Ionization of the E Region of the Ionosphere by Precipitated Electrons

A.D. Haschick
and
J.A. Gledhill

Department of Physics,
Rhodes University, Grahamstown

It is shown that there is a good correlation between the fluxes of electrons with energies greater than 40 keV observed by Alouette I near the L shell 2,4 and the critical frequency of the E-layer observed at Argentine Islands, which lies on the same L shell. The increase of f_0E observed agrees reasonably well with that calculated on the basis of a precipitated electron flux with characteristic energy 50 keV, of which the portion above 40 keV is observed by Alouette. It is shown that the rate of ionization by the precipitated electrons can exceed that due to solar ultraviolet radiation at times.

Daar word aangetoon dat 'n goeie korrelasie bestaan tussen die vloed van elektrone met energie hoër as 40 keV wat deur Alouette I naby die L-skil 2,4 waargeneem is en die kritiese frekwensie van die E-laag wat by die Argentine-eilande waargeneem is en wat op dieselfde L-skil lê. Die waargenome toename van f_0E stem taamlik goed ooreen met wat bereken is op grondslag van 'n gepresipiteerde elektronvloed met karakteristieke energie van 50 keV, waarvan die gedeelte bo 40 keV deur Alouette I waargeneem word. Daar word aangetoon dat die tempo van ionisasie deur die gepresipiteerde elektrone soms hoër kan wees as wat ultraviolet-sonstraling veroorsaak.

Introduction

In the course of a study of the relationship between ionospheric behaviour and the precipitated electron fluxes observed by the satellite Alouette I, *Gledhill et al.* (1967) showed that there was a very significant correlation between the flux of electrons with energies greater than 40 keV, observed in the vicinity of an ionospheric station, and the critical frequency of the F2 layer there. Since electrons with such high energies have little direct effect on the atmosphere at F-region heights, depositing their energy around the 85 km level far below, it was clear that the correlations found by *Gledhill et al.* (1967) must imply that the energetic electrons were accompanied by fluxes of lower-energy particles which were the effective agents in ionizing the F-region. Further, these low-energy electrons must vary in much the same way spatially and temporally as did the fluxes above 40 keV, which were being used as indicators of their presence.

The energetic electrons actually observed by Alouette I should be effective in ionizing the D region, where their main observable influence would be to increase the absorption of radio waves and to alter the height of reflection of low frequency waves. The only routinely published ionospheric parameter which depends on conditions in the D region is f_{min}, the lowest frequency at which an echo is observed with an ionosonde. This is a notoriously unreliable parameter, which varies with transmitter efficiency, receiver gain, antenna and ground characteristics and so even with such quantities as the mains supply voltage unless this is regulated, which is often not the case at remote stations. Attempts *(Haschick,* 1973) to correlate f_{min} with the precipitated electron flux for Sanae (2° 21′ W; 70° 18′ S) and for Argentine Islands (64° 16′ W; 65° 15′ S) led to barely significant results. This may have been because no real-time telemetry was receivable while the satellite was in the immediate vicinity of Sanae; while it was later learned that the attenuator setting on the ionosonde receiver at Argentine Islands was sometimes altered according to conditions, so that f_{min} loses much of its significance for correlations of this type.

Although 40 keV electrons leave only about 1/30 as much energy per unit volume at 120 km as they do at their peak near 85 km *(Rees,* 1963), it was felt that their flux might be more closely correlated with that of the 5 keV electrons which have their peak loss rate in the E region, than with the flux of soft electrons which would ionize the F region. An analysis was therefore made of the relationship between the critical frequency of the E layer, f_OE, observed at Argentine Islands, and the flux of electrons above 40 keV measured overhead by Alouette I.

The choice of Argentine Islands for this purpose was governed by several considerations:

(i) the ionograms obtained there were of a uniformly good quality, and it was usually possible to scale f_OE with reasonable precision;
(ii) the station lies within the area from which real-time telemetry was received at the South Atlantic station, so that flux measurements could be selected, which were made within an acceptable distance of the overhead point at the station;
(iii) the station lies on the western edge of the South Atlantic Anomaly region *(Vernov et al.,* 1967), so that electron precipitation from the radiation belts would be more frequent and intense there than at other stations for which ionograms were available;
(iv) although the station is situated near the Antarctic Peninsula (64° 16′ W; 65° 15′ S), it is not near the auroral zone (its L value is only 2,4) and it is indeed a middle latitude station from the geomagnetic point of view (geomagnetic latitude −53,8°).

