurements (Whalen *et al.*, 1978; Yau *et al.*, 1983).

Direct observations of upflowing, thermal ionospheric ions in the magnetosphere by satellites are very difficult because of the presence of floating spacecraft potentials, which are often larger than the thermal energies of the ions. Some observations have been possible by applying a bias potential to the detector, in other cases significant fluxes have been observed at energies above the threshold set by the satellite potential (see review by Lockwood, 1986), or by the instrument (Yau *et al.*, 1986). At lower altitudes, Lockwood (1982) examined topside soundings from the *Alouette* satellite and identified large upward field-aligned fluxes in the topside ionosphere, which he explained in terms of a plasma pressure gradient effect, where the ions respond by moving along the magnetic field line to fill a hole left by the ions expelled due to some acceleration process at greater altitudes. Smith *et al.* (1985) combined radar and optical measurements of the component of the convection velocity along the magnetic meridian, and inferred the presence of large (200–400 m s$^{-1}$), downward flows of oxygen ions along the magnetic field.

Such field-aligned flows of thermal ions will play an important role in the structure and dynamics of the *F*-region ionosphere, in particular the formation of high-latitude electron density troughs (Williams and Jain, 1986; Winser *et al.*, 1986). On occasion, very large upward fluxes ($>10^{13}$ m$^{-2}$ s$^{-1}$) have been observed directly using the EISCAT incoherent scatter radar (Williams and Jain, 1986; Winser *et al.*, 1986, 1988a,b, 1989; Jones *et al.*, 1988). The field-aligned ion velocities associated with these large fluxes were of the order 200–500 m $s^{-1}$, which is significantly higher than previously reported. These large flows are closely related to enhancements in the local ion temperature associated with rapid changes in the convection velocity, such as those caused by the passage of a velocity shear over the observing field of view. Recent model predictions (Gombosi and Killeen, 1987) have suggested that large upward fluxes of thermal ions can be driven by typical auroral energy inputs, which is in substantial agreement with many of the observations described above. However, other recent EISCAT observations by Wahlund and Opgenoorth (1989) have shown that some large upflows are not apparently associated with any ion heating but may be caused by particle precipitation. Furthermore, Yeh and Foster (1990) have observed a dramatic ion upflow event at Millstone Hill which occurred during a major geomagnetic storm. These authors suggest both plasma heating and intense $O^+$ production contributed to this upflow.

The observations of flux magnitudes in the lower topside ionosphere cannot be considered as direct measurement of ion outflow fluxes into the magnetosphere (even allowing for the variation in flux tube cross-sectional area), for a number of reasons. Firstly, there may be some production of plasma at altitudes above the observation; secondly large velocities of undetected minor ion species could considerably alter the flux estimate (EISCAT observations in the lower topside ionosphere are effectively of the dominant $O^+$ ion gas but a low concentration of $H^+$ or $He^+$ ions may exist, yet remain undetected, and may constitute a large number density flux if their velocity is very large) and lastly, steady-state outflow may often not exist. The latter may, for example, mean that an observed upward flow results in a rise in density of the upper topside ionosphere, but does not give outflow into the magnetosphere: at some time later this high-altitude density may decrease giving a return downward flow into the lower ionosphere; because this upper topside enhancement may consistently occur in one location the subsequent depletion may occur after the flux tube has convected to a different location, averaging the data for a given location will not remove this effect. Nevertheless, magnetospheric observations of very large ionospheric $O^+$ ion upflows do require that there be large upflows in the lower ionosphere and hence occurrence of ionospheric upflow events is of interest as an indicator of outflow events into the magnetosphere. To the present time, many of the examples of the very large field-aligned fluxes of thermal ions observed by radars, as described above, have been presented as case studies. In view of the very large database which the EISCAT (European Incoherent Scatter) radar (Folkestad *et al.*, 1983) has built up over the last few years, it seems pertinent to carry out a statistical study of the occurrence of these events. The EISCAT radar was operated in such a mode (Common-Programme 1) that profiles of the main ionospheric parameters (including the field-aligned velocity) were obtained with excellent height and time resolution, in the height range 100–500 km. Such a dataset has not been available before. In this paper we use selection criteria for defining a field-aligned flow event (FAFE) based on the measurements of Winser *et al.* (1989). We then calculate the frequency of occurrence of these FAFEs as a function of Universal time and season, and attempt to correlate them with the plasma temperatures and density.

## OBSERVATIONS

This study investigates the occurrence of large field-aligned flows of thermal plasma at Tromsø (69.6°N, 19.2°E) using EISCAT, the European incoherent scatter radar. We have examined 3 years (1985–1987) of EISCAT Common-Programme One (CP-1) data for observations of "field-aligned flow events" (FAFEs). CP-1 is a programme in which the radar at Tromsø makes measurements parallel to the geomagnetic field line, providing a continuous record of changes in ionospheric parameters with very good time resolution.

The event described by Winser *et al.* (1989) which occurred around 21:00 U.T. on 6 May 1987, was used to select the criteria for establishing the occurrence of a typical upflow event in this study and is reproduced in Fig. 1. Note the clear correlation of large upflux and elevated ion temperature in this case. It was decided to apply the criteria for increased flux, or increased velocity alone, in the search for events and to then perform statistical correlations between the magnitude of the flux associated with the upflow events, and ion/electron temperature profiles. Following the work of Winser *et al.* (1989), we consider an event to have occurred if either of the following are observed:

(i) an ion velocity, upward or downward in excess of 100 m $s^{-1}$;

(ii) an upward/downward ion flux exceeding $10^{13}$ $m^{-2}$ $s^{-1}$.

These criteria are based upon theoretical analysis of flows in the topside ionosphere: the speed threshold is larger than typical field-aligned velocities due to thermospheric winds and plasma pressure. The flux threshold is an order of magnitude greater than the

