IONOSPHERIC ELECTRON CONTENT AT TEMPERATE LATITUDES DURING THE DECLINING PHASE OF THE SUNSPOT CYCLE

by

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Abstract

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The values of electron content obtained by observations of Faraday effect for the period July 1961 to October 1964 are presented. These values, when combined with values obtained by other workers at a time when the sun was more active, enable us to study the diurnal, seasonal, and sunspot dependence of the electron content and the slab thickness. These experimentally measured quantities are then related to the physical quantities such as the diffusion coefficient, and the electron and ion temperatures by using a diffusion transport model.

The seasonal dependence of the electron content and the slab thickness are not in agreement. Possible causes of seasonal anomaly are examined in terms of a diffusion transport layer. The most favored mechanism seems to be the change of composition of the minor constituent O_2 or N_2.

The slab thickness is found to increase with increasing magnetic activities.

Author

1. Introduction

The study of the electron content in the ionosphere has been carried out for about half of the sunspot cycle. A major portion of these measurements makes use of transmissions from satellites, and the remaining portion makes use of reflections from the moon. This paper deals with some of these results.

The paper starts with the presentation of data deduced from observations of Faraday effect on 54 mc/s transmitted by the satellite 1961 Omicron 1 (Transit 4A). This satellite was launched into orbit on June 29, 1961. The nodal period of the satellite is 103.8 minutes, inclination 66.82^{o}, apogee 1006 km and perigee 873 km. The observations, made at Urbana, Illinois, cover the period from July 1961 to October 1964.

Curves are presented to show that, seasonally, the electron content at midday has maxima in equinoxes and minima in solstices (see section 4), while the slab thickness has a maximum in summer and a minimum in winter (see section 7). This suggests that temperature plays an important role, especially on the coupling of the conjugate ionospheres through the protonosphere. A tentative explanation is given in section 4.

The electron content at midday has been found to have a non-linear dependence on the sunspot number near the minimum solar activity, while many observers have found that a linear relation exists for sunspot number larger than 50 (see section 5). The decay of electron content at night is predicted to be exponential by the diffusive transport model. The exponential decrement is proportional to the ratio of the diffusion coefficient at the base of the layer and to the square of the ionic scale height. Therefore, the study of electron decay at night gives some information on the diffusion coefficient and the ion temperature as shown in section 6. The seasonal and diurnal variations of slab thickness are discussed in section 7. If the gas temperature (assumed to be equal to ion temperature) is obtained by other methods, such as those provided by satellite drag studies, the slab thickness can be used to compute the electron temperature. It is also shown in section 7 that the best model appears to be a hybrid layer since the computed electron temperature then agrees with the electron temperature values measured by the incoherent scatter method. In section 8, evidence is given for the magnetic activity dependence of slab thickness. Some discussion on observations made in this paper are included in section 9, and the theory of the equilibrium diffusive transport layer is presented in Appendix A.

2. Method of Analysis

The rotation of the plane of polarization in a magneto-ionic medium under quasi-longitudinal approximation is given by

$$\Omega = \frac{K}{f^2} \int NM \, dh \quad \text{radians} \tag{1}$$

where, in MKS rationalized units, $K = 2.97 \times 10^{-2}$, N = electron density, f = radio frequency, M = magnetic parameter (Yeh and Gonzalez, 1960) and dh = differential height element. Since the magnetic parameter is a slowly varying function of height, and the electron density is rather peaked, (1) may be rewritten as

$$\Omega = \frac{K \overline{M}}{f^2} \int N \, dh \quad \text{radians} . \tag{2}$$

As long as N is a continuous function of height, the mean value theorem guarantees the existence of $\overline{M}$ such that (2) is true. The difficulty, of course, is that the mean value theorem states that $\overline{M}$ is the value of M at some height, but leaves the value unspecified. Therefore, model studies are required to find the exact height for $\overline{M}$ evaluation. These studies indicate that the exact height for a given model ionosphere depends on the direction of the ray and may have a value in the range of 340 to 400 km (Yeh and Gonzalez, 1960). If we restrict ourselves to rays with a zenith angle of 40° or less, a height of 350 km seems to be the optimal choice (Roger, 1964). Therefore, in this study, $\overline{M}$ is evaluated at a height of 350 km.

The second difficulty in all satellite beacon experiments is that the time rate of change of Ω, rather than the absolute value of Ω, is measured. The time rate change is, to a large extent, due to change in $\overline{M}$. In the present analysis, the values of $\overline{M}$, typically separated by about one minute, are evaluated and the corresponding polarization rotation is measured from the record and the values of electron content can be calculated. This method (called rotation angle method) also was used in an earlier paper (Yeh and Swenson, 1961). Probably the weakest assumption in this method of analysis is the neglect of horizontal electron density gradient, which has been criticized by Garriott and de Mendonca (1963). These authors have analyzed 35 passages of Transit 2A, using many different methods, and showed that the rotation angle method yields values of electron content about 25 per cent higher than the hybrid method. The difficulty in an error analysis of this sort is that the exact content is never known. One possible test of the data is a self-consistency test. Therefore, in the data analysis, as many values of electron content as possible have been calculated for that portion of the satellite passage in which the zenith angle is less than 40°. The mean as well as the per cent standard deviation for each pass can then be computed. A histogram showing the number of cases with a given standard deviation is presented in Fig. 1. In each of nearly six hundred passages for which two or more content values are obtained, the mean and the standard deviation were computed; eighty-five per cent of passages have a standard deviation of 10 per cent or less. This standard deviation is much smaller than that obtained by Garriott and de Mendonca (1963) who analyzed only thirty-five passages of Transit 2A. It should be emphasized that this is only a self-consistency test and not an error analysis. The estimated error is probably somewhat higher.

3. Diurnal Variation

The values of electron content deduced from observations of satellite 1961 Omicron 1 are shown in Fig. 2. Due to westward motion of the nodes the time of observation advances each day. Roughly, it takes a little more than three months to cover a complete day. Therefore, the diurnal variation, shown by curves in Fig. 2, is also contaminated by the seasonal variation as discussed in the next section.

In Fig. 2, dots are used to indicate the points when the satellite zenith angle is 40° or less and crosses are used when the zenith angle is larger than 40°. The content values are averaged over two-hour intervals. When there are more than five points with zenith angle less than 40°, the averaged value is indicated by a solid line; otherwise, the average is shown by a dotted line.

In addition to the diurnal variations, seasonal as well as solar cycle dependences also are obvious from the curves in Fig. 2. These are discussed in the following sections.

4. Seasonal Dependence

The study of f_0F2 has revealed a number of anomalies in its behavior (Ratcliffe and Weekes, 1960). In particular, it has been found that the local noon F2 region critical frequency is higher in winter than in summer. Therefore, it is interesting to study whether or not similar behavior exists in the electron content.

Although the experimental study of electron content has been carried out for over a decade, the detailed study of seasonal dependence has not been done, perhaps because such studies require relatively continuous probing of the ionosphere. The most continuous data known to us seem to be those of Webb who records lunar reflected signals (Webb, 1963). Unfortunately, his experiment was performed on a single frequency and hence is hampered by ambiguity resolution. Since his and the present experiments were carried out at nearly the same locality, the electron content values of both experiments should agree. One can therefore use our values, perhaps measured at a time other than the local noon, to adjust Webb's monthly average curves in order to obtain the noon values. These adjusted monthly noon values are plotted in Fig. 3 for the period from July 1961 to December 1962.

The curve depicted in Fig. 3 shows a seasonal variation that is remarkably strong, a change of at least a factor 2. During the period studied, the sunspot number changed from about 50 to 30. As shown in the next section, such a change will not influence the content very much and hence the curve shown in Fig. 3 is predominately seasonal in behavior. An interesting point to note is the double humped nature of the seasonal curve showing maxima in March and October and minima in January and July. Satellite drag studies have revealed a semiannual variation in atmospheric temperature and density (Jacchia, 1963) which is somewhat similar in nature to the content variation shown in Fig. 3. But the direct dependence of content on temperature is not enough to explain the observed seasonal dependence. This is discussed in section 9.

5. Solar Cycle Dependence

The study of solar cycle dependence of electron content has been made by a number of authors (Taylor, 1963; Hibberd, 1964; Bhonsle, et al., 1965); however, all such studies were made for the sunspot number larger than about 50. Most of the content values obtained in the present investigation were for sunspot number 50 or less. Therefore, the present data have been combined with values of other investigators. The results are shown in Fig. 4. Again, the double humped nature of the seasonal dependence is apparent and such seasonal dependence becomes more pronounced with an increase in sunspot number.

The approximate linear relationship between content and sunspot number, as found by other authors for sunspot number larger than 50, is no longer valid for sunspot number less than 50. This seems reasonable at first sight since the sun still produces ionization radiation even if it is spotless. However, if the conversion of Nicolet (1963) is used from the sunspot number to the solar flux at 10.7 cm, the electron content is still found to be flat for the solar flux unit less than about 100. It seems that there may be nonlinear dependence between solar radiation at 10.7 cm and the ionizing part of the solar spectrum near minimum in solar activities.

6. Rate of Loss of Electrons at Night

The behavior of the electron density after sunset has been studied by Pound and Yeh (1965). The diffusive transport model used predicts that the electron density may rise at the peak immediately after sunset, depending on the initial electron to ion temperature ratio. This agrees with experimental observations. The theory also predicts that the electron content during this same period will be held nearly constant. This is again supported experimentally as shown in Fig. 5. A few hours after sunset, the electron density at all heights approaches asymptotically an exponential decay with an exponential decrement equal to $D_a \pi^2 / 16H_i^2$. Therefore, the study of electron content decay after sunset provides information on the ratio of the ambipolar diffusion coefficient at the base of the diffusive transport layer and the square of the scale height. In section 9 it will be shown that D_a, to the first approximation, can be assumed to be nearly constant. This means that the exponential decrement has an inverse temperature square dependence.

