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MIDLATITUDE TOTAL ELECTRON CONTENT AND SLAB THICKNESS-A SUMMARY--ETC(U)
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Midlatitude Total Electron Content and Slab Thickness

A Summary of Seasonal, Solar Cycle, and Magnetically Disturbed Behavior

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10 March 1977

SPACE PHYSICS DIVISION PROJECT 4643
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FOR THE COMMANDER

John Howard

Chief Scientist

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This paper is a summary of the results of nearly a full solar cycle of recordings of Total Electron Content, TEC, taken from Hamilton, Massachusetts, a northern midlatitude station. While many of the aspects of TEC behavior from this station have been published separately, the completion of a nearly full solar cycle of data recordings provides a convenient time to compile a summary of the conclusions drawn from this work. The major features of diurnal, seasonal, and solar-cycle dependence of TEC and equivalent slab thickness are described. → next page

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The seasonal anomaly in daily maximum TEC has a pronounced peak during equinoxes, as does N_{max} from a nearby ionosonde. Daytime equivalent slab thickness, however, has no seasonal anomaly and a negligible semiannual component. Slab thickness is also shown not to be a useful measure of daytime neutral temperature. Average changes in TEC, N_{max}, and slab thickness during magnetic storms are summarized as well.

N(max)

Preface

This summary paper on TEC results from Hamilton, Mass., includes the work of many people. Foremost among these is M. Mendillo who did virtually all of the magnetic storm studies and contributed in major ways to many other aspects. G. S. Hawkins did the solar flux dependence work on TEC and H. Hossienieh Hajeb did a major portion of the slab thickness studies. C. Malik has made all this possible by his careful attention to all experimental data aspects from original equipment design to careful data recording. Finally, the continued interest and encouragement of Dr. J. Aarons is much appreciated.

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1. INTRODUCTION

The Total Electron Content (TEC) of the northern midlatitude ionosphere has been measured for nearly a complete solar cycle by means of continuous monitoring of the Faraday polarization rotation of VHF radio waves transmitted from geostationary satellites. The observations described here were made at Hamilton, Massachusetts, using signals transmitted from the satellite ATS-3, located, for most of this period, directly south of the station at an elevation angle of 40 deg. In Figure 1 the locations of the TEC and N_{max} monitoring stations, as well as the ionospheric intersection of the ray to the ATS-3 satellite, are shown.

A summary of the major seasonal and solar-cycle dependent results is presented here, along with a description of the average behavior during large geomagnetic storms. The TEC, as measured by the Faraday effect, is mainly an F_2-region parameter; and it has been useful to combine measurements of N_{max} from the nearby ionosonde at Wallops Island, Virginia, with the TEC data to form values of equivalent slab thickness, a first order F_2-region shape parameter. The diurnal, seasonal, and solar cycle behavior of this parameter will also be presented.

(Received for publication 8 March 1977)

