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ABSTRACT

Langmuir probe measurements of the winter diurnal behavior of the electron density (N_e) and temperature (T_e) at 1000 km at high latitudes are presented. The data are represented by contour plots of N_e and T_e on a grid of geomagnetic latitude and local time. The time period studied is Nov. 1, 1965 through Feb. 12, 1966. The N_e distribution is characterized by a zonal structure where the auroral oval is the transition region between the midlatitude and polar zones. N_e in the midlatitude zone exhibits a quasi-steady state through most of the night and both N_e and T_e increase in value to an afternoon maximum. N_e in the dark polar zone decays until midnight after which the ionization increases toward a daytime level. The transition region, represented by the oval, shows enhancements in N_e suggestive of particle flux sources. In general, the dayside T_e contours do not correlate with the N_e contours. Limited comparisons between winter and summer indicate strong seasonal effects in the N_e pattern and unusually large values of T_e in the winter midlatitude zone. Characteristic troughs in N_e appear on the nightside for both seasons. Possible ionization sources which would be consistent with the observed ionization patterns are considered.

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CONTENTS

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INTRODUCTION

Data pertaining specifically to the ionosphere at northern high latitudes has been documented in many papers. Duncan (1962), Hill (1963) and Oguti and Marubashi (1966) studied $f_0 F_2$ in the Arctic and Antarctic zones. Sharp (1966) observed an ion density trough at high latitudes in early Nov. '63 and Liszka (1967) reported a similar trough in the total electron content. Muldrew (1965), Calvert (1966), Hagg (1967), Nishida (1967), Thomas and Andrews (1968) and Andrews and Thomas (1969) used topside sounder records to investigate the high latitude electron density behavior. Among these authors, Muldrew (1965) and Nishida (1967) derived density contours from Alouette I sounder data in order to study high latitude electron density distributions in the topside ionosphere. Muldrew showed the geographic distribution of $f_0 F_2$ at high latitudes for Oct. '62. Nishida showed the electron density behavior at several altitudes in the high latitudes for the autumnal equinoxes of 1962-63.

This paper presents high latitude satellite observations of the winter diurnal behavior of electron density (N_e) and temperature (T_e) at 1000 km. For seasonal contrast, some summer data is also included. The measurements employed in this study are from the Explorer 22 Langmuir probe experiment. The data are represented by contours of constant N_e and T_e on coordinates of local time and geomagnetic latitude. To reduce longitudinal effects, only data taken within narrow longitudinal ranges are plotted together. The longitudes considered were determined by the location of the telemetry stations at Grand Forks (-30° to -60° geomagnetic longitude) and Newfoundland (20° to 50° geomagnetic longitude).

The form of presentation is intended to provide a synoptic view of the time-averaged ionization structure of the high latitude ionosphere. Through the use of contour plots, the general structure and the development of special features, such as ionization troughs, can be followed in local time. Since the contour plots use coordinates of local time and geomagnetic latitude, any mention of time and latitude in the body of this paper refers to these quantities unless otherwise specified.

EXPERIMENTAL METHOD

The Explorer 22 Langmuir probe experiment consists of a pair of cylindrical electrostatic probes mounted on opposite ends of the satellite. A sawtooth voltage is alternately applied to the probes and the resulting current is measured. N_e and T_e are deduced from the volt-ampere characteristics using the Langmuir probe equations. The equations, details of the measurement technique and accuracies of the experiment have been discussed in previous papers (Brace and Reddy, 1965; Brace, et al., 1967; Brace, et al., 1968). The absolute accuracy of the deduced T_e and N_e values is believed to be better than 10% and 20% respectively while relative accuracies are 5% and 10%.

RESULTS

Figure 1 illustrates the type of data display from which contours were obtained. The locus of a satellite path is shown for several passes by joining consecutive data points with straight lines. The field of data points represents measurements made over half of an orbital precession period. The figure demonstrates the density of data points and the resolution of measurements during a satellite pass. A sample contour representing 3×10^3/cc is indicated by the dotted curve. Since three months was required for the satellite orbit to pass through 24 hours of local time, some long term effects are necessarily included in the time averaged results.

The contours in Figure 2 are typical for the winter polar ionosphere. The region labelled "auroral oval" (Feldstein, 1963) appears to coincide with the transition between two zones of behavior in the N_e contours. In the midlatitude zone, latitudes below the oval, the nightside N_e contours are nearly concentric about the pole whereas these contours become more radial on the dayside. Typical nighttime N_e values for this zone were $1\text{-}7 \times 10^3$/cc, N_e increasing towards the equator. Typical dayside densities ranged from 7×10^3/cc at sunrise to 2×10^4/cc in the afternoon maximum.

In the zone poleward of the oval, N_e contours tend to be radial at all times. The nighttime N_e continues to decay until midnight. This is a contrast to the quasi-steady state of N_e in the nightside midlatitude zone. Typical nighttime densities ranged from 3×10^3/cc near 1800 hours to 0.2×10^3/cc in the midnight minimum. Winter daytime solar radiation in the polar zone propagates from large zenith angles hence N_e does not undergo a great diurnal change through the period of illumination. A typical daytime value of N_e in the polar zone is 1.2×10^4/cc.

Several enhancements are evident within the transition region. These are outlined by jagged boundaries.

As the Newfoundland data in Figure 3 shows, the general trends displayed at Grand Forks by Figure 2 are not limited to that longitude. However, the isolated enhancements in the oval do not occur at the same times as at Grand Forks.

Figures 4 and 5, containing T_e distributions for Grand Forks and Newfoundland, show only slight similarity to the corresponding N_e contours. The nighttime T_e contours for the midlatitude zone bear some resemblance to the N_e behavior, but the dayside T_e contours do not follow the dayside N_e contours. There are common trends in N_e and T_e ; for example the afternoon maximum occurs similarly in both parameters.

Figures 6 and 7 display N_e and T_e contours for the June '65 solstice at Grand Forks as a contrast to the winter contours of Figures 2 and 4. The general behavior is glaringly different from that in the winter, as will be discussed later.