The theory has been applied to some experimental observations and the results are tabulated in Table 1 where the quantity D_a/H_i^2, as well as temperature ratios, are given. In obtaining the temperature ratio, it has been assumed that the 1961 summer value at Jodrell Bank has 1 unit value. Since not all observations were made at the same site, magnetic dip angle corrections have also been made in computing the temperature ratio. The nighttime temperature results, given in Table 1, reveal both the seasonal and the sunspot dependences in temperature which are in rough agreement with the values obtained by studying satellite drag.

For $T_i = 820^\circ K$ (corresponding to the average value given by Nicolet, 1963, for the summer night of 1961), the ionic scale height is 48 km. The ambipolar diffusion coefficient, after correcting for the dip angle effect, is calculated to be 2.2×10^5 m^2/sec at the base of the diffusive transport layer.

7. Slab Thickness Variation

Slab thickness, defined as the ratio of total electron content to the electron density at the peak, has been used by a number of investigators as a temperature indicator at midday in the ionosphere (Ross, 1960; Hibberd, 1964; Bhonsle, et al., 1965). The exact relation between slab thickness and temperature depends on the models used. Many investigators have used the Chapman model because it is convenient (Bhonsle, et al., 1965). Whatever reason there is for using the Chapman model above the peak cannot now be justified, especially since it is known that electrons may not be in thermal equilibrium with the ions. A theory without such a restriction is the diffusion transport layer which has been developed in Appendix A and which is expected to apply above the peak but not below. Therefore, we are proposing a hybrid layer made up of a diffusion transport layer above the peak and a Chapman layer below the peak. The dependence of slab thickness on electron-to-ion temperature ratio for this hybrid layer, as well as for pure Chapman and pure diffusion transport layers, is shown in Fig. A-2 in Appendix A. This theory will be used to discuss temperatures in the ionosphere after the presentation of data.

The seasonal dependence of the average midday slab thickness is shown in Fig. 6. The maximum electron density used was obtained from Ft. Monmouth ionograms. Random checks of Ft. Monmouth ionograms with those obtained locally indicate similar diurnal behavior, but the local values of maximum density seem to be consistently higher than the Ft. Monmouth values at the corresponding local time by about ten per cent. Therefore, such longitudinal corrections must be kept in mind.

The seasonal dependence of the slab thickness as shown in Fig. 6 is distinctly different from the seasonal dependence of the total content depicted in Fig. 3. Fig. 6 shows the single summer maximum and the single winter minimum in each year instead of the double maxima in equinoxes and the double minima in solstices for the electron content shown in Fig. 3.

The diurnal variation of the slab thickness is shown in Fig. 7. The interesting features are the early morning rise, the approximate constancy during the day and the evening dip. The last phenomenon can be explained as a relaxation of electron temperature to ion temperature. This relaxation introduces a downward electron flux which may enhance the electron density at the peak and which, at the same time, tends to maintain the electron content value, resulting in a dip in slab thickness (Evans, 1965a; Pound and Yeh, 1965).

Using the slab thickness data published by Bhonsle, et al. (1965), the ratio of electron-to-ion temperature for the Chapman layer, the diffusion transport layer and the hybrid layer has been computed and tabulated in Table 2. In the computation, the gas temperature and ion temperature are assumed identical and the mass of the gas and the ion is assumed to have an atomic weight of 16. Originally, the gas temperatures used by Bhonsle, et al. (1965) were taken from the table computed by Nicolet (1963). This is not quite correct since these temperatures were computed for the diurnal bulge, while the observations were made at a fixed latitude. The gas temperature at midday, shown in Table 2, is computed by using the formula derived by Jacchia (1963), with the nighttime temperature given by Nicolet (1963).

It can be noted that the diffusion transport layer gives a consistently higher ratio and the Chapman layer gives a consistently lower ratio. The electron temperature for 1962 can be computed to be 1500°K, 1800°K and 2200°K for winter, equinox and summer, respectively, if one uses the hybrid layer. This compares rather favorably with the incoherent scatter results of Evans (1965), who measured the electron temperatures at 350 km at midday to be 1800°K and 2400°K in November and July, 1963. The computed electron temperature would have been too low, when compared with the incoherent scatter results, if the Chapman layer had been used, and too high if the diffusion transport layer had been used.

8. Magnetic Dependence of Slab Thickness

During the period of investigation there were no major magnetic storms. Since, as shown in Fig. 7, the slab thickness is relatively constant during the day from 0600 to 1600, the average slab thickness measured during this period is divided into three separate time intervals and plotted against the K_p index. The result is shown in Fig. 8. All three curves indicate an increase of slab thickness with increasing magnetic activities. The large fluctuations on these curves for K_p above 4 are due to lack of data.

The increase of neutral atmospheric temperature with magnetic activity was revealed by satellite drag studies (Jacchia, 1961). The mechanism by which the atmosphere is heated during magnetic storms is not well understood at present. The experimental evidence indicates that heating is taking place mainly below 200 km. One possible heating mechanism is the dissipation of hydromagnetic waves (Dessler, 1959). The dissipation of these waves to neutral particles depends on the ion-neutral collisional frequency, while the dissipation to plasma particles depends on the electron-ion collisional frequency. Therefore, the heating of neutral atmosphere is expected to take place below about 200 km where the ion-neutral collisional frequency becomes appreciable. On the other hand, the heating of the plasma particles is expected to take place mainly in the F2 region, since the electron - ion collisional frequency has a maximum there.

9. Discussion

One of the most puzzling phenomena in the study of F-region aeronomy is the seasonal anomaly (Ratcliffe and Weekes, 1960). It has been found that the maximum electron density at local noon is higher in winter than in summer. Such anomaly is again manifested in the present investigation of noon electron content and in the similar investigations by other researchers. The aim of this section is to discuss possible causes of this anomaly.

Let subscripts S, E and W denote summer, equinox and winter quantities respectively. The noon content values of these three seasons given in Fig. 3 for approximately the same solar condition are

$$N_{TS}:N_{TE}:N_{TW} = (1.0:2.2:1.4) \times 10^{17} \text{ electrons/m}^2. \tag{3}$$

An attempt will be made to try to understand (3) by using diffusion transport layer as a model. The electron content for a diffusion transport layer derived in Appendix A as (A-8) is

$$N_T = q_0 H_i^3 / 2D_{0i} \; . \tag{4}$$

This formula will be used as a basis of discussion in the remaining part of this section.

As shown in (4) the value of electron content depends on a number of physical processes, each of which is discussed in the following. It is important to note that the content value is independent of electron temperature.

(i) Production. The electron content is directly proportional to the rate of production at the base of diffusion transport layer, which in turn depends on the atomic oxygen density and the solar zenith angle. (It is assumed that the solar condition is unchanged through these seasons.) For simplicity it seems reasonable to assume that the dependence on the solar zenith angle is through the factor cos x, where x is the solar zenith angle at local noon for different seasons.

(ii) Ion scale height. The ion scale height is directly proportional to ion temperature (assumed equal to gas temperature).

(iii) Diffusion coefficient. The ion diffusion coefficient is directly proportional to $T^{1/2}$ and inversely proportional to the density of atomic oxygen (Quinn and Nisbet, 1965). The use of theoretical model of Harris and Priester (1962) shows that the atomic oxygen density has $T^{0.3}$ and $T^{0.5}$ dependence. Hence, the ion diffusion coefficient has a very weak temperature dependence and can be assumed to be roughly constant for the present discussion.

(iv) Protonosphere flux. In solving the equation of continuity in Appendix A it is assumed that the upper boundary condition is zero flux. It is a simple matter to remove this restriction and replace it by the condition of a finite flux as done by Geisler and Bowhill (1965). This generalization merely constitutes an addition of a term.

(v) Recombination. The effect of loss of electrons through chemical processes is assumed to be lumped as a lower boundary condition in the theory of diffusion transport layer. Therefore, the increase of loss is equivalent to raising the lower boundary and the decrease of loss is equivalent to lowering of the lower boundary. Now, the loss rate is proportional to the density of either molecular oxygen or molecular nitrogen. Both are minor constituents in the F region.

If it is assumed that the first three processes are the only ones operative, then the noon content should be roughly proportional to T_i^3 cos x. Using the temperature model derived by Jacchia (1963), the temperatures for 1961-62 period at 40^oN at noon are found to be 1035^oK, 1085^oK and 900^oK for summer, equinox and winter, respectively. The theoretically expected ratios can be computed by using (4), resulting in

$$N_{TS}:N_{TE}:N_{TW} = 2.4:2.2:0.73 \quad (5)$$

Comparison of (5) against (3) shows the poor agreement and therefore other processes must also be considered. A logical step in this direction is the inclusion of a protonosphere flux. This is especially tempting because the slab thickness shows a maximum in summer and a minimum in winter and hence the protonosphere may act like a reservoir, being filled up in the day time at the expense of the summer hemisphere ionosphere and being emptied at night perhaps to both summer and winter hemispheres. Such protonosphere-ionosphere coupling was first suggested by Rothwell (1962). A more critical examination of this hypothesis indicates that the maximum permissible flux is not large enough to explain the seasonal anomaly. The bottle-neck seems to be at the base of protonosphere and at the top of the diffusive barrier region (Geisler and Bowhill, 1965). The protonosphere-ionosphere coupling no doubt exists but it seems too weak to explain the seasonal anomaly.

The last remaining process on the list is the recombination process. The loss through such a process is proportional to the density of a minor constituent (O_2 or N_2) whose proportion cannot be detected easily from studies such as the decay of the artificial satellites. Suppose that the proportion of O_2 (or N_2) is increased while the density of major constituent, atomic oxygen, remains unchanged. Its effect on both the maximum electron density and the electron content is through the increase of the base of diffusion transport layer. Now both q_0 and $1/D_{0i}$ decrease exponentially with the height of the base. Hence the net effect is a decrease in both the maximum density and the content. For example, an increase in the base of a half ion scale height (about 45 km in sunspot maximum and 28 km in sunspot minimum) will decrease both the maximum density and the content by a factor of 1/e. Similarly, a decrease in the base of the diffusion transport layer by a half ion scale height will increase both the maximum density and the content by a factor of e. Therefore, it is seen that the maximum density and the content are very sensitive to changes in the proportion of minor constituent O_2 or N_2. Note that the slab thickness, being the ratio of content to maximum density, does not depend on the proportion of minor constituent (see (A-8)), it depends only on the ion and electron temperatures. This observation seems to be supported by the expected seasonal behavior of the noon slab thickness as shown in Fig. 6, and the agreement of the behavior of the noon slab thickness with the ion and electron temperatures measured independently by other totally different methods, as discussed in section 7. Therefore, evidence seems to be strong in support of the hypothesis that the change of composition is a possible cause of seasonal anomaly.