The analysis covers the period 1-18 November 1962. No ionograms were available for Argentine Islands from 19 to 26 November, while background counts due to Russian high-altitude nuclear explosions earlier in the year made

Table 1

Nominal local time (h)	Solar zenith angle (°)	Correlation coefficient r	Significance level	Slope (MHz^4 cm^2 s sr)	Intercept (MHz^4)	f_0E_0 ± (std. dev.) MHz
0200	95,00	0,59	0,07	0,216	0,254	0,71 ± 0,25
0300	91,34	0,81	0,003	0,327	2,11	1,20 ± 0,05
0400	86,57	0,43	0,2	0,362	7,35	1,65 ± 0,06
0500	81,00	0,07	0,7	0,13	18,4	2,07 ± 0,05
1700	68,95	0,91	3×10^{-5}	1,57	40,7	2,52 ± 0,01
1800	74,91	0,85	10^{-4}	1,39	27,4	2,20 ± 0,03
1900	81,00	0,88	3×10^{-4}	1,34	13,7	1,92 ± 0,02
2000	86,57	0,77	0,02	0,615	6,27	1,58 ± 0,05

the electron flux measurements rather unreliable before the end of October. During this interval, particle counts were available for morning (02-05 h LT) and evening (17-20 h) passes and there was a relatively high level of variation in the fluxes measured from pass to pass, thus giving a good chance of finding the correlation if it existed.

Preliminary Analysis

The L value at about 200 km above Argentine Islands is 2,45. The shell 2,26 <L<2,63 corresponds to a region of width about 350 km centred on this point. All telemetered passes of the satellite through this shell were considered, covering the longitude range 275° to 330°E and thus extending about 1 000 km west of Argentine Islands and 1 500 km east of it. Since trapped electrons drift along such shells, it seems reasonable to expect a good correlation over a considerably greater distance along the shell than across it. The height of the satellite was a little above 1 000 km.

The electron counters on Alouette I have been described by *McDiarmid et al.* (1963). The count rates from the Anton 223 counter with the 40 keV threshold, the Anton 223 counter with the 250 keV threshold and the Anton 302 counter were used as described by *Greener & Gledhill* (1972) to derive corrected directional fluxes of electrons > 40 keV and > 250 keV. The latter was then subtracted from the former to give the flux between 40 and 250 keV. Several 10-second counts were recorded during each pass through the L-shell considered and the average was taken for further consideration. No account was taken of the pitch angle at which the electron flux was observed.

Copies of the ionograms from Argentine Islands were carefully examined for times within 1,5 hours of a satellite pass. The frequencies of all cusps in the vicinity of the normal f_0E were very carefully scaled and plotted against

