SOME IONOSPHERIC SPORADIC-E
STUDIES

by

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THESIS SUBMITTED FOR THE DEGREE OF DOCTOR OF
PHILOSOPHY IN THE UNIVERSITY OF LONDON

1971

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ACKNOWLEDGEMENTS

I would like to acknowledge my indebtedness to Dr. E. S. Owen-Jones, my Supervisor, and to offer him my sincere thanks for his encouragement and guidance during the present work. I am also grateful for his valuable suggestions, discussions and continued interest in the progress of the work.

I wish to thank the staff of the World Data Centre, Radio and Space Research Station Slough, particularly Miss E. Cottenham, for providing all the data used in the present work without which it could not have been completed.

I am grateful to the Council of Bedford College for awarding me a College Scholarship and a Demonstratorship during my research period.

I am very much obliged to the Central Research Fund, University of London, the Convocation Trust, University of London and the Edwina Mountbatten fund of Sir Ernest Cassel Educational Trust for additional financial support during the period 1966-69.

CONTENTS

ABSTRACT

Ionospheric data relating to the height and incidence of Sporadic-E (E_s) has been considered for a number of stations, the normal parameter used being the percentage incidence of E_s greater than a certain specified frequency. Variations in this incidence have been studied on a diurnal and seasonal basis, with respect to magnetic activity, and for different levels of solar activity as represented by the IGY (1957/58) and IQSY (1964/65) periods.

The behaviour of E_s in the auroral region has been examined in detail both in relation to occurrences of all types of E_s and those types which occur specifically at high latitudes. An E_s auroral zone has been defined and its properties determined in relation to diurnal, seasonal, solar cycle and magnetic activity changes.

The behaviour of the critical frequency and equivalent height of E_s layers has been interpreted in terms of a two zone model containing a diffuse and a discrete zone. The properties of the two zones and of the E_s layers are related to the energy of the precipitated electrons.

Rocket and satellite measurements of electron energy spectra have been used to calculate electron density profiles as a function of latitude and reflection heights compared with those based on ground based observations. Reasonable agreement is obtained between the two sets of measurements.

The Phillips' Rule relating to the cumulative distribution of E_s has been found to apply to all the stations considered at a frequency above the most probable frequency. Possible interpretations have been given for the gradient of the straight line obtained with the distribution and this gradient is found to show a dependence on latitude which is similar for quiet and disturbed magnetic conditions.

A study has also been made of different types of E_s and their relationship to magnetic activity. Evidence is given to suggest that the changes in the incidences of low type E_s may be related to changes in the magnetic field.

Changes in the behaviour of cusp-type E_s are considered to be related to the interaction of the quiet solar and disturbed polar current systems. It has also been found that the superposition of low and high type E_s has a magnetic dependence which is very similar to that of flat type.

CHAPTER I

INTRODUCTION

The vertical incidence ionospheric-sounder (Ionosonde) has been used for many years for the collection of sporadic-E data in terms of the parameters of height, critical frequency and type. These are observed continuously on an hourly basis in various parts of the world. In the International Geophysical Year (July57-Dec.58) the number of such stations increased greatly but some of them were later closed down following the completion of the IGY programme. There is thus a large quantity of data relating to sporadic-E (i.e. its frequency, height and type) in existence for the IGY and for subsequent years. This data is published with the various parameters at hourly intervals and has been used in the present work.

Recent developments in rocket experiments have provided detailed information about the electron concentration in, and the height of, sporadic-E layers. Prior to the IGY some analysis had been made of vertical incidence sporadic-E data on a world-wide basis, e.g. Phillips (1947), Matsushita (1953), Prechner (1955) and Smith (1957). The first three authors confined their studies to the variation of certain E_s characteristics with latitude. Smith (1957), however, examined vertical incidence data on a geographical rather than a latitude basis for the period 1948-54 with a world-wide distribution of stations.

Following the IGY, with its enormous quantity of data, most workers have restricted their studies to particular characteristics of sporadic-E and limited to a zone or to a specific type of sporadic-E. More general studies with the IGY data have been undertaken by Leighton, Shapley and Smith (1962) and Saksena (1964,65) who considered the sporadic-E data on a world wide geographical and latitude basis respectively. The relationship between sporadic-E and magnetic activity at various stations, combinations of stations and without regard to the different types of E_s has been examined by several workers, e.g. Smith (1957), Thomas (1962), Bellchambers and Piggott (1962), Singh (1963), Gocharova (1964), Saksena (1964), Yien-Nien (1965), Huang (1966), Ovezgel'dyyev and Ostamina (1966), Taieb (1966), Shvarb and Anreyeva (1967), Chawdhery and Guha (1967), Morgan (1967) and Closs (1969).

The various types of E_s have been analysed separately by Leighton et al (1962), Bellchambers and Piggott (1962), Kotadia and Jani (1967) and Shaeffer (1967). Little work has been done on the variation of the height of the E_s layer and the only workers to have considered this aspect in detail are Gladden (1962) and Oguti (1963). The evidence for the dependence of the occurrence of E_s on the solar cycle is conflicting and different results have been obtained by Chadwick (1962), Thomas (1962), Das Gupta and Mitra (1962), Mitra and Das Gupta (1963), Bossolasco and Elena (1963) and more recently by Reddy and Matsushita (1968) for temperate latitude E_s. The results of Reddy and Matsushita are explained in general by the windshear theory of formation of E_s.

The temperate latitude zone E_s has been theoretically studied by Whitehead (1961, 62), Axford (1961, 63), Storey and Merse (1963) and Hines (1964) with various modifications of the windshear theory.

In addition to these authors' work, extensive appraisals of the existing knowledge of and information on E_s are given in Radio Science (1966) and the Colorado Conference on the cause and structure of E_s (1968). Apart from the above works, E_s data has been analysed by a number of workers in relation to various specific problems, such as the survey of E_s by Thomas and Smith (1959); the relative day and night occurrence of E_s by Smith (1957) and Saksena (1965); the effect of ionospheric current systems on E_s by Matsushita (1955, 1966) and Beynon (1959); the effect of blanketing E_s on high frequency absorption by Beynon and Jones (1965); problems associated with midlatitude E_s by Cole (1966); the dependence of f_oE_s on the magnitude of absorption by Kirblay (1967); continuous reflection from E_s by Chernsheva (1967) and Ovezgel'dyyev (1967).

1.2 Purpose of the present investigation

In the present study it was proposed to examine the vertical incidence E_s data on a geographical and on a latitudinal basis. The stations used in this analysis were distributed over a wide range of latitude and longitude and were chosen to represent the polar, auroral, high temperate latitude, low temperate latitude and equatorial zones. Eastern, Western and Intermediate zones have also been studied on a longitudinal basis.

The basic data employed in this analysis is for years of maxiuum solar activity 1957-58 (IGY) and of minimum solar activity 1964-65 (IQSY). In some cases continuous data has been used between 1957 and 1967, while in a few cases, where the data was not available for IQSY, that for the periods 1963-64 or 1953-54 has been substituted.

An attempt has been made to compare the occurrence of sporadic-E in the eastern and western longitude zones during sunspot maximum and sunspot minimum years and also during the five International magnetically quiet and disturbed days in each month. In some cases the occurrence of E_s has been examined for different degrees of magnetic activity rather than by considering the two extremes of low and high magnetic activity as represented by the quiet and disturbed days.

The diurnal variation of the height of the E_s layer has also been examined at high latitudes both as a function of latitude and of magnetic activity.

The boundaries of the auroral zone have been determined for sunspot maximum and minimum years by comparing the occurrence of E_s on disturbed days to that on quiet days. This gives a pronounced effect over the auroral zone since the dependence of E_s on magnetic activity is positive inside the auroral zone but negative on the adjacent polar and high temperate latitude regions.

The various types of E_s have also been examined separately for certain of the temperate and auroral zone stations.

1.3 Formation of sporadic-E

1.3.1 Solar Corpuscles

It is recognized that solar corpuscles are responsible for much of the sporadic-E ionization in the auroral zone. Appleton et al (1937) first showed that auroral E_s is positively correlated with magnetic activity while Knecht (1952, 1956) and Heppner et al (1952) have obtained a correlation between E_s activity and the various auroral forms. If the common cause of aurorae and magnetic activity is considered to be corpuscular radiation from the sun, it may be accepted that most of the auroral zone E_s is due to these solar corpuscles.

It was shown by Stormer that charged particles approaching the earth would be guided by its magnetic field towards the polar regions and would arrive there along spiral lines curling towards the pole. He also showed that these spirals would curl in opposite directions for positively and negatively charged particles. Hagg et al (1959) and Thomas (1960) have shown that, at any instant, sporadic E activity tends to be concentrated along spirals which are closely similar to Stormer precipitation spirals for negatively charged particles. It would thus appear that electrons are precipitated at high latitudes at about 100 km. height and can be regarded as the source of auroral zone sporadic-E ionization.

Ivanov-Kholodmi and Lazarev (1966) have found that a flux of about 10^{10} electrons/cm^{2}sec. with an electron energy of 30 Kev is necessary for the formation of an E_s layer at a height of 110 km, with the height of the layer depending upon the energy of the electrons and increasing with decreasing electron energy for the same flux.

More recently, Feldstein (1963, 1966) has shown that the auroral region should be considered in terms of an oval rather than a more general zone. The centre of this oval is slightly displaced from the geomagnetic pole and always lies on the night side of the polar region. Consequently, as the earth rotates about its axis, this oval exhibits a diurnal oscillation in its position with respect to the earth. Hence, as opposed to the previous idea of a station having a fixed position with regard to the old auroral zone, it may now, according to Feldstein, move into and out of the auroral oval during the course of the day. With this approach it is no longer necessary to describe auroral zone E_s phenomena in terms of the spiral patterns referred to above.

1.3.2 Windshear theory of temperate latitude E_s

The development of windshear theory provided the first real insight into the understanding of temperate zone sporadic-E. The original suggestion for the possible effect of windshear was made by Dungey (1956, 1959) and Heisler and Whitehead (1960) later found a relationship between the occurrence of sporadic-E ($f_oE_s > 5$ Mc/s) and the horizontal component of the earth's magnetic field (H). In conjunction with this horizontal component of the earth's field, it was shown by Whitehead (1960, 1961) that this theory could offer an explanation for the high Asiatic and low South African occurrence of E_s, since in these areas H is slightly greater and less respectively than a simple dipole model would predict.

The theory indicates that a mid-latitude sporadic-E layer is formed by a vertical shear in the East-west component of the horizontal wind in the E-region. When combined with the horizontal component of the earth's magnetic field, a horizontal wind in the neutral gas of the E-region of the ionosphere can move the ionization in an upward and downward direction below and above, respectively, the maximum shear level, thereby causing a concentration of ionization to occur.

The correlation between the occurrence of sporadic-E and the horizontal component of the earth's magnetic field holds over the whole of the temperate latitude zone by day but does not do so at night.

The simple theory predicted that the minimum in electron density should be very much less than the ambient and that the electron density profile should tend towards a cusp shape near the peak of the E_s-layer. In practice, these predictions are not found to be true and it has been suggested that this disagreement can be overcome by having at least two types of positive ion present, each having a different recombination coefficient.

It has also been pointed out by Axford and Cunnold

(1966) and Whitehead (1966) that the windshear theory would result in a relatively greater concentration of slowly recombining species, such as metallic ions, in the layer.

It is now generally agreed that the sporadic-E layers in temperate latitude zones are produced by a windshear mechanism and are principally composed of long lived metallic ions, except possibly at higher altitudes where molecular ions may be involved.

Johnson (1968) has discussed the planar ion-trap and radio-frequency ion mass spectrometer results from two Aerobee rocket flights that traversed sporadic-E events above Whitesands, New Mexico, in January 1966 and August 1967. Ion mass spectra were taken when the rocket was within an unusually dense E_s event and showed the layer to be composed of atomic metallic ions of Sodium, Magnesium, Silicon, Calcium and Iron with Magnesium being the dominant ion detected in the mass spectra. Neither Nitric oxide nor molecular oxygen ions were observed within the layer. In the weaker E_s layer only Magnesium, Calcium and Iron ions were detected in the peak density region of this weaker layer.

Narcisi (1968) has observed an E_s-layer with Iron, Magnesium and Calcium ions present but no nitric oxide on the day following a meteor shower. Metallic ions were also detected in E_s-layers during other flights at sunrise and sunset from Florida and during the 1966 solar eclipse above Brazil.

These results have been interpreted as indicating the action of a mechanism which maintains metallic ion ionization throughout the night. All rocket mass spectrometer flights through E_s events have detected metallic ions within the E_s layer but the presence of metallic ions does not necessarily indicate an E_s event.

Using equations first derived by Axford and Cunnold (1966) and subject to certain assumptions, Reddy and Matsushita (1968) derived the following equation for the neutral windshear (U') giving rise to the observed E_s-layer:

$$U' = \frac{dU}{dz} = -\left(\frac{\nu_i}{w_i \cos I}\right)\alpha\, n_m \left(1 - {n_o^2}/{n_m^2}\right) \qquad (1)$$

where ν_i = the ion collision frequency;

w_i = the ion gyro-frequency;

I is the dip angle

α is the recombination coefficient;

n_m is the peak electron density of the E_s region;

and n_o is the average ambient ionization density in the E region.

Reddy and Rao (1968) have shown that the peak ionization density in an E_s layer is fairly accurately represented by the blanketing frequency (f_bE_s) and thus

$$n_m = 1.24 \times 10^{-8} (f_bE_s)^2 \qquad (2)$$

The average ambient ionization density n_o in the E region will be proportional to the peak ionization in the E region i.e.

$$n_o \propto S\ (f_oE)^2 \qquad (3)$$

Where S is an arbitrarily chosen constant and represents that fraction of the peak E region electron density which is equal to n_o and is here taken to be $2/3$

Thus equation (1) for the windshear can be written as

$$U' = -\left(\frac{k\nu_i}{w_i \cos I}\right) \quad \alpha\ (f_bE_s)^2 \left[1 - S^2\left(\frac{f_oE}{f_bE_s}\right)^4\right]$$

where $k = 1.24 \times 10^{-8}$

and f_bE_s is in cycles/sec.

This equation was used by Reddy and Matsushita to calculate the windshear responsible for E_s and it was found that a positive correlation existed between noon windshears and solar activity for all the temperate latitude stations used in their analysis. A similar correlation with solar activity was found for the noon value of f_bE_s and also for the occurrence of E_s at higher frequencies i.e. $f_bE_s \geqslant 4.0$ mc/s.

1.3.3 Ionospheric Currents

It has been recognized for many years that the amplitude of the variation in the horizontal component of the geomagnetic field, H, at Huancayo is unusually large (Chapman and Bartels, 1940). This enhancement in the variation of H occurs near the magnetic equator and is centred on a narrow zone. This zone arises from a strong eastward electric current during daylight hours, which has been called the equatorial electrojet (Chapman, 1951).

Matsushita (1951) first found a correlation between this particular type of E_s (equatorial) and the flow of the daytime eastward current at E-region heights. Rawer (1953) and Smith (1953) have also pointed out that this current could act as an energy source for the production and maintenance of ionization inhomogeneities which then serve as scattering sources and give rise to equatorial-type E_s. This would then explain the correlation between the daytime equatorial-type sporadic-E observed at Huancayo and the overhead current flowing around the magnetic equator. The diurnal variations for both are found to be the same and show similar day-to-day changes.

The effects on sporadic-E of the ionospheric current system, S_q have been discussed by Matsushita (1955, 1966) who has also suggested that the tidal wind estimated from the solar (S_q) and lunar (L) ionospheric current systems may play a role in forming the E-W windshear which produces E_s. The lunar current system also has some effect on E_s near the magnetic equator. The E_s disappearance at Huancayo, according to Matsushita (1957), is caused by a westward lunar current which opposes the eastward electrojet. This theory has also been supported by Bhargava and Subrahmanyam (1961) for Kodaikanal, an equatorial station.

1.3.4 Thunderstorms

Wilson (1925) suggested that thunderstorms might be a source of ionization in the upper atmosphere before any experimental observation of sporadic-E had been made. Appleton and Naismith (1933) treated the conducting ionosphere as a cathode and a thunder cloud as an anode and suggested, through the analogy with a vacuum tube, that ion production would be a maximum around 7 km. below the conducting layer.

Ratcliffe and White (1934) and Isted (1954) in England, Colwell (1934) and Mimmo (1934) in the United States and Bhar and Shyam (1937), Chattergee (1953) and Mitra and Kunda (1954) in India have all considered the possibility of thunderstorms as possible energy sources of sporadic-E. Appleton, Naismith and Ingram (1937) and Best, Farmer and Ratcliffe (1938) in England have found no correlation after making various corrections in the previous work, while Kirby and Judson (1935) have found no correlation in the United States.

Indian scientists have long favoured thunderstorms as an ultimate energy source due to an apparently good day-to-day correspondence in India. No evidence for the thunderstorm theory was found by Berkner and Wells (1937) when they compared the incidence of blanketing and strong but non-blanketing E_s as observed at Watheroo with that observed at Huancayo. As thunderstorms are much more frequent at Huancayo this appeared to demonstrate that thunderstorms could not play an important part in the production of strong E_s. However, the weak, non-blanketing type of E_s which is a regular day-time phenomenon was not then included as a form of E_s. Also, the relation between the occurrence of E_s and thunderstorms is not convincing elsewhere other than in India.

There is, nevertheless, a need for a re-examination of the role of thunderstorms, if only as occasional sources of E_s, in that they represent a possible source of gravity waves (Layzer, 1967). These waves might then, when propogated upwards in the E region, produce the ionization inhomogeneties which appear as partial sporadic-E.

1.3.5 Meteors

For many years, meteors have been considered as the primary sources of E_s. Unusual E_s was observed during meteor showers by Mitra, Syam and Ghosh (1934) in India, Skellet (1935) in the United States and Appleton and Naismith (1947) in England. In particular, Appleton and Naismith demonstrated that, during an intense meteor shower, meteors can produce E_s. Naismith (1954) found that the meteors are associated with weak E_s, while Smith (1957) showed that the diurnal and seasonal variations of "y-type" sporadic-E are associated with sporadic meteors.

Kotadia (1958) found a positive effect of meteor showers on E_s as observed in sporadic-E ionization at Ahmedabad and Yamagawa but Kotadia and Jani (1967) detected no change in the occurrence of E_s in middle latitude stations in Europe during an anomalous increase in the rate of radar meteor counts during 1963. On the contrary, the low type of E_s was found to be less frequent during this period of high meteor activity. Wright (1967), however, found a positive correlation between f_bE_s and the meteor flux effectively averaged over periods of days around the time of occurrence of the most prominent meteor showers.

While there may be a relationship between meteors and sporadic-E the evidence so far is not conclusive and it is probable that in any case only a certain type or types of sporadic-E will be related to meteor activity.

1.4 Choice of the parameter for measuring sporadic-E

In this study sporadic-E data has been considered for a number of stations from the North pole to the equator during sunspot maximum, sunspot minimum and intermediate years and distributed over a wide range of longitudes. The data from the tables of f_oE_s, fE_s and $h'E_s$ have been taken for the variation in the occurrence and height of sporadic-E.

The use of f_bE_s as a parameter rather than fE_s or f_oE_s was first suggested by Matsushita (1966). Recently Reddy and Rao (1968) and Reddy (1968) have concluded, after simultaneous observations of mid-latitude sporadic-E by rockets and ionsondes, that f_bE_s is a better parameter as far as a measure of the electron concentration in a sporadic-E layer is concerned. However, Reddy (1968) has pointed out that the use of fE_s or f_oE_s rather than f_bE_s is more appropriate and advantageous in certain types of studies, while fE_s has been used very effectively by Smith (1957) to demonstrate many basic morphological features in the occurrence of sporadic-E. There is no doubt that fE_s or f_oE_s is a very useful E_s parameter as an indicator of sporadic-E occurrence and as an approximate indicator of relative E_s intensity. Since the occurrence of and height of sporadic-E have been examined in this analysis, the parameter f_oE_s rather than f_bE_s has been chosen.

In addition to this, sporadic-E has been considered in all latitude zones rather than just in the temperate zone. The strong correlation between the changes in fE_s and changes in H, the horizontal component of the geomagnetic field, found by Morgan (1966) suggests that fE_s is again an effective parameter for studying certain aspects of the auroral ionosphere. Satisfactory use of f_oE_s has also been made for studying the correlation between the occurrence of various types of E_s and magnetic activity at Halley Bay by Bellchambers and Piggott (1962) and between low type sporadic-E and radar meteor counts by Kotadia and Jani (1966). Thus the study of the occurrence of various types of E_s and its relation to magnetic activity, even at temperate latitudes, will not be affected by the choice of f_oE_s rather than f_bE_s

It was noted that f_bE_s values tend to be much lower than f_oE_s and so make a detailed morphological study of sporadic-E using the scaled values of f_bE_s

rather difficult, especially since the night-time values of f_bE_s are very often lower than 1.0 Mc/s which is normally about the lower frequency limit of most ionosondes. Additionally, many of the night-time f_bE_s values in the 1.0 to 1.6 Mc/s range are usually lost owing to interference by the broadcast bands and so any study of night-time f_bE_s data collected by these ionosondes will not be very reliable.

Similarly, low day-time values of f_bE_s which are usually less than f_oE by about 1.0 Mc/s or more, occur commonly at many temperate latitude stations during winter and these are likely to be partly lost at those stations where f_{min} values are high.

The hourly values of f_bE_s for the equatorial station Huancayo show that the blanketing frequency occurs predominantly within 0.2 - 0.3 Mc/s of f_oE, with few exceptions, and the apparent blanketing in this case appears to result from a combination of deviative absorption near f_oE and intense scattering from the ionization inhomogeneities produced by the electrojet.

In the present study a comparison of the following aspects of sporadic-E has been made, viz: its occurrence on quiet and disturbed days and as a function of solar activity for stations at complementary longitudes. This type of study will not be affected by choosing f_oE_s or fE_s rather than f_bE_s as far as the occurrence of sporadic-E is concerned. The height variation of sporadic-E will of course, be independent of whether f_oE_s or f_bE_s is chosen and so for this parameter the question does not arise.

Many workers have suggested that it is difficult to compare the frequency occurrence of E_s at different stations because the number and top frequency of E_s observations depends largely on the equipment characteristics and on the interpretation of the ionograms by the observer.

However, Chasovitin and Solchatova (1963) and Chasovitin (1966) have shown that for all types of E_s the dependence is invariably weak, even for considerable changes in the equipment parameters. As far as the interpretation of the ionograms is concerned, the observer is in any case not the same all the time at a particular station. The qualifications referred to above, it may be noted, refer basically to a period when there was little uniformity amongst ionosondes and their power output was often barely sufficient to distinguish the echo from the background noise.

If, in fact, there were any major errors of interpretation due to the observer at any one station these would become apparent during the analysis in relation to the behaviour of the same parameter at adjacent stations. In practice no such obviously anomalous behaviour has been encountered. Thus, bearing in mind these possible uncertainties in the data, the various comparisons between stations have been made but on no occasion has it been felt that they have been affected by the quality or validity of the data.

1.5 The various symbols used in the data

In order to calculate the percentage occurrence of sporadic-E, the symbols B and S, i.e. observations were not possible because of a blackout and noise respectively, were not considered and similarly for the symbol C which means that the observations were not possible because of a non ionospheric reason. However, the symbols E, when observations were not possible because of the lower frequency limit of the ionosonde, and G, when reflections were not possible due to a thin ionization layer, have been taken as observations. The other numerical values, together with the symbols E and G, have been taken as total observations and the percentage occurrence of sporadic-E calculated by considering the number of occurrences above some limiting frequency e.g. $f_oE_s \geqslant 3$ Mc/s, 5 Mc/s and 7 Mc/s etc.

For the individual types of E_s the percentage occurrence has been calculated by considering the number of occasions when that particular type occurred in relation to the total number of observations. In order to determine the frequency dependence of the occurrence of E_s, the number of occurrences for each half megacycle frequency (f_oE_s) range have been plotted against the central frequency.

1.6 Reduction of data

In order to avoid undue complexity in the study of E_s it is highly desirable to reduce the raw data to certain specific conditions or forms such as quiet magnetic conditions or constant solar activity etc. This reduction has been done in the present work by considering only the five International magnetically quiet and disturbed days for each month.

Recently Yien-Nien (1965) has suggested that in order to select quiet and disturbed days some limiting value of k_p should be taken for each month. In such a division the number of quiet and disturbed days will not, in general, be equal in a given month. For some studies where an equal amount of data is needed for a comparison in a given period, e.g. the frequency distribution of occurrence of sporadic-E, this selection of days prevents a valid comparison from being made. For this reason the above five days have been taken as the basic period for comparison in this analysis.

When analysing the occurrence of sporadic-E with k_p this division of the data into two groups has not been done and each day has been classified separately according to the mean value of k_p on that day.

1.7 Types of sporadic-E traces

The most commonly occurring E_s traces are of the flat (f), low (l), cusp (c) and high (h) types in temperate latitudes. They are summarized below.

flat - An E_s trace which shows no appreciable increase of height with frequency. The trace is usually relatively solid at most latitudes. This classification is only used at night since apparently flat E_s traces observed during the day time are classified according to their virtual height, viz: h, c or l. [fig. 1(a)]

low - A flat E_s trace at or below the normal E layer minimum virtual height. This is only used in the day time. [fig. 1(b)]

cusp - An E_s trace showing a relatively symmetrical cusp at or below the E region critical frequency (f_oE). This is usually continuous with the normal E layer trace except that when deviative absorption is large, part or all of the cusp may be missing. This type is also found in the day time only. [fig. 1(c)]

high - An E_s trace showing a discontinuity in height with the normal E layer trace at or above f_oE. The cusp is not symmetrical, the low frequency end lying clearly above the high frequency end of the normal E trace. This again is used only in the day time. [fig. 1(d)]

In addition to these types auroral (a), retardation (r) and slant (s) E_s occur but only rarely in temperate latitudes. However, at higher latitudes these types occur commonly in addition to the normal flat, low, cusp and high types.

auroral - An E_s pattern having a well defined flat or gradually rising lower edge with stratified and diffuse traces present above. These sometimes extend over a hundred kilometers or more of the virtual height range. [fig. 1(e)]

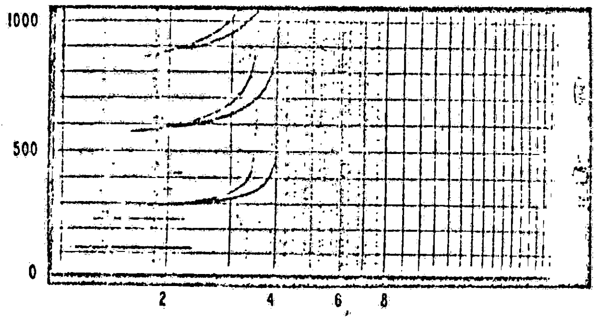
retardation - An E_s trace which is non-blanketing over part or all of its frequency range and which shows an increase in virtual height at the high frequency end similar in appearance to group retardation. This is distinguished at present from group retardation by the lack of group retardation in the F-region traces at corresponding frequencies. [fig. 1(f)]

slant - An E_s trace which rises steadily with frequency. This type usually emerges from another E_s layer which is normally classified separately. At high latitudes it usually starts to rise from a horizontal E_s trace, l, h or f, at frequencies which greatly exceed the layer critical frequency (e.g. about 6.0 Mc/s) whereas, at low latitudes, it rises from equatorial type E_s at frequencies near the E-region critical frequency. [fig. 1(g) and 1(i)]

At equatorial latitudes there is, in addition to the slant type of E_s, a different and localized equatorial (q) type of E_s.

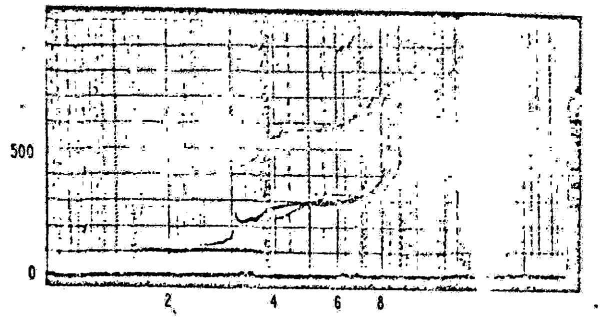
Equatorial - This trace is completely transparent without any multiple reflection and is found during the day time only with a very high frequency [fig.1(h)]

A more detailed discussion of the classification of ionogram echoes and interpretaion is given in URSI Handbook of ionogram interpretation and reduction (Piggot and Rawer, 1961)



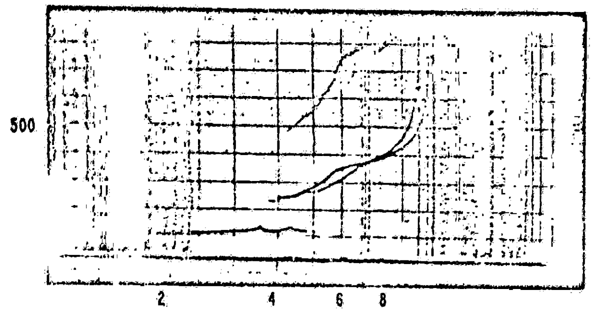
f-FLAT

(a)



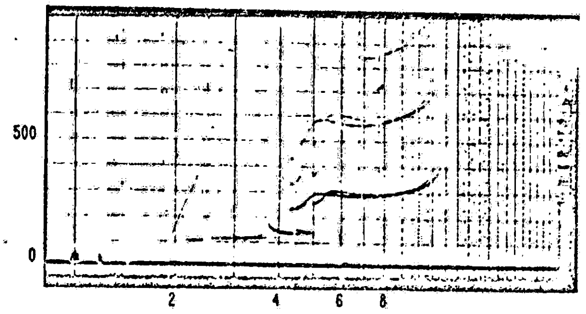
l-LOW

(b)



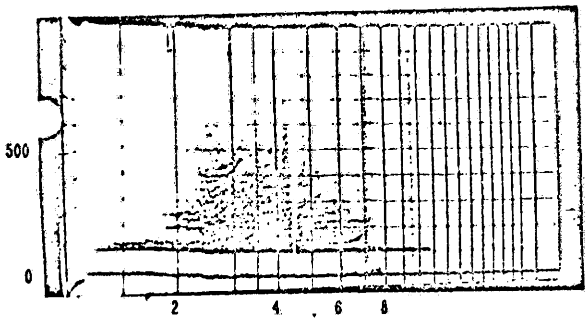
c-CUSP

(c)



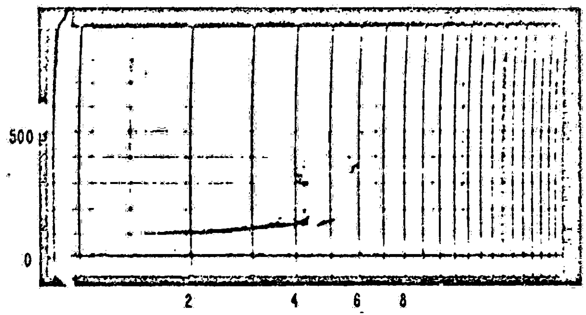
h-HIGH

(d)



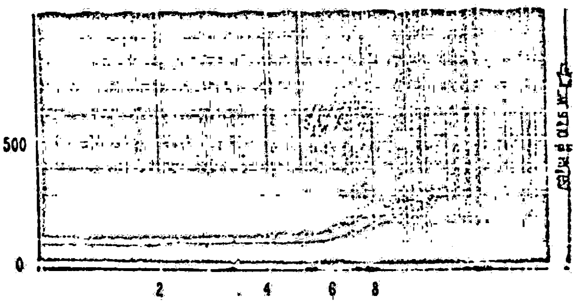
a-AURORAL

(e)



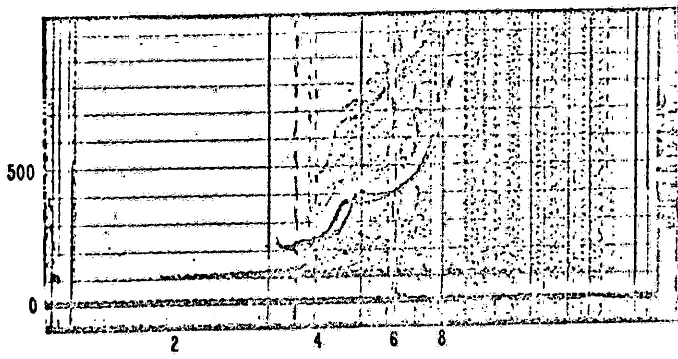
r-RETARDATION

(f)



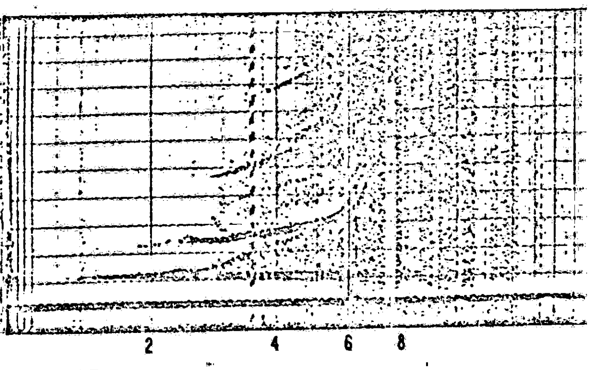
s-SLANT

(g)



q-EQUATORIAL

(h)



s- SLANT

(i)

FIG. 1 IONOGRAMS OF SPORADIC-E TYPES

CHAPTER 2

SPORADIC-E AT COMPLEMENTARY STATIONS

2.1 Introduction

Smith (1957) has conducted an analysis of the occurrence of E_s ($fE_s > 5$Mc/s) at various stations in the temperate latitude zone and portrayed the results by means of contour maps. He noted that the longitudinal variation was not apparent when yearly data were considered but on taking data for 1948-54 found that sporadic-E was more frequent at eastern as compared to western stations. A similar global analysis has been done for 1958 by Leighton, Shapley and Smith (1962). The contour maps show that the intense E_s zone is bounded between 170°E and 30°E at high latitudes in the northern hemisphere. At lower latitudes another intense E_s zone exists with boundaries at 100°E and 70°W, approximately, in the summer and equinoxes. However, in winter, it moves towards the southern hemisphere. It is of interest to compare the occurrence of E_s at pairs of stations, around the intense E_s zones, with the same geomagnetic latitude but with a longitude difference of about 180° i.e. complementary stations. For this purpose seven such pairs of stations have been compared during sunspot maximum and minimum years at high and low latitudes.

2.2 Data

Data for the IGY and IQSY has been used for the analysis of the following stations. In order to have an equal amount of data for both periods the IQSY data has been taken between July, 1964 to December, 1965. The stations have been divided into arbitrary western and eastern zones and are referred to as such in the text. The positions of these stations are given in fig.2.1 and Table 2.1

TABLE 2.1

Eastern				Western			
Station	Geomag. Lat. °N	Geographic Lat. °N	Geographic Long	Station	Geomag. Lat. °N	Geographic Lat. °N	Geographic Long. °
Heiss * Island	70.9	80.6	E58.0	Resolute* Bay	82.9	74.7	W94.9
Point Barrow	68.4	71.1	W156.8	Tromso	67.2	69.7	E19.0
Providence Bay	58.7	64.4	W173.3	Uppsala	58.6	59.8	E17.6
Adak	47.3	51.9	W176.7	Slough	54.3	51.5	W0.6
Akita+	29.5	39.7	E140.1	Puerto+ Rico	30.0	18.5	W67.2
Taipei	13.7	25.0	E121.5	Bogota	15.9	4.6	W74.1
Kodaikanal	0.6	10.2	E77.5	Huancayo	-0.6	-12.1	W75.3

* IQSY data for Heiss Island was not available, so the data between July 1963 and December 1964 has been used instead.

+No comparison has been made for this pair of stations in the IQSY since no data was available for Puerto Rico.

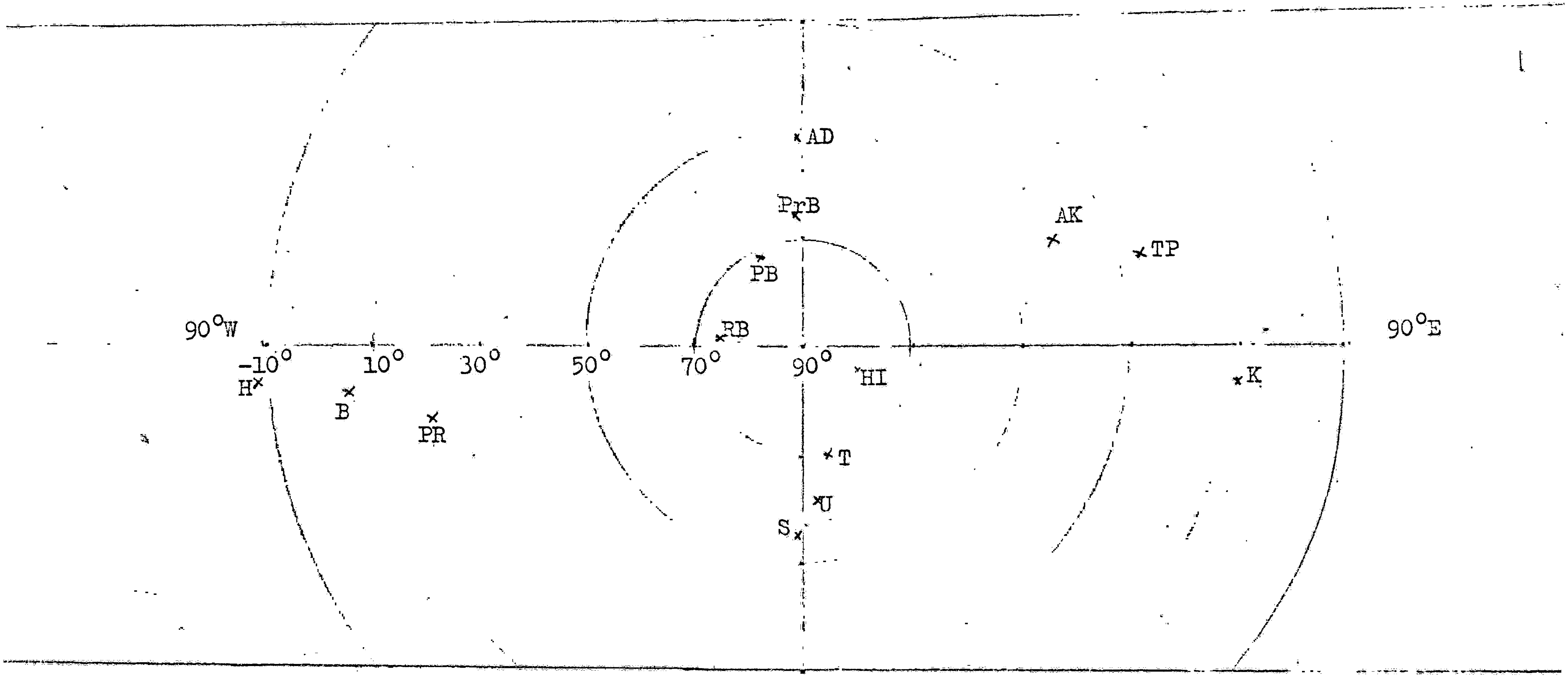


Fig.2.1: Positions of the complementary stations

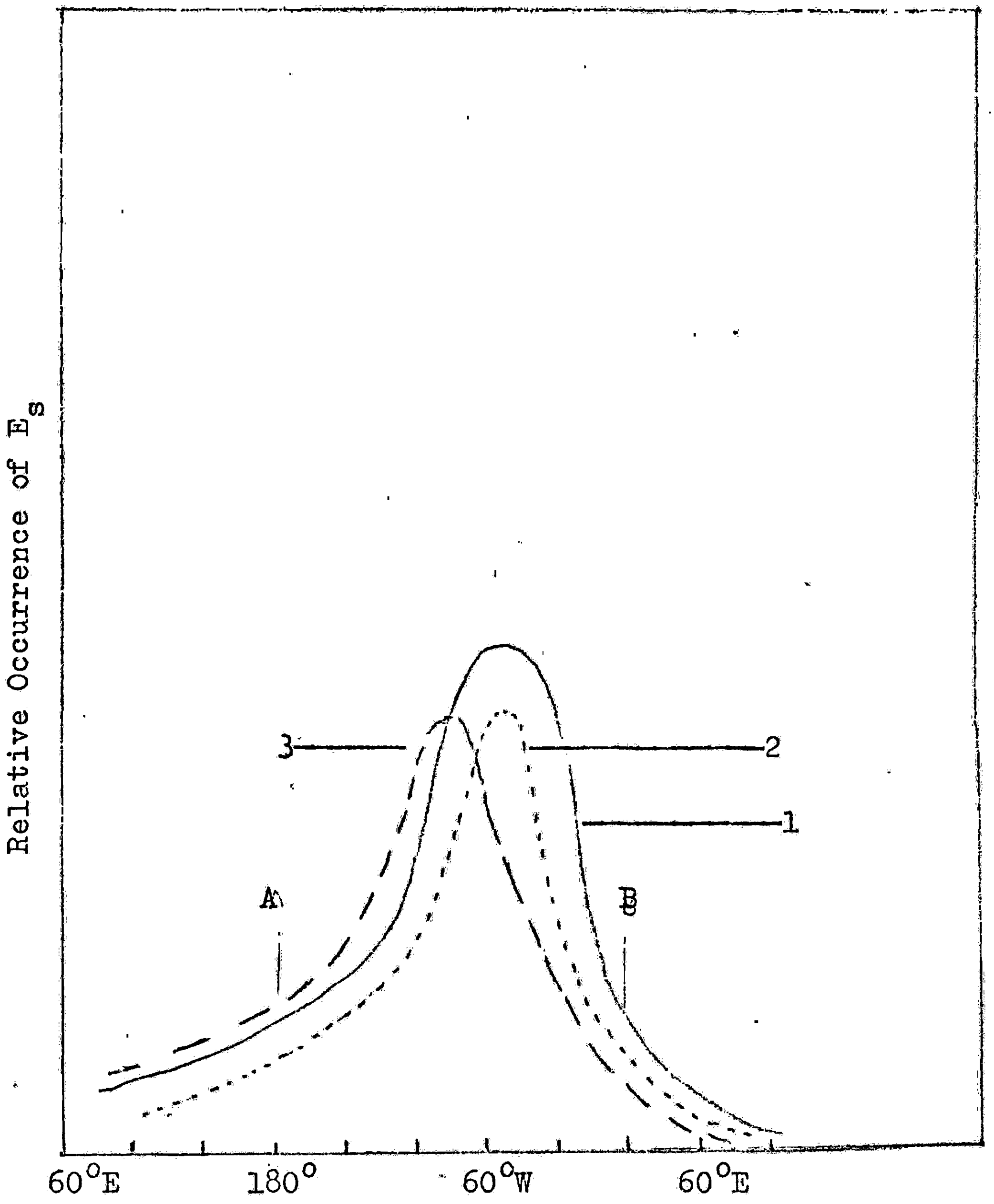


Fig.2.2: Longitudinal distribution of E_s occurrence

2.3 Polar Stations

Heiss Island and Resolute Bay

The diurnal and seasonal variations of the occurrence of sporadic-E on quiet days for Heiss Island, as an eastern station, are compared with Resolute Bay, as the corresponding western station, during the IGY in fig.2.3. It will be noticed that the percentage occurrence of sporadic-E ($f_oE_s \geqslant 3$Mc/s) is greater at Resolute Bay as compared to Heiss Island up to 1600 hrs whereas the situation reverses after 1600 hrs till midnight for all the seasons. A similar situation between Heiss Island and Resolute Bay is found for sunspot minimum years (fig.2.3). However, the difference in the occurrence of E_s between the two stations reduces up to 1600 hrs and increases afterwards as compared to IGY during the summer and equinoxes.

The frequency distribution of sporadic-E during IGY (fig.2.8) shows a greater occurrence of E_s at Heiss Island as compared to Resolute Bay in the lower frequency range and less in the higher frequency range ($f_oE_s > 3.5$ Mc/s). This agrees with Leighton et al (1962) who showed that E_s was more frequent ($f_oE_s > 5$Mc/s) in the North American portion than in the Siberian portion during 1958. However, the frequency distribution during sunspot minimum years (fig.2.8) shows a greater occurrence of sporadic-E at Heiss Island than at Resolute Bay over virtually the whole of the frequency range. This shows a reduction in the occurrence of sporadic-E

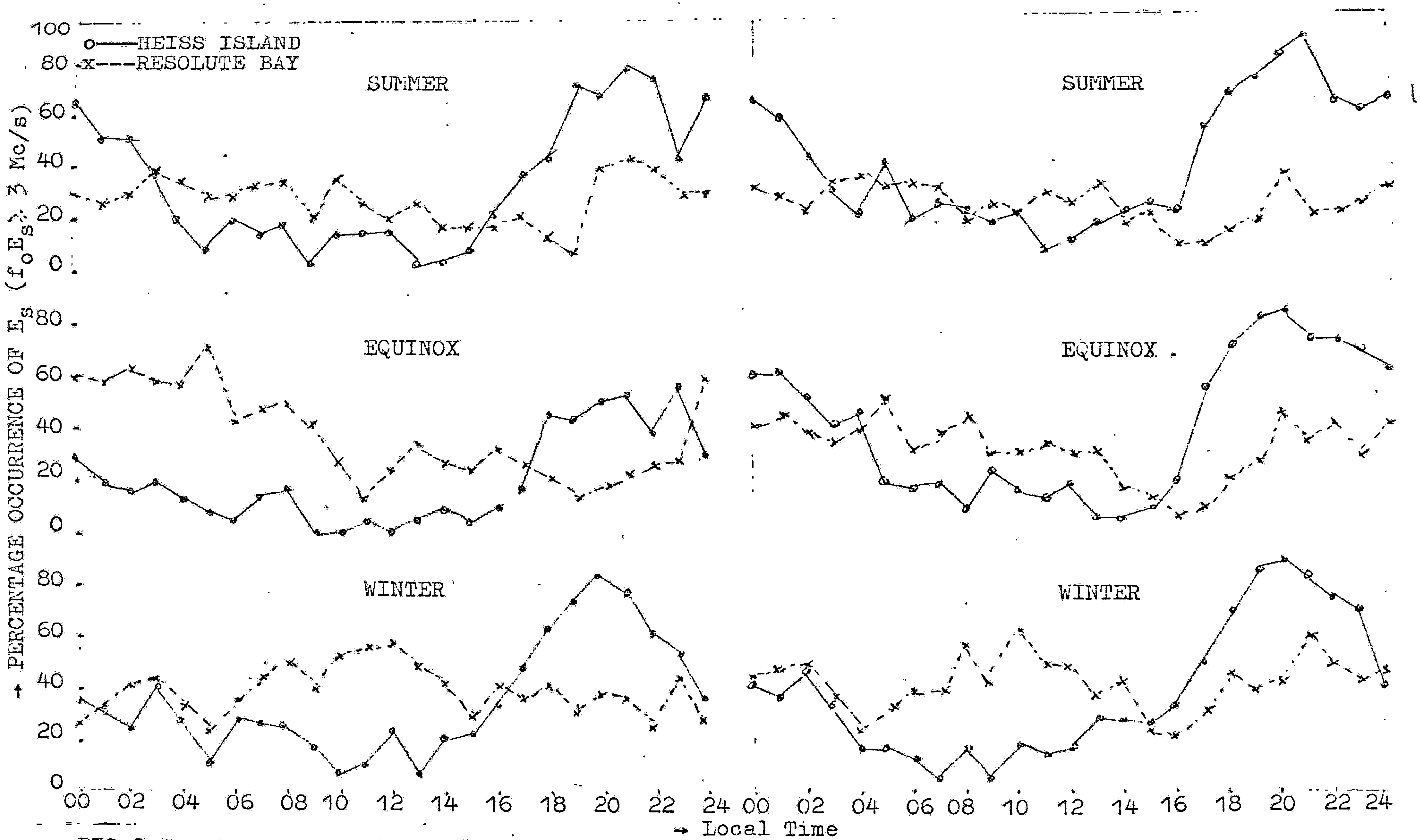


FIG.2.3: Diurnal variation of E_s on quiet days during IGY(left) and IQSY (right)

at Resolute Bay relative to that of Heiss Island in the years of sunspot minimum years as compared to Leighton et al (1962) for 1958, the year of sunspot maximum. A possible reason for this change may be related to the position of the magnetic pole.

It is well established that there is a movement of the dip-pole and its position has been measured as follows:

TABLE 2.2

Year	Geographic Latitude	Geographic Longitude
1900	71.2° N	96.9°W
1930	72.6° N	99.0°W
1950*	74.2° N	100.1°W
1955*	74.6° N	100.4°W
1960	75.1° N	100.7°W
1965	75.5° N	101.0°W

*These positions are found by interpolation.

These positions have been plotted in fig. 2.4 together with that of Resolute Bay and it will be seen that Resolute Bay is closest to the dip-pole about 1955 and that before and after this period its separation increases.

If the occurrence of E_s is to a certain extent dependent upon the position of the dip-pole, as suggested by Bellchambers and Piggott (1960) since the location of the E_s zone in the Canadian side is

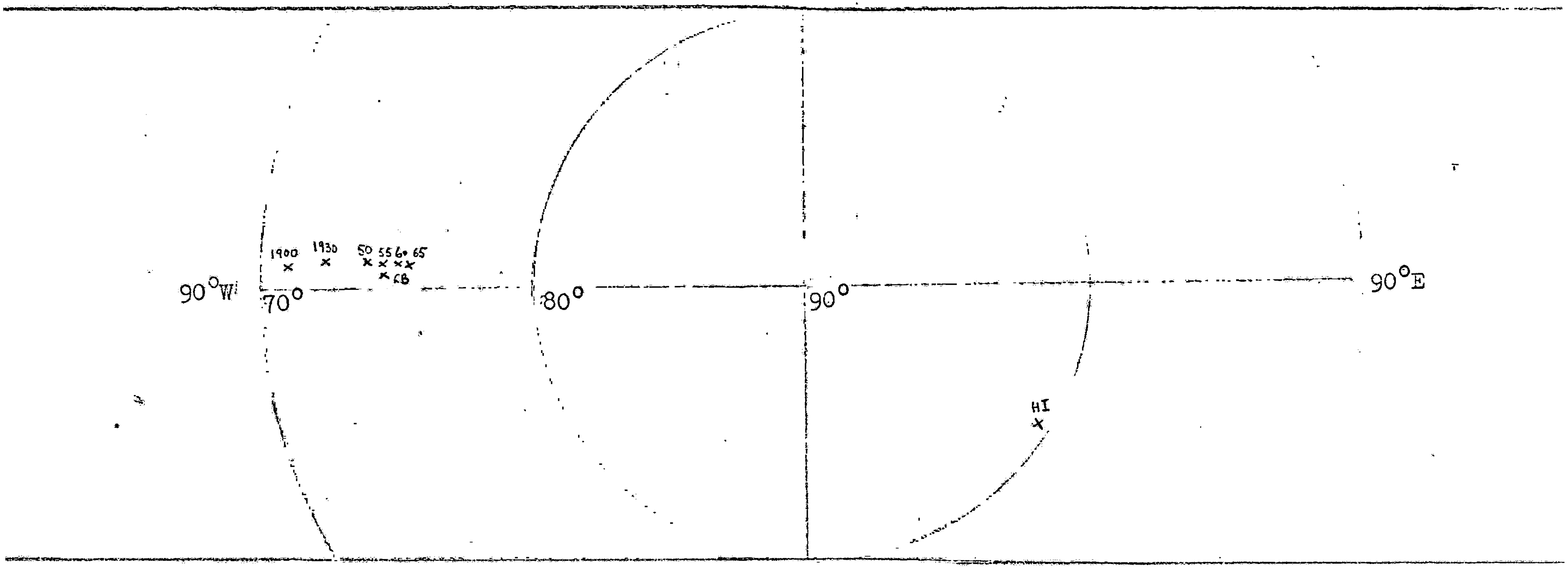


Fig.2.4: Positions of Resolute Bay, Heiss Island and North dip-pole (Geographic Coordinates)

caused by the position of the magnetic pole in that region, then a change in the occurrence of E_s before and after 1955 might be expected. A decrease in the occurrence of E_s was found by Thomas (1962) when he analysed data taken between 1950 and 1958 for Resolute Bay. As such, he pointed out the negative correlation between the occurrence of E_s and solar activity because the maximum occurrence was found in the year of low sunspot activity 1955 as compared to a minimum occurrence in the years of high sunspot activity - 1950 and 1958. However, in the present study the overall occurrence of E_s ($f_oE_s > 3$ Mc/s) has been found to increase by 17% with sunspot activity when data has been analysed for 1957-58 and for 1963-64, years of high and low sunspot activity respectively. Thus at Resolute Bay a decrease in the occurrence of E_s with increasing solar activity is observed in one solar cycle (1950-57) while an increase is observed in the succeeding half solar cycle (1957-65).

A tentative and qualitative explanation of this anomalous behaviour can be accordingly made by ascribing this increase and decrease in the occurrence of E_s before and after 1955 to the movement of the dip-pole relative to Resolute Bay. It should be stressed that this is only a qualitative explanation since the magnitude of the decrease from 1957-58 to 1963-64, i.e. 17%, is rather more than would seem probable from the observed movement of the dip-pole.

A similar explanation may be applied to Heiss Is, which is also a polar cap station like Resolute Bay, where by contrast an increase in the E_s incidence is observed from 1957-58 to 1963-64. In Chapter 5 it is shown that there is a contraction of the auroral zone between solar maximum and minimum conditions. Consequently, since Heiss Island is on the edge of the polar cap in the IGY, it may change to an auroral position in 1963-64. If such a change did occur then the number of occurrences on quiet and disturbed days should decrease and increase respectively from 1957-58 to 1963-64 on account of this apparent change of position. Furthermore, Heiss Is. is situated near the trough in E_s occurrence which is nearly opposite to the enhanced Canadian zone and hence any movement of the pole should produce a movement of this trough. In 1963-64 the quiet day occurrence, which should decrease due to the auroral position, is in fact slightly increased and this is largely ascribed to a movement of the trough. On disturbed days, however, the presence of the trough is of much less importance than the auroral position and a very pronounced increase in the E_s occurrence is observed i.e. 142% ($f_oE_s > 3$ Mc/s). Again, therefore, it would seem that the movement of the dip-pole has an effect on the incidence of E_s.

2.4 High Latitude Stations

Point Barrow and Tromsö

The diurnal and seasonal variations of occurrence of sporadic-E for Point Barrow and Tromsö (fig.2.5) show that E_s is more frequent at the western station during summer in the IGY. During the equinoxes the variation remains much the same as in summer except for a reversal between 0300 and 0700 hrs. This reversal is also repeated throughout most of the winter day. The overall seasonal variation shows a consistently greater incidence at Tromsö than at Point Barrow, apart from a short early morning period. In sunspot minimum years the occurrence of sporadic-E is found to be higher at the eastern station, Point Barrow, for most of the early morning hours in all the seasons. During other winter hours at Tromsö the incidence is greater than that at Point Barrow but in the other seasons there is no significant difference between the two stations (fig.2.5). The overall seasonal variation this time shows a consistently greater incidence at Point Barrow apart from a short period around noon. It is found after examining the frequency distribution during the IGY (fig.2.8) that the occurrence of sporadic-E is more frequent at Point Barrow only at the higher frequencies, i.e. after 6 Mc/s whereas, at lower frequencies, the occurrence of E_s is greater at the complementary station, Tromsö, in the western zone. During IQSY (fig.2.8) the occurrence of sporadic-E at Point Barrow is found to generally exceed

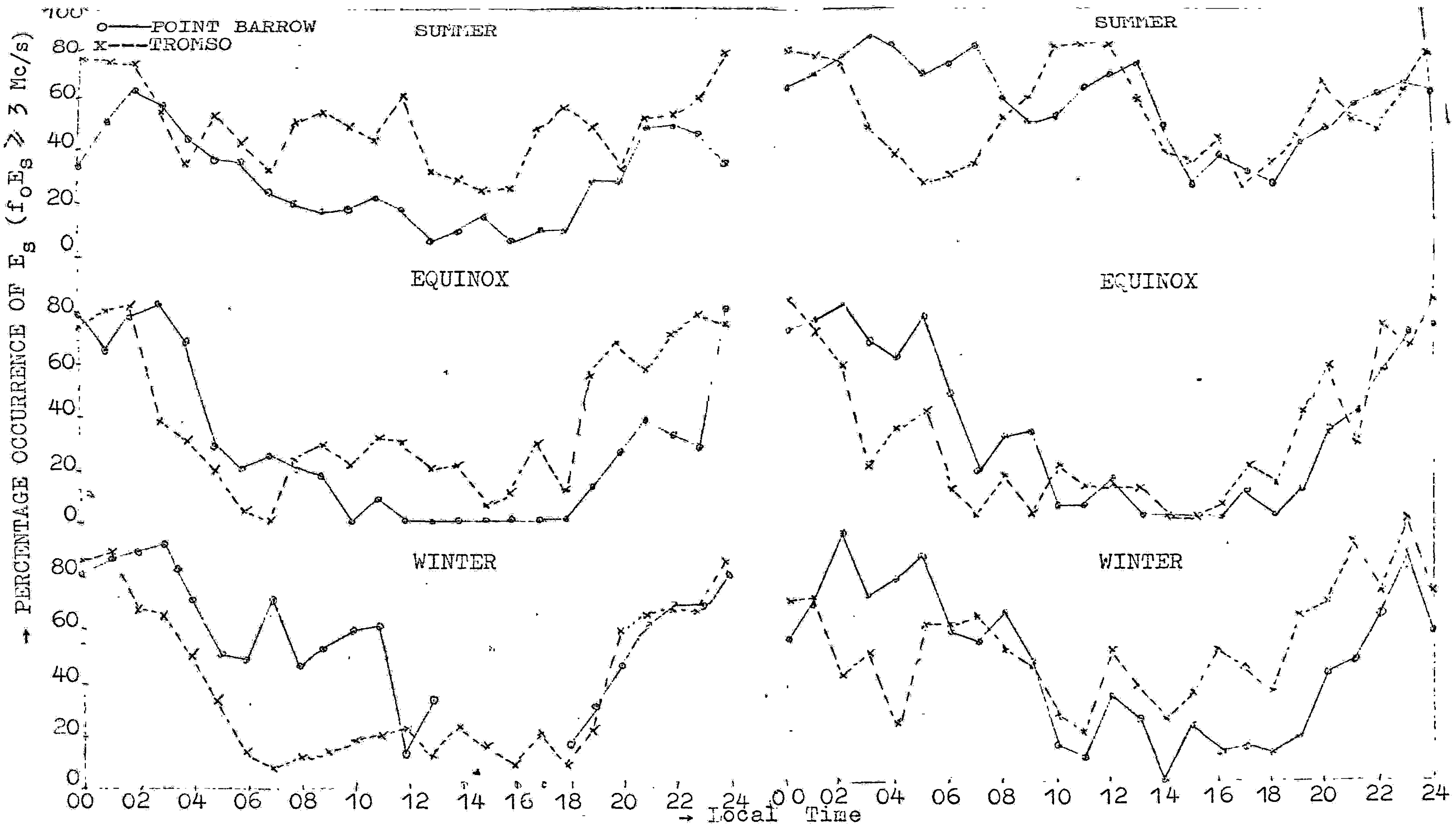


FIG.2.5: Diurnal variation of E_s on quiet days during IGY (left) and IQSY (right)

that at Tromsö. The occurrence of E_s is thus higher at the eastern station as compared to that at the western station for high frequencies in sunspot maximum and minimum years. At lower frequencies, however, the situation remains the same in sunspot minimum years, but in sunspot maximum years the situation is essentially reversed with more E_s at Tromsö. According to Leighton et al (1962), at these longitudes in 1958 the relative east and west occurrence of sporadic-E ($f_oE_s > 5$ Mc/s) is similar and agrees with the results for sunspot maximum years. Insofar as the situation when $f_oE_s \geq 3$ Mc/s is concerned, there is a greater incidence at Tromsö during IGY but little significant difference on average in IQSY. However, when the total incidence of E_s is considered, i.e. the frequency of appearance, there would seem to be a more significant change in IGY, in that there is a greater incidence at Tromsö whereas in IQSY the situation is reversed.

Providence Bay and Uppsala

During IGY, the occurrence of E_s is found to be very much less at the eastern station, Providence Bay, as compared to that at the corresponding western station, Uppsala, for all the seasons and for all hours of the day.(fig.2.6). In sunspot minimum years, however, the incidence at Uppsala only exceeds that at Providence Bay during the period approximately between 0800 hrs and 1300 hrs and then only by a small amount. For all other hours of the day the incidence

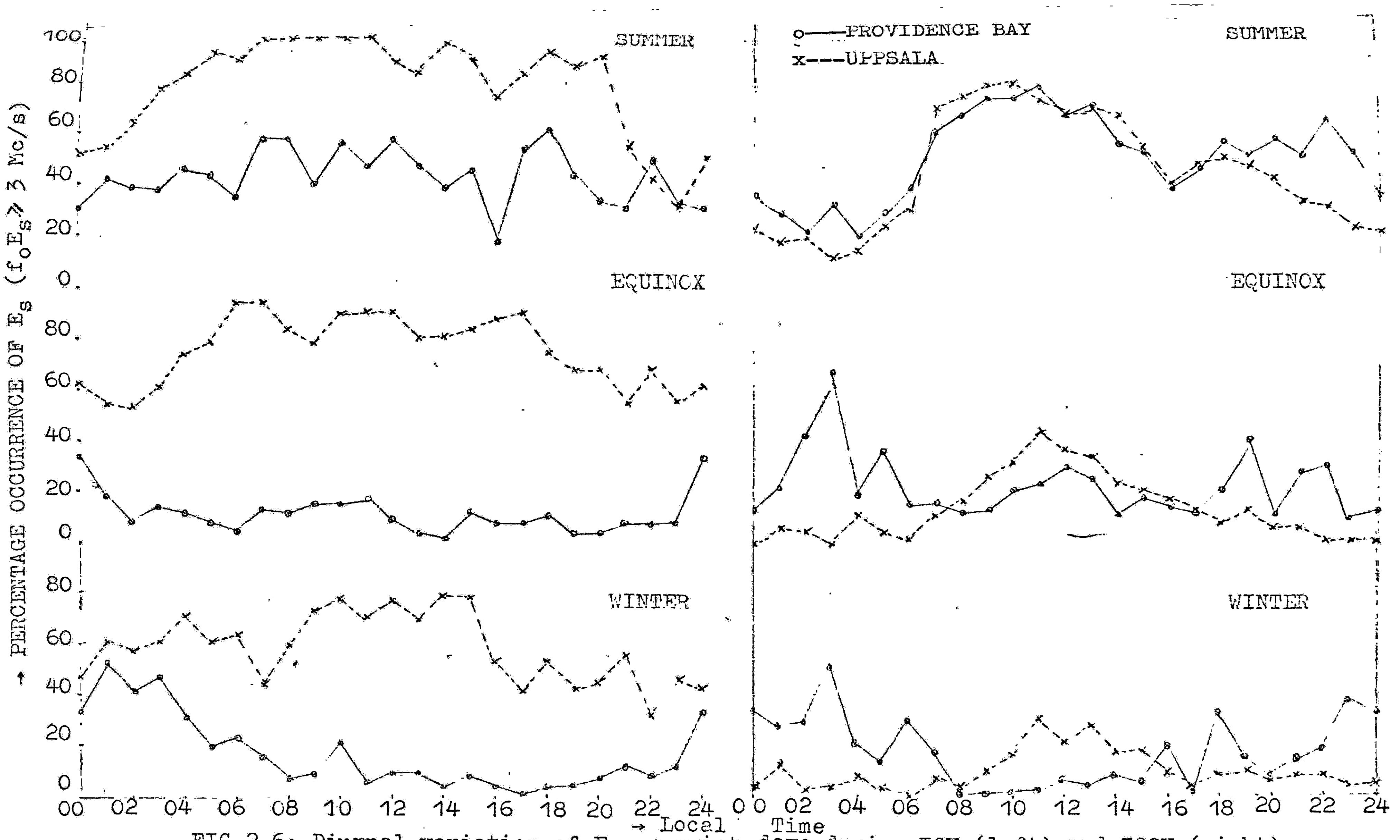


FIG.2.6: Diurnal variation of E_s on quiet days during IGY (left) and IQSY (right)

at Providence Bay is greater than that at Uppsala and this applies to all the seasons (fig.2.6)

The frequency distribution during IGY shows more E_s at Uppsala for the entire frequency range. In IQSY the difference between Uppsala and Providence Bay becomes almost zero at frequencies above 3 Mc/s, but below this frequency the incidence remains higher at Uppsala than at Providence Bay (fig.2.9).