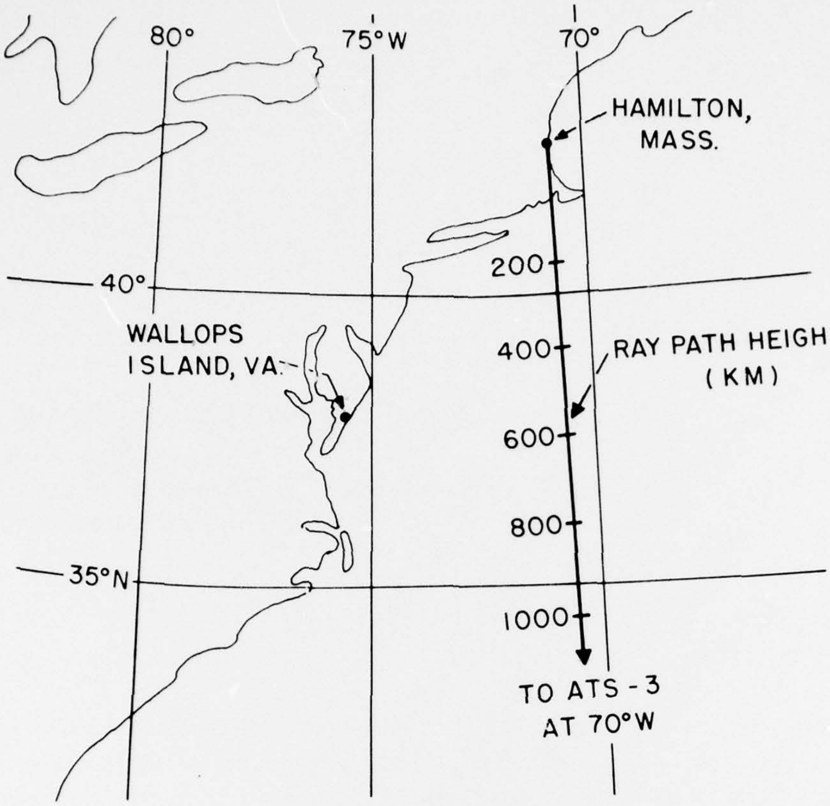
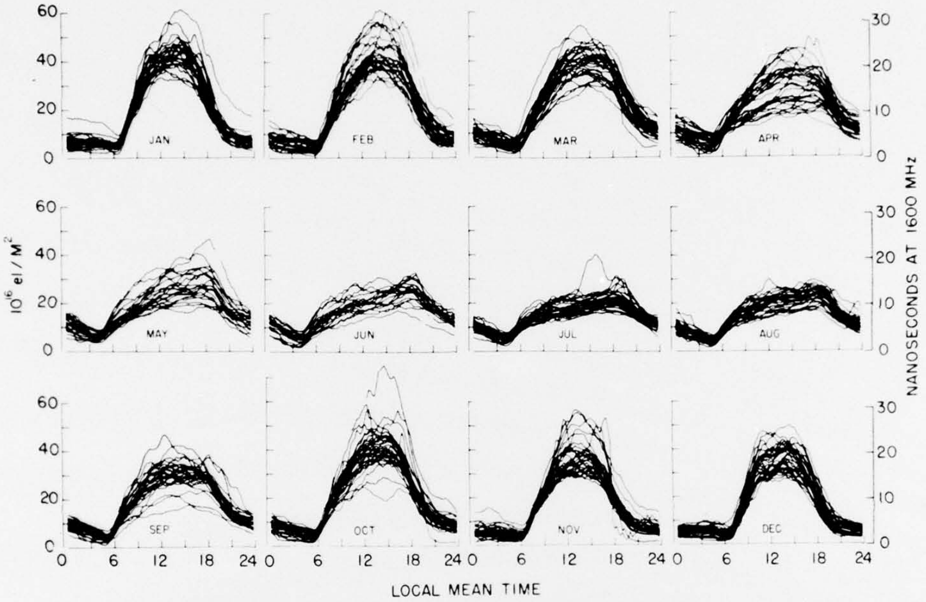


Figure 1. Location of TEC and N_{max} Monitoring Stations and Ionospheric Intersection Heights of the Ray to the ATS-3 Satellite

2. DIURNAL AND SEASONAL BEHAVIOR OF TEC

The diurnal maximum in TEC generally occurs at or near 1400 local time, with later times occurring during the summer months when the daytime values are nearly constant for several hours. A phenomenon often referred to as midday bite-out manifests itself as a pronounced decrease in TEC which lasts for several hours and produces a local minimum near the time at which the diurnal maximum normally occurs. The midday bite-out is not as large in the North American longitudes as in Europe, though it is still present in the summer TEC monthly mean curves. Figure 2 shows 12 monthly mass overplots of TEC for the solar maximum year 1968. The seasonal maximum during high sunspot number years occurs during the March equinox month with a secondary maximum value during the October equinox. Summer values are lowest. The semiannual dependence with a summer daytime seasonal minimum is generally recognized to be due to the seasonally larger concentration of molecular nitrogen at F-region heights during the summer, thereby increasing the loss mechanism. In years of solar minimum there is no seasonal anomaly in TEC. Interestingly, if the mean diurnal TEC hourly values are normalized by dividing the 24-hr mean value, the normalized diurnal behavior does not show any semiannual dependence, as shown by Hawkins et al.[1] The normalized diurnal curves show a winter maximum and a clear summer minimum.