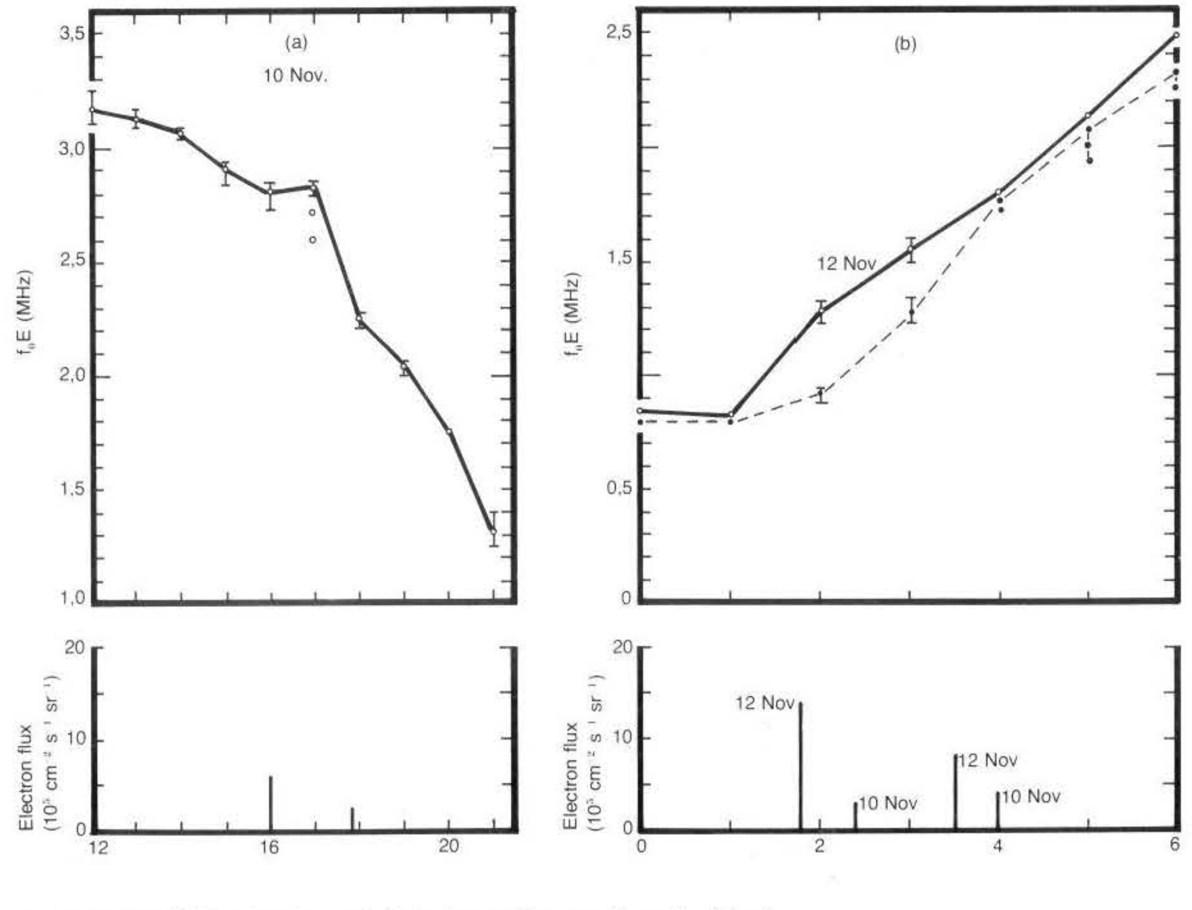

Fig. 1. Increases of f_0E coinciding with high electron fluxes at Argentine Islands.

time. The limits of error within which each cusp certainly lay were recorded. The r.m.s. error limit was 0,05 MHz, though sometimes the frequency of a cusp could not be determined to better than 0,1 MHz, while sometimes it could be established to within 0,01 MHz. It soon became clear which cusp represented the ordinary E layer critical frequency. On several occasions when the electron flux measured by the satellite was high, a small digression of f_oE from its normal diurnal variation was noted. Fig. 1 shows two such occasions, *viz* when an unusually high f_oE, with two extra cusps, followed a fairly high flux by an hour or so; and where the diurnal variation of f_oE on two days follows much the same course, except for the period 01-04 h, when an increase in f_oE on 12 November coincides with two high fluxes, while lower values on 10 November accompany lower fluxes.

Fig. 2 shows the f_oE values, with their scaling limits, for 03 h 00, together with the values of the directional electron flux recorded by Alouette I on the pass between 02 and 04 h. The similarity in shape of the graphs is striking and suggests that there is indeed a definite correlation between the two. Similar graphs for other times are equally encouraging and prompted the more thorough examination reported in the following sections.

Correlation analysis

During November the solar zenith angle, χ, at a given local time changes fairly rapidly as the month progresses, so that part at least of the general increase of f_oE towards the end of the period in Fig. 2 is due to this cause. For the purpose of correlation, the values of f_oE at each hour of local time were therefore corrected to the value they would have had, if the solar zenith angle had been the same as it was in the middle of the period, on 9 November. These standard values of the solar zenith angle are given in the second column of Table 1.

To make this correction, the relationship between f_oE and χ was first found, using only data for days and times when the flux of electrons measured by the satellite was low. When the solar zenith angle is near to 90°, as in our case, the relationship can be expressed in the form

$$f_oE = k\,[Ch(x,\chi)]^{-n} \qquad (1)$$

where k and n are constants and $Ch(x,\chi)$ is the "grazing incidence function" introduced by *Chapman* (1931) and tabulated by *Wilkes* (1954). Here x is the minimum radial distance from the centre of the earth to the ray from the sun to the point under consideration, expressed in atmospheric scale heights. At Argentine Islands the virtual heights of the E layer sometimes rise as high as 180 km during sunrise and sunset, and fall to about 110 km at midday. Since we are concerned with times when the solar zenith angle is close to 90°, we have chosen x = 150 as a working value, corresponding to a scale height of 42 km. This agrees well with Fig. 15 of *Nicolet* (1960) but may be too large a scale height according to later work (*Jacchia*, 1971). The smallness of the correction which we are computing makes the approximation quite acceptable.