DISCUSSION

General Ionospheric Structure

Figures 2 and 3 demonstrate how the winter high latitude N_e distribution at 1000 km can be separated into two zones where the auroral oval generally marks a transition between them. The zonal nature of the ionization pattern is reasonable when the differing ionic composition and magnetic field line configurations for the zones are considered. The midlatitude zone is primarily a closed field line region which contains the plasmapause (Williams and Mead, 1965; Brinton, et al., 1968). At the altitude of these measurements the latitudes below 60° are generally within the protonosphere (Taylor, et al., 1968). By contrast, most of the polar zone is traversed by open field lines (Williams and Mead, 1965) and is primarily composed of O^+ (Taylor, et al., 1968). The composition difference between zones implies that the response of the ionization to changes at the F_2 peak will be different because the diffusion properties for the zones differ. The geomagnetic field line difference implies that any source and loss mechanisms associated with the magnetotail may influence the ionization in the polar zone but not that in the midlatitude zone.

The Characteristic Polar Troughs

Minima in nightside ionization such as those shown in Figures 2, 3 and 6 have been observed by many authors (Thomas and Sader, 1964; Yonezawa, 1965; Liszka, 1965; Muldrew, 1965; Thomas, et al., 1966; Sharp, 1966). The contours at Grand Forks in Figure 7 show a midlatitude N_e trough at 60° on the nightside. This midlatitude trough was also evident in the equinox data presented by Nishida (1967). In winter, at both Grand Forks and Newfoundland, the northern boundary of the midlatitude trough falls in the polar trough region. Therefore, the two troughs merge into a broad polar depression. A small remnant of the midlatitude trough appears at both stations (Figures 2 and 3) between 0400 and 0600 hours. Both Figures 5 and 7, representing summer and winter contours, associate a maximum in T_e with the midlatitude N_e trough. The implication is that the mechanism which produces this trough is still active in winter even though the effect on N_e is modified. As shown in Figure 7, the summer midlatitude N_e trough persists into times when the F_2 region is illuminated. This characteristic suggests that the midlatitude trough may be caused by a magnetically controlled mechanism which operates continuously but whose effects are masked by photoionization.

The polar depression is a winter phenomenon which was first identified by Hagg (1967) at slightly higher altitudes. It is not evident in the equinox data of Nishida (1967) or in our summer contours at Grand Forks (Figure 6). T_e values associated with this trough are not available as the concentrations are too low to permit a temperature to be derived. The various high latitude winter troughs which have been reported may be part of the same trough, as can be seen by comparing Figures 2 and 3 corresponding to different longitudes. Figure 3 contains enhancement periods which distort the trough shape. A latitude profile taken through this structure would seem to contain several troughs. It is possible that the formation mechanism for the polar depression is similar to that for the midlatitude trough even though the two phenomena are located within different zones of ionospheric behavior. The investigation of Brace, et. al. (1969) indicates that the seasonal behavior in the nightside polar region is a zenith angle effect and hence the increased ionization poleward of 60° is due to photoionization.

The Afternoon Maximum

In winter, an afternoon maximum in N_e and T_e occurs in the midlatitude zone. This maximum is actually a double maximum which falls roughly between 1300 and 1700 hours. Its double nature shows more clearly in the N_e contours than in T_e. The maximum in T_e and N_e which appears in the summer contours at Grand Forks falls at noon for latitudes above 60° but at 0900 hours for latitudes below 60°. These features are consistent with radar backscatter observations by Evans (1965) for 1963 which showed an afternoon N_e maximum at midlatitudes in all seasons and a morning maximum in summer. The measurements of Liszka (1967) show that this trend of ionization also occurs in the total electron content and hence does not represent only a change in electron scale height. The identification of a summer afternoon T_e and N_e maximum within the Grand Forks data was not possible because data for those hours was not available.

Seasonal Comparisons

Contrasting the general winter behavior with that of the more limited summer data (Figures 6 and 7) emphasizes the strong seasonal variation. The seasonal variation in the nightside trough system has been discussed previously. The pattern of behavior shown by Nishida (1967) is apparently transitional since it does not resemble the patterns for either summer or winter as shown in this paper. Nishida's September equinox data shows neither the characteristic winter polar depression nor the summer daytime structure of Figure 7.

Further seasonal effects at midlatitudes are evident in Figure 9. Winter T_e values are higher than summer values, especially in the afternoon. The data suggests that winter nighttime T_e values exceed summer values, but too few winter data points are available to make this characteristic conclusive. A difference in phase between the time of the summer and winter afternoon ionization maxima produces winter N_e values in excess of summer values near noon but this feature does not continue through a wide range of local times as in the T_e values. Similarly high, winter T_e values have been observed at lower altitudes by Evans (1965). He specifically showed that, near the F_2 peak nighttime T_e in November '63 were 500°K higher than those in July '63. Evans (1967) also showed that the mean winter daytime T_e was higher than for summer.

Short Enhancement Periods in the Auroral Oval

Hartz and Brice (1967) define a zone of soft electron precipitations corresponding approximately to the auroral oval, which has been identified as a transition region in this study. The enhancements in N_e which occur in winter within the oval may represent the ionospheric response to these auroral precipitations. Such enhancements appear in Figure 2 at 2000 hours and 1400 hours and in Figure 3 near midnight. The summer contours do not show similar events, but they are probably less prominent because of the high level of summertime photoionization.

High Latitude Source Mechanisms

Any general model of polar ionospheric processes should be able to account for the winter average behavior described earlier. Apparently the isolated enhancements just discussed can be related to the precipitation of energetic auroral particles.

During solar maximum, Thomas (1966) indicated that photoionization contributes significantly to winter polar daytime N_e up to within 10° of the geographic pole but that an additional source is needed for solar minimum conditions. Our data suggests that the behavior of this additional source must be such as to generate an afternoon maximum in N_e and T_e as well as to supply the extra ionization required by Thomas.