Appendix A. Diffusion Transport Layer

Since the interpretation of the content data makes use of the diffusion transport layer, it seems appropriate to discuss some properties of this layer.

The diffusion transport layer was first introduced by Bowhill (1962). The derivation here represents a slight generalization of his case from the assumption of equal electron and ion temperature to unequal temperatures. A fuller discussion of this model, and especially the study of the time dependent model will be the subject of a different report (Pound and Yeh, 1965).

The starting point is the equation of continuity. Let a subscript zero denote quantities referred to the lower boundary of the layer. Equal gas and ion temperature is assumed, but the ratio of electron to ion temperatures, r, may in general be different from 1. The equation, when it is approximately time stationary, takes the form

$$q_0 \exp\left(-\frac{h-h_0}{H_i}\right) + D_{0i}(1+r)\exp\left(\frac{h-h_0}{H_i}\right)\cdot\left[\frac{d^2N}{dh^2} + \frac{2+r}{H_i(1+r)}\frac{dN}{dh} + \frac{N}{H_i^2(1+r)}\right] = 0 \qquad h \geq h_0 . \tag{A-1}$$

The boundary conditions are

$$N = 0 \quad \text{when } h = h_0 , \tag{A-2}$$

$$\frac{\partial N}{\partial h} + \frac{N}{H_i(1+r)} = 0 \quad \text{when} \quad h = \infty . \tag{A-3}$$

In this model layer, the effect of recombination is lumped by demanding that the electron density vanish at the lower boundary, as given by (A-2). The upper boundary condition (A-3) comes from the condition that the electron particle flux is assumed to vanish at infinity. In (A-1), q_0 is the rate of production at h_0, D_{0i} is the diffusion coefficient of the ion (atomic oxygen ion in case of ionosphere) at h_0 and the dip angle dependence is assumed to have been absorbed, $r = T_e/T_i$ and is assumed to be independent of height, and $H_i = kT_i/mg$ = scale height of ions and neutrals. The solution of (A-1) with boundary conditions (A-2) and (A-3) is

$$N(h) = \frac{q_0 H_i^2}{D_{0i}(2r+1)} \quad \exp[-\frac{h-h_0}{H_i(1+r)}] - \exp[-\frac{2(h-h_0)}{H_i}] \quad , \quad h \geq h_0 \quad . \qquad \text{(A-4)}$$

This profile has a peak density at a height given by

$$h_{max} = h_0 + \frac{H_i(1+r)}{1+2r} \ell n \; 2(1+r) \; , \qquad \text{(A-5)}$$

which predicts an increase in h_{max} as r increases, as shown in Fig. A-1. The corresponding peak density is

$$N_{max} = \frac{q_0 H_i^2}{2D_{0i}(1+r)} [2(1+r)]^{-1/(2r+1)} \quad . \qquad \text{(A-6)}$$

The electron content is obtained from (A-4) by integrating from h_0 to infinity.

$$N_T = q_0 \; H_i^3/2D_{0i} = \frac{H_i N_{max}}{(1+r)} [2(1+r)]^{1/(2r+1)} \qquad \text{(A-7)}$$

Note that N_T depends on the production, the ion scale height and the ion diffusion coefficient and not on the electron temperature. The change of electron temperature will only redistribute electrons as a function of height so that the content is unaffected. The slab thickness is obtained by taking the ratio of (A-7) to (A-6).

$$d = H_i(1+r) \; [2(1+r)]^{1/(2r+1)} \qquad \text{(A-8)}$$

The dependence of the slab thickness on r is shown in Fig. A-2. It is almost linear in the region of interest.

The diffusion transport layer is expected to apply to the region of the ionosphere above the F2 peak. Therefore, the electron content can be computed above the peak as

$$N_a = N_{max} H_i \frac{3+8r+4r^2}{2(1+r)} \quad . \qquad \text{(A-9)}$$

The diffusion transport layer gives an electron density which is too small below the peak. Perhaps a better model is the Chapman layer which gives the content below the peak,

$$N_b = 0.656 H_i N_{max}(1 + r) \quad . \qquad \text{(A-10)}$$

Let us choose a hybrid layer with the diffusion transport layer above the peak and the Chapman layer below the peak. The slab thickness of the layer can be obtained from (A-9) and (A-10). Its dependence on r is shown in Fig. A-2. For comparison purposes, the slab thickness of a pure Chapman layer is also shown on the same figure.

The ratio of electron content above the peak to that below the peak is another quantity of interest. For the hybrid layer the ratio is

$$\frac{N_a}{N_b} = \frac{3 + 8r + 4r^2}{1.312(1+r)^2} , \qquad \text{(A-11)}$$

which is 2.87 if r = 1 and 2.94 if r = 2. These ratios are larger than the experimental values because (A-10) ignores the ionization contribution from the F_1 and E regions and because experimentally measured content in many cases is the content below about 1000 km. Perhaps a better, but equally empirical, model for electron content below the peak would be one with a higher multiplying factor than that given by (A-10).

Fig. 1 Histogram showing the number of cases with a given per cent standard deviation.

Fig. 2 Diurnal variation of electron content. The dots indicate the average content for which the zenith angle is less than 40^o and crosses when the zenith angle is larger than 40^o.

(a) 1961 (b) 1962 (c) 1963 (d) 1964

Fig. 3 Seasonal variation of midday electron content, July 1961 to December 1962.

Fig. 4 Sunspot dependence of midday electron content. Present values are shown by dots for years 1961-1964. Values obtained earlier at the University of Illinois are also shown as dots for years 1958-1959 (Yeh and Swenson, 1961). Values obtained by other authors are as shown.

Fig. 5 The average behavior of electron content after sunset for the period May 5-August 11, 1965. Replotted from Klobuchar, Allen and Whitney (1965).

Fig. 6 Seasonal dependence of midday slab thickness. The content value is obtained at Urbana, Illinois, the peak density at Ft. Monmouth, New Jersey. The longitudinal correction would lower the value of slab thickness by about twenty per cent. Similar corrections should apply to all slab thickness values presented in this paper.

Fig. 7 Diurnal variation of slab thickness.

Fig. 8 Dependence of slab thickness on magnetic index.

Fig. A-1 The height of maximum electron density above the lower boundary measured in scale height as a function of electron-to-ion temperature ratio in a diffusion transport layer.

Fig. A-2 Slab thickness as a function of electron-to-ion temperature ratio in a Chapman layer, a diffusion transport layer and a hybrid layer.

Table 1 D_a/H^2 and temperature ratio obtained from observation of electron content decay at night.

Table 2 Slab thickness and the electron-to-ion temperature ratio at midday. The values of slab thickness are those given by Bhonsle et al. (1965).

Table 1. D_a/H^2 and temperature ratio obtained from observation of electron content decay at night

Authors	Year	Measurement	Place	D_a/H_i^2 /sec	Temperature Ratio
Evans and Taylor (1961)	1960 winter	Content	Jodrell Bank	10.7×10^{-6}	0.88
Taylor (1964)	1961 summer	Content	Jodrell Bank	8.2×10^{-5}	1
Pound and Yeh (1965)	1963 summer	f_0F2	Ft. Monmouth	11×10^{-5}	0.84
Klobuchar, et al. (1965)	1965 summer	Content	Sagamore Hill	11.3×10^{-5}	0.82

Table 2. Slab thickness and the electron-to-ion temperature ratio at midday. The values of slab thickness are those given by Bhonsle et al. (1965).

Year	Season	$T_g = T_i$	H_i km	d km	d/H_i	Chapman r	Diffusion r	Hybrid r
1958-59	Winter	1590	93	420	4.5	1.2	2.2	1.5
	Equinox	1570	92	450	4.9	1.4	2.5	1.7
	Summer	1530	90	500	5.6	1.7	3.1	2.1
1962	Winter	945	55	260	4.7	1.3	2.4	1.6
	Equinox	960	56	300	5.3	1.6	3.0	1.9
	Summer	965	57	330	5.9	1.8	3.4	2.3