TOTAL EQUIVALENT VERTICAL ELECTRON CONTENT FROM HAMILTON, MASS (looking towards ATS-3), 1968

Figure 2. Monthly Mass TEC Overplots for the Solar Maximum Year 1968

The nighttime mean values of TEC do not show a seasonal anomaly; summer values are highest and winter values are lowest. This can also be seen in Figure 2 as well as in the normalized values given by Hawkins et al.[1] Occasionally, increases in nighttime TEC are observed which occur over a several hour period. These are especially obvious in the winter nighttime data in which TEC values normally remain constant for many hours. An example of night-to-night variability

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[1] Hawkins, G.S., and Klobuchar, J.A. (1974) Seasonal and Diurnal Variations in the Total Electron Content of the Ionosphere at Invariant Latitude 54 Degrees, AFCRL-TR-74-0294.

in TEC increases is shown in Figure 3. Note, on some nights, the large observed increases in TEC. These increases can be of 100 percent magnitude and are not well correlated in shape or occurrence over distances of a few hundred kilometers.

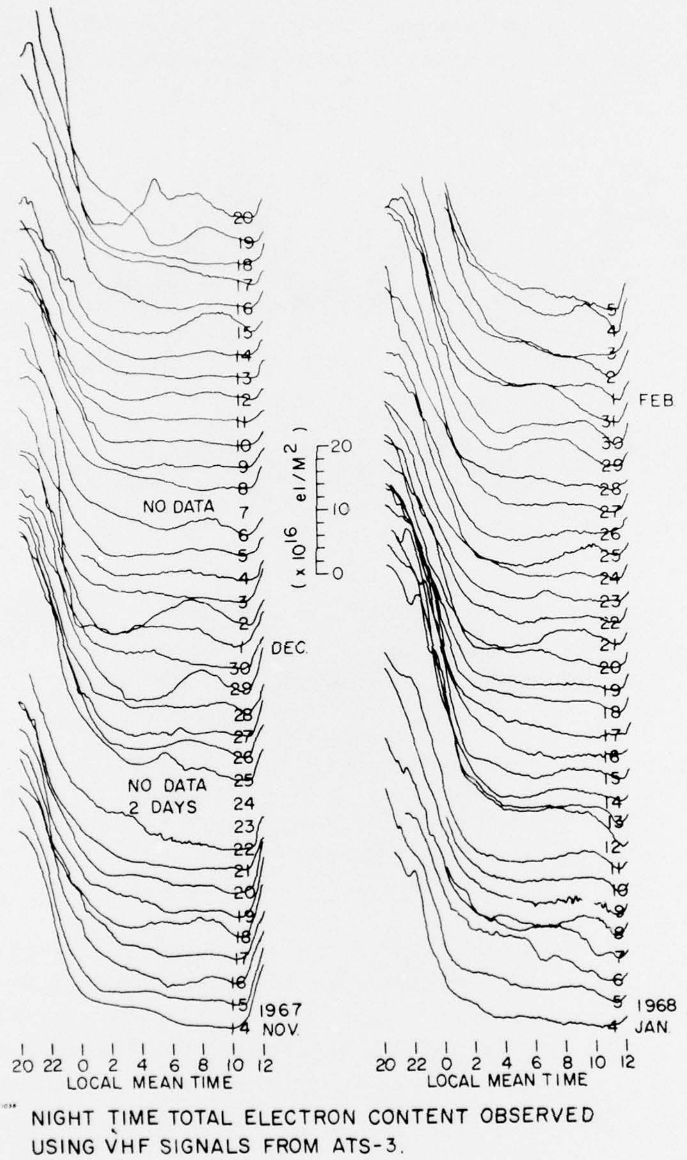

Figure 3. Nighttime TEC Changes Observed from ATS-3 VHF Radio Wave Polarization Changes