Mechanisms proposed for maintenance of the nighttime midlatitude F region have included corpuscular ionization sources (Antonova and Ivanov-Kholodnii, 1961), downward diffusion of ionization stored in the protonosphere (Risbeth, 1963; Yonezawa, 1965) and horizontal winds (Hanson and Patterson, 1964) or electrodynamic drifts (Stubbe, 1968) which lift the ionization and thereby minimize recombination effects. It appears that the only mechanism which can be simultaneously consistent with the time variation of N_e in both the polar and midlatitude zones is electrodynamic drifts.

Stubbe (1968) proposed an electrodynamic model for midlatitude nighttime F_2 maintenance which contained an electric field with eastward and southward components. The eastward field provided a vertical $E \times B$ drift which raised the ionization along field lines to altitudes where the recombination coefficient is lower. The drifts caused by the southward field were from west to east and supplied ionization from the dayside to replenish the nighttime ionization.

If this model is extended to fit the observed N_e behavior at high latitudes a northward electric field serves better than the southward one which Stubbe invoked. The midlatitude zone is then maintained as in the original model except that the nightside ionization supplied from the dayside ionosphere comes from the dawn portion rather than the evening portion. As before the recombination coefficient is less effective because the ionization has been raised to a higher altitude and the midlatitude nightside N_e loss is balanced by the flow of ionization from the dayside.

In the polar zone the altitude of ionization is not raised by the horizontal electric field because the geomagnetic field lines are nearly vertical. Therefore, recombination proceeds rapidly. However, ionization is supplied from the dawn ionosphere through the plasma drifts caused by the northward electric field. This plasma drift may produce the post-midnight increase in ionization that is a characteristic of the nightside polar zone. A further test of the reasonableness of the electrodynamic mechanism will be the measurement of electric fields in the topside ionosphere.

SUMMARY AND CONCLUSIONS

The data which have been analyzed describe the winter ionosphere above

50° at 1000 km during solar minimum. The N_e distribution can be characterized as zonal with the auroral oval serving as the transition region between the midlatitude and polar zones. Through most of the night, the midlatitude N_e is in a quasi-steady state in which N_e contours are approximately magnetically aligned. In the daytime, N_e and T_e both display an afternoon maximum. The polar zone ionization shows continuous nighttime decay until midnight. After midnight this ionization increases monotonically.

Comparisons of winter data with limited summer data show strong seasonal differences in the nightside N_e contours. Taking into account the equinox data of Nishida affirmed that even the transitional period between the two seasons has an N_e distribution unique to that period. Further seasonal comparisons showed that the midlatitude zone contained afternoon T_e values that were higher in winter than during summer.

Characteristic troughs in N_e occurred on the nightside both in the winter polar zone and near 60° in the midlatitude zone in both summer and winter. A maximum of T_e is correlated with the position of the midlatitude N_e trough during both seasons. The midlatitude trough is considered to be the result of some type of magnetically controlled mechanism whose effects are more obvious in the nightside ionosphere.

In the auroral oval were a number of isolated enhancements in N_e. The presence of enhancements at this location is consistent with the measurements reported by Hartz and Brice (1967) who defined a zone of soft electron precipitations resembling the oval.

Some of the ionization source mechanisms for lower latitudes can be extended to the high latitude ionosphere. Among the mechanisms considered, only electrodynamic drifts could qualitatively reproduce the observed nighttime high latitude ionosphere. Daytime ionization at high latitudes requires photoionization plus an unknown source to account for the afternoon maximum and the generally high level of ionization at solar minimum.

Since the winter data were taken over limited longitudinal ranges, the differences between N_e contours at different stations point up that the properties of an event may have important longitudinal dependences. All of the data were taken near solar minimum and therefore some differences should be expected at solar maximum, though the general pattern may persist.

ACKNOWLEDGMENTS

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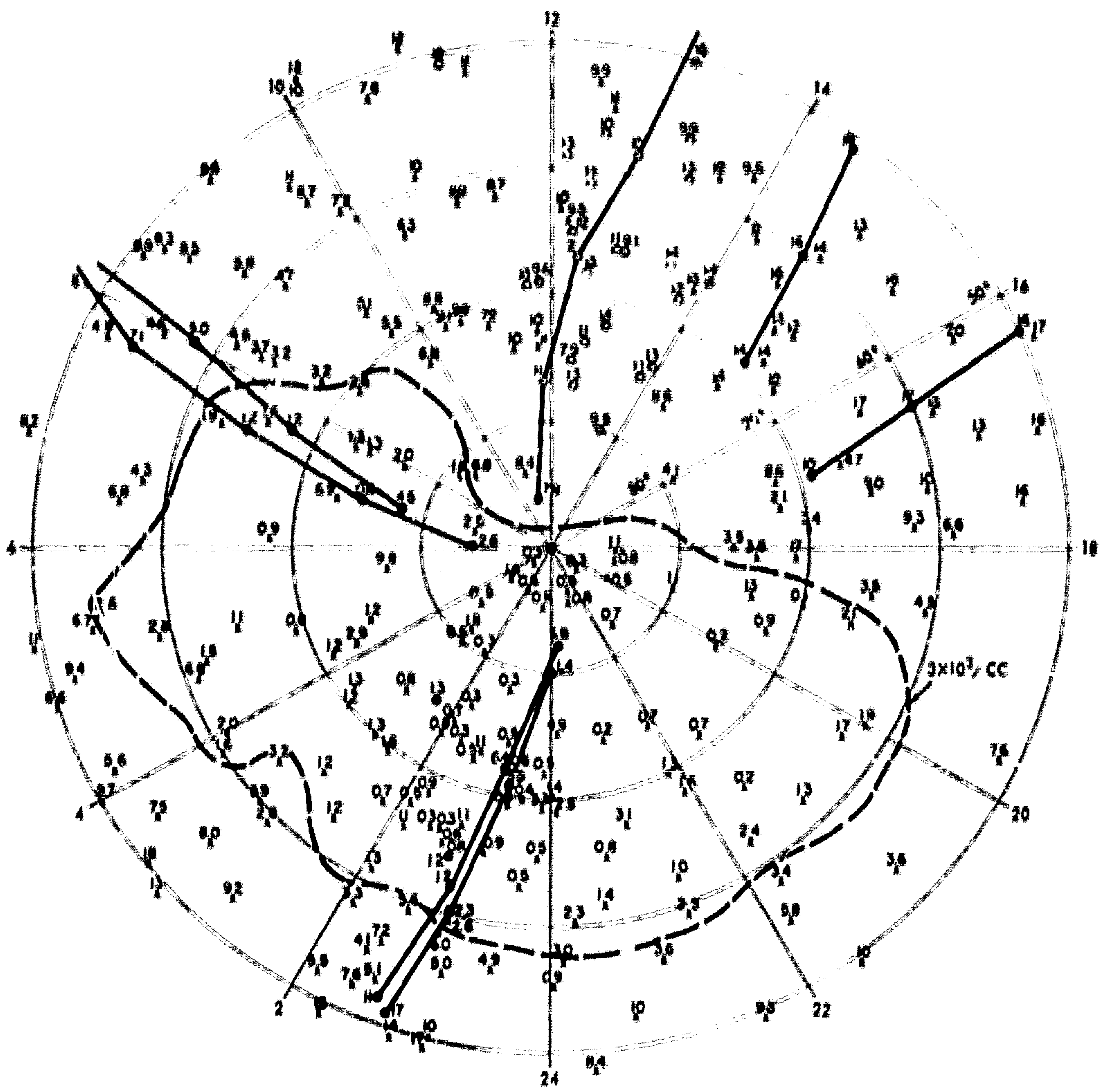