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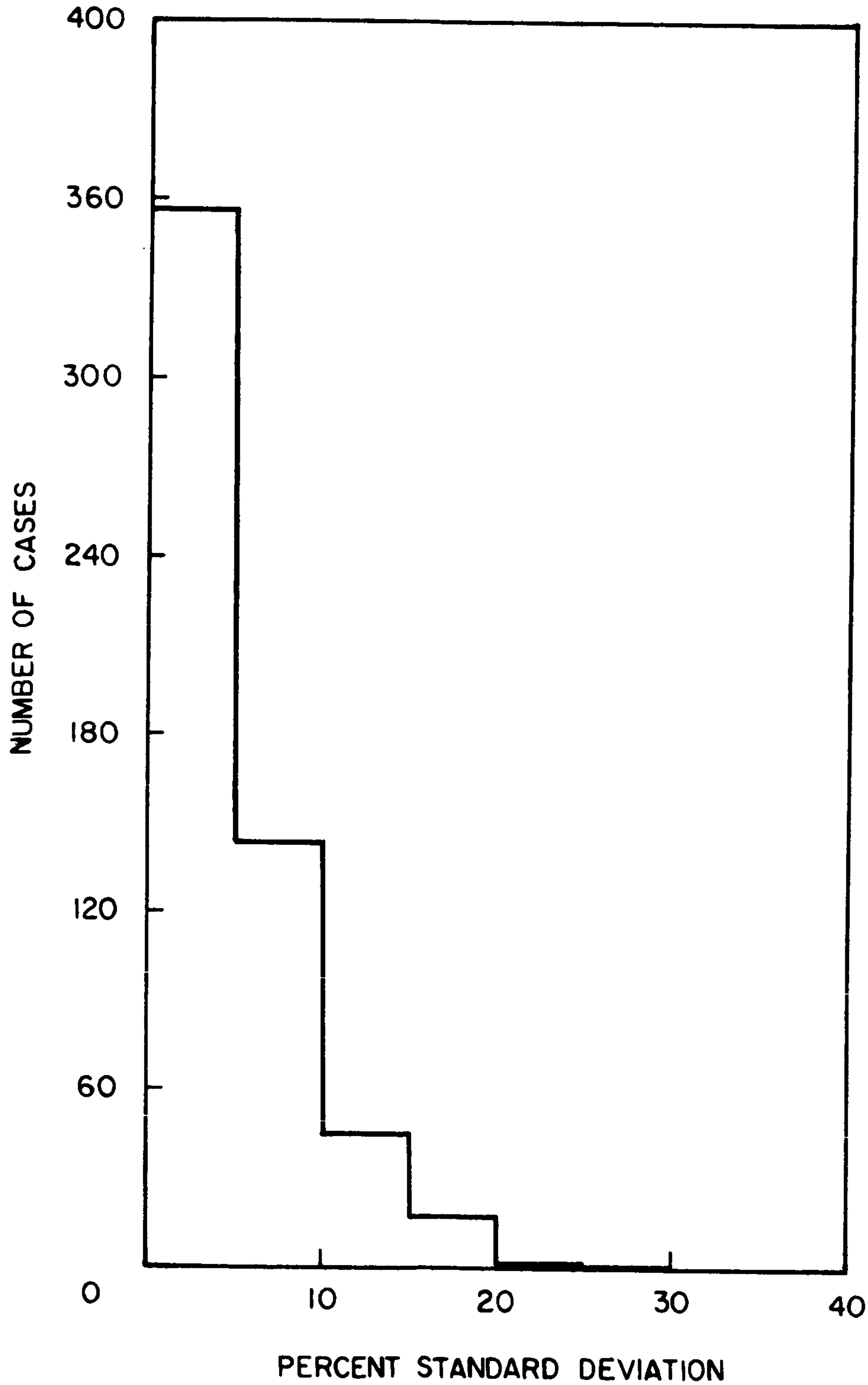

Fig. 1. Histogram showing the number of cases with a given per cent standard deviation.

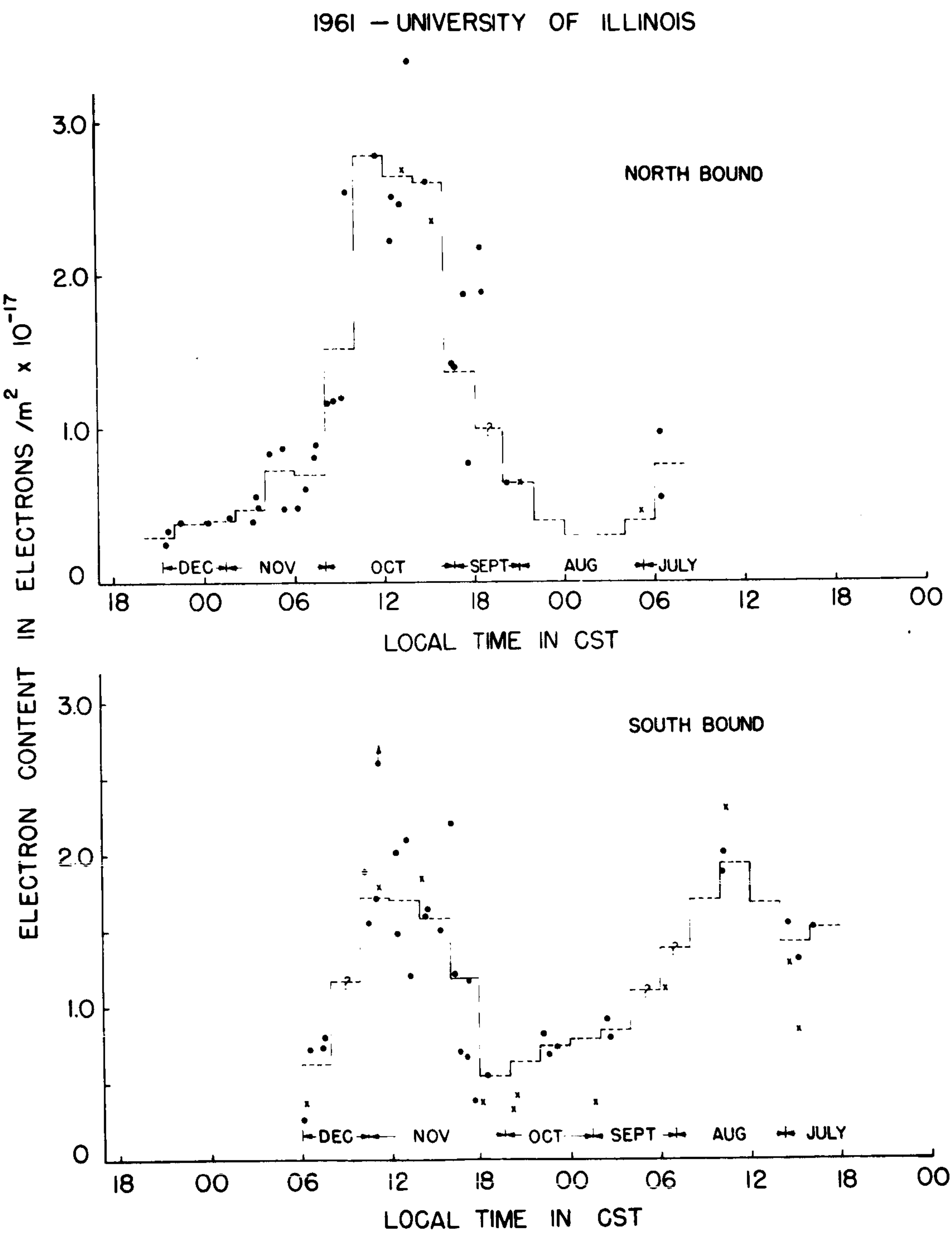

Fig. 2. Diurnal variation of electron content. The dots indicate the average content for which the zenith angle is less than 40° and crosses when the zenith angle is larger than 40°.

(a) 1961

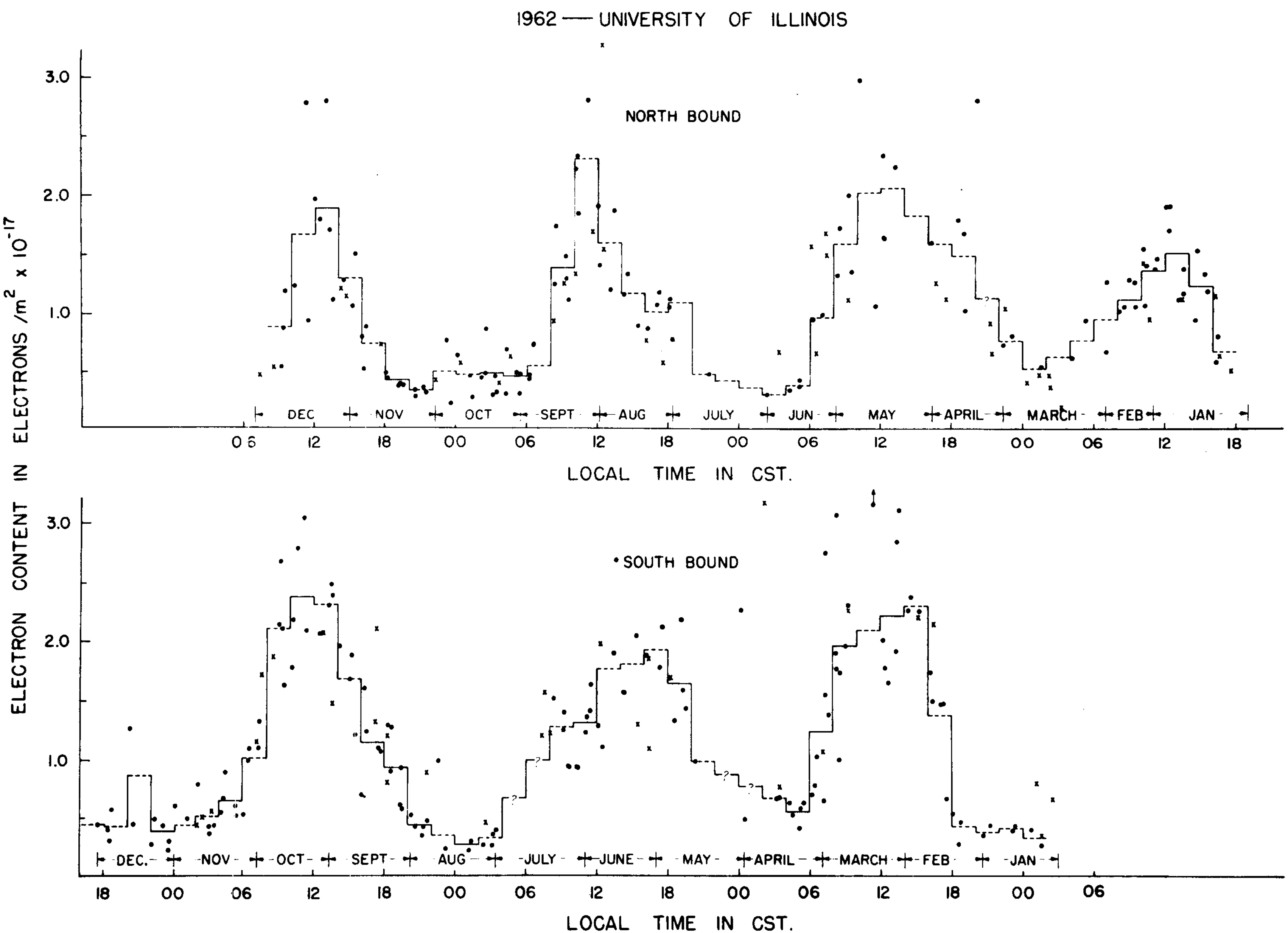
1962 — UNIVERSITY OF ILLINOIS
NORTH BOUND
SOUTH BOUND
ELECTRON CONTENT IN ELECTRONS /m² x 10⁻¹⁷
3.0
2.0
1.0
DEC
NOV
OCT
SEPT
AUG
JULY
JUN
MAY
APRIL
MARCH
FEB
JAN
JUNE
06
12
18
00
LOCAL TIME IN CST.