Adak and Slough

In the IGY the E_s incidence is found to be greater at Slough, the western station, than at the complementary eastern station, Adak, during winter daytime and slightly less during summer daytime. For the night hours the only significant difference is the greater incidence in winter at Adak than that at Slough since, for the other seasons, the incidence figures for Adak are subject to considerable uncertainity due to the large number of occasions when blackouts were present (fig.2.7). The total number of occurrences are found to be more at Slough as compared to Adak on an annual basis. In IQSY the diurnal variation (fig.2.7) shows that the percentage occurrence of E_s is more at Adak as compared to Slough for all the hours of the day except between 1000 and 1300 hrs in winter, 0900 and 1500 hrs in the equinoxes and 1300 and 1600 hrs in summer, where the incidence of E_s is more at Slough. The overall incidence tends to be greater at Adak than Slough except over the noon

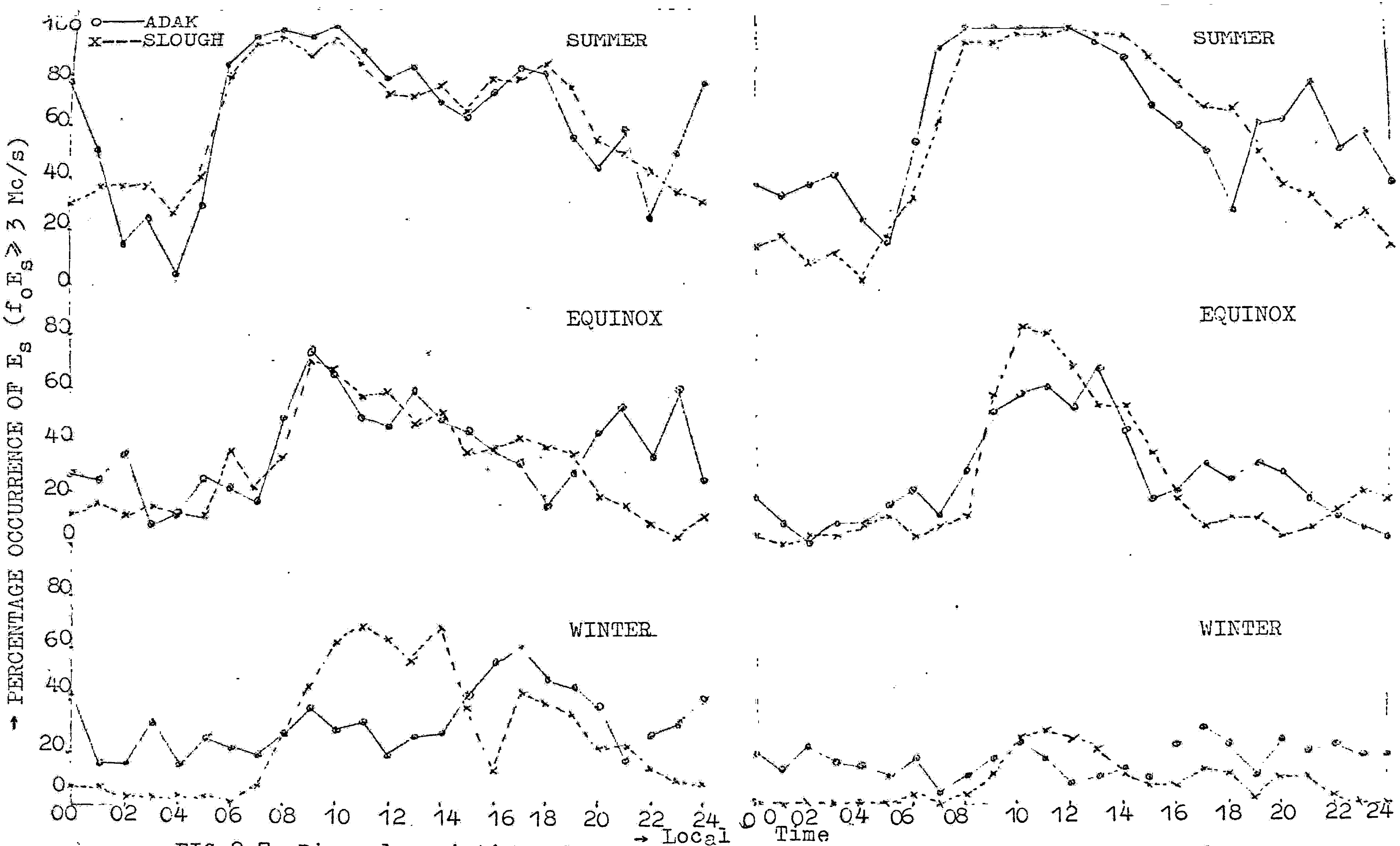


FIG.2.7: Diurnal variation of E_s on quiet days during IGY (left) and IQSY (right)

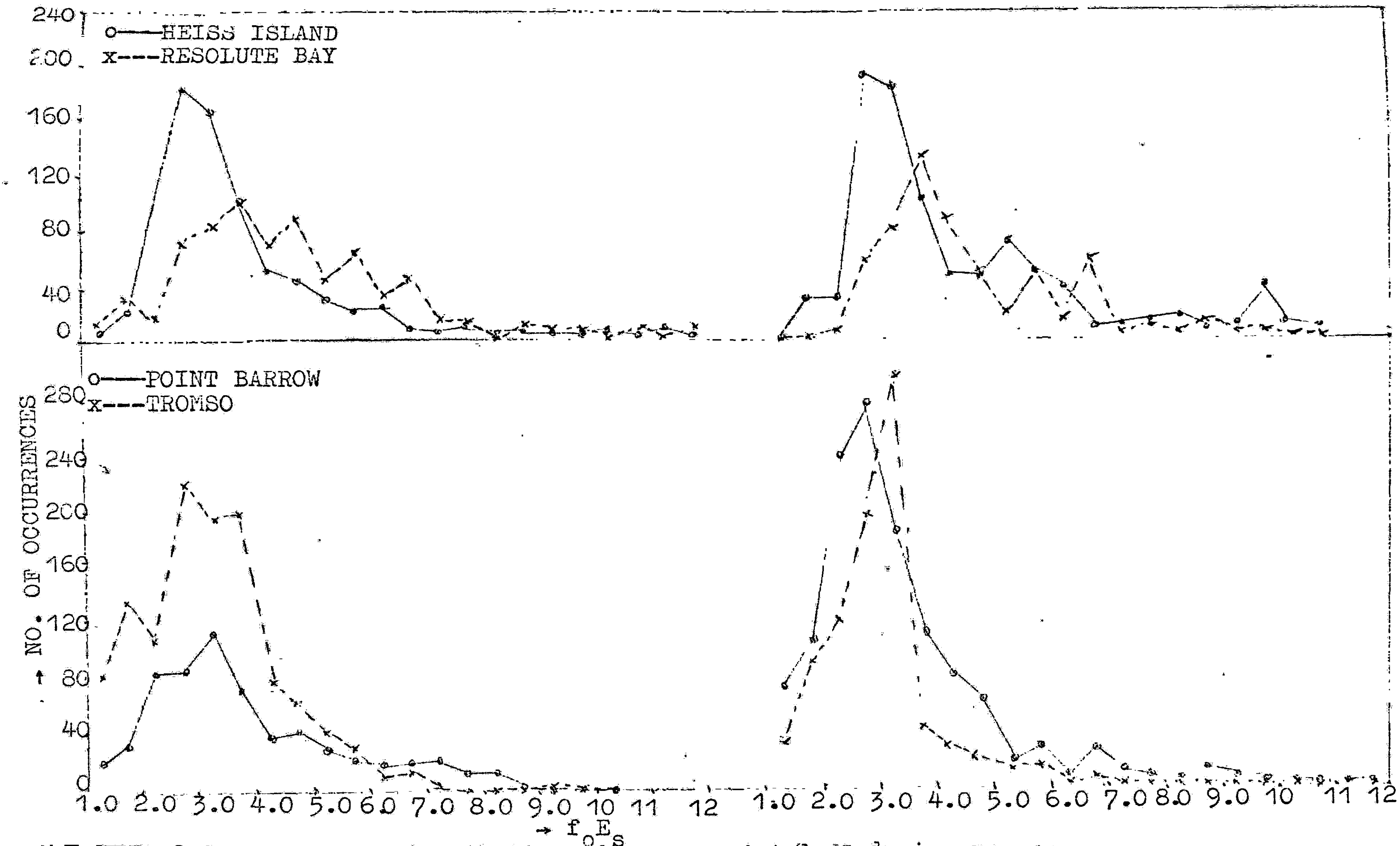


FIG.2.8: Frequency distribution of E_s on quiet days during IGY (left) and IQSY (right)

period. One feature of the IGY and IQSY results has been found in that there is a close similarity in the seasonal changes. It is observed that the relative difference between the occurrence of E_s at Slough and Adak decreases from winter to equinoxes then to summer during the daytime. In fact, the difference in the incidence of E_s between Slough and Adak is positive in winter and becomes slightly negative in summer.

The frequency distribution during IGY shows that the number of occurrences for $f_oE_s > 3$ Mc/s at Slough is greater than that at Adak, while during IQSY there is little difference between them (fig.2.9). This situation is also observed when the average diurnal variation of total occurrence is considered.

At high latitudes the approximate longitudinal variation in the occurrence of E_s is given by curve 1 in fig. 2.2 for stations at a common geographic latitude of 65° N. This has been derived from the contour maps given by Leighton et al (1962). The data actually relates to the equinoxes and so is representative of the mean annual behaviour thereby allowing a comparison of the annual results to be made.

If the occurrence of E_s is, to a certain extent, dependent on the position of the dip-pole (as is suggested by Resolute Bay), then the occurrence of E_s will decrease from IGY to IQSY in the intense E_s zone i.e. in the Canadian sector and will increase in the complementary zone on the other side of the pole.

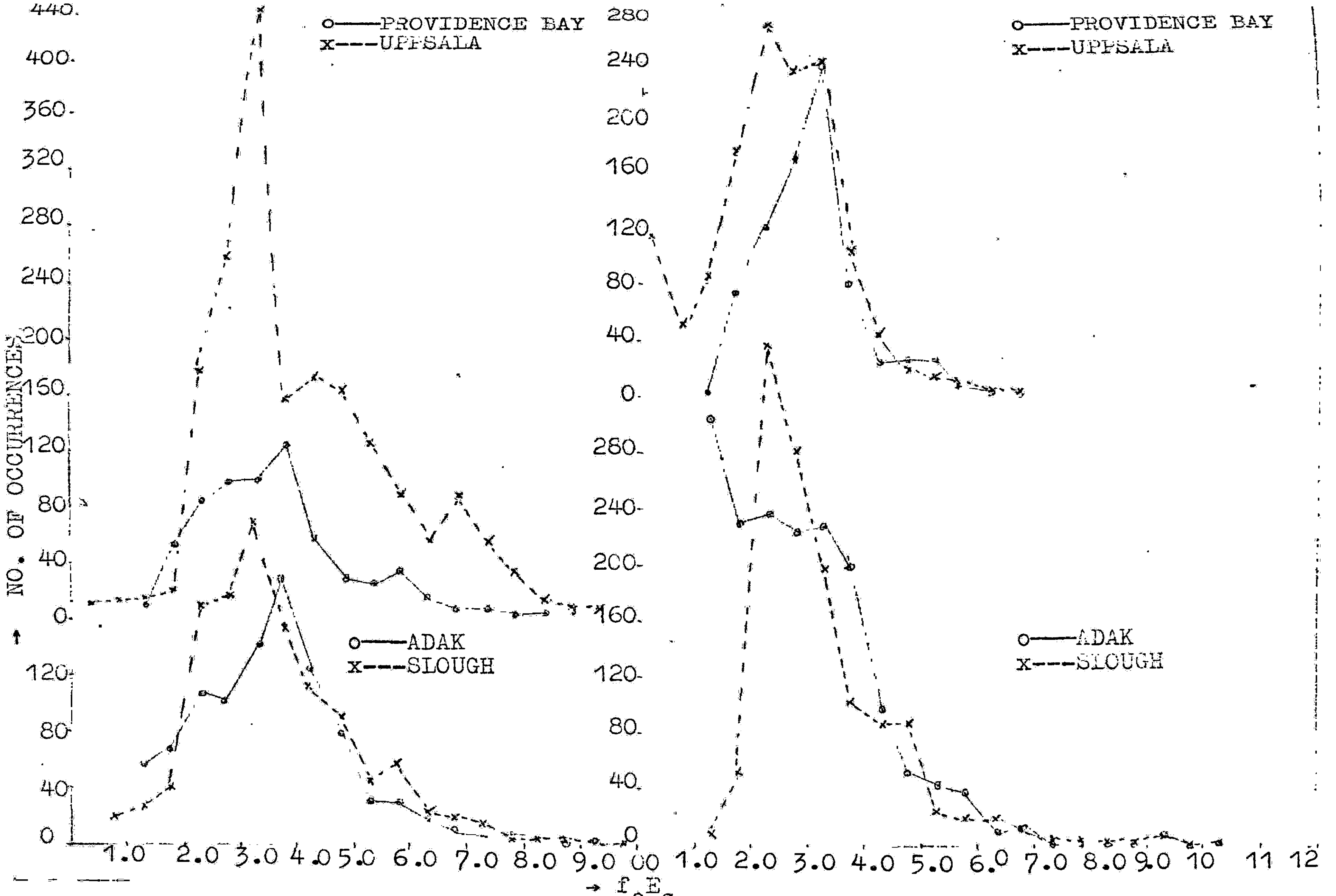


FIG.2.9: Frequency distribution of E_s on quiet days during IGY (left) and IQSY (right)

This distribution of E_s occurrence is shown by curve 2 when the meridional component of the movement of the dip-pole is considered. If the westward or zonal component of the dip-pole is considered then the distribution shown by curve 2 would be shifted towards the left hand side and will be shown by curve 3. On comparing curves 1 and 3, which represent the longitudinal distribution of E_s in IGY and IQSY respectively, it will be observed that a small increase will occur at stations near A while there will be a larger decrease at complementary stations near B.

In the present analysis a small increase in the occurrence of E_s ($f_oE_s > 3$ Mc/s) of 9%, 5% and 6% at Point Barrow, Providence Bay and Adak respectively has been found from IGY to IQSY on quiet days. On disturbed days also there is an increase of 6% at both Point Barrow and Adak but a decrease of 36% at Providence Bay. This anomalous decrease in the occurrence of E_s, as against the increase which might be expected, is caused by the contraction of the auroral zone from IGY to IQSY changing the nature of Providence Bay from a wholly auroral station in IGY to a marginal auroral-temperate latitude one in IQSY and so is not, in fact, a contradictory result. These three stations are situated near A. At the complementary stations near B, large decreases have been found, viz. 28% at Tromsö, 66% at Uppsala and 24% at Slough from IGY to IQSY on quiet days. On disturbed days the figures become

33%, 75% and 20% respectively. It would thus appear that there has been an effective movement of the intense E_s zone in the Canadian sector from IGY to IQSY which is not so much directly related to the change in solar activity but rather is related to the movement of the dip-pole. There may, of course, be a solar activity effect but so far there is no available evidence from other fields, such as riometer measurements, particle precipitation or flux observations which would provide support for a preferential longitudinal movement.

Again, while the zonal movement of the dip-pole is in the same sense and compatible with that of the intense E_s zone, its E-W movement between 1957 and 1965 is only about $\frac{1}{2}^{\circ}$. The intense E_s zone, however, requires an E-W movement of some degrees to explain the observed changes in E_s occurrence. Thus, while there is a superficial relation between the movement of the dip-pole and the intense E_s zone, the magnitude of this relative change implies that the precise link between them has yet to be determined.

2.5 Low Latitude Stations

Akita and Puerto Rico

The diurnal variation of occurrence of sporadic-E is found to be significantly more at Akita, an eastern station, as compared to Puerto Rico, the complementary western zone station during the IGY summer morning. (fig.2.10). For the remaining summer hours the difference is not pronounced and in the equinoxes and

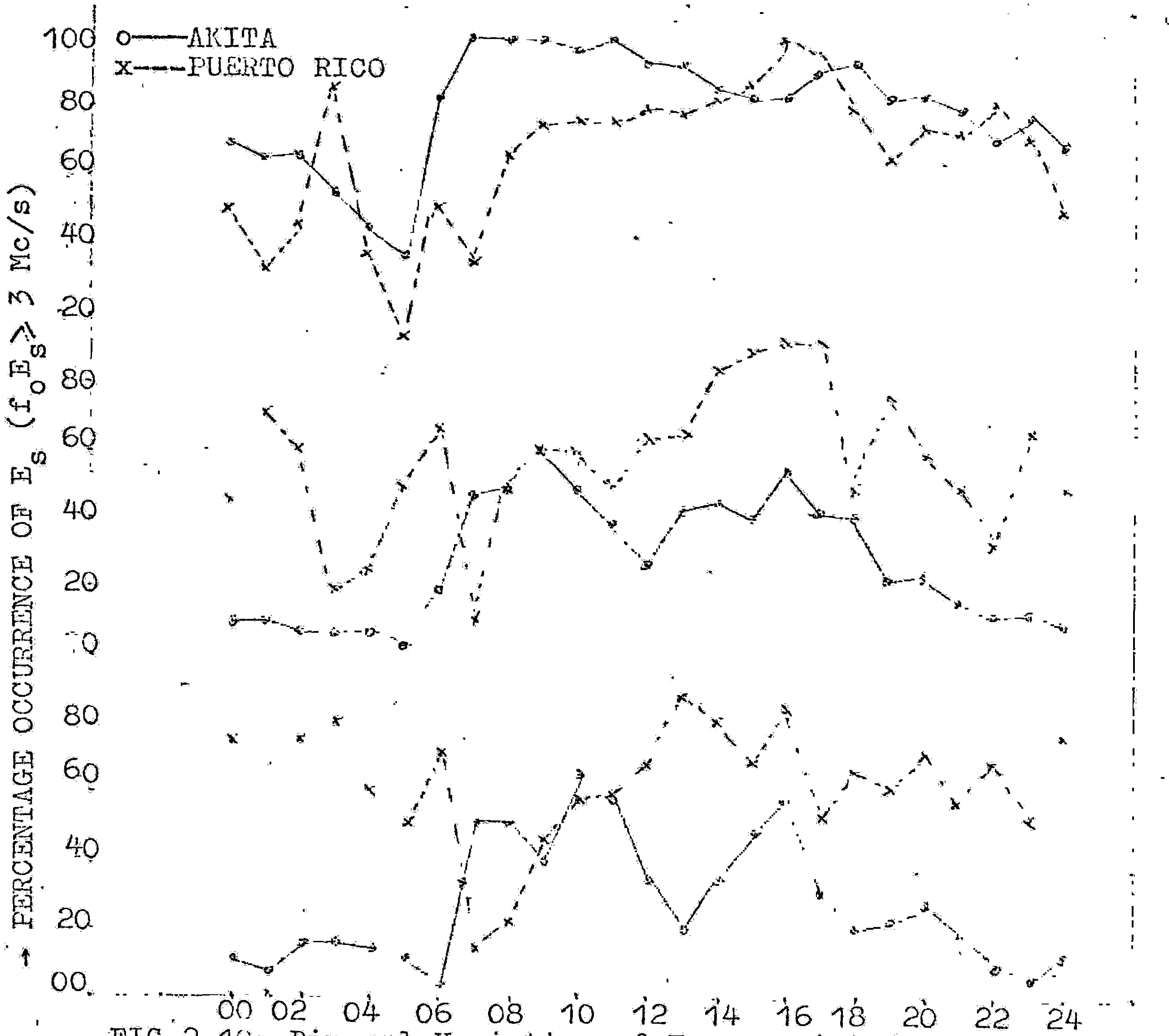


FIG.2.10: Diurnal Variation of E_s on quiet days during IGY

winter months the incidence at Puerto Rico is greater than at Akita. The situation is similar to that described by Smith (1957) for eastern and western zone stations during summer and winter.

Taipei and Bogota

At lower temperate latitudes also the diurnal variation of sporadic-E is found to be consistently greater during summer at an eastern station, Taipei, as compared to its complementary station, Bogota, during sunspot maximum and sunspot minimum years (fig.2.12). This difference decreases seasonally until in winter the Taipei incidence only exceeds that at Bogota for a relatively short noon period, again during both IGY and IQSY. This agrees with the temperate zone maps of Smith (1957) for summer and winter.

As there is a seasonal change in the relative occurrence of E_s at Akita and Puerto-Rico, the frequency distributions for summer and winter have been plotted separately. It will be seen that in summer E_s is more frequent at Akita than Puerto Rico for most of the frequency range while, in winter, it is completely reversed except for the very low frequency end (fig.2.11). It will be noted that there is more E_s at Akita than Puerto Rico in the lower frequency range in both seasons. Now Akita and Puerto Rico have almost the same geomagnetic latitude (29.5°N and 30°N respectively) but differ greatly in geographic latitude (39°44/N and 18°31/N respectively) i.e. by almost 21° with Puerto

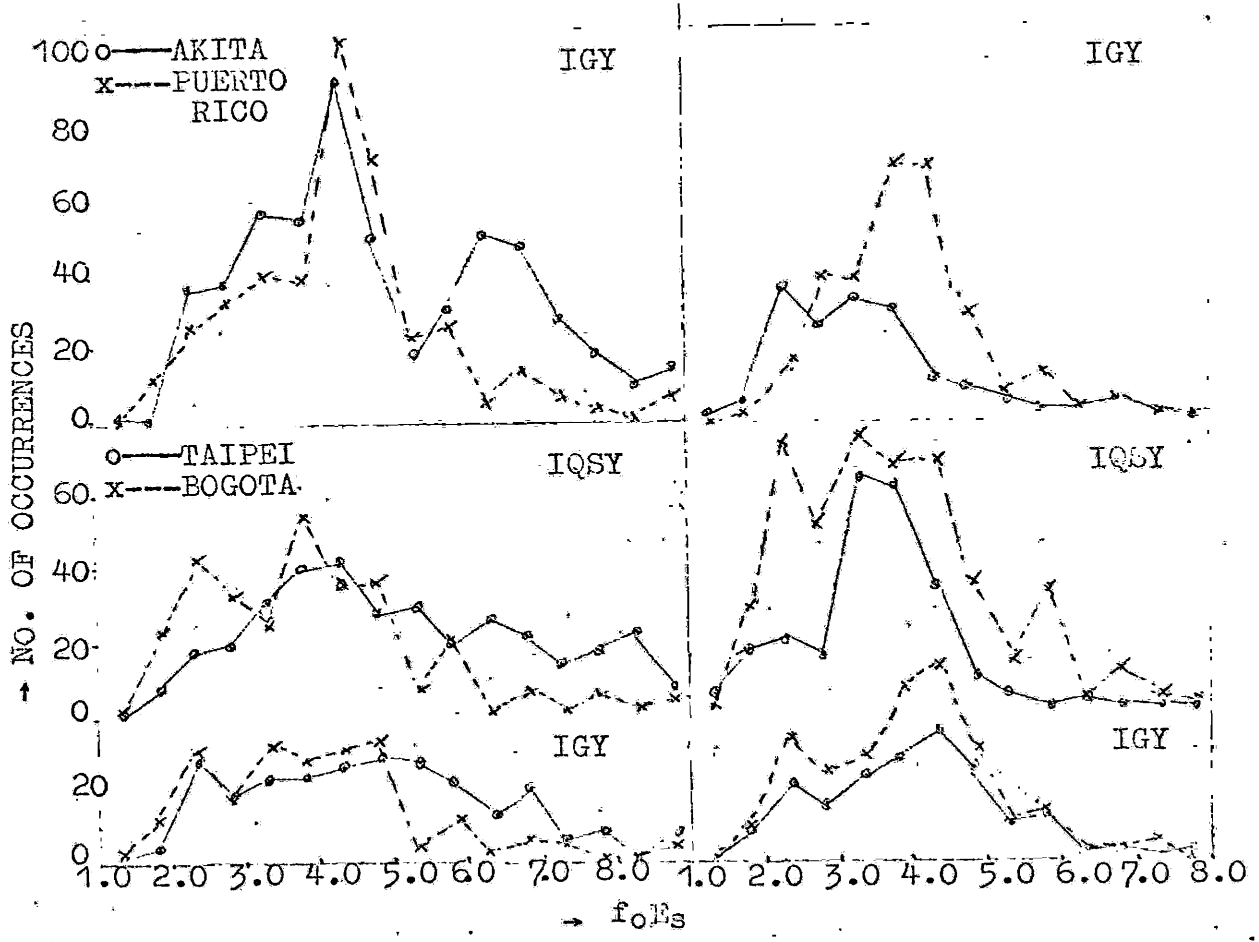


FIG.2.11: Frequency distribution on quiet days in summer (left) and winter (right)

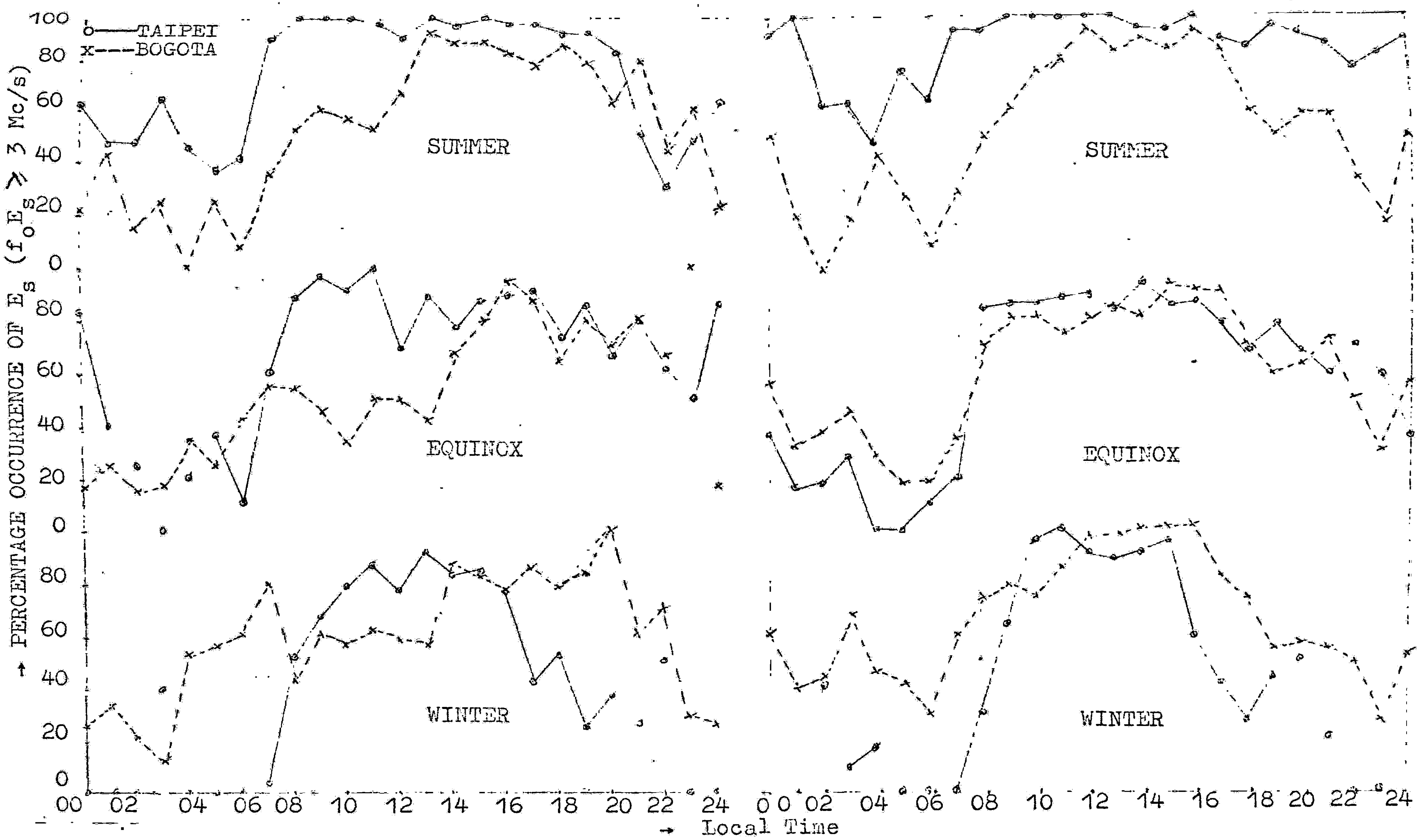


FIG.2.12: Diurnal variation of E_s on quiet days during IGY (left) and IQSY (right)

Rico being nearer to the tropic of Cancer than Akita. Thus the average ambient ionization density (n_o) of the E-layer at Puerto Rico will be greater than that at Akita.

Reddy and Matsushita (1968) have shown that a small windshear can produce detectable E_s when the ambient electron density (n_o) is small but the same windshear will not produce a detectable E_s-layer for large values of n_o provided that there is a certain threshold or critical value of E_s below which it will not be detected by the system. Since n_o is smaller at Akita than at Puerto Rico in all seasons, a small windshear at Akita produces detectable E_s in all seasons, but the same windshear will consequently not produce detectable E_s at Puerto Rico where n_o is always larger. Thus a more frequent occurrence of E_s in the lower frequency range may be expected at Akita in both summer and winter.

A similar relative seasonal change in E_s occurrence has been noted at Taipei and Bogota and the frequency distributions for these stations are shown in fig.2.11 for IGY and IQSY. E_s is found to be relatively more frequent at Taipei in the high frequency range during the summer of IGY but less frequent at the low frequency end in both summer and winter. The high frequency range shows a reversal in winter. This different behaviour at the high and low frequency ends of the scale is repeated in IQSY and so is not a purely random situation. By analogy with the results at Akita and Puerto Rico these changes can be qualitatively explained. Taipei and Bogota also have nearly the same geomagnetic latitude (13.7°N and 15.9°N respectively) but about the same difference in geographic latitudes (25°2/N and 4°38/N respectively) as Akita and Puerto Rico. In this case, however, Taipei, an eastern station is nearer to the tropic of Cancer and hence the ambient ionization density (n_o) at Taipei is greater than at Bogota in summer. Thus small windshears should produce relatively more detectable E_s at Bogota than at Taipei since n_o is smaller at Bogota.

According to this explanation one would expect more E_s in the low frequency range at Taipei in winter because the average n_o is smaller at this station relative to Bogota. This result is not in fact found in either IGY or IQSY. It must be presumed, therefore, that since Taipei is only just outside the tropic the ambient electron density is insufficiently less than that at Bogota for the threshold criterion to apply. At Akita, however, which is 15° to the north of Taipei and where the low frequency reversal effect does take place, it would appear that n_o has decreased enough for the threshold limit to be reached.

In order to explain the difference in the seasonal occurrence in the higher frequency range, a comparison has been made between Kokubunji and Grand Bahama of the windshears deduced by Reddy and Matsushita (1968).

These stations have been chosen as representative of low temperate latitude conditions in the eastern and western zones respectively (Kokubunji, Akita and Taipei are all at higher latitudes than their complementary stations Grand Bahama, Puerto Rico and Bogota and so meaningful comparisons can be made between them.)

TABLE 2.3

U' (m/sec/km)

Year → Station	58	59	60	61	62	63	64
Kokubunji	90	98	76	62	67	61	50
Grand Bahama	60	61	47	52	57	52	45
$\Delta U'$	30	37	29	10	10	9	5

Table 2.3 above shows the mean noon July windshears deduced from these authors' results and it will be noticed that the values at Kokubunji are consistently greater than those at Grand Bahama, but that the difference decreases steadily from IGY to IQSY. These figures suggest that the windshears in the eastern zone are permanently greater than those in the western zone. At high frequencies, therefore, where the windshear theory of E_s predicts that the E_s occurrence increases with the magnitude of the windshear, it might be expected that in summer there will be a relatively greater occurrence of E_s in the eastern zone. Fig. 2.11 shows that for Akita and Puerto

Rico in IGY and for Taipei and Bogota in IGY and IQSY this is indeed the situation.

TABLE 2.4

U' (m/sec/km)

Year → Station	58	59	60	61	62	63	64
Kokubunji	38	40	33	30	41	31	22
Grand Bahama	34	30	33	33	38	35	35
$\Delta U'$	+4	+10	0	-3	+3	-4	-13

The mean noon December windshear values are given in table 2.4. It is immediately apparent that the large differences evident in summer do not occur in winter. In IGY the windshear values are slightly greater at Kokubunji than those at Grand Bahama, the difference falling to zero and then becoming slightly negative in IQSY. There is thus a very large seasonal change in the windshear at Kokubunji and a relatively small one at Grand Bahama. This is reflected in the winter occurrence of E_s where it will be seen that at the high frequency end, the E_s occurrences at Taipei and Akita have actually fallen below those at Puerto Rico and Bogota respectively in all the three cases shown.

It may also be noted that the IQSY winter, when the eastern zone windshear is actually less than that in the western zone, is also the period when there is more E_s in the western relative to the eastern zone than at any other time.

This comparison between the high frequency E_s occurrences suggests that the greater seasonal changes in the eastern sector and the apparent reversal in the relative occurrence in summer and winter between eastern and western zones is closely related to the tendency for greater windshears to occur in the eastern zone. While it is true that the horizontal component of the earth's field is also greater in the eastern zone, this factor by itself would not produce any seasonal or relative east to west changes.

It will be noted that there is a decrease in the occurrence of the most probable frequency at Akita and Puerto Rico from summer to winter with a converse situation at Taipei and Bogota. This is not a physical effect and is due to the fact that, in order to compare the frequency distributions at any two stations, the periods for which data is included must be identical. The absolute levels of the distribution from season to season are therefore not significant for Taipei and Bogota where small gaps existed in the published data.

2.6 Equatorial Stations

Kodaikanal and Huancayo

At equatorial stations, the diurnal variation ($f_oE_s \gg 3$Mc/s) shows consistently more sporadic-E at Huancayo, a western station, as compared to the complementary station, Kodaikanal, during nighttime in all seasons and in both sunspot maximum and minimum years (fig.2.13). During the daytime for IGY the frequency of occurrence is very high for both stations and, what differences there are, are so small as to be barely significant. The consistently higher level of nighttime occurrences at Huancayo has already been commented upon and there is no similar daytime situation. There does, however, appear to be a small seasonal effect in that in winter the incidence at Huancayo is slightly more while in summer the tendency is for the situation to reverse. In view of the difference in the width of the electrojet between eastern and western hemispheres (Rao, 1964) this small change is not of great significance.

Since both Huancayo and Kodaikanal are equatorial stations it might be expected that they are both affected to the same effect by changes in solar activity. It will be seen from fig.2.13 though that there is actually a greater decrease at Kodaikanal from maximum to minimum solar activity. Some indication of the latitudinal extent of the electroject has been given by Gates (1959) and by Kotadia (1962) for maximum and minimum solar activity conditions. This has been used to construct fig.2.14(b) which shows the occurrence of E_s as a function of magnetic dip for maximum and minimum solar activity, and also shows the position of Huancayo and Kodaikanal.

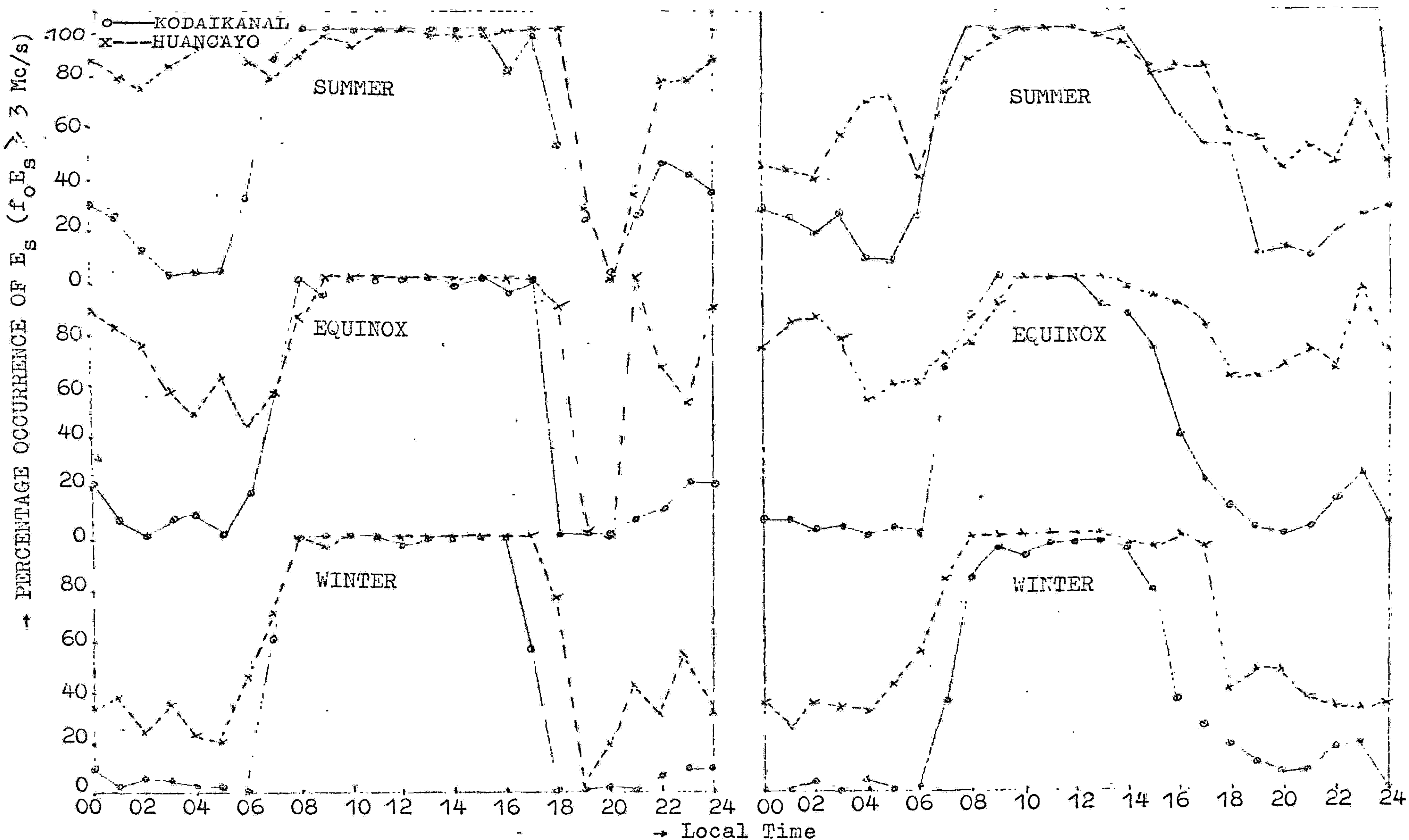


FIG.2.13: Diurnal variation of E_s on quiet days during IGY (left) and IQSY (right)

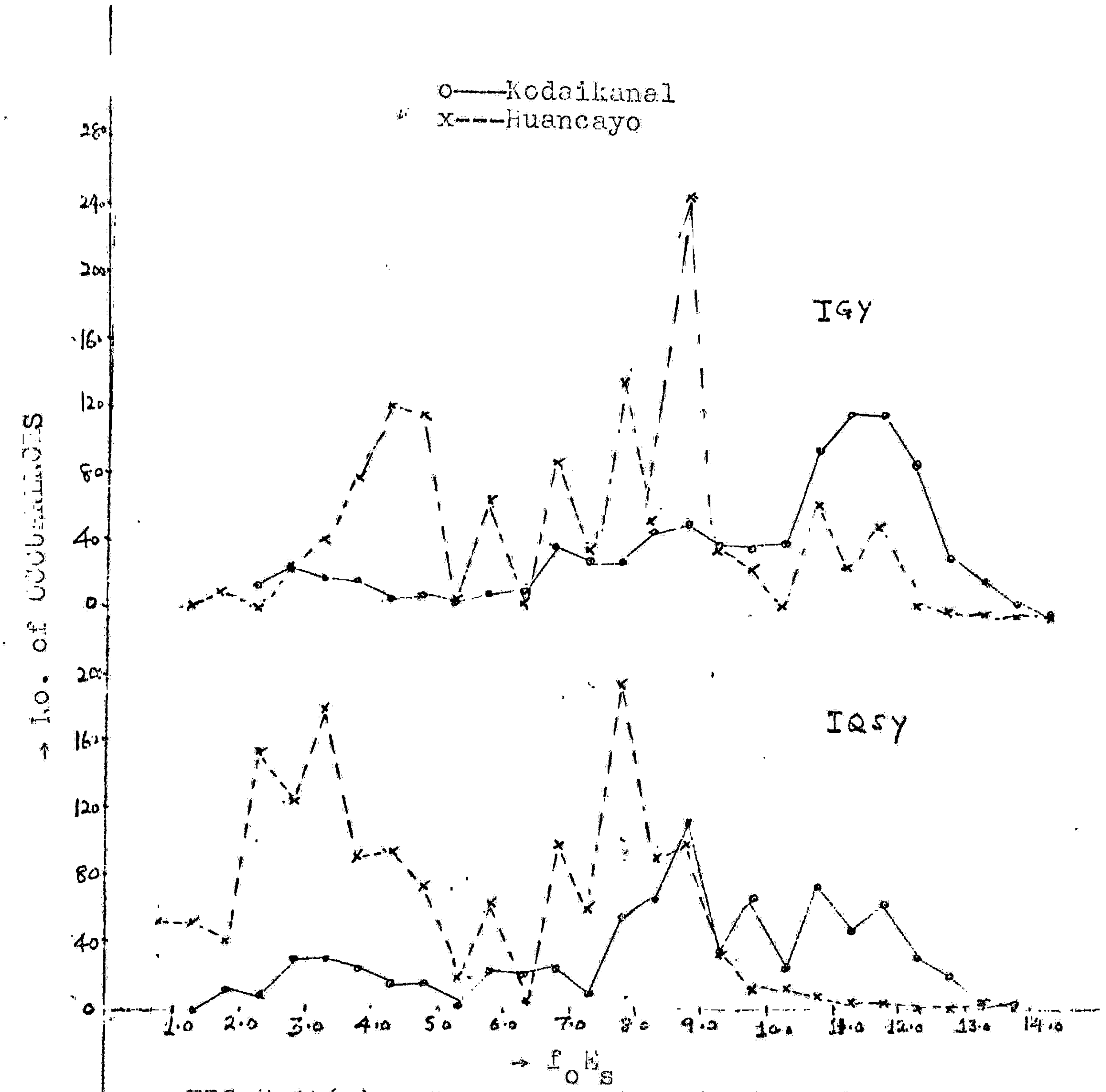


FIG.2.14(a): Frequency distribution of E_s on quiet days during IGY and IQSY

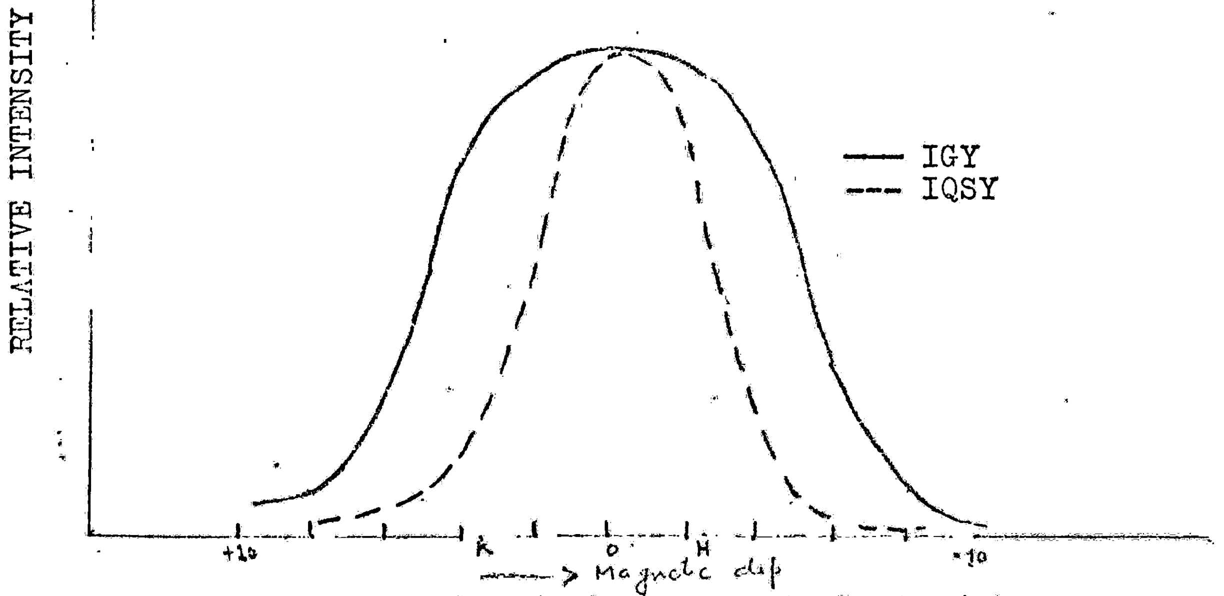


FIG.2.14(b): Latitudinal extent of electrojet

It is clear that at Huancayo there will be only a small decrease in the occurrence of E_s while at Kodaikanal there will be an apparently greater decrease from IGY to IQSY. It is also worth noting that at Rarotonga q or equatorial type E_s was observed in IGY but not during IQSY, again indicating the reduction in the width of electrojet with decreasing solar activity (Kerblay and Karochkina, 1966).

The frequency distribution shows more sporadic-E at Kodaikanal above 9.0 Mc/s during both 1957-58 and 1964-65 whereas very much more E_s is found at Huancayo at lower frequencies (fig.2.14).

CHAPTER 3

SPORADIC-E DURING SUNSPOT MAXIMUM AND SUNSPOT MINIMUM YEARS

3.1 Introduction

The relationship between sporadic-E and solar activity has been studied by many workers. Mitra and Das Gupta (1962, 1963) found a positive correlation between noon f_oE_s values and the occurrence of sporadic-E ($f_oE_s > 5$ Mc/s) at most of the stations examined. Chadwick (1961) obtained a negative correlation between the occurrence of E_s and solar activity at Fairbanks, Washington and Huancayo representing auroral, temperate and equatorial stations respectively. Thomas (1962) found a negative correlation at Resolute Bay, Baker Lake and Churchill and a positive one at Winnipeg.

More recently, Reddy and Matsushita (1968) showed that a positive correlation existed between solar activity and the blanketing frequency (f_bE_s) and the occurrence of E_s for $f_bE_s \geq 4.0$ Mc/s but below this frequency a negative correlation was observed at temperate latitudes. They studied this relationship by dividing the day into six periods of four hours each. In order to have a complete picture, the diurnal and seasonal variation of the occurrence of E_s has been compared from pole to equator during years of maximum and minimum solar activity. For the same period comparisons have also been made of the frequency distributions and latitudinal variation of sporadic-E in the present study.

The data used is the same as in Chapter 2 except that Puerto Rico has been omitted due to the absence of IQSY data.

3.2 Relationship between E_s and solar activity

The diurnal variation of occurrence ($f_oE_s > 3$ Mc/s) for Resolute Bay, a polar station, shows (fig.3.1) that E_s is found to be more frequent during sunspot maximum years in the equinoxes between 0600 hrs and 1800 hrs and in winter between 1100 hrs and 1800 hrs whereas, in the remaining period, it is more frequent in sunspot minimum years. There is no significant difference in the occurrence of E_s during summer for 1957-58 and 1963-64. The frequency distribution of sporadic-E (fig.3.3) shows a greater occurrence in sunspot maximum than in minimum years over most of the frequency range considered.

For Heiss Island the diurnal variation in summer and equinoxes (fig.3.1) shows a negative correlation with solar activity and also between 1800 hrs and 0200 hrs in winter. There is no significant difference in the remaining winter period. The frequency distribution for Heiss Island (fig.3.3) shows a greater occurrence of E_s in sunspot minimum than maximum years for all frequencies greater than 2.5 Mc/s

The diurnal variation of occurrence for Point Barrow shows (fig.3.2) a very clear negative correlation with solar activity during summer throughout the day. In the equinoxes the correlation effectively remains

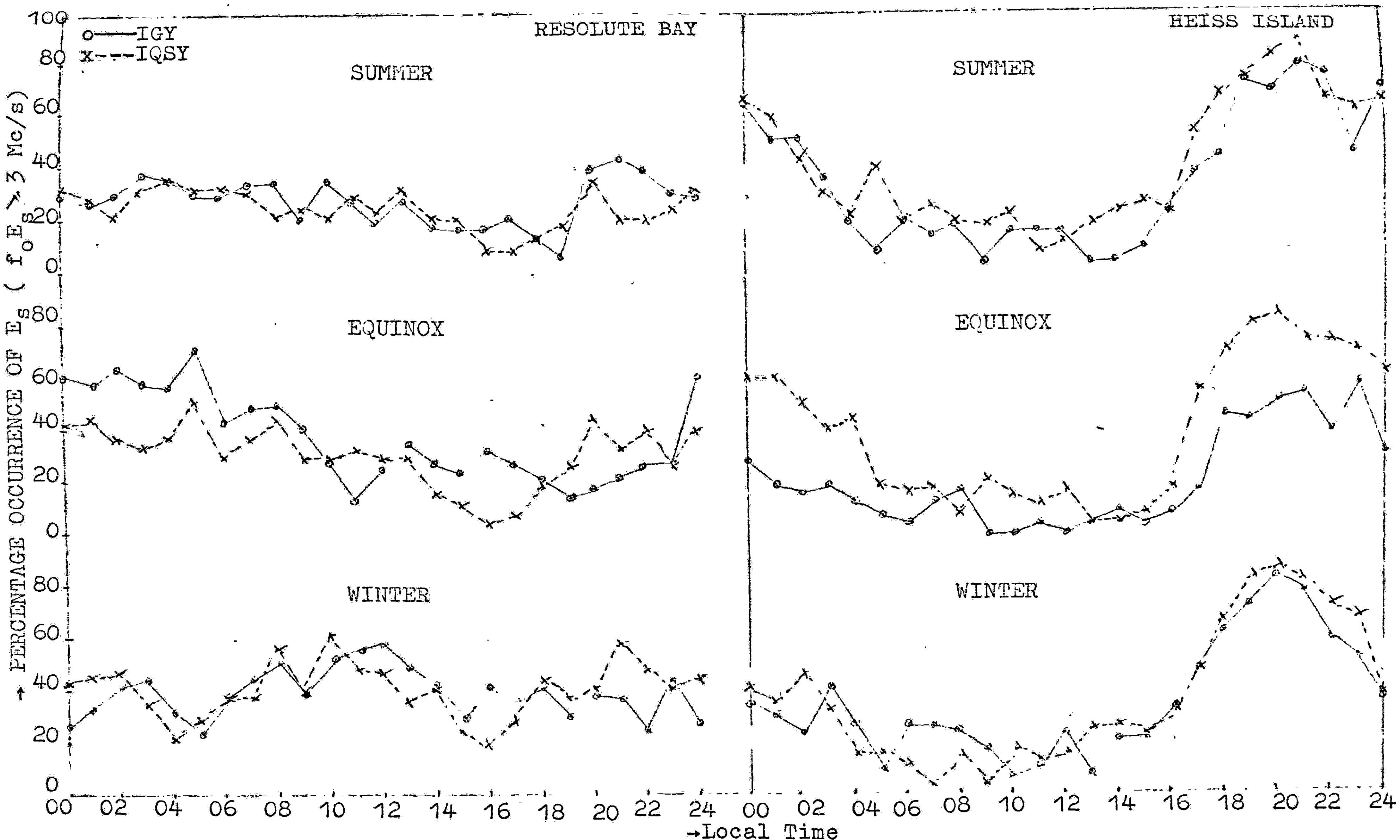


FIG.3.1: Diurnal variation of E_s on quiet days at Resolute Bay and Heiss Island.

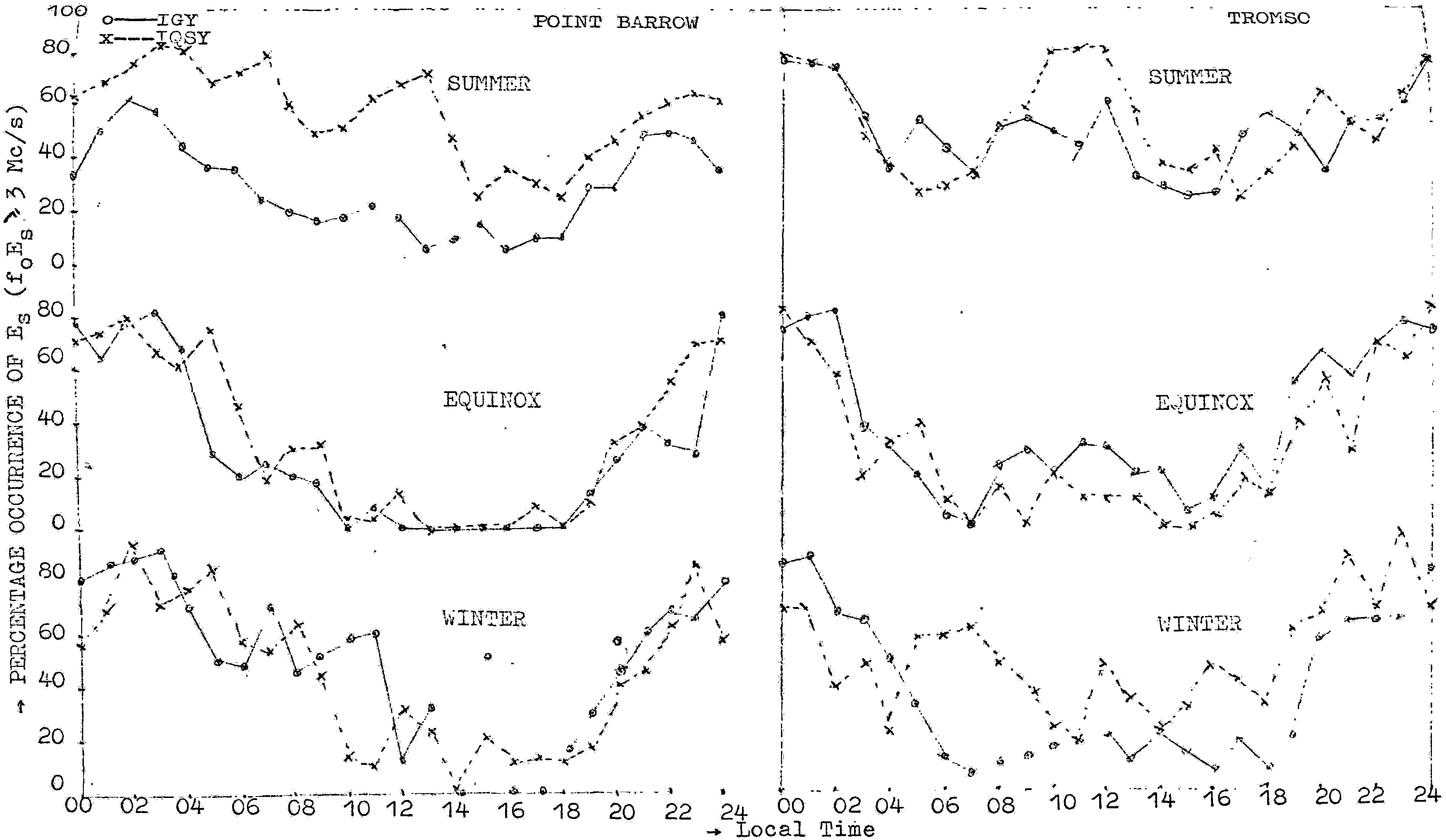


FIG.3.2: Diurnal variation of E_s on quiet days at Point Barrow and Tromso

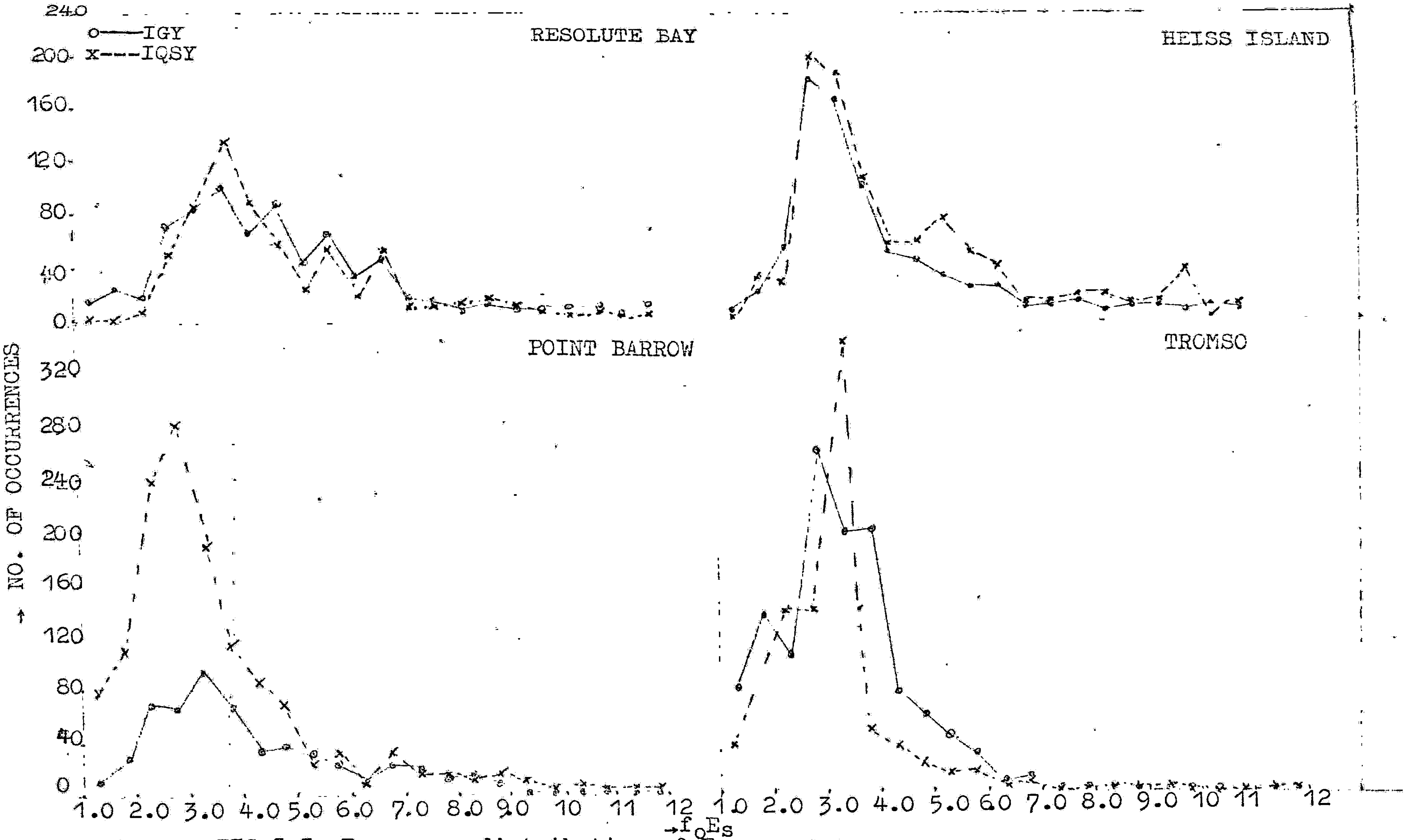


FIG.3.3: Frequency distribution of f_oE_s on quiet days.

but at a much reduced level relative to that in summer. During winter the diurnal variation does not show any apparent correlation. It will be noticed that in the frequency distribution (fig.3.3) the occurrences are very much more during sunspot minimum than during maximum years. However, the difference is barely detectable at the higher frequencies because of a paucity of data in this range.

At Tromsö the diurnal variation (fig.3.2) shows a negative correlation in winter for all hours of the day apart from the period 00-0400 hrs, between the occurrence of E_s and solar activity. This negative correlation occurs in summer during daytime hours only while in the equinoxes what correlation there is, is positive. It will be noted that the negative correlation in winter differs from the overall correlation which is positive, this is probably not physically significant since the raw data sample for IQSY is exceedingly small and thus the error in the points on the graph will be very large. Too much importance, therefore, is not attached to this negative relationship. Although Tromso is strictly an auroral station the frequency distribution of the occurrence of E_s (fig.3.3) is nevertheless typical of that of many temperate latitude stations. The number of occurrences are found to be greater after 3.5Mc/s during sunspot maximum years, while below this frequency the distribution tends to be reversed. This "Crossover" frequency above and below which the correlation with solar activity is positive and negative respectively varies only slightly between temperate latitude stations. Mitra and Das Gupta (1963) found an overall positive correlation with solar activity during noon. The only other station at higher latitudes considered by these authors was Point Barrow and this showed no correlation at noon for the occurrence of E_s ($f_oE_s > 5.0$ Mc/s).

At Providence Bay the diurnal variation of E_s occurrence (fig.3.4) shows no strong evidence for a solar activity dependence. During the period 07-1500 hrs in summer and winter the dependence is negative and positive respectively but at other periods there is no significant difference, apart from a negative one during the equinox night. The frequency distribution is similar to that at Tromso with a positive and negative correlation above and below 3.5 Mc/s (fig.3.6).

In contrast with all the stations which have been examined here, the diurnal variation at Uppsala is remarkable for not only exhibiting a consistently strong positive correlation for all hours of the day, but also for the seasonal consistency (fig 3.4). The strength of the solar dependence is surprising in that stations at only slightly different latitudes exhibit nothing like the same consistency of Uppsala. As might be expected, the frequency distribution also shows a very strong dependence, particularly at the high frequency end of the range, with a crossover frequency slightly lower than the two previous stations at 2.5 Mc/s (fig.3.6).

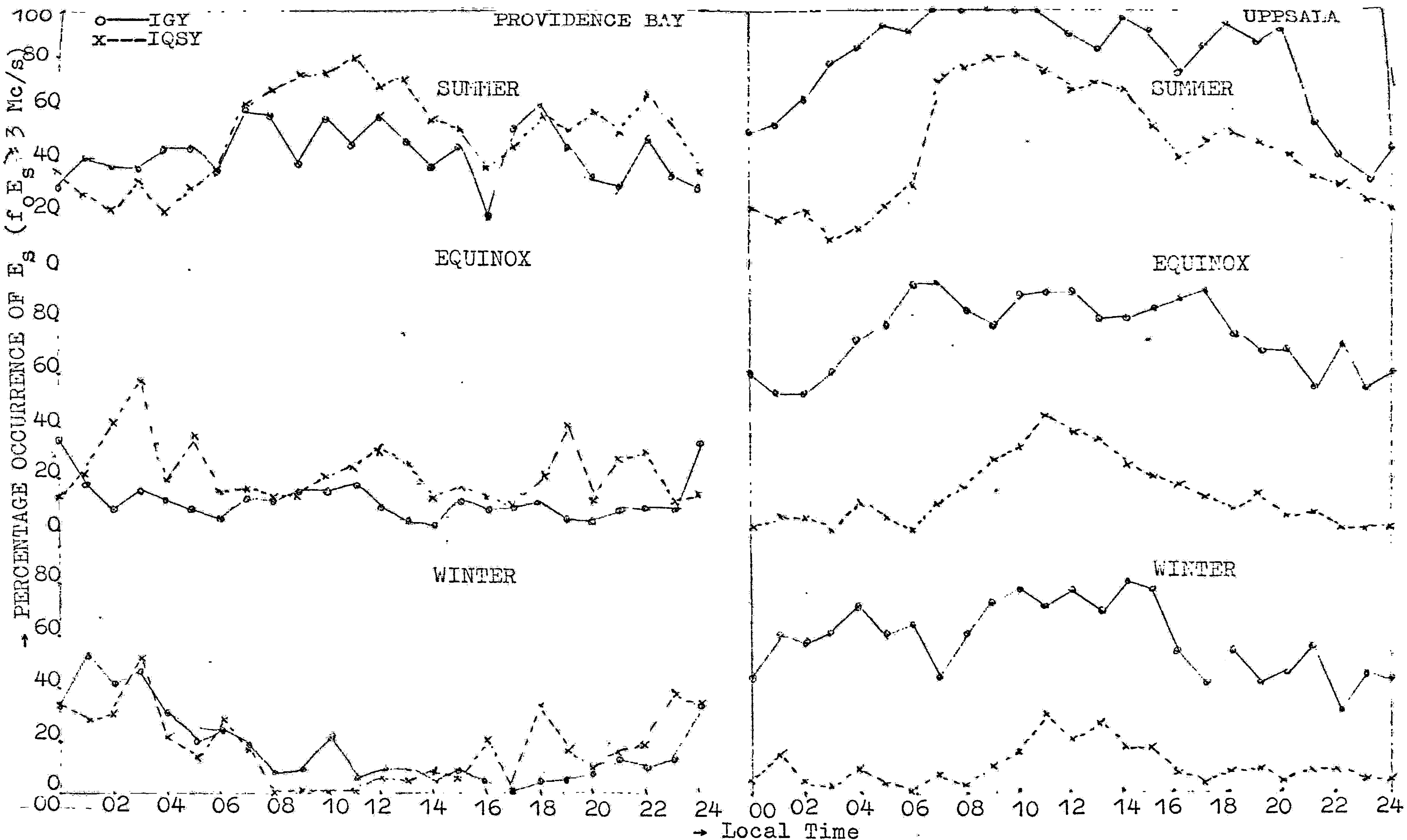


FIG.3.4: Diurnal variation of E_s on quiet days at Providence Bay and Uppsala

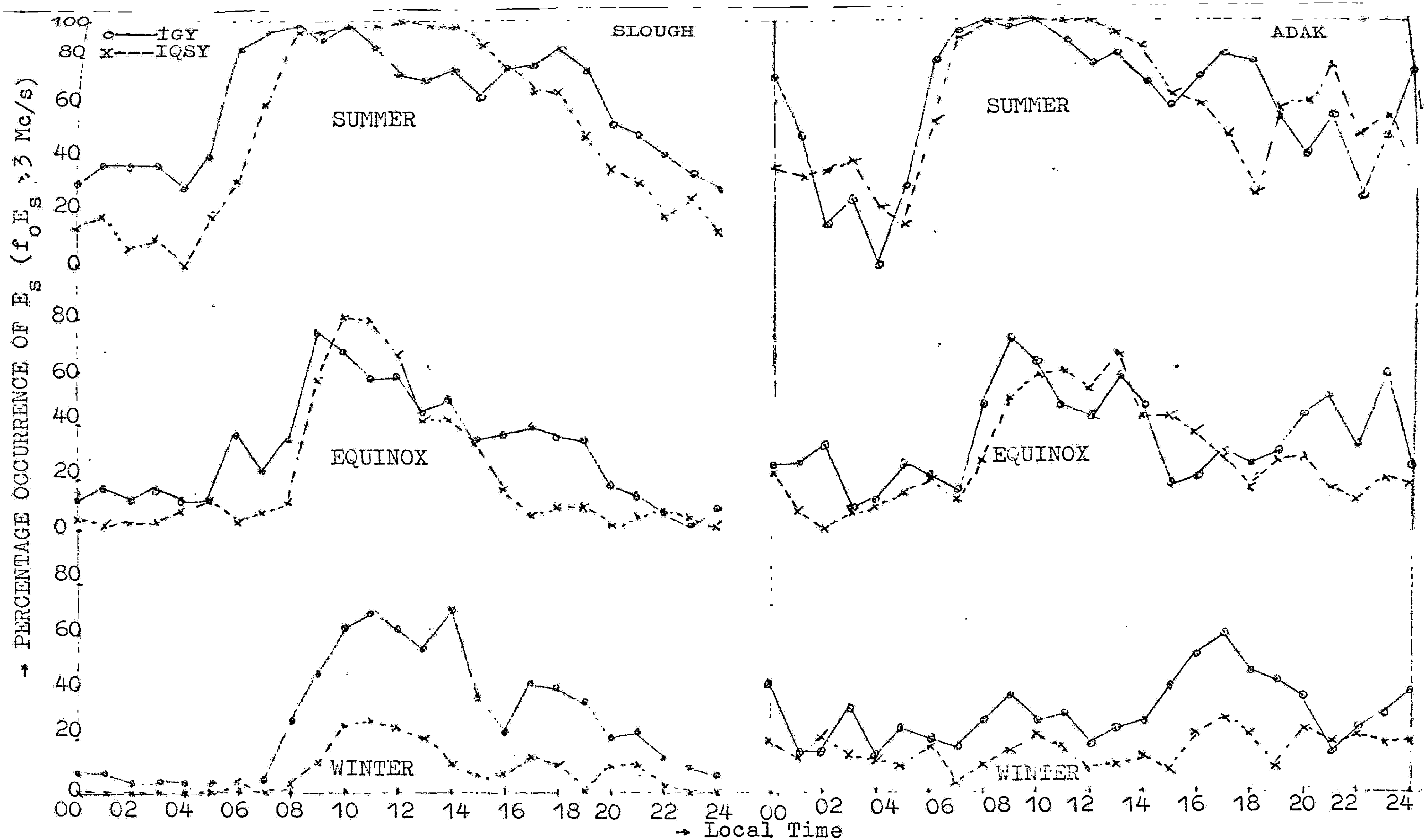


FIG.3.5: Diurnal variation of E_s on quiet days at Slough and Adak

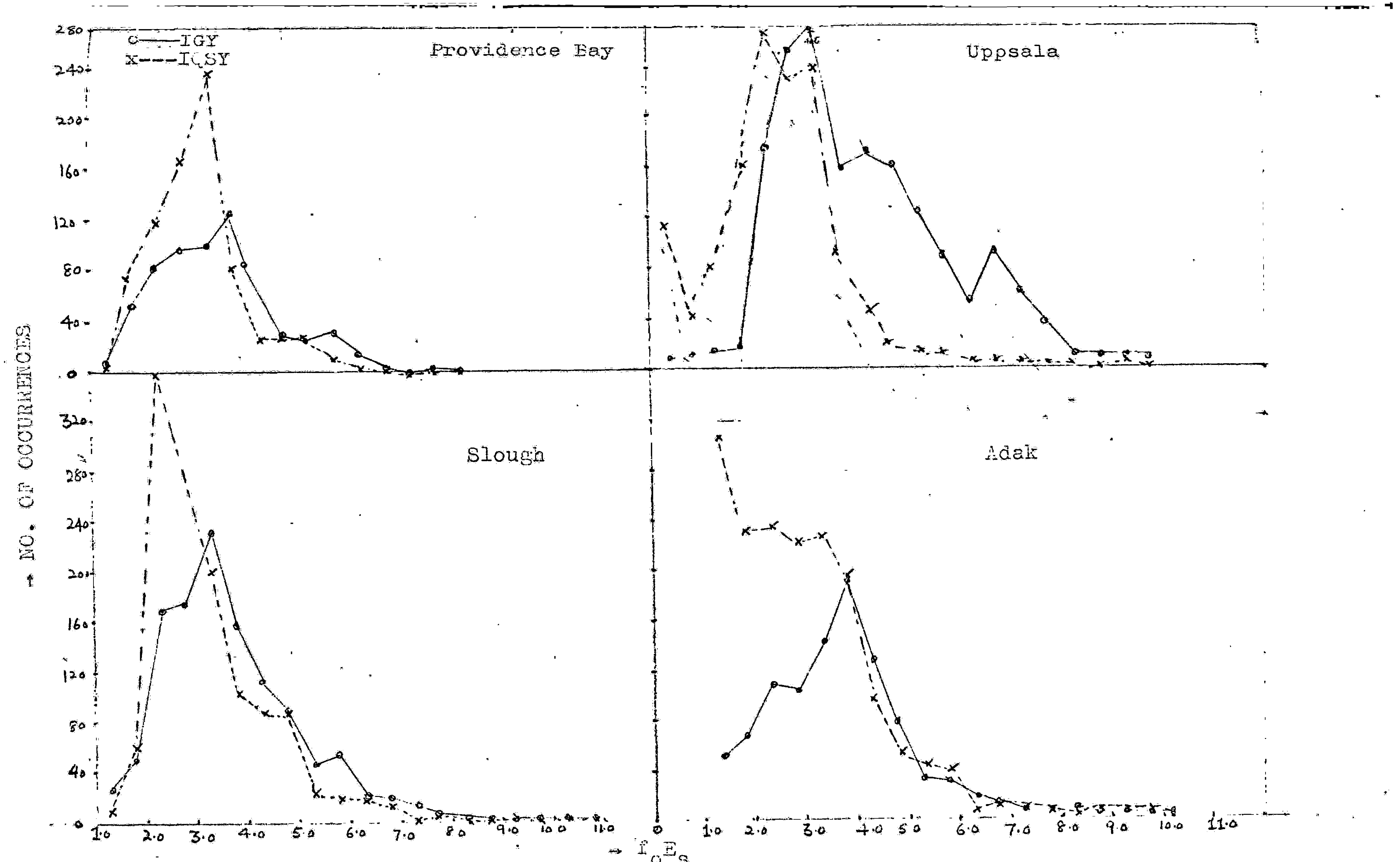


FIG.3.6: Frequency distribution of E_s on quiet days

At Slough a regular diurnal variation in the E_s occurrence (fig.3.5) has been found in all seasons for sunspot maximum and minimum years. In summer between 0800 and 1600 hrs and in the equinoxes between 0900 and 1300 hrs more E_s is found during sunspot minimum years. At all other times and during winter there is a positive dependence on solar activity. The frequency distribution at Slough (fig.3.6) is similar to that already described with a crossover frequency of 3.5 Mc/s for quiet and disturbed days.