Figure 1. A sample point plot upon which contours are drawn. N_e in units of 10^3/cc is plotted on coordinates of geomagnetic latitude and local time. The points from a few individual passes are connected by lines to demonstrate how the field of points is generated.

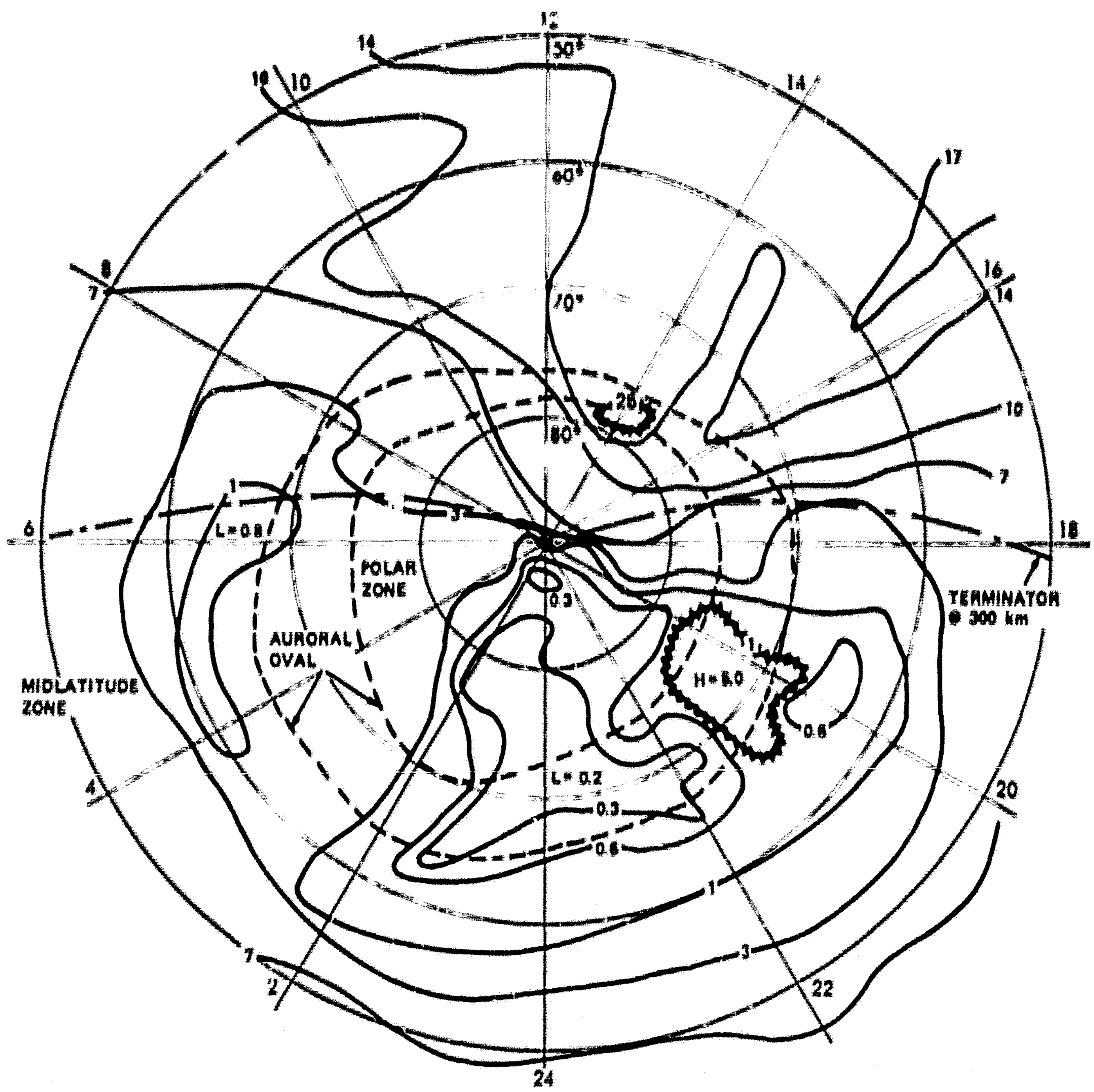

Figure 2. N_e in units of 10^3 /cc at 1000 km at Grand Forks during Nov. 1, 1965 to Feb. 12, 1966. L designates a minimum value and H designates a maximum value. Jagged lines bound areas of N_e enhancement. Coordinates are geomagnetic latitude and local time.