Fig. 2(b) 1962

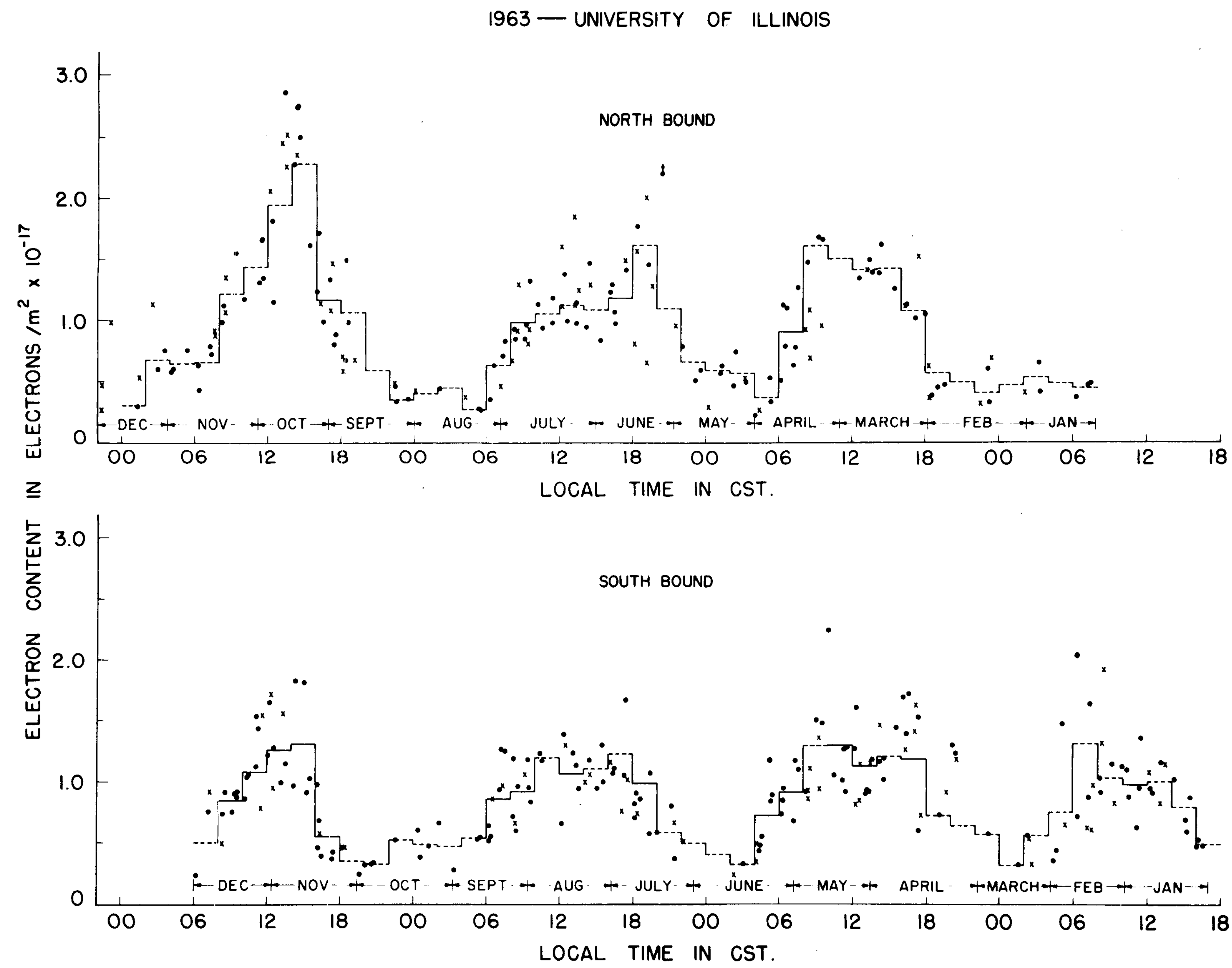
1963 — UNIVERSITY OF ILLINOIS
NORTH BOUND
SOUTH BOUND
ELECTRON CONTENT IN ELECTRONS /m^2 x 10^{-17}
LOCAL TIME IN CST.
DEC
NOV
OCT
SEPT
AUG
JULY
JUNE
MAY
APRIL
MARCH
FEB
JAN

Fig. 2(c) 1963

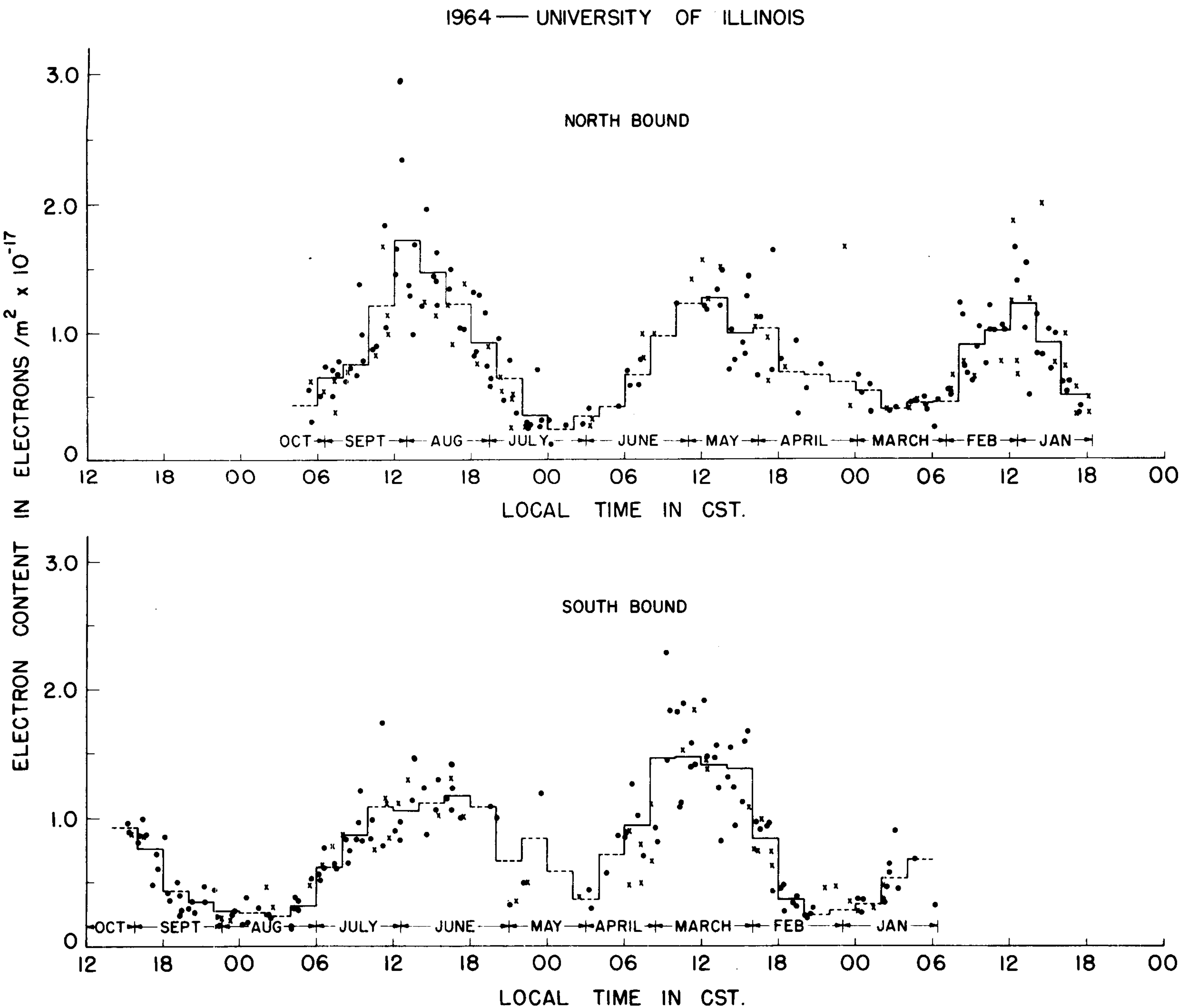
1964 — UNIVERSITY OF ILLINOIS
NORTH BOUND
SOUTH BOUND
ELECTRON CONTENT IN ELECTRONS /m² x 10⁻¹⁷
LOCAL TIME IN CST.
OCT
SEPT
AUG
JULY
JUNE
MAY
APRIL
MARCH
FEB
JAN