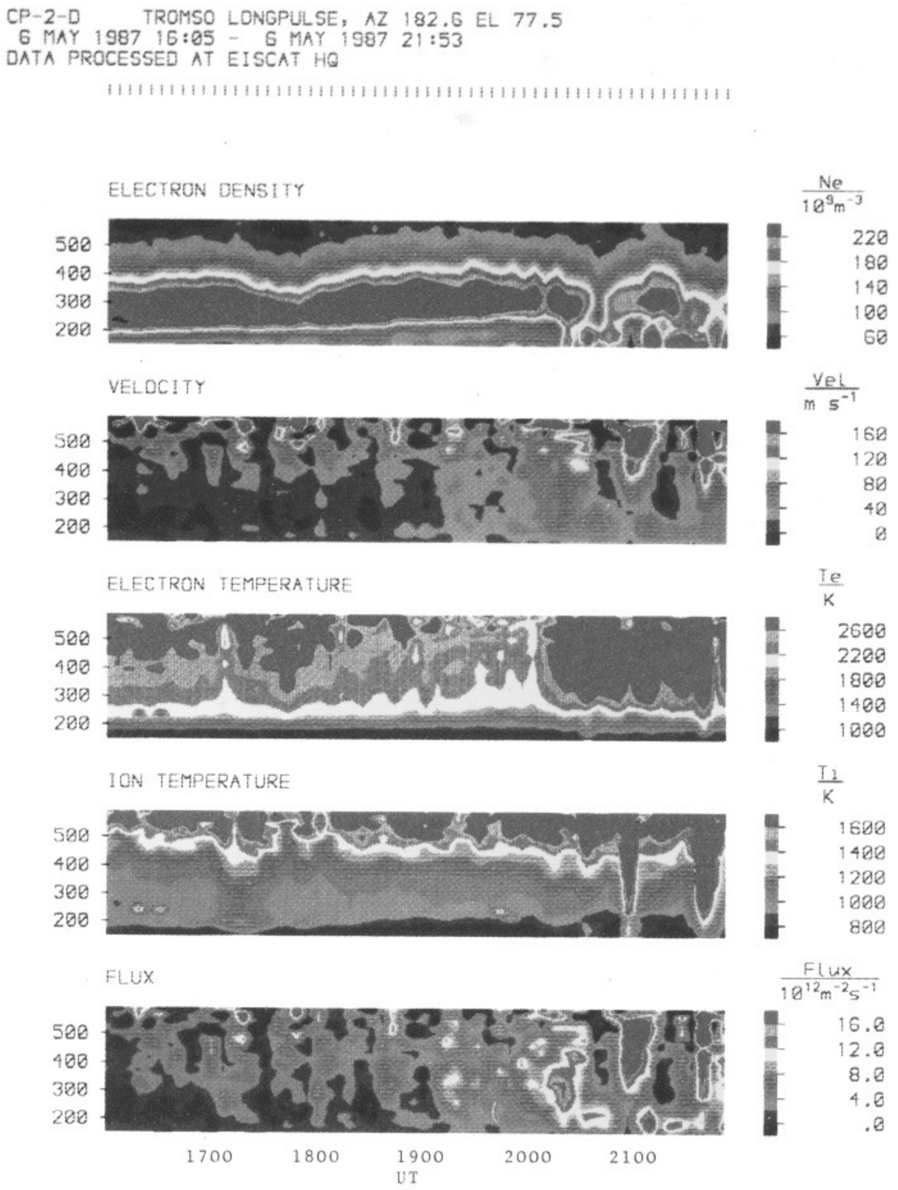
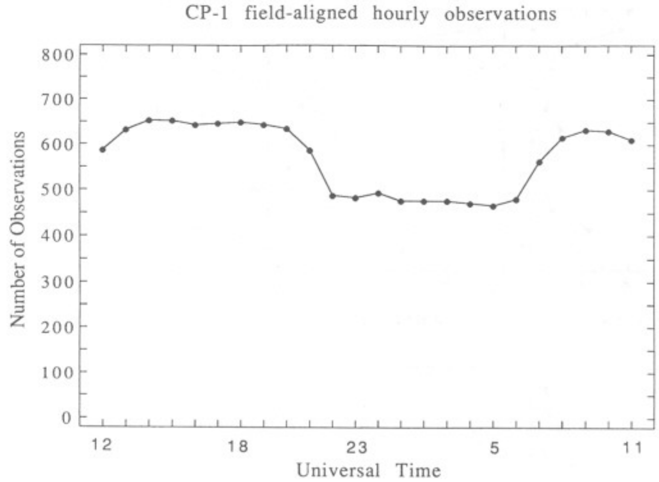
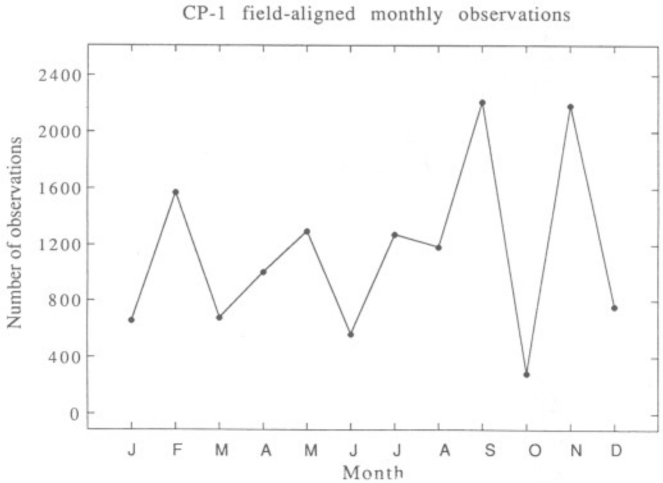



FIG. 1. FIELD-ALIGNED OBSERVATIONS MADE BETWEEN 16:00 AND 22:00 U.T. ON 6 MAY 1987 BY THE EISCAT COMMON-PROGRAMME CP-2-D.




(a)




(b)

FIG. 2. (a) DIURNAL VARIATION IN THE NUMBER OF 5-min CP-1 FIELD-ALIGNED OBSERVATIONS DURING THE PERIOD 1985–1987.
(b) Annual variation in CP-1 field-aligned observations for the same period.

predicted flow required to support the "classical" polar wind outflow of light ions (Banks and Holzer, 1969). Experience with EISCAT observations (e.g. Jones *et al.*, 1988; Winser *et al.*, 1989) shows that flow does not usually exceed these threshold values, but there are limited periods ("events") when it does.

The raw data were post-integrated into 5-min intervals, each referred to here as an "observation". A "percentage frequency occurrence" parameter was then computed for various hourly and monthly bins, which effectively normalized the FAFE occurrence to the total number of observations made along a field-line within the period of interest. This parameter is defined as the total number of observations meeting one or both of the above criteria, expressed as a percentage of the total number of observations made in the field-aligned position during that bin. Figure 2a shows the diurnal variation in the total of all available CP-1 field-aligned observations (irrespective of flow derived) for the 3 year period, while Fig. 2b shows the corresponding annual variation. The FAFEs were then subdivided into upflow and downflow events and further organized into six height bins, each of 30 km centred on altitudes 200, 250, 300, 350, 400 and 500 km.