From a graph of log (f_oE) against log [$Ch(x,\chi)$] the

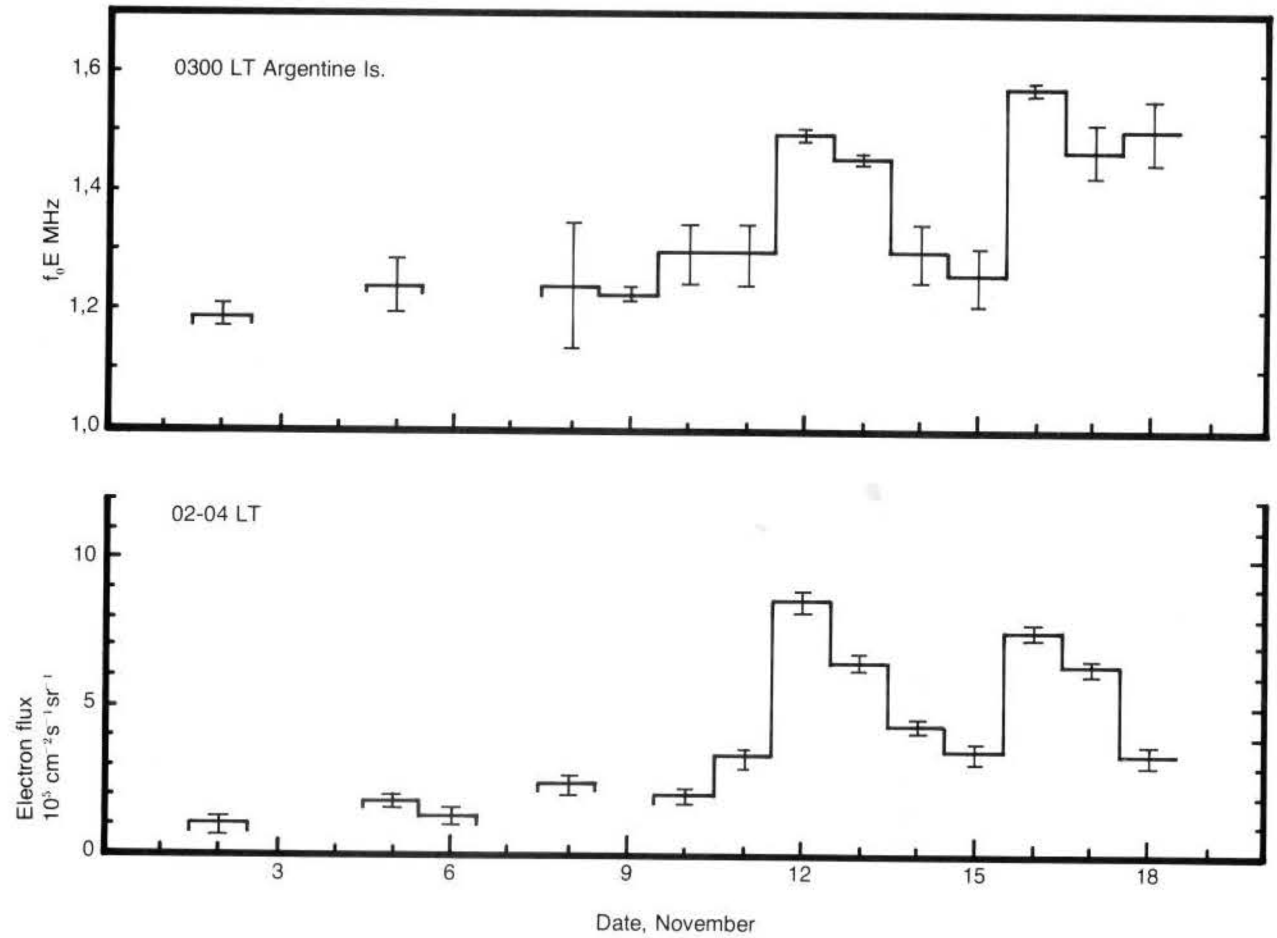

Fig. 2. Variation of f_oE at 03 h 00 at Argentine Islands and of electron flux observed by Alouette I between 02 h 00 and 04 h 00 in the vicinity.