Various mechanisms for this nighttime TEC increase have been proposed including plasmaspheric-ionospheric exchange, electric fields producing regions of horizontal ionization excesses, and localized neutral wind enhancements. Nighttime ionospheric disturbances have been related to magnetospheric substorm activity by Park and Meng.[2] At present, no mechanism satisfactorily explains the observations which also have been made at latitudes as low as with a 20-deg dip by Young et al.[3]

3. SOLAR-CYCLE BEHAVIOR OF TEC

The 24-hr mean TEC was calculated by Hawkins et al[1] for each month and a best linear fit with solar radio flux at 10.7-cm wavelength was made for each month. The slope of the linear dependence with 10.7-cm radio flux shows a semiannual change with maximum at the equinoxes and minima at the solstices. Similar semiannual behavior of TEC with solar flux is seen at Stanford, California, and Hawaii. For the Hamilton data the correlation between monthly 24-hr mean TEC and solar radio flux was carried out for solar radio flux at wavelengths of 2 cm and 50 cm, in addition to 10.7 cm. The residual error in the straight line correlation was least when the 5-month running mean 10.7-cm radio flux was used against 24-hr monthly mean TEC values. Huang[4] has found that a 12-month running average of TEC at each hour has an excellent linear correlation with a 12-month running average value of monthly mean sunspot number by using published data from the Hamilton, Mass., station. Huang has also reported that the linear correlation coefficient between monthly mean hourly TEC values and monthly mean sunspot number is large; however, the linearity may not extend to the sunspot minimum period.

4. SLAB THICKNESSES–DIURNAL AND SEASONAL BEHAVIOR

Equivalent slab thickness, the ratio of TEC divided by the density at the peak of the F_2 region, N_{max}, has been studied by using N_{max} data from the Wallops Island, Virginia, ionosonde located near the mean ionospheric intersection height of 420 km. Values of f_oF_2 for this purpose were kindly provided by the World Data Center A, Boulder, Colorado. The diurnal values of slab thickness for solar-maximum years have a maximum during summer midday as shown in Figure 4. During the equinoxes

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[2] Park, C. G., and Meng, C. I. (1973) Distortions of the nightside ionosphere during magnetospheric substorms, J. Geophys. Res. 78:3828.

[3] Young, D. M. L., Yuen, P. C., and Roelofs, T. H. (1970) Anomalous nighttime increase in total electron content, Planet. Space Sci. 18:1163-1180.

[4] Huang, Nien Yien (1976) Solar cycle variations in the total electron content at invariant latitude 54 degrees, Proceedings of the COSPAR Beacon Studies Symposium, Boston University, Boston, Mass.

there is little diurnal variation, and in the winter, the daytime values are lower than those at night. There is little seasonal change at night and little nighttime diurnal change. The summer daytime seasonal maximum and winter minimum show no evidence of a seasonal anomaly and the semiannual dependence is negligible. Thus, even though TEC and N_{max} separately show semiannual variations with equinox maxima, their ratio, slab thickness, is devoid of anamalous behavior.