Figure 3a shows the percentage frequency occurrence of upflow events for each of the size altitude regions as a function of Universal time. Maximum

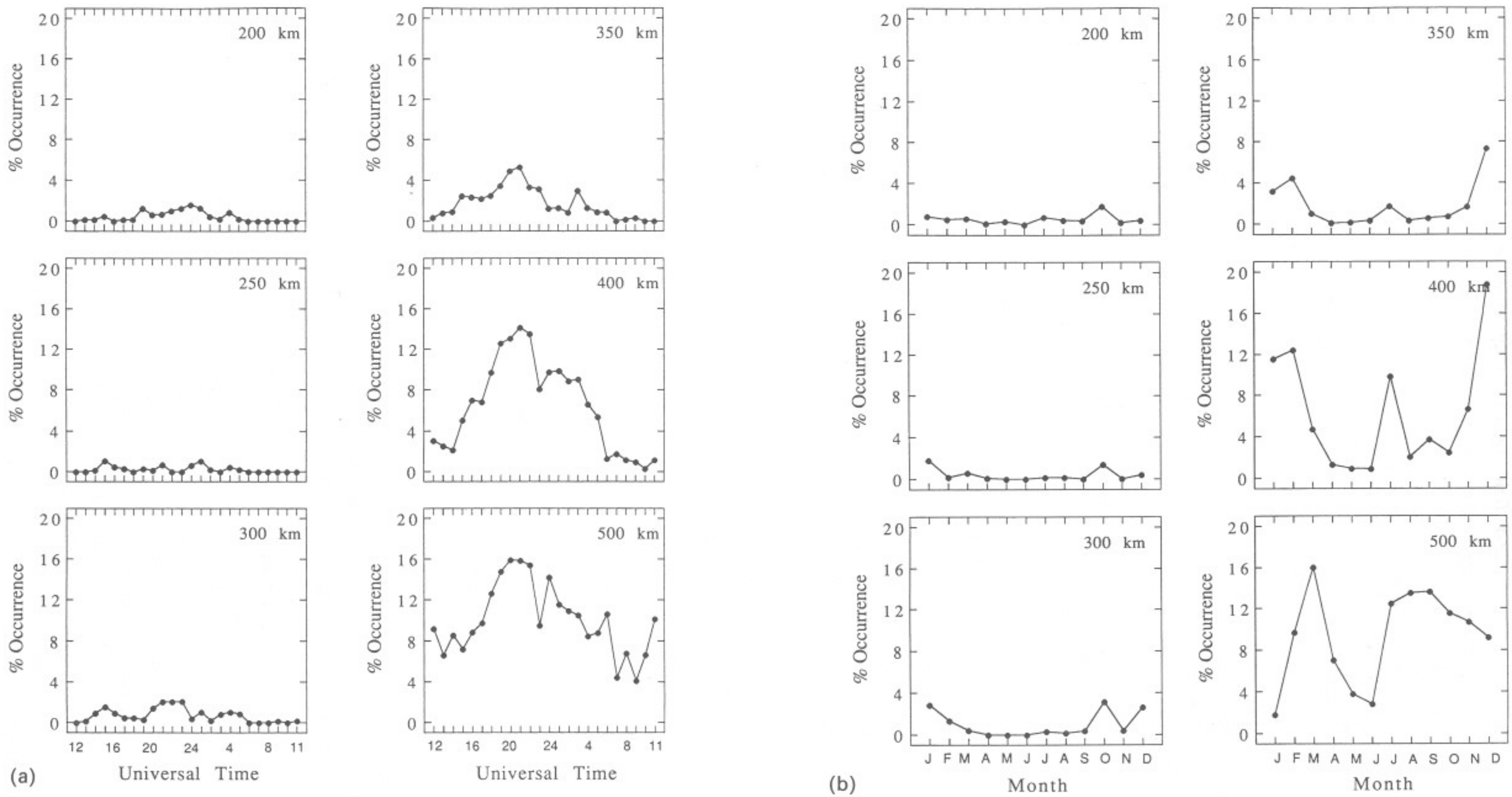



FIG. 3. (a) DIURNAL VARIATION (IN HOURLY BINS) OF FAFE FREQUENCY OCCURRENCE FOR SIX ALTITUDE LEVELS BETWEEN 200 AND 500 km. (b) Annual variation (in monthly bins) of FAFE frequency occurrence for the same six altitude levels.

occurrence is confined to the night-time period (19:00–04:00 U.T.) at the highest altitudes, with very few events observed below 350 km. A peak value is observed at 21:00 U.T. for the altitude range 350–500 km. The peak value reaches a maximum at 400 km but does not appear to be significantly greater at 500 km. This peak is asymmetric in shape and tends to be spread over the whole night-time period and indicates that more upflows occur after 21:00 U.T. than beforehand. This broadening of the peak may be due to seasonal variations or differences in geomagnetic conditions at the time of measurement. Figure 3a also shows that the overall number of daytime events increases with increasing altitude. This increase is particularly evident over the 400–500 km range. However, the signal-to-noise ratio decreases rapidly with altitude (as plasma densities are lower giving lower scattered power, and range is greater) and this may give large scatter in derived velocity and flux values, causing more observations to exceed the threshold criteria. This effect may explain many, if not all, dayside observations of FAFEs. Quantifying an acceptable limit for the signal-to-noise ratio is difficult. However, later we discuss observations where upflow is consistently observed at the various altitudes, in which case the probability that this is due to low signal-to-noise ratio is very low.

The annual variation for the same altitude levels is given in Fig. 3b, showing that most events occur during the winter period, especially at 400 km. However, a substantial number of events are also recorded for July above 300 km. A breakdown of the annual variation at 400 km for each of the individual years is given in Fig. 4 and shows that there is a fairly clear winter dependence. The only exception is for January at 500 km where the frequency occurrence is low and is due to fewer field-aligned observations for this month than any other over the 3 year period. The summer peak observed at 300 and 400 km in Fig. 3b is due solely to a 41% occurrence of upflows during July 1987. This very interesting period is presently under scrutiny and a future paper will detail the results of our analysis. We conclude that FAFEs at Tromsø are a regular winter phenomenon but can occur in summer during "disturbed periods".

We examined the two altitude regions centred on 350 and 400 km for the occurrence of *simultaneous* upflow events at both heights for both hourly and monthly bins. Figure 5a gives the diurnal variation and shows a well-defined peak which is almost symmetrical about 21:00 U.T. but having magnitude which is considerably smaller than that observed at 400 km. This reduction in peak magnitude is not inconsistent with the result that most FAFEs appear above 400 km altitude. The occurrence of simultaneous upflows (in the 350–400 km range) is limited only by the number of events occurring at 350 km. The fact that simultaneous events were observed over this altitude range reinforces our belief that these are real upflow events. A similar analysis was carried out using the 350–500 km range, and although similar trends are evident, fewer events were observed. The winter dependence, together with the effect of the disturbed period in July 1987 referred to earlier, is also evident in Fig. 5b.