At Adak, the relatively regular diurnal variation is found to be similar to that at Slough (fig.3.5). Again there is a daytime period between 0800 and 1500 hrs in summer and between 1000 and 1400 hrs in the equinoxes when a negative solar activity dependence exists but, in winter, the dependence is entirely positive. In the remaining period in summer and equinoxes the dependence tends to be positive but is rather variable.

The frequency distribution at Adak is normal and much as would be expected by comparison with other stations at similar latitudes (fig.3.6). During solar minimum conditions, however, the distribution below 3.0 Mc/s is anomalous and quite at variance with the other stations. At frequencies greater than 3.5Mc/s there is no significant difference between the solar maximum and solar minimum graphs. Below 3.5 Mc/s the distribution shows no sign of reaching a peak and keeps increasing towards the lowest frequency at which observations were made.

If the seasonal frequency distributions (fig.3.9) are examined though, very real changes are observed. The summer distribution is similar to what would be expected in that there is a maximum with a crossover frequency at 4.0 Mc/s. In the equinoxes the maximum has largely disappeared giving a plateau region while, in winter, a steady monotonic increase towards zero frequency is observed. It is more probable, therefore, that this anomalous resultant frequency distribution (fig.3.9) is a consequence of the equinox and winter values. If the threshold frequency for Adak, therefore, is low then a high negative correlation will be observed due to the dominating effect of the equinoxes and winter.

The diurnal variation at Akita (fig.3.7) shows more prolonged periods of negative correlation between the occurrence of E_s and solar activity than at Slough or Adak viz., summer between 0800 and 1700 hrs, equinoxes between 0700 and 1500 hrs and in winter between 0900 and 1400 hours. These periods correspond approximately to the changes in the time of sunrise and sunset between summer and winter. At other times of the day the correlation is predominantly positive. By analogy with the results found at Adak, Slough and Tromsö a cross-over frequency in the frequency distribution (fig.3.9) can be identified at 4.0 Mc/s for quiet and

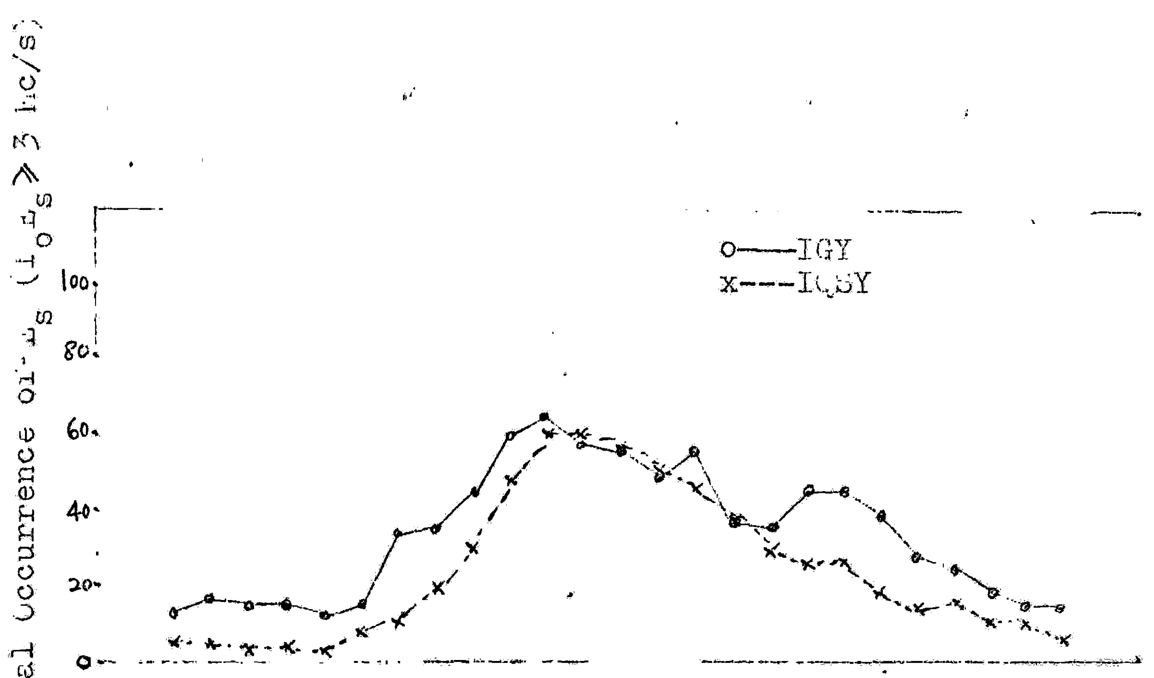


FIG.3.7(a): Diurnal variations on Quiet days at Slough

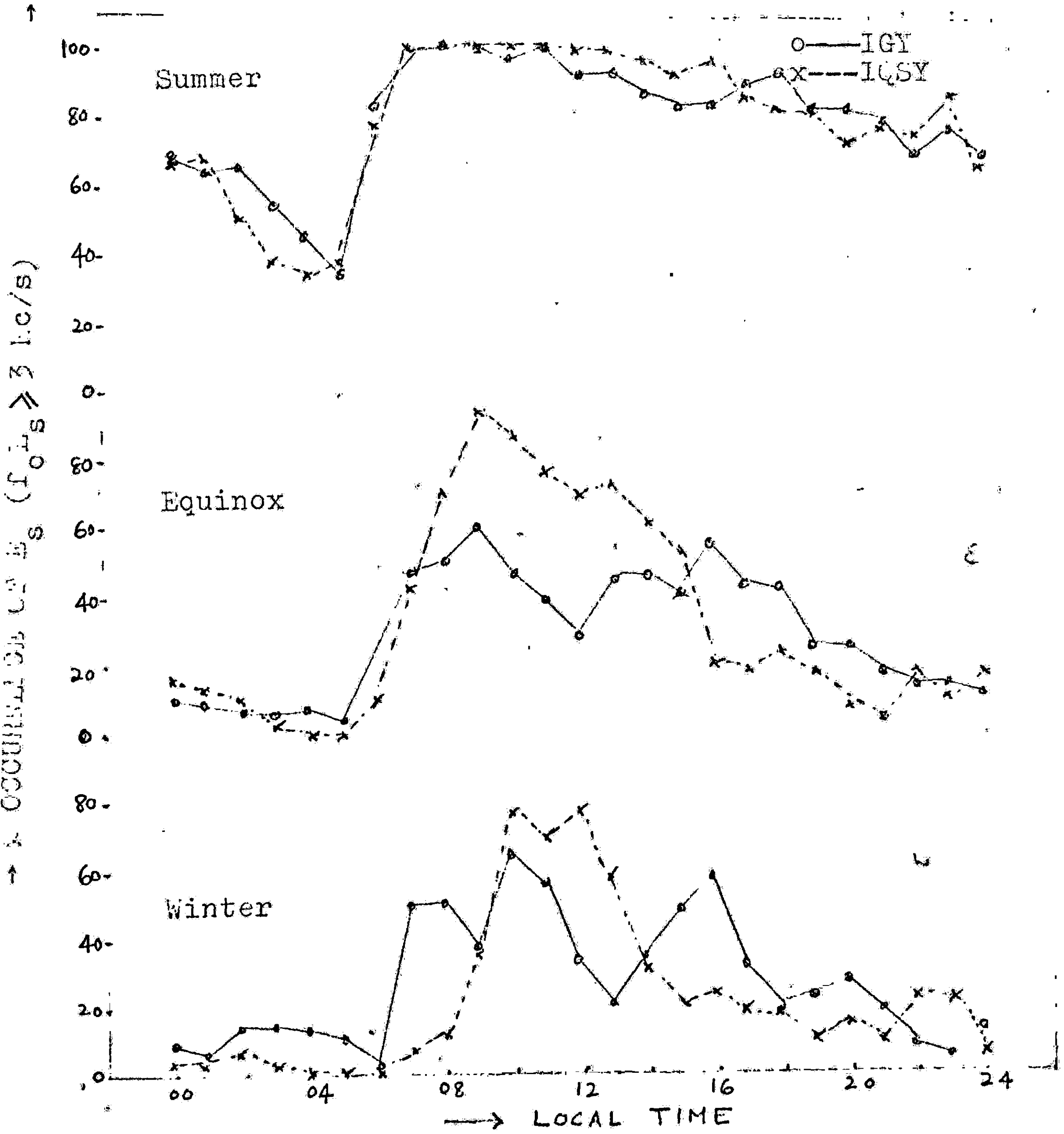


FIG.3.7: Diurnal Variations on Quiet days at Akita

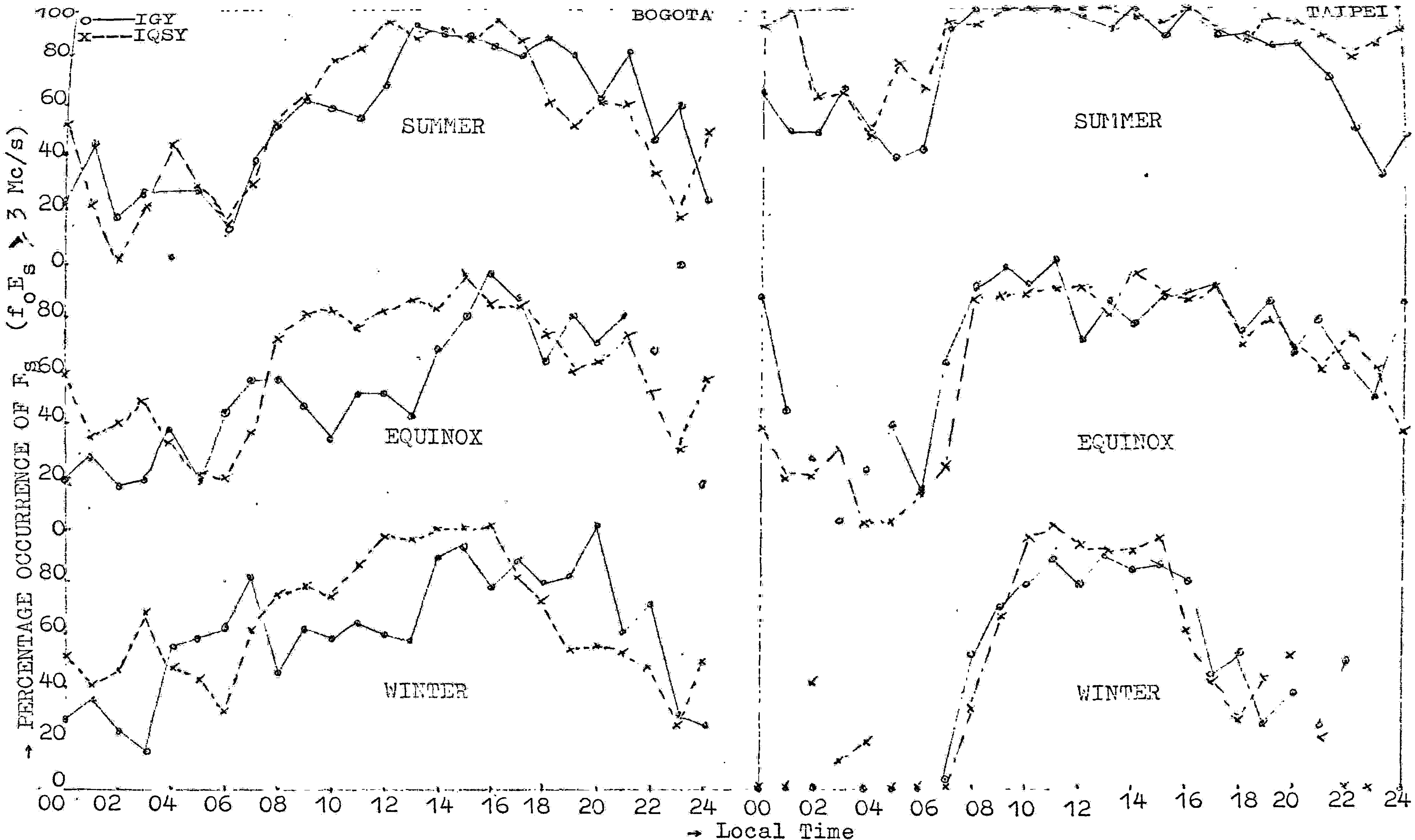


FIG.3.8: Diurnal variation of E_s on quiet days at Bogota and Taipei

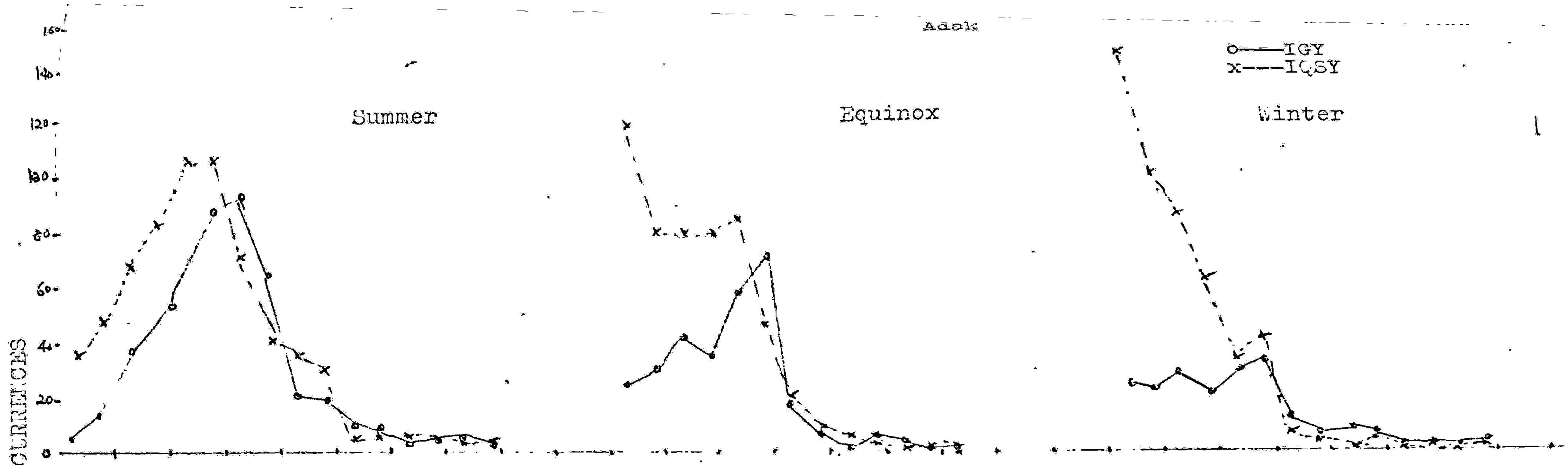


FIG.3.9: Frequency distributon on quiet days.

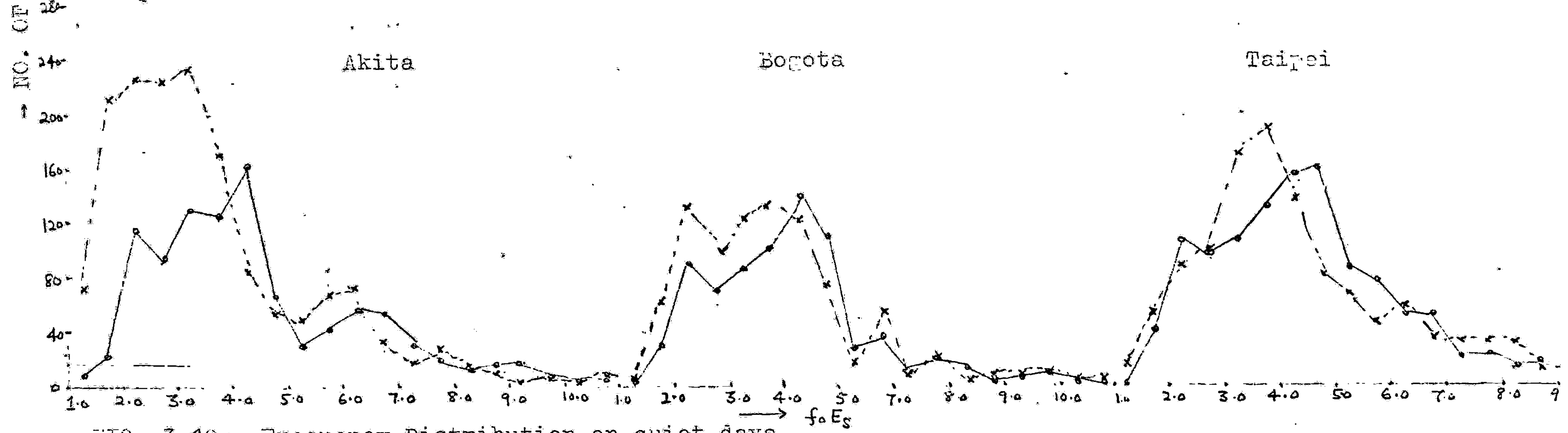


FIG. 3.10: Frequency Distribution on quiet days.

disturbed conditions, there being a strong negative correlation for frequencies less than this value. At greater frequencies any correlation is hidden by random fluctuations.

The fluctuations in the diurnal variation curves (fig.3.8) for Bogota largely conceal any possible relation between the occurrence of E_s and solar activity. A winter period between 0800 and 1700 hrs and, in the equinoxes, one between 0800 and 1500 hrs are the only occasions when a sustained relationship is apparent. At all other times no appreciable difference can be observed. The frequency distribution (fig.3.9) again indicates a crossover frequency of 4.0 Mc/s for quiet and disturbed conditions with a negative correlation between the occurrence of E_s and solar activity below this value. At higher frequencies there is no significant difference between solar maximum and minimum conditions in the occurrence of E_s.

Unlike other temperate latitude stations, Taipei shows more sporadic-E during the night hours of summer at solar minimum as compared to solar maximum conditions (fig.3.8). For other seasons there is no significant difference in the occurrence of E_s apart from a winter day-time period between 0900 and 1500 hrs when the occurrence is found to be more in sunspot minimum years. At Taipei, like other temperate latitude stations, the frequency distribution (fig.3.9) shows a negative correlation between the occurrence of

E_s and sunspot activity below 4.0 Mc/s and a positive one between 4.0 and 6.0 Mc/s.

A negative correlation between the occurrence of sporadic-E and solar activity has been found at the high latitude stations of Heiss Island and Point Barrow and no significant correlation at Providence Bay and at Adak. However, this negative correlation has not been found at Resolute Bay, Uppsala, Tromsö or Slough in the present analysis since, on the contrary, a positive correlation is observed. As the discussion in the previous chapter has indicated, there was a relative increase in the occurrence of E_s from sunspot maximum to minimum years for all the stations in the eastern zone as compared to those in the western zone. It is suggested that the opposite modes of behaviour are due to a change in the position of the north dip-pole from sunspot maximum to minimum years towards the northwest. Thus this negative correlation at Heiss Island and Point Barrow and the zero correlation at Providence Bay and Adak between the occurrence of E_s and solar activity at these eastern stations might reasonably have been expected.

In this analysis the occurrence of sporadic-E has been examined during 1957-58 (sunspot maxima) and 1964-65 (sunspot minima) from f_oE_s data and a negative correlation between the occurrence of sporadic-E and solar activity has been found at lower frequencies at all temperate latitudes. This agrees with the analysis of Reddy and Matsushita (1968) who examined f_bE_s data from 1958 to 1965 in a different manner for temperate latitudes and for which an explanation has been offered. The negative correlation at lower frequencies arises from small windshears, e.g. $\frac{dU}{dZ}$ = 5m/sec/km which can produce detectable E_s when ambient E-region ionization (n_o) is small and with $\frac{n_m}{n_o} > \left(\frac{n_m}{n_o}\right)_{min}$ during low sunspot activity, but cannot produce detectable E_s during high sunspot activity when $\frac{n_m}{n_o} < \left(\frac{n_m}{n_o}\right)_{min}$ and n_o is larger. Therefore, even if the smaller windshears have no appreciable solar cycle variation, the smaller f_oE_s values resulting from these small shears will show a marked negative variation with solar activity.

3.3 Equatorial stations

At Kodaikanal, which is an equatorial station, there is a small but significant change in the diurnal variation of E_s occurrence between solar maximum and minimum conditions (fig.3.11). In all seasons there is an increase in occurrence during the late afternoon for solar maximum conditions. This is not accompanied by a corresponding early morning change when no appreciable difference is observed. During the night-time hours the incidence is very slight for all solar conditions and little can be said about this period. The frequency distribution for Kodaikanal has been plotted in terms of one rather than half Mc/s intervals on account of the irregular distribution (fig.3.12). The result is

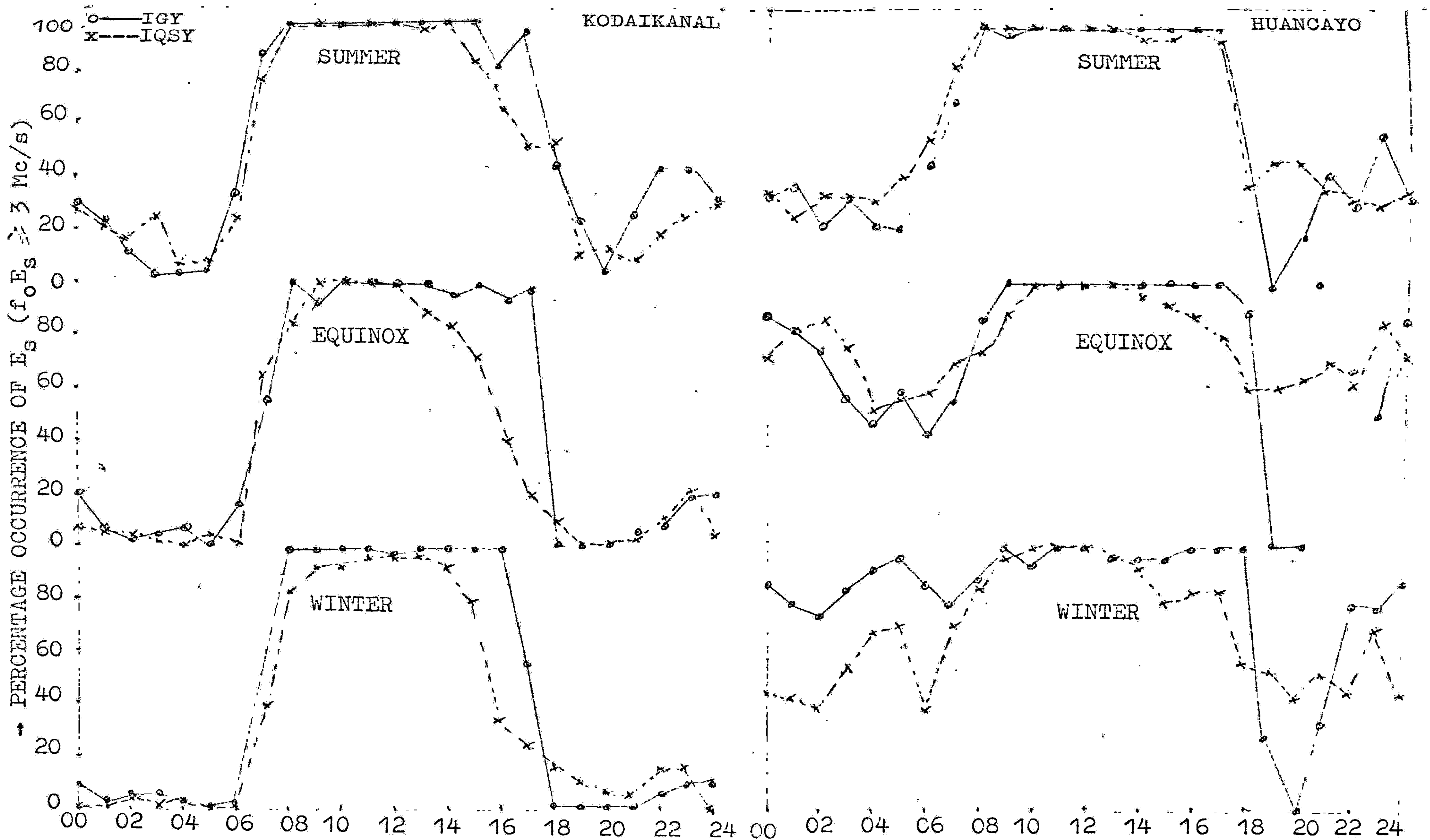


FIG.3.11: Diurnal variation of E_s on quiet days at Kodaikanal and Huancayo

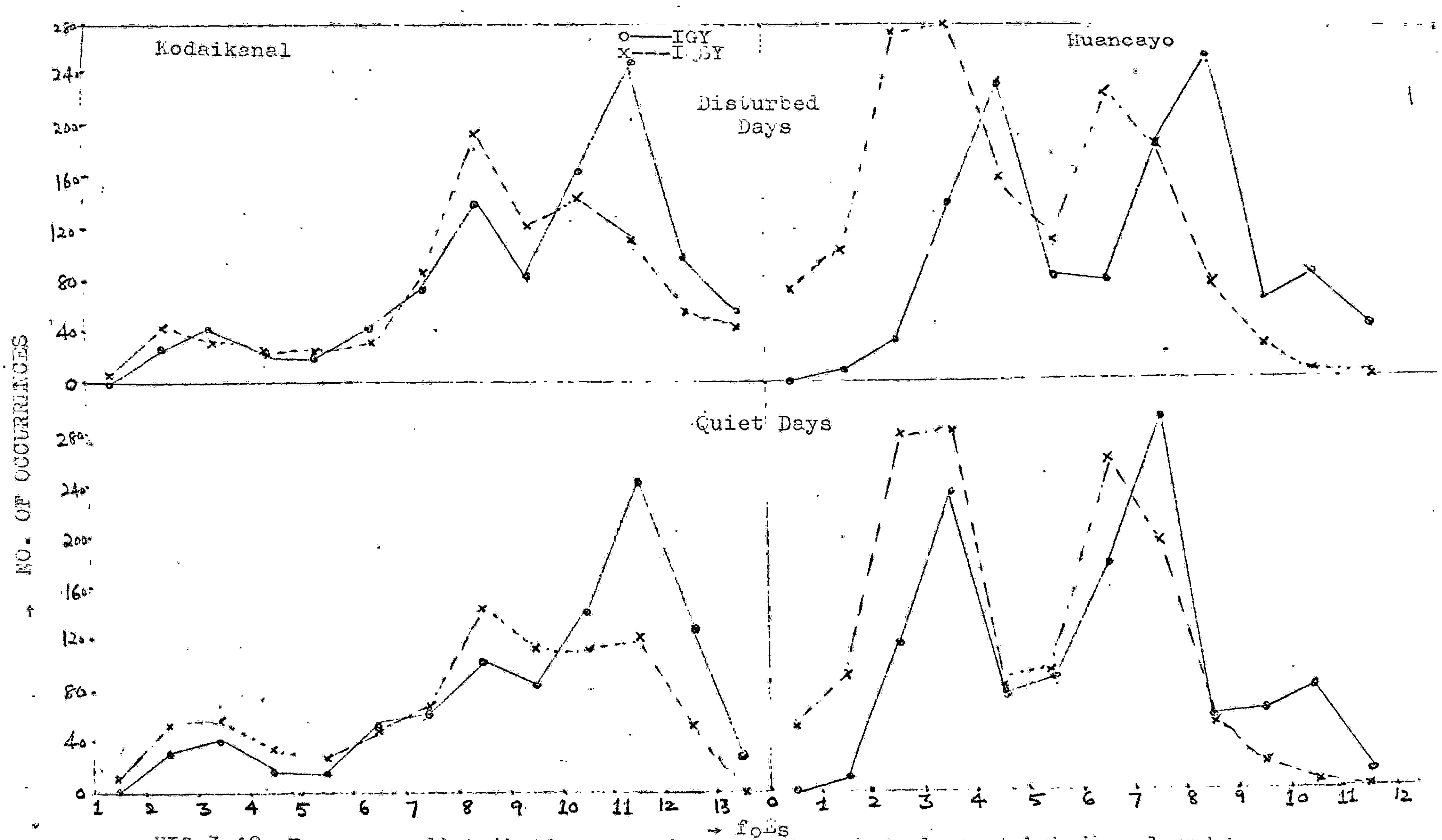


FIG.3.12 Frequency distribution on quiet and disturbed days at Kodaikanal and Huancayo

very different from that at any other latitude in that there is a tendency for a bimodal distribution to be present with a small peak at about 3Mc/s and a larger and broader peak in the range 9.0 to 12.0 Mc/s. The two peaks are a consequence of the data covering a twenty-four hour period, since, as has been shown (Saksena, 1965), the 3Mc/s peak is a night event while the large high frequency peak relates to the day-time period. It should be pointed out also that this large change in behaviour from day to night does not occur at other latitudes and the frequency distributions for the temperate and auroral stations considered earlier in this chapter, which also cover twenty-four hour periods, are not misleading in the sense that Kodaikanal might be. When total occurrences greater than 3.0Mc/s are considered it is not immediately obvious from the distribution whether there is any correlation with solar activity and this is reflected in the fact that there is only a small difference in the diurnal curve for IGY and IQSY.

The results at the other equatorial station Huancayo are qualitatively very similar to those at Kodaikanal. The late afternoon increase and no early morning change in IGY is again observed but the night-time incidence is, however, very much greater than at Kodaikanal (fig.3.11). The frequency distribution has a much more pronounced bimodal form than that at Kodaikanal with the low frequency, 3 to 4 Mc/s peak, again relating to night-time (fig.3.12).

The frequency distribution does, nevertheless, show a decrease in the most probable frequency with decreasing solar activity. The most striking feature is the reduction in the most probable frequency for both high and low frequency modes from maximum to minimum solar activity. This indicates a clear dependence of the day and night modes on solar activity. What is also noticeable is the close similarity between the distributions for quiet and disturbed days in IGY and again for IQSY. The two sets of data for quiet and disturbed days are completely independent of each other and hence the close agreement between the two distributions for two solar conditions indicates that a valid physical interpretation can be placed on the results.

3.4 Seasonal Variations

The frequency distribution for summer and winter has been compared during IGY and IQSY for four temperate latitude stations. In winter E_s is found to be more frequent than in summer in the lower frequency range at Slough and Adak (fig.3.13) during both IGY and IQSY. Over the same frequency range at Akita and Taipei, which are typically representative of low latitude temperate stations, E_s is more frequent during the IQSY only (fig.3.13). At the higher frequencies, however, the incidence of E_s is greater in summer relative to winter for all the cases considered. Matsushita and Reddy (1967) have suggested that there

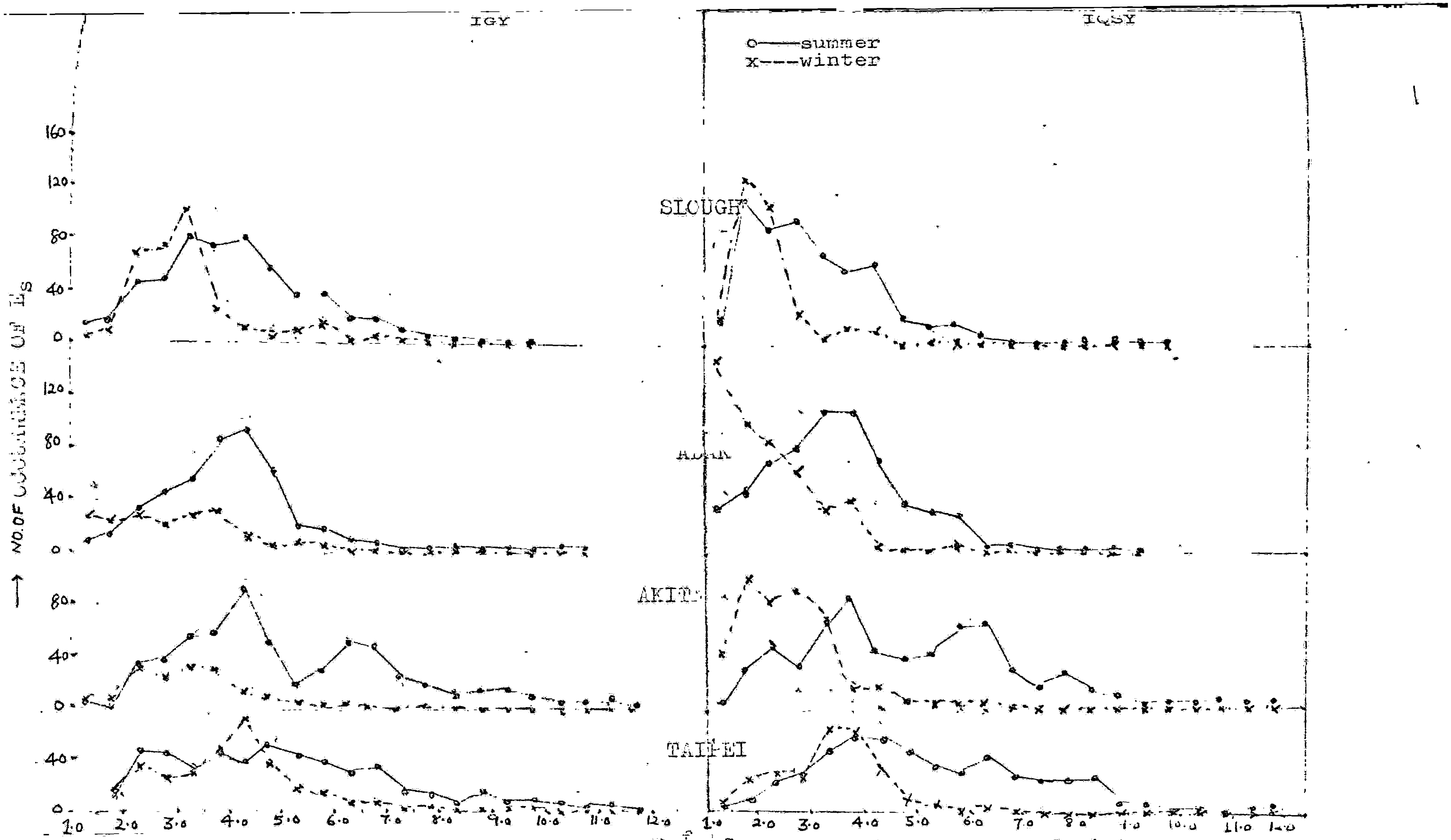


FIG.3.13: Frequency distribution of E_s on f_oE_s Quiet days during summer and winter

is a dependence of the maximum ionization in E_s layers on the maximum background ionization in the E region. Reddy and Matsushita (1968) also suggested that the negative correlation with solar activity, which occurred at low frequencies, arises from small windshears which can produce detectable E_s when n_o, the ambient ionization, is small i.e. in low solar activity, but cannot produce detectable E_s when n_o is larger during high solar activity. This has been confirmed in the present study using f_oE_s data by computing the frequency distribution of E_s for IGY and IQSY. Since the ambient ionization is smaller in winter than in summer, the small windshears ($U' \approx 5$ m/sec/km) can produce detectable E_s in winter but the same value of windshear will not be able to produce detectable E_s in summer when n_o is larger. Thus the sporadic-E in the lower frequency range at these stations should be more in winter than in summer. At the higher temperate latitude of Slough and Adak, such a distribution has been obtained for both high and low solar activity whereas, at the lower temperate latitudes, Akita and Taipei, this distribution is only observed in low solar activity. During high solar activity at Akita and Taipei the ambient ionization in winter is apparently not small enough, as compared to its summer value, to produce detectable E_s. Hence there is little difference in the incidence of E_s between winter and summer in the low frequency range at these stations.

From tables 2.3 and 2.4 it will be noticed that higher windshears occur in summer than in winter for both stations. Thus the more frequent occurrence of high frequency E_s in summer follows directly from this. This effect has been found for all the stations considered here i.e. Slough, Adak, Akita and Taipei.

Additionally, of course, the ambient E-region electron density is greater in summer than in winter and this factor by itself will result in the most probable frequency being increased from winter to summer.

3.5 Latitudinal Variation

The solar activity dependence of E_s as a function of latitude has also been examined by using the frequency distributions which have already been derived. From such a distribution the most probable value of f_oE_s can be measured and these have been plotted as a function of latitude in fig.3.14 for IGY and IQSY. The error bars relate to that frequency spread which has an occurrence probability of 80% of the most probable frequency.

The southern hemisphere values during IGY are based on data given by Saksena (1964) and also relate to a twenty-four hour period. Fig.3.14 shows that the most probable value decreases from the equator, where the values are anomalously high, due to the electrojet during the day time, through a plateau-like region in the low temperate latitudes to a trough in

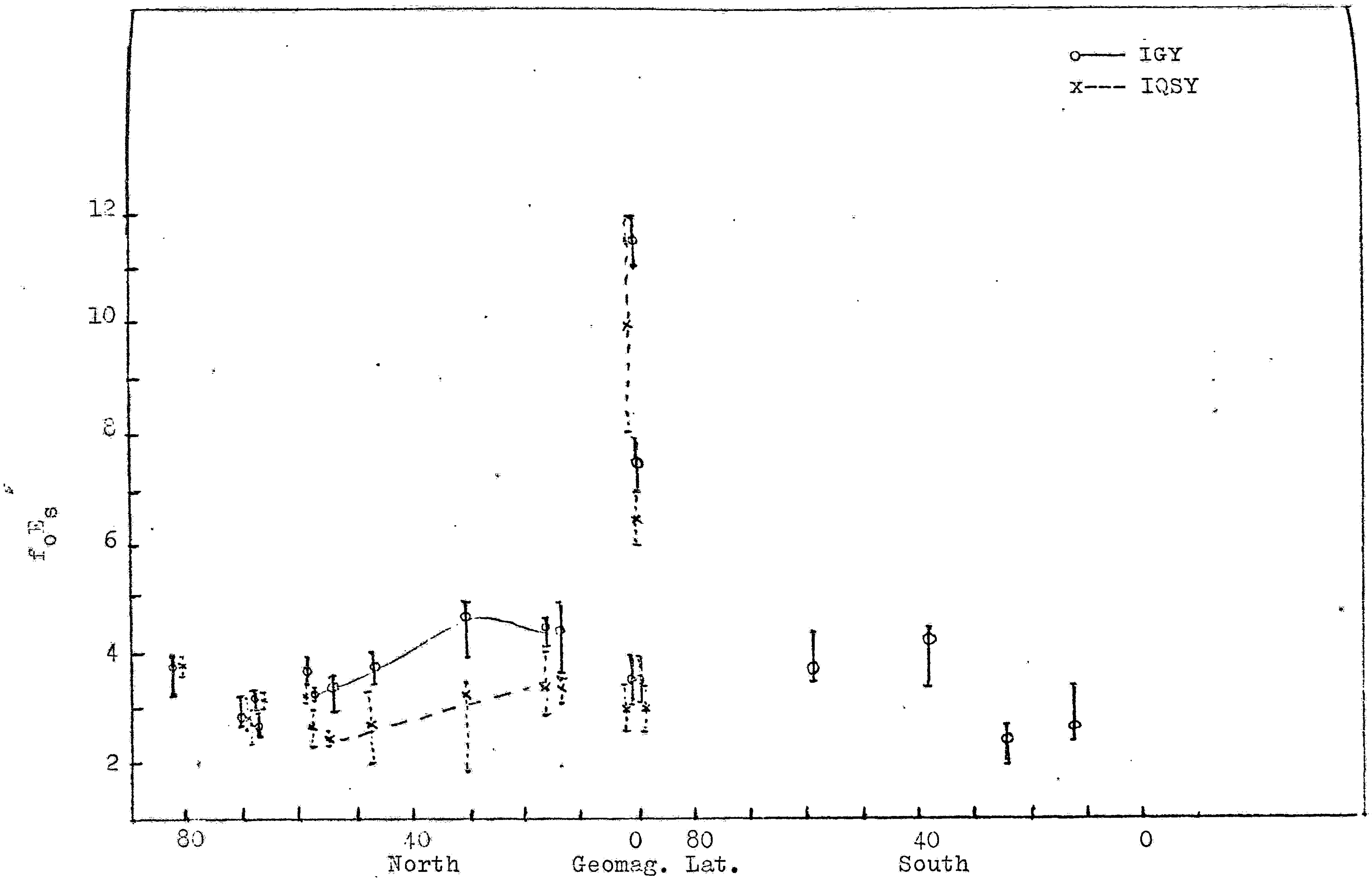


FIG.3.14: Latitudinal variation of most probable frequency

the auroral zone and then increases again towards the polar cap in IGY. In IQSY the general features remain the same except that the high latitude trough appears to be displaced by a few degrees towards the equator. While the auroral zone proper moves polewards, it is not characterized by any unusual most probable value. Thus, since all the E_s between there and the equator is primarily of the windshear type and it is known that both windshear and f_oE decrease from IGY to IQSY, this together with the lack of change in the most probable value of f_oE_s in the polar and auroral region makes such a movement of the trough quite feasible.

It is clear that there is a distinct increase in the most probable value over the range of latitudes from equator to at least 60° North between IQSY and IGY. This positive dependence on solar activity is far more distinct than that found by using occurrence values. The magnitude of the change, about 1.0 Mc/s, is in fact very similar to that observed in noon f_oE values. This positive correlation has been suggested in a different way by other workers, Das Gupta and Mitra (1962), Mitra and Das Gupta (1963) using occurrence probabilities and Reddy and Matsushita (1968) using both occurrence probabilities and average frequency.

These approaches, including that in the present work, suffer from the disadvantage that if the data sample tends to become small the results will be unreliable. With the most probable frequency, though, even a small data sample allows this quantity to be determined with reasonable accuracy. Apart from the equatorial stations there is a small reduction in the most probable frequency from day to night at all other stations.

The points in fig.3.14 thus refer to data over a twenty-four hour period. The equatorial values, however, have been separated into day and night-time ones on account of the exceedingly large change. This large change, of course, is responsible for the bimodal distributions for Huancayo and Kodaikanal shown in fig. 3.12.

The latitudinal variation in the noon occurrence of E_s for $f_oE_s \geqslant 3$ Mc/s and 5 Mc/s is shown in fig.3.15 for IGY and IQSY. The results for the equinoxes are given since summer and winter show no noticeable difference in behaviour. It is immediately obvious that in temperate latitudes a negative correlation with solar activity exists for $f_oE_s \geqslant 3$ Mc/s whereas there is a positive correlation for $f_oE_s \geqslant 5$ Mc/s.

This change from a positive to negative dependence is misleading for it is not a physically meaningful result. Some idea as to how this situation arises is given by the following examples.

Fig.3.16 shows two frequency distributions on quiet days for IGY and IQSY as being representative

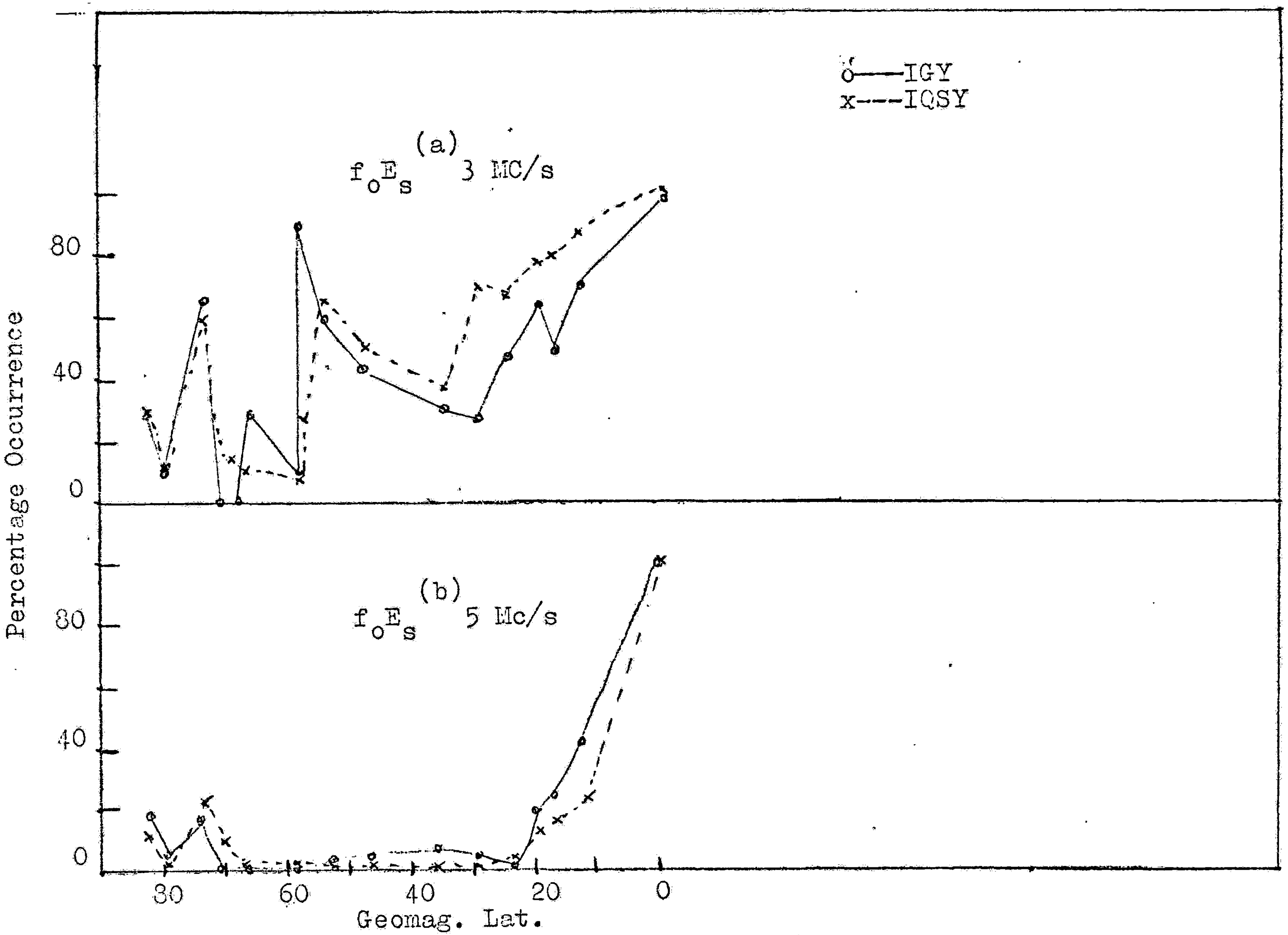


FIG.3.15: Latitudinal variation in the percentage occurrence of E_s at noon.

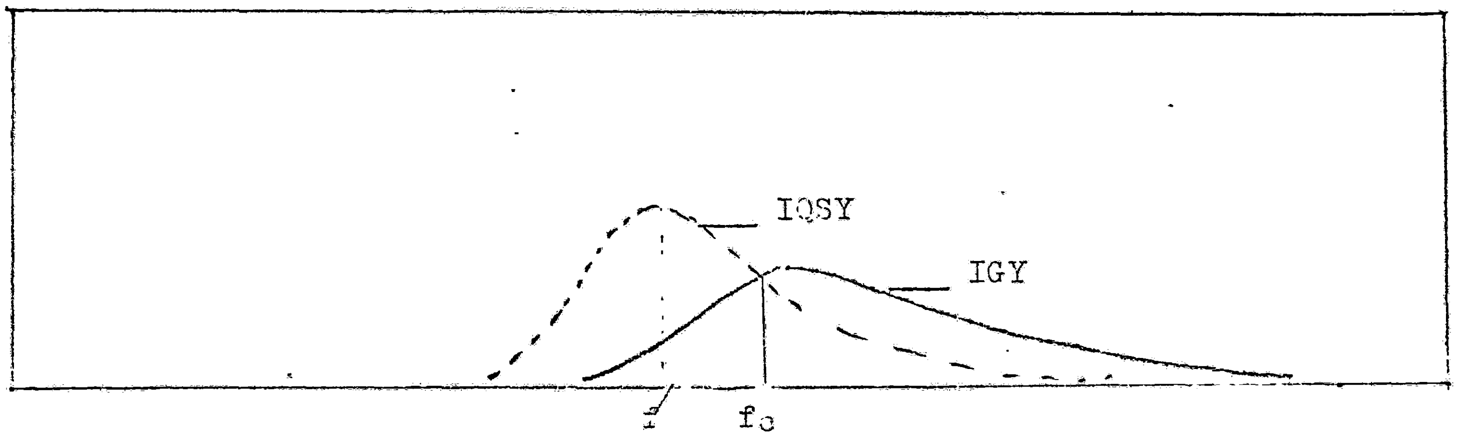


Fig.3.16: Frequency distribution for IGY and IQSY

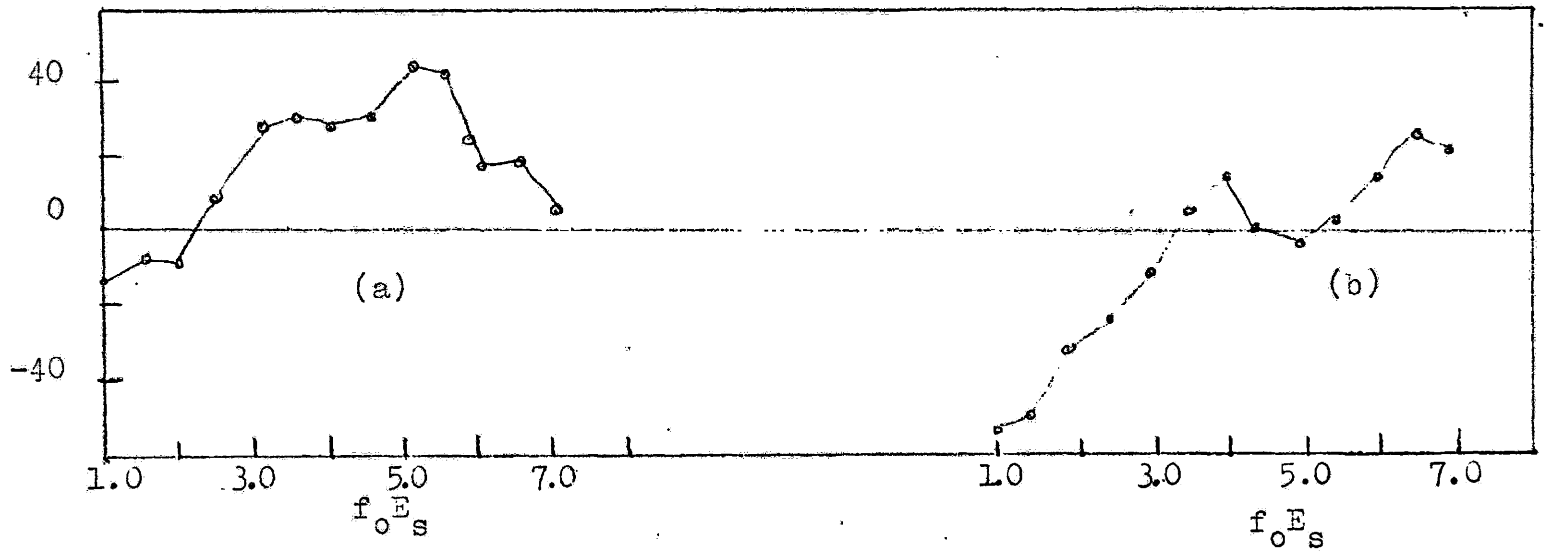


Fig.3.17: Variation of with frequency

of typical temperate latitude stations. It is clear that if the occurrence probability for all frequencies greater than a certain frequency value is the parameter being used, then for all frequencies greater than f_c there will be a greater occurrence probability for IGY than IQSY. This is simply because the occurrence probability is the area under the curve. For a frequency slightly less than f_c the dependence on solar activity will still be positive but less than for frequencies slightly greater than f_c. Clearly also, as the frequency is further reduced, so also will the dependence be reduced until a frequency f' will be reached where there is no dependence i.e. the areas under the two curves are equal. For frequencies less than f' the area under the IQSY curve will be greater than that under the IGY curve and thus a negative dependence will exist.

The difference between occurrence probabilities in IGY and IQSY has been calculated for a number of different frequencies and normalized to the IGY occurrence i.e.

$$\Delta = \frac{(\text{No. of occurrence in IGY} - \text{No. of occurrence in IQSY}) > f}{(\text{No. of occurrence in IGY}) > f} \times 100\%$$

Fig. 3.14(a) shows Δ for Slough on quiet days and the change from negative to positive dependence is readily apparent. The actual frequency distributions to which this graph refers are shown in fig. 3.6. Reference to fig.3.7(a) for the annual diurnal curve shows a fairly consistent positive relationship for frequencies greater than 3 Mc/s. This is in agreement with fig. 3.17(a). Figs 3.7(a) and 3.17(a) both refer to twenty-four hour periods whereas fig.3.15(a) refers to the noon period and at $f_oE_s > 3$ Mc/s a negative relationship is observed in fig.3.5 in summer and equinoxes. If fig.3.17 had been plotted for the noon period it would have been displaced to the right on account of the most probable frequency being higher and Δ at 3Mc/s would have been slightly negative. This would then be in agreement with the results of fig. 3.15(a). In fig. 3.15(b) for $f_oE_s \geqslant 5$ Mc/s there is a positive relationship as indicated by fig.3.17(a). A second example in fig.3.17(b) shows Δ for quiet days at Akita again for a twenty-four hour period. The minimum in the curve at 5 Mc/s is due to the rather irregular decrease in the high frequency range of the distribution curve (fig.3.10). The cross-over frequency f' is higher than at Slough since Akita is at a lower latitude. Comparison with figs 3.15(a) and 3.15(b) for $f_oE_s \geqslant 3$ Mc/s and $\geqslant 5$ Mc/s shows that the relationship is negative and positive respectively. If allowance is made for a small horizontal shift of the curve 2b to relate to the noon period, the above observations are seen to agree.

Thus the sign of the dependence of the occurrence probability on solar activity with frequency can be fairly simply explained in terms of a decrease in the most probable value i.e. a sideways shift of the frequency distribution curve. Since f_oE_s is closely related to f_bE_s, which is in turn closely related to f_oE the solar activity dependence of E_s in temperate latitudes can be qualitatively accounted for.

One factor which is necessary for the above explanation to hold is that the number of occurrences of the most probable frequency (f_m) shall increase as f_m decreases with solar activity.

CHAPTER 4

THE OCCURRENCE OF SPORADIC-E ON QUIET AND DISTURBED DAYS

4.1 Introduction

Appleton et al (1937) first studied E_s in the auroral zone and found a positive correlation between auroral sporadic-E and magnetic activity. Smith (1957) also found a positive correlation at an auroral station but a negative one in high temperate latitudes between the occurrence of E_s and magnetic activity in the Northern hemisphere. A similar result for the southern hemisphere was observed by Saksena (1964) together with a negative correlation in the southern polar cap. Thomas (1962) showed that there was a positive correlation between the occurrence of E_s and magnetic activity at various northern hemisphere auroral stations and a negative correlation at the polar station with a different approach.

Positive correlations in the low temperate latitude zone have been claimed by Singh (1963) for one station and Yien-Nien (1965) for a number of stations. It is thus of some interest to study the occurrence of sporadic-E during sunspot maximum and sunspot minimum years in order to find the difference between the two for quiet and disturbed days.

A number of stations from the pole to the equator, especially those stations near the upper and lower boundaries of the northern auroral zone, have been studied. The result of this work gave rise to the idea of a possible movement of the auroral zone from sunspot maximum to sunspot minimum years and that the apparent correlation between the occurrence of E_s and magnetic activity at low temperate latitudes depends on different conditions such as solar activity, the season and the type of E_s. For this work a number of stations additional to those in Chapter 2 have been used.

4.2 The Diurnal and Seasonal variation of the occurrence of sporadic-E on quiet and disturbed days.

The diurnal variations have been drawn in figs 4.1 - 4.14 for the percentage occurrence of E_s ($f_oE_s \geqslant 3$ Mc/s). At Resolute Bay (fig.4.1) the percentage occurrence of E_s in IGY is generally greater on quiet as compared to disturbed days for most hours of the day in all seasons, apart for a period between 0600 and 1800 hrs in summer where the situation reverses. During sunspot minimum years the percentage occurrence of E_s is again found to be more on quiet than disturbed days in all seasons and for all hours of the day with only a minor exception during summer midday.

Fletcher's Ice Island (fig.4.2) during the IGY shows a strong negative dependence of the

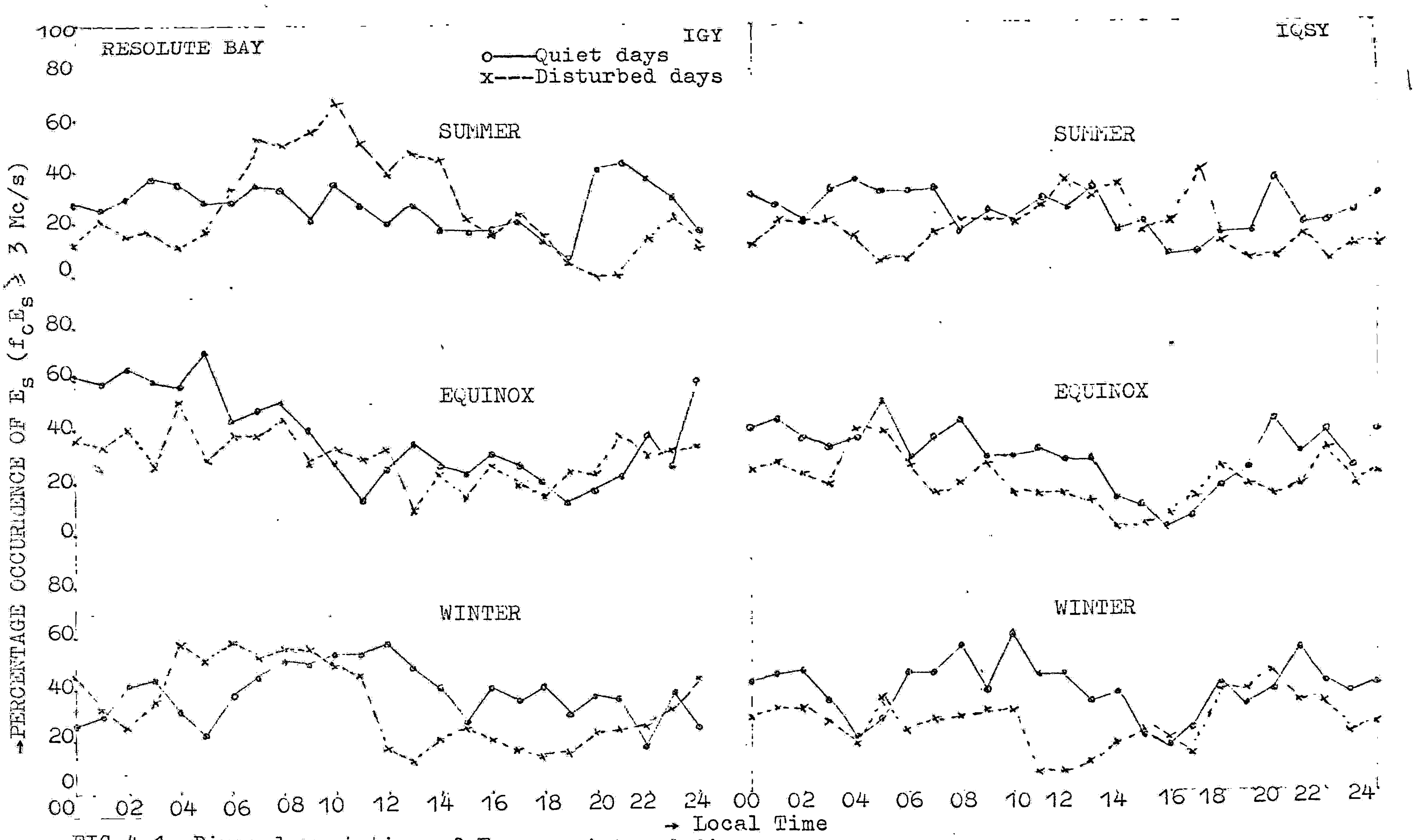


FIG 4.1: Diurnal variation of E_s on quiet and disturbed days at Resolute Bay

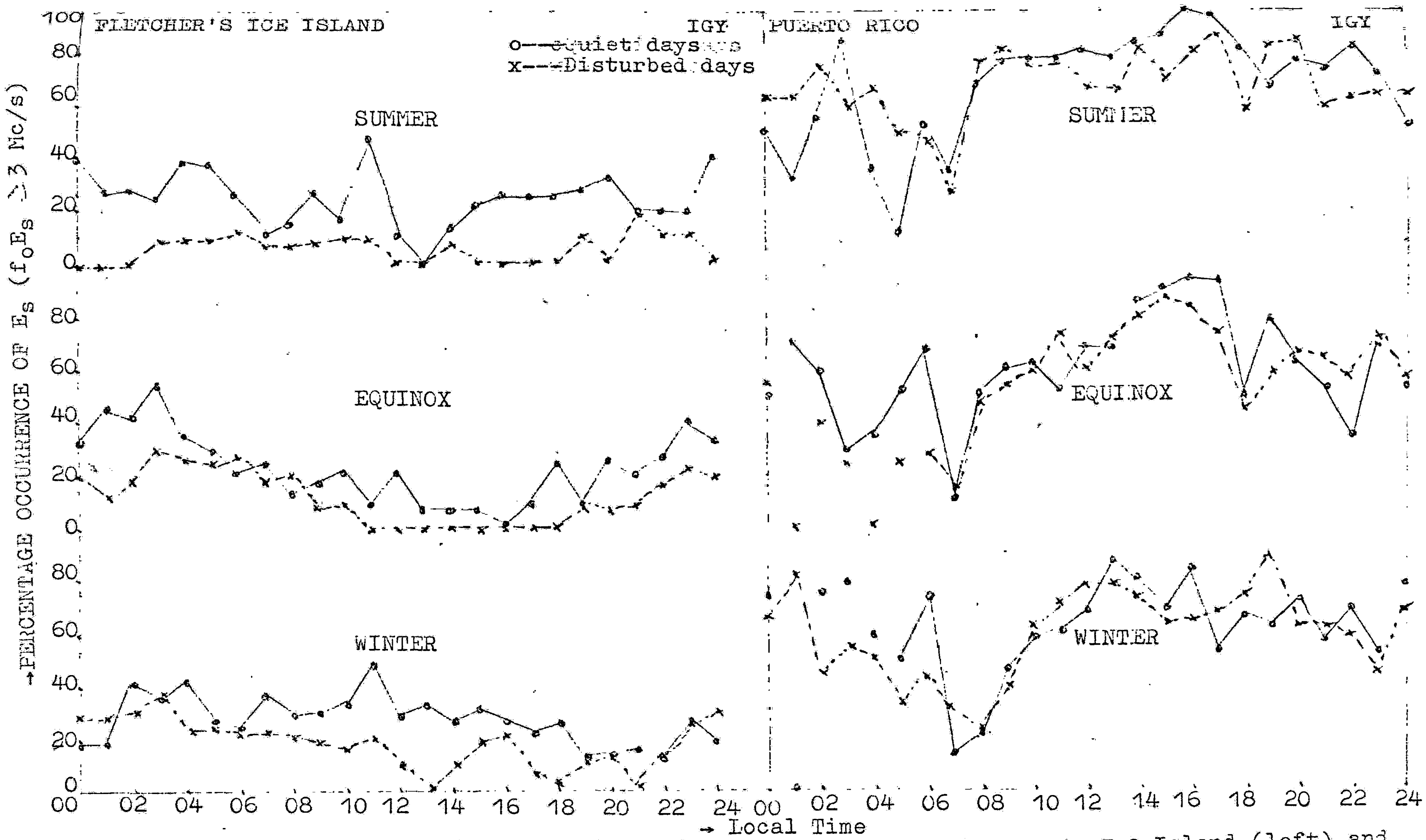


FIG.4.2: Diurnal variation of E_s on quiet and disturbed days at Fletcher's Ice Island (left) and Puerto Rico (right)

occurrence of E_s on magnetic activity for all hours of the day in all seasons.

In the years of minimum sunspot activity at Heiss Island (fig.4.3) a clear positive correlation is observed in all the seasons apart from a period in the late evening i.e. between 20-2200, 18-00 and 18-2300 hrs in summer, equinox and winter respectively. During these periods there is a very clear negative dependence on magnetic activity. There is an almost identical situation during IGY with this late evening reversal in the magnetic dependence.

The principal differences lie in the enhanced positive daytime dependence in IQSY and the slightly greater negative dependence at night in IGY. It will also be observed that while there is a trend towards a positive magnetic dependence in the IGY it is not nearly so pronounced as during the IQSY.

At both Resolute Bay and Fletcher's Ice Island the occurrence of E_s on quiet and disturbed days in IGY and IQSY exhibits features characteristic of polar stations and similar to those described by Thomas (1962) and Saksena (1964) using different methods.

At Heiss Island the situation changes from IGY to IQSY. The greater occurrence of E_s on disturbed days for much of the time suggests that

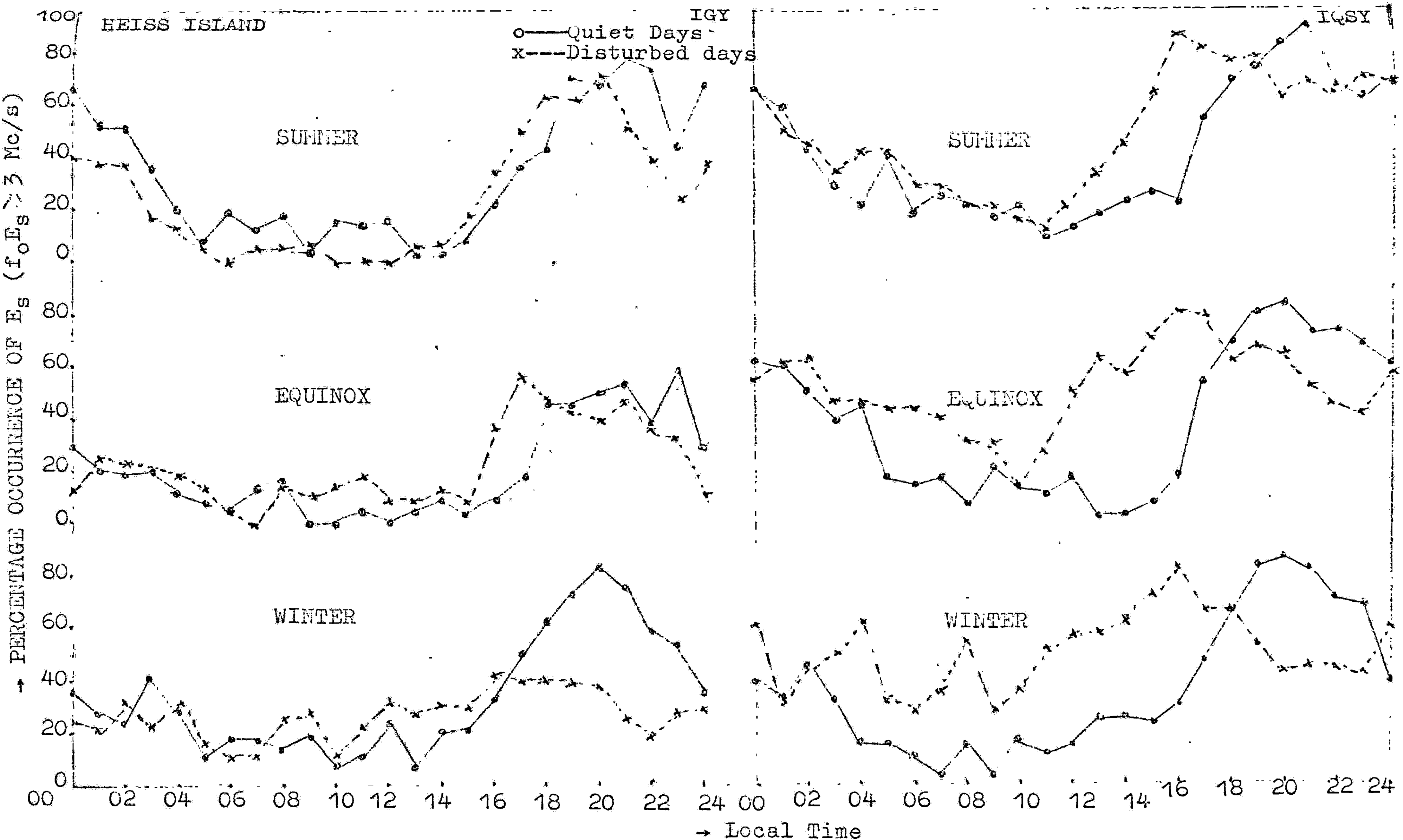


FIG.4.3: Diurnal variation of E_s on quiet and disturbed days at Heiss Island

the station was well within the auroral zone in sunspot minimum years but the absence of any significant difference between quiet and disturbed days suggests that the station lay only on the edge of it in sunspot maximum years.