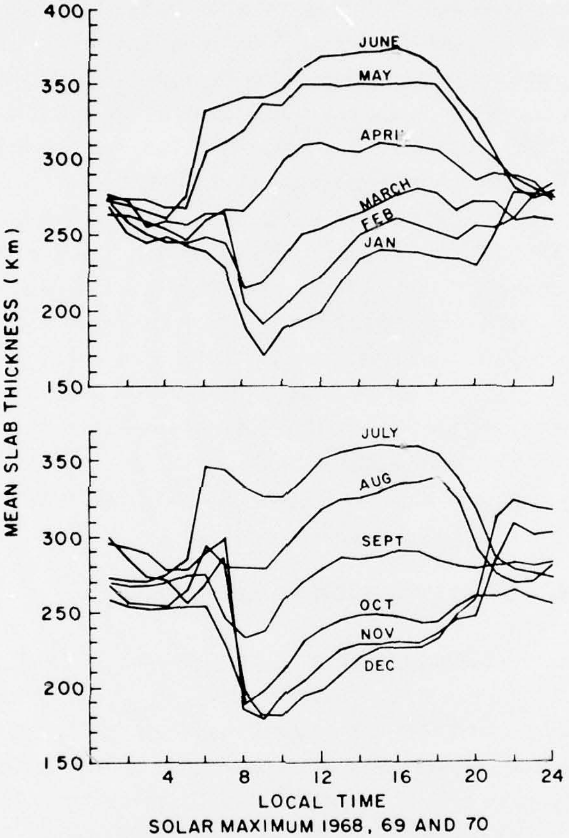

Figure 4. Diurnal Variation in Monthly Mean Slab Thickness for Solar Maximum Years

5. SLAB THICKNESS–SOLAR-FLUX DEPENDENCE

Mean daytime and mean nighttime values of slab thickness were calculated for each month and were plotted against monthly average 10.7-cm radio flux (see Figure 5). The daytime mean values of slab thickness show good correlation in the summer and autumnal equinox months, as shown in Figure 6, with poor correlation in the winter and spring equinox months. Mean nighttime slab-thickness values, illustrated in Figure 7, show poor correlation with 10.7-cm solar radio flux during all months, except April when there is an unexplained high correlation. The mean daytime slab thickness—solar-flux dependence shows some evidence of a seasonal asymmetry which may be due to a seasonal lag in F-region composition change.

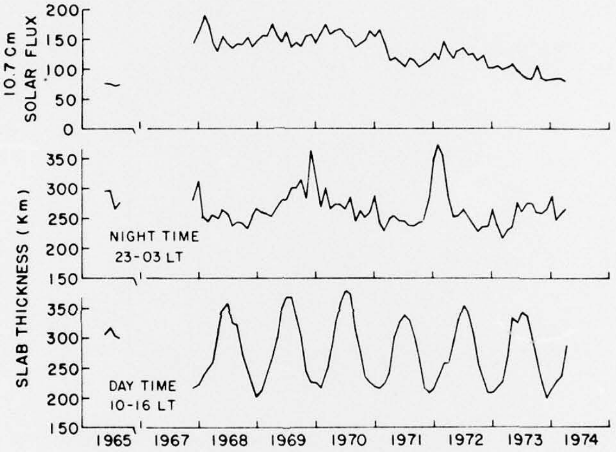

Figure 5. Mean Daytime and Mean Nighttime Slab Thickness and 10.7-cm Solar Flux During the Declining Phase of a Solar Cycle