Figure 5a also shows a dramatic reduction in the

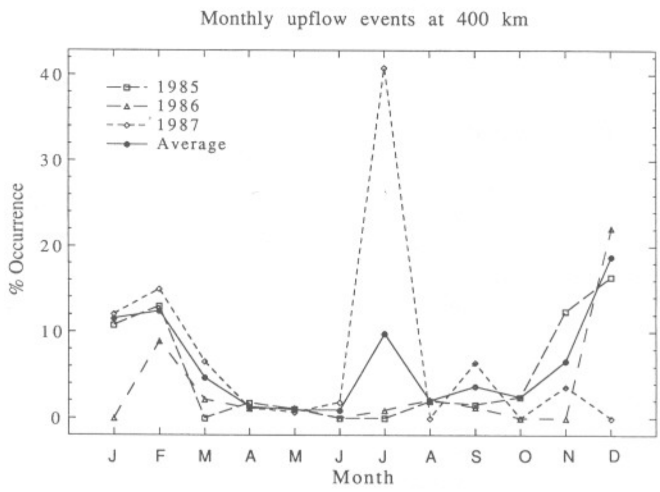
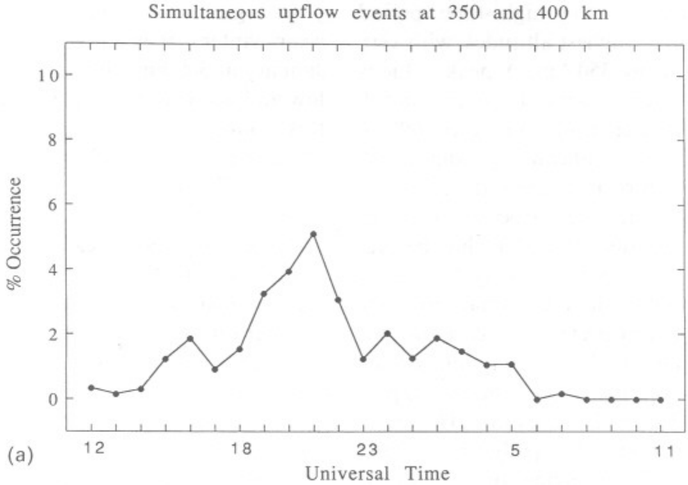
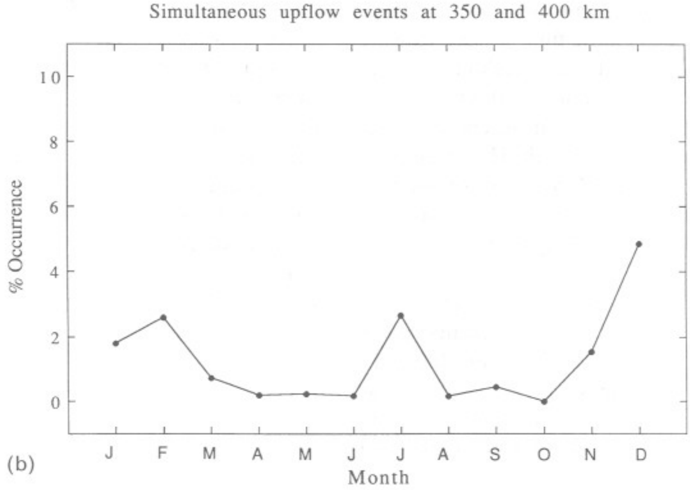



FIG. 4. ANNUAL VARIATION IN UPFLOW OCCURRENCE AT 400 km FOR THE FOLLOWING YEARS: (i) 1985; (ii) 1986; (iii) 1987; AND (iv) 1985–1987.




(a)




(b)

FIG. 5. (a) DIURNAL AND (b) ANNUAL PERCENTAGE FREQUENCY OCCURRENCE OF SIMULTANEOUS UPFLOW EVENTS AT 350 AND 400 km.

number of daytime upflows, compared with results for 500 km (Fig. 3a) indicating that many of the dayside FAFEs at great altitudes may be caused by spectrum noise and hence that these events are predominantly night-time occurrences. It must be stressed at this point, however, that EISCAT makes measurements in the auroral regions during the night-time period only—the location of Tromsø is such that it is South of the polar cusp at midday. Although our results show a night-time maximum around 21:00 U.T., this does not preclude the existence of other regions with high percentage occurrence rates in the dayside auroral or cusp region, which are nearly always to the North of Tromsø.

Figure 6a shows the diurnal variation of field-aligned downflow occurrence at the same six altitude levels considered for the upflow case. There is a significant difference between the two sets of results with the maximum downflow frequency observed to be about half that of the upflows. The peak occurrence is again observed at 400 km but at the later time of 02:00 U.T. Examination of Fig. 6b shows that the downflows also appear most frequently during winter but with overall occurrence frequencies much less than those observed for the upflows. There appears to be no dramatic increase in the number of downflows for the July period. At 500 km there is no clear universal time variation which suggests again that a low signal-to-noise ratio is a problem. The simultaneous occurrence of downflows across the 350–400 km altitude