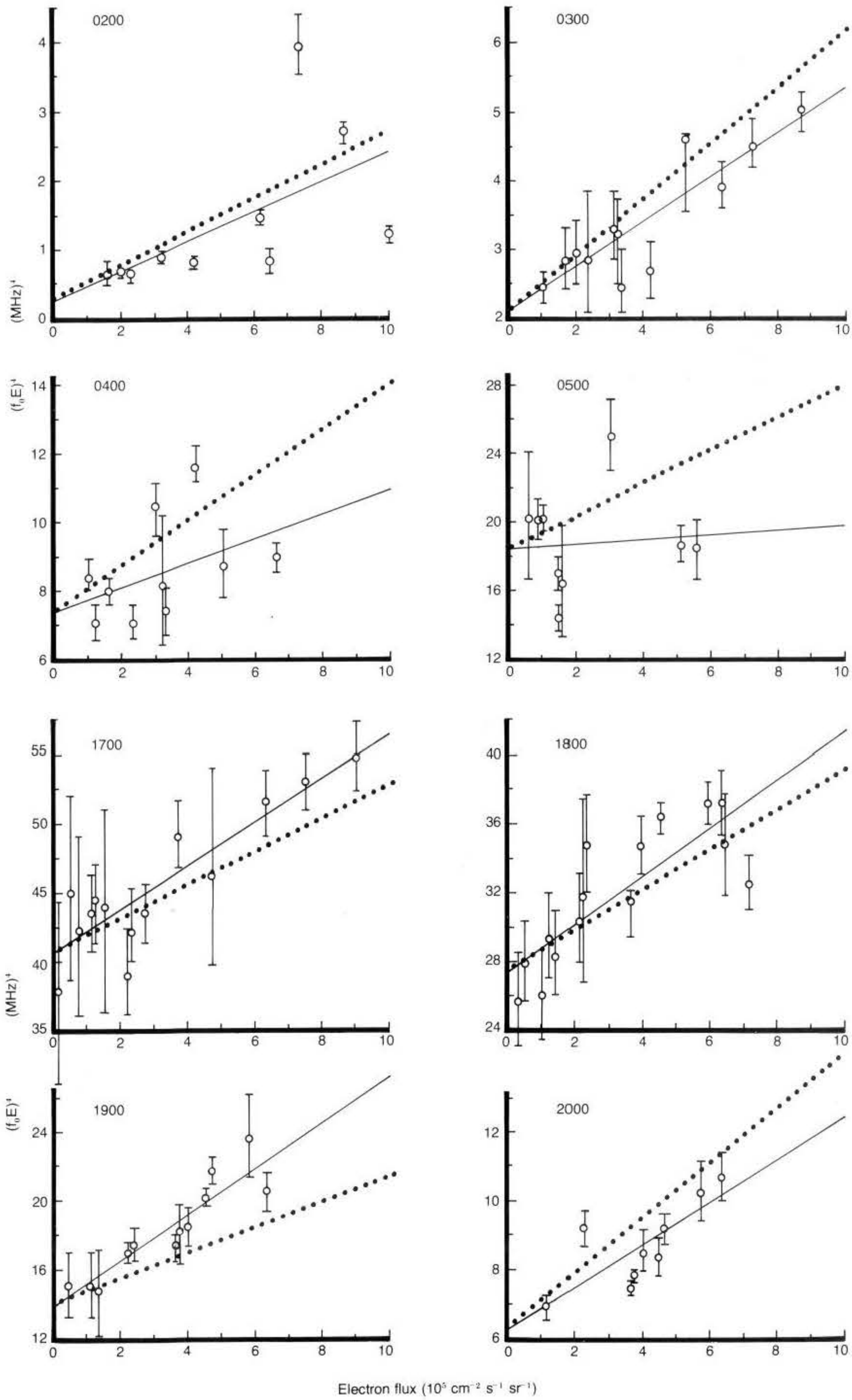

Fig. 3. Plots of $(f_0E)^4$, corrected to a constant solar zenith angle at each local time, against the directional electron flux >40 keV recorded within 1,5 hours by Alouette I. Full lines – least squares fitted straight lines; Dotted lines – theoretical straight lines calculated approximately from observed electron fluxes.

values of k and n in equation (1) were found to be 3,67 MHz and 0,36 respectively. Each observed value of f_OE was then corrected by subtracting from it the difference of the value calculated for that time and date and the value calculated for the standard solar zenith angle for the same time. The corrections were typically about 0,03 MHz and never exceeded 0,12 MHz. No corrections were applied to the data for 02 h 00, nor to those for 03 h 00 before 9 November, because χ was greater than 90° under these conditions and $Ch(x,\chi)$ then became so large and sensitive to changes in the scale height that it was thought better not to attempt the correction.

f_OE has also been shown to vary with the Zürich sunspot number, R_Z. *Beynon & Brown* (1959) have shown, for example, that there is on occasions a close correlation between day-to-day variations of f_OE and R_Z. It seems doubtful, however, whether individual hourly values could properly be corrected to a standard sunspot number using a relationship derived for longer-period variations. Fortunately, R_Z was very low, of the order of 10, for most of the period we are considering, and only approached 50 on three days. A calculation gave the increase of f_OE corresponding to $R_Z = 50$ as less than 0,05 MHz. It has therefore been assumed that the effect of sunspot number variations on our f_OE values is minimal and no correction has been made.