Point Barrow and Tromso (figs 4.4 and 4.5), both of which are within the auroral zone, show more frequent E_s during disturbed conditions for the IGY and IQSY for all hours of the day. This applies to all seasons, the only consistent departure being for a short period centred around noon in summer when the relation becomes zero or negative.

At Providence Bay (fig.4.6) in IGY there is more E_s on disturbed days than on quiet days for most hours of the day, apart from the period between 0100 and 1500 hrs in summer, when the relative occurrence reverses. During sunspot minimum years, however, this pronounced difference between quiet and disturbed days has effectively vanished. The higher occurrence of E_s in disturbed conditions thus suggests that this station was well within the auroral zone in the IGY but was on the edge of it in the IQSY. This is the reverse of the situation which was observed at Heiss Island on the northern side of the auroral zone. There is, therefore, a possibility that the sporadic-E auroral zone may have moved between sunspot maximum and sunspot minimum years towards the pole.

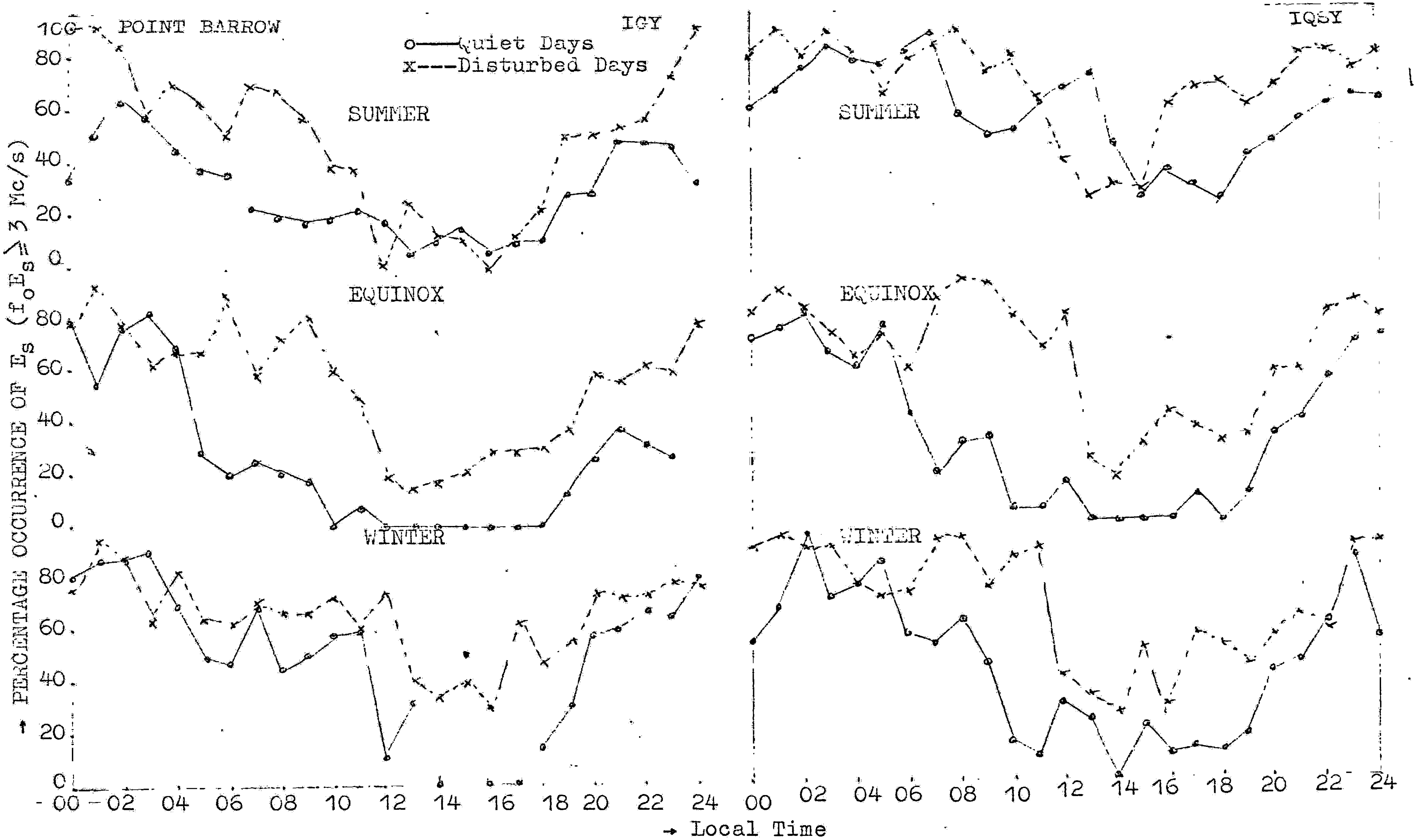


FIG.4.4: Diurnal Variation of E_s on quiet and disturbed days at Point Barrow

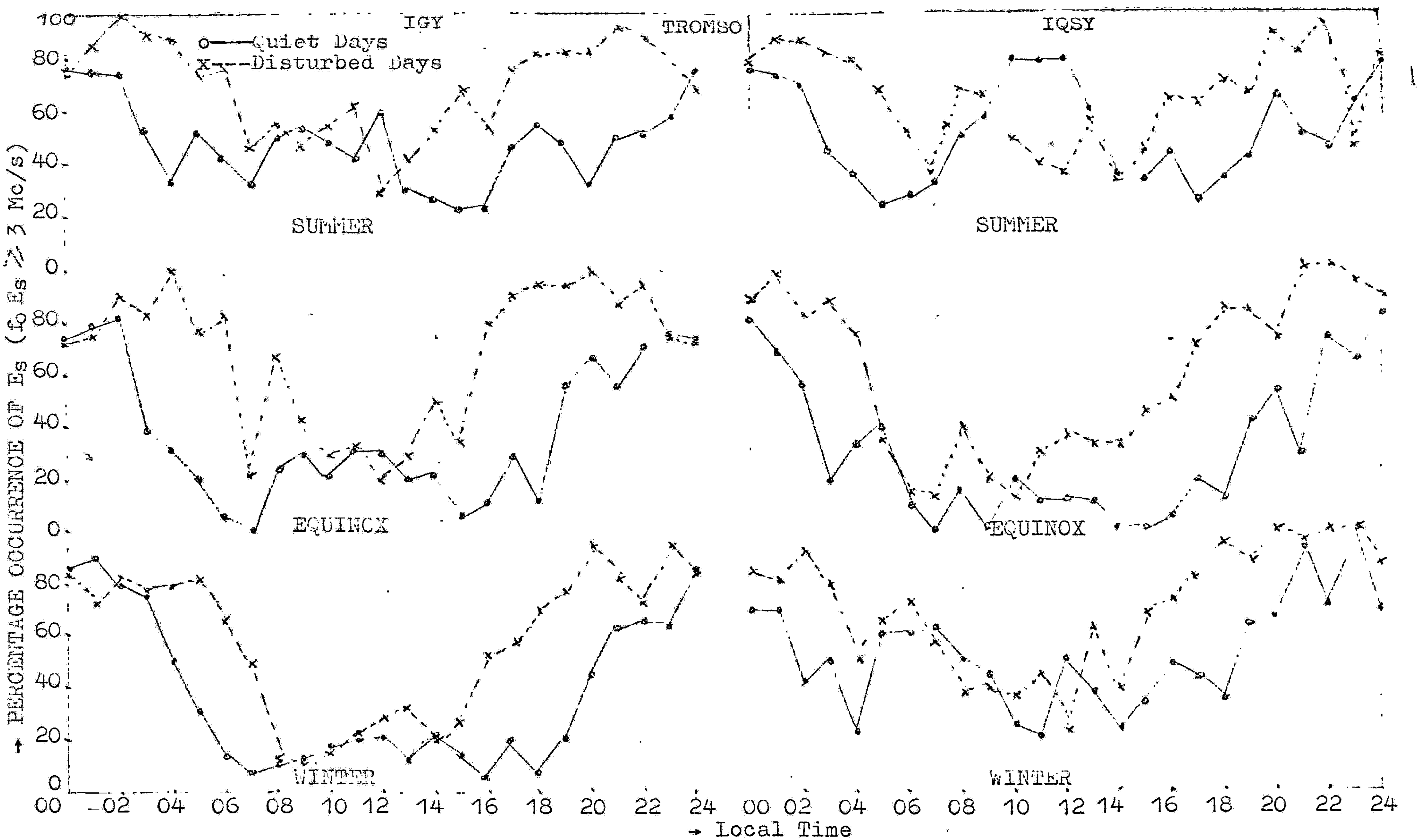


FIG.4.5: Diurnal variation of E_s on quiet and disturbed days at Tromso

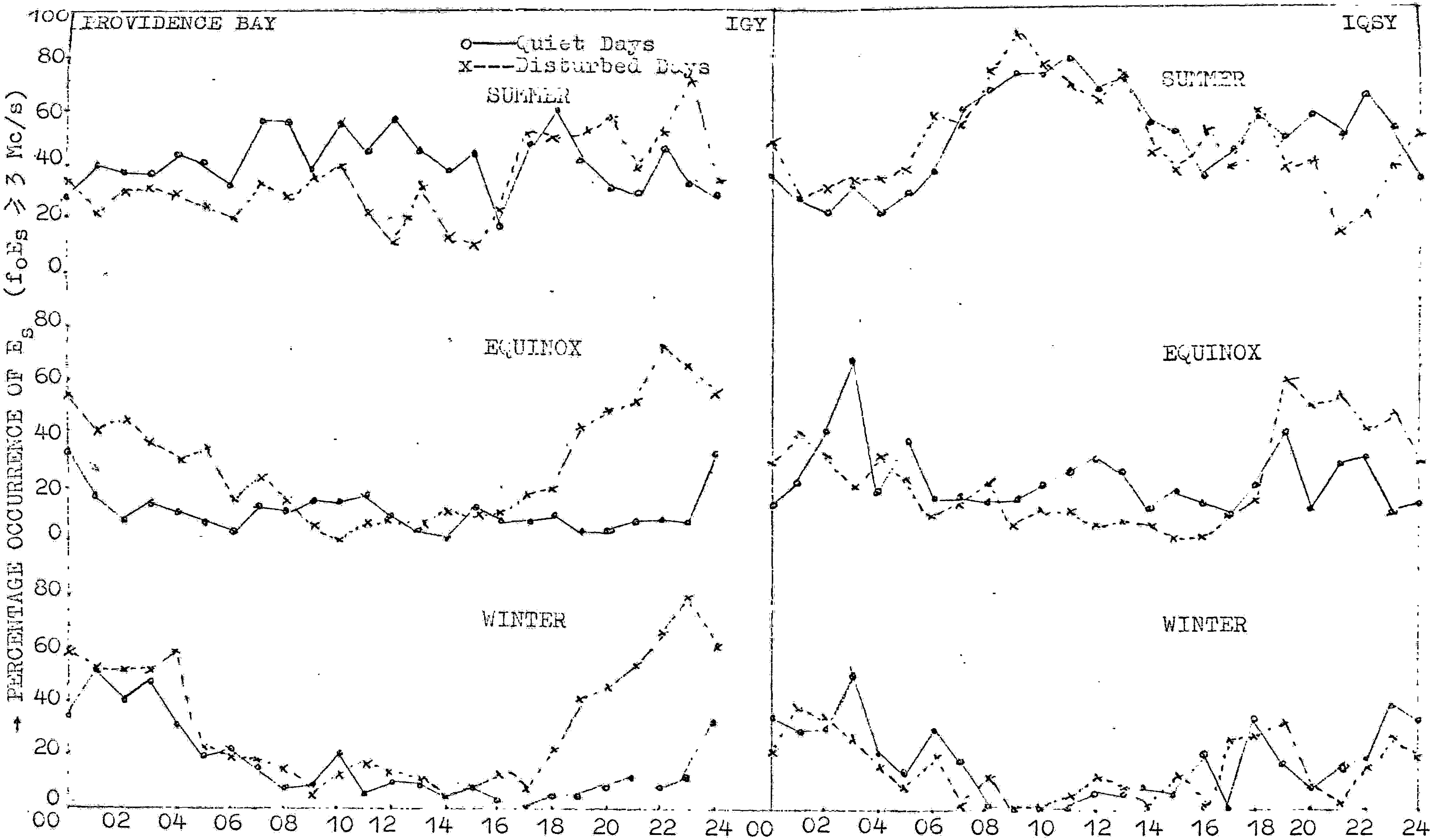


FIG.4.6: Diurnal variation of E_s on quiet and disturbed days at Providence Bay

The occurrence of E_s at Uppsala (fig.4.7) is found to be generally greater on quiet as compared to disturbed days in all seasons of the IGY and IQSY throughout the day, but the difference between quiet and disturbed days is not very significant in IQSY winter. This station is at only a slightly lower latitude than Providence Bay and it does not show the different magnetic behaviour between sunspot maximum and minimum years that is evident at the latter station. The variations at Uppsala are, in fact, more similar to those of a high temperate latitude station.

Slough (fig.4.8) which is also a high temperate latitude station, again shows slightly more frequent E_s on quiet as compared to disturbed days for most hours of the day and in all seasons. This applies to the IGY and IQSY but, in the latter period, the difference between quiet and disturbed days appears to be smaller. The negative relationship tends to remain in the night-time hours but the data sample is so small as to make any comparison of doubtful value.

The diurnal and seasonal variations during the IGY and IQSY at Adak (fig.4.9) do not show any significant differences between the quiet and disturbed day incidence of E_s. This result is somewhat unexpected since, as a high temperate latitude station, it would be expected to show a

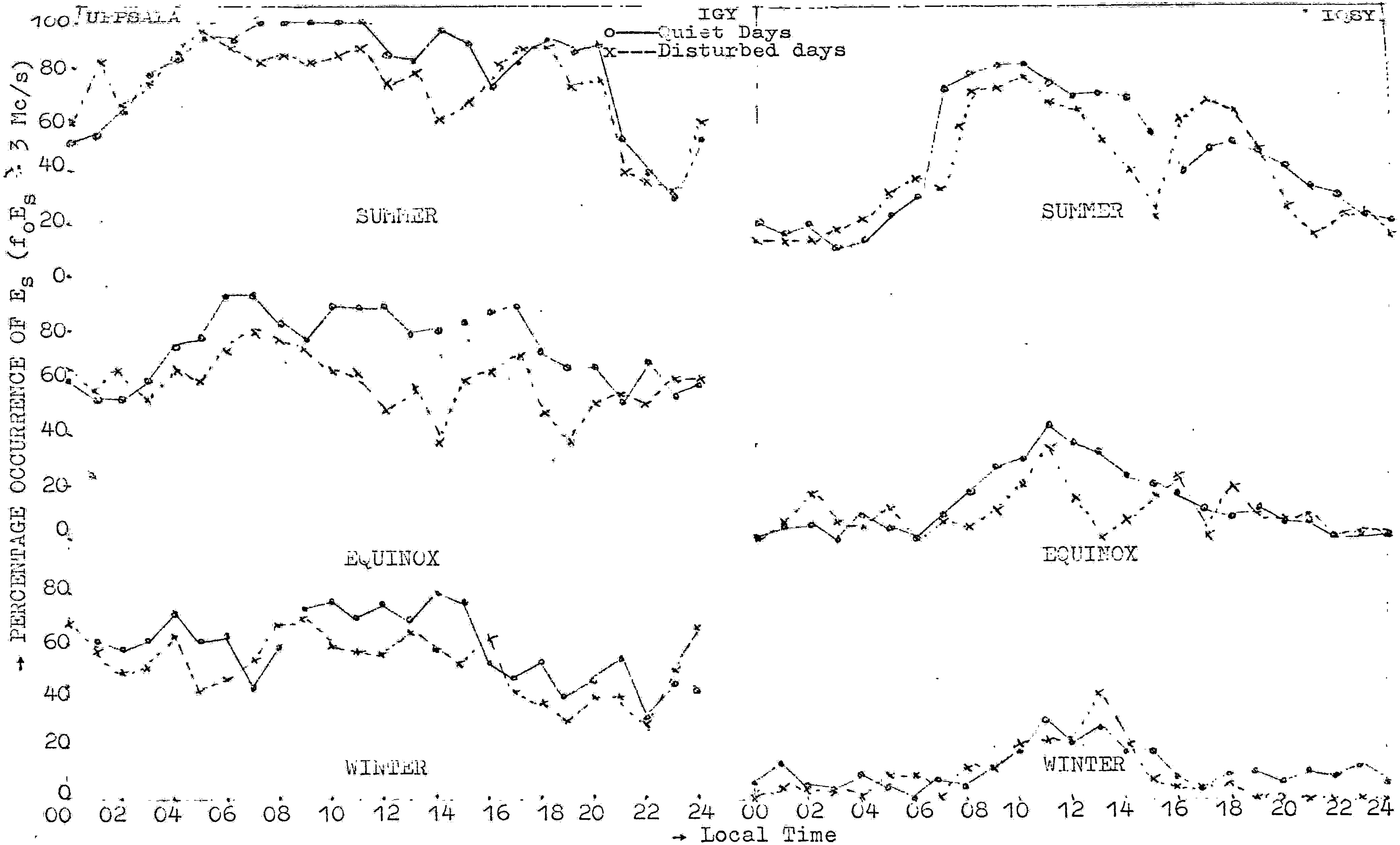


FIG.4.7: Diurnal Variation of E_s on quiet and disturbed days at Uppsala

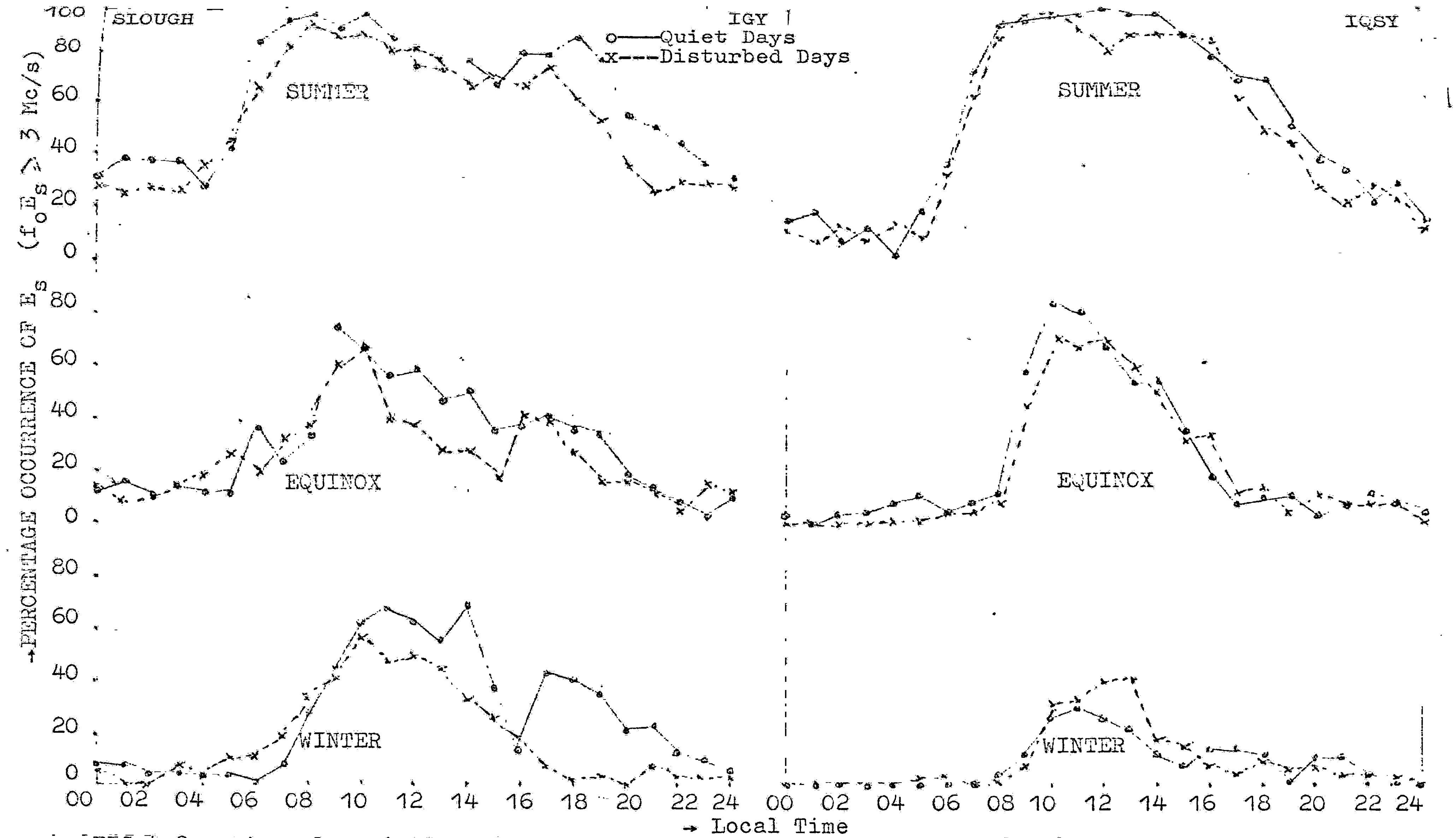


FIG.4.8: Diurnal variation of E_s on quiet and disturbed days at Slough

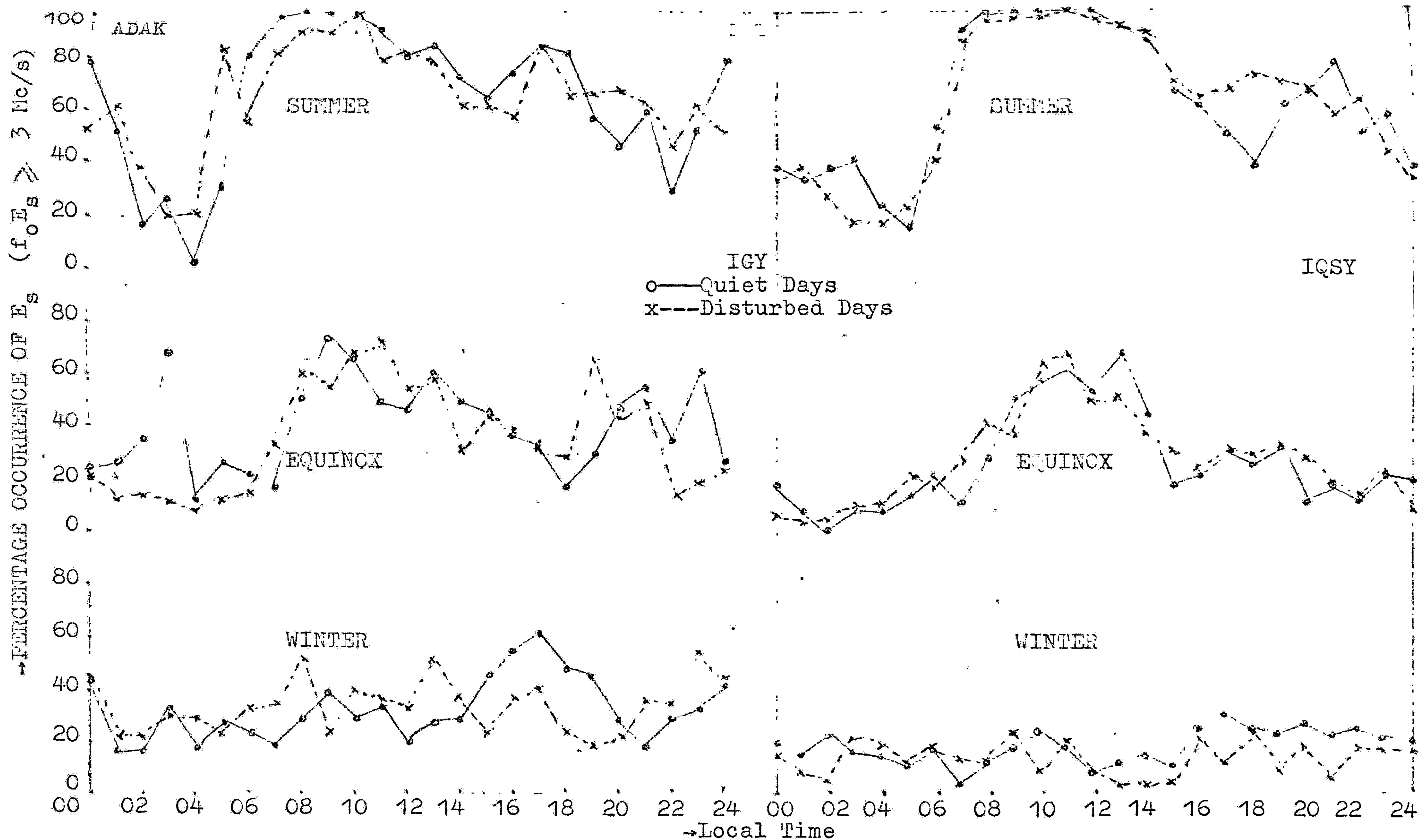


FIG.4.9:. Diurnal variation of E_s on quiet and disturbed days at Adak

slight negative dependence on magnetic activity. It can only be concluded that the random fluctuations from hour to hour are sufficient to conceal any such dependence or relation. The raw data itself contains no obvious anomalies, but it might be noted that the frequency distribution in IQSY shows an abnormally large number of occurrences at the low frequency end and this may, perhaps, have some influence on the IQSY diurnal curve.

In order to explain the apparently irregular behaviour in the diurnal variation of E_s occurrence on magnetically quiet and disturbed days, an attempt has been made to interpret this behaviour in terms of short and long term movements of the auroral zone.

The manner in which this has been done will be described in Chapter 5 but fig. 5.7 shows the diurnal variation for the northern and southern boundaries of the sporadic-E auroral zone for the summer and the winter seasons during IGY and IQSY. The positions of the stations considered in this analysis are also indicated on the diagram and the station latitude has been measured in terms of the number of geomagnetic degrees away from the mean visual auroral zone. It should be noted that most of the high latitude stations have been used to produce this diagram, which is thus a mean representative curve, and will now be compared with the results for each individual station.

The diagram is not an independent result but provides a check on the internal consistency of the data for each station. In this section the summer and winter seasons only are considered, since they represent the extreme positions, while the equinoxes are only intermediate positions.

Fig. 5.7 shows clearly that both the northern and southern boundaries of the sporadic-E auroral zone are at a higher latitude at noon than at midnight and that they are in general at a higher latitude in IQSY than in IGY.

In figs 4.1-4.8, when the disturbed day curve is above or below the quiet day curve, the ratio (k) of the occurrence on disturbed to that on quiet days will be greater or less than unity respectively. The boundaries of the sporadic-E auroral zone are defined as those latitudes where this ratio is unity. Thus points above the upper boundary i.e. in the polar cap and below the lower boundary, i.e. in high temperate latitudes, will have a ratio less than unity, while those between the two boundaries, i.e. in the auroral zone, will have a ratio which is greater than unity.

The position of Resolute Bay suggests that this station was near the auroral zone during the IGY and IQSY only. The only time when an auroral effect has been observed in the E_s occurrence is around IGY summer noon (fig.4.1). In the IGY summer night-time and throughout the winter day in the IGY, this station is completely outside the auroral zone. This agrees with the quiet day occurrences being greater than those on disturbed days. In IQSY the same reasoning applies and the lack of any dependence of E_s occurrences on magnetic activity around summer noon is to be expected if the position of Resolute Bay is on the edge of the auroral zone.

The Fletcher's Ice Island station was on a drifting floe during the IGY and so its position can only be defined as within the range 80-83°N (geographic latitude). Even with this limitation the station is seen to be always above the upper boundary in IGY. Similarly the quiet day E_s occurrence is greater than that on disturbed days in both summer and winter so that this station was always in the polar zone in the IGY (fig.4.2).

The results at Heiss Island show that there is a discrepancy between the diurnal curve and fig.5.7 In IGY winter the disturbed day occurrence is greater and less than the quiet day one at noon and at night respectively, with the night difference being greater than at noon. This situation is what would be expected from fig.5.7. In summer, a greater disturbed day occurrence would be expected at noon, changing to a smaller one at night. The diurnal curve of E_s (fig.4.3) shows that, while the latter feature is observed, the situation at noon is not in agreement in that at and before noon the quiet day occurrence is predominant while only in the afternoon does it become less than the disturbed day one. While there is no apparent explanation for this discrepancy it might be noted that the 1100-1300 point, which if increased to >1 would remove the discrepancy, is based on a very small number of disturbed day occurrences and so is statistically unreliable.

In the IQSY the summer variation is simpler than in IGY in that $k > 1$ throughout the day time period, although only marginally so during the morning, while at night k is only on average < 1. During winter k becomes very large in the day time, suggesting that the station is now located more towards the centre of the auroral zone and not on the edge as in summer, while at night $k < 1$.

Point Barrow and Tromso, which are about 1° apart in latitude, show similar diurnal changes, the essential features of each station being the same (figs 4.4 and 4.5). At Point Barrow in summer k is a minimum around noon, being about one in IGY and much less than one in IQSY corresponding to a position near the edge of or boundary of the auroral and high temperate latitude regions.

During the morning and afternoon k increases above one and then during the night returns towards one again. This corresponds in fig.5.7 to passage across the auroral zone towards its northern boundary at about midnight. During winter in both IGY and IQSY k is greater than one throughout the whole of the day but tends towards one at midnight, again corresponding to a position on the upper boundary of the zone.

Tromsö, in summer, exhibits an almost identical variation to that at Point Barrow with k in IQSY being much less than one. In both IGY and IQSY it increases above one in the morning and afternoon and then returns to one at midnight. Winter also shows k to be one at midnight and midday with greater values in the morning and afternoon.

It will be seen from fig.5.7 that it is only around midnight that Providence Bay is situated near the southern edge of the sporadic-E auroral zone. At all other times of the day it is below the zone. During summer, therefore, k should be less than one apart from a short period centred on midnight when it will be equal to or slightly greater than one. This behaviour is basically observed with k greater than one for a period near midnight in IGY and for a period after midnight in IQSY. The minimum value of k which would be expected near noon is observed in IGY but is not so apparent in IQSY. In IQSY winter the diurnal variation is confused and cannot readily be interpreted but in IGY winter night, when Providence Bay is farthest inside the auroral zone, very large values of k are observed. (fig.4.6).

According to fig.5.7 the only time when Uppsala should be an auroral station is again a short period around midnight. At all other times it should behave as a high temperate latitude station with $k < 1$. On a diurnal basis (fig.4.7) this is generally observed with the minimum values of k at or near noon and values tending to one towards midnight. There is also a tendency for k to be greater than one in IGY winter midnight but in IQSY, when Uppsala should be some distance south of the lower boundary, k actually becomes zero.

Slough should be permanently south of the auroral zone with k being consistently <1. During the IGY this is in fact observed, while during IQSY summer k is marginally <1 but during winter the number of occurrences is relatively small and no significant differences can be observed (fig.4.8).

The general agreement between the diurnal variations at the individual stations and the composite diurnal variation of the sporadic-E auroral zone in fig.5.7 has been summarized in Table 4.1.

TABLE 4.1

Station	Summer IGY				Winter IGY				Summer IGSY				Winter IGSY			
	Noon		Mid-Night		Noon		Mid-night		Noon		Mid-night		Noon		Mid-night	
Resolute Bay	+		−	x	−	x	o		⊖	x	−	x	−	x	−	x
Fletcher's Island	o		−	x	−	x	+									
Heiss Island	−		−	x	+	x	−	x	+	x	o		+	x	o	
Point Barrow	+	x	+	x	+	x	+	x	−	x	+	x	+	x	+	x
Tromso	⊕	x	+	x	+	x	⊕	x	−	x	+	x	+	x	+	x
Providence Bay	−	x	+	x	+		⊕	x	⊕		⊖		+		−	x
Uppsala	−	x	+	x	−	x	+	x	−	x	−	x	⊕		−	x
Slough	−	x	−	x	−	x	−	x	−	x	−	x	+			

In this table noon and midnight refer to three-hour periods centred around these times. The + and − signs represent values of $k > 1$ and $\leqslant 1$ respectively and o indicates that k is equal to 1. Ringed signs are those in which k is only slightly different from one. An x in the adjoining column indicates agreement between an individual station and the composite curve.

It is clear from the table that overall this is good and implies that a self-consistent explanation has been obtained. Thus, in the light of the above discussion, most of the apparently irregular changes in the diurnal variation of E_s occurrence on magnetically quiet and disturbed days can be explained. The model requires that the sporadic-E auroral zone itself has a diurnal movement with a minimum latitude about midnight and a high latitude limit about noon and the overall agreement between observations and model is satisfacory in view of the non-uniform distribution of the stations with latitude and the relatively small number of stations available to determine the boundaries of this auroral zone.

At the low temperate latitude station, Akita, a seasonal change has been noticed in the relationship between the occurrence of E_s and magnetic activity during the IGY (fig.4.10). A small negative dependence has been found for most of the twenty-four hour period of the summer months and a slightly larger positive dependence for the equinox months at all hours of the day. No significant difference has been found in the occurrence of E_s on quiet and disturbed days in winter nor in any season in IQSY.

Puerto Rico does not show any relation between the occurrence of E_s and magnetic activity in any season during the IGY (fig.4.2).

At a lower latitude, Bogota shows more frequent E_s in the summer and equinox on disturbed days as compared to quiet days for most of the day during both sunspot maximum and minimum years (fig 4.11). However, in winter months, the occurrence of E_s

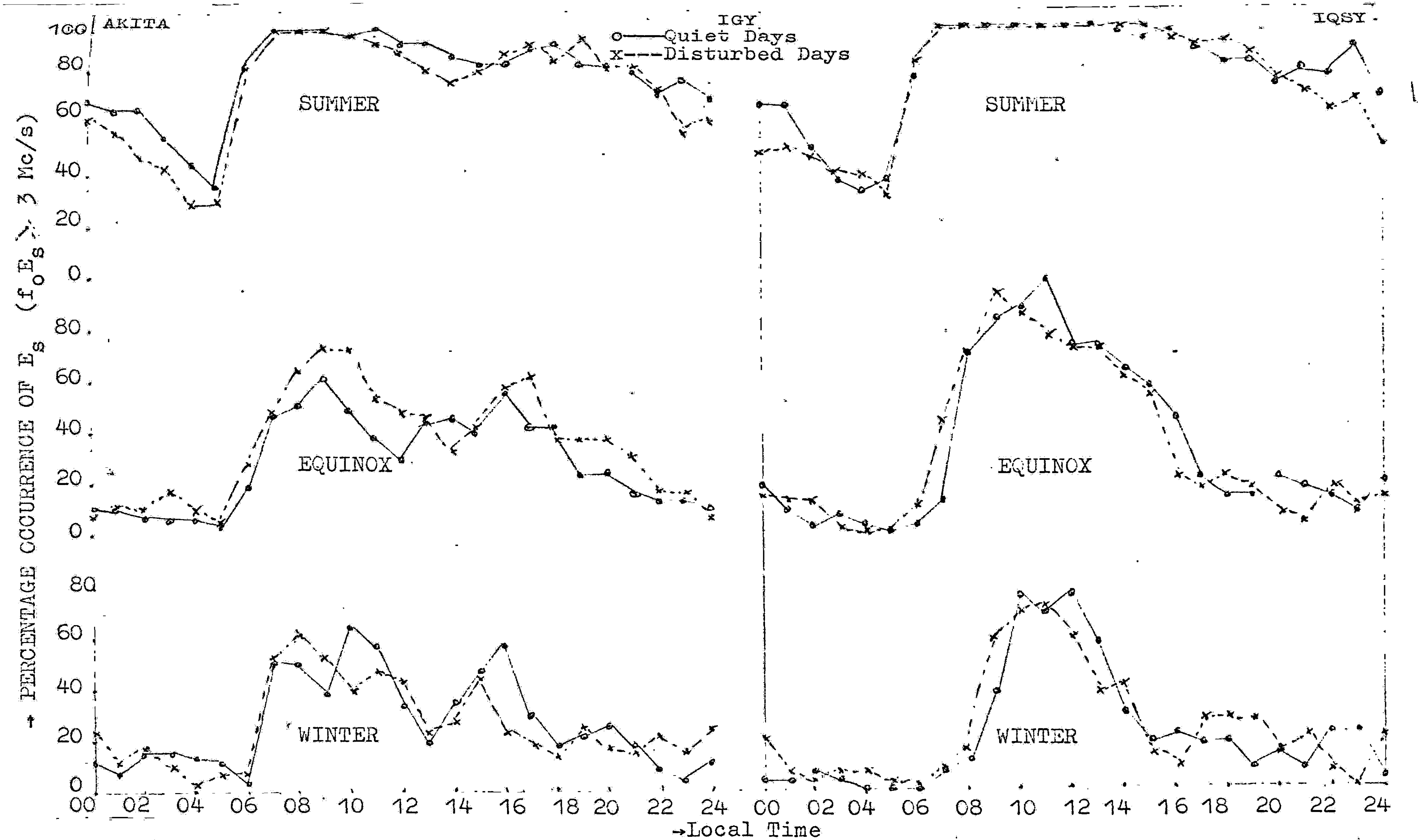


FIG.4.10: Diurnal variation of E_s on quiet and disturbed days at Akita

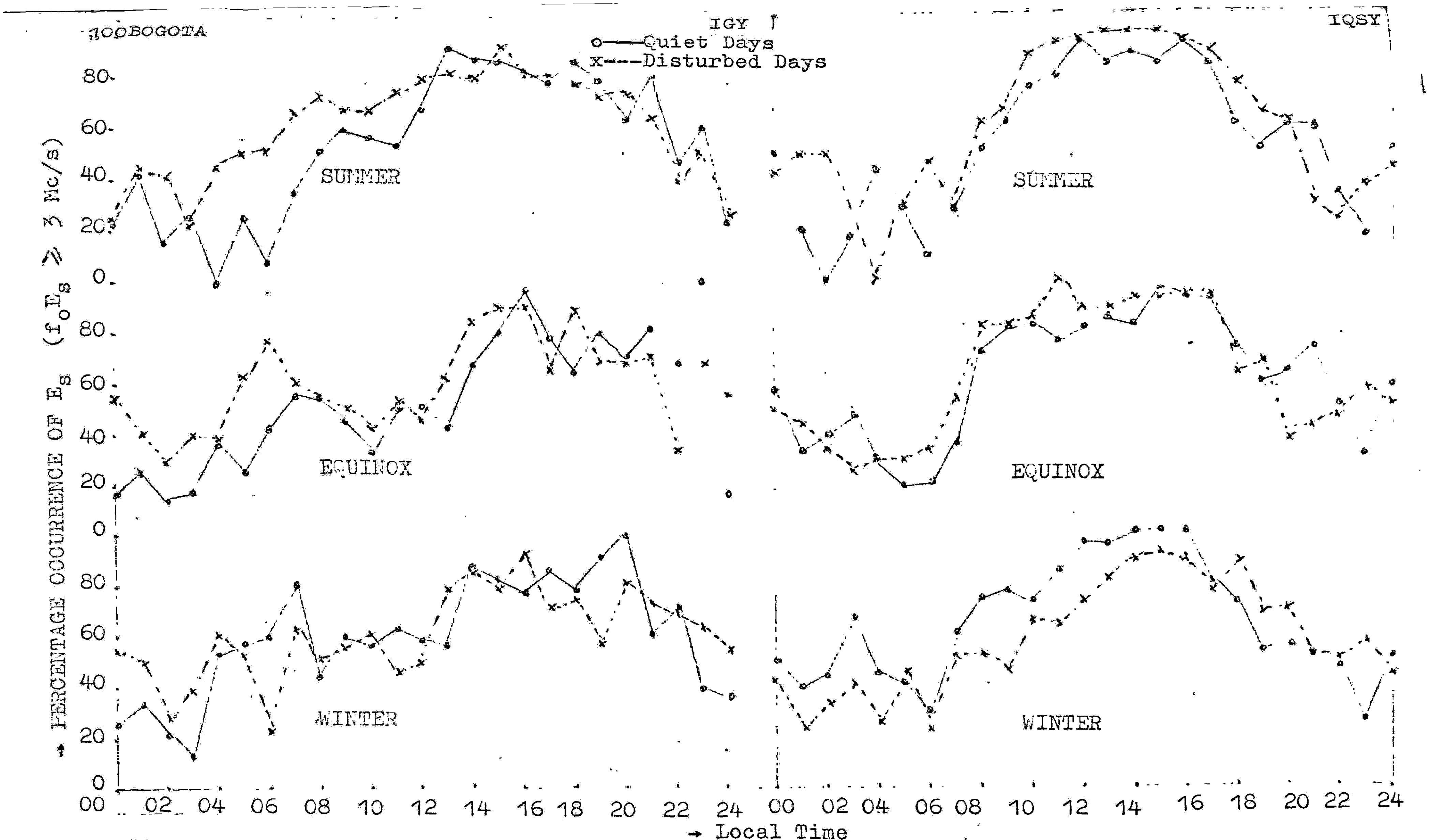


FIG.4.11: Diurnal Variation of E_s on quiet and disturbed days at Bogota

exhibits a negative dependence on magnetic activity during IQSY and none at all during IGY.

At Taipei no significant variations are observed for either the IGY or the IQSY apart from a small positive and negative dependence during the forenoon and afternoon respectively in the IQSY equinox (fig.4.12).

The above dependences can be provisionally accounted for in terms of the varying predominances of the various types of E_s which have different relationships with magnetic activity. These will be considered in more detail in Chapter 6.

At both the equatorial stations Kodaikanal and Huancayo (figs 4.13 and 4.14), the diurnal variation shows a very high incidence of E_s during daytime in all seasons for both quiet and disturbed days, which tends to be one hundred percent for much of the time. A slight but significant negative dependence is observed during the IGY and IQSY.

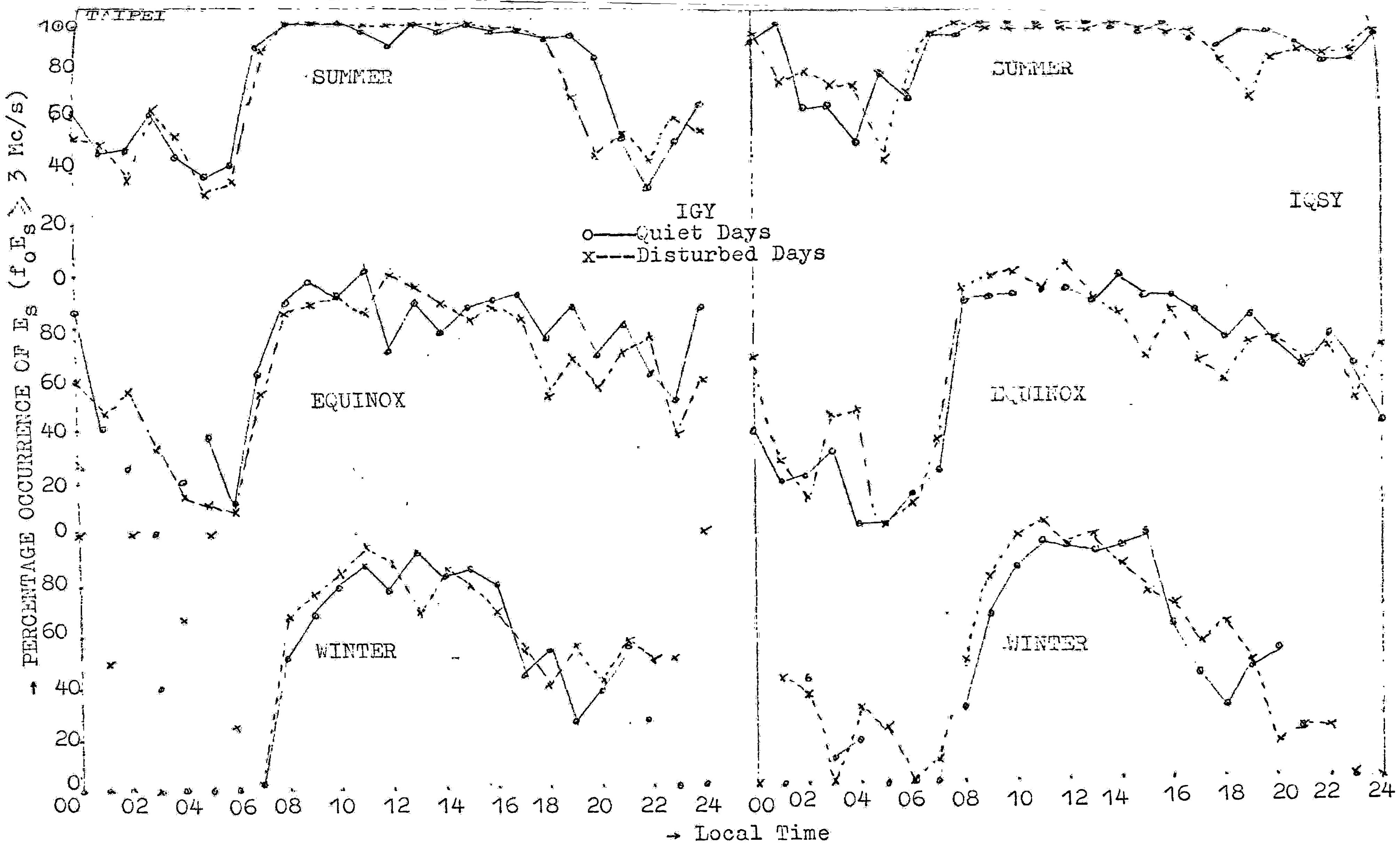


FIG.4.12: Diurnal variation of E_s on quiet and disturbed days at Taipei

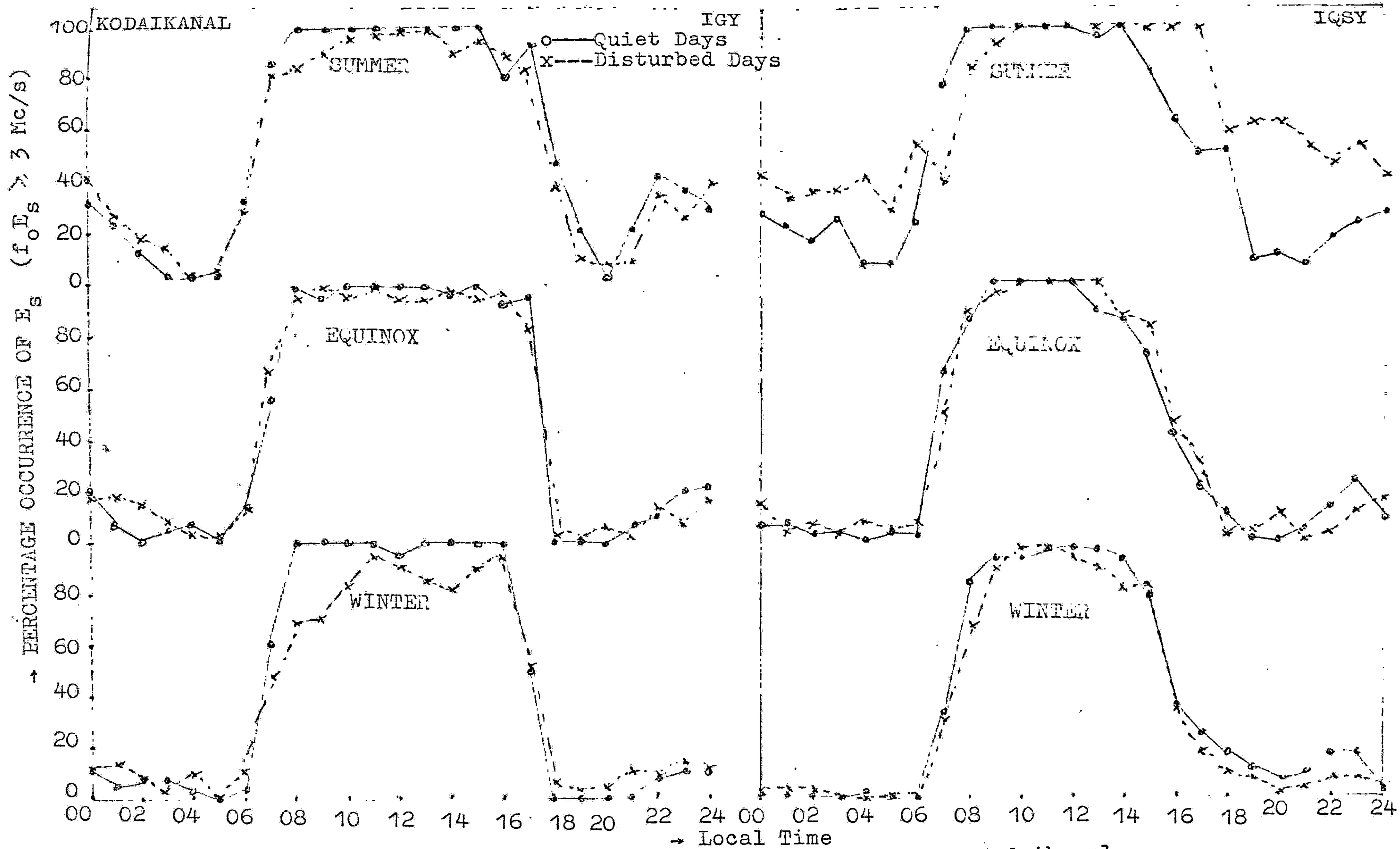


FIG.4.13: Diurnal variation of E_s on quiet and disturbed days at Kodaikanal

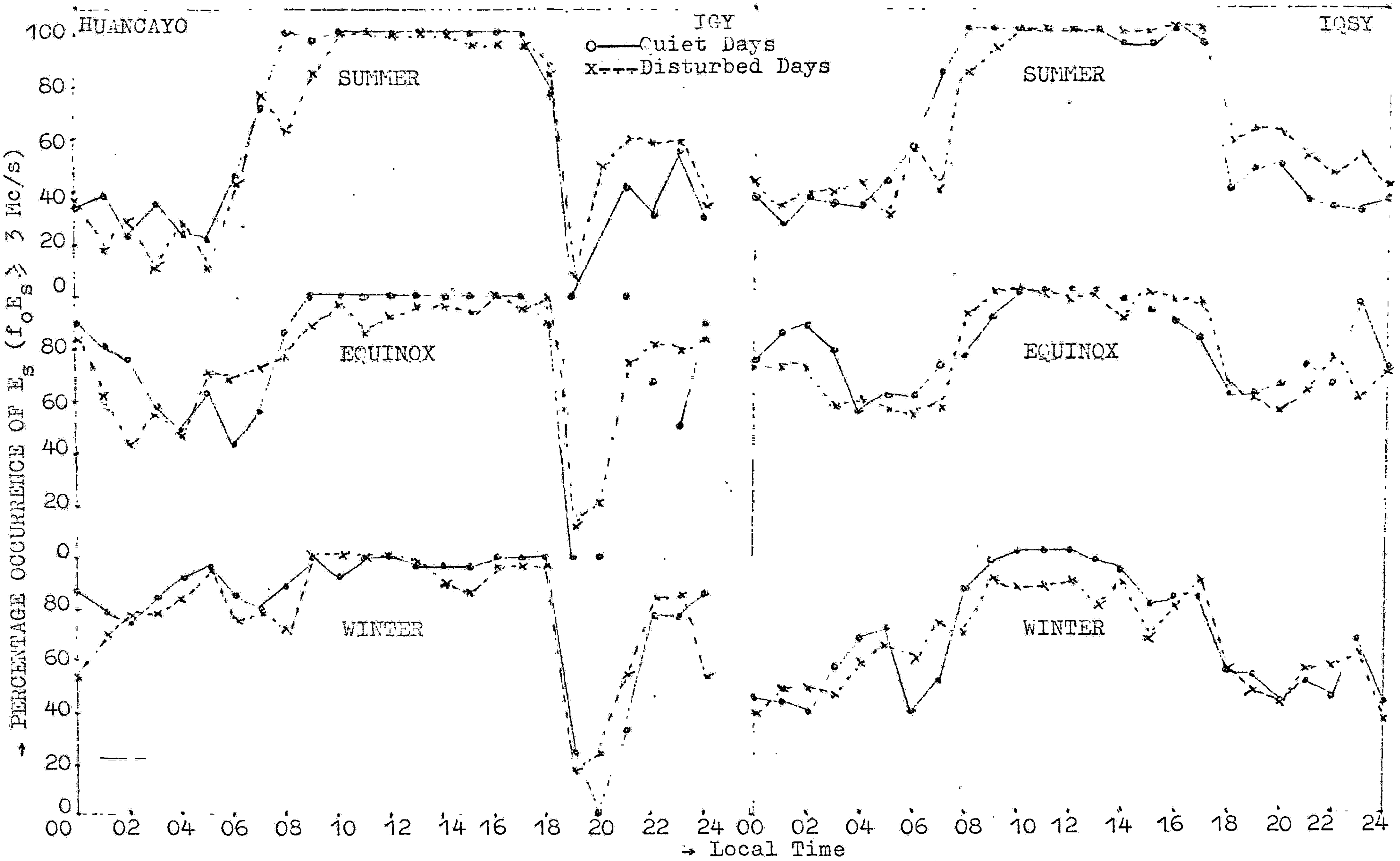


FIG.4.14: Diurnal variation of E_s on quiet and disturbed days at Huancayo

4.3 Frequency distribution of E_s

The frequency distributions as a function of quiet and disturbed magnetic conditions have been plotted in figs 4.15-4.18. The distributions discussed here represent data taken over all hours of the day and all seasons of the years considered. The distributions are thus averages over all hours and seasons and the comparison made should be compared with the overall behaviour of the stations in the previous section.

At Resolute Bay, Fletcher's Ice Island and Heiss Island the E_s occurrence is found to be greater on quiet days as compared to disturbed days for most of the frequency range in the IGY. During IQSY the frequency distribution at Resolute Bay is similar to that in IGY but at Heiss Island the opposite effect is observed (fig.4.15).

At this station the E_s occurrence is more frequent on disturbed days rather than quiet days throughout the whole of the frequency range. This behaviour is characteristic of that found in the auroral zone and similar to that found for the auroral stations observed below. This approach provides additional evidence for regarding Heiss Island as a station on the edge of the auroral zone or just inside the polar cap in sunspot maximum years but inside the auroral zone during sunspot minimum years. This change in magnetic activity

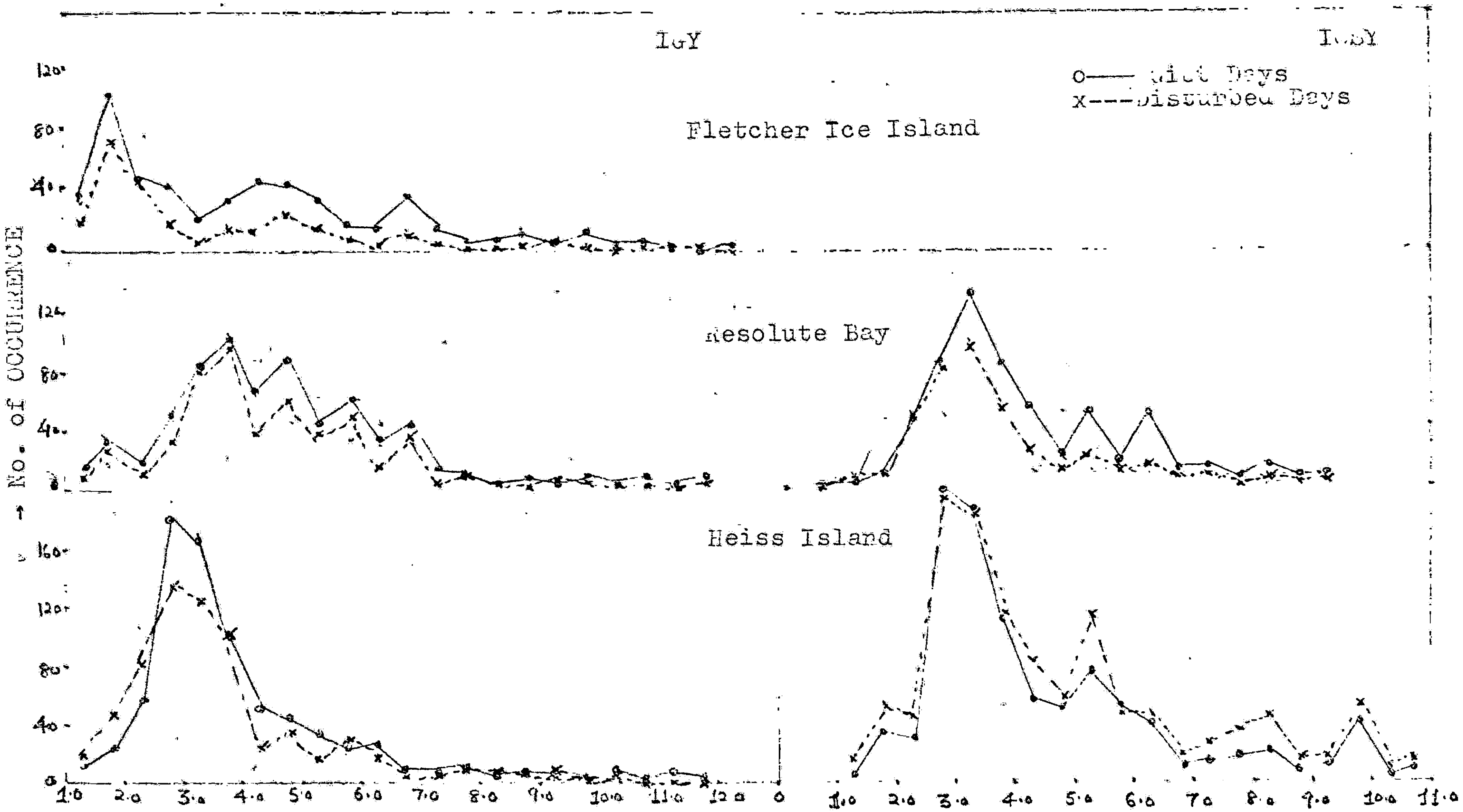


FIG.4.15: Frequency distribution of f_s on quiet and disturbed days

behaviour thus again suggests that there is a movement of the auroral sporadic-E zone from sunspot maximum to sunspot minimum conditions.

At Tromso and Point Barrow the frequency distribution shows that E_s is more frequent in disturbed than in quiet conditions during both the IGY and IQSY for all the frequency range above 3.0 Mc/s. Below this frequency the situation is confused and an interpretation is difficult but this is of little consequence as the important range is at higher rather than at lower frequencies (fig 4.16.) This is the distribution to be expected for auroral stations having a positive dependence and a similar result is obtained for Providence Bay in the IGY in fig 4.17.

During the IQSY, however, Providence Bay (fig.4.17) shows a greater E_s incidence on quiet days which, as has been noted, is the behaviour expected of a high temperate latitude station. It is again concluded, therefore, that in contrast to the situation at Heiss Island, Providence Bay has, on average, an auroral zone location during the IGY but a high temperate latitude one during the IQSY, again lending support for an auroral zone movement.

At Uppsala and Slough the distribution on quiet days is greater than that on disturbed days throughout most of the frequency range during the IGY. In IQSY the same effect is observed but the difference between quiet and disturbed days is not

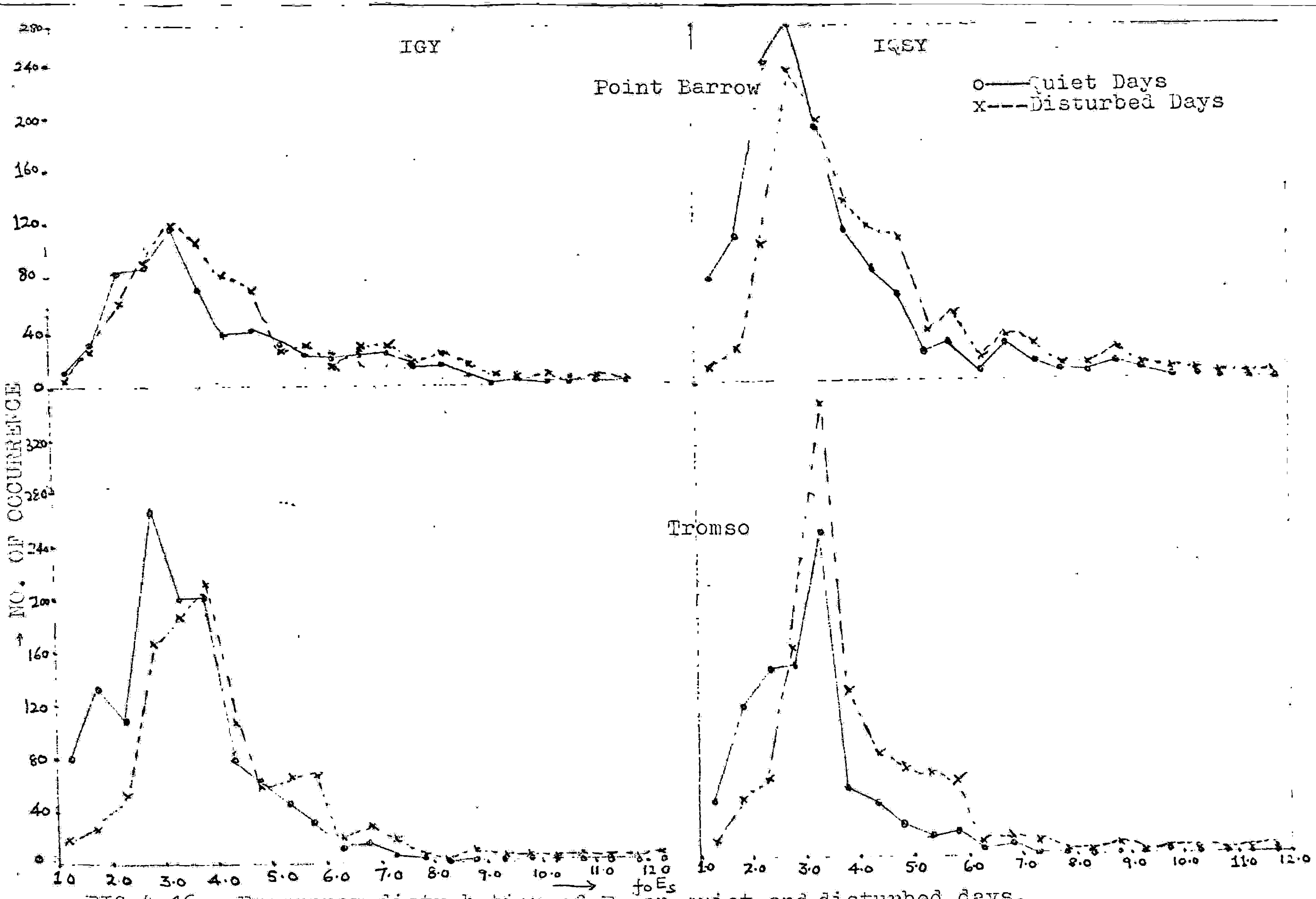


FIG.4.16: Frequency distrubution of E_s on quiet and disturbed days.

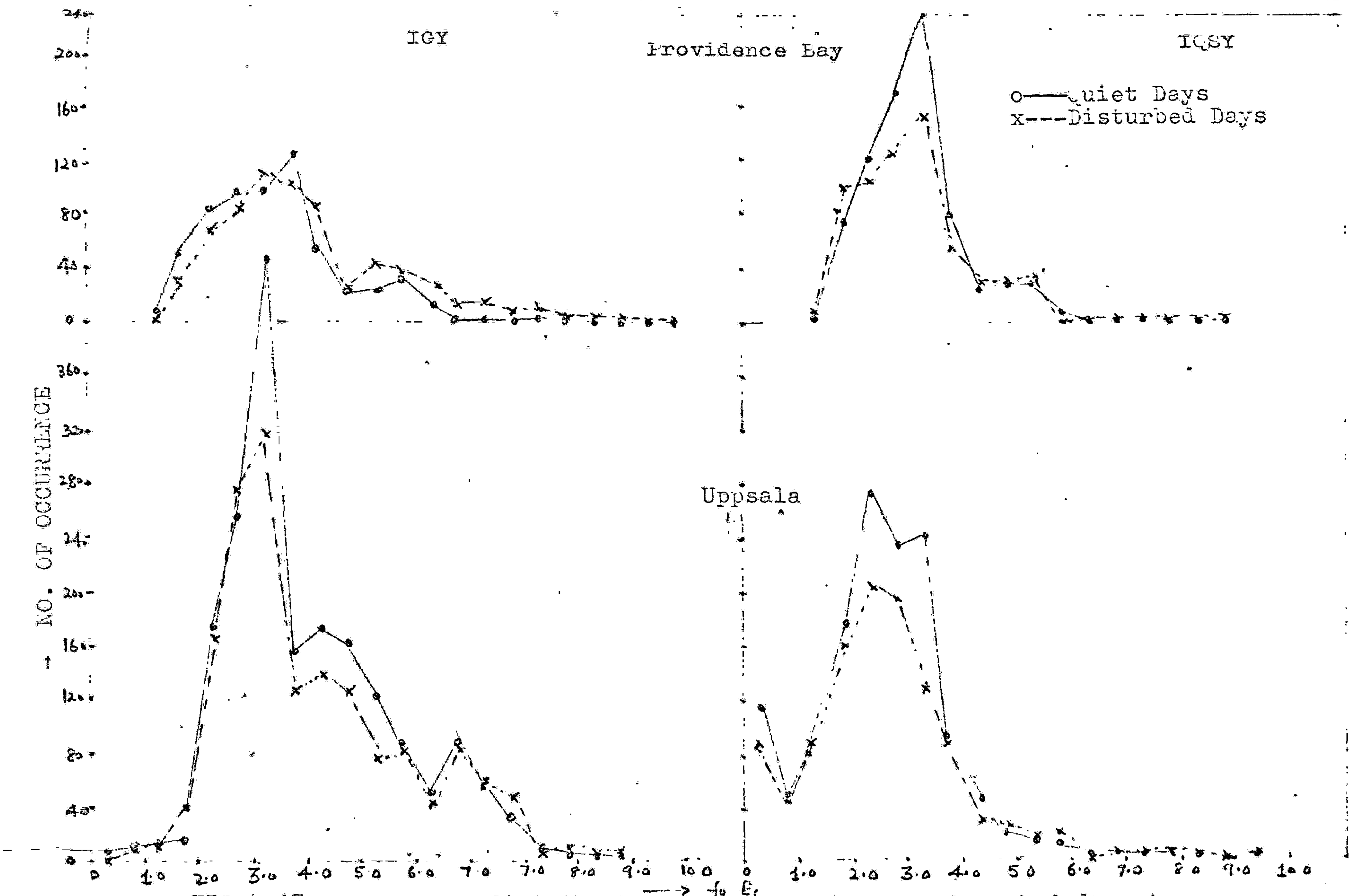


FIG.4.17: Frequency distribution of E_s on quiet and disturbed days.

so great (figs.4.17 and 4.18).

The frequency distribution for Adak (fig.4.18) however, which is at a lower latitude than Slough, shows no significant difference between the quiet and disturbed day occurrences, which is to be expected as one moves towards mid latitudes. As at Adak, all the low temperate latitude and equatorial stations show no significant difference between the occurrence of E_s on quiet and disturbed days and so indicate the lack of any dependence of E_s on magnetic activity. Since the distributions provide no useful information, they are not shown here.