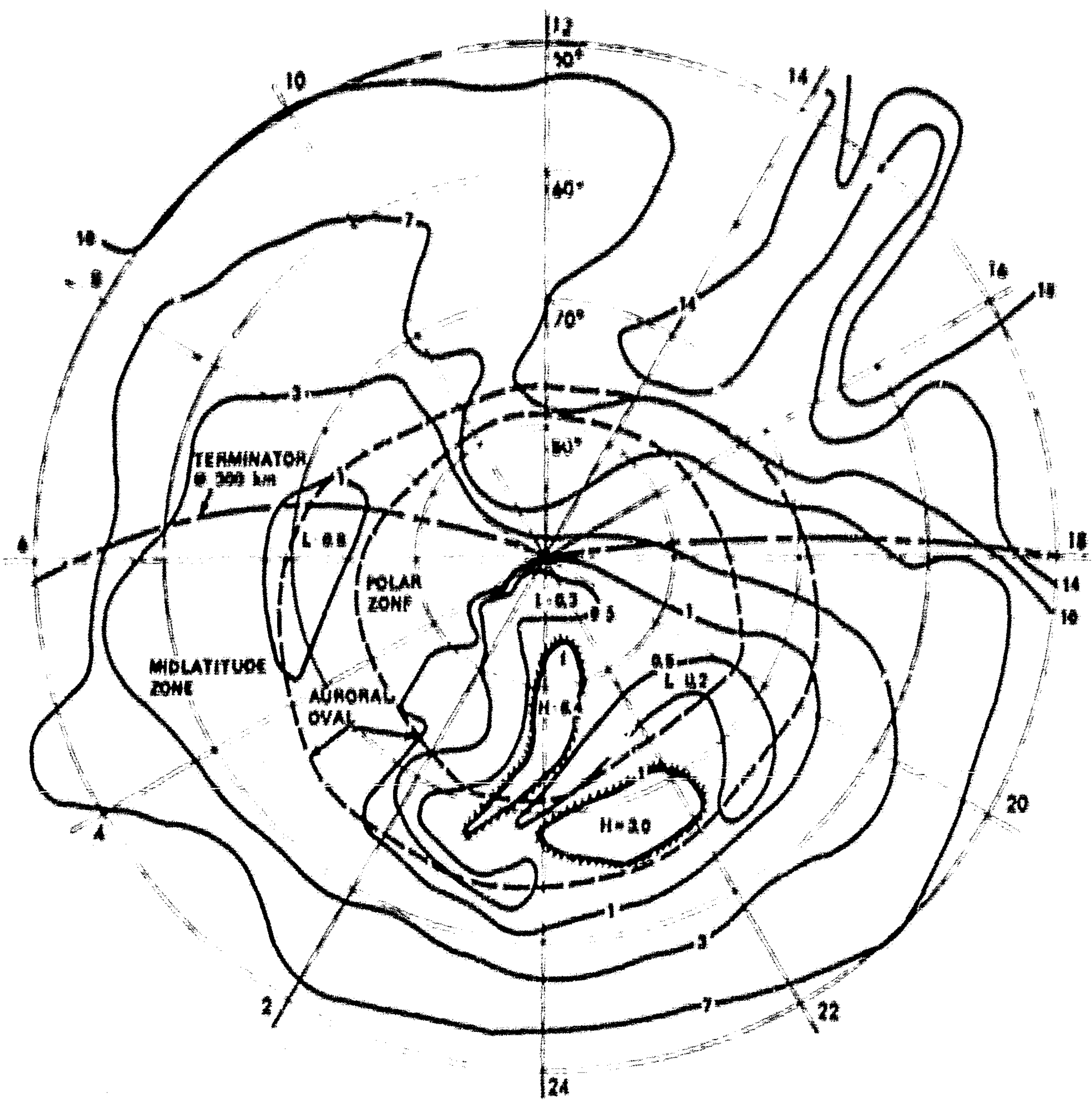

Figure 3. N_e in units of 10^3/cc at 1000 km at Newfoundland between Nov. 1, 1965 and Feb. 12, 1966. L designates a minimum value and H designates a maximum value. Jagged lines bound areas of N_e enhancement. Coordinates are geomagnetic latitude and local time.