If the E region were ionized by solar electromagnetic radiation alone, the continuity equation for electrons would be written:

$$\frac{dN_o}{dt} = Q_o - \alpha N_o^2 \qquad (2)$$

If dN_O/dt is negligible in comparison with Q_O and $\alpha\ N_O^2$, as it is in our case, we can write

$$Q_o = \alpha N_o^2 \qquad (3)$$

Here Q_O is the production rate of electrons due to the sun, α is the recombination coefficient and N_O is the number of electrons per cm^3, all at the E layer peak. If the precipitated electron flux produces Q_e ion pairs per cm^3 per second, then, still assuming that $dN/dt=0$, the total electron density N is given by

$$Q = Q_o + Q_e = \alpha N^2 \qquad (4)$$

Since $N = 1{,}24 \times 10^4\,(f_oE)^2$

we can combine equations (3) and (4) to get

$$(f_oE)^4 = (f_oE_o)^4 + Q_e/(1{,}54 \times 10^8\,\alpha) \qquad (5)$$

where f_OE_O is the critical frequency which the E layer would have in the absence of ionization by the precipitated electrons.

Now the production rate Q_e is proportional to the flux J of the precipitated electrons *(Chamberlain*, 1961). Thus if we plot $(f_OE)^4$ against J, we should obtain a straight line, the intercept of which will be $(f_OE_O)^4$. The corrected values of $(f_OE)^4$ are shown plotted against the average values of the electron flux during the nearest pass in Fig. 3. The error limits shown are derived from those estimated during the scaling of the ionograms. Ambiguous cases with several cusps of doubtful significance have been omitted.

There can be no doubt about the reality of the connection between the electron flux and f_OE. The correlation coefficient r is given in the third column of Table 1 and its significance level *(David*, 1938) in the fourth column.

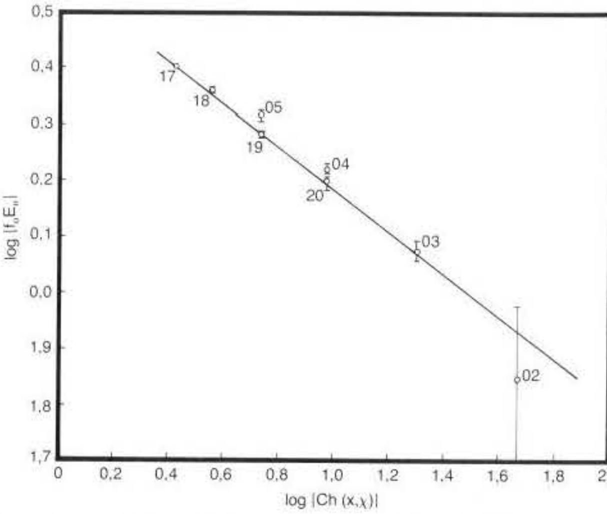

Fig. 4. Relationship between the logarithms of f_OE_O and the Chapman grazing incidence function $Ch(x, \chi)$.

The correlation is a little weak for 02 h 00, where the correction for solar zenith angle change could not be used, but breaks down for 04 h 00, where the significance level is only 0,2, and especially for 05 h 00, where it is completely insignificant. We are unable to give any explanation for this behaviour, which is surprising in view of the good correlation at the same solar zenith angles in the evening hours. It may be significant that there are, at both these times, only two data points corresponding to large fluxes, so that there may be insufficient data on which to base a conclusion.

The straight lines in Fig. 3 have been fitted by a least squares method and their slopes and intercepts are given in Table 1, together with the resulting values of f_OE_O and their estimated error limits, in this case derived from the standard deviations of $(f_OE_O)^4$. The logarithms of these values of f_OE_O are plotted against log $Ch(x, \chi)$ in Fig. 4. The straight line is a least squares fit, weighting the points inversely as the squares of the standard deviations in $\log(f_OE_O)$. It corresponds to k=3,614 MHz and n=0,374 in equation (1).