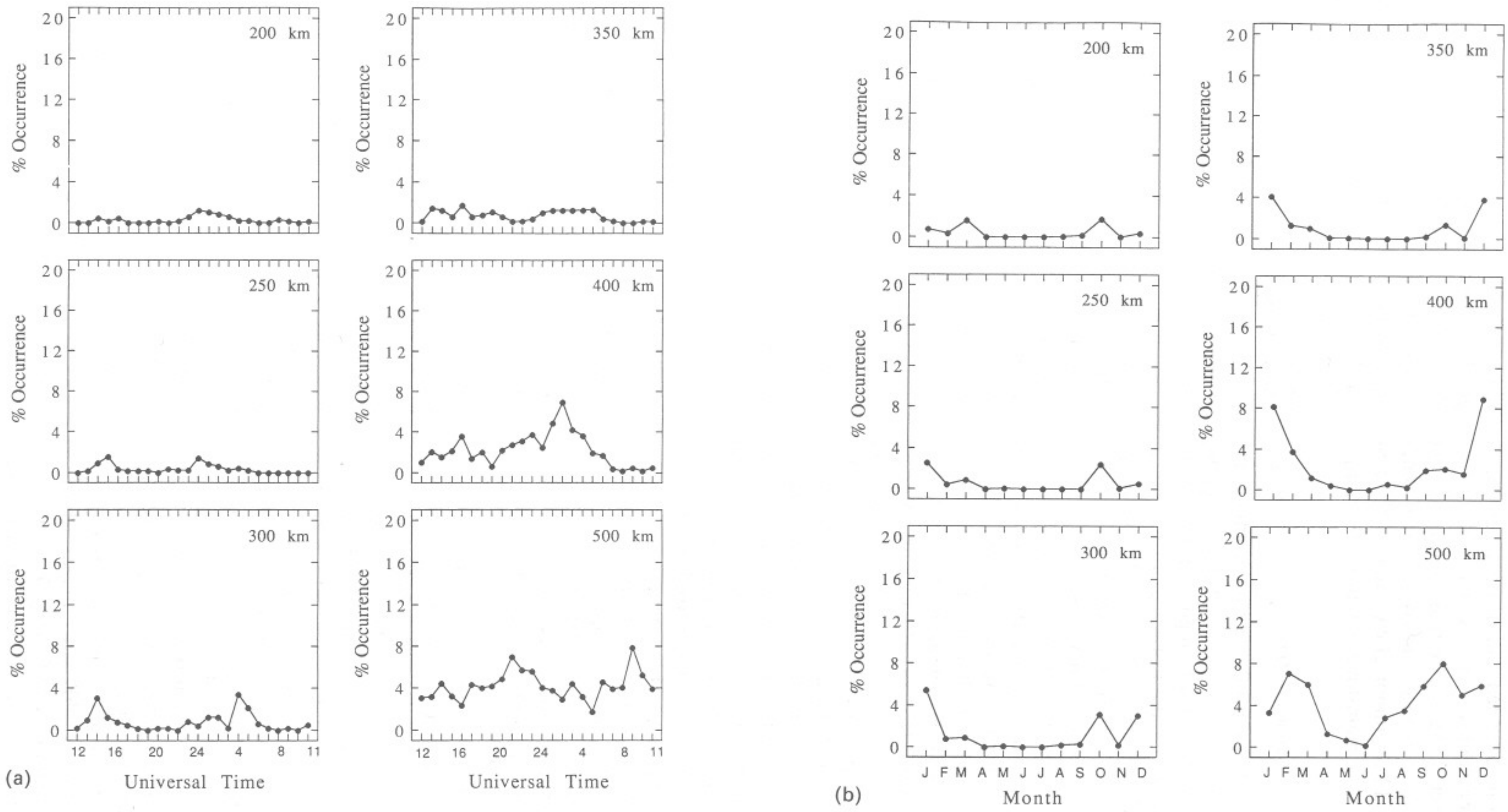



FIG. 6. (a) DIURNAL VARIATION OF FIELD-ALIGNED DOWNFLOW FREQUENCY OCCURRENCE FOR SIX ALTITUDE LEVELS BETWEEN 200 AND 500 km. (b) Annual variation of field-aligned downflow monthly frequency occurrence for the same six altitude levels.

range was also investigated and it was again found that the number of upflow events exceeded the number of downflow events. Again, we must remember that our observations are only for Tromsø and hence downflows could be common elsewhere (e.g. the central polar cap or the night-time sub-auroral region).

## DISCUSSION

It is known that upward-flowing ion events in the topside ionosphere are partly responsible for populating the magnetosphere with high energy $O^+$ ions, especially in the cusp and auroral regions (Shelley *et al.*, 1972; Ghielmetti *et al.*, 1978; Yau *et al.*, 1986) and lower energy $O^+$ ions in the cusp and polar cap—the "Cleft ion fountain" (Lockwood *et al.*, 1985a; Lockwood, 1986) and nightside "X events" (Moore *et al.*, 1985; Lockwood *et al.*, 1985b; Lockwood, 1986). It is interesting to note that the time sector in which the FAFEs, identified in this study, were most frequently observed is the same as that for which most ion conics and beams (energy $>90$ eV) are observed at higher altitudes (Gorney *et al.*, 1981). Yau *et al.* (1986) report $O^+$ upflows (energy $>10$ eV) are larger in the nightside auroral oval after 21:00 M.L.T., which corresponds to after 19:00 U.T. at EISCAT. Again, this is broadly consistent with the occurrence reported here in Fig. 3a. It may be possible, therefore, that the FAFEs are responsible for providing $O^+$ ions which are then expelled into the magnetosphere by these high-altitude mechanisms. The remaining ions, under the action of gravity would eventually come down again some time after the initial upflow. With this in mind, the peak occurrence at 02:00 U.T. associated with the field-aligned downflows, may represent a fraction of downflowing $O^+$ ions which were driven upward at 21:00 U.T.

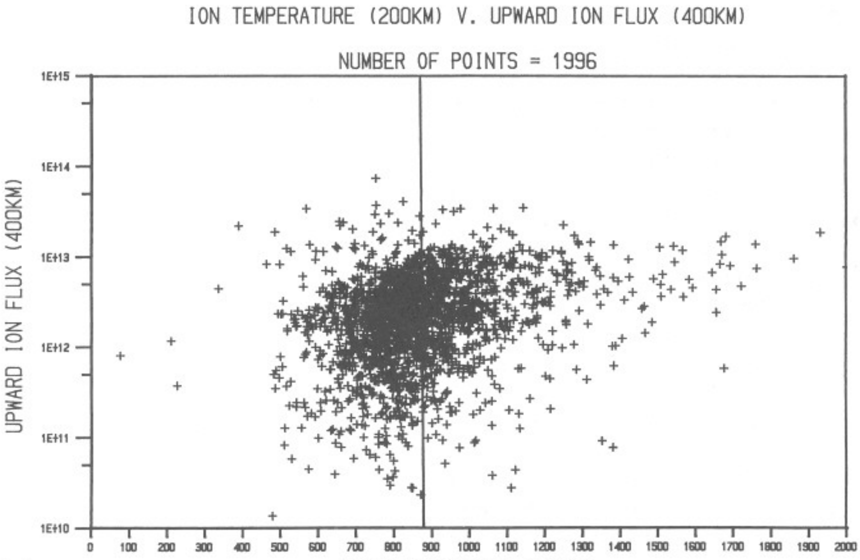
Lockwood (1982) inferred upflows from topside soundings and found occurrence probabilities of flows exceeding $0.75 \times 10^{13}$ m$^{-2}$ s$^{-1}$ (i.e. three quarters of the threshold used here) of over 40% in the pre-midnight sector in winter, but below 10% in summer—consistent with the seasonal dependence found here. The higher occurrence rates may be partly due to the lower threshold but may well also be because observations were available above 500 km, where low signal noise becomes a problem with our radar data. This (or the latitude of Tromsø) may also explain why Lockwood also found higher occurrence frequencies (20–40%) in the dawn sector.

The reduced number of simultaneous downflow observations in the 350–400 km range also leads to the supposition that the downflowing $O^+$ ions are just the relaxation phase of the earlier, directly-driven, upflow events, i.e. ions returning under the action of gravity. However, the work of Williams *et al.* (1990) shows that large field-aligned downflows can occur across a range of altitudes at high latitudes. These authors have noted that above some threshold value for the electric field there is a dramatic increase in the $O^+$ recombination rate. This results in a depletion of electrons at *F*-region altitudes and the action of plasma pressure is thought to drive the ions downward with large velocities. On the other hand, Jones *et al.* (1988) have also found that the *F*-region may become depopulated by upward flows, following high ion/electron temperatures in response to an enhanced electric field. These authors have found that the action of diffusion alone may cause very large upflows of $O^+$ ions with velocities as high as 500 m s$^{-1}$. A steady increase in upward field-aligned velocity with altitude has also been observed. The large upflows observed by these authors occurred in the region of the Harang discontinuity where there is a high degree of frictional heating. Winser *et al.* (1986, 1988) have presented a quantitative study of the high-latitude ionospheric trough using 18 days of EISCAT's Common Programme data and report increased numbers of field-aligned upflows in the post-midnight trough region with velocities in the range 90–120 m s$^{-1}$. These observations are readily confirmed by the results of the present study, with the peak occurrence observed around 21:00 U.T. corresponding to the radar making measurements in the region of the Harang discontinuity. Increased numbers of upward field-aligned events for the 3 h period after midnight (U.T.) at 400 km is in good agreement with the upflows recorded by Winser *et al.* (1986, 1988) following the appearance of the post-midnight trough at high latitudes.