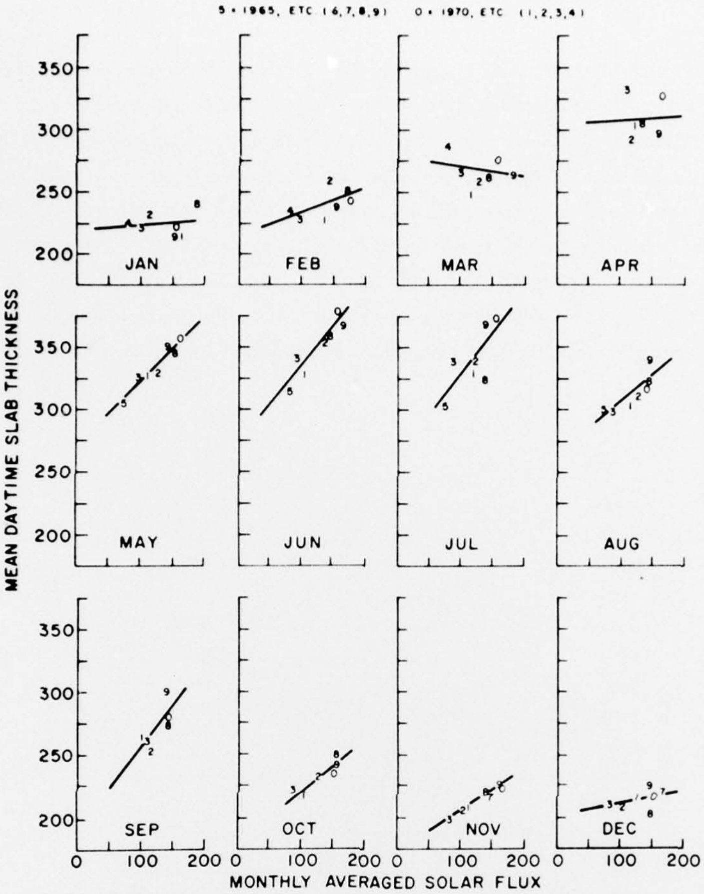

Figure 6. Monthly Mean Daytime Slab Thickness vs 10.7-cm Solar Flux

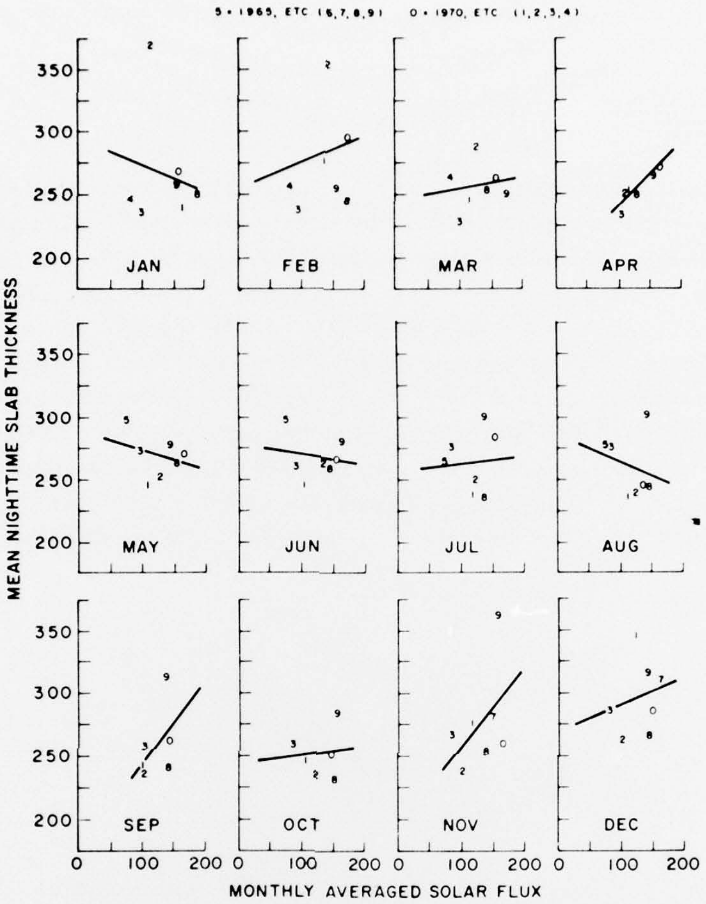

Figure 7. Monthly Mean Nighttime Slab Thickness vs 10.7-cm Solar Flux

6. SLAB THICKNESS AS A MEASURE OF NEUTRAL TEMPERATURE

It has been suggested by Titheridge[5] that slab thickness may be a useful measure of upper F_2-region neutral temperature, T_N. He derived the relation between the two:

$$T_N = \frac{S - 15}{.225} .$$

The Hamilton, Mass., —Wallops Island, Va., pair of ionospheric stations are ideally suited to test this relation because of the nearby location of the Lincoln Laboratory Millstone Hill incoherent scatter facility, which has been used to determine directly the neutral temperature. An analytic model of T_N has been derived by Salah and Evans[6] for the solar maximum years of 1969 and 1970 by using Millstone Hill measurements. In order to find the F_2-region equivalent slab thickness only, the equivalent slab thickness of the E and F_1 regions was determined and was subtracted from the total slab thickness. The remaining F_2-region slab thickness was then used in the Titheridge relation to determine monthly mean daytime values of T_N. These values were then compared with those obtained from the Salah and Evans model and are plotted in Figure 8. Note that, while the annual mean values