Discussion

It would be interesting to compare the values of f_OE, as observed, and shown in Fig. 3, with the variations which we would expect theoretically from the measured electron fluxes. There are several reasons why this cannot be done with much confidence.

(i) The electrons observed by Alouette I are in the energy range 40-250 keV, whereas the E region is most affected by electrons of energy about 4 keV.

(ii) The instruments on Alouette I only observed the directional flux over a very limited range of pitch angles during one pass through the region of interest. Thus no information on the pitch angle distribution of the electrons at the time of the events is available.

(iii) The only data available on the energy spectrum of the electrons are the fluxes > 40 keV and > 250 keV from the two counters on the satellite.

In the absence of this detailed information it is not possible to compare N-h profiles, calculated from the ionograms, with the profiles to be expected from the precipitated electron flux. This would clearly be the most satisfactory way of proving the hypothesis of a connection between the two.

It was, however, possible to make a rough estimate of the effect in the following way. From the fluxes measured by the counter with a threshold of 40 keV and that with its threshold at 250 keV, corrected for background, a characteristic energy, E_O, was estimated, assuming that the spectrum could be represented by an equation of the type (*Bailey*, 1968)

$$J_{>E} = J_o \exp(-E/E_o) \qquad (6)$$

From an examination of the results for the period under investigation an average value of $E_O = 50$ keV seemed appropriate. Further, *Greener* (1973) has examined the pitch angle distribution of the electrons observed by Alouette I, in the range of L values of interest here, and from his figures an average pitch angle distribution was found. With this information, the omnidirectional flux at 300 km could be estimated and then the method of *Wulff & Gledhill* (1974) was used to calculate the production rate, Q_e, at 120 km due to this flux. Assuming a value of 2×10^{-7} cm^3 s^{-1} for α at this height (*Bailey et al.*, 1970), the production rate Q_O was found from the values of f_OE_O in Table 1 and added to that due to the precipitated electrons to give the new value of $(f_OE)^4$ using equation (4). The results of this rough calculation are shown by the dotted lines in Fig. 3. They are seen to agree far better than we have any reason to expect, considering the multitude of approximations in the calculation. They do, however, go some way towards confirming that the effects reported are in fact due to the electrons precipitated from the radiation belts.

Many criticisms may be levelled at details of the very simple approach which we have used in our analysis. For example, our use of the recombination coefficient α as if the recombination were a simple square law process is surely incorrect even at 150 km. Again, the exponents n in equation (1) which we have evaluated, of the order of 0,37, show that the assumption that Q_O will be proportional to $(f_OE_O)^4$ must be wrong. The increase of this value over the figure of 0,25 derived from simple theory is probably mainly due to the temperature gradient in the vicinity of 150 km (*Rishbeth & Garriott*, 1969). Nevertheless, the changes in f_OE with which we are dealing are in fact so small that it makes little difference what power is plotted against the electron flux; simple graphs of f_OE against flux give good straight lines, and extrapolated values for f_OE_O which are almost identical with those found in Table 1. Therefore we believe that our work does demonstrate the effect of the precipitated electrons in a way which merits confidence.

Conclusions

The increases of f_OE reported in this paper are relatively small, of the order of 0,3 MHz for an observed flux >40 keV of 10^6 electrons cm^{-2} s^{-1} sr^{-1}, but, as the error bars show, they can be accepted with some confidence as real variations. As equations (4) and (5) show, even a production rate Q_e, due to precipitated electrons, equal to that due to solar radiation, Q_O, would only increase f_OE by 20%. In other words, f_OE is not a sensitive indicator of changes in the ion production rate. Looked at from this point of view, the ionization rate due to precipitated electrons exceeds the solar rate by factors which may be greater than 100 at 02 h 00, often exceeds the solar rate at 03 h 00, and may equal it when the flux is high even at 04 h 00, 19 h 00 and 20 h 00. The importance of electrons as ionizing agents in the E region is certainly not negligible over these periods at Argentine Islands. Similar analyses at other stations would show whether this is a consequence of the station's proximity to the South Atlantic Anomaly or whether the phenomenon is more widespread, as the work of *Ivanov-Kholodny & Kazatchevskaya* (1971), for example, suggests.

Clearly the method used here is capable of very considerable elaboration. With the availability of modern soft electron spectra and pitch angle information, such as that provided by the LEPEDEA detectors flown on several satellites by *Frank* (1967) and the instruments used by *Heikkila et al.* (1970) on the ISIS satellites, it should be possible to make detailed comparisons of the N-h profiles derived from ionograms, both topside and ground-based, with the effects to be expected on the basis of the energy and pitch angle spectra of the precipitated electrons as simultaneously observed nearly overhead. This aspect of the work is currently being pursued.