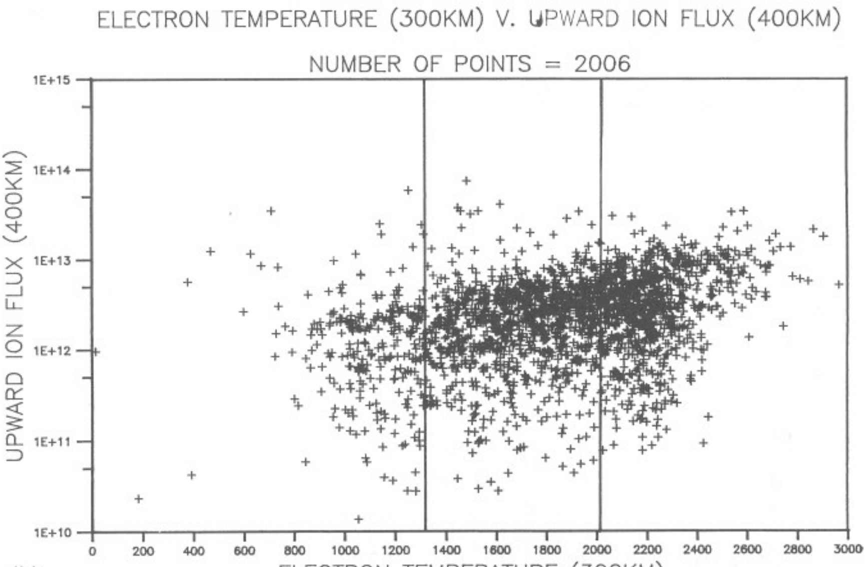
It is evident from the literature (Winser *et al.*, 1986, 1988, 1989; Wahlund and Opgenoorth, 1989; Jones *et al.*, 1988; Lockwood, 1982) that field-aligned flows of thermal ions, although transient in nature, occur with sufficient frequency to warrant more attention. In this study we have examined the temporal variation of frequency of occurrence of FAFEs at Tromsø, most of which had fluxes at least an order of magnitude greater than the classical polar wind, across a range of altitudes. However, experimental results presented to date, mostly in the form of isolated case studies, show that FAFEs may be correlated with increased ion/electron temperature (Jones *et al.*, 1988; Winser *et al.*, 1989) at low altitudes and often occur during periods of enhanced electron precipitation (Wahlund and Opgenoorth, 1989). In an effort to understand the mechanisms which produce these events, we present some statistical relationships between the flux at

400 km and the electron/ion temperature and electron precipitation at lower altitudes. We have concentrated our attention on fluxes observed in the altitude bin centred on 400 km since this is high enough such that the frequency of upflow events is large, yet not so open to uncertainties caused by low signal-to-noise ratios as at 500 km.

Figure 7a shows the relationship between the upward flux at 400 km and the ion temperature at 200 km for all data including FAFE events. There is very good agreement with temperatures recorded at 200 km during the 6 May 1987 event (Fig. 1). Winser *et al.* (1989) found that the ion temperature increases quite dramatically with altitude during one of these events from an examination of individual temperature profiles. This increase in temperature was caused by




(a)




(b)

FIG. 7. RELATIONSHIP BETWEEN THE UPWARD FLUX AT 400 km AND (a) ION TEMPERATURE AT 200 km, (b) ELECTRON TEMPERATURE AT 300 km.

the passage of a velocity shear through the radar field of view. The vertical line shown in Fig. 7a is the mean ion temperature at 200 km altitude and 21:00 U.T. wintertime for the years 1985–1987. This value was obtained from an empirical model based on *all* Common Programme measurements made at Tromsø during 1985–1987, including the measurements used in this study (Farmer *et al.*, 1990). The mean model ion temperature compares well with the neutral temperature at 200 km from the MSIS model (which quotes a temperature which is about 100 K lower). From Fig. 7a we conclude, therefore, that about half of the events identified in this study occurred during periods when the ion temperature is enhanced (sometimes considerably) above mean values. However for the remaining cases we find that the upflow is not associated with any significant increase in ion temperature above mean values. This is also evident for the upward flux at 400 km vs the ion temperature at 300 km (not shown). Figure 7a also shows that when ion temperatures are below average fluxes can be large or small (ranging from $5\times10^{10}$ to $5\times10^{13}$ $m^2$ $s^{-1}$), but when they are above average, upfluxes tend to be larger ($>5\times10^{11}$ $m^{-2}$ $s^{-1}$).

Figure 7b shows there is a correlation between the upward ion flux at 400 km and the electron temperature at 300 km. The two vertical lines represent the RAL model electron temperature at 300 km for 21:00 U.T. wintertime (lower) and summertime (higher). If we chose the wintertime model for comparison (because most of the FAFEs occur around 21:00 U.T. during the winter period) we see that fluxes which are greater than the classical polar wind occur for periods of above-average electron temperatures (1000–2600 K). These values also compare favourably with electron temperatures obtained for the event shown in Fig. 1.

It was suggested by Winser *et al.* (1989) that high electron temperatures may aid the upward ion motion, especially during periods of enhanced ion temperature as it was found that upflows only occurred when both ion and electron temperatures were large. Indeed Barakat *et al.* (1983) have suggested that sufficiently high electron temperatures may raise the ambipolar electric field to the point where $O^+$ ion energies are explained without further acceleration mechanisms. Figures 8a–c show the relationship between those upward ion fluxes at 400 km which are *greater* than the classical polar wind and the ion temperature at 200 km. Each event is further classified according to the electron temperature at 200 km using three bins corresponding to three electron temperature ranges; 700–1100, 1100–1500, and greater than 1500 K. Using the RAL model temperatures for comparison it may be seen that more events occur during periods when both ion and electron temperatures are higher than are normally observed. Examination of Fig. 8c shows that at higher tem-