4.4 Cumulative distribution of E_s

Using the frequency distribution of section 4.3 the cumulative distribution of E_s with a logarithmic ordinate has been drawn during conditions of maximum and minimum solar activity for a number of stations from the equator to the north pole. Linear relationships are obtained at all stations between the frequency (f_oE_s) and the percentage occurrence of E_s exceeding it for all frequencies which are greater than the most probable frequency (f_pE_s) at that particular station. For high and temperate latitude stations f_pE_s lies in the range of 2 - 5 Mc/s but, for the two equatorial stations Kodaikanal and Huancayo, f_pE_s is approximately 11 Mc/s and 9 Mc/s respectively and so the straight lines are only obtained at the extreme end of the

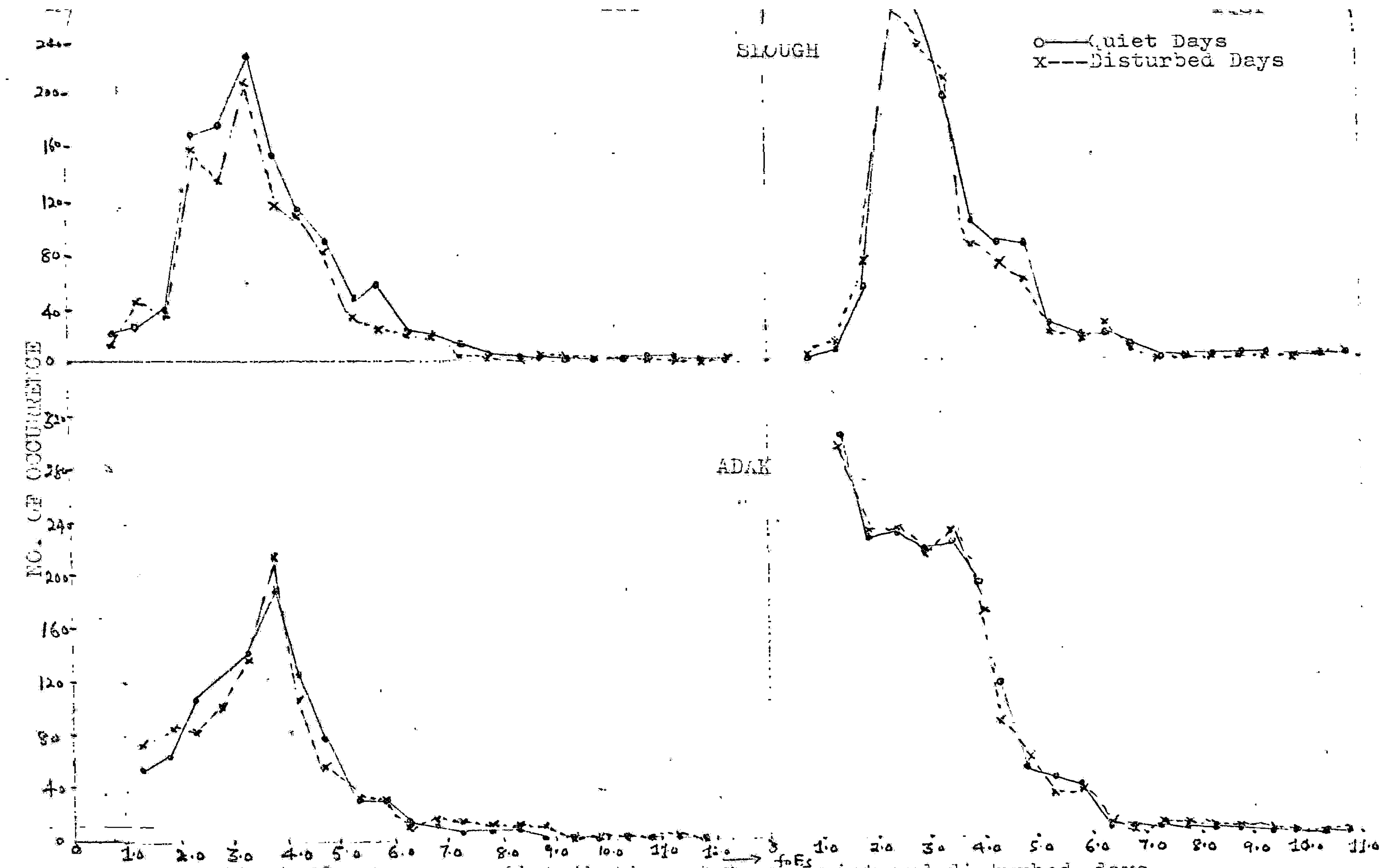


FIG.4.18: Frequency distribution of E_s on quiet and disturbed days.

frequency range.

It is thus to be noted that Phillips' Rule (Phillips', 1947), which states that the E_s cumulative distribution is linear, is only valid above f_pE_s but is then applicable to all stations. Provided that this condition is fulfilled this linear relationship is true for magnetically quiet and disturbed days for different conditions of solar activity, for different seasons and for different times of the day.

The cumulative distributions for 15 stations in IGY and 13 stations in IQSY are basically similar with no obviously distinguishing features. For this reason only three stations are here given as examples (fig.4.19):

a) Quiet and disturbed days in IQSY at Huancayo.

b) Summer and winter quiet days in IQSY at Akita

c) Quiet and disturbed days in IGY at Heiss Island.

While the changes in the graph between quiet and disturbed conditions for summer and winter are relatively small, the most striking feature in the graphs shown is the sharp change at about 7.5 Mc/s at Huancayo. This frequency, as will be seen from fig.3.11 corresponds to the day time value of f_pE_s. If night values alone are considered, when f_pE_s fall to about 3.0 Mc/s, then this bend in

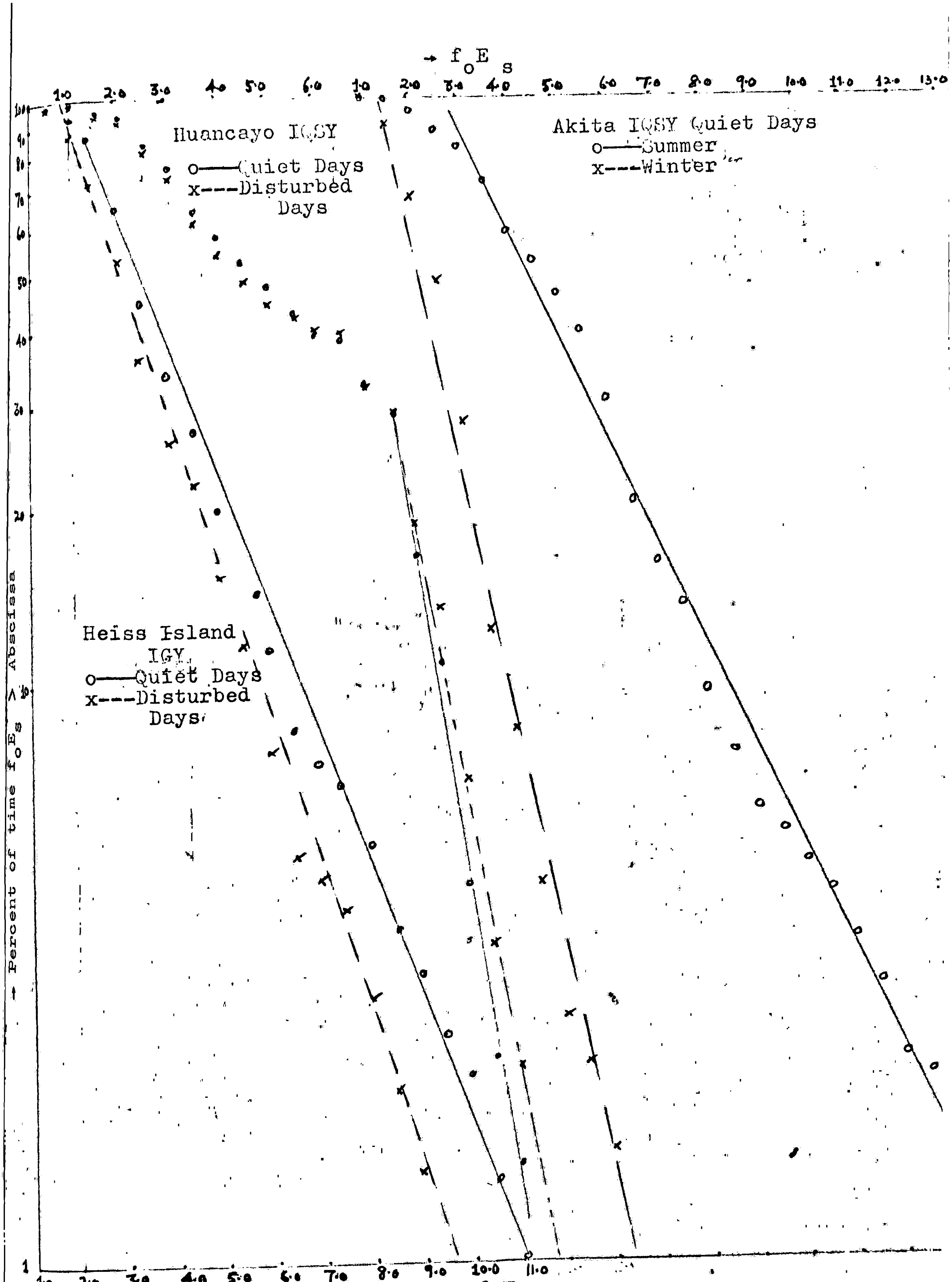


FIG.4.19: Cumulative distribution of E$_s$

the distribution disappears and a single straight line is obtained (Saksena, 1965).

The Phillips' Rule has been applied by Smith (1957) to Washington and Slough for day time and night time. The criterion employed by Smith for assessing the incidence of E_s was the probability of f_oE_s exceeding 3.0 Mc/s. Since this is approximately equal to f_pE_s at these stations, Smith found a linear relationship. Similarly, Yien-Nien (1965) with the same limiting frequency has also found the same results.

Both of the above authors infer that their results are valid for frequencies exceeding 3.0 Mc/s. This figure is taken from that quoted originally by Phillips (1947) and ascribed to the blanketing effect of the normal E-region. However, consideration of the distributions at equatorial stations and at other latitudes shows that the frequency above which Phillips' Rule applies is governed not so much by the blanketing effect of the E-region as by the most probable frequency of occurrence of E_s. This frequency, as is clearly seen from the equatorial results, can be markedly different from 3.0 Mc/s. It may be concluded, therefore, that Phillips' Rule is applicable above the most probable f_oE_s at any place under any conditions.

The cumulative distribution possesses an advantage over those analyses which consider the occurrence of E_s greater than a particular frequency, (which is invariably required), in that the linear part of the distribution eliminates the random fluctuations which inevitably occur in the raw data. Equally it has a disadvantage as used in the present work in that it only provides the occurrence of E_s greater than a given frequency as a percentage of the number of occasions on which E_s is observed and not as a percentage of all the occasions when observations of E_s were possible. The latter quantity is, of course, the form required for communication prediction purposes and the results given here are only qualitatively suitable for such a purpose.

4.5 Latitudinal variation

Of the various paramenters associated with the cumulative distribution the most obvious is that of the gradient of the linear part of the distribution above f_pE_s. This gradient has been measured for all the stations considered and plotted against geomagnetic latitude. This has been done for quiet and disturbed days during sunspot maximum and minimum years and also for quiet days in summer and winter during sunspot minimum only.

These variations are shown in fig.4.20

from which it will be seen that there is a clear and systematic change with latitude. The linear parts of the cumulative distribution have, on a very approximate basis, a common origin on the probability axis. It then follows that the steeper the line the lower will be the probability of E_s occurring above a given frequency. The plot of gradient against latitude may consequently be interpreted as a very rough approximation to the latitude variation of the incidence of E_s above a given frequency. It may thus be regarded as comparable to fig.3.15 which relates to the noon equinox values only.

It should be stressed that this comparison is wholly qualitative and in no sense quantitative. In particular, fig.3.15 shows the equatorial stations as having a very high occurrence while the gradient has a large negative value caused, as has been indicated above, by the high values of f_pE_s at these stations. In this case the interpretation of the gradient given here will be misleading.

Despite these misleading equatorial values the curves in fig.4.20 show a broad maximum at about 30° and a much steeper peak at 70°. While the latter can be identified with the auroral and polar region, the mid latitude peak is not so readily understood.

There is an alternative interpretation

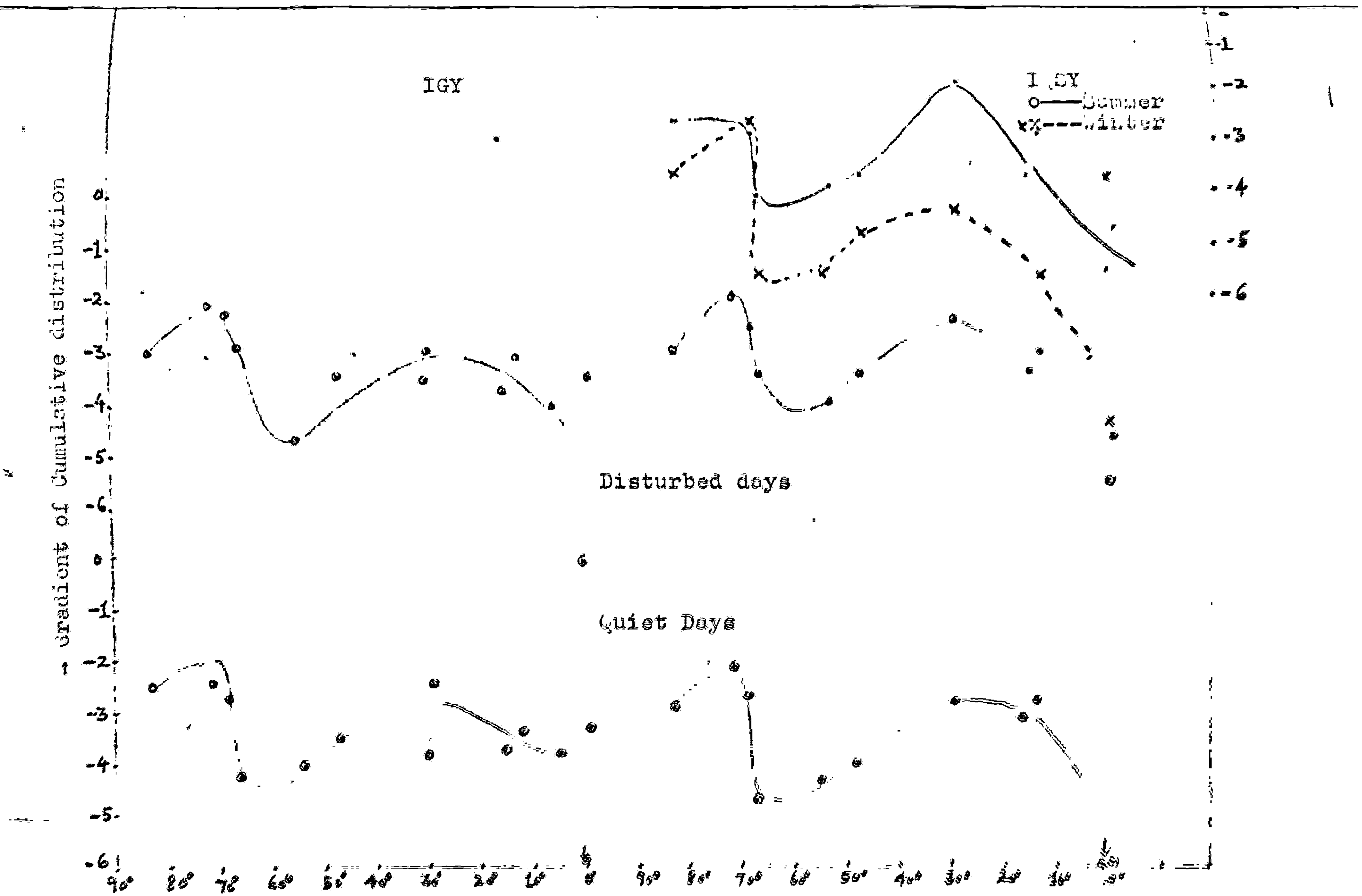


FIG.4.26: Latitudinal variation of gradient of cumulative distribution of D_s

which can be placed on the gradient in terms of the distribution with frequency of the individual E_s values. This interpretation is restricted to the frequencies greater than f_pE_s since, below this value, both the cumulative and the frequency distributions are confused and irregular. For values above f_pE_s, therefore, the greater their rate of decrease with increasing frequency the greater will be the gradient of the cumulative distribution. Conversely, the slower the rate of decrease i.e. more frequent high values of E_s, the smaller would be the gradient. The gradient can then be regarded as a measure of the mean deviation of the individual E_s values from f_pE_s, being inversely dependent upon it.

On a simple qualitative consideration a large deviation, which corresponds to a small gradient and to relatively frequent high values of E_s, might reasonably be expected to be associated with high wind velocities. Although global information on high altitude winds is limited, it is known that there is a strong zonal component occurring at about 100 km and centred at about 30° N in summer and with a decreasing intensity at higher and lower latitudes. In winter this component decreases in altitude to about 70 km and has a greatly reduced intensity at 100 km (Batten, 1961).

Fig. 4.20 shows the latitudinal distribution for summer and winter from which it would appear that the maximum is at about 30°N in summer and slightly reduced in winter. It is just possible that this maximum in the gradient-latitude curve may be produced by the high zonal wind component which flows at about 30°N. It will be noted that in fig.4.20 the point corresponding to the winter gradient at Bogota has been ignored in drawing the curve. This is because as shown in Chapter 2 the seasonal variations at Taipei (Geomagnetic Lat. 13.7°N) and Bogota (Geomagnetic Lat. 16) are in opposite sense and if Bogota had been included the curve would have exhibited a spurious maximum at about 16°N Geomagnetic Lat. Examination of fig.4.20 suggests that, with the limited range of stations available, there is little change in either the position and magnitude of the high and mid-latitude maxima between quiet and disturbed conditions or between maximum and minimum solar activity.

The cumulative distribution may also be used to determine the percentage of E_s exceeding a given frequency or, alternatively, that minimum frequency required for a given percentage incidence of E_s. These are, fundamentally, different ways of expressing the same results. Figs 4.21 and 4.22 show the percentage of E_s exceeding 5 and 7 Mc/s and the frequencies necessary to produce 10 and 30 percentage incidence of the total occurrence of E_s for quiet and disturbed conditions during IGY and IQSY.

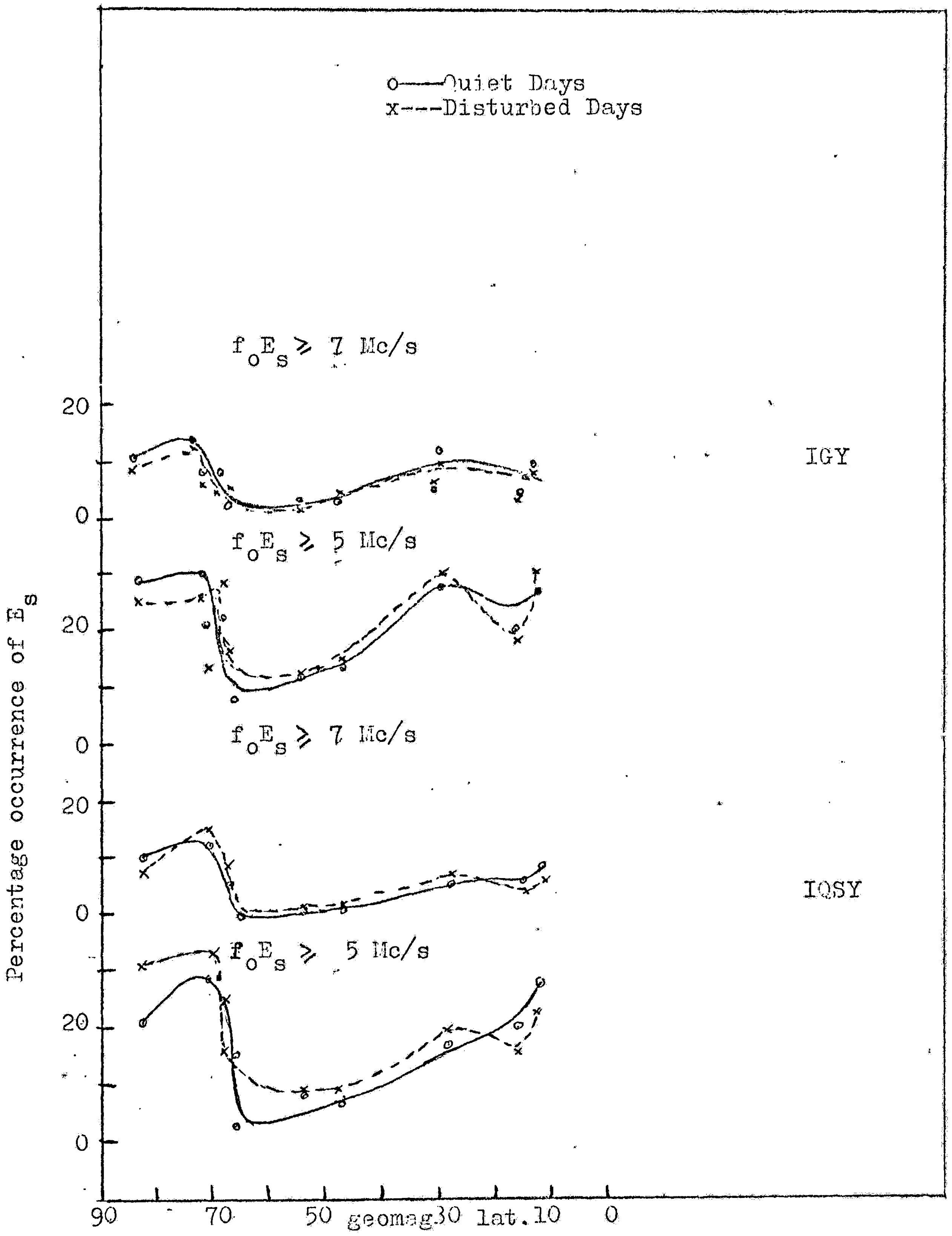


FIG.4.21: Latitudinal variation of percentage occurrence of I

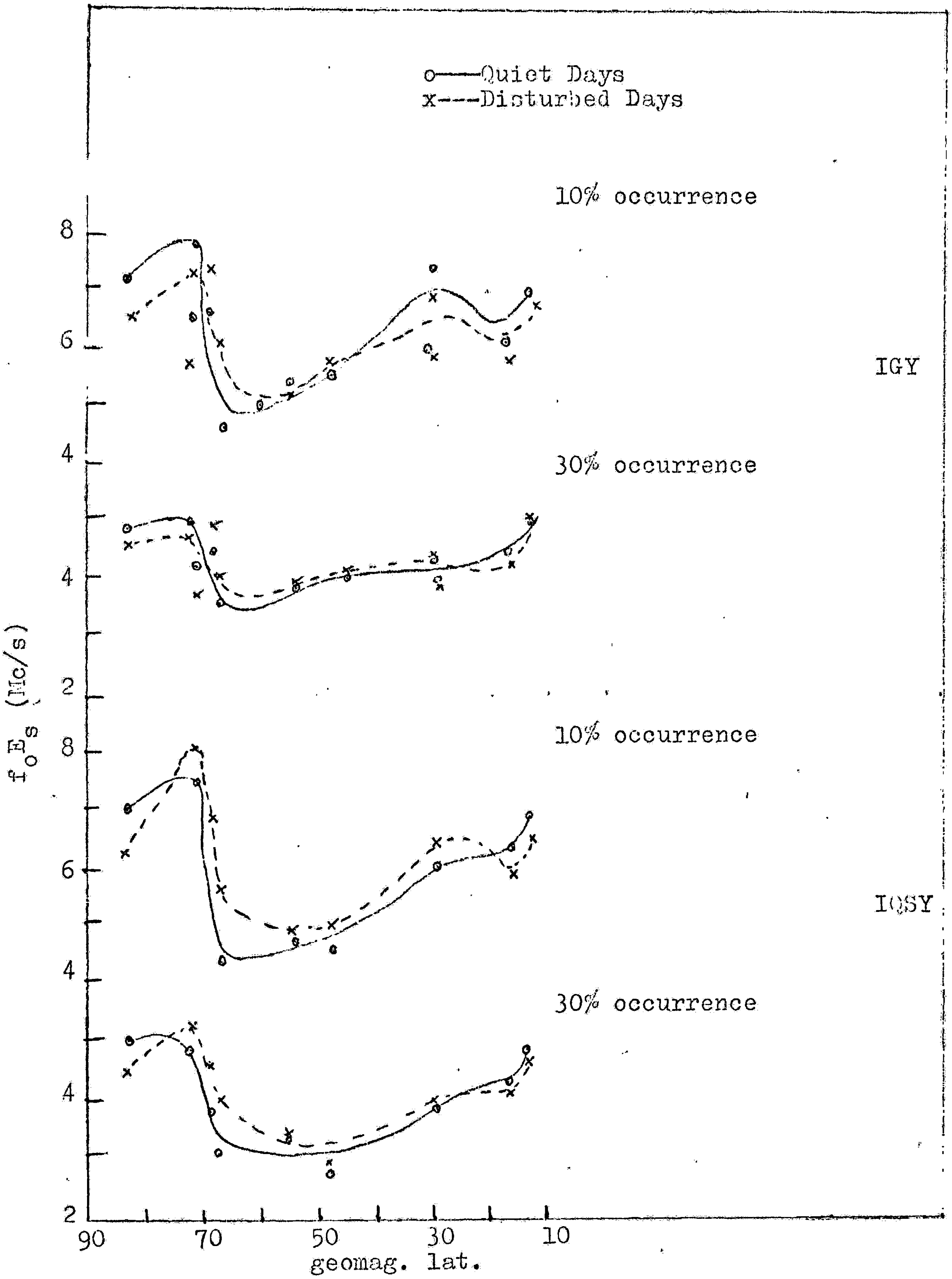


FIG.4.22: Latitudinal variation of the frequency

As far as magnetic activity is concerned the frequency or percentage, as the case may be, is generally greater on disturbed days but this should not be taken as indicating a positive magnetic dependence since the figures relate to the percentage of E_s observations, rather than to the total number of observations on quiet and disturbed days separately. Neither should they be confused with the D/Q ratio which refers to the total number of occurrences on disturbed days to those on quiet days.

There is, in these diagrams, a sharply defined rapid increase in the occurrence and the frequency at about 67°N and also an indication of a plateau or maximum at about 30°N (which persists even if the Bogota point is ignored). With the limited number of stations used in the present study it is not possible to define this latter region and so no investigation of the extent of, firstly, its reality and, secondly, its behaviour can be made.

The latitudinal variation of the ratio of the number of occurrences of sporadic-E on disturbed days to whose on quiet days is shown in fig.4.23. At low temperate latitudes this ratio is found to be slightly more than one for most of the stations between 13°N and 35°N geomagnetic latitude during sunspot maximum years, but is rather less than one during sunspot minimum years.

This negative relationship between the occurrence of sporadic-E and magnetic activity during IQSY and the positive one during IGY are found when all the various types of E_s in all seasons are taken together. In Chapter 6, which considers each type of E_s

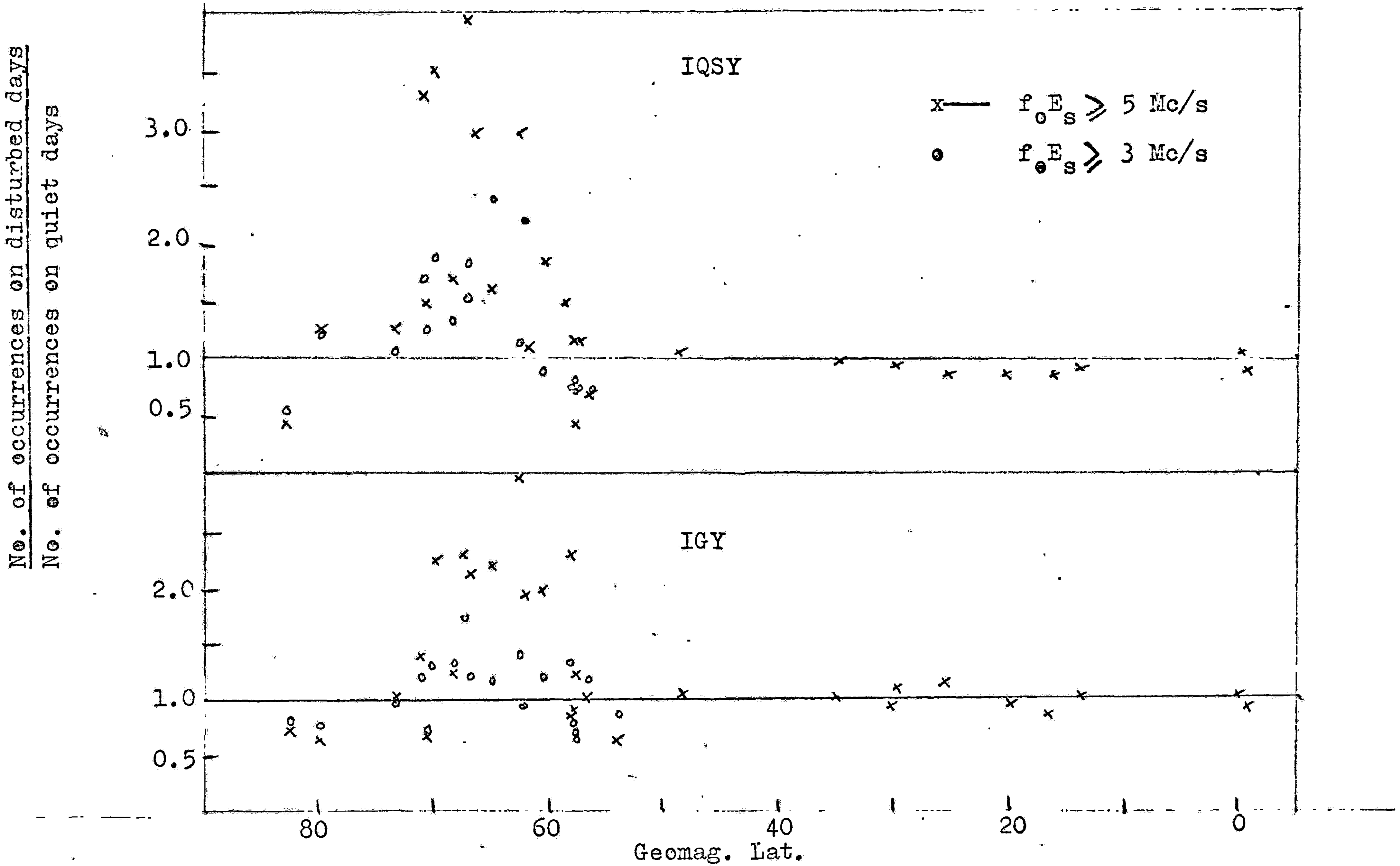


Fig.4.23: Latitudinal variation of occurrence of E_s

individually, it is shown that these positive and negative correlations depend on the type of E_s and its relative occurrence at different times of the day and in different seasons.

At higher latitudes, this ratio is found to be much greater than one for all the stations between 60° and 70° geomagnetic latitude. There is thus a strong positive correlation between the occurrence of sporadic-E and magnetic activity in this latitude range. At stations within the polar cap and at high temperate latitudes the correlation again reverts to a negative one.

However, it was noted that at a few stations just north of 70°N and just below 60°N geomagnetic latitude, this ratio is less than one in sunspot maximum years and more than one in sunspot minimum years and vice-versa respectively. In other words, according to these few stations at the upper boundary of the classical auroral zone, sporadic-E is negatively correlated with magnetic activity in sunspot maximum and positively correlated in sunspot minimum years with a similar effect taking place at the lower boundary.

This feature suggested a more detailed study in the auroral region of the occurrence of E_s on quiet and disturbed days.

An attempt has thus been made, in the next chapter, to see whether these changes in behaviour at the edge of the auroral zone provide any insight into the formation of the E_s auroral zone and any temporal changes which may occur there.

CHAPTER 5

SPORADIC-E IN THE AURORAL ZONE

5.1 Introduction

In the previous chapter it has been seen that when the parameter k, the ratio of the number of occurrences greater than a given frequency on disturbed days to those on quiet days, is plotted against geomagnetic latitude, there is a distinct increase in the auroral zone. The values do not show a smooth variation with geomagnetic latitude nor do they exhibit the well-defined maximum in or near the auroral zone, which might be anticipated during either solar maximum or minimum conditions.

While the auroral zone behaviour of E_s has been examined in greater detail using k, this approach has also been found to possess certain disadvantages and consequently an alternative approach has also been employed. This and the following chapter, therefore, contain two methods of examining the auroral zone behaviour of E_s, each method possessing certain merits of its own.

The use of k means that data can be used from all the stations, thereby providing comprehensive spatial coverage and enabling a reasonable appreciation of the E_s auroral zone to be obtained simply and without the danger of the data sample becoming too small.

The use of k presumes that there is no movement of the zone with magnetic activity. Consequently, this method gives no indication of any fine structure of the auroral zone, such as the presence of discrete and diffuse events, to which further reference will be made in section 6.5 Further, as that section will show, any variation in k will arise primarily from the discrete events and, in the light of this latter feature, the interpretation of the results provided by k is not straight forward.

The alternative approach is to examine E_s in terms of those types which occur specifically in the auroral zone, namely auroral, retardation and slant types. This imposes severe restrictions, however, on the information which can be obtained for a study of the auroral zone, only three European, six Russian and no American stations reporting E_s data classified by types during the IGY. There has subsequently been a small increase in this type of data.

This method, however, does provide strong evidence of the fine structure of E_s in the auroral zone. It is also found that during winter a-, r- and s-types predominate strongly over f-, l-, h- and c-types and thus any results obtained from this period are comparable with those obtained from the use of all types of E_s. Such a comparison cannot be made during the summer and equinoxes.

5.2 Latitudinal variation of the parameter k

With this approach a plot of k against geomagnetic latitude for all the available data results in the scattered distribution shown in fig. 4.23. Replacement of geomagnetic latitude by magnetic dip produces only a marginal reduction in the degree of scatter.

In order to obtain a physically more meaningful variation of k, an alternative parameter for measuring the position of a station was required. This uses the mean visual auroral zone (Feldstein, 1960) and the position of the station relative to this zone was found by measuring its departure from the nearest point of the zone in terms of geomagnetic latitude.

Since the centre of this zone is displaced from the geomagnetic pole, stations with the same geomagnetic latitude will not, in general, be the same number of degrees from this mean auroral zone.

In figs 5.1 and 5.2, k has been plotted against this latitude difference $(\Delta\Phi)$ for a number of high latitude stations and it is immediately clear that a much smoother variation is obtained than with either geomagnetic latitude or magnetic dip. The values of k in figs 5.1 and 5.2 are twenty-four hour average values over the whole of IGY and IQSY and are given for $f_oE_s \geqslant 3$ Mc/s and $f_oE_s \geqslant 5$ Mc/s. In all the cases a reasonably well-defined peak is observed which lies between 2° and 5° south of Feldstein's auroral zone.

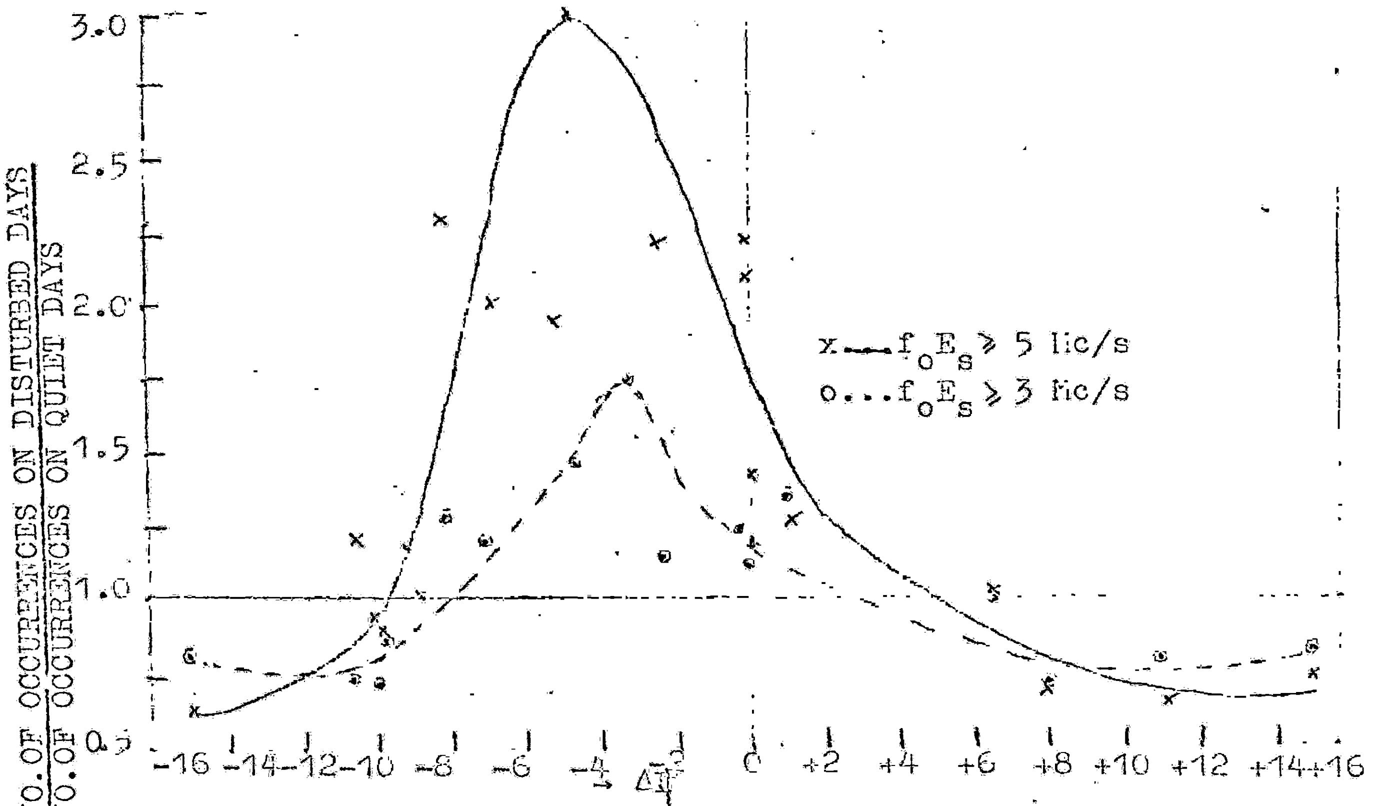


FIG.5.1: Latitudinal variation of k during the IGY

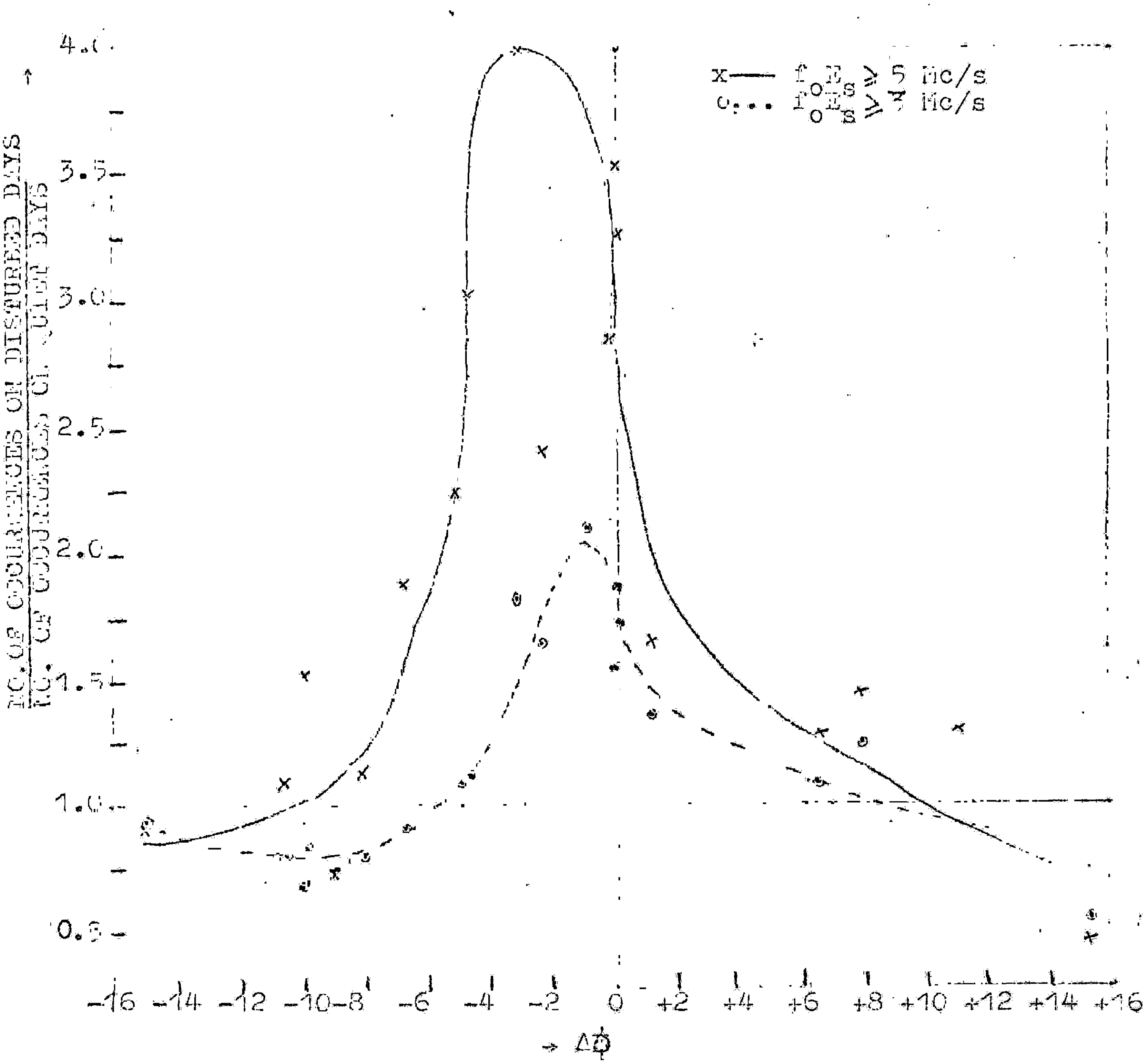


FIG.5.2: Latitudinal variation of k during the IQSY

The polar diagram in fig. 5.3 shows the average value of k for all the high latitude stations in IGY. The solid line A is the approximate locus of the maximum value of k as a function of longitude and thus represents the region of maximum E_s auroral activity. The two dotted lines B and C correspond to values of k equal to one and thus represent the mean upper and lower boundaries of the zone. Curve D is the mean visual zone and is seen to be about 5^o north of the E_s zone and concentric with it. In order to provide slightly more uniform coverage the values of k for some stations have been derived from data given by Thomas (1962).

The position of the E_s auroral zone in IQSY is given in fig. 5.4. Although not so clearly defined as during IGY it would appear to have moved to a higher latitude, while there is a definite poleward movement of the upper boundary.

This movement may be demonstrated more effectively by plotting (^{k}IQSY - ^{k}IGY) for each station (fig. 5.5). At lower latitudes this quantity is negative while, at higher latitudes, the difference becomes positive indicating a poleward movement of the E_s auroral zone.

A more detailed examination of the position of the E_s auroral zone has been made by dividing the day into three-hour periods (23-01, 02-04, 05-07, 08-10, 11-12, 14-16, 17-19 and 20-22 LT) and calculating the

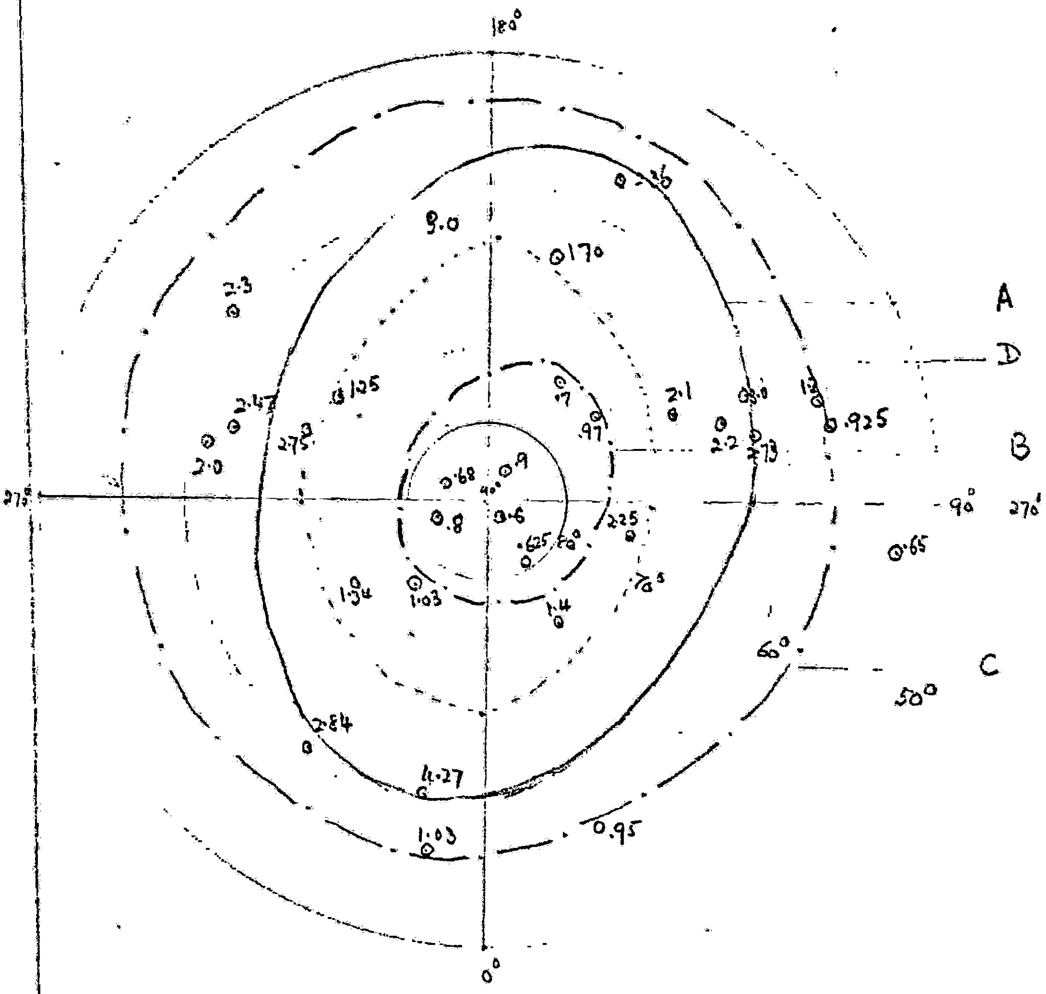


FIG.5.3: Polar diagram during the IGY for k

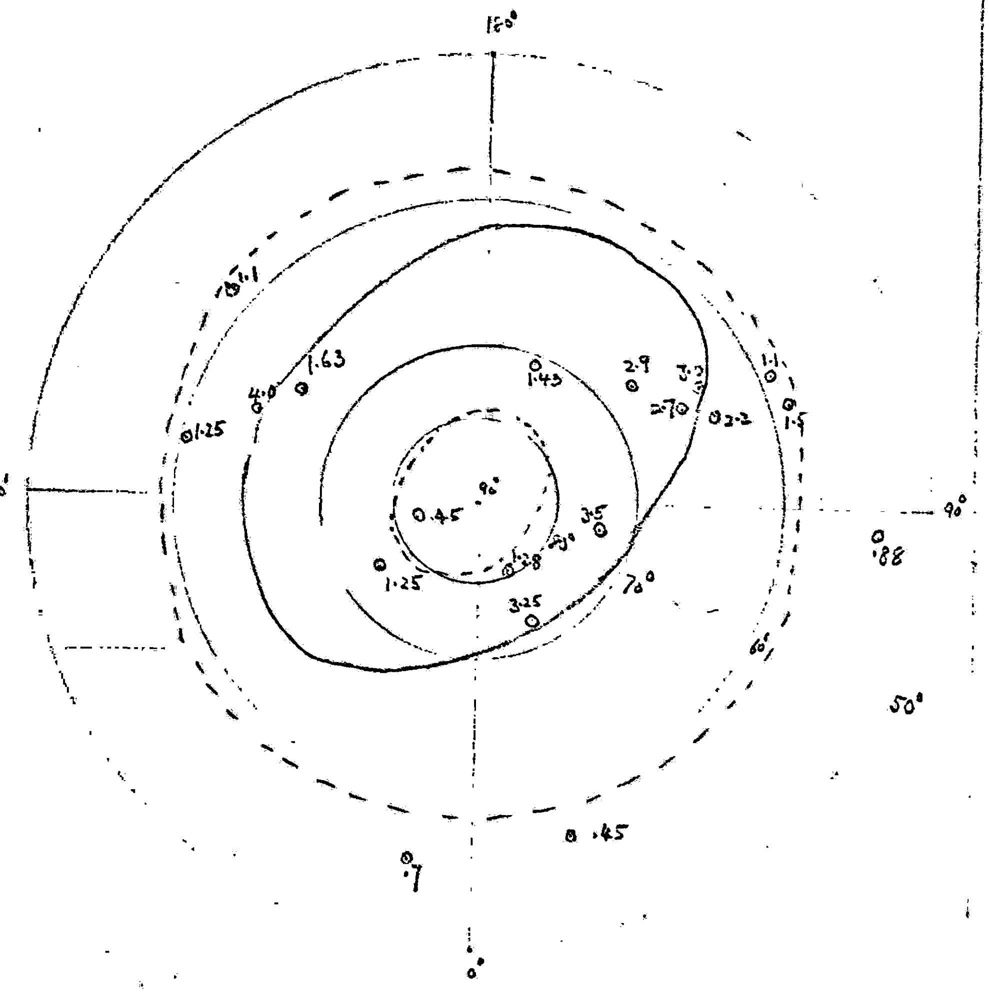


FIG.5.4: Polar diagram during the IQSY for k

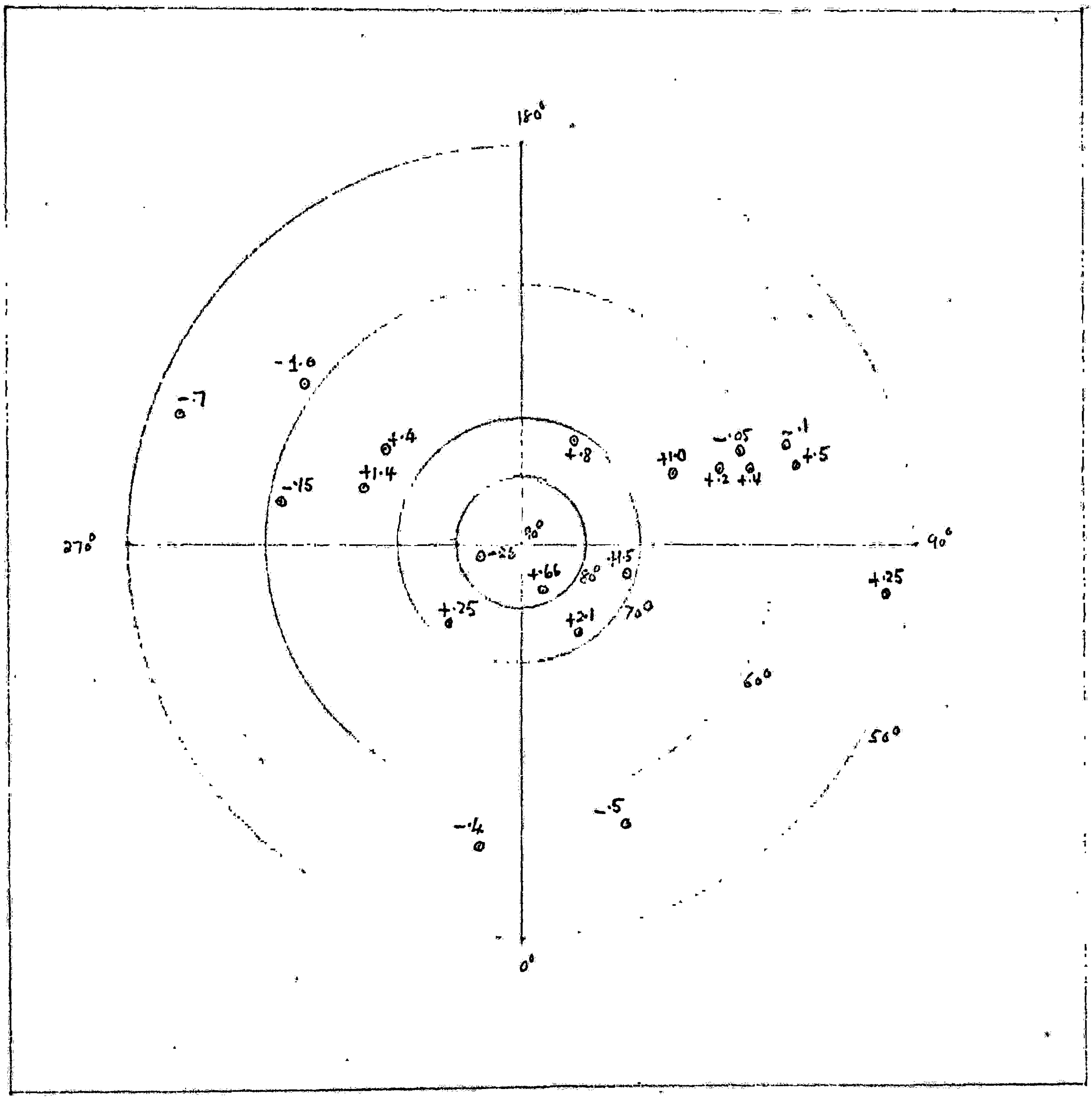


FIG.5.5: Polar diagram for $k_{IQSY} - k_{IGY}$

average value of k during each of these periods for each station. The latitude variation in terms of and as a function of local time is given in fig. 5.6 for the summer period of IQSY. It is clear that there is a strong diurnal variation in k with the result that there is a pronounced peak which has a minimum latitude at about local midnight and which moves northwards to a maximum latitude at about local noon.

Similar plots have been obtained for the three other periods viz: Winter IQSY, summer IGY and winter IGY. In all these three periods very similar variations in k are observed, the only differences being detailed ones in the position and magnitude of the peak in k. It is thus clear that there is a relatively large diurnal movement in the position of the region with values of $k > 1$, i.e. the E_s auroral zone, with an average latitude movement of about 9°.

The actual latitudinal extent of this E_s auroral region has been determined by measuring the two latitudes ($\Delta\phi$) at which k becomes equal to one for each period of time in fig. 5.6. While this choice is somewhat arbitrary it does represent the latitude at which the relationship between E_s and magnetic activity changes from being a negative to a positive one and vice-versa. These upper and lower boundaries have been plotted separately as a function of local time in fig. 5.7(a) for summer and winter in IGY and IQSY.

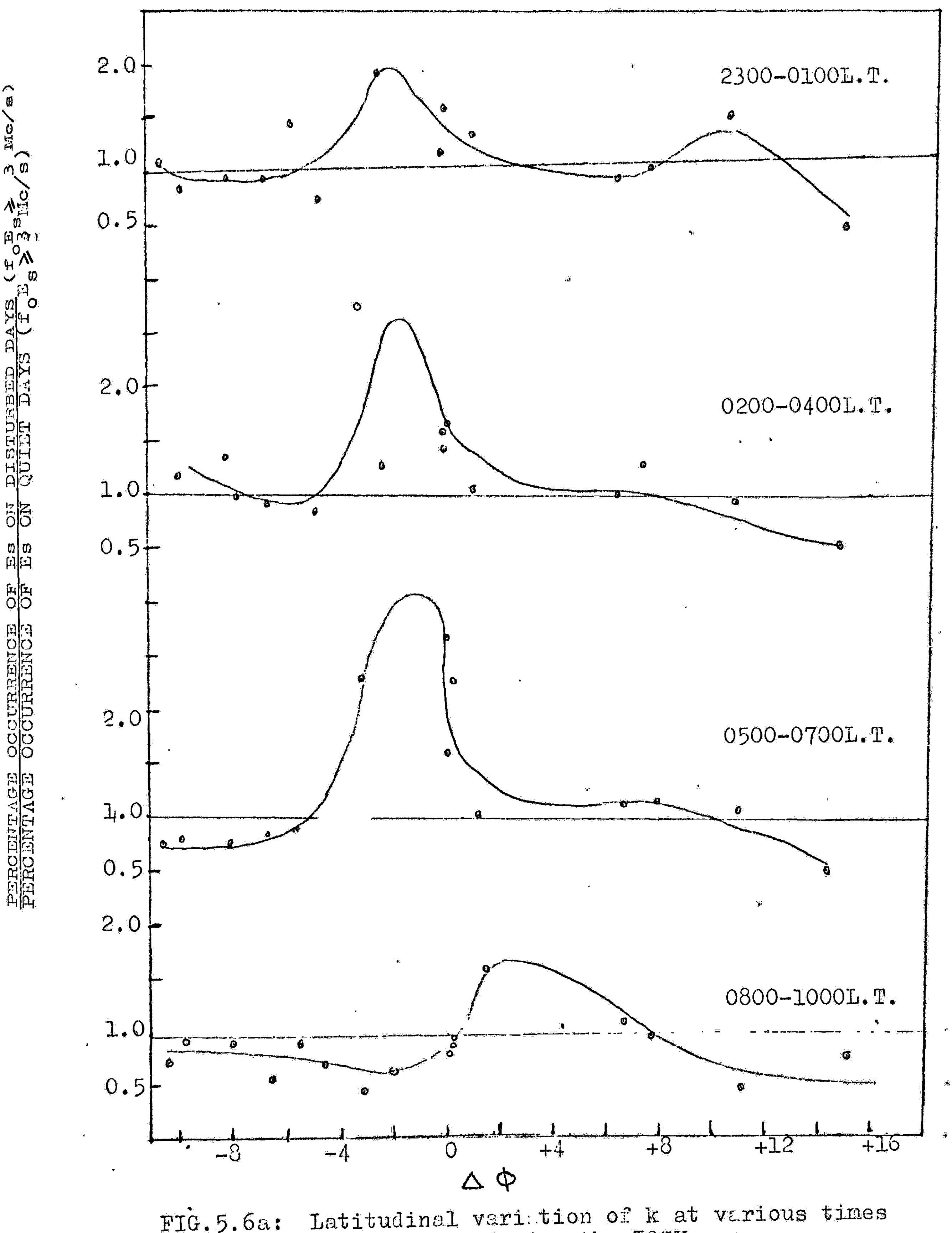


FIG. 5.6a: Latitudinal variation of k at various times of the day during the IQSY summer

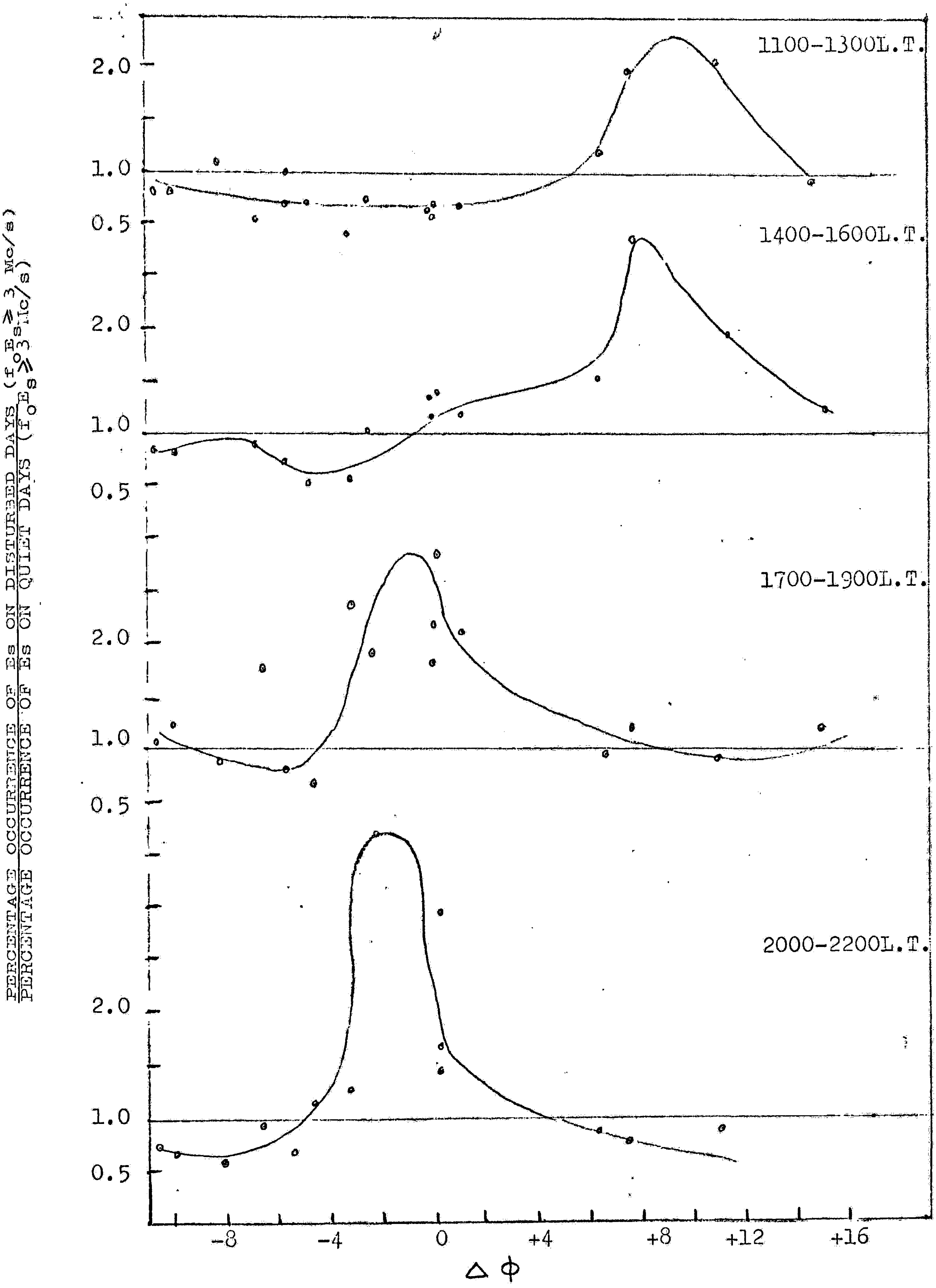


FIG. 5.6b: Latitudinal variation of k at various times of the day during the IQSY summer

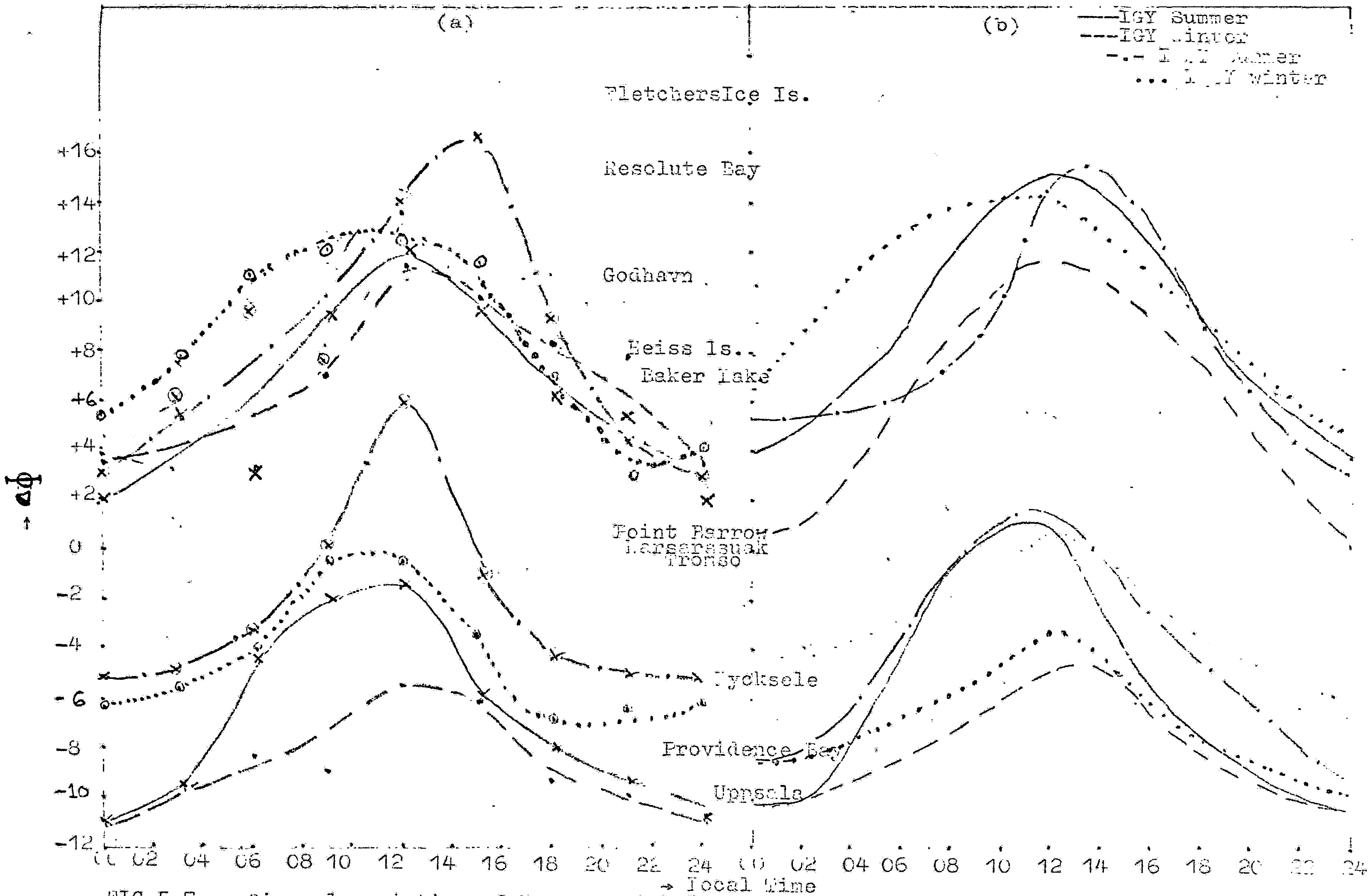


FIG.5.7: Diurnal variation of E_s auroral belt

While the diurnal variations in this figure are rather irregular, it is nevertheless apparent that there is a definite poleward movement from IGY to IQSY of the lower boundary which also indicates that, for a given solar activity, the winter position is lower than that in summer. The general variation for the upper boundary is similar but the above seasonal and solar activity changes are not so well pronounced.

An alternative means of determining the boundaries of the E_s auroral belt is to plot the diurnal variation of k for each individual station, for which some typical examples are shown in fig. 5.8. From these individual plots of k the time or times at which k becomes equal to one are found and then plotted as a function of $\Delta\phi$. This represents the time at which the boundary of the auroral belt is passing overhead of the station in a north- or south-bound direction. From the resulting distribution of points smooth curves are drawn to define the upper and lower boundaries of the E_s auroral belt. These are given in fig. 5.7(b) for the same conditions as in fig. 5.7(a).

With this approach smoother diurnal variations are obtained and there is clear evidence for a poleward movement from IGY to IQSY and for the winter boundaries to be lower than those in summer.

The incidence of E_s at auroral stations in relation to varying degrees of magnetic activity can

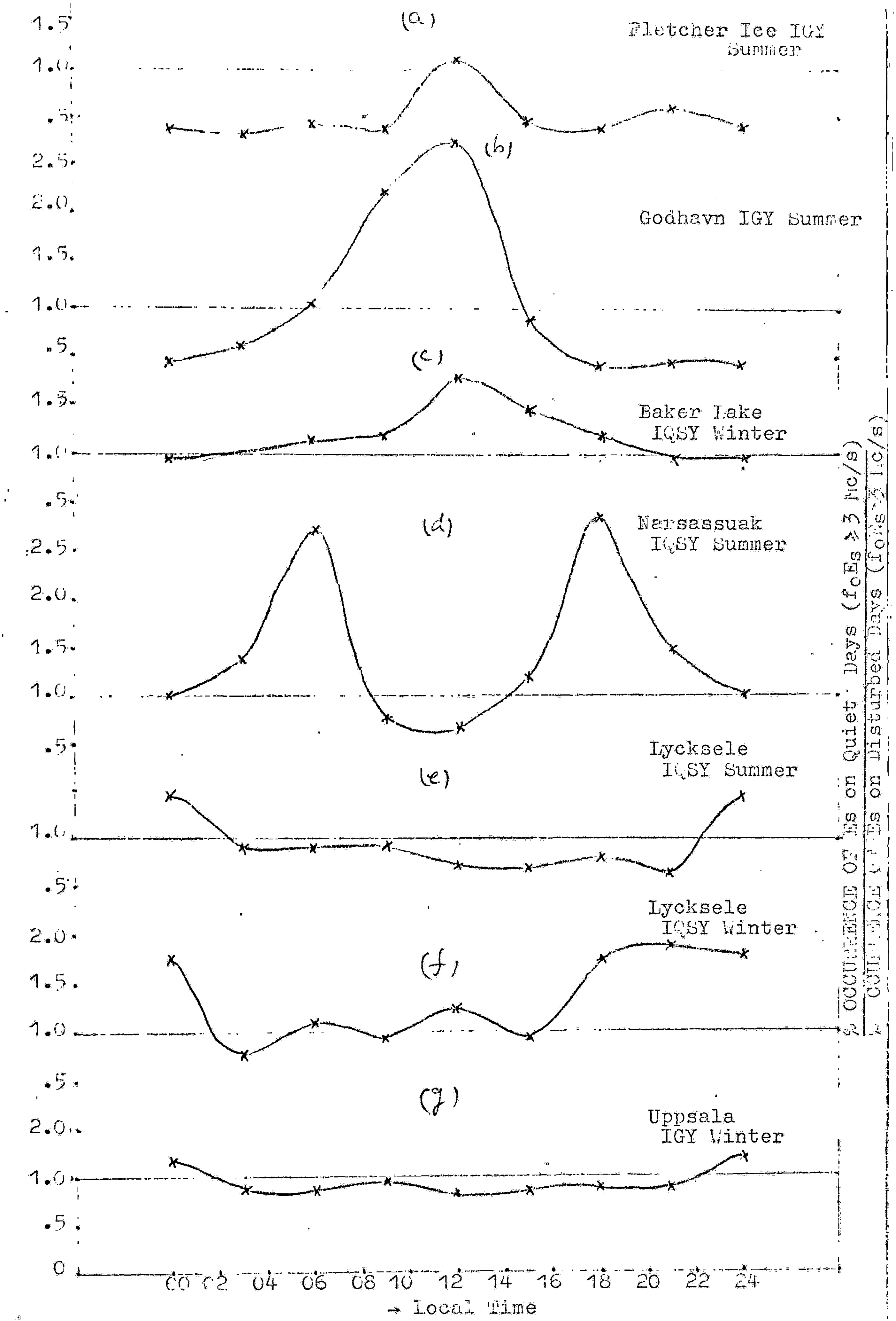


FIG.5.8: Diurnal variation of k

now be seen to follow directly from the diurnal motion of the auroral belt and the examples in fig. 5.8 illustrate this.