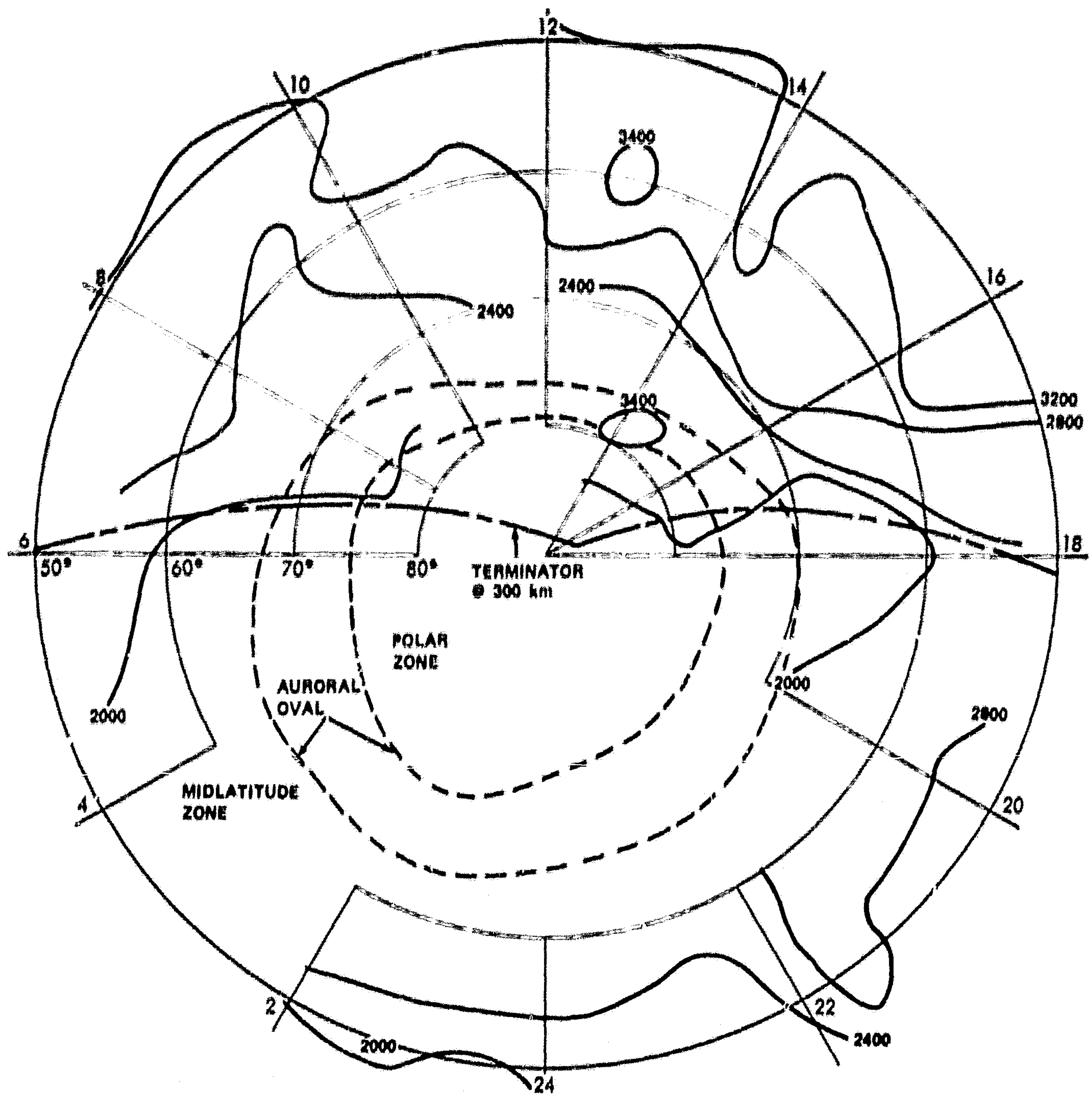

Figure 4. T_e in °K at 1000 km at Grand Forks between Nov. 1, 1965 and Feb. 12, 1966. Coordinates are geomagnetic latitude and local time.

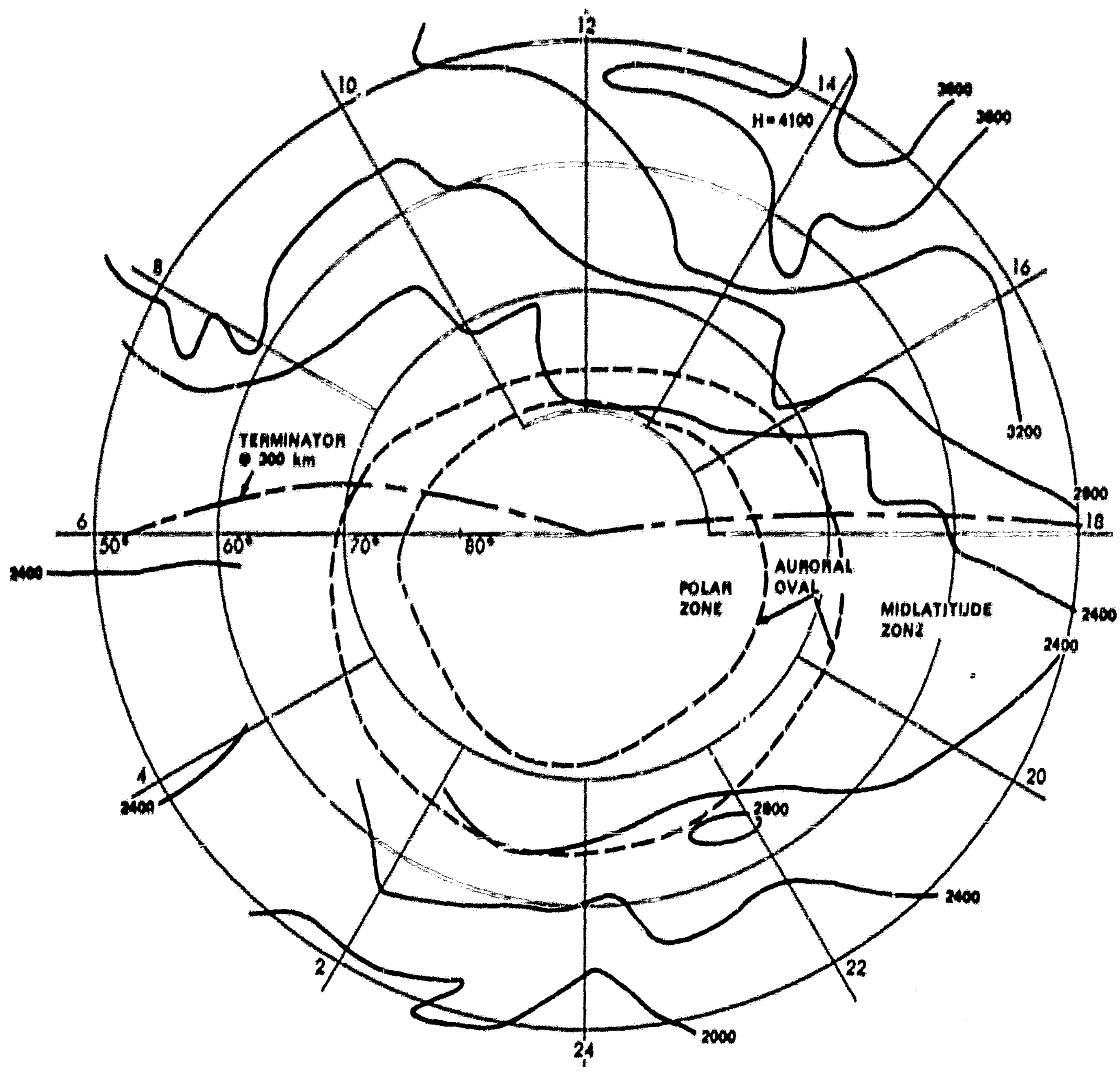

Figure 5. T_e in °K at 1000 km at Newfoundland between Nov. 1, 1965–Feb. 12, 1966. H is a maximum value, coordinates are geomagnetic latitude and local time.