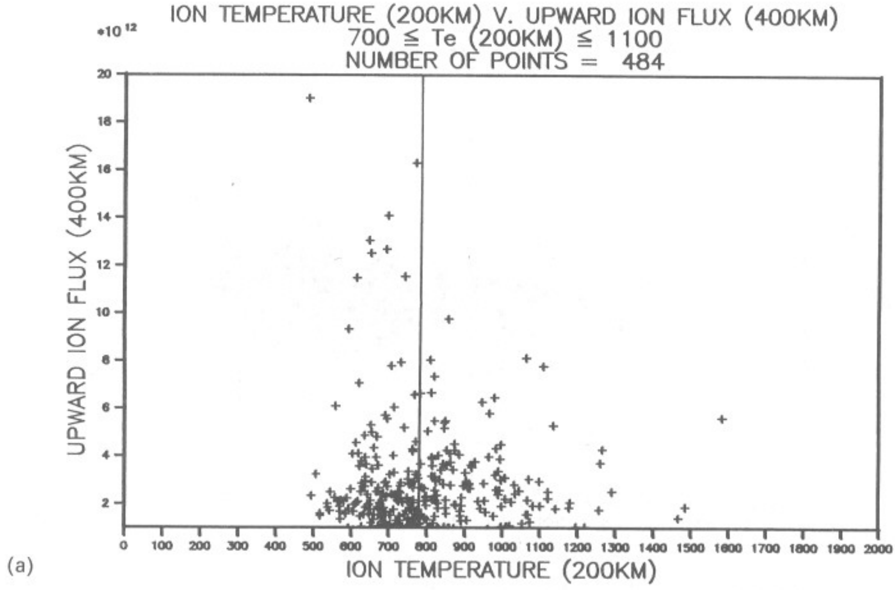
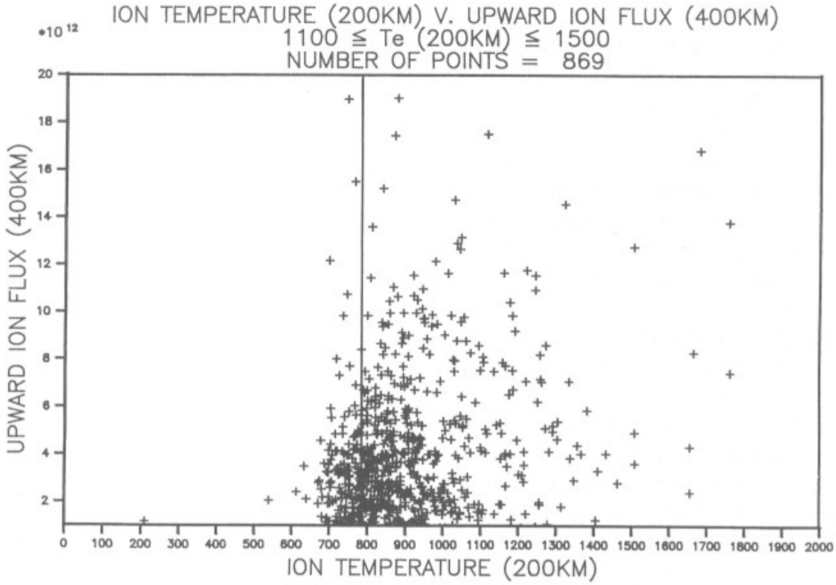
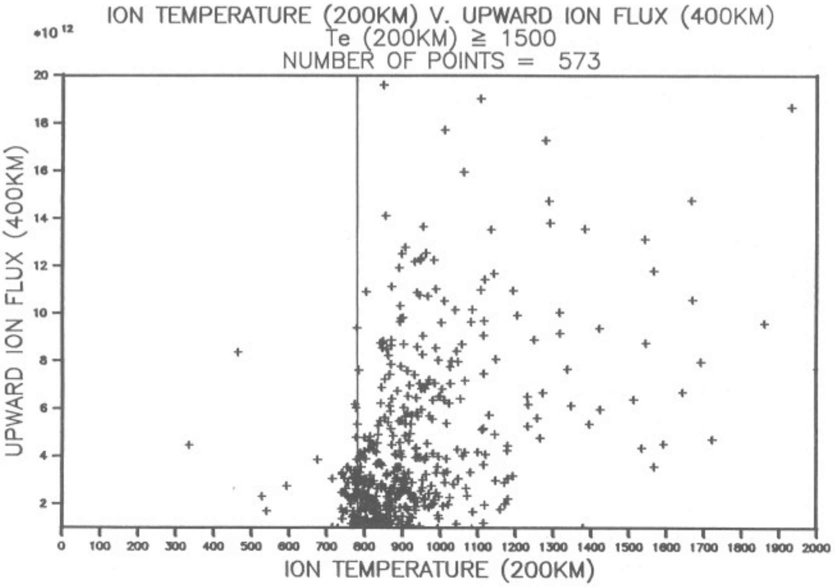



FIG. 8(a).




(b)




(c)

FIG. 8. RELATIONSHIP BETWEEN UPWARD ION FLUX AT 400 km WITH MAGNITUDE GREATER THAN $10^{12}$ $m^{-2}$ $s^{-1}$ WITH SIMULTANEOUS ELECTRON TEMPERATURE IN THE RANGE (a) 700–1100 K, (b) 1100–1500 K AND (c) >1500 K.

peratures the magnitude of the flux at 400 km increases with increasing electron temperature.

It is evident from these temperature correlations that ion upflows at 400 km are associated with heating events at lower altitudes, for example across the 200–300 km range. The increase in ion temperatures may be associated with large velocity shears causing frictional heating. This would be especially true in the region of the Harang discontinuity where most of these events occur. Elevated electron temperatures in the presence of high ion temperatures appear to produce more upflows, especially when the electron temperature exceeds 1100 K. It is very difficult, however, to deconvolve the effects of both ion and electron temperature enhancements in this study and further investigation in this area is essential. The theoretical work of Li *et al.* (1988) shows that high electron temperatures give rise to an enhanced ambipolar electric field which will result in the upward motion of $O^+$ ions. A reduction in the threshold for production of these upflows is observed for elevated electron temperatures in the presence of ion heating. Although Li *et al.* (1988) show this increase in the number flux of upflows for altitudes which are higher than the exobase ($>1.0\ R_e$), it is possible that the same heating processes may be responsible for upflow production at ionospheric altitudes.

Intense particle precipitation may give rise to elevated electron temperatures. Winser *et al.* (1989) observed significantly enhanced electron densities at lower altitudes (150–200 km, as observed with 2.6 km resolution by the multipulse coding technique) during ion upflow events on 6 May 1987. We have examined the variation of the upward ion flux at 400 km with electron density at 110 km and the upward flux against the highest value of electron density below or equal to 130 km altitude. We have found that many events are recorded at 400 km during periods of high electron density at low altitudes. Large fluxes are observed over quite a wide range of electron densities which may indicate that the electron density is not the most important factor influencing the production of ion upflows. It is suggested that electron precipitation is responsible in some way towards the production of upflows; however, this may be because elevated *F*-region electron temperature may be most effective when the ion temperature is also elevated (by strong ion–neutral frictional heating).

## CONCLUSIONS

In this study we have shown the temporal variation of field-aligned upflows and downflows at high-latitudes using all available EISCAT CP-1 Common Programme data for the years 1985–1987. Many of the events had fluxes which were at least an order of magnitude greater than the value associated with the classical polar wind. It was found that maximum occurrence of upflows occurs around 21:00 U.T. and at altitudes above 400 km. This peak occurs at the time that the observing station usually passes through the Harang discontinuity where increased ion and electron temperatures due to velocity shears and particle precipitation are observed. The downflows also show a maximum at and above 400 km but at a later time (02:00 U.T.) and it is tentatively suggested that some fraction of these events may be the earlier upflowing ions returning under the action of gravity. The number of upflow events at 400 km shows a dependence on high electron temperature at lower altitudes. The magnitude of the fluxes at 400 km also increases with increasing ion temperature above 1000 K especially during periods of enhanced electron temperature. There appears to be less of a dependence on electron density at low altitudes (indicating electron precipitation), although there is an increase in the number of events with increased electron precipitation below 130 km. A possible explanation of this is that the precipitation is mainly responsible for increasing the electron temperature, which in turn produces more upflows.