At Fletcher's Ice Island, fig. 5.8(a), it will be observed that, apart from a short period at local noon, k is much less than one throughout the whole of the day. Comparison with fig. 5.7 of the movement of the upper boundary of the auroral belt for IGY summer shows that, at local noon, this station is very nearly situated on the edge of the auroral belt, corresponding to k = 1. For the remainder of the day it is situated well inside the polar region accounting for the low observed values of k.

At Godhavn (fig. 5.8b) the auroral belt passes over the station for the middle of the day giving $k > 1$ while, for the remaining period, it is situated in the polar region with $k < 1$.

In fig. 5.8(c), which is for Baker Lake in IQSY winter, k is equal to or greater than one throughout the day apart from a short period near local midnight when k falls slightly below one. This implies that the station is almost entirely within the auroral belt and comparison with the appropriate curve in fig. 5.7 shows that this is so.

For the above three stations the diurnal variation is simple with a single maximum in k at midday. In fig. 5.8(d), which is for Narsarssuak in IQSY summer, however, there is a striking change in the diurnal variation of k in that two maxima are observed at 0600 and 1800 hrs local time. At midnight k falls to unity while at midday it falls to less than one. By reference to fig. 5.7 the two maxima can be interpreted in terms of the central and most intense part of the auroral belt passing northward over Narsarssuak in the morning and southward again in the evening. Also, the midnight value of $k=1$ corresponds to a position on the boundary between the auroral and polar regions while the values of $k<1$ at midday correspond to Narsarssuak being a high temperate latitude station, since the lower edge of the auroral belt has actually gone to a latitude higher than that of the station.

The two curves given for Lycksele for IQSY summer in fig. 5.8(e) and IQSY winter in fig. 5.8(f) are provided to illustrate the seasonal movement of the auroral belt. From fig. 5.7 it will be observed that the equatorward boundary of the belt is at a lower latitude in winter than in summer. Consequently, a station such as Lycksele will be in the auroral region for a longer period of night and also will be approached more closely by the centre of the belt. Both these features are observed in figs 5.8(e) and 5.8(f) in that k is greater than one for a longer period in winter and also reaches higher values. It will be noted that k falls only slightly below one during winter as compared to its much lower values in summer. The two peaks evident at Narsarssuak have also approached each other and coalesced so that it can be inferred that the centre of the auroral belt does not extend to a lower latitude than that of Lycksele.

The diurnal variation of k at Uppsala for IGY winter (fig. 5.8g) may be regarded as the reverse of that at Fletcher's Ice Island. In this case $k < 1$ during the whole of the day, corresponding to a high temperate latitude position, apart from a single value greater than one at midnight. This, as will be seen from fig. 5.7, is when the southern edge of the belt briefly extends down to the latitude of Uppsala.

The above examples have been selected to show how the model (fig. 5.7) agrees with the observed magnetic dependence of E_s. While the diurnal variations of k for all the other stations during summer and winter in both IGY and IQSY do not agree in precise detail on all occasions with the model, they do provide, when considered collectively, the above internally consistent results.

The variation of k at Narsarssuak, as described above, shows that the station behaves as a high temperate latitude one at midday and very nearly as a polar one at midnight. The possibility exists, therefore, that a station at a slightly higher latitude might behave as a high temperate and a polar one within one day.

In fact, as fig. 5.7 shows, there is only one occasion when the lower latitude limit of the upper boundary at midnight becomes equal to or less than the high latitude limit of the lower boundary at midday. This is in IQSY summer in fig. 5.7(a).

The region of overlap, however, is one in which no station exists and hence the possibility of a station behaving in a cyclic fashion of polar, auroral, high temperate, auroral and polar could not be established. The group of stations Tromso, Reykjavik, Narsarssuak and Point Barrow situated within a 1° interval of $\Delta\phi$ and approaching this condition on occasions did not in practice reach it.

The two approaches used above to show the diurnal movement of the E_s auroral belt, i.e. the latitude variation of k at a fixed time or the time variation of k at a fixed station, should lead to the same result since they employ the same basic data. The corresponding curves in fig. 5.7(a) and 5.7(b) should thus be similar. As will be seen, insofar as the seasonal and solar activity changes are concerned, the relative changes in both the diagrams are closely comparable for the lower boundary. For the upper boundary the comparison is not so good, principally because only a few stations were available to define it. While the division of the data into three-hour periods reduces the size of each sample and thereby increases the statistical error of each point, **if** the data is averaged over a twenty-four hour period it is still possible to observe the seasonal movement of the belt.

Fig. 5.9 shows the latitude variation of k for June-July and Dec.-Jan. for solar maximum and minimum conditions. There is a clear seasonal movement for $f_oE_s \geqslant 3$ Mc/s and $\geqslant 5$ Mc/s of some $2 - 3^{o}$ in a poleward direction from winter to summer. These two frequencies are given because for the 3 Mc/s level the IGY curve shows little evidence of a peak in k and in all cases the 3 Mc/s variation of k shows a lower peak value than for 5 Mc/s.

There is one major difference in the above two methods for finding the boundaries of the E_s auroral belt. When using the individual latitude plots, as in fig. 5.6, the location of the most intense inner part of the belt, where the incidence of E_s will be a maximum, can be readily read off from the graphs. This has been done for summer and winter in IGY and IQSY and fig. 5.10 shows the diurnal movement of the most intense part of the belt for these periods. As with fig. 5.7 it will again be observed that this region is at a lower latitude in winter than in summer in IGY and IQSY.

This diurnal variation is not so readily determined when the method using the diurnal variation of k is adopted. In this case it is only possible to find the centre of the belt when it passes directly over a station and such a passage can only be identified unambiguously when two separate maxima in k are

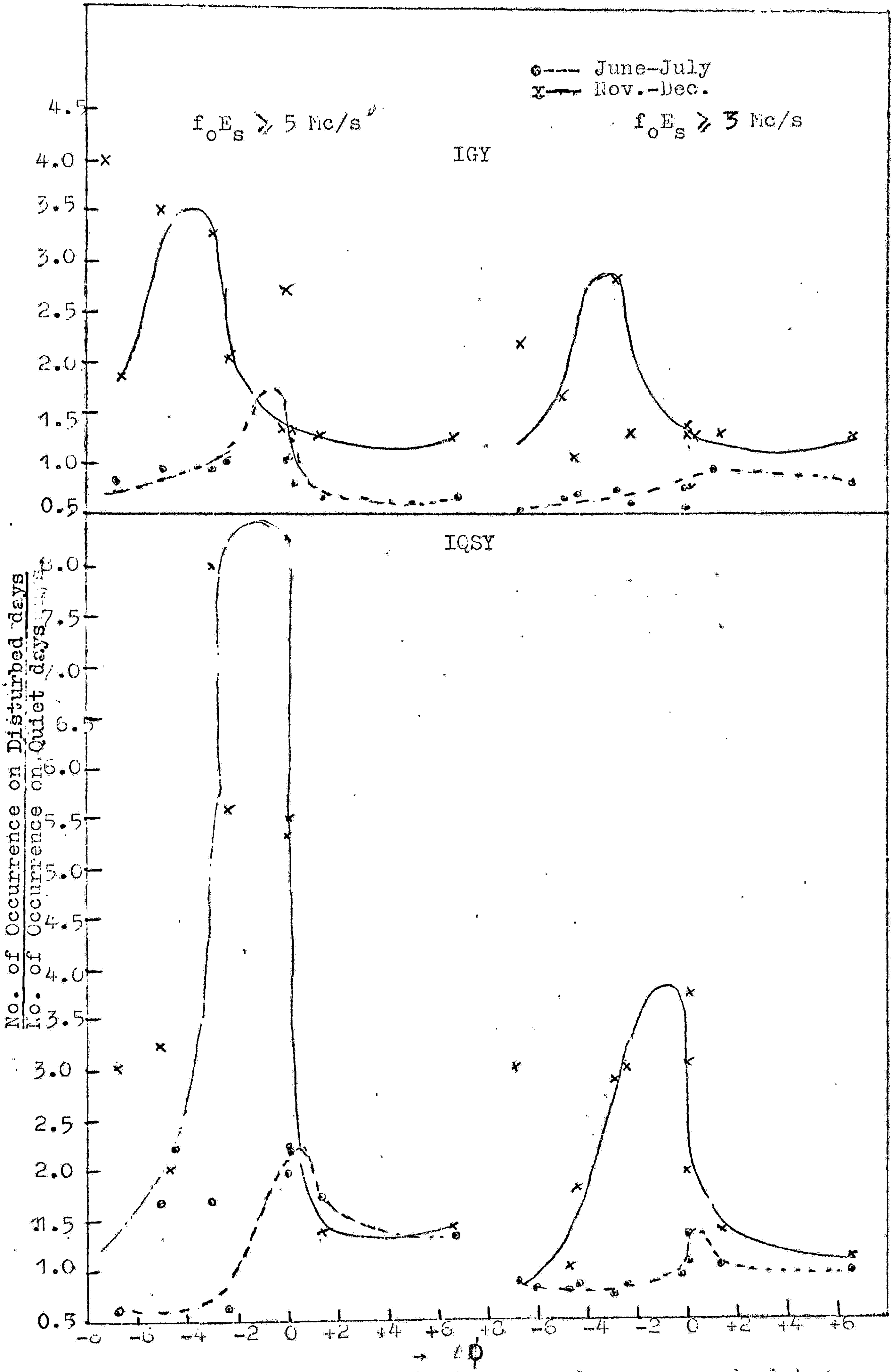


FIG.5.9: Latitudinal variation of k in summer and winter

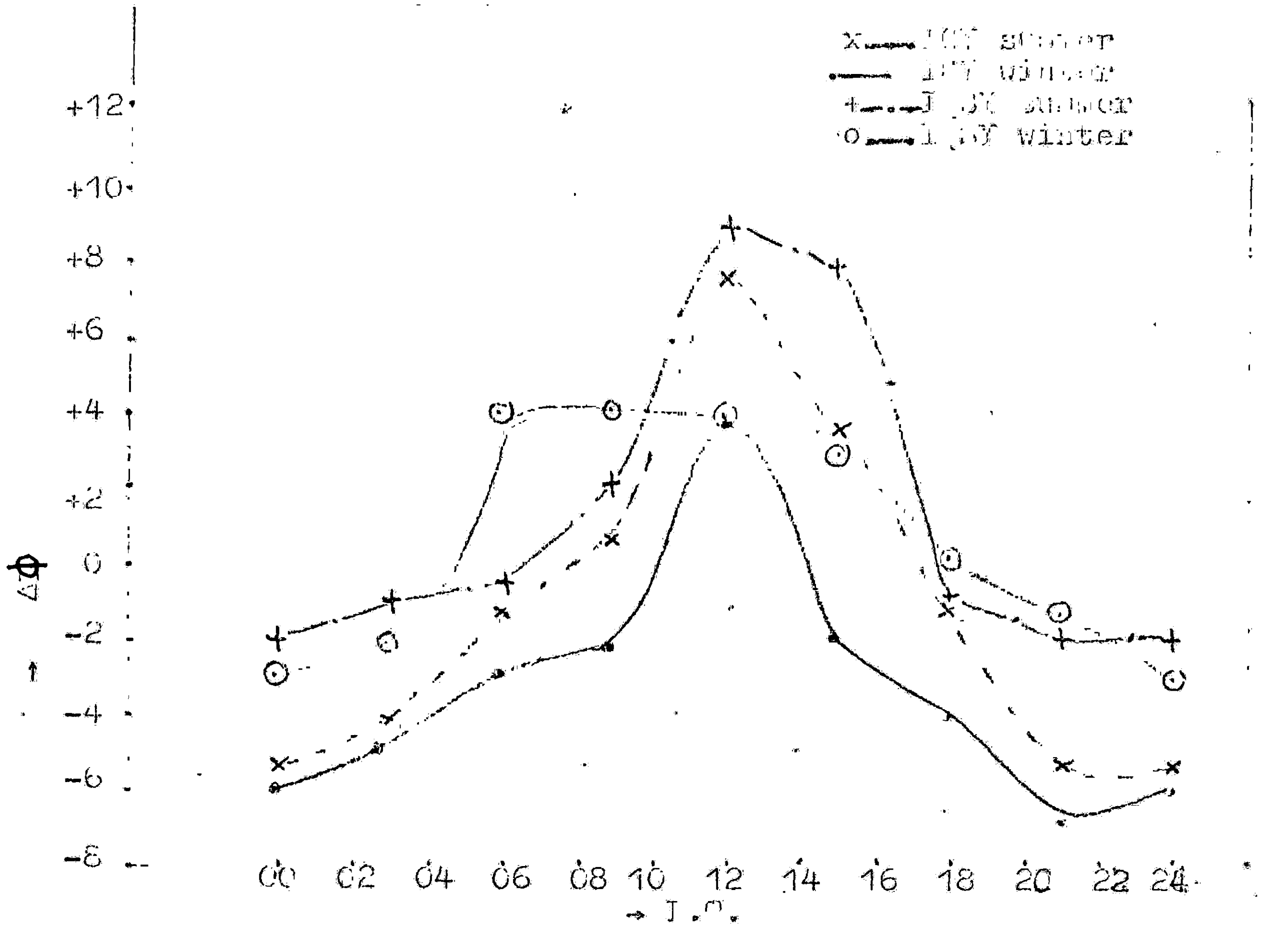


FIG.5.10: Diurnal variation of maximum E_s auroral belt

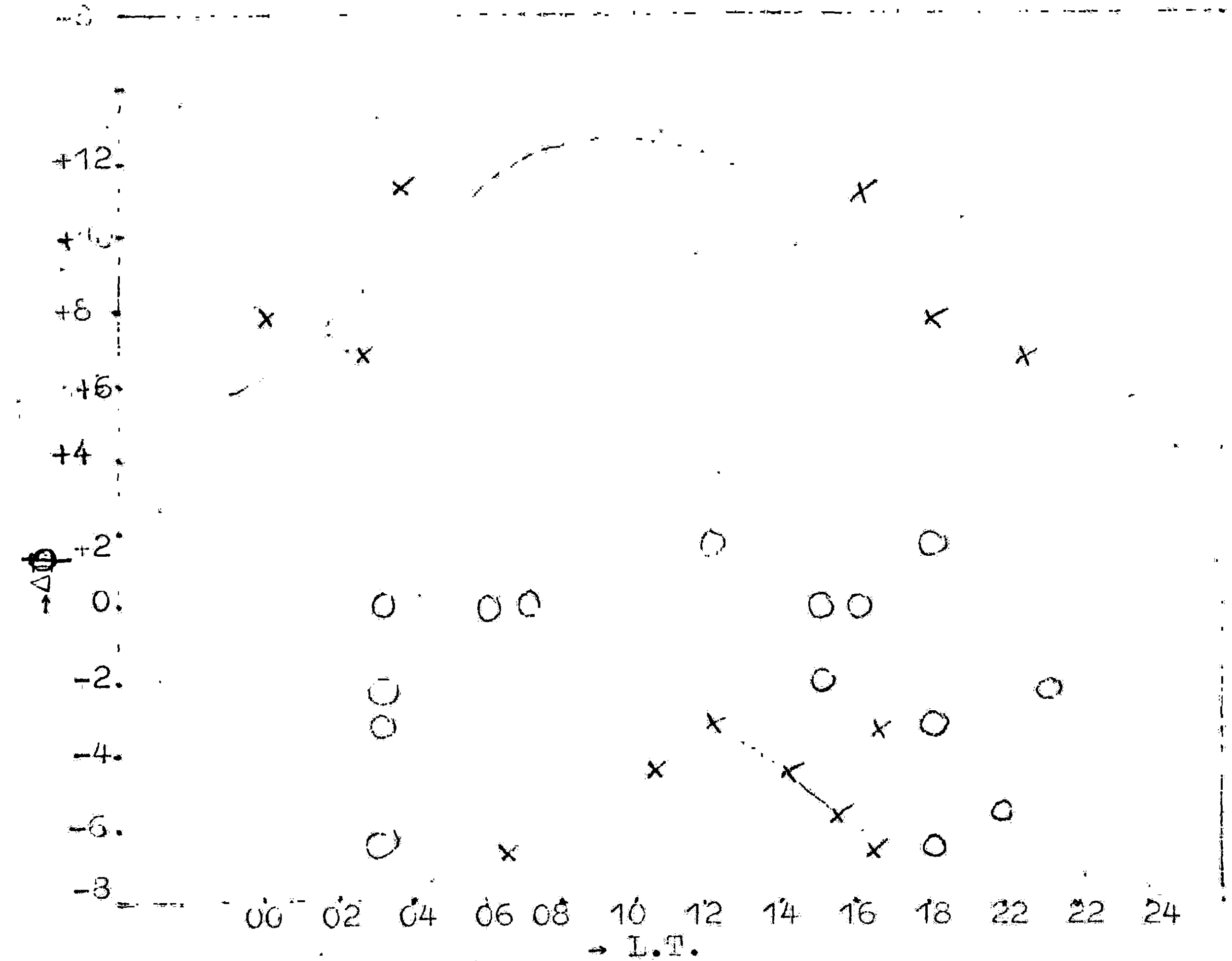


FIG.5.11: Diurnal variation of maximum auroral belt during IQSY winter with upper and lower boundaries.

observed, as in fig. 5.8(d) where the centre can be seen to have passed over in a northward direction at 0600 and in a southward direction at 1800 LT. An example of the times of the overhead passage of this centre for IQSY summer is given in fig. 5.11.

Although there is considerable uncertainty in each point due to the division of the data into three-hour intervals, they nevertheless form a reasonably consistent pattern. The absence of points around midnight and noon arises from the coalescence of the morning and afternoon maxima for, as they approach closely together, they cannot be resolved. It is then not possible to say whether the centre is passing overhead or whether one is simply observing the single maximum in k which will be obtained for all the stations above and below the midday and midnight latitude limits, respectively, of the diurnal variation of the centre.

5.3 Diurnal and seasonal movements of the auroral belt

The midday to midnight movement of the upper and lower boundaries, as shown in fig. 5.7, clearly varies from winter to summer and from IGY to IQSY, but has an approximate change of 8 - 9°.

This diurnal movement of the belt implies that the former simple classification of stations into polar, auroral and high temperate latitude types needs to be modified. While this reconsideration has also been suggested by Akasafu (1967), it has proved difficult to define the polar cap region due to the paucity of visual auroral observations around midday. With the E_s auroral zone measurements, however, this may readily be done and a diagram which illustrates this is given in fig. 5.12. The two pairs of curves B, B', and C, C' represent the upper and lower boundaries of the belt during IGY summer and for two opposing solar positions. The shaded area lying inside curve D is the "true" polar cap within which all stations will exhibit polar behaviour. Between curves A and D stations will behave in a manner which will vary between polar, auroral and high temperate latitude forms, apart from the area bounded by curves E and E'. In the region E E' all stations will behave throughout the day as auroral and thus it may be regarded as the true auroral zone. Curve E corresponds to the upper or midday position of the lower boundary and E' to the lower or midnight limit of the upper boundary, as may be seen in fig. 5.7.

The region between curves D and E' contains stations where behaviour will vary between polar and auroral, while those between E and A will similarily be of the auroral and high temperate latitude types. A represents the extreme lower limit of the lower boundary and so all stations beyond A will be of the high temperate latitude variety.

It thus follows that the polar cap is a

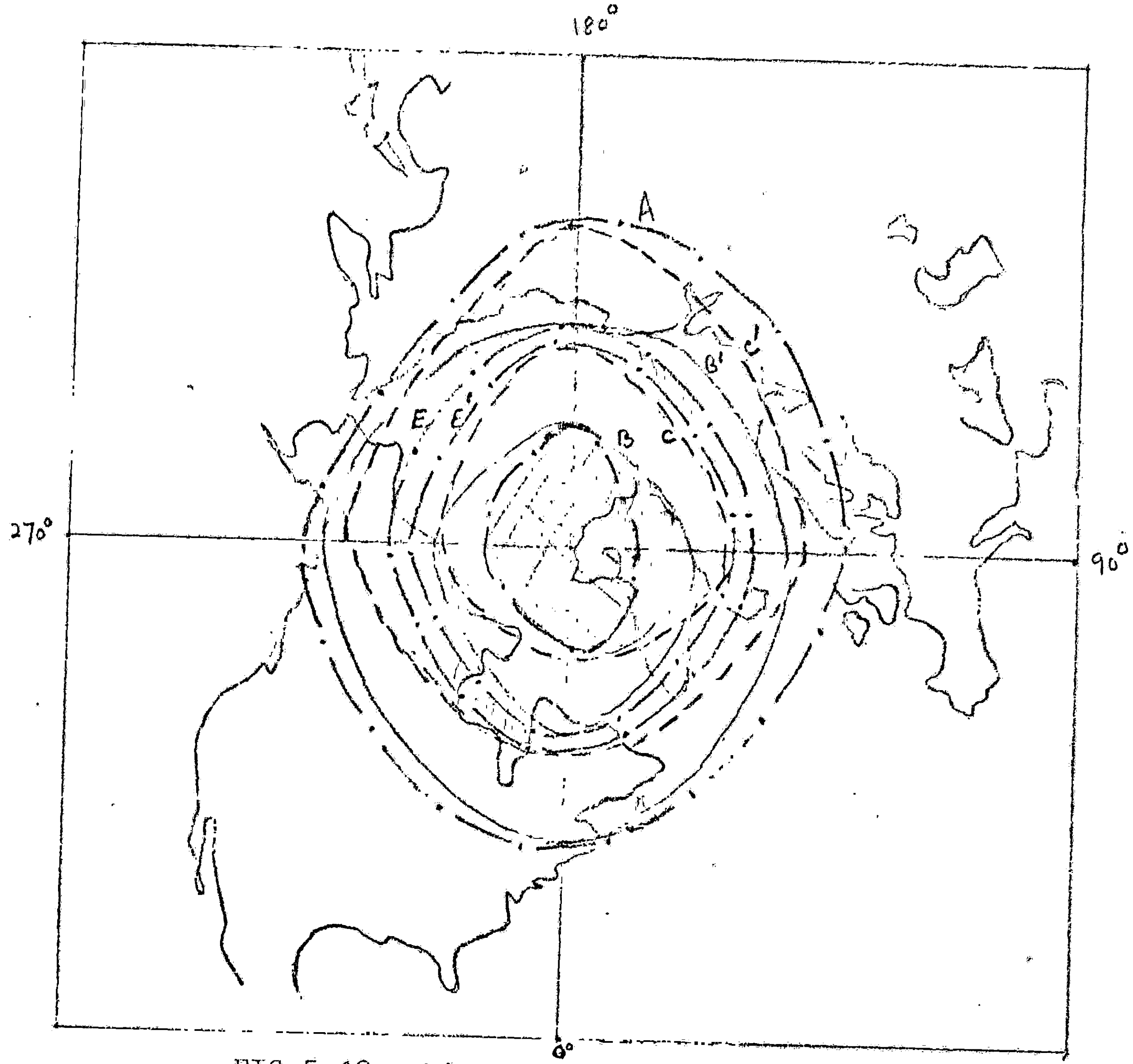


FIG.5.12: Diurnal movement of E_s auroral belt

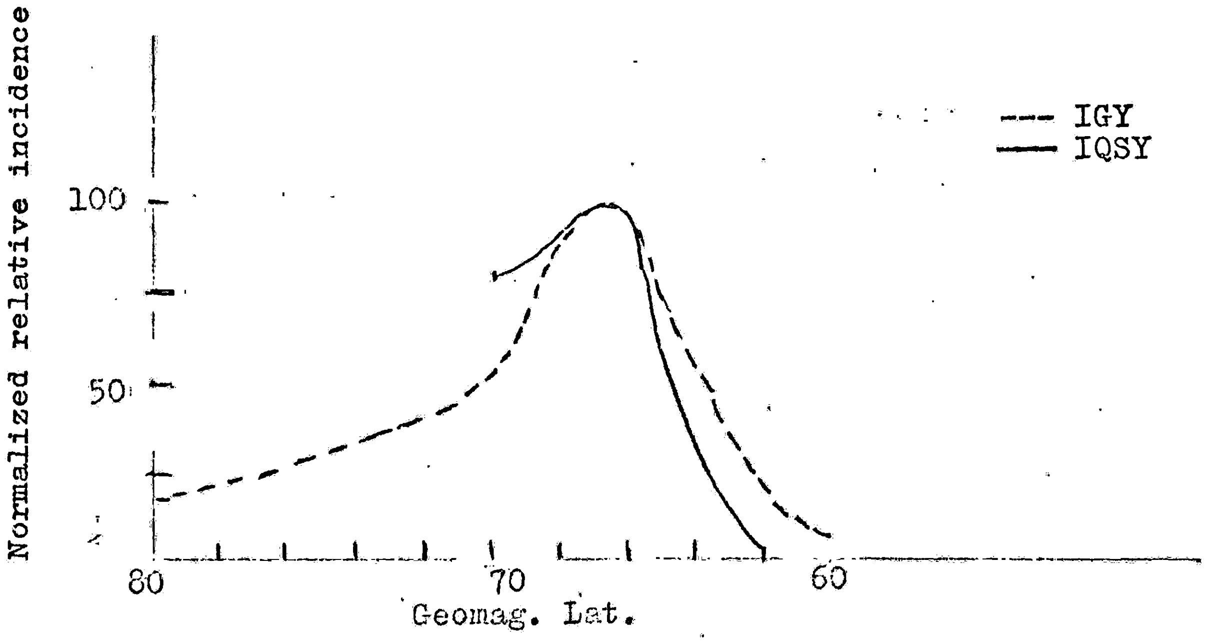


FIG.5.13: Variation of visual auroral belt.

relatively small area while true auroral stations only occur in the narrow range E E′. These considerations relate to the situation in one season and for a fixed solar activity only. As has been shown, there will be small changes with the seasons and for differnet levels of solar activity in the position and width of the auroral belt and in the low latitude limit D of the polar cap region.

While the above applies only to the E_s and not to the visual auroral zone, there is a well established diurnal movement of the visual belt. The relative positions of the two may thus be compared, but only a few values for the movement of the visual auroral oval are available due to the lack of visual observations during the middle of the day. The most comprehensive assessment of the IGY measurements by Feldstein (1963) gives an average movement over the whole of the IGY of 9^o, which compares well with the figure of 8^o obtained from fig. 5.7, and averaged over summer and winter. Observations for a single winter night by Davis (1961) give a movement between 1800 and 0100 LT of 7^o while the movement based on a large number of observations gives 6^o between 1700 and 0100 local time (Davis, 1962).

The curve given by Feldstein, and referred to in section 5.1, for the visual auroral zone relates to the average position of the centre of the zone around hours of darkness. Reference to fig. 5.10 shows that for the nighttime hours the average position of the centre of the E_s auroral zone is 1° to 4° south of the visual belt, depending on season and solar activity.

5.4 The effect of solar activity on the movement of the auroral belt

The solar cycle variation in the E_s auroral oval is quite pronounced and, although there are minor differences between corresponding curves in figs 5.7(a) and 5.7(b), the overall movements are basically the same. No single unique figure can be given for the solar cycle movement, since it depends to some extent on the time of day, but for the lower boundary a figure of approximately 2° in a poleward direction from IGY to IQSY can be given when averaged over the day for both summer and winter.

The centre of the zone (fig. 5.10) also shows a movement of about 2° in summer and a slightly greater one in winter. The diurnal movement of the upper boundary is more variable than that of the lower one and the solar actvity movement is not so well pronounced, giving an average movement which is somewhat less than 2°.

A similar figure of 2° is also observed from fig. 5.1 where the data is averaged over a twenty-four hour period and applies to both the 3 and 5 Mc/s distributions. This poleward movement of about 2° for the E_s oval compares closely with a value of

1 - 1.5° deduced by Starkov and Feldstein (1967) for the southern or midnight position of the centre of the visual auroral zone.

It will also be noted from figs 5.1 and 5.7 that there is no significant change in the overall width of the ovals, a result which has also been found for the visual auroral zone by Starkov and Feldstein (ibid). The similar movements of the centre of the visual and E_s auroral zones referred to above contrast with the visual zone results quoted by Davis (1962) which, although showing a 1° to 2° poleward movement of the southern boundary, show no evidence for any movement of the centre of the oval. This is a somewhat unexpected result since there is a well established short term equator-ward movement of the centre of the zone by a few degrees during a magnetic storm. Movements of the plasmapause from an L- shell of 2 or 3 during disturbed periods to L = 5 or 6 during quiet periods have also been observed (Carpenter, 1968). This is particularly relevant since the projection of the shell with L = 4 onto the surface of the earth falls very closely on the 15% visual auroral isochasm. Thus, since the change in solar activity from IGY to IQSY corresponds to a reduction in the average level of the magnetic activity, an accompanying movement of the plasmapause and hence of the auroral oval would be anticipated.

It might be noted that from the scale of the diagram given by Davis a displacement of the centre by 1 to $1\frac{1}{2}^{\circ}$ would be barely detectable while the IQSY curve is terminated only 3° on the poleward side of the centre. On the evidence, therefore, it would appear that there is a poleward movement of both E_s and visual auroral belts from solar maximum to solar minimum conditions.

CHAPTER 6

VARIATION OF a-, r- & s-type SPORADIC-E IN THE AURORAL ZONE

6.1 Introduction

An alternative approach to the problem of the incidence of E_s at high latitudes is to consider the behaviour of those types only of E_s which occur specifically at auroral latitudes. These are auroral (a), retardation (r) and slant (s) which are quite distinctive and not readily confused with the h-, l-, f- and c-types.

The number of high latitude stations which classify their E_s data is, however, small and during the IGY the only stations which reported types were Kiruna, Sodankyla and Lulea and six Russian stations. The latter were distributed over a wide range of longtitude and raise problems of interpretation when considered with three closely spaced European stations. The additional European stations Tromso, Lycksele and Uppsala commenced E_s type classification in 1959. Since a-, r- and s-types occur predominently during winter, data from all the above available stations has been used to study E_s behaviour during the winter of 1957/58, 1959/60 and 1964/65. Additional data is available from 1966 for College, Narsarssuak and Godhavn and this has also been used for winter 1966/67.

6.2 Diurnal variation of a-, r- and s-types E_s

The six European stations have been used to examine the diurnal variation within a narrow zone of longitude. Heiss Island has also been included, although it is some 30° of longitude away, since without it there would be a complete lack of data on the polar side of the auroral zone. Figs 6.1 and 6.2 show three-hour running averages for the percentage occurrence of a-, r- and s-types during the winter period for 1959/60 and 1964/65.

In 1959/60 the variations at Uppsala and Lycksele are similar when the maxima on disturbed days are at 2100 LT and a much smaller maximum incidence on quiet days is displaced later in the night. At Uppsala, it may be noted, the quiet day incidence is so low that it may be inferred that this station lies either inside or outside the auroral zone according to the intensity of magnetic activity.

As with the above pair of stations the disturbed days maxima at Lulea and Sodankyla preceed those for quiet conditions.

At Kiruna and Tromso broad plateaux for both quiet and disturbed conditions are observed with approximately 90% occurrence. In the three degrees of latitude between Tromso and Heiss Island there is a very pronounced change and no a-, r- or s-type E_s is observed at Heiss Island under any geomagnetic

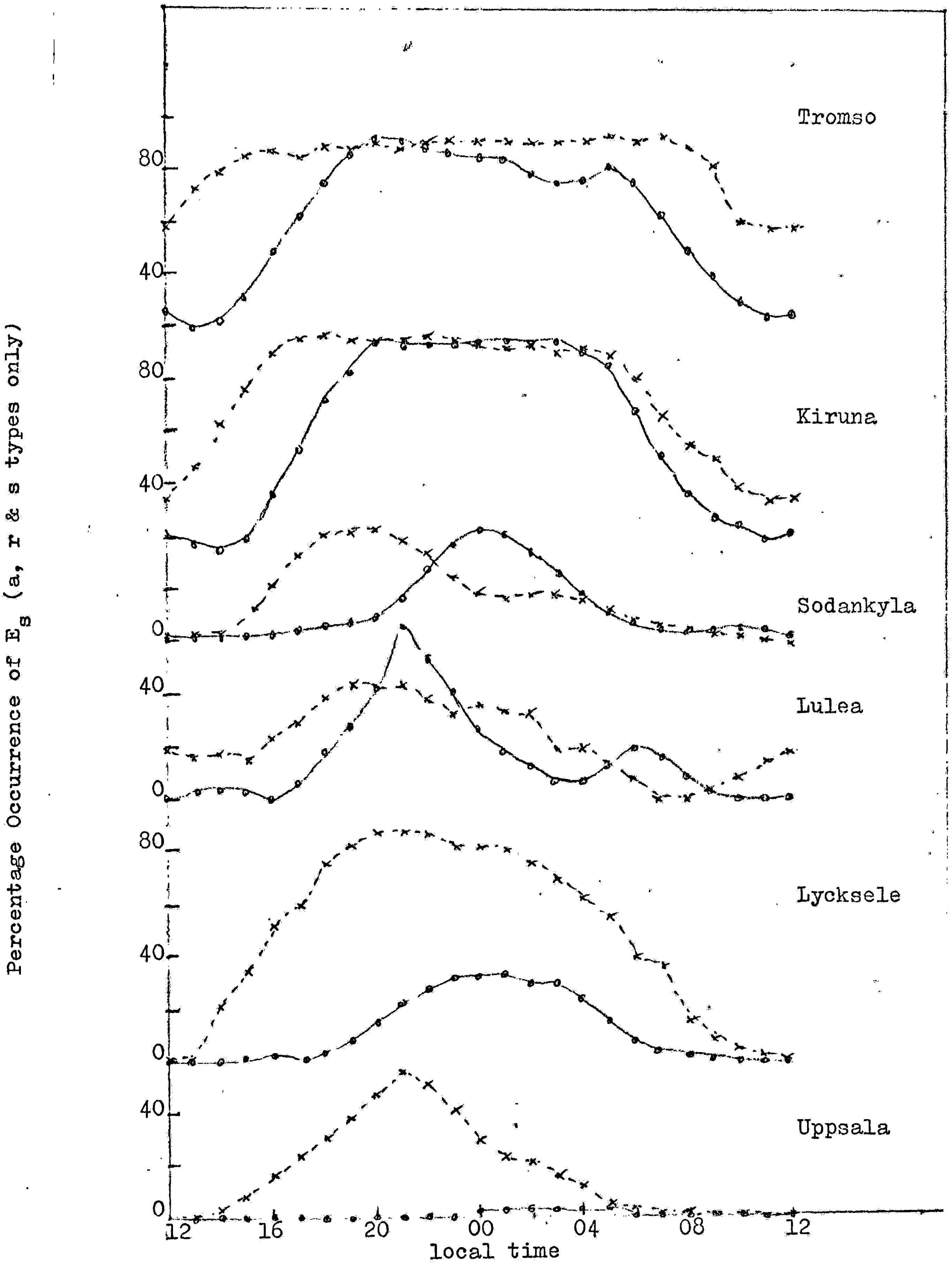


Fig.6.1: Diurnal variation of occurrence of E_s for winter 1959/60
o- quiet days and x— — disturbed days

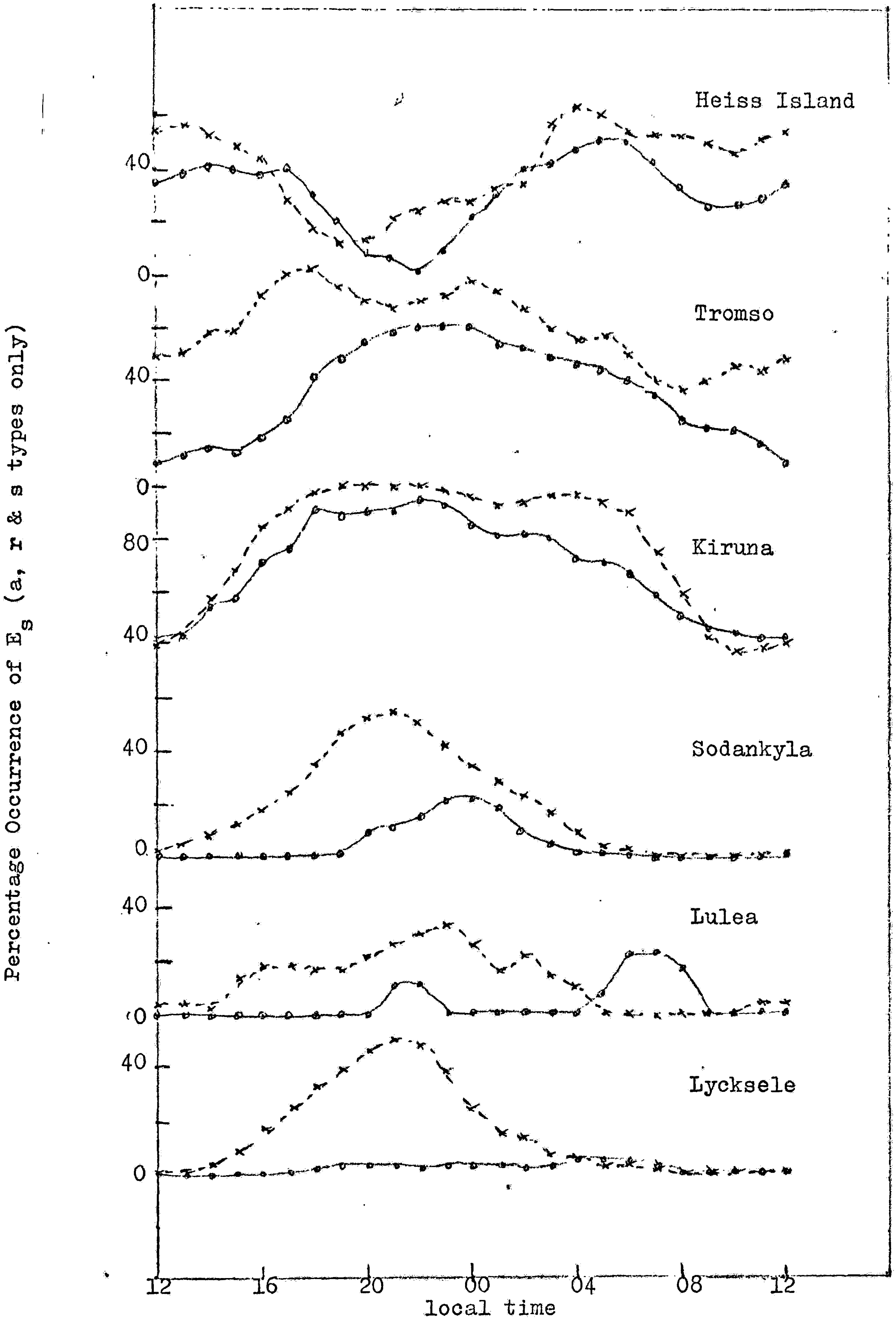


Fig.6.2:Diurnal variation of occurrence of E_s for winter 1964/65
o— quiet days and x-- disturbed days

conditions. The polar boundary of the oval must therefore lie in the narrow region between Heiss Island and Tromso.

In 1964/65 (fig. 6.2) there is no E_s at Uppsala under any magnetic conditions and at Lycksele, Lulea and Sodankyla the incidence is greatly reduced. At Tromso and Kiruna the maximum levels of occurrence are little changed, but the broad maxima are now considerably reduced in duration. The converse applies at Heiss Island where a relatively high level of E_s is observed. All these changes, and especially the appearance and disappearance of E_s at Heiss Island and Uppsala respectively, provide clear evidence for a poleward movement of the auroral E_s oval, as determined by a-, r- and s-types, between 1959/60 and 1964/65.

This movement of the oval may also be shown by means of the technique used to construct fig. 5.10 by considering the time of maximum occurrence as a function of geomagnetic latitude. These times are shown in fig. 6.3 for quiet and disturbed conditions during 1959/60 and 1964/65. The equatorward movement from quiet to disturbed conditions is evident together with the poleward movement from 1959/60 to 1964/65.

By removing the restriction on the longitude range it is possible to include data from the Russian stations by using the parameter $\Delta\phi$ as defined in section 5.2 and fig. 6.4 shows the time of maximum

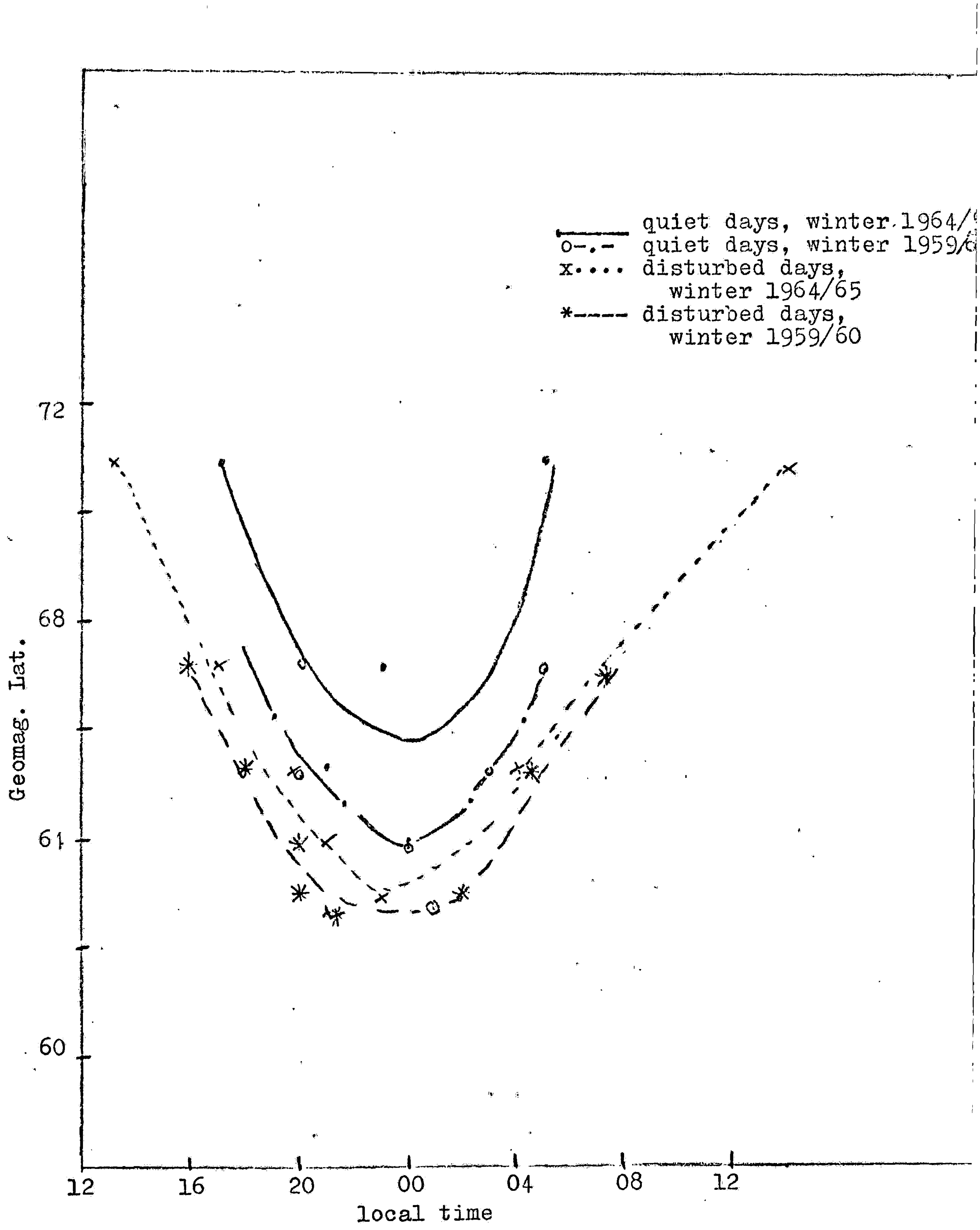


Fig.6.3:Diurnal variation of time of maximum occurrence of E_s

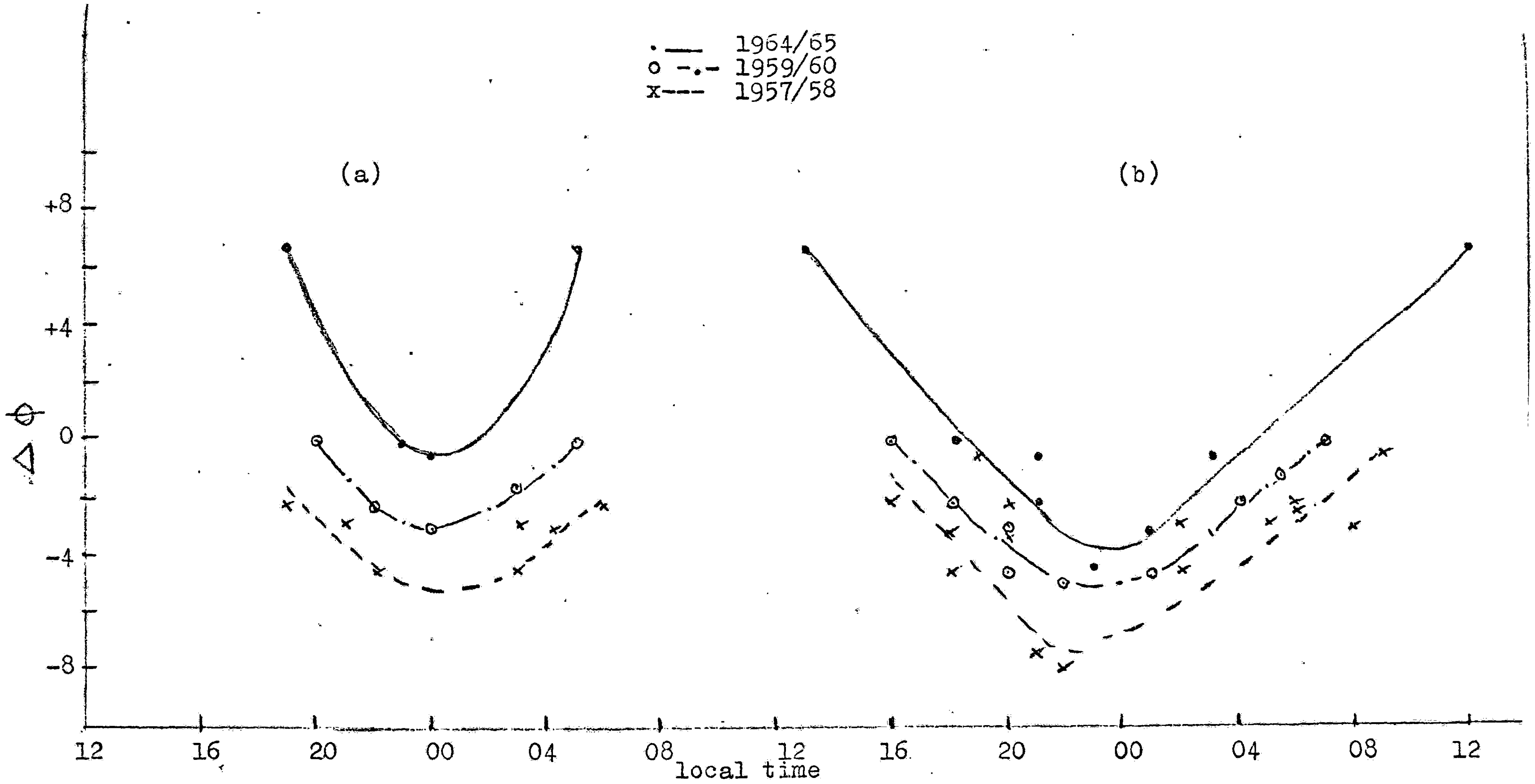


Fig.6.4: Diurnal variation of time of maximum occurrence of E_s

(a) on quiet days, (b) on disturbed days occurrence as a function of $\Delta\Phi$ using all the available data. The use of this additional data confirms the observations made from fig. 6.4 with regard to the changes associated with solar and magnetic activities.

6.3 Latitudinal variation of f_oE_s

So far in this work the effect of magnetic activity has been investigated by selecting the two groups of days corresponding to quiet and disturbed conditions. This has the disadvantage that only two levels of activity are studied and that the average magnetic activity on the selected quiet days in 1964/65 will be less than that on the corresponding group of days in 1957/58 and 1959/60 due to the increase in the overall level of disturbance.

To overcome this ambiguity in the results the variation of a-, r- and s-type E_s has been examined as a function of the planetary magnetic activity index (K_p).

The data from the six above European stations together with that for Heiss Island has been used to calculate the mean values of f_oE_s ($\overline{f_oE_s}$) during the period 00-03 and 06-09 LT for values of K_p ranging from $K_p = 0$ to $K_p \geq 5$. The resulting variation of $\overline{f_oE_s}$ with latitude for each value of K_p is shown in figs 6.5(a) and 6.5(b) for winter 1959/60 and winter 1964/65. Considering first the variation in fig. 6.5(a) for 00-03LT at $K_p = 0$, f_oE_s shows little variation with latitude having values of approximately 3.2 Mc/s.

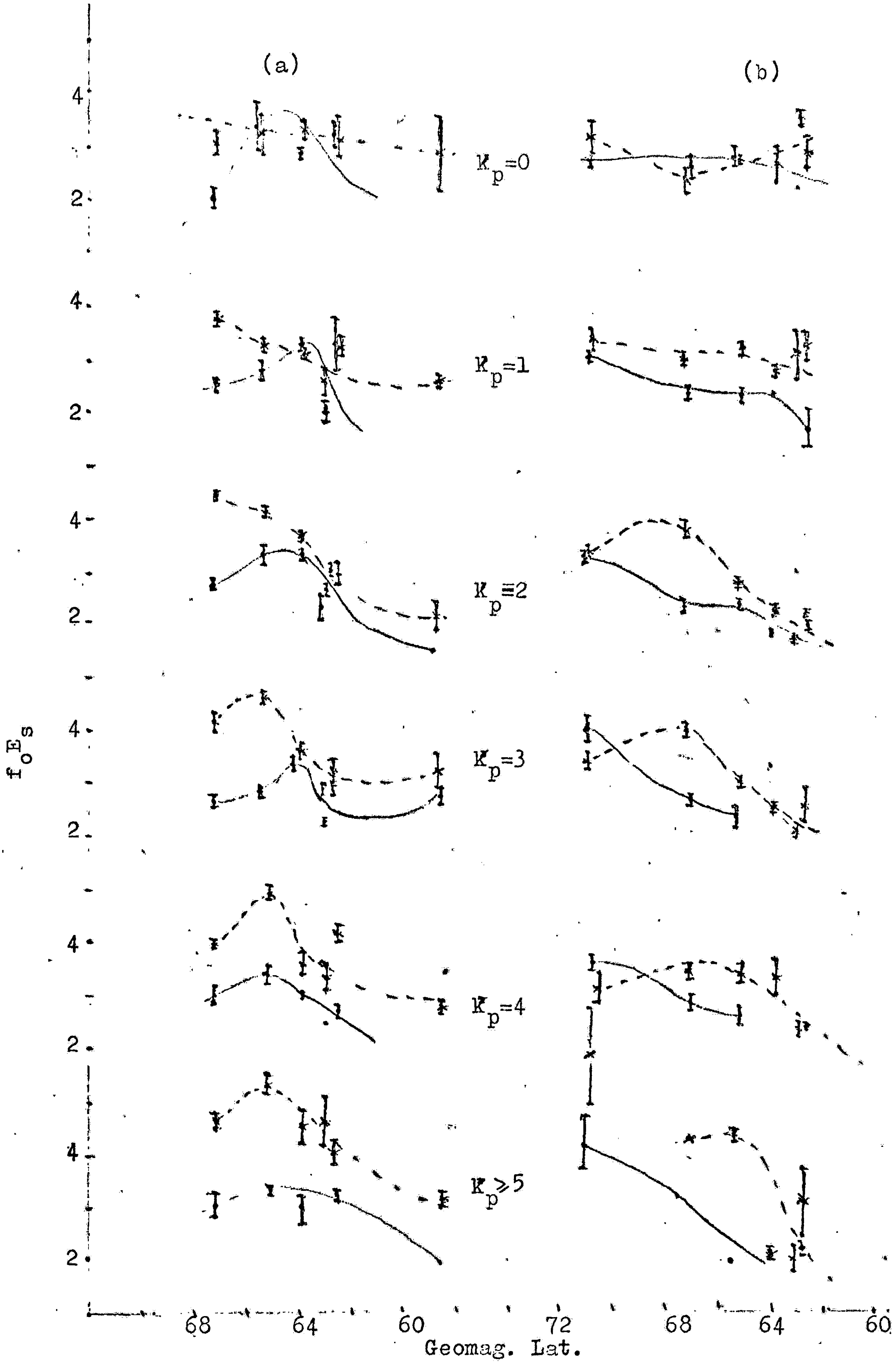


Fig.6.5: Latitudinal variation of f_oE_s with k_p for
(a) winter 1959/60 and (b) winter 1964/65
x--- for 00-03LT and o—— for 06-09LT

As K_p increases so a region of increased f_oE_s appears at high latitudes until $K_p \geqslant 5$ when a well-defined maximum exists centred at about 65^o. The shape of these variations suggests that for $K_p=0$ a maximum $\overline{f_oE_s}$ may well exist, but at a latitude beyond that for which data is available. The most important difference between the curves for 00-03LT and 06-09LT in fig. 6.5(a) is that for the latter period a maximum in $\overline{f_oE_s}$ is observed for all values of K_p and maintains a constant latitude, i.e. unlike the 00-03LT results, the position of the $\overline{f_oE_s}$ maximum during 06-09LT is independent of magnetic activity.

Although data from Heiss Island has been examined in this figure, only three occurrences of these types of E_s were observed throughout the whole period. These points have not been plotted since, from the statistical standpoint, they have little or no significance.

The curves in fig. 6.5(b), which are for winter 1964/65, repeat the behaviour shown in fig. 6.5(a) for 00-03LT with a maximum in $\overline{f_oE_s}$ which moves progressively equatorward as K_p increases.

There is no obvious peak for 06-09LT corresponding to that in 1959/60 and, as was evident from fig. 6.2, the incidence of E_s at Lulea, Lycksele and Uppsala is so greatly reduced that no data is available for some values of K_p.

Equally there are a large number of occurrences at Heiss Island. There is evidence, nevertheless, of a maximum developing at a latitude $> 70^{\circ}$ and dependent on K_p.

To accentuate an aspect which has already been observed in more general terms, the points in fig. 6.5 have been replotted in fig. 6.6 to compare the values of $\overline{f_oE_s}$ for the same value of K_p and local time but for different phases of the solar cycle. The poleward movement from maximum to minimum solar activity is clearly evident for 00-03LT. The period 06-09LT also suggests a similar movement but this may be coincidental in that the fixed latitude maximum in 1964/65 is not so apparent.

Bars giving the root mean square (r.m.s.) deviation for each point are shown in figs 6.5 and 6.6. They have been specifically included here in order that the maxima and the relative movements of each pair of curves might be identified as being statistically significant. The r.m.s. deviations are such that in all cases the observations above are clearly significant. (see also Appendix II).

6.4 Diurnal and latitudinal variation of $h'E_s$

Examination of $h'E_s$ data also reveals certain similar features when considering a-, r- and s-type E_s. The diurnal curves are given in figs 6.7, 6.8 and 6.9 for winter 1959/60, 1964/65 and 1966/67. The salient feature of these curves is a distinct pre-midnight maximum height on quiet days. Some curves, i.e. Tromso, 1959/60, 1966/67; Lycksele, 1959/60 and Kiruna 1964/65,

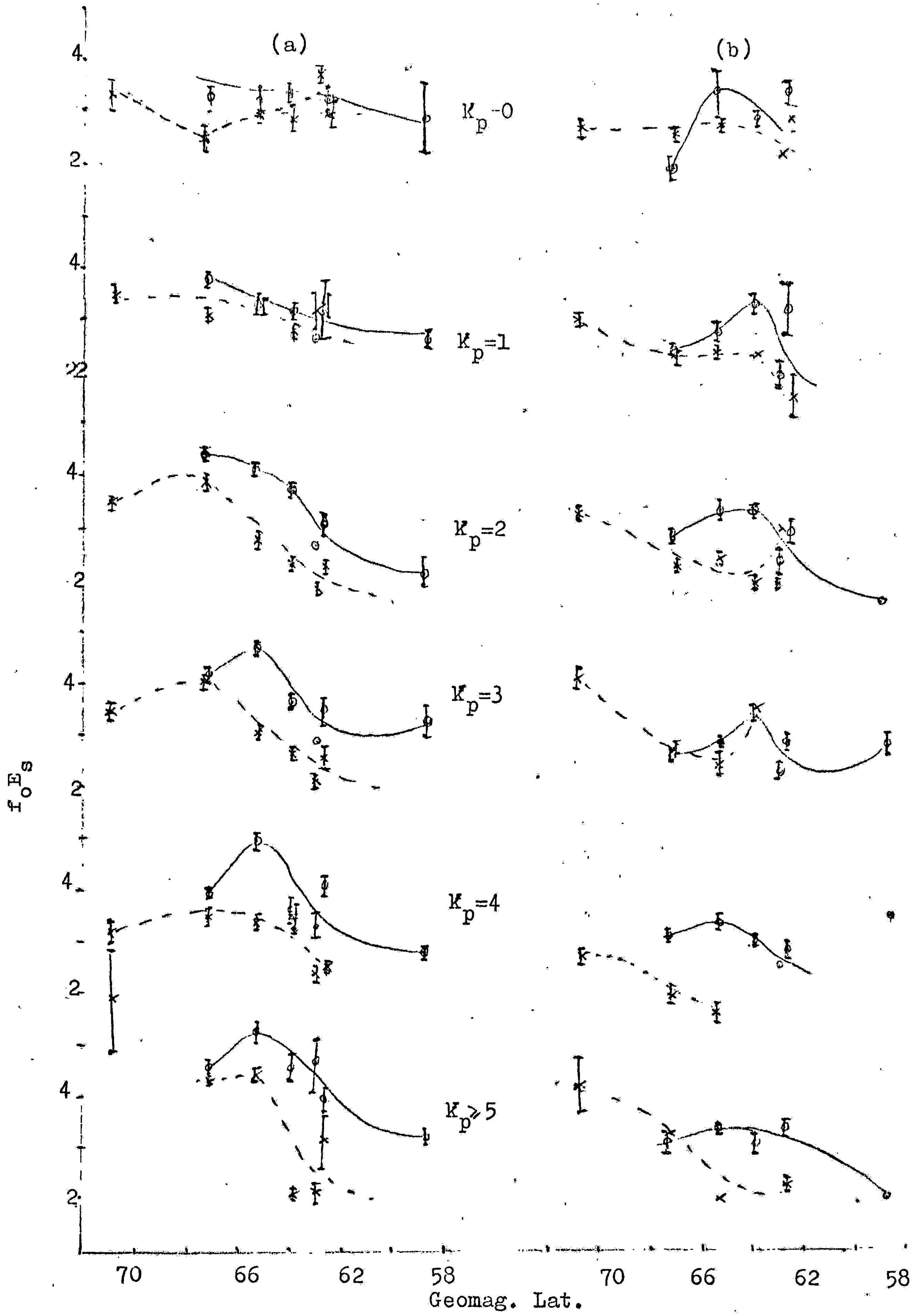


Fig.6.6: Latitudinal variation of f_oE_s with k_p for (a) 00-03LT and (b) 06-09LT

o—— for winter 1959/60 and x--- for winter 1964/5

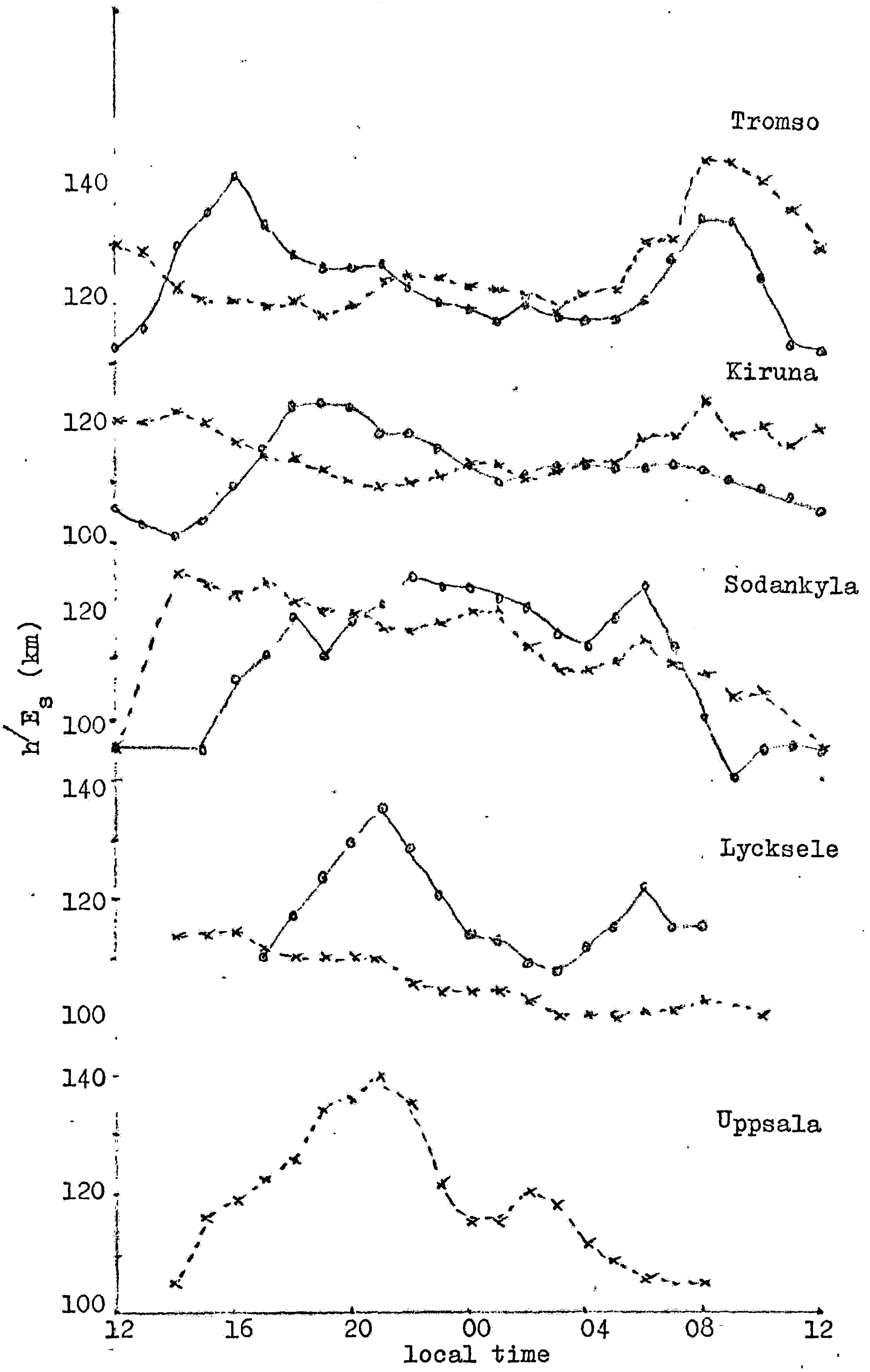


Fig.6.7: Diurnal variation of $h'E_s$ during winter 1959/60

o—— quiet days and x--- disturbed days

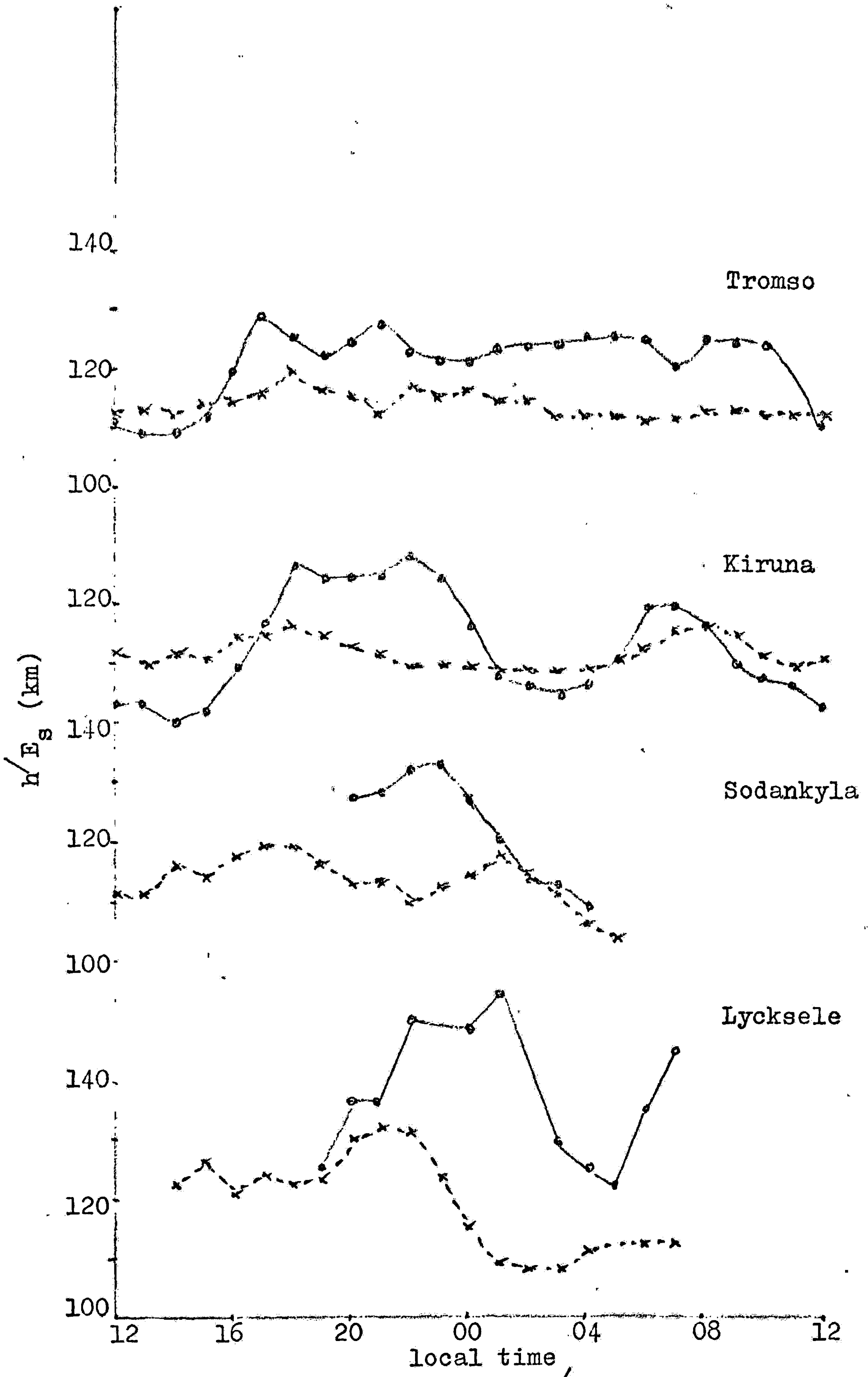


Fig.6.8: Diurnal variation of h/E$_s$ during winter 1964/65
o— quiet days and x--- disturbed days

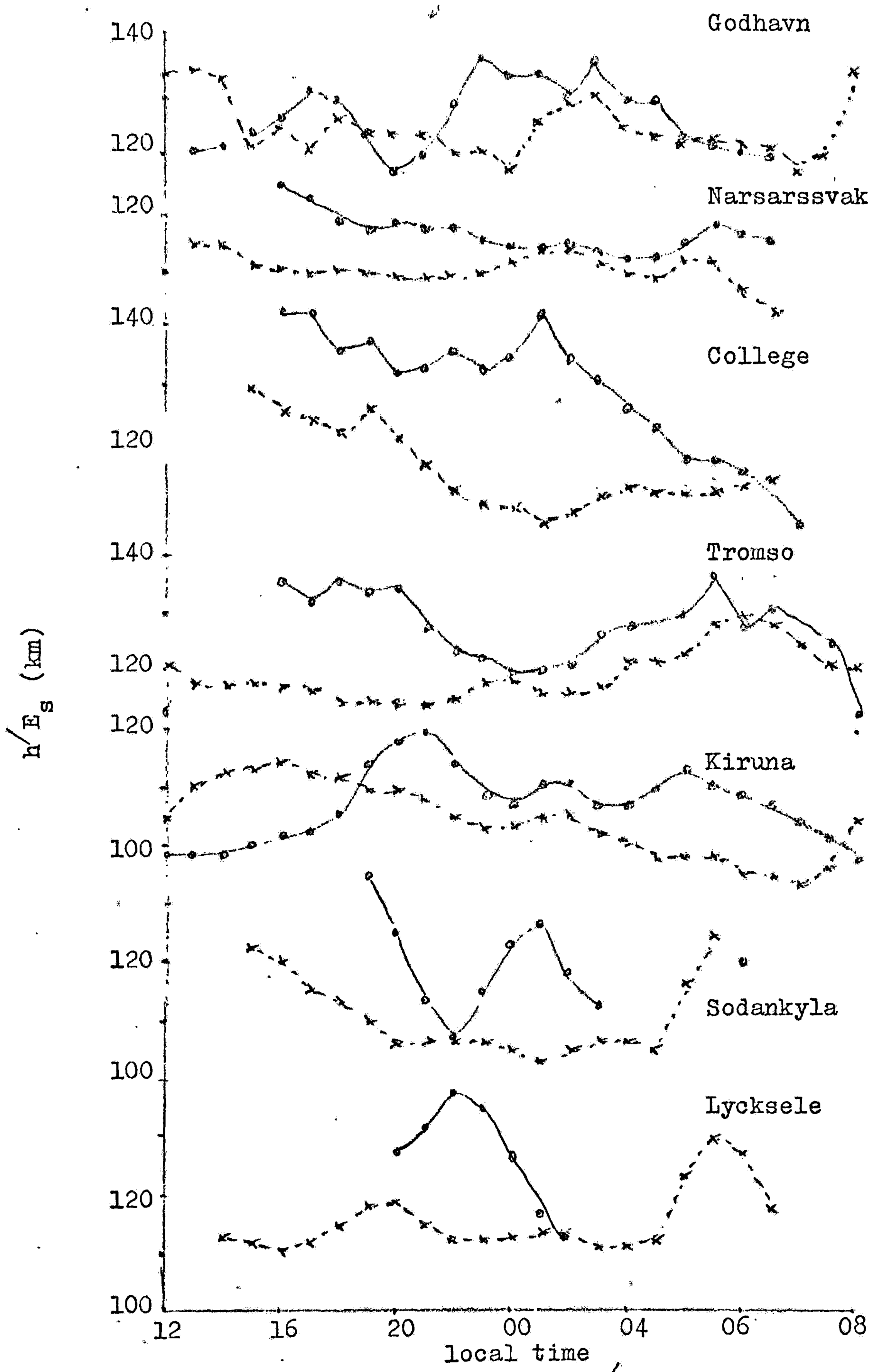


Fig.6.9: Dirunal variation of $h'E_s$ during winter 1966/67
o—— quiet days and x--- disturbed days

1966/67, show a second maximum in the morning while, in other curves, the pattern although suggested is not readily apparent. It will also be observed that the main peak tends to occur later in time as latitude decreases.