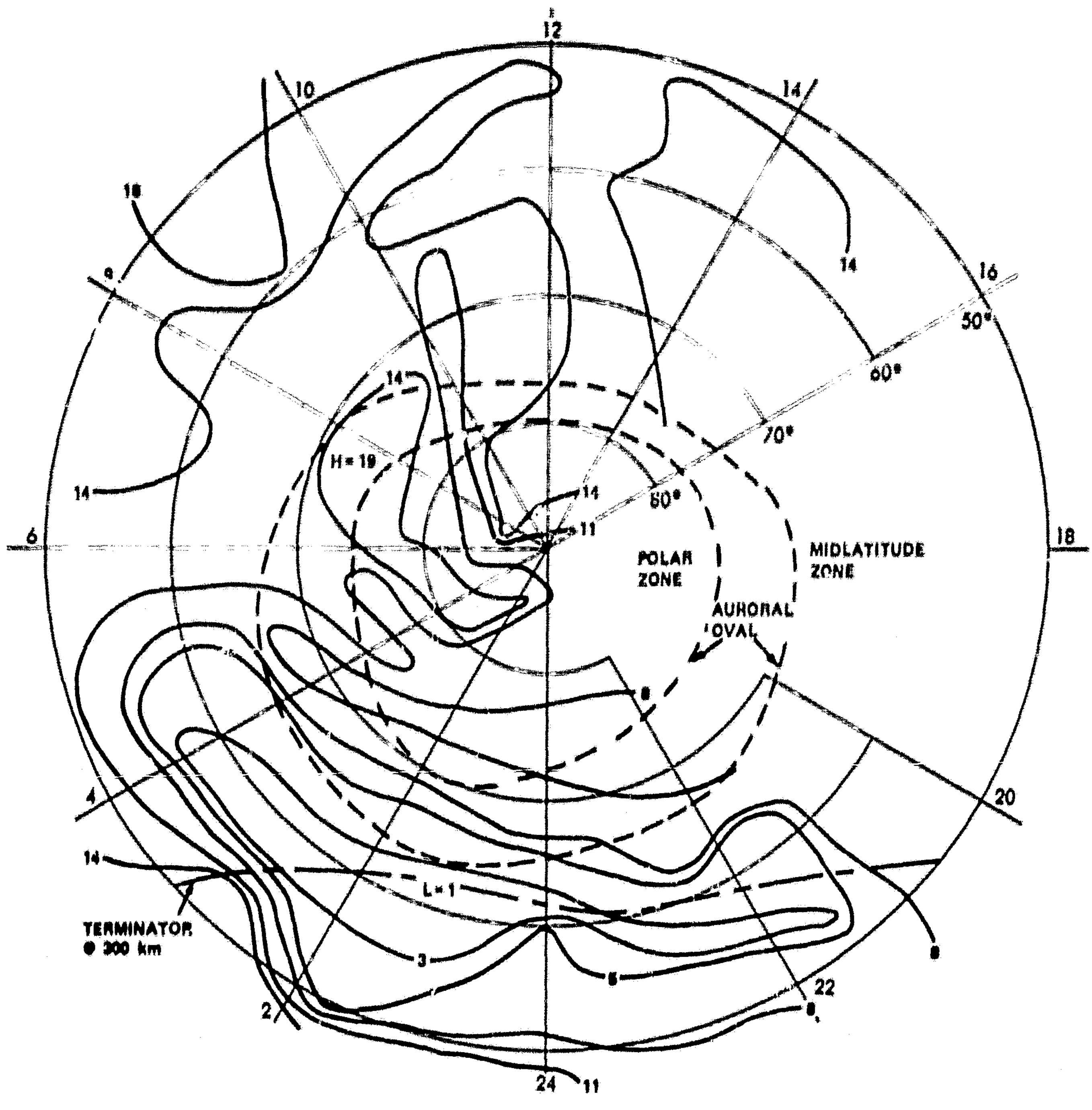

Figure 6. 10^{-3} N_e at 1000 km at Grand Forks during May–June '65. L is a minimum value and H is a maximum value. Coordinates are geomagnetic latitude and local time.