Fig. 2(d) 1964

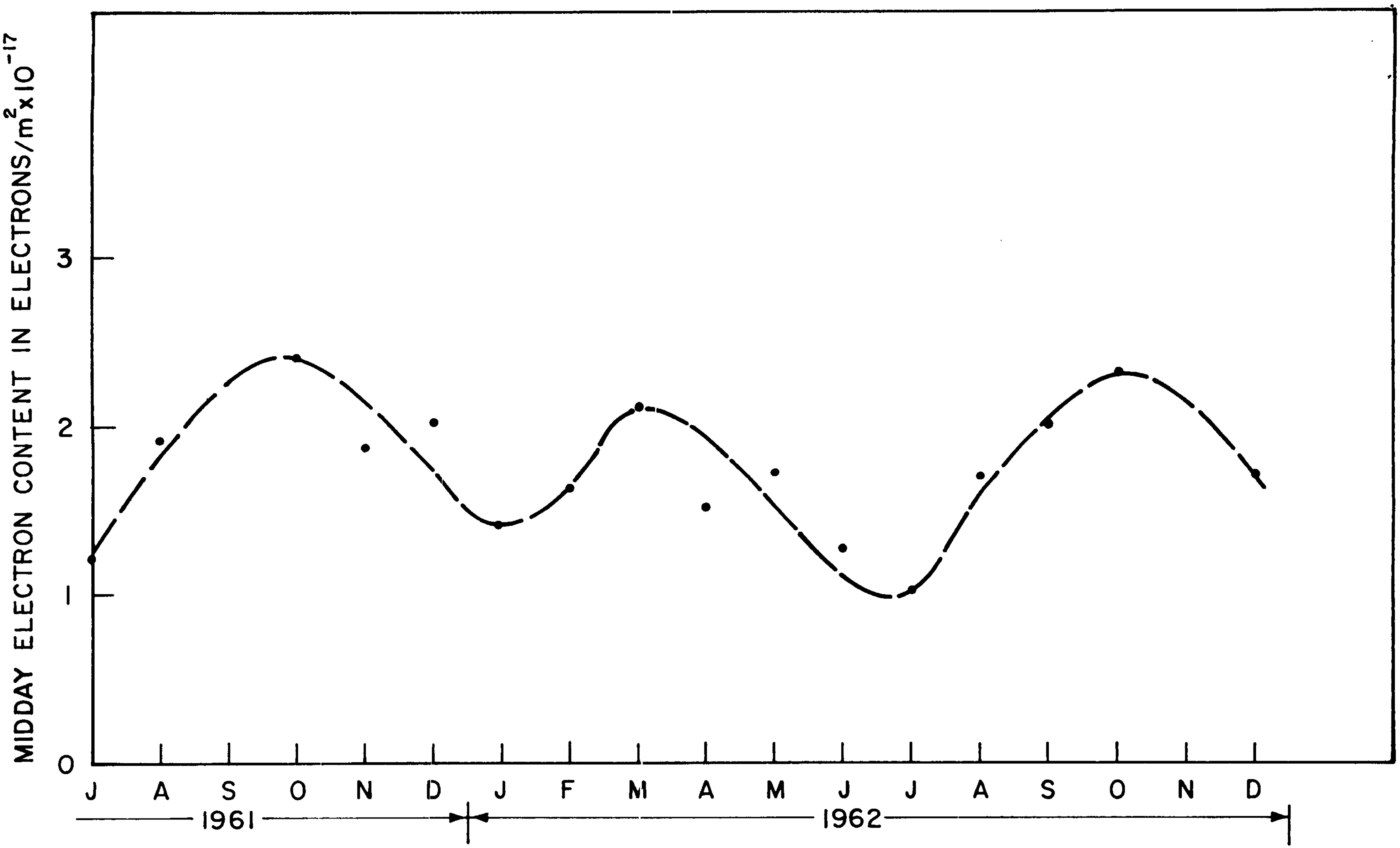

Fig. 3. Seasonal variation of midday electron content, July 1961 to December 1962.

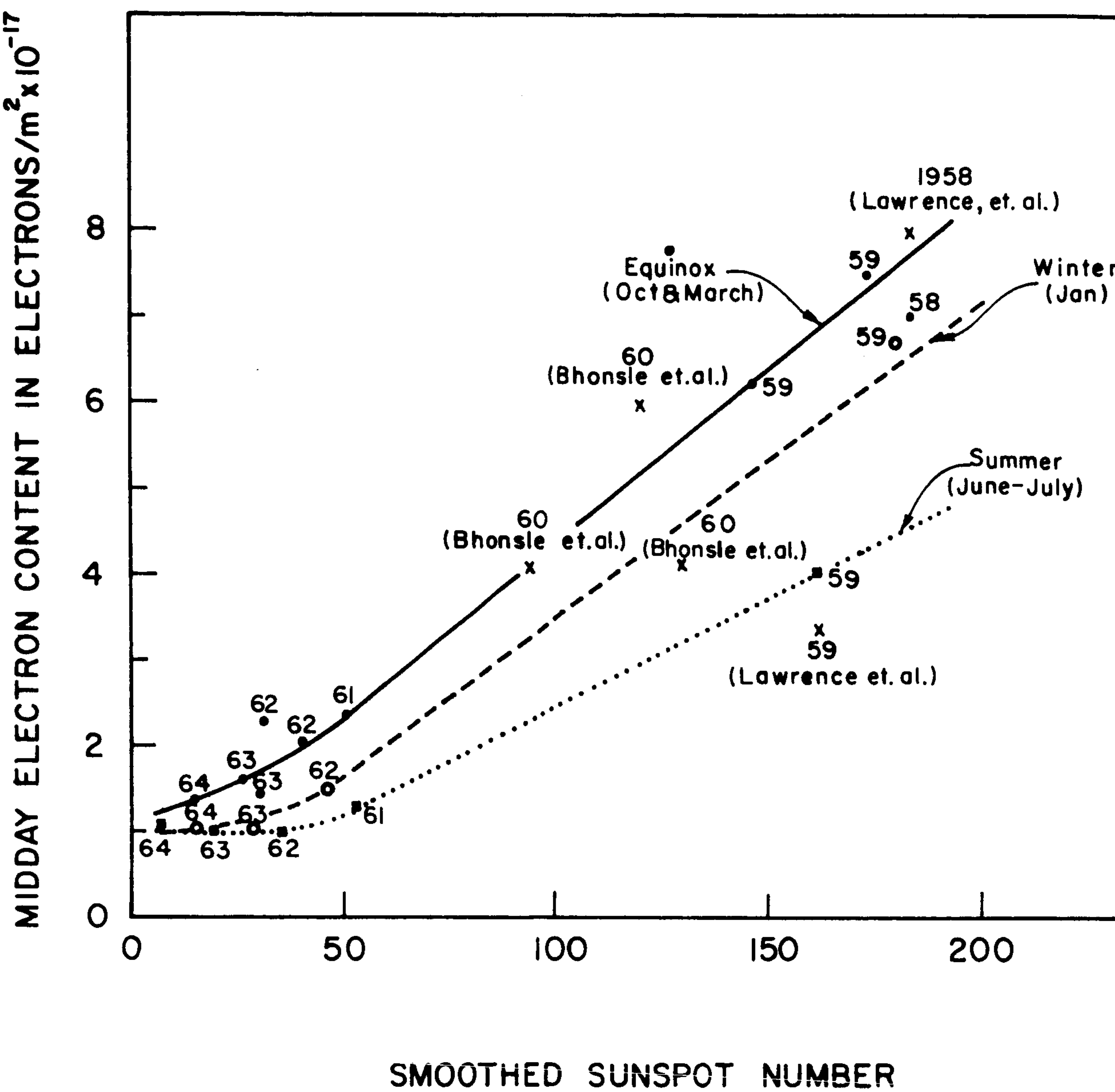

Fig. 4. Sunspot dependence of midday electron content. Present values are shown by dots for years 1961-1964. Values obtained earlier at the University of Illinois are also shown as dots for years 1958-1959 (Yeh and Swenson, 1961). Values obtained by other authors are as shown.

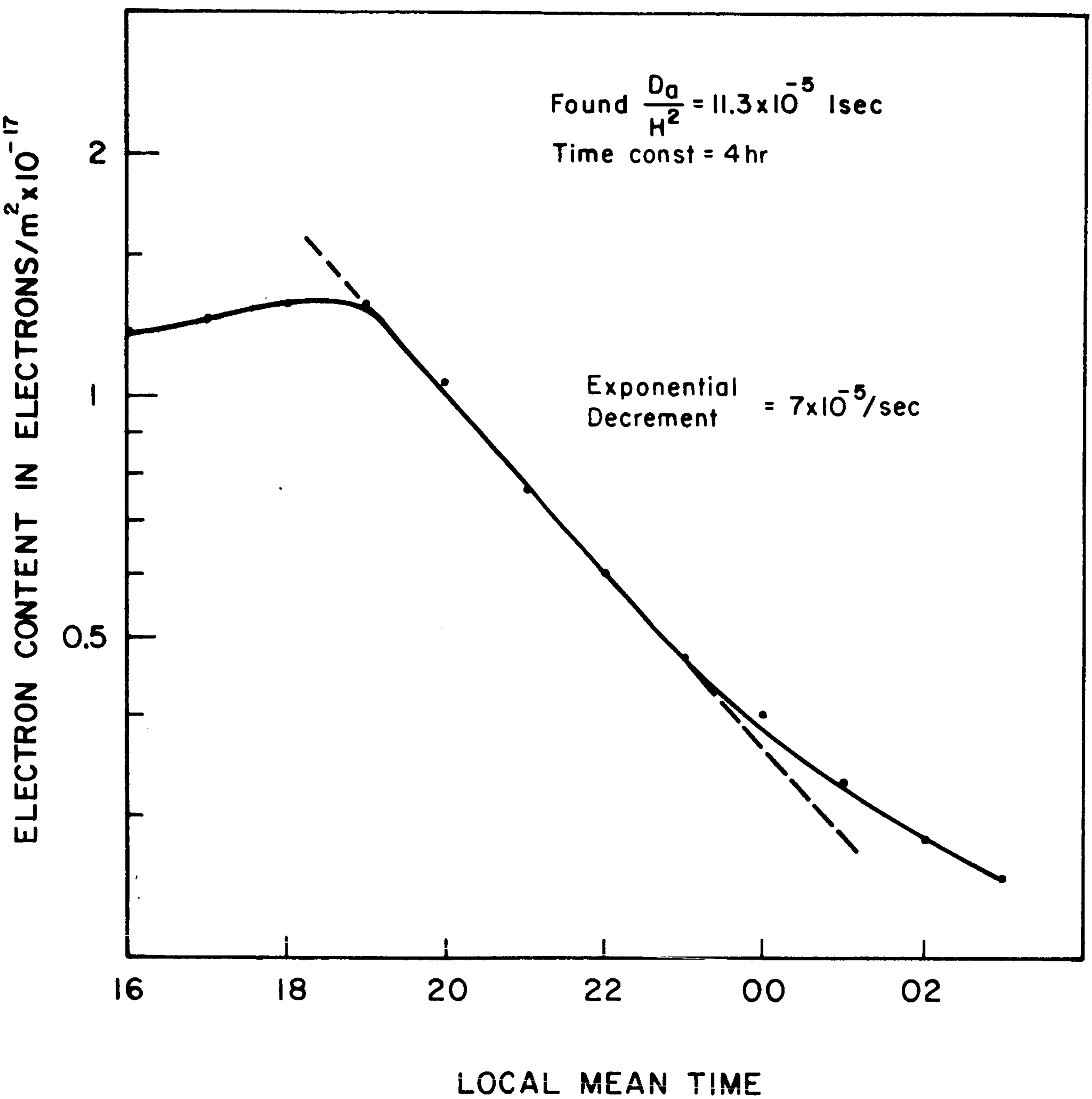

Fig. 5. The average behavior of electron content after sunset for the period May 5-August 11, 1965. Replotted from Klobuchar, Allen and Whitney (1965).