Acknowledgements

The work reported in this paper forms part of the Antarctic Ionosphere Research Programme of the Department of Physics, Rhodes University; the support of this programme by the Department of Transport is gratefully acknowledged. A.D.H. records his gratitude to the Council for Scientific and Industrial Research and to the Council of Rhodes University for scholarships. J.A.G. wishes to thank the Council for Scientific and Industrial Research for a Senior Research Bursary, and the Director of the Radio and Space Research Station, Slough, England, for his hospitality during a period of leave from Rhodes University, when part of this work was revised and discussed with colleagues on the staff. Thanks are especially due to Dr I.B. McDiarmid, of the Division of Pure Physics, National Research Council, Ottawa, Canada, for providing the particle counter data from his experiments on Alouette I, and to Miss E.M. Cottenham, of World Data Centre C1, Slough, England, for supplying the copies of the Argentine Islands ionograms.

References

Bailey, D.K. Some quantitative aspects of electron precipitation in and near the auroral zone. *Rev. Geophys.*, **6**, 289, 1968.

Bailey, D.K., Brown, R.R., & Rees, M.H. Simultaneous forward-scatter, riometer, and bremsstrahlung observations of a daytime electron precipitation event in the auroral zone. *J. atmos. terr. Phys.*, **32**, 149, 1970.

Beynon, W.J.G. & Brown, G.M. Region-E and solar activity. *J. atmos. terr. Phys.*, **15**, 168, 1959.

Chamberlain, J.W. *Physics of the aurora and airglow*. New York and London, Academic Press, 1961.

David, F.N. *Tables of the correlation coefficient*. Cambridge University Press, 1938.

Frank, L.A. Initial observations of low-energy electrons in the earth's magnetosphere with OGO-3. *J. geophys. Res.*, **72**, 185, 1967.

Gledhill, J.A., Torr, D.G. & Torr, M.R. Ionospheric disturbance and electron precipitation from the outer radiation belt. *J. geophys. Res.*, **72,** 209, 1967.

Greener, J.G. *Some properties of magnetospheric electrons observed west of Sanae.* M.Sc. thesis, Rhodes University, 1973.

Greener, J.G. & Gledhill, J.A. Electron fluxes observed near Sanae, Antarctica, by the satellite Alouette I during 1962-63. *South African Journal of Antarctic Research*, no. 2, 35-39, 1972.

Haschick, A.D. *Electron effects in the ionosphere.* M.Sc. thesis, Rhodes University, 1973.

Heikkila, W.J., Smith, J.B., Tarstrup, J. & Winningham, J.P. The soft particle spectrometer in the ISIS-I satellite. *Rev. Scient. Instrum.*, **41,** 1393, 1970.

Ivanov-Kholodny, G.S. & Kazatchevskaya, T.V. Ionization of the E-region by precipitating electrons. *J. atmos. terr. Phys.*, **33,** 285-287, 1971.

Jacchia, L.G. Revised static models of the thermosphere and exosphere with empirical temperature profiles. *Smithsonian Astrophysical Observatory, Special Report*, 332, 1971.

McDiarmid, I.B., Burrows, J.R., Budzinski, E. & Rose, D.C. Satellite measurements in the 'Starfish' artificial radiation zone. *Can. J. Phys.*, **41,** 1332, 1963.

Nicolet, M. The properties and constitution of the upper atmosphere. In *Physics of the upper atmosphere*, edited by J.A. Ratcliffe. New York and London, Academic Press, 1960.

Rees, M.H. Auroral ionization and excitation by incident energetic electrons. *Planet. Space Sci.*, **11,** 1209, 1963.

Rishbeth, H. & Garriott, O.K. *Introduction to ionospheric physics*, Sections 3.22, 3.23. New York and London, Academic Press, 1969.

Vernov, S.N., Gorchakov, E.V., Shavrin, P.I. & Sharvina, K.N. Radiation belts in the region of the South Atlantic magnetic anomaly. *Space Science Reviews*, **7,** 490, 1967.

Wilkes, M.V. A table of Chapman's grazing incidence integral $Ch(x,\chi)$. *Proc. phys. Soc.*, **B76,** 304, 1954.

Wulff, A. & Gledhill, J.A. Atmospheric ionization by precipitated electrons. *J. atmos. terr. Phys.*, **36,** 79, 1974.

(Received 5 June 1974)