Both these features might be interpreted in terms of the overhead poleward and equatorward movement of the auroral oval, analogeous to that described for k in section 5.3.

These diurnal curves, although lacking in consistency and possessing a considerable degree of scatter, when used to construct a latitude variation of $h'E_s$ for 16-06LT result nevertheless in a fairly consistent picture. These are shown in figs 6.10 and 6.11. Only isolated E_s is found between 07 and 15LT for all stations.

Due to the different number of stations for each of the three periods considered, together with the total absence of E_s under some conditions, the most comprehensive set of curves occurs for 1966/67.

Despite the fact that $h'E_s$ is frequently regarded as being most undependable, the quiet and disturbed days curves for each two-hour interval show a high degree of consistency. For all hours on disturbed days and 20-02LT on quiet days a minimum in $h'E_s$ is observed at about 65°. This minimum does not move between quiet and disturbed conditions.

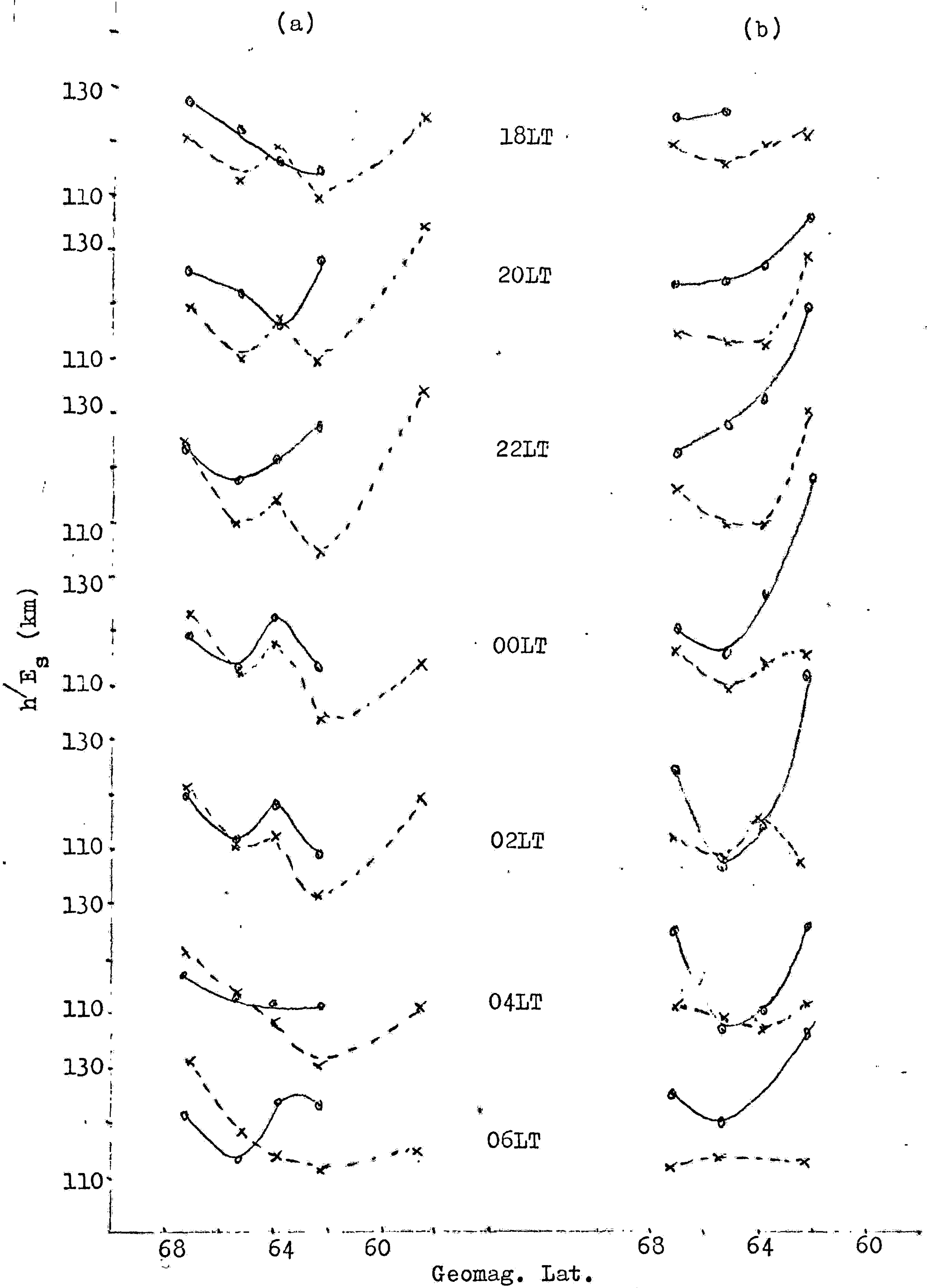


Fig.6.10: Latitudinal variation of h′E_s for
(a) winter 1959/60 and (b) winter 1964/65
o—— quiet days and x--- disturbed days

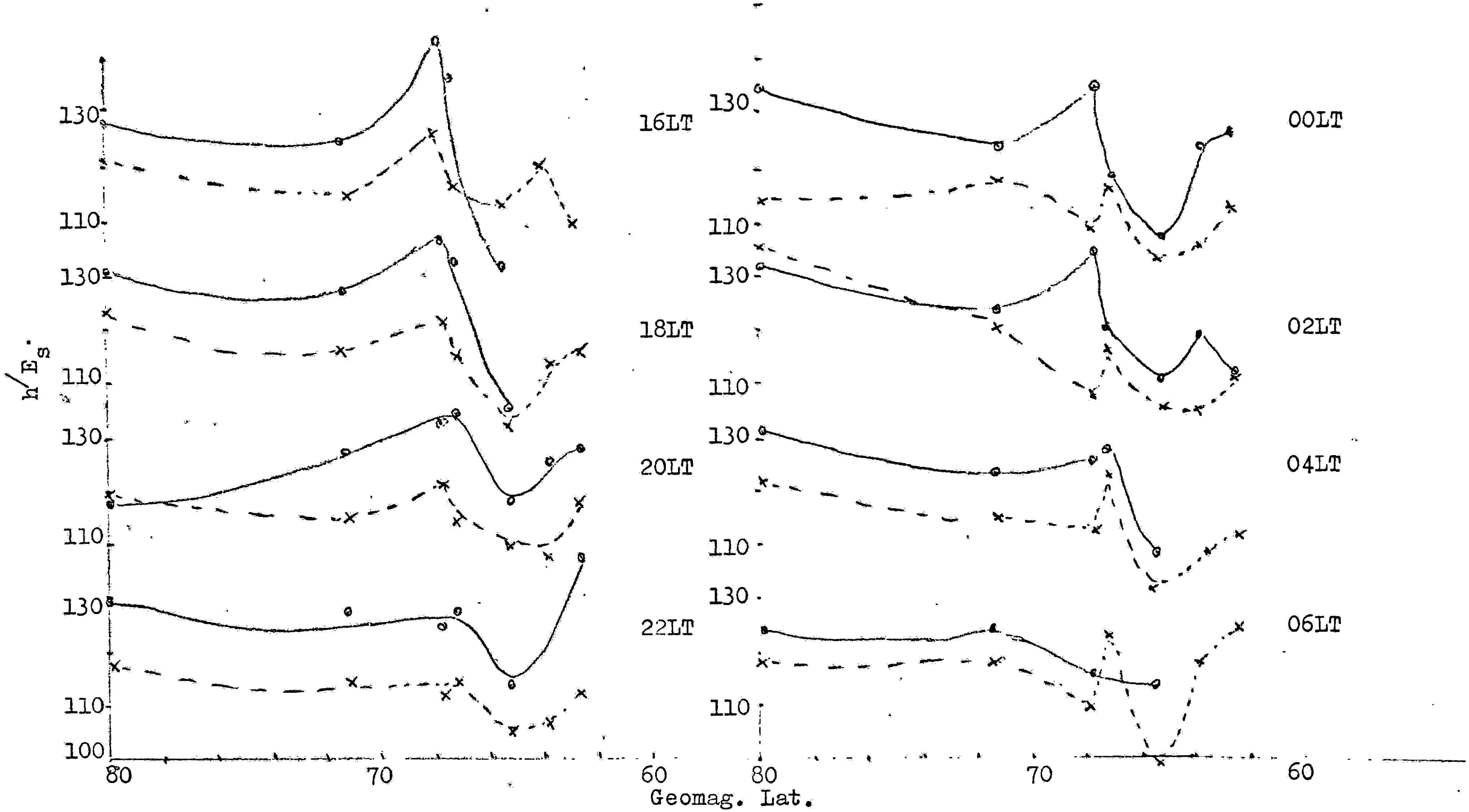


Fig.6.11 : Latitudinal variation of $h'E_s$ during winter 1966/67

o—— quiet days and x--- disturbed days

There is also, on quiet days, a very broad minimum in $h'E_s$ moving equatorwards and polewards before and after midnight respectively. On disturbed days there is a sharper minimum evident from 00 to 06LT with slight evidence for an equatorward movement before 00LT

In 1959/60 there is again on disturbed days a minimum in $h'E_s$ at about 62° which is independent of time, together with a smaller minimum which has latitude of 65°. The quiet days data is less and, there being no E_s at Uppsala under these conditions, the resulting incomplete curves only provide an indication of a fixed minimum at about 62°. Throughout 1964/65 data for only four stations is available and no conclusion can be drawn from the latitudinal curve.

6.5 Diffuse and discrete zone model of the auroral region and its relationship with a-, r- and s-type sporadic-E

The behaviour described here whereby both f_oE_s and $h'E_s$ exhibit characteristics which can be either independent of or a function of K_p is apparently anamalous and is not paralleled by any of the results in the earlier part of this chapter. It is possible, however, to interpret these results in terms of a model involving a multiple zone structure of the auroral region.

The general concept of this model was suggested independently by Piddington (1965), on the basis of visual auroral data, and by Hartz and Brice (1967), using artificial satellite measurements of energetic particle fluxes and energies and ground based observations of the upper atmosphere.

The Hartz and Brice schematic model is reproduced here in fig. 6.12 and is seen to consist of two main zones. The outer zone maintains a constant latitude throughout the day, i.e. there is no observable diurnal movement. It exhibits also, as postulated by Hartz and Brice, no movement when there is a change in magnetic activity. On account of its relative insensitivity to all geophysical changes and its continuous existence, this region is now referred to as the Diffuse Zone.

The inner zone has a pronounced diurnal movement from about 66° at midnight to about 77° at midday. Its position is also strongly dependent on magnetic activity. Because this zone tends to be associated with individual events, so that the diagram really represents a gross average of all observations, it is referred to as the Discrete Zone.

The principal geophysical phenomena associated with the diffuse zone are:-

(a) stable, mantle aurorae
(b) riometer absorption
(c) continuous geomagnetic micropulsations
(d) hard quasi-constant balloon x-ray events
(e) relatively intense continuous fluxes of electrons with energies of about 40KeV or more.

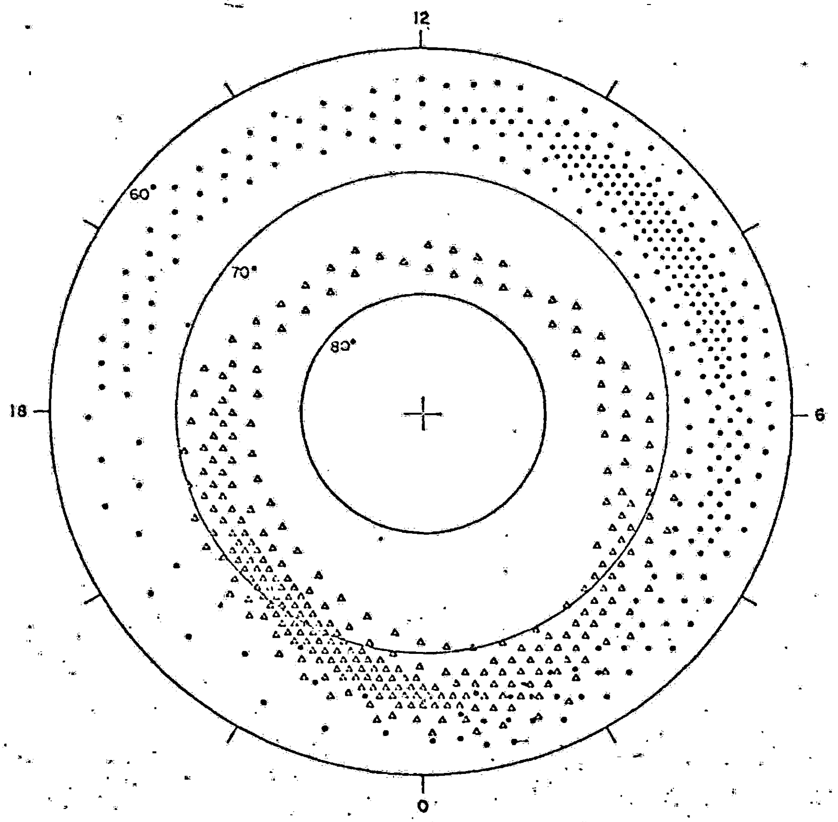


Fig.6.12: An idealized representation of the two main zones of auroral particle precipitation. The discrete events and the associated splash type precipitation are represented by the triangles, and the diffuse events together with the drizzle type of precipitation are indicated by the dots. (Hartz and Brice, 1967).

The continuous events and the height at which they occur are consistent with relatively hard electron fluxes. By contrast, the events which lead to the concept of the discrete zone tend to be of a relatively localized nature both temporarly and spatially and include:-

(a) sudden changes in the riometer absorption

(b) balloon absorption of sudden, short-duration soft x-rays

(c) soft electron fluxes with individual energies of about 1KeV and of limited duration,

All these phenomena are associated with heights greater than those pertaining to the diffuse zone. Unlike the diffuse zone and events associated with it, which are always present, the discrete zone and its events raise difficulty in the analysis because ideally a single event should be studied in terms of its behaviour in all the different phenomena.

This, with the present availability of the data and observing stations, has only been attempted for a few single events. This has met with only limited success due to the limited spatial extent of the event and the wide dispersion of the sources of the data. Thus in this and all other current work the discrete zone is treated in terms of an overall average of all relevant data.

The overall concept is thus one of a fixed, steady outer zone arising from a hard electron flux and a variable, moving inner zone produced by soft electron fluxes and whose position is strongly dependent on magnetic activity.

In their original paper Hartz and Brice adduced as evidence for the diffuse zone behaviour of intense sporadic-E echoes. However, for both the instances quoted, no information was available on E_s types and thus the result used to support their conclusions contained all known types of E_s. In particular, data was averaged for a whole year and the known E_s types associated with high latitude are infrequent in summer. This, as seen in the present work, may lead to a confused interpretation and in the diffuse case noted above does do so. As will be shown, however, high latitude types of E_s do provide strong evidence in support of this zone model.

Rocket and satellite experiments have now provided much information on the distribution, energy and fluxes of energetic particles, but their means of acquiring their energy has not been completely determined.

The overall concept of the particles responsible for the diffuse zone is one of hard electrons, i.e. with energies greater than approximately 20KeV and having a steady and relatively flat spectrum. The electrons are located just inside the magnetosphere and are in the outer radiation belt. Those electrons which are quasi-stably trapped, and therefore unable to complete a drift cycle right around the earth, are accelerated by the convective electric field in the magnetosphere, as they drift around the earth on the night side. They are then precipitated on the morning side with maximum energy around dawn.

After dawn the electric field will tend to decrease rather than increase the flux and some other electron accelerating processes must be operative. Such a probable source of energy may arise from the flow upwards along the magnetic field lines from the ionosphere into the magnetosphere where a wave - particle interaction will take place due to pitch - angle scattering of the particles. The resulting plasma wave may then in turn acclerate other particles.

Of the flux and spectrum measurements that have been taken there are two features of considerable relevance. Firstly, an effective measurement of the flux of electrons with E $>$ 40KeV shows that the latitude of maximum flux has little, if any, movement between low and high K_p values, as shown in fig. 6.13. Secondly, day-time measurements of soft and hard precipitated electron fluxes by O'Brien (1967) show the existence of two separate areas.

The hard electron zone is located at latitudes some 6^o higher than the soft electron one. By contrast, at night, a single zone of electron precipitation

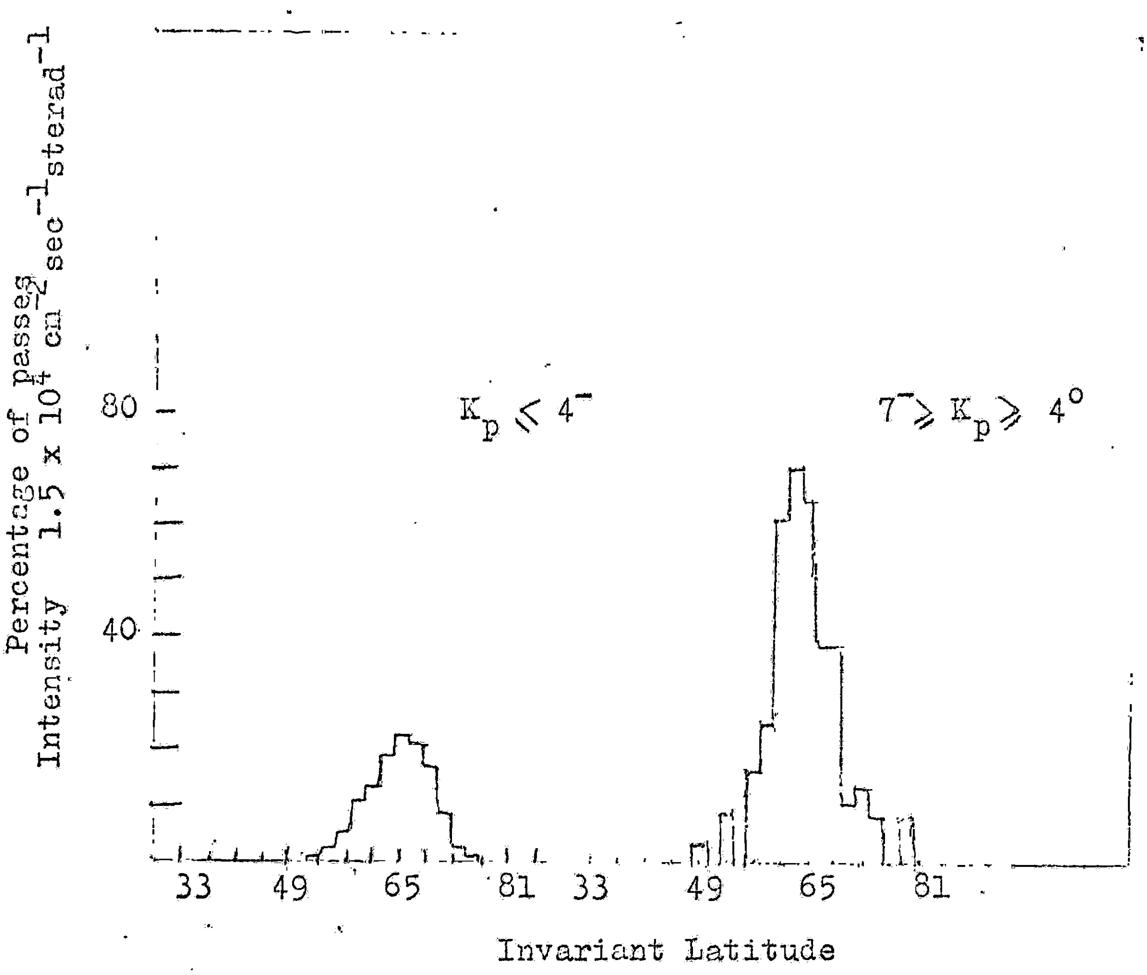


Fig.6.13: Percentage of passes in which intensity of precipitated electrons with energies is greater than 40KeV (McDiarmid et al, 1963)

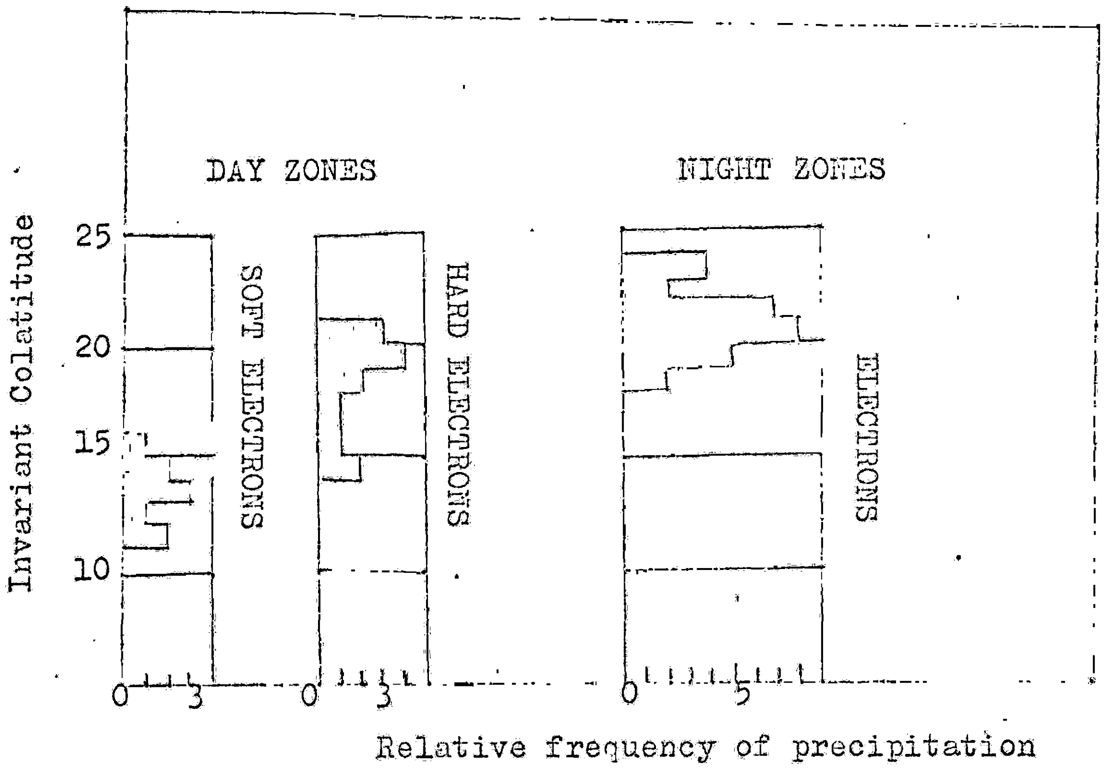


Fig.6.14: Latitudinal distribution of electron precipitation (O'Brien, 1967)

is found when the soft electron zone has moved to a lower latitude and appears to have merged with the hard electrons.

In the discrete zone the electron spectrum is found to be softer, principally in the range 1-10KeV, but there is a high flux and a high total energy. The region of precipitation is situated on the poleward side of the boundary of the magnetosphere proper. In fig. 6.15 particles from the magnetosheath can have direct access into the polar cusps via the neutral points but will not have sufficient energy or large enough pitch-angle to be precipitated.

These polar cusps only exist on the day-side and as the earth rotates the field lines stream backwards until those from the north and south polar regions lie in approximately parrallel but opposite directions to each other along the plasma sheet and are effectively open lines. Within the plasma sheet will be a relatively thin neutral sheet between the two opposing magnetic fields. This will be the region of potential instability and ions in the plasma sheet may, under certain circumstances, acquire energy from the magnetic field. This loss of energy from the field is compensated for by a "reconnection" of two opposing magnetic field lines.

The particles will now be on a closed field line and will ultimately be precipitated on the night-side of the earth.

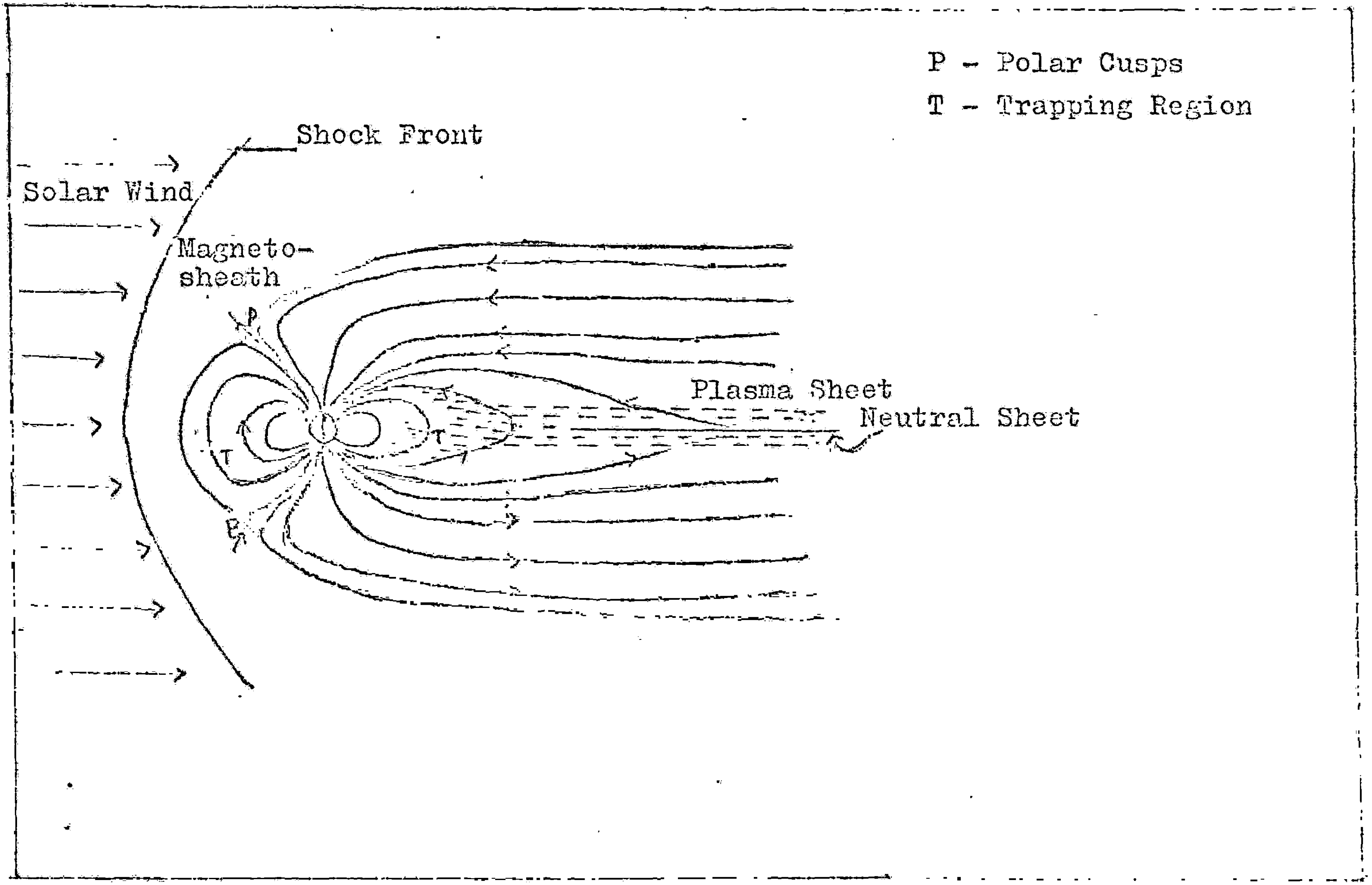


Fig.6.15: Diagram showing the relationship between the geomagnetic field and the solar wind

Measurement of the spectrum of the precipitated electrons shows the spectrum is harder by day than by night (Sharp and Johnson, 1968a) and that at about 1KeV the spectrum softens with increasing latitude (Fritz and Gurnett, 1965; O'Brien, 1966; Johnson et al, 1966, 1967). For electrons with energy less than 40KeV the precipitated spectrum hardens with increasing magnetic activity (Sharp and Johnson, 1968 a, b, c). It is in this region also that the spectrum of auroral electrons is found to be virtually monoenergetic.

The only physically conceivable mechanism which could produce such a spectrum is that of acceleration by an electrostatic field. Such a field can only exist along the open magnetic field lines. These electrons could not, therefore, be precipitated from the outer radiation belt which encompasses closed field lines.

Examination of the gross features of the diffuse and discrete zones in fig. 6.12 shows that around midnight both zones should have coalesced and that the discrete zone should have its maximum intensity at these hours. Between 06 and 09LT the two zones have separated and the diffuse zone has attained its maximum intensity. It is for this reason that the periods 00-03 and 06-09LT were chosen for analysis in section 6.3 with the results given in fig. 6.5. While there would be greater separation between 12-15LT the distribution of stations does not allow representative variations to be obtained over such a wide range of latitude.

According to the diffuse - discrete zone model any effect associated with the diffuse zone should be independent of K_p and it will be observed in fig. 6.5 that the position of the peak in $\overline{f_oE_s}$ at 06-09LT does not vary with K_p but maintains a constant latitude at 64° to 65°.

During the period 00-03LT, however, a maximum in $\overline{f_oE_s}$ is found to move equatorwards to the extent that, whereas for $K_p = 0$ the f_oE_s variation is flat, for $K_p \geqslant 5$ a well-defined maximum is observed at about 65°. This equatorward movement with K_p is thus in agreement with the other parameters on which the concept of a discrete zone is based, e.g. the normalized auroral incidence as a function of [illegible]. (Stringer and Belon, 1967).

These features are emphasized in figs 6.16 and 6.17 where the positions and values of the maximum in $\overline{f_oE_s}$ are plotted as a function of K_p for 00-03 and 06-09LT. The constant maximum value of $\overline{f_oE_s}$ of 3.3 Mc/s at 06-09LT, irrespective of K_p, indicates that the flux of hard electrons responsible for the diffuse zone is essentially constant whereas there is a pronounced increase in the soft electron flux in the discrete zone. The position of the maximum in $\overline{f_oE_s}$ behaves in an analogeous manner.

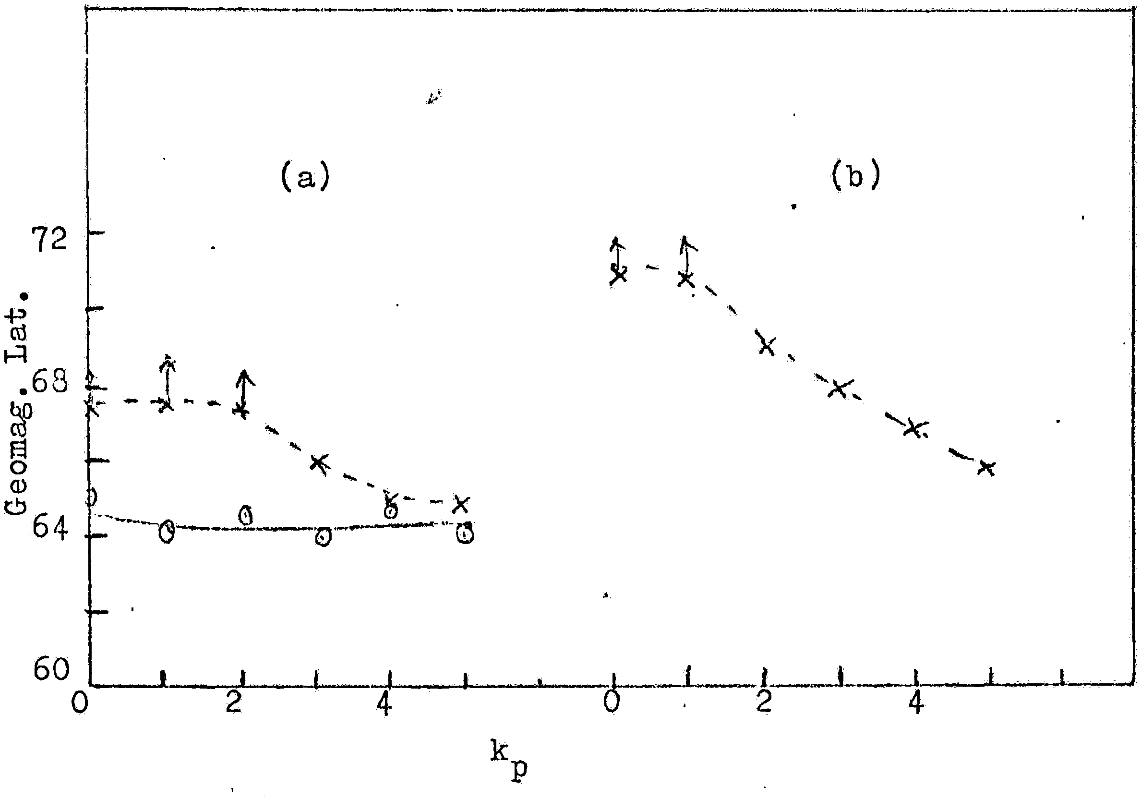


Fig 6.16: Variation of latitude of maximum f_oE_s with k_p for (a) winter 1959/60 and (b) winter 1964/65
x--- 00-03LT and o— 06-09LT

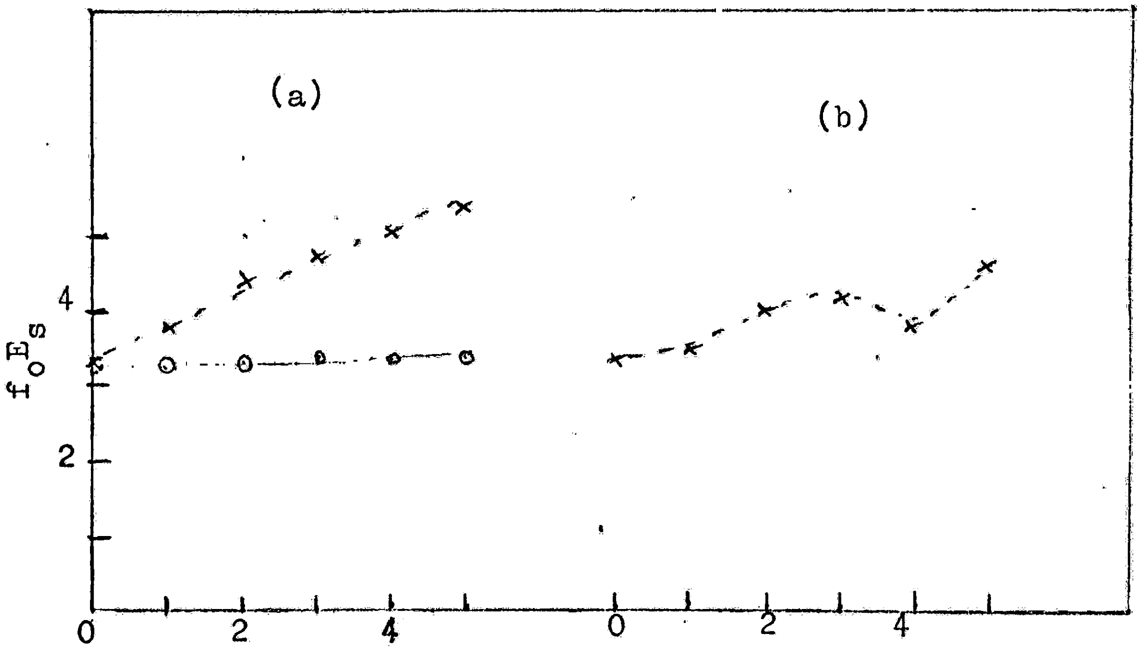


Fig.6.17: Variation of maximum f_oE_s with k_p for (a) winter 1959/60 and (b) winter 1964/65
x--- 00-03LT and o—— 06-09LT

This movement of the discrete E_s zone is such that it only coincides with the diffuse zone for values of $K_p \geqslant 4$ (assuming that on the basis of all the other evidence the position of the diffuse E_s zone does not change with time). For $K_p = 0$ its position must have moved about 5° in a poleward direction. Thus, insofar as the idealized representation in fig. 6.12 is concerned, it is concluded that the discrete and diffuse E_s zones only coalesce around 00LT for $K_p \geqslant 4$.

In fig.6.5(b) at 00-03LT the maximum in $\overline{f_oE_s}$ of increasing magnitude and decreasing latitude is again found as K_p increases. Compared with the discrete peak in 1959/60 its position is approximately 1^o-2^o poleward of the latter as seen in fig. 6.6(a) (cf. a movement of 1.5° in section 5.4 for the visual aurora).

For 06-09LT there is very little evidence of a maximum in $\overline{f_oE_s}$ at a fixed latitude, inferring that the diffuse electron flux in 1964/65 was significantly less than in 1959/60. There is evidence, however, of a maximum at higher latitudes whose position and magnitude varies with K_p and which might thus be identified with the mid-morning position of the discrete E_s zone.

No data for 06-09LT are plotted in figs 6.16(b) and 6.17(b) on account of the absence of a discernible peak, but for 00-03LT variations similar to those in 1959/60 are observed.

The f_oE_s data for 1959/60, although derived from a small number of stations, is nevertheless internally consistent and, as has been shown, can readily be interpreted in terms of a two-zone model.

The $h'E_s$ data for the same period, however, does not present such a simple picture as seen in fig. 6.10. Here it is not clear whether, on account of the small number of stations within a limited range of latitude, the various maxima and minima are in fact physically significant. It is easier, therefore, to consider the result for 1966/67 (fig. 6.11).

The most prominent feature is the minimum in $h'E_s$ with a constant latitude at about 65° under both quiet and disturbed conditions, which suggests its correspondence with the diffuse zone. The evidence for a discrete zone is not nearly so apparent, there being only an indication of a high latitude minimum at about 74°-76° at 1600LT and which moves south until at 22LT there is no minimum above 68°. A minimum then reappears at 00LT and probably then moves polewards.

This description applies only to quiet conditions and in the light of the foregoing discussion a minimum in $h'E_s$ should be evident under disturbed conditions but displaced to a low latitude by 3° to 5°. Apart from a sharp change in $h'E_s$ between 67.2° to 67.7° during the period 00 to 06LT there is no clear indication of such a variation.

The minimum values in $h'E_s$ associated with the diffuse zone are all lower than those associated with the discrete zone. This would be expected if the two zones are produced by hard and soft electrons respectively. Apart from three instances, all the minima associated with the diffuse and discrete zones are higher on quiet than on disturbed days, again implying spectral hardening. This is in agreement with the observation of Sharp and Johnson (1968, a, b, c) that the spectrum of precipitated electrons, i.e. $E < 40$KeV, hardens when K_p increases.

For 1959/60 and 1964/65 the heights on disturbed days are lower than those on quiet days, but the broad minimum in 1959/60 at about 62°-63° is considerably displaced from that in 1966/67.

The interpretation of the minimum at 65° at 2200LT on quiet and disturbed days corresponding to the discrete zone must remain of a speculative nature with the number of stations available.

There is again in 1964/65 a minimum at about 66° for some hours but it does not display the constancy evident in 1966/67 and in terms of a discrete - diffuse zone model the data from four stations for 1964/65 does not admit of any dependable conclusion.

CHAPTER 7

THE RELATIONSHIP BETWEEN a-, r- and s- type SPORADIC-E AND THE IONIZATION PRODUCED BY ELECTRON PRECIPITATION

7.1 Derivation of electron density profile

The formation of auroral type E_s takes place as a result of the precipitation of charged particles and the consequent ionization of the neutral atoms and molecules. There have been many measurements of charged particle fluxes and densities in the ionosphere and magnetosphere by means of rockets and artificial satellites. It should, therefore, be possible with this knowledge to determine the morphology of the behaviour of the E_s auroral ionization, once the various ionization parameters have been determined. In this section measurements of electron energy spectra will be used to calculate the ionization production rate as a function of altitude and then comparison will be made with the calculated and observed equivalent height of reflection.

In practice, however, despite the large number of space observations, relatively few of them are suitable for the calculation of ionization rates. Since most of the auroral effects result from electron rather than proton bombardment, only electron measurements will be discussed here. The most frequent observations result in the flux of electrons as a function of their energy, i.e. an energy spectrum to which either power or exponential laws may be fitted.

The energy spectrum can be of two types, measuring either the total number of electrons whose energy is greater than a certain fixed energy, i.e. E_0, E_1, E_2 ....., which is an integral spectrum, or the number of electrons within a number of very narrow energy ranges. This latter is the differential spectrum and is the form used for the construction of ionization profiles. Other experiments measure the total energy flux of all particles at various fixed energies. In all these three types of observation it is necessary that the energy range measured shall be appropriate to the ionization process responsible for E_s, i.e. between about 0.5KeV and 40KeV under normal conditions.

A further parameter which is also important is the pitch angle or range of pitch angles over which the flux is measured, because this angle determines, at a given altitude, whether the electrons will either remain trapped or be precipitated. (See Appendix III).

There is a constraint imposed upon the height of measurement also. Satellites with a useful life-time cannot orbit below 300km while deductions from measurements made above 1000km involve a great deal of uncertainty when extra-plotted to E-region heights. Finally, auroral region phenomena vary so rapidly with a small change in latitude that a single energy spectrum is of limited value. A series of spectra covering a range of latitudes is much to be preferred, since, even if absolute values of the height of ionization are uncertain, relative changes should be of some significance. The published energy spectra only contain two examples of spectra over a range of latitudes (Burch, 1970 and Fedorova et al, 1971) and all other spectra relate to isolated single measurements.

The first stage in the determination of the real height of reflection is the conversion of the electron energy spectrum J (E) into an ionization profile q (h). It has been shown by Rees (1963) that the ionization rate q per unit incident electron flux F is given by the expression:-

$$\frac{q}{F} = \frac{E_0/r_0}{\Delta E_{ion}} \lambda\left[\frac{z}{R}\right]\frac{n(M)_z}{n(M)_R}$$

where E_0 = Initial energy of the electron

E_{ion} = Mean energy loss per ion formed

$n(M)_z$ and $n(M)_R$ = Number of densities of ionizable atoms or molecules at atmospheric depth z and R (in g/cm^2) respectively

$r_0 = \frac{R}{\rho}$ = the range (in atm-cm) at the "top of the atmosphere"

ρ = Mass density (in g/cm^3) at the lowest altitude of penetration

$\lambda(z/R)$ = Normalized energy dissipation distribution function

An expression for R has been given by Grun (1957) in the form:-

$$R = 4.57 \times 10^{-6} E_o^{1.75}$$

This expression can be used to calculate the ionization rate as a function of height for different values of E_o and for an isotropic angular distribution of the electrons. For any given value of E_o there will be a corresponding height (hm) where the ionization production rate is a maximum. The results of Rees have been used here to calculate hm as a function of E_o and the resulting dependence of hm on E_o is shown in fig. 7.1.

Also on the basis of Rees' theory a curve has been constructed giving the variation of the maximum value of $\frac{q}{F} - \left(\frac{q}{F}\right)_{max.}$ as a function of E_o (fig.7.2). Thus for any experimental electron energy spectrum the flux at any given value of energy E_o is read off by means of fig. 7.2. The maximum ionization rate (q_m) corresponding to a particular energy E_o can now be found. From fig. 7.1 the height appropriate to q_{max} may also be found. By repeating this process for each data point on the energy spectrum the distribution of ionization production rate with height q(h) may be drawn.

For the present purpose it is the resulting electron density profile N (h) which is required. Under normal equilibrium conditions $q = \alpha N^2$ where α is the recombination coefficient and hence the

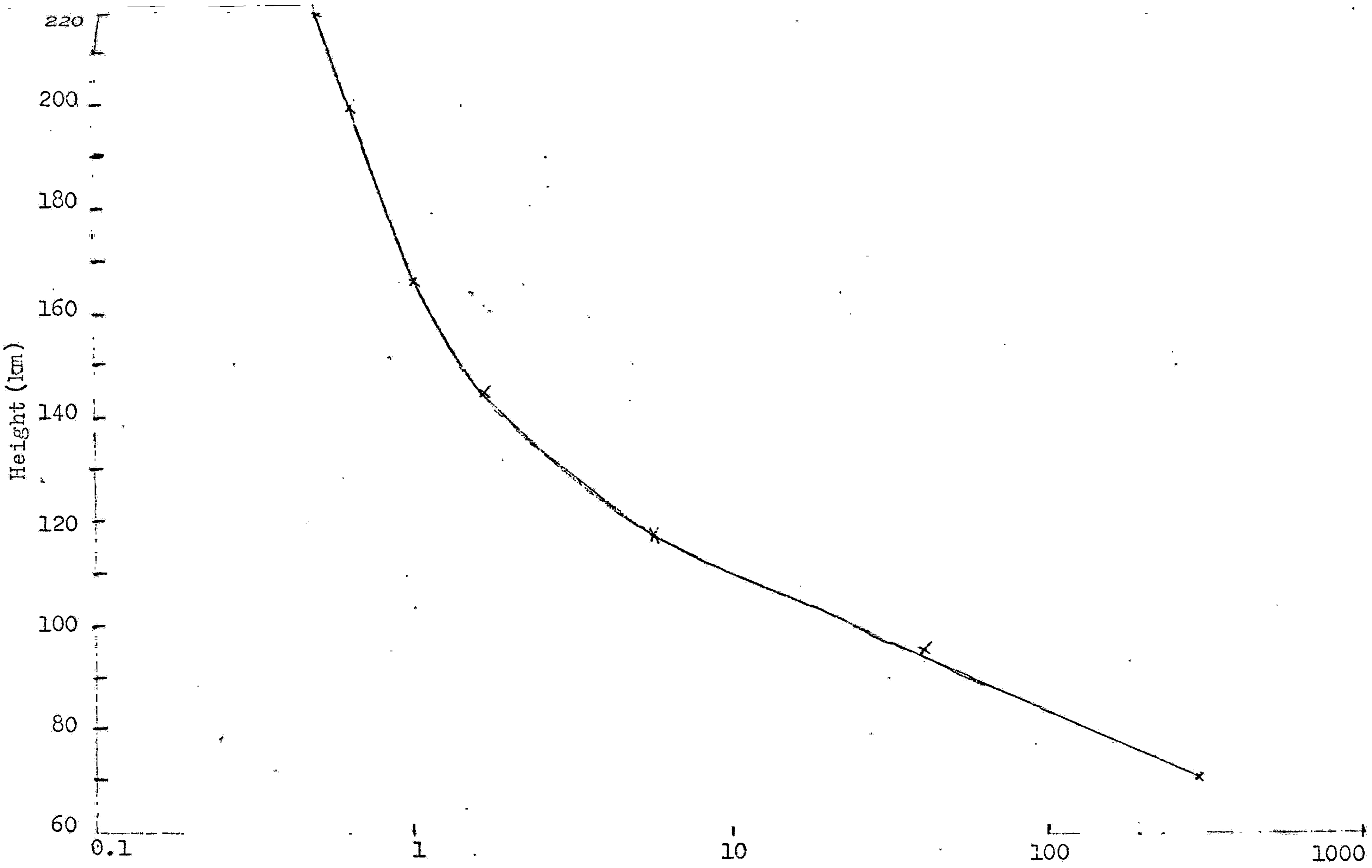


Fig.7.1: Variation of height of $\left(\frac{Q}{Fm}\right)$ with energy E

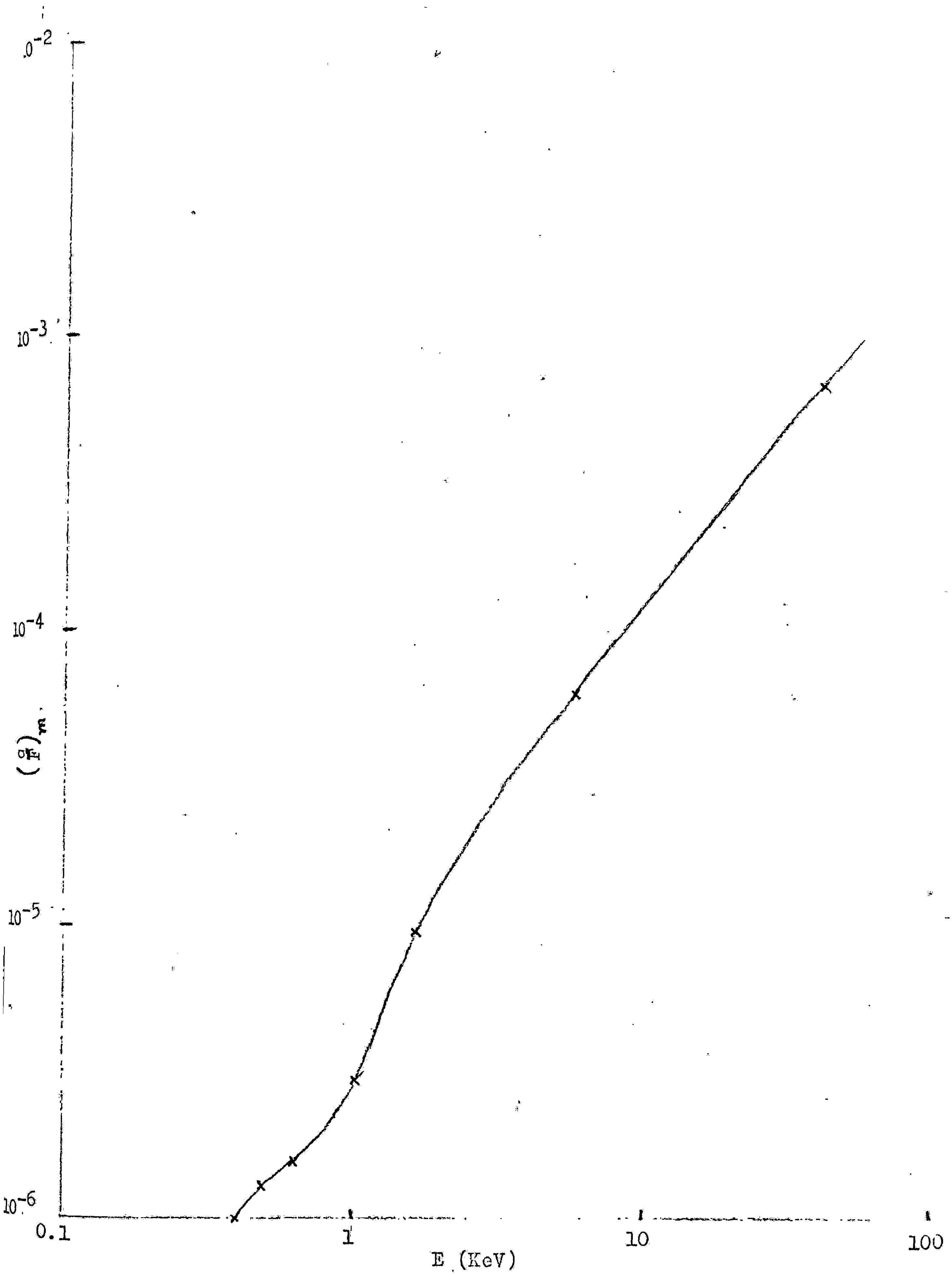


Fig.7.2: Variation of $\left(\frac{q}{F}\right)_m$ with energy E

final N (h) profile produced by the initial spectrum is obtained. A value of $\alpha = 10^{-7}$ cm^3/S has been taken for this final conversion.

The N (h) obtained by the above method will enable the real height of reflection (h) at any given frequency to be found. Normal ionospheric data, however, only provides the equivalent height of reflection (h'), there being group retardation in E and D regions, and therefore cannot be compared directly with h.

In practice the ionization gradient produced by electron precipitation is sufficiently great and the D-layer ionization density sufficiently small for the group retardation up to the reflection level to be disregarded in the present work. This may be shown by calculating h' for two different ionization profiles by means of numerical integration of the expression:-

$$h' = \int_{0}^{h} \frac{dh}{\sqrt{1 - \frac{KN}{f^2}}}$$

where K = 80.5 (c/s)^2 cm^3

N = electron density per cubic metre

and f = frequency in c/s

The first N (h) profile used is one obtained by Mechtly et al (1969) from a rocket flight on November, 12, 1966 at a latitude of 30°S . Fig. 7.3(a) shows the group retardation (h' - h) as a function of frequency.

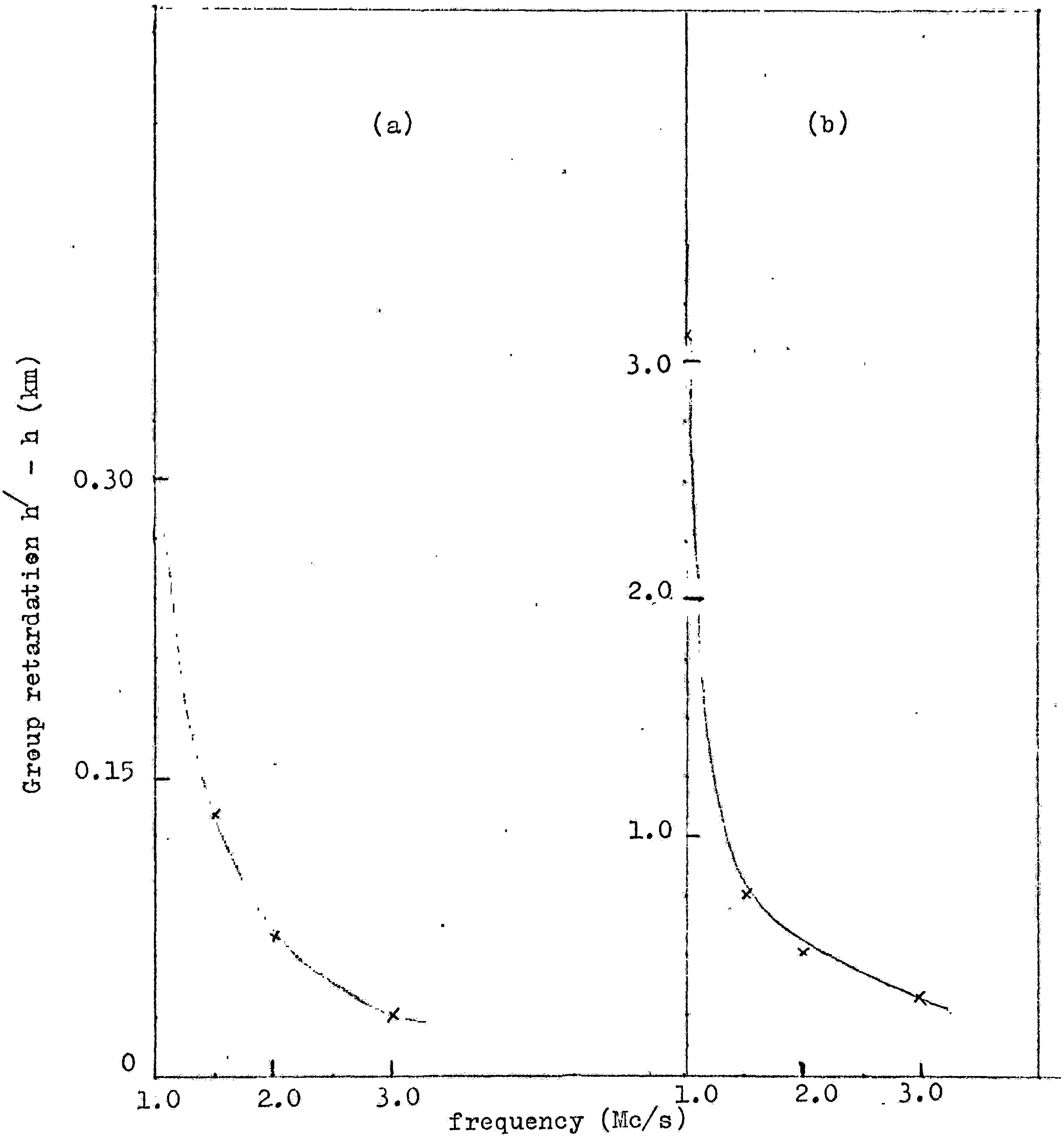


Fig.7.3: Variation of group retardation with frequency

The second profile used was obtained from a rocket flight on June, 17, 1965 at a latitude of 38°N by Sechrist et al (1969) and the corresponding results are given in fig. 7.3(b).

The ionospheric data for the stations considered in this chapter rarely contain a value of f_{min} (i.e. the minimum frequency at which any echo can be observed) which is less than 1.5 Mc/s. For such a frequency fig. 7.3 shows that the difference between the equivalent and real height of reflection has a maximum value of 0.75 km. For higher frequencies this rapidly falls to much lower values. Such a difference is less than the error in measuring h' from an ionogram. Thus for the purposes considered in this work the difference between h' and h may be regarded as negligible.

It would clearly have been desirable to use profiles appropriate to auroral latitudes but no such relevant results were available.

7.2 Comparison of electron density profile with the variation of $h'E_s$

The Aurora 1 satellite electron energy spectra obtained by Burch (1970) each consists of a six point spectrum in the energy pass bands 0.096 - 0.163 KeV, 0.150 - 0.820 KeV, 1.075 - 1.910 KeV, 1.7 - 8.6 KeV, 10.8 - 19.5 KeV and 17.5 - 100 KeV. Nine of these spectra were obtained at various times and L-shell positions at an altitude of about 4,000 km on the night side of the earth. The lowest energy band produces little ionization below 250 km and has been omitted.

The flux in each of the five bands has been taken as applying to the centre point of the band. The ionization rate and height for each energy band has been used to construct N (h) profiles.

An average value of f_{min} of 1.8 Mc/s has been taken which corresponds to an electron density at reflection of $N = 4 \times 10^4$ electrons/cm^3. The real height of reflection for these spectra is shown in fig. 7.5. A minimum value of hE_s at 65° to 66° is indicated and may be regarded as significant.

Although the absolute accuracy of the detectors is no better than a factor of two the internal consistency between each set of measurements is nevertheless high.

There is also an indication of a maximum in hE_s at 67° to 68°. Both the maximum and minimum may be compared with those in fig. 6.11 which occur at very closely corresponding latitudes. The minimum hE_s deduced here may thus be regarded as representing the diffuse zone and associated with a hard spectrum on account of the low values of h.

The average value of $K_p = 2$ for the duration of Burch's measurements corresponds to an average value of $h'E_s$ in fig. 6.11 of 105 km. This may be compared with the minimum value of hE_s in fig. 7.5 of 105 km.

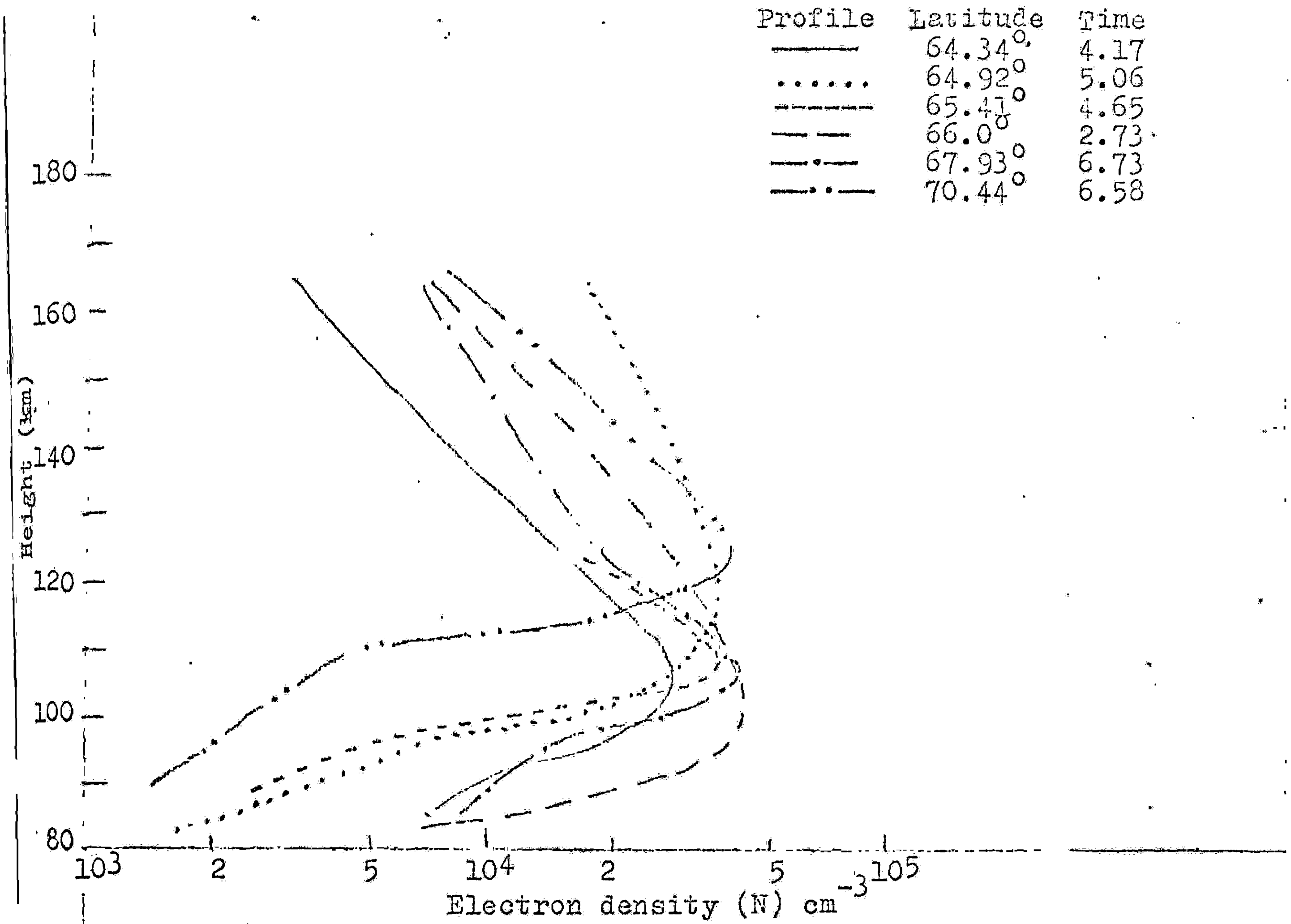


Fig.7.4: Electron density profile deduced from energy spectra of Fedorova et al (1971)

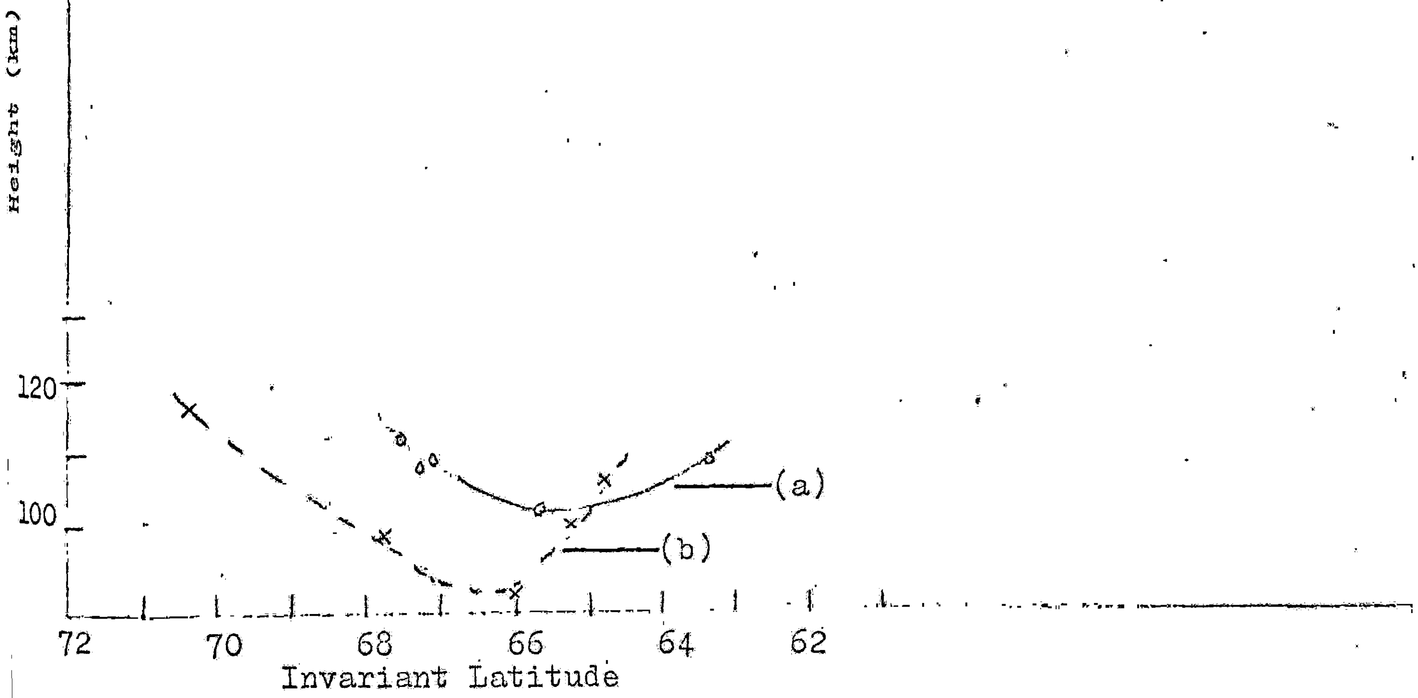


Fig.7.5: Latitudinal variation of height of reflection from
(a) electron density profile deduced from Burch (1970)
(b) electron density profile deduced from Fedorova et al (1971)

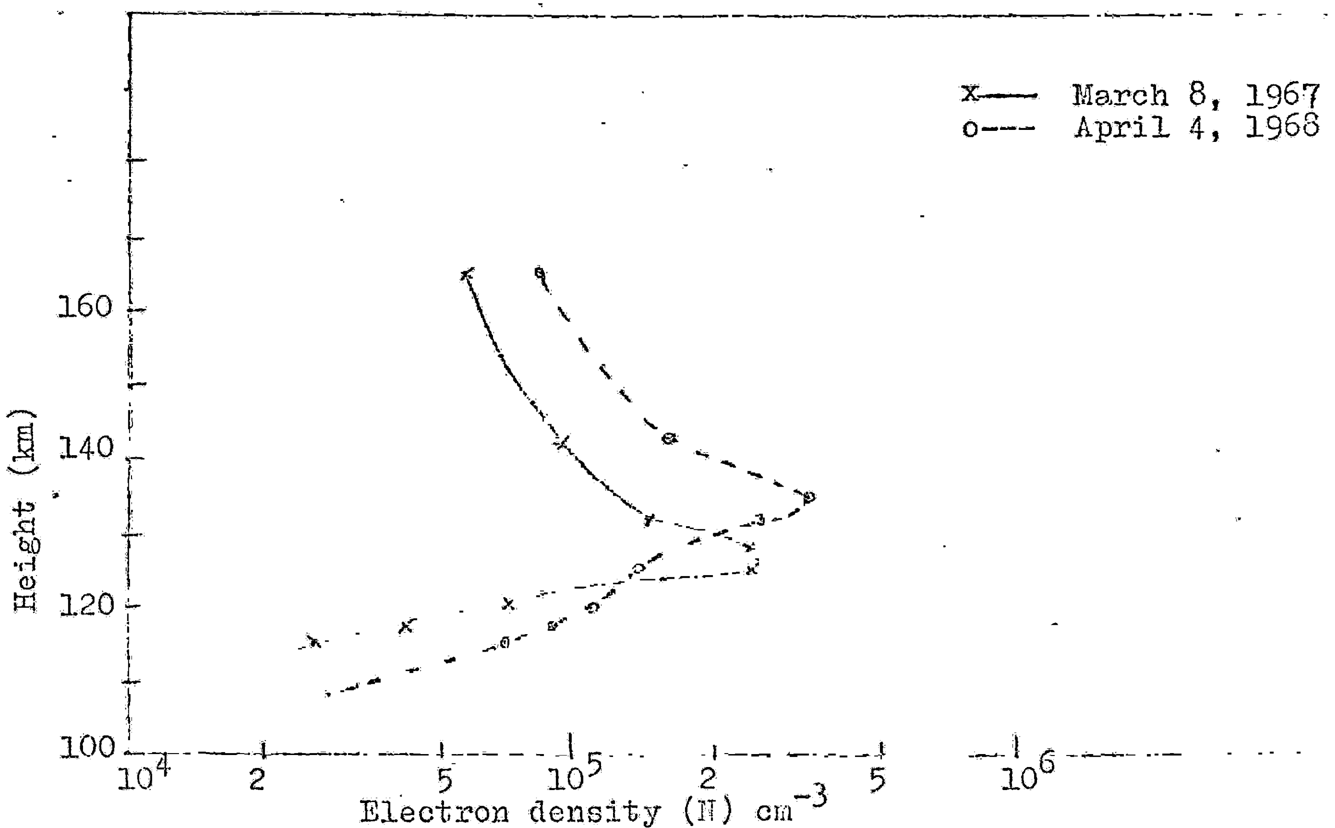


Fig.7.6: Electron density profile deduced from energy spectra of Evans (1968)

A number of spectra have also been given by Fedorova et al (1971). These were obtained on the 'Cosmos 261' satellite in winter 1968/69 at altitudes varying from 217 to 670 km. N (h) profiles have been calculated in the present work for each of the northern hemisphere spectra. The N (h) profiles calculated from the spectra are shown in fig. 7.4 and the resulting variation of hE_s in fig. 7.5 for a value of $f_{min} = 1.56$ Mc/s. As with the previous measurements a minimum in hE_s is observed at 66° to 67°.