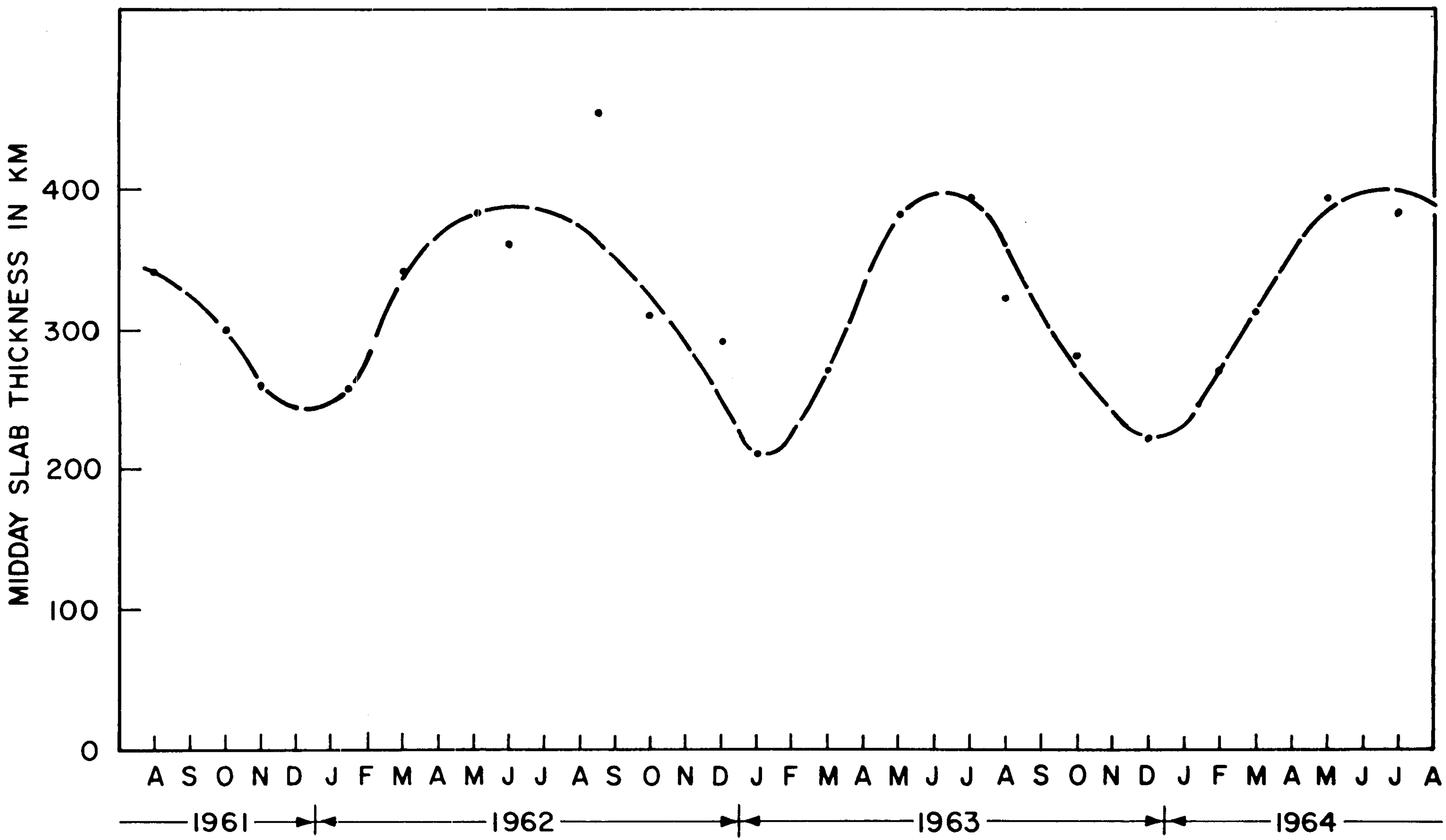

Fig. 6. Seasonal dependence of midday slab thickness. The content value is obtained at Urbana, Illinois, the peak density at Ft. Monmouth, New Jersey. The longitudinal correction would lower the value of slab thickness by about twenty per cent. Similar corrections should apply to all slab thickness values presented in this paper.

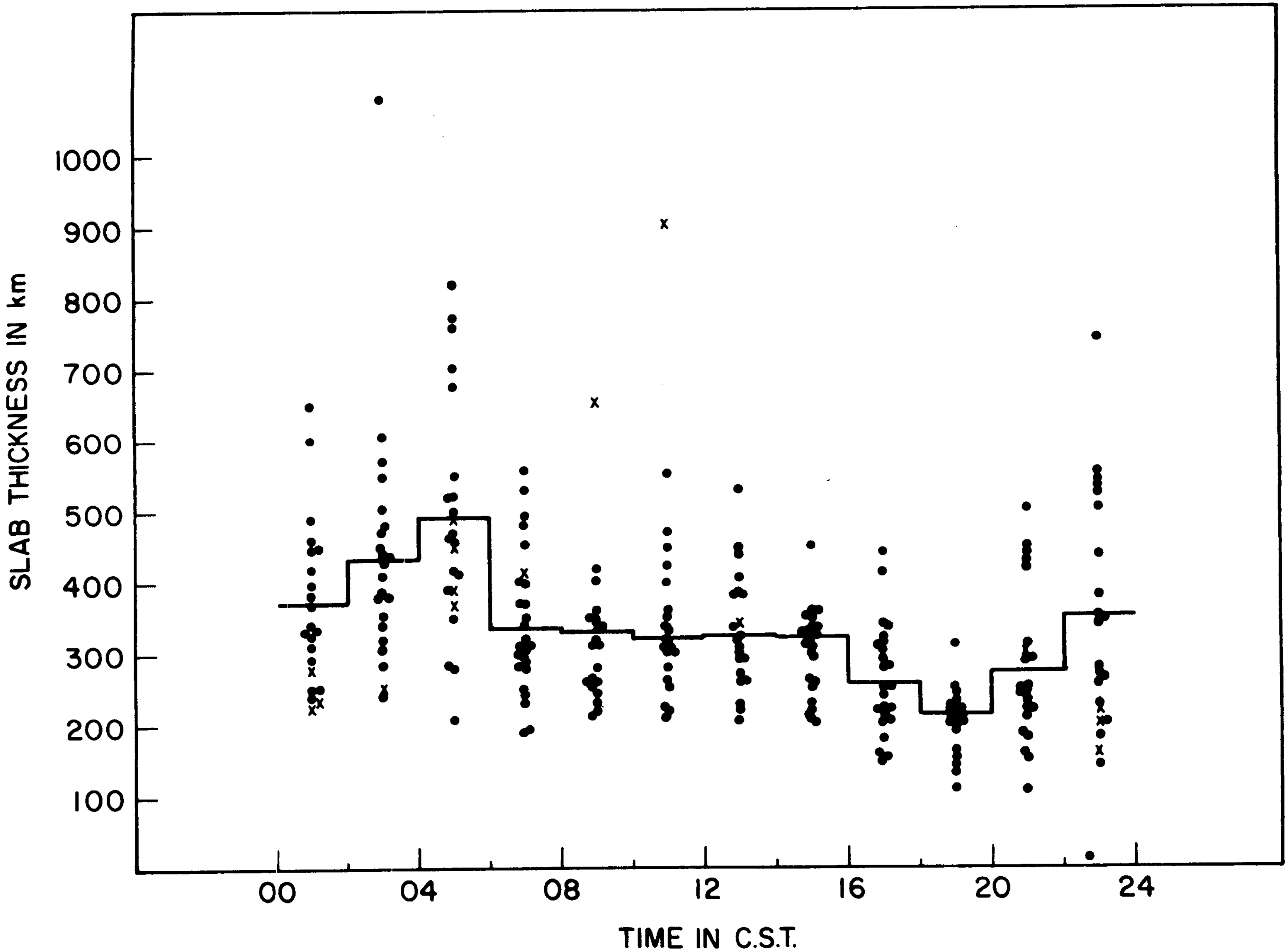

Fig. 7. Diurnal variation of slab thickness.