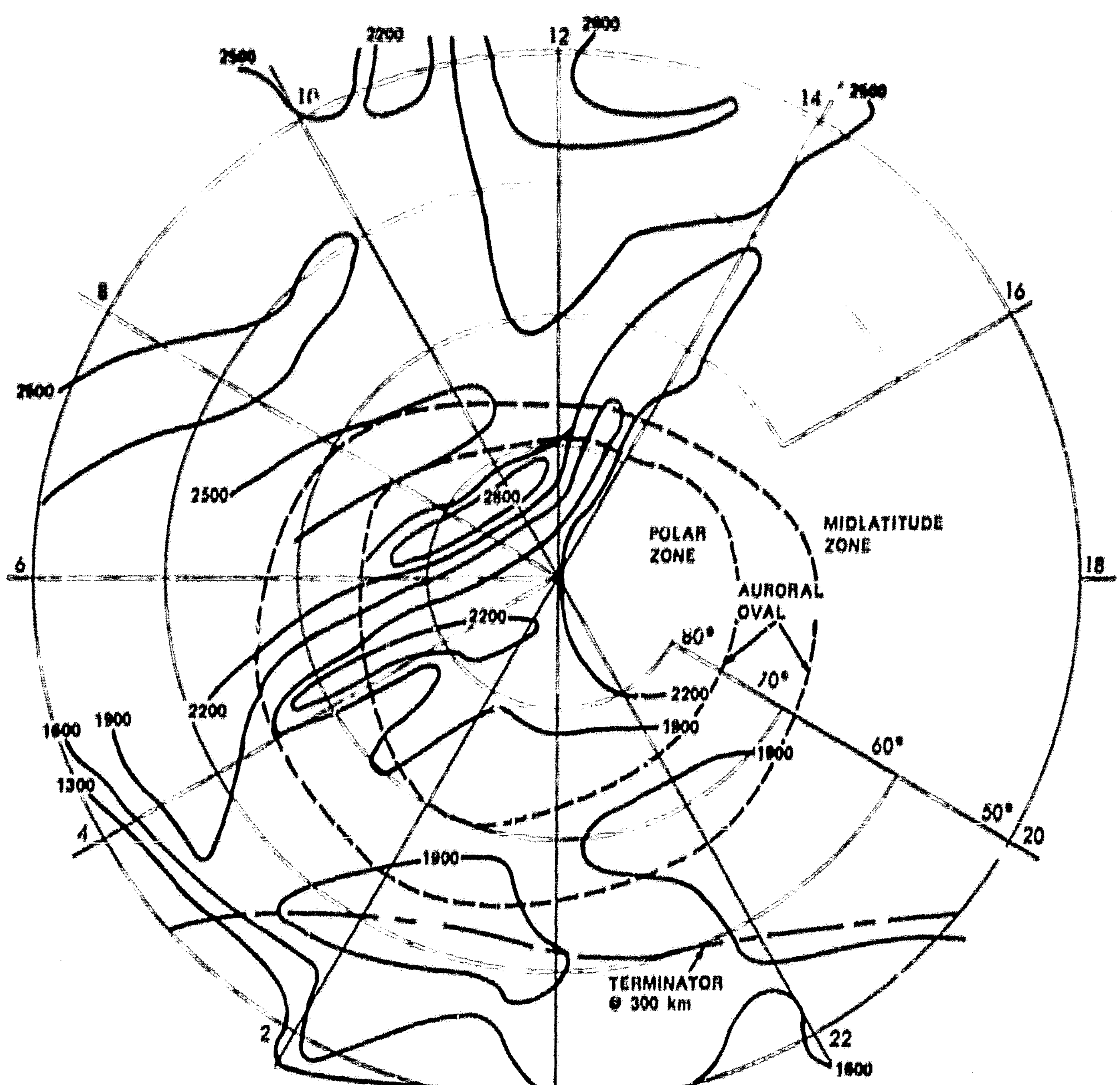

Figure 7. T_e in °K at 1000 km at Grand Forks during May–June '65. Coordinates are geomagnetic latitude and local time.

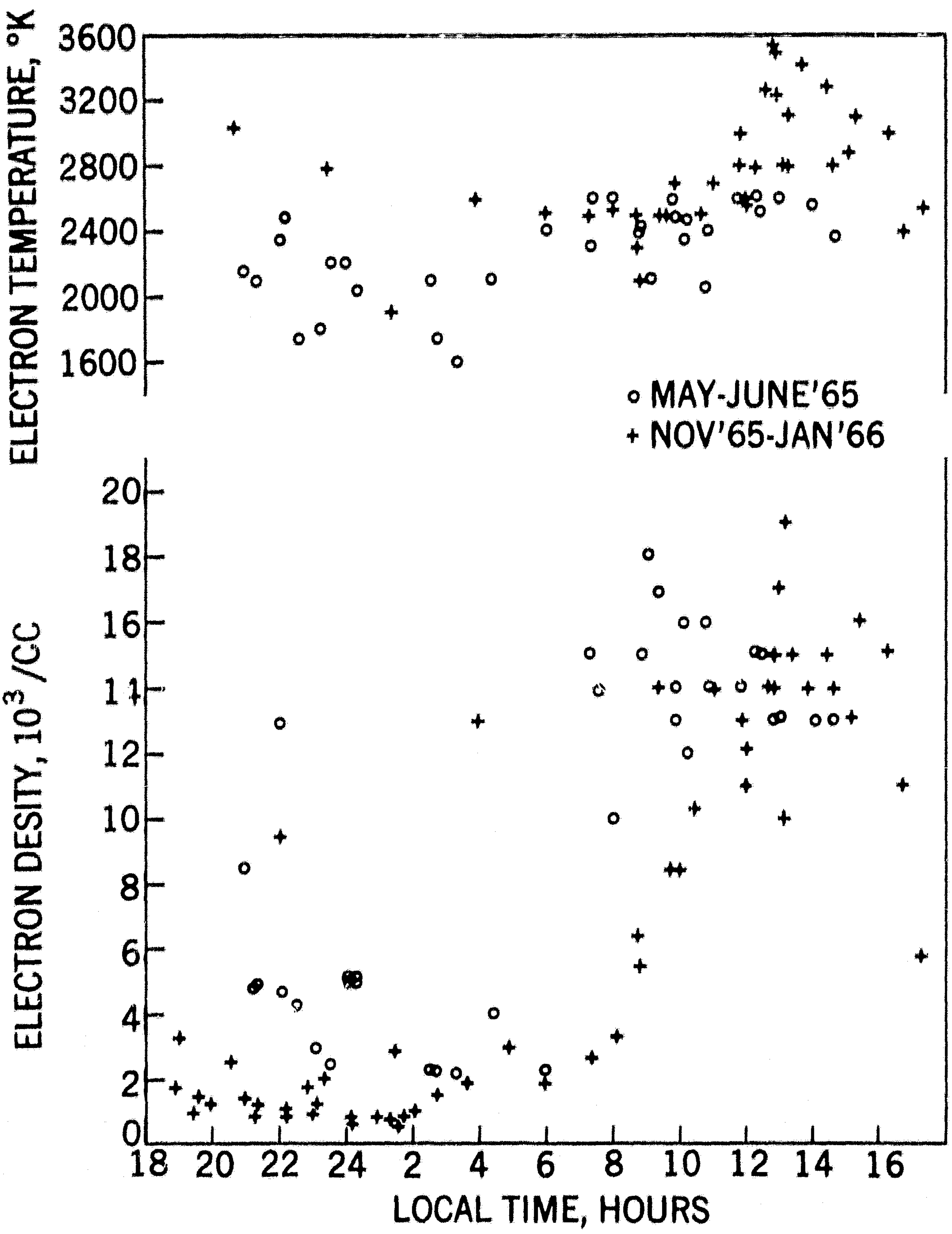

Figure 8. Winter and summer diurnal behavior at Grand Forks between 58–62° latitude.