Within the limits imposed by the data the agreement between the latitude position of the minimum value of hE_s as deduced here from the results of Burch and Fedorova et al and of $h'E_s$ can be regarded as reasonable.

N (h) profiles have been calculated from other published spectra, i.e. Westerlund (1969), Ogilvie (1968) and Evans (1968). But of these only those of Evans provide information which can be directly related to ground based $h'E_s$ observations.

Evans has given two spectra obtained from rockets launched from Ft. Churchill (Geomag. Lat. 68.7°N) into aurorae on separate occasions. One spectrum was obtained during the quiet phase of an aurora and the other during the active break-up phase. The two N (h) profiles corresponding to the spectra are shown in fig. 7.6 and, as would be anticipated, a greater value of N is observed during the intense final phase. The profiles indicate that hE_s is approximately 5 km lower during the break-up phase.

The approximate values of K_p during the quiet and break-up phases were 0 and 2 respectively. Reference to the behaviour under quiet and disturbed conditions at College, which has the same latitude as Ft. Churchill, shows that $h'E_s$ is some 10 – 20 km lower on disturbed days. The two changes in the heights are clearly very different and it may well be that individual comparisons of hE_s on separate days and under different magnetic conditions may be subject to much uncertainty.

CHAPTER 8

THE RELATIONSHIP BETWEEN VARIOUS TYPES OF E_s AND MAGNETIC ACTIVITY

8.1 Diurnal and Seasonal Variation

In view of the availability of data which provides the type of E_s present on a given occasion the incidence of the E_s relative to magnetic activity has been considered over a range of temperate latitude stations for low, cusp and high types. The percentage incidence of each type of E_s relative to the total number of observations has been calculated for the five quiet and disturbed days each month and on an hourly basis. Since the low, cusp and high types are never observed at night the diurnal curves effectively cover the period from sunrise to sunset.

The diurnal variations for each type show no great difference from one station to the next and so are not shown here. Instead the difference between the percentage occurrences on disturbed and quiet days $S_D(E_s)$ has been found and is given for the stations listed in Table 8.1 below for IGY (fig.8.1) and IQSY (fig.8.2) during equinoxes (as examples).

Table 8.1

Station	Slough	Wakkanai	Akita	Kokubunji	Yamagawa	Taipei
Geomag.Lat.	54.3°N	35°N	29.5°N	25°N	20.3°N	13.7°N

Also indicated is the average difference between

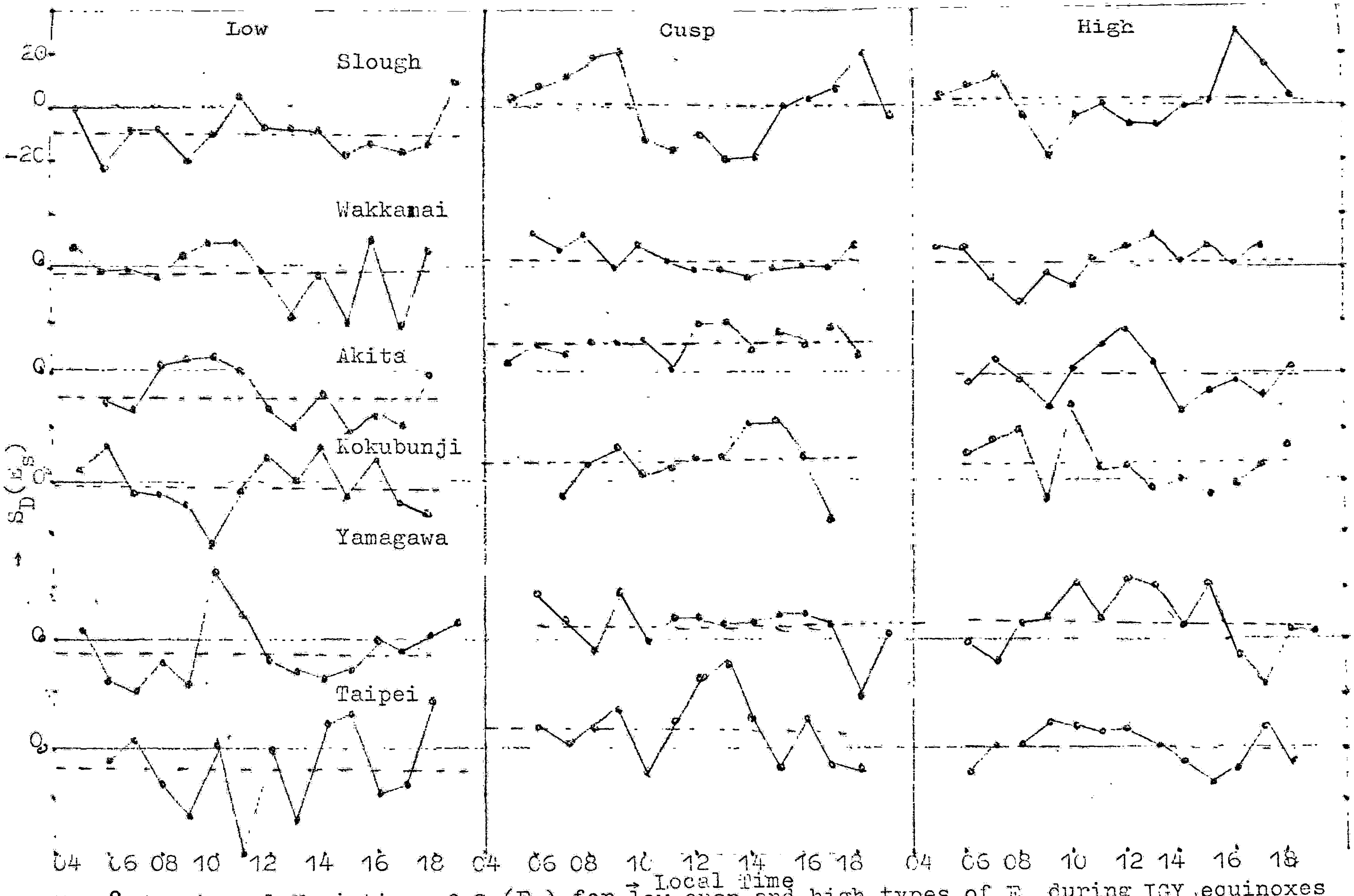


FIG.8.1: Diurnal Variation of $S_D(E_s)$ for low cusp and high types of E_s during IGY equinoxes

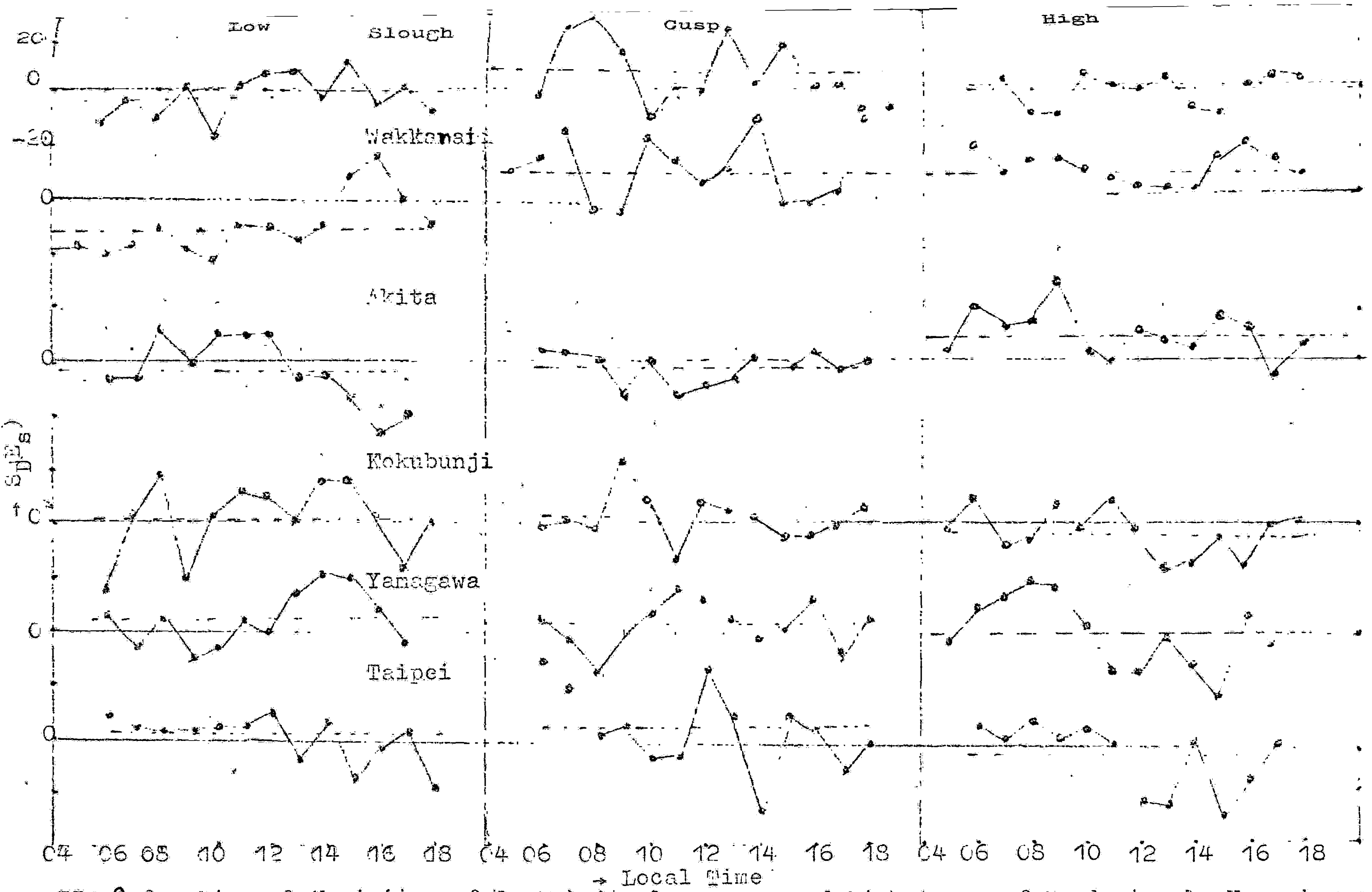


FIG.8.2: Diurnal Variation of $S_D(E_s)$ for low, cusp and high types of E_s during IQSY equinoxes

the quiet and disturbed day occurrence and this is shown by the appropriate dotted line. Negative values for this line will thus indicate an overall negative dependence on magnetic activity, while for positive values the converse will be true.

The individual diurnal graphs exhibit, at nearly all stations, a large degree of fluctuation, so that in most cases only a general conclusion is possible. A very simple indication of the magnetic dependence can be found by considering the number of occasions that the mean value is greater than ± 4%. This is an arbitrary level chosen because percentage differences less than 4% are probably not significant. The difference between the number of ocassions when the mean value exceeds +4% and is less than -4%(D) is given in table 8.2.

Table 8.2

	l	c	h
Total number of occasions	36	36	36
4 MV -4	14	23	24
+ 4	4	8	6
- 4	18	5	6
D	-14	+3	0

From this table it is evident that low type E_s has a significant negative dependence on magnetic activity, cusp type a slight positive one and high type no significant dependence at all.

There is, particularly with low type E_s, a suggestion that the morning and afternoon values tend to be greater and less respectively than the mean value. This difference between the disturbed and quiet day incidences effectively represents the magnetic storm effect and this, as is well recognized, varies with latitude.

The most obvious parameter to be used is the difference between the disturbed and quiet variation in the geomagnetic field i.e. $S_D(H)$. This is given in fig. 8.3(a) for a number of latitudes (Chapman and Bartels) Alongside it is the equivalent variation of the difference between the disturbed and quiet day incidence of E_s i.e. $S_D(E_s)$ for a single season, IGY summer, and for the low type of E_s. While no precise one-to-one relationship between $S_D(E_s)$ and $S_D(H)$ could be claimed, there is nevertheless a certain similarity both in the diurnal and in the latitudinal behaviour with a reversal between 51° and 56° geomagnetic latitude.

In other seasons the correspondence with $S_D(H)$ is not so apparent or even absent but, equally, individual stations in the other seasons provide better agreement with $S_D(H)$. For cusp and high type E_s there are single isolated instances of stations having similar variations to those in fig. 8.3(b) but in no one season is there such a correspondingly reasonable agreement with $S_D(H)$.

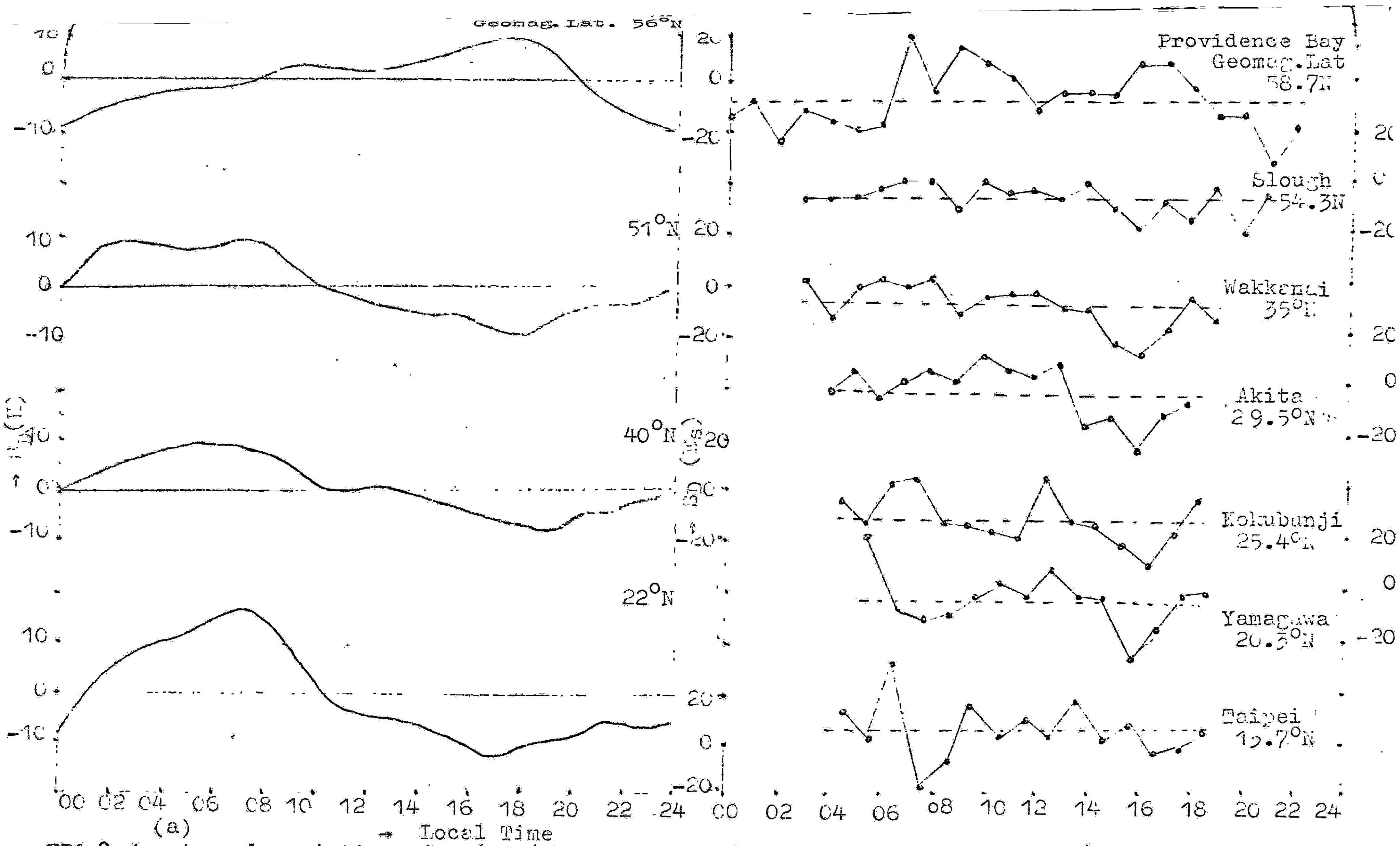


FIG.8.3: Diurnal variation of Sq(H) (Chapman & Bartels)

(b) Diurnal variation of $S_L(E_s)$ in IGY summer for low type of E_s

There is thus a qualitative similarity between $S_D(E_s)$ and $S_D(H)$ but further work is necessary before any formal relationship between them can be established. When it is borne in mind that the percentage variation in $S_D(H)$ relative to the main field is of the order of 0.1%, a pronounced effect on E_s would not normally be expected. The random fluctuations in E_s, which are unavoidable, might thus hide any $S_D(H)$ effect and a more refined analysis than that used in the present work will need to be adopted.

8.2 Latitudinal Variation

The latitudinal variation of each type of sporadic-E has been considered separately and is given in fig.8.4 in terms of k, as defined on page 86, for each season in IGY and IQSY. The only form which shows any consistent variation with latitude is the low type for which k increases from high to low latitudes in 5 out of 6 cases. It is also, in general, less than one, i.e. negatively correlated with magnetic activity as indicated in the previous section.

The variation of cusp type in IGY in each of the three seasons indicates a maximum value of k at 25° to 30° Geomagnetic Latitude. This consistent feature in three independent sets of data would normally be regarded as significant. In IQSY, however, there is some slight indication of a maximum in summer but a very irregular variation in the other two seasons. The evidence for a mid-latitude peak in the magnetic

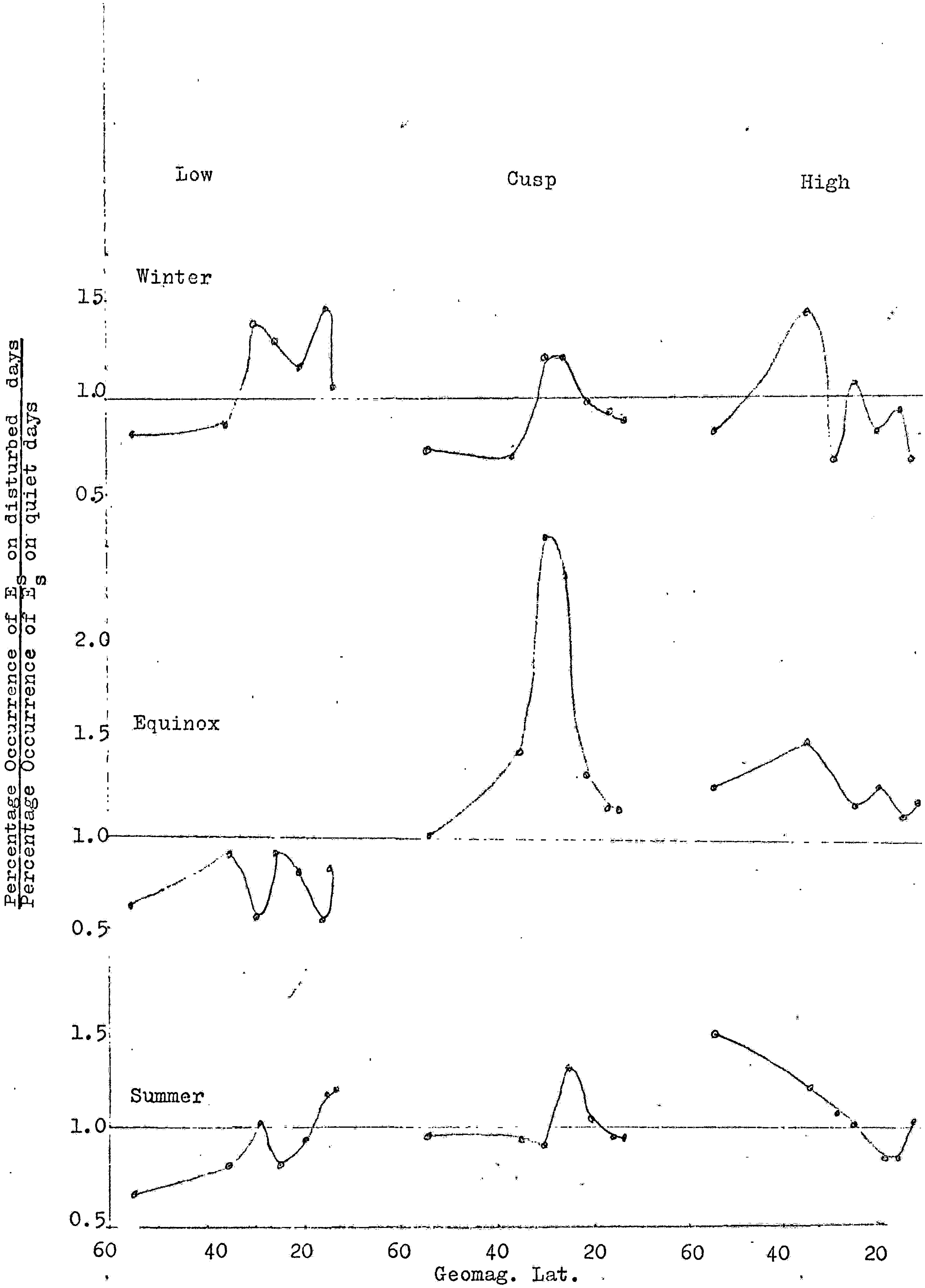


Fig.8.4(a): Latitudinal variation of k for low, cusp and high type E_s during the IGY

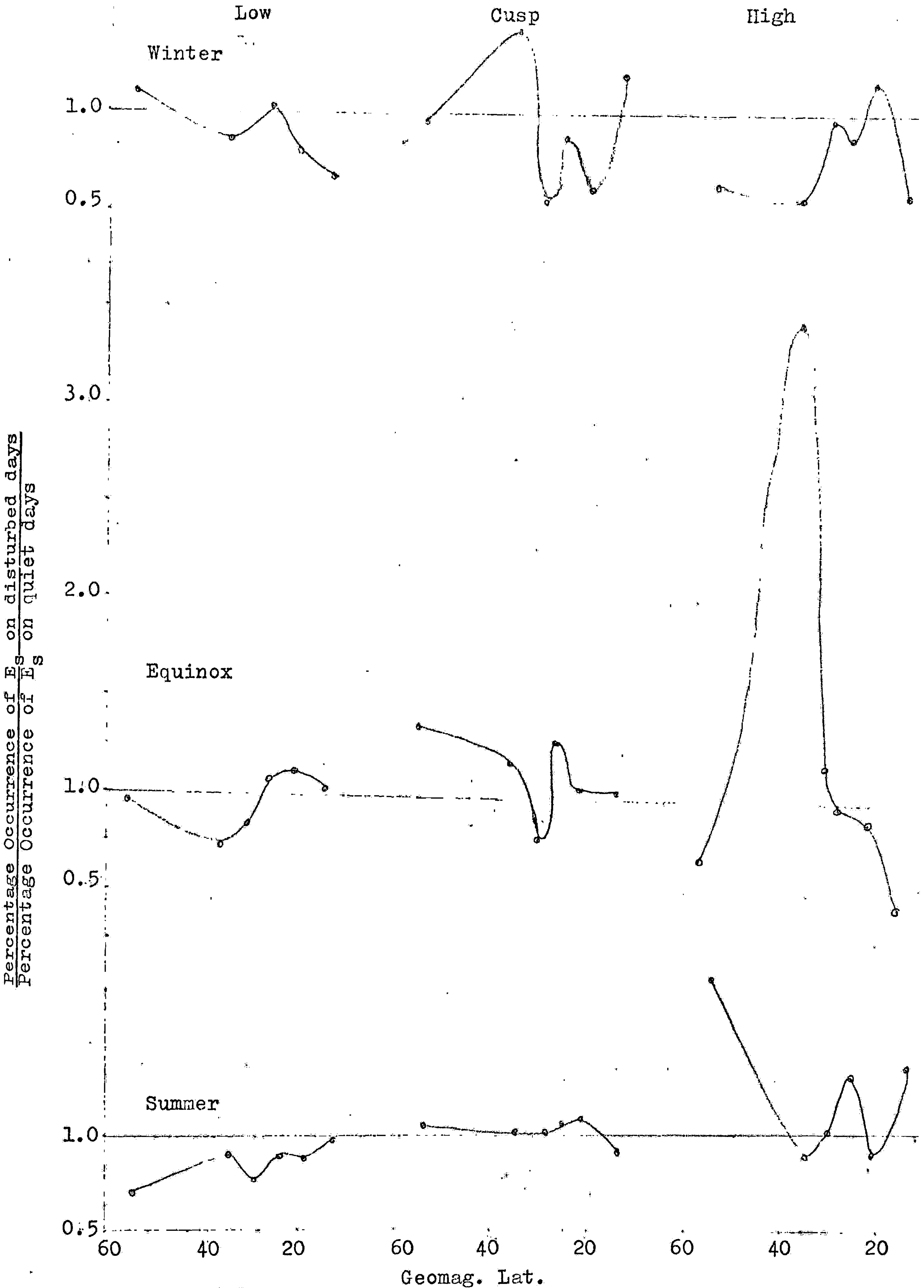


Fig.8.4(b): Latitudinal variation of k for low, cusp and high type E_s during the IQSY

dependence of k is thus not conclusive. There is, nevertheless, an overall tendency for k to be slightly greater than one i.e. a slight positive dependence on magnetic activity.

The high type of E_s shows a most irregular variation with latitude with, possibly, a slight decrease in k with decrease in latitude. There is no obvious preference for values of k greater or less than one, implying that the high type of E_s is unrelated to changes in magnetic activity.

It is thus clear that any consideration of the overall dependence of the incidence of E_s on magnetic activity and as a function of latitude will depend on the relative composition of the total number of occurrences between low, cusp and high types.

In the light of the above results a preponderance of low-type will result in values of k being less than one while a large proportion of high type would result in k being equal to one. It will also be possible, of course, for a mixture of high type, a small amount of low type and a relatively large amount of cusp type to result in a value of k equal to one. Consequently the small changes in k between IGY and IQSY shown in fig.4.23 may not be due to any profound dependence on solar activity but simply to a change in the relative composition of high, low and cusp types.

8.3 Variation of Cusp and Auroral type E_s with K_p

The positive correlation of auroral zone E_s with magnetic activity has been well established for many years, while high temperate latitude E_s is also correlated, but to a lesser extent, negatively when all E_s types are considered collectively. In this section the relative occurrence of cusp type (C-type) over a range of latitudes has been studied mainly for the equinoxes since, as shown in section 8.1, there is some evidence for a positive dependence of this type on magnetic activity. For the auroral region the incidence of auroral type E_s has also been included.

The C-type E_s data is for IQSY equinoxes and covers the range 19° to 54°N Geomagnetic latitude. The incidence of C-type in auroral latitudes during summer has also been included as an appreciable amount of C-type E_s is found to occur in this season. The incidence of a-type at auroral stations covers only the winter of IQSY since little of it occurs in the other seasons.

The percentage incidence of C-type as a function of magnetic activity (K_p) is given in fig. 8.5(b). Each day is characterized by the mean value of K_p for that period and, unlike all the preceding analysis, the E_s data covers every day of the month. There is a small but significant increase of C-type E_s with K_p for all temperate latitude stations. However, at some latitude greater than 54°, a large change takes

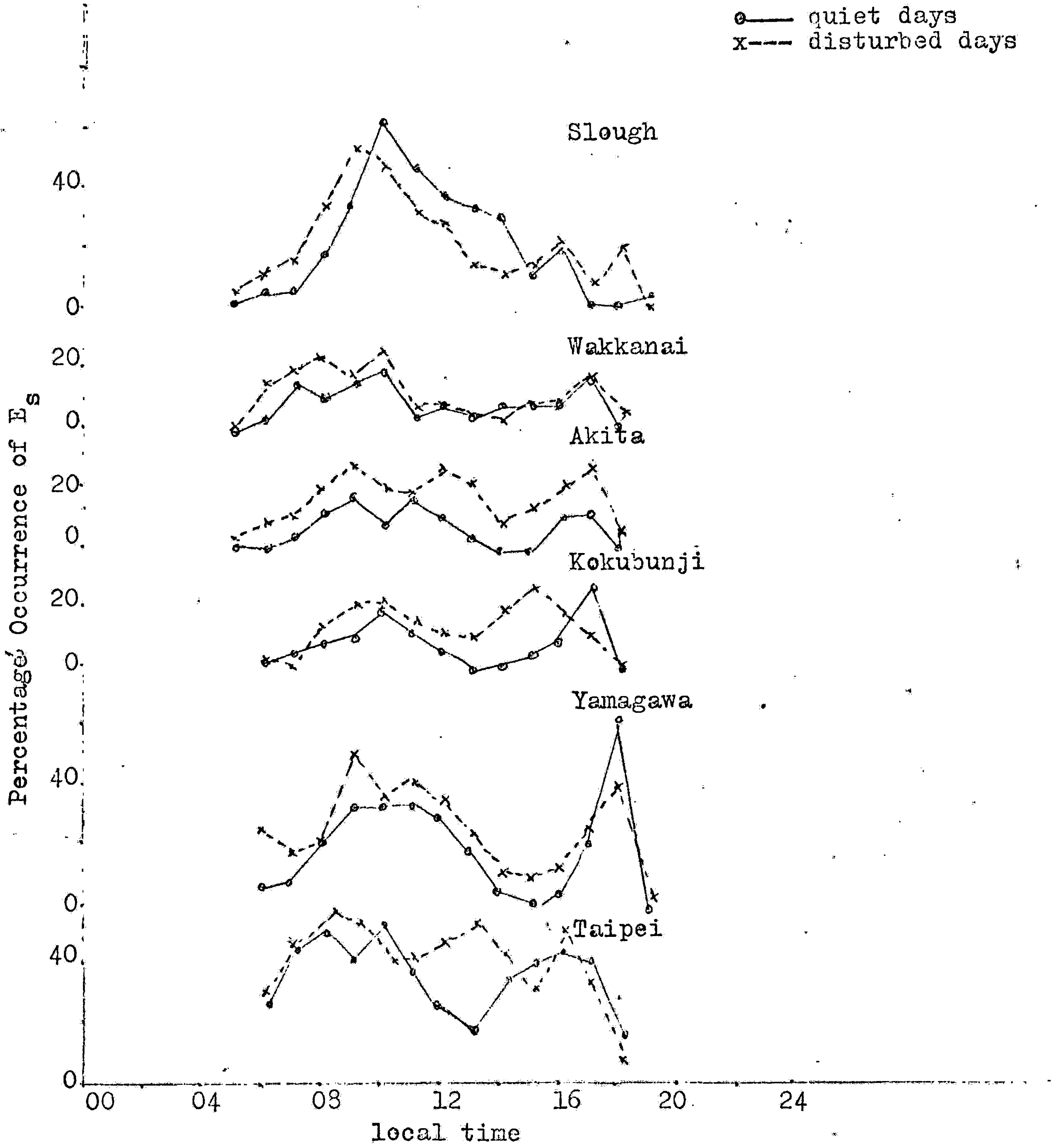


Fig.8.5(a): Diurnal variation of cusp type E_s for IGY equinoxes

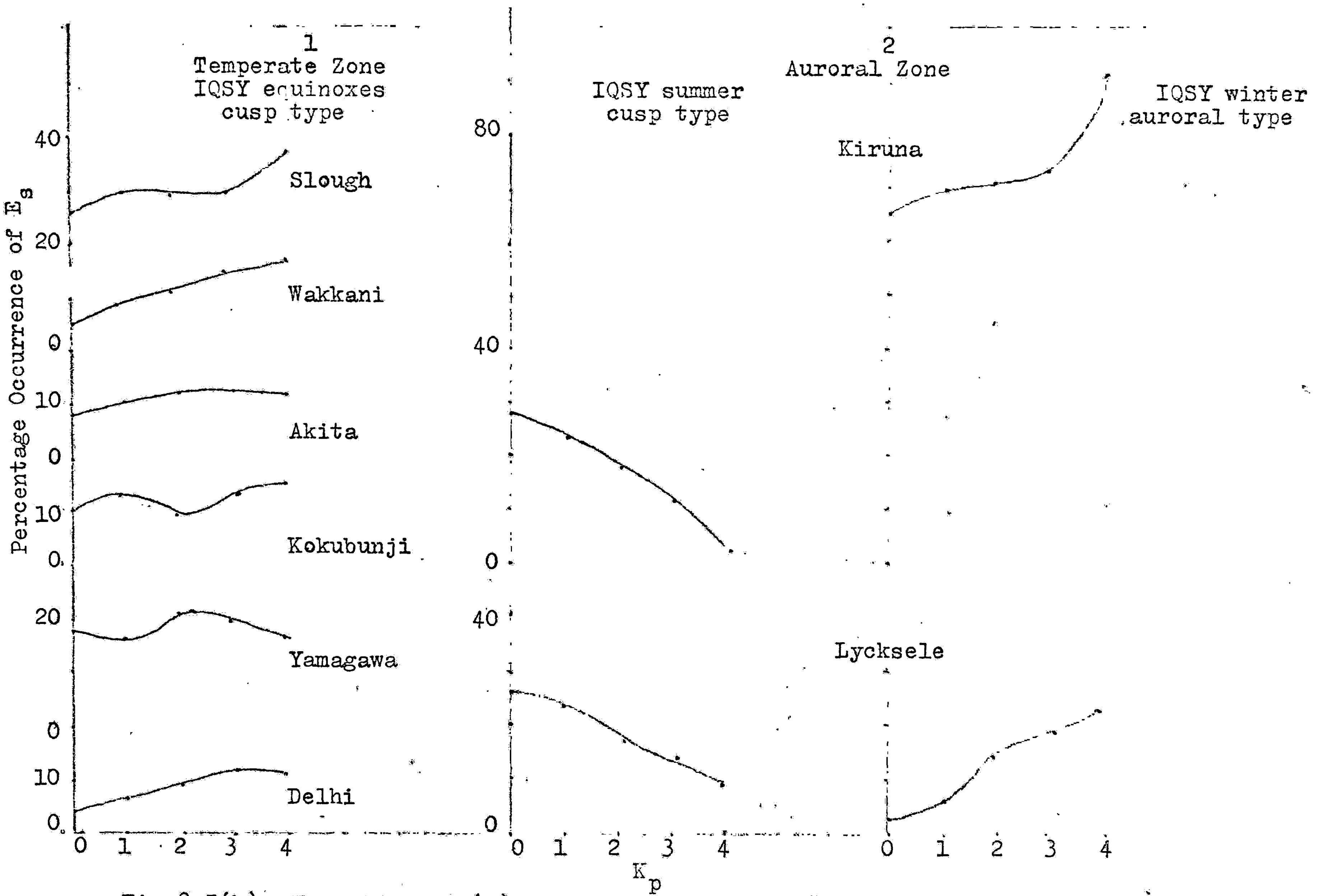


Fig.3.5(b): Variation of (1) occurrence of c-type E_s in temperate zone
(2) occurrence of c-type and a-type E_s in auroral zone with K_p

place and for Kiruna and Lycksele a sharp decrease in C-type with K_p is observed.

As is to be expected for these last two stations, there is an almost equally sharp increase in a-type E_s with K_p. This latter feature is in accordance with this type of E_s being produced by solar corpuscular precipitation, which increases with magnetic storm activity.

The opposite behaviour of C-type in auroral to latitudes is not in agreement with corpuscular effects and would seem to require a different explanation.

The general form of the S_q current system (e.g. Chapman and Bartels, 1940; Matsushita, 1960) shows that the current flows in an anti-clockwise direction at all latitudes in the Northern hemisphere during day-time. When a magnetic disturbance occurs, additional currents flow in the ionosphere at E-region heights and are superimposed on the S_q system. It is then found that the two currents flow in mainly opposite directions at auroral latitudes but in the same direction at high and mid-temperate latitudes. (Afonina and Feldstein, 1969; Silsbee and Vestine, 1942)

This additional polar disturbed current is very strong and might be expected to largely counteract the S_q system. Outside the auroral zone, however, the polar current is much reduced in amplitude and would thus only slightly augment the S_q current.

This interaction of the S_q and polar currents seems to be closely similar to the C-type variations in fig.8.5(b). At the auroral stations there is the rapid decrease of C-type E_s with K_p while, at lower latitudes, there is a much smaller increase. There would thus seem to be reasonable evidence for supposing that the S_q current system may be at least responsible, either directly or indirectly, for the occurrence of C-type E_s over the geomagnetic latitude range 19° to 65°N considered here.

If this is so then the maximum local time effect on C-type E_s should occur when the S_q current system is flowing perpendicularly to the earth's magnetic field.

Reference to the S_q field, as given by Chapman and Bartels, shows that in the equinoxes this occurs at 1030 to 1100 Local time and again at about 1830 Local time. Fig. 8.5(a) shows the diurnal vatiation of C-type E_s for the equinoxes and it is clear that there are two maxima in the occurrence, one at about 1000 L.T. and the other at about 1700 L.T. There is also a tendency for the evening peak to be less pronounced than that in the morning, a feature which is also observed with the S_q current system.

8.4 Variation of flat, low and high type E_s with K_p

For the temperate latitude stations the incidence of flat (f), low (l) and High (h) type E_s has been considered for the equinoxes. The l- and h-types occur by day and f-type by night. For Kiruna, however, there is little l and h type in the equinoxes and hence summer has been used; equally, winter has been used for the f-type, the data in all cases being on a twenty-four hour basis. Fig.8.6 shows the variation with K_p for flat, low and high type E_s.

At Kiruna, an auroral station, it is found that l and h-type are positively and negatively correlated with magnetic activity respectively. For the other three stations there is a tendency for l-type to exhibit a negative dependence and h-type a positive one, but the significance of these trends with the present data is limited. The f type shows no simple dependence on magnetic activity. If, however, the incidences of l and h are combined then the resultant variation, as shown by the dotted lines, shows a marked resemblance to that of f-type for all the stations considered here.

Thus the almost bimodal distribution in f-type can be regarded as equivalent to a combination of h and l-types. Since C-type can clearly not occur in the night in the absence of a visible E-region and since f-type is the only form which can be classified at temperate latitudes, this equivalence of f and l plus h is not therefore surprising.

Equally if l and h types have different signs in their dependence on the magnetic activity, then f-type is also not to be regarded as a single type but as

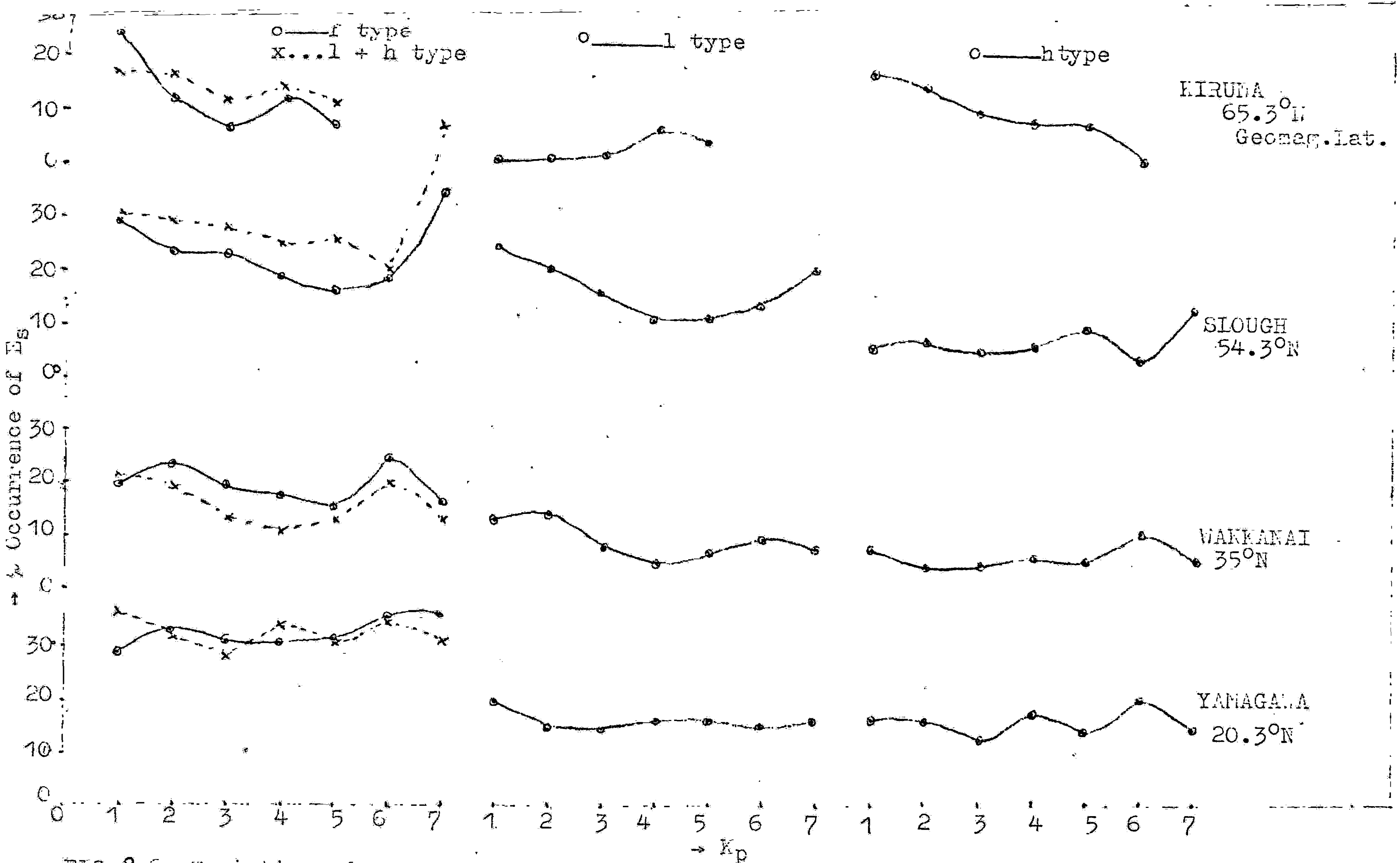


FIG. 8.6: Variation of occurrence of f, l and h-types of E_s with K_p

a combination of the two. The overall variation of f-type will hence depend upon the relative composition of l and h-types.

It will again be noticed that the dependence of l and h-types at Kiruna is opposite to that at temperate latitudes. While it might be thought that the variation of C-type, as described above, is similar to h-type the diurnal variation of the latter form for all stations and all seasons is very irregular and, in general, shows little similarity to the double maxima distribution found with C-type.

8.5 Absorption by an intense E_s layer resulting in no echoes from higher layers

The symbol 'A' used in the tables of the critical frequencies of the F_2 layer (f_oF_2) signifies that the underlying E_s layer is sufficiently intense, with a high critical frequency, to completely obscure all higher layers.

During the IGY the symbol 'A' only appears at high latitude stations and only these can be considered for this period. In IQSY 'A' occurs down to low latitudes and allows a wider range of stations to be used.

The percentage occurrence of 'A' on five quiet and five disturbed days for IGY and IQSY is given in fig.8.7. The diurnal variations in IGY are clearly similar to the diurnal variation of k described in fig.5.8 and can be interpreted on a

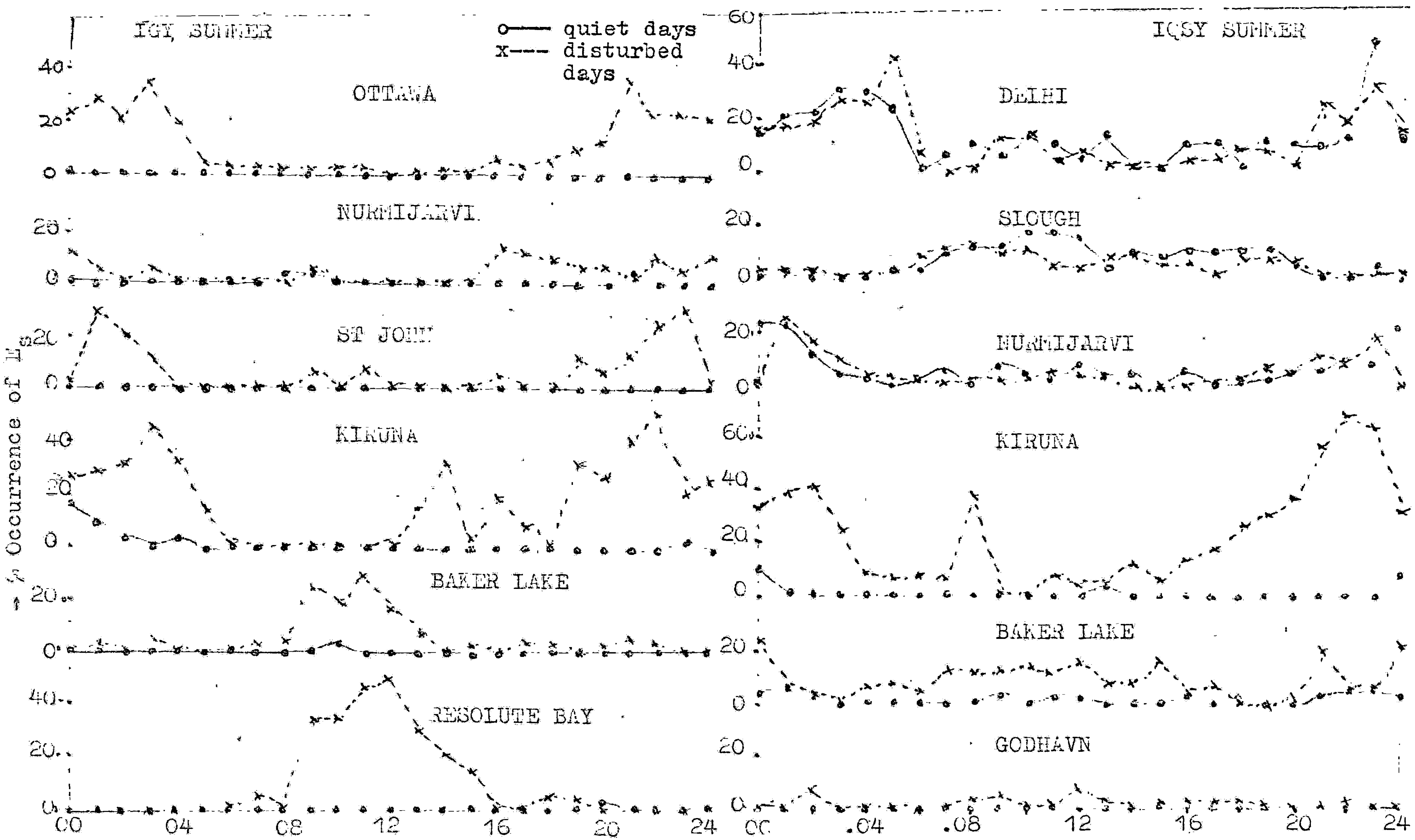


FIG.8.7: Diurnal variation of 'A' on quiet and disturbed days

similar basis. Passage into the auroral zone results in a large increase in the number of precipitated electrons and hence in the ionization density.

This, in turn, may be sufficient to blanket the upper layers and give rise to 'A'. Thus at Resolute Bay and Baker Lake, which lie in the true auroral zone around noon, the percentage occurrence of 'A' is high but falls to zero around midnight.

For the other high latitude stations the late evening and early morning peaks correspond to the passage of the centre of the auroral belt above the station in South- and North-bound directions respectively. On quiet days the precipitation is presumably insufficient to create a strong blanketing E_s layer and no 'A' symbols are observed.

In IQSY the high latitude stations behave in a similar manner but there are also found to be significant variations at lower latitudes. For the two examples given, Slough and Delhi, there is an appreciable occurrence of blanketing E_s. If this were to be interpreted solely in terms of electron precipitation, it would be a very surprising result, particularly at the latitude of Delhi.

A possible explanation for this is that the variation in f_oF_2 from minimum to maximum solar activity can be in the ratio of 1 to 2 or more. The corresponding changes in the E_s critical frequencies fE_s, f_oE_s or f_bE_s are, however, very much less.

This will then result in f_oF2, during IGY, being on average well above the mean values of f_bE_s whereas, in IQSY, f_oF_2 will be greatly reduced and will fall to a value much closer to that of f_bE_s. Hence the number of occasions when f_bE_s exceeds f_oF_2 may be correspondingly greater in IQSY.

SUMMARY OF THE CONCLUSIONS

1. The Longitudinal variation in the occurrence of E_s at high latitudes depends on the position of the dip-pole; the occurrence of E_s increasing in the same sense as the meridional and zonal movement of the dip-pole for a number of high latitude stations.

2. The positive correlation between the occurrence of E_s and solar activity at western stations and the negative or zero correlation at eastern stations is caused by the meridional movement of the dip-pole towards the north and by the zonal movement towards the west, i.e. towards eastern stations between IGY and IQSY.

3. At temperate latitudes the occurrence of E_s at low frequencies depends on the ambient electron density. Small windshears can produce E_s when the ambient electron density is small but the same windshears cannot produce detectable E_s with a high ambient electron density. This is observed when the seasons and years of high and low ambient electron density are compared.

4. A comparison of pairs of stations situated at longitudes 180° apart shows a relative reversal in the occurrence of E_s between summer and winter at temperate latitudes. The horizontal component of the earth's magnetic field is considered to be responsible for the greater occurrence in the eastern zone, when compared with western zone stations. This is true for summer and a reversal takes place during winter.

This reversal can be accounted for by means of the windshear which also shows a similar behaviour.

5. The reduction in E_s occurence at Kodaikanal as compared to Huancayo from IGY to IQSY is explained in terms of decrease in width of the electrojet in the latter period. A positive correlation between the most probable value of E_s and solar activity is observed at these stations.

6. The behaviour of E_s at high latitudes can be interpreted in terms of two distinct zones, namely a discrete and a diffuse zone.

7. The overall correlation between the occurrence of E_s and magnetic activity at certain high latitude stations changes sign between IGY and IQSY. This is interpreted in terms of a movement of the E_s auroral zone.

8. This movement is subject to diurnal, seasonal and solar cycle variations.

9. Electron energy spectra converted to electron density profiles yield reflection heights which vary with latitude in a similar way to those obtained from ground based measurements.

10. The cumulative distribution of E_s has been used to show that the Phillips' Rule is applicable only above the most probable frequency, but to all stations and for all times. The gradient of this distribution has a definite and pronounced latitudinal variation.

11. In temperate latitudes a negative magnetic dependence for low type E_s occurrence and a slightly positive one for cusp type E_s has been found. Changes in l-type E_s occurrence are considered to be related

to magnetic field changes.

12. The positive and negative dependence with magnetic activity of C-type E_s in temperate and auroral latitudes respectively can be explained in relation to the S_q and disturbed polar current system.

13. The bimodal distribution of f-type E_s with respect to magnetic activity may be regarded as the superposition of low and high types.

APPENDIX I

Stations used for E_s data

Station	Geographic Latitude	Geographic Longitude	Geomagnetic Latitude	Geomagnetic Longitude
Huancayo	12.1°S	75.3°W	0.6°S	358.8°
Kodaikanal	10.2°N	77.5 E	0.6°N	147.1°
Taipei	25.0°N	121.5°E	13.7°N	189.8°
Bogota	4.6°N	74.1°W	15.9°N	354.5°
Delhi	28.6°N	77.2°E	18.9°N	148.9°
Yamagawa	31.2°N	130.6°E	20.3°N	197.8°
Kokubunji	36.7°N	139.6°E	25.4°N	205.4°
Akita	39.7°N	140.1°E	29.5°N	205.4°
Puerto Rico	18.5°N	67.2°W	30.0°N	2.0°
Wakkanai	45.4 N	141.8°E	35.3°N	206.0°
Adak	51.9°N	176.7°E	47.3°N	240.0°
Slough	51.5°N	0.6°W	54.3°N	83.2°
Ottawa	45.4°N	75.7°W	55.9°N	351.3°
Nurmijarvi	60.5°N	24.7°E	57.9°N	112.6°
St.John's	47.7°N	52.8°W	58.5°N	21.4°
Uppsala	59.8°N	17.6°E	58.5°N	105.9°
Providence Bay	64.5°N	173.3°W	58.7°N	235.8°
Anchorage	61.2°N	149.9°W	60.9°N	258.1°
Lycksele	64.6°N	18.7°E	62.7°N	110.8°
Lulea	65.6°N	22.1°E	63.0°N	114.7°
Kiruna	67.8°N	20.4°E	65.3°N	115.9°
Tromso	69.7°N	19.0°E	67.2°N	116.3°
College	64.9°N	147.8°E	67.7°N	256.5°
Point Barrow	71.1°N	156.8°W	68.4°N	241.2°
Reykjavik	64.1°N	21.8°W	70.2°N	70.9°
Heiss Island	80.6°N	58.0°E	70.9°N	156.5°
Narsarssuak	61.2°N	45.4°W	71.2°N	37.0°
Baker Lake	64.3°N	96.1°W	73.7°N	315.1°
Godhavn	69.3°N	53.6°N	79.8°N	32.5°
Resolute Bay	74.7°N	94.9°W	82.9°N	289.3°
Fletcher Ice Island	80-83°N			

APPENDIX II

Choice of limiting frequency and variation in data

In the present work a constant limiting frequency has not been used throughout since a rigid adherence to a fixed value ignores the distribution of and number of values in any one sample of data. The optimum limiting frequency is determined by a subjective judgement such that it is not so high that few values remain in the final sample and preferably not so low that every conceivable value of E_s is included, irrespective of its type or association. Tests of different limiting frequencies for different stations, seasons, solar and magnetic conditions were carried out. A representative sample for the percentage occurrence of E_s ($f_oE_s \geqslant 5$ Mc/s, $f_oE_s \geqslant 3$ Mc/s and for all frequencies) is given in fig. AII.1 for Lycksele during winter 1959/60 for quiet and disturbed conditions. There is clearly little difference between each of the three criteria and similar results were obtained for all the other test samples. The different absolute levels of occurrence in the three samples are of no consequence since for a given study, or dependence upon a given parameter, a constant value of limiting frequency has been chosen.

In general a limiting frequency of 3 Mc/s has been adopted. The principal exception to this is the study of different types of E_s when the number of values

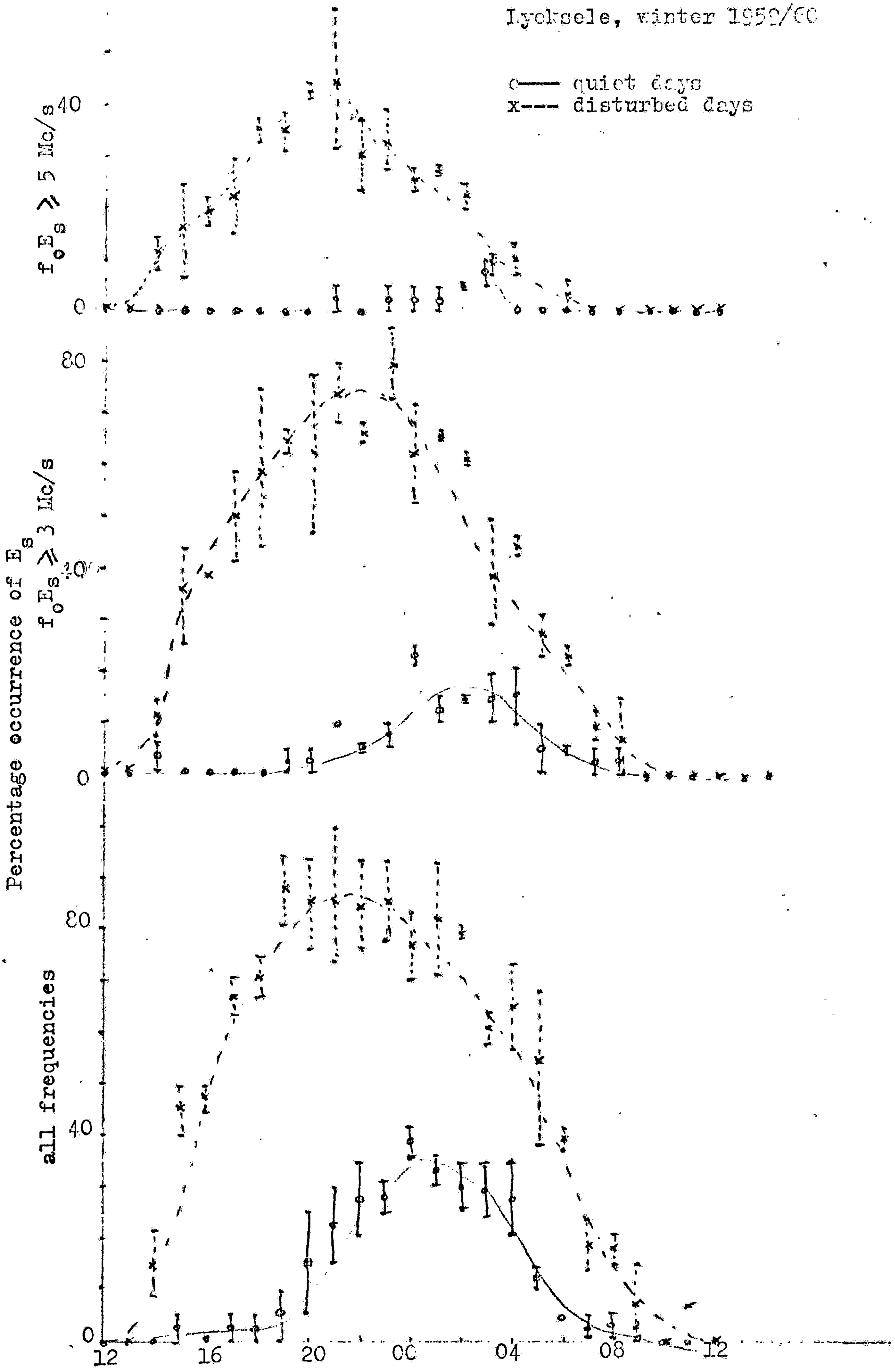


Fig.AII.1: Diurnal variation of occurrence of E_s

for $f_oE_s \geqslant 3$ Mc/s would have been small. For this analysis all occurrences of a particular type have been considered in order to retain a statistically significant sample.

The conventional concept of an error is not applicable when applied to the number of occurrences greater than a predetermined frequency and thus the normal error bars cannot be indicated on graphs. When considering, for example, the different levels of occurrence on quiet and disturbed days, the significance of the separation between the curves is difficult to assess. One approach to resolving this difficulty is to divide the data into two groups using alternate days and the percentage occurrences of each of the groups of days are then taken as the upper and lower limit of the "error bar". An example of this division is given in fig. AII.1. It is clear that there is no ambiguity between the quiet and disturbed days behaviour. Again similar results have been found for other test samples and consequently "error bars" are not included in the graphs presented in this work. In those instances where the two curves being compared are close together, due consideration has been given to this fact in the interpretation for those cases where the internal consistency of the data is not by itself sufficient.

APPENDIX III

Determination of pitch angle

The pitch angle of a particle trapped in a radiation belt, i.e. the angle between the direction of motion of the particle and the guiding magnetic field line, will determine the altitude at which the particle mirrors or bounces back along the same path.

Calculations indicate that if a particle will mirror at about 100 km then the probability of a collision is sufficiently great for the particle to be regarded as precipitated. A knowledge of the pitch angle at any given altitude will, therefore, determine whether the particle will be precipitated or mirror indefinitely. If α_1, B_1 and α_2, B_2 are the pitch angles and the magnetic fields at two points along the guiding field lines respectively, then it is well established that

$$\frac{\sin^2\alpha_1}{\sin^2\alpha_2} = \frac{B_1}{B_2}$$

at the mirror point $\alpha_1 = 90^\circ$ and if the magnetic field at 100 km is B_{100} then

$$\frac{1}{\sin^2\alpha_c} = \frac{B_{100}}{B_H}$$

where α_c is the critical pitch angle for a magnetic field B_H. Any particle with a pitch angle less than α_c will mirror below 100 km and so be precipitated.

For satellite and rocket observations the magnetic field B_H at the site of the measurement can be calculated and thus α_c determined. This has been done for the measurements referred to in section 7.1 and α_c calculated for a particle at an equatorial position. The resulting variation of α_c with the L-shell value is given in fig. AIII.1 and, provided the acceptance cone of the detector is known, it may be readily determined whether the observed particle flux relates to trapped or precipitated particles. For the Aurora 1 satellite orbiting at 4,000 km, $\alpha_c = 30^\circ 22'$ at $L = 6$ which compares with the acceptance cone of the detector of $\pm 30^\circ$ so that all the detected particles will be precipitated.

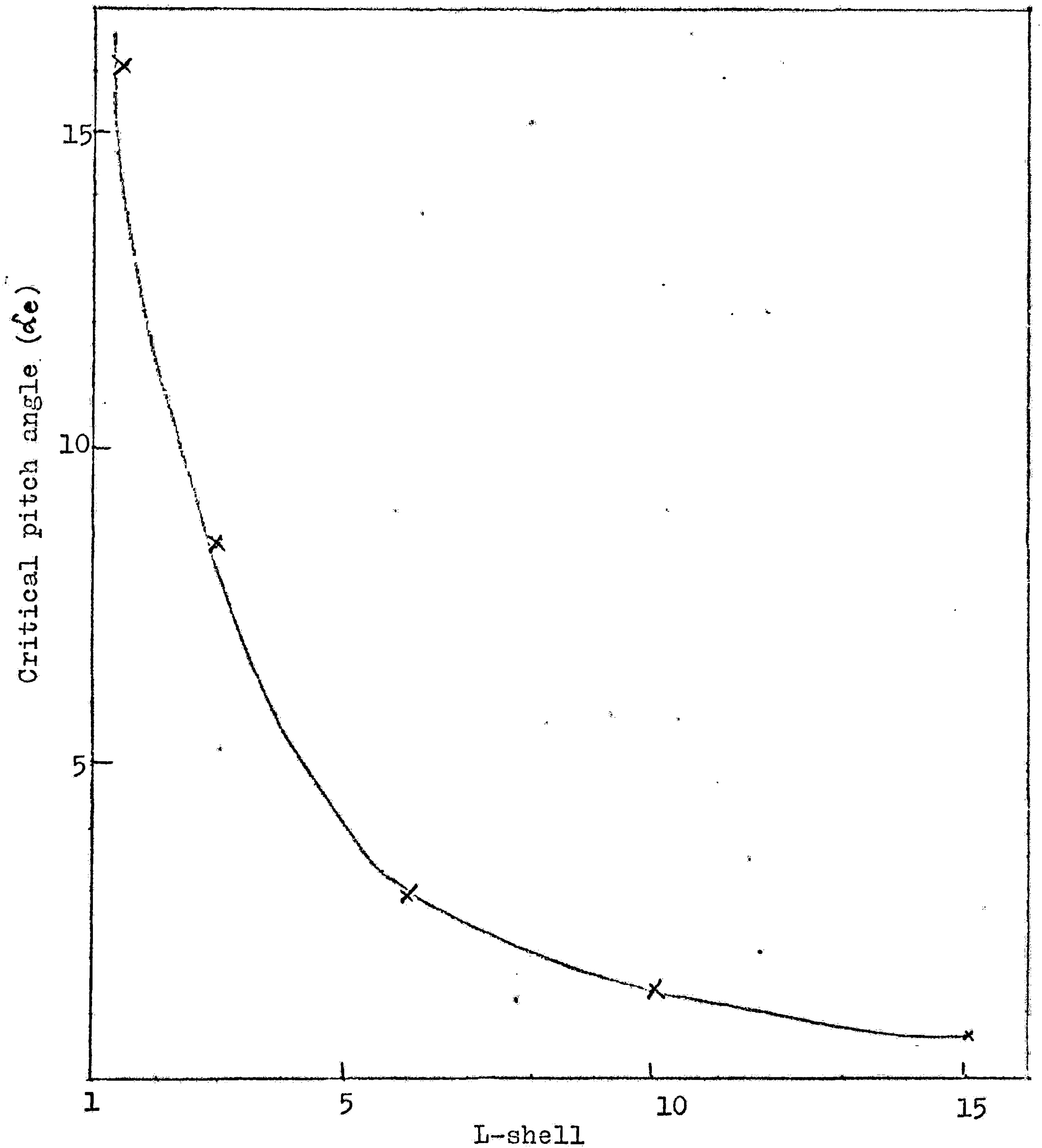


Fig.AIII.1: Variation of critical pitch angle (αe) with L-shell at equatorial position

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