*Acknowledgements*—We thank the director and the staff of EISCAT for providing the data used in this paper. EISCAT is supported by the French CNRS, West German MPG, Swedish NFR, Norwegian NAVF, Finnish SA and British SERC. J. G. Keating is greatly indebted to Prof. J. A. Slevin (St Patrick's College, Maynooth) for funding a recent visit to Rutherford Appleton Laboratory where this research was undertaken. Special thanks are also extended to Dr D. M. Willis for arranging this visit. We wish to thank Dr A. Farmer for providing the RAL empirical model temperatures used in this paper.

## REFERENCES

Banks, P. M. and Holzer, T. E. (1969) High-latitude plasma transport. *J. geophys. Res.* **74**, 6317.

Barakat, A. R. and Shunk, R. W. (1983) $O^+$ ions in the polar wind. *J. geophys. Res.* **90**, 7887.

Farmer, A. D., Fuller-Rowell, T. J. and Quegan, S. (1990) Comparing numerical simulations of the high latitude ionosphere to an empirical mean model based on EISCAT data. *Adv. Space Res.* **10**, 143.

Folkestad, K., Hagfors, T. and Westerlund, S. (1983) EISCAT: an update description of technical characteristics and operational capabilities. *Radio Sci.* **18**, 167.

Ghielmetti, A. G., Johnson, R. G., Sharp, R. D. and Shelley, E. G. (1978) The latitudinal, diurnal and altitudinal distribution of upward flowing energetic ions of ionospheric origin. *Geophys. Res. Lett.* **5**, 59.

Gombosi, T. I. and Killeen, T. L. (1987) Effects of thermospheric motions on the polar wind: a time-dependent numerical study. *J. geophys. Res.* **92**, 4725.

Gorney, D. J., Clarke, A., Croley, D., Fennell, J., Luhmann, J. and Mizera, P. (1981) The distribution of ion beams and conics below 8000 km. *J. geophys. Res.* **86**, 83.

Jones, G. O. L., Williams, P. J. S., Winser, K. J., Lockwood, M. and Suvanto, K. (1988) Large plasma velocities along the magnetic field line in the auroral zone. *Nature* **336**, 6196, 231.

Klumpar, D. M. (1979) Transversely accelerated ions: an ionospheric source of hot magnetospheric ions. *J. geophys. Res.* **84**, 4229.

Li, Peng, Wilson, G. R., Horowitz, J. L. and Moore, T. (1988) Effects of mid-altitude ion heating on ion outflow at polar latitudes. *J. geophys. Res.* **93**, 9753.

Lockwood, M. (1982) Thermal ion flows in the topside auroral ionosphere and the effects of low-altitude, transverse acceleration. *Planet. Space Sci.* **30**, 595.

Lockwood, M. (1986) Low energy ion flow into the magnetosphere. *Adv. Space Res.* **6**, 63.

Lockwood, M., Chandler, M. O., Horwitz, J. L., Waite, J. H., Jr., Moore, T. E. and Chappell, C. R. (1985a) The cleft ion fountain. *J. geophys. Res.* **90**, 9736.

Lockwood, M., Waite, J. H., Jr., Moore, T. E., Johnson, J. F. E. and Chappell, C. R. (1985b) A new source of suprathermal $O^+$ ions near the dayside polar cap boundary. *J. geophys. Res.* **90**, 4099.

Moore, T. E., Chappell, C. R., Lockwood, M. and Waite, J. H., Jr. (1985) Suprathermal ion signatures of auroral acceleration processes. *J. geophys. Res.* **90**, 1611.

Shelley, E. G., Johnson, R. G. and Sharp, R. D. (1972) Satellite observations of energetic heavy ions during a geomagnetic storm. *J. geophys. Res.* **77**, 6104.

Smith, R. W., Winser, K. J., van Eyken, A. P., Quegan, S. and Allen, B. T. (1985) Observation and theoretical modeling of a region of downward field-aligned flow of $O^+$ in the winter dayside polar cap. *J. atmos. terr. Phys.* **47**, 489.

Ungstrup, E., Klumpar, D. M. and Heikkila, W. J. (1979) Heating of ions to superthermal energies in the topside ionosphere by electrostatic ion cyclotron waves. *J. geophys. Res.* **84**, 4289.

Wahlund, J.-E. and Opgenoorth, H. J. (1989) EISCAT observations of strong ion outflows from the *F*-region ionosphere during auroral activity: preliminary results. *Geophys. Res. Lett.* **16**, 727.

Whalen, B. A., Berstein, W. and Daly, P. W. (1978) Low altitude acceleration of ionospheric ions. *Geophys. Res. Lett.* **5**, 55.

Williams, P. J. S. and Jain, A. R. (1986) Observations of the high latitude trough using EISCAT. *J. atmos. terr. Phys.* **48**, 423.

Williams, P. J. S., Jones, G. O. L. and Winser, K. J. (1990) In preparation.

Winser, K. J., Jones, G. O. L. and Williams, P. J. S. (1986) A quantitative study of the high latitude ionospheric trough using EISCAT's common programs. *J. atmos. terr. Phys.* **48**, 893.

Winser, K. J., Jones, G. O. L. and Williams, P. J. S. (1988a) Variations in the field-aligned plasma velocity with altitude and latitude in the auroral zone: EISCAT observations and the physical interpretation. *Phys. Scr.* **37**, 640.

Winser, K. J., Jones, G. O. L. and Williams, P. J. S. (1988b) Large field-aligned velocities observed by EISCAT. *J. atmos. terr. Phys.* **50**, 379.

Winser, K. J., Jones, G. O. L., Williams, P. J. S. and Lockwood, M. (1989) Observations of large field-aligned flows of thermal plasma in the auroral ionosphere. *Adv. Space Res.* **9**, 57.

Yau, A., Shelley, E. G. and Peterson, W. K. (1986) Accelerated auroral and polar cap ions: outflow at DE-1 altitudes, in *Ion Acceleration in the Magnetosphere and Ionosphere* (Edited by Chang, T.). Geophysical Monograph 38, American Geophysical Union, Washington.

Yau, A., Whalen, B. A., McNamara, A. G., Kellogg, P. J. and Bernstein, W. (1983) Particle and wave observations of low-altitude ionospheric ion acceleration events. *J. geophys. Res.* **88**, 341.

Yeh, H.-C. and Foster, J. C. (1990) Storm-time heavy ion outflow at mid-latitudes. *J. geophys. Res.* **95**, 7881.