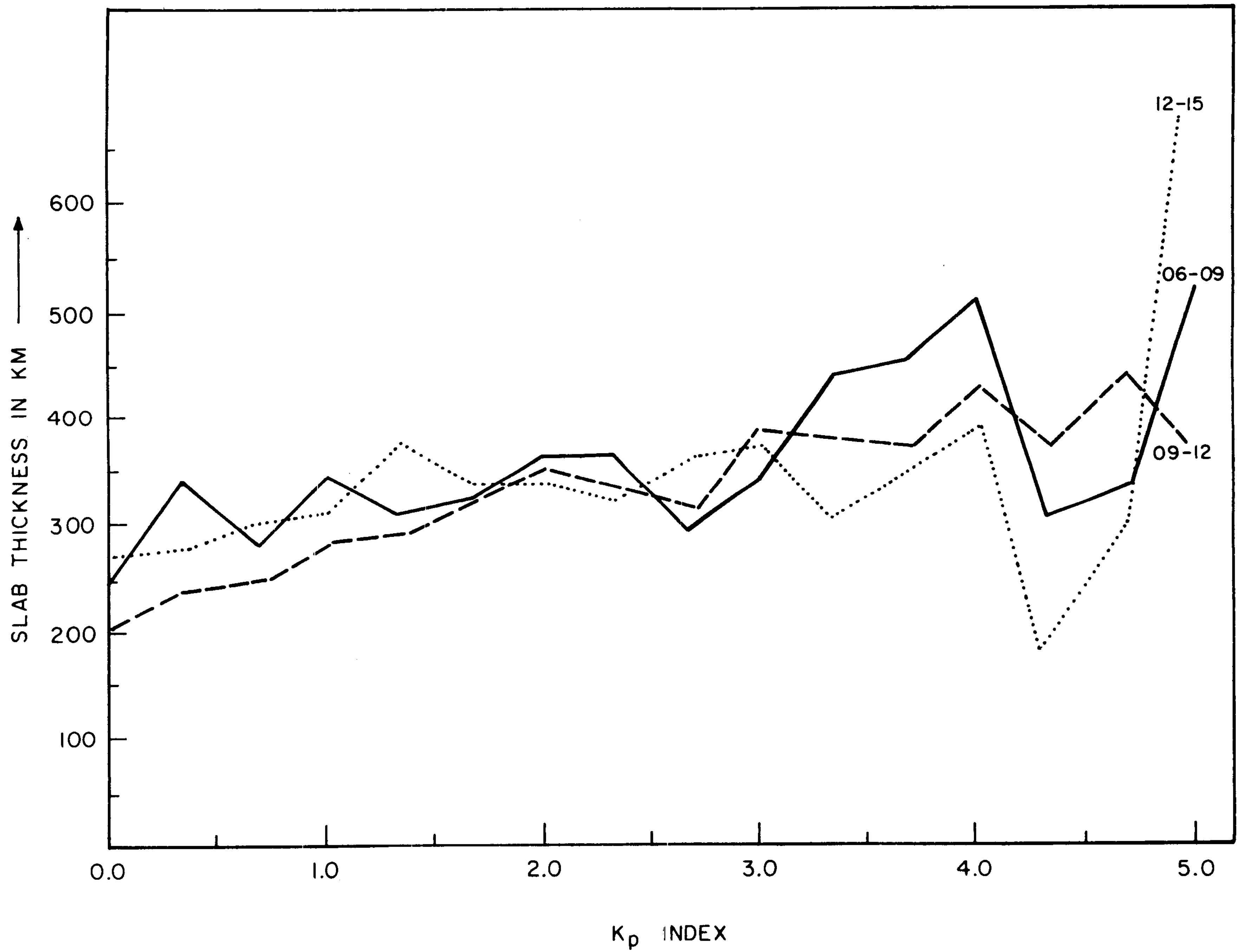

Fig. 8. Dependence of slab thickness on magnetic index.

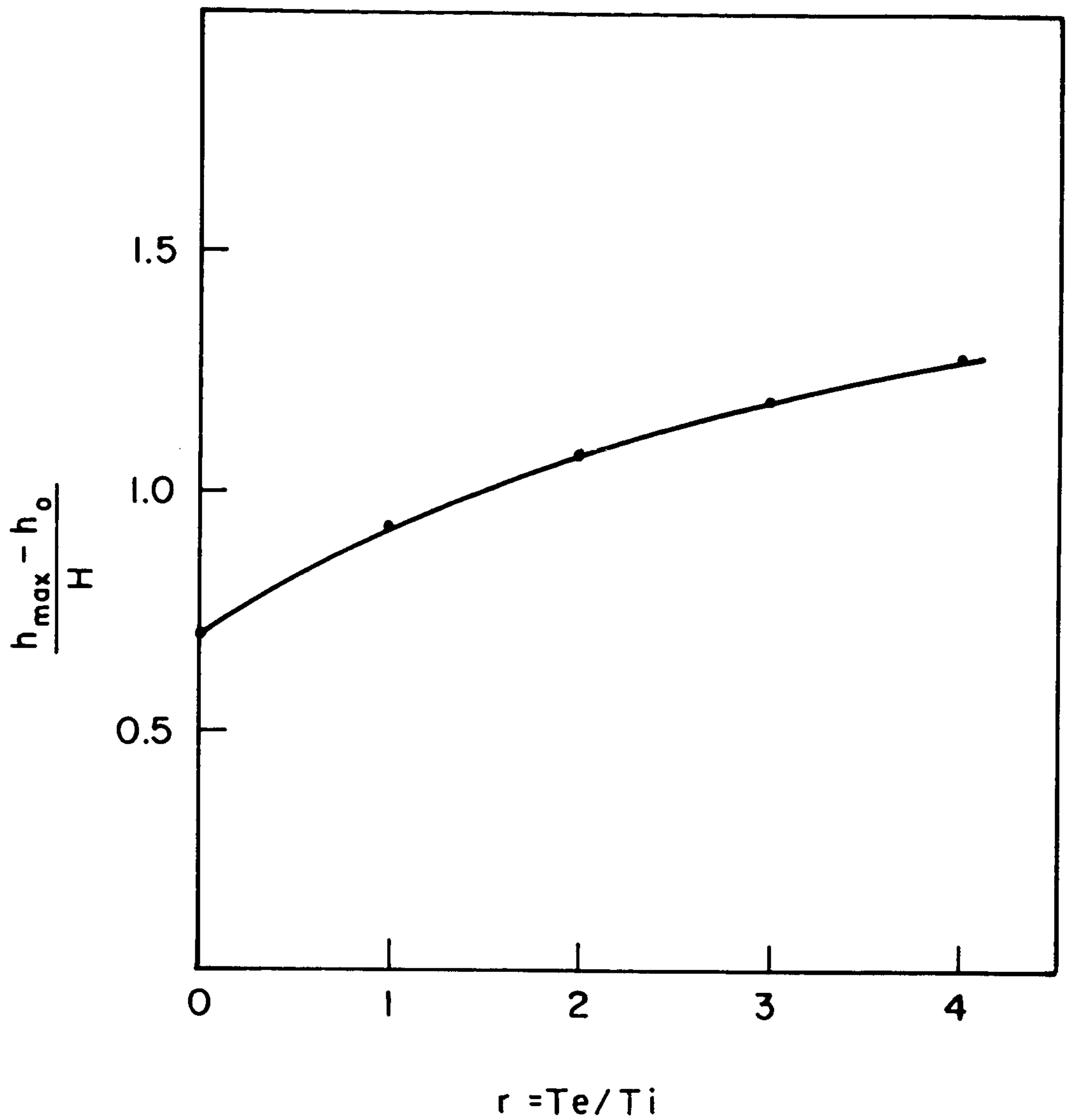

Fig. A-1. The height of maximum electron density above the lower boundary measured in scale height as a function of electron-to-ion temperature ratio in a diffusion transport layer.

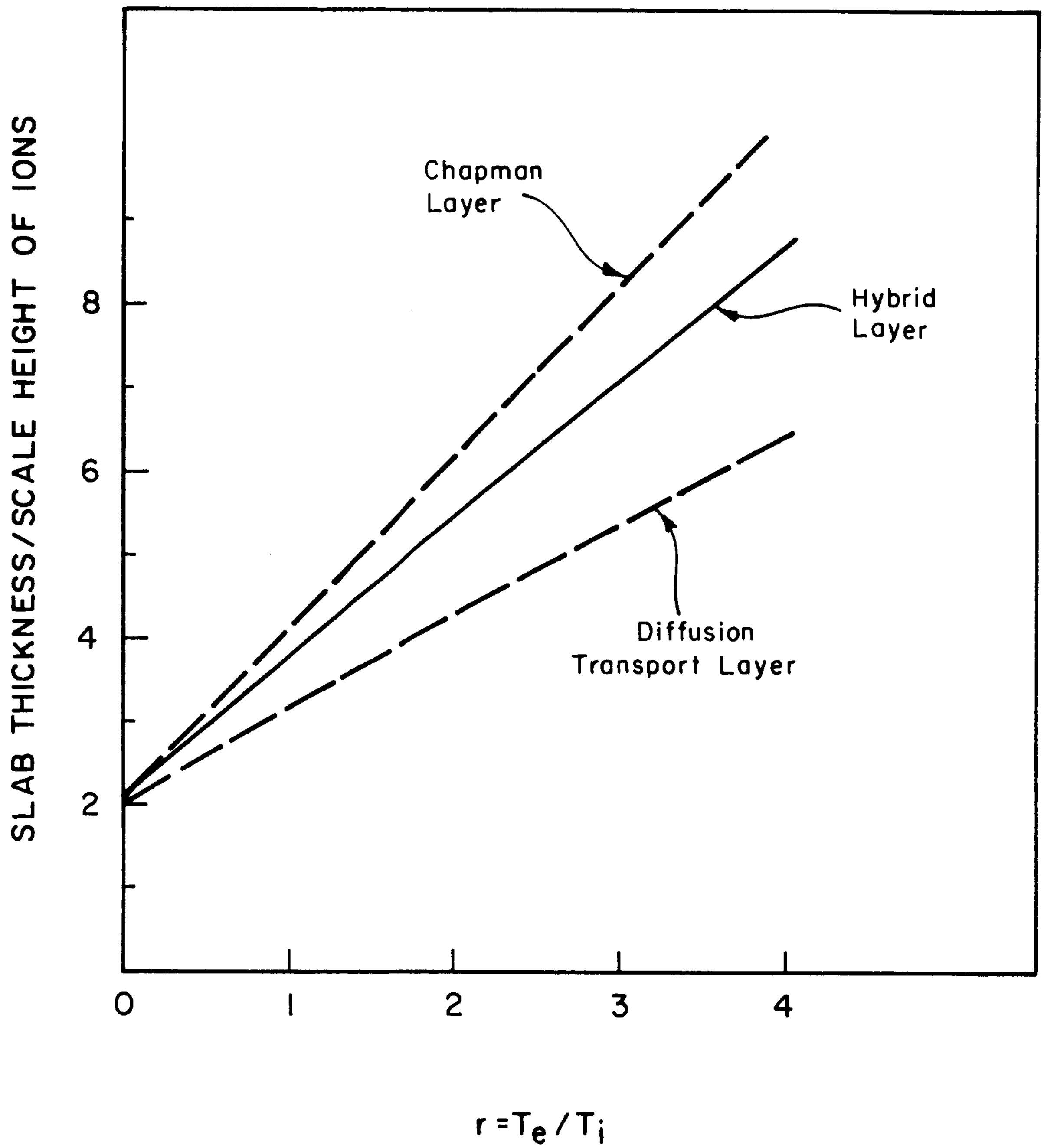

Fig. A-2. Slab thickness as a function of electron-to-ion temperature ratio in a Chapman layer, a diffusion transport layer and a hybrid layer.