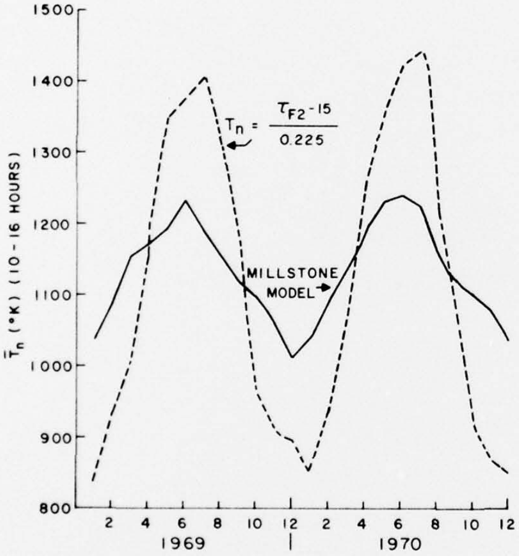

Figure 8. A Comparison of Mean Monthly Daytime Values of Neutral Temperature for 1969 and 1970

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[5] Titheridge, J.E. (1973) The slab thickness of the mid-latitude ionosphere, Planet. Space Sci. **21**:1775-1793.

[6] Salah, J.E., and Evans, J.V. (1973) Measurements of thermospheric temperature by incoherent scatter radar, Space Research XIII:267-286, Akademie-Verlag, Berlin.

agree reasonably well, the seasonal change of T_N determined from the slab-thickness values is approximately 2.8 times as large as the actual seasonal change, indicating that the Titheridge relation is not a good measure of T_N. This large difference may in part be due to the contribution of the T_e/T_i ratio, which was not considered by Titheridge.

7. MAGNETIC STORM DEPENDENCE OF TEC, N_{max}, AND SLAB THICKNESS

Major magnetic storms, those which begin with a sudden commencement or gradual commencement of magnetic activity, and which had an A_p index of 30 or greater during at least one day of the storm, have been studied for the changes in TEC, N_{max}, and slab thickness observed at Hamilton, Mass., and Wallops Island, Va. A total of 75 storms have been studied over the five-year period from 1968 through 1972.[7] The mean diurnal patterns of the behavior of all three ionospheric parameters as a function of local time and of storm time have been determined separately for each season.[8] Following the sudden commencement of a storm the afternoon values of TEC and N_{max} are enhanced by approximately 30 percent above the mean value. This initial enhancement phase does not occur for all storms. Storms where the sudden commencement occurs after dusk, and before dawn, generally exhibit only the second phase, or depletion phase, which can last up to several days following sudden commencement. These average patterns are seasonally dependent, with the recovery phase being as short as one day in the winter, and up to five days in summer. In addition, at the subauroral latitude of Hamilton, Mass., the location of the main trough of electron density can be seen during the early morning hours when it is at its southernmost latitude. The minima in TEC occurring at 0400 local time can be seen for several days following a magnetic storm, especially during the winter period. Figure 9 shows the mean behavior of TEC vs local time for four days following magnetic storms. Similar curves of average disturbed behavior of N_{max} are shown in Figure 10. The initial late afternoon enhancement in N_{max}, followed by several days of lower than normal values, and clearly showing the 0400 local time minima, are also shown in this figure. Slab thickness, shown in Figure 11, on the other hand, shows increases during the daytime periods for the first few days after a sudden commencement, particularly during the summer and spring equinox storms. During winter the slab thickness following magnetic storms shows remarkably little systematic change, except for a depressed level during the first night.

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[7] Mendillo, M., and Klobuchar, J.A. (1974) An Atlas of the Mid-Latitude F-Region Response to Geomagnetic Storms, AFCRL-TR-74-0065.

[8] Mendillo, M., Papagiannis, M.D., and Klobuchar, J.A. (1972) Average behavior of the mid-latitude F-region parameters N_T, N_{max}, and τ during geomagnetic storms, J. Geophys. Res. 77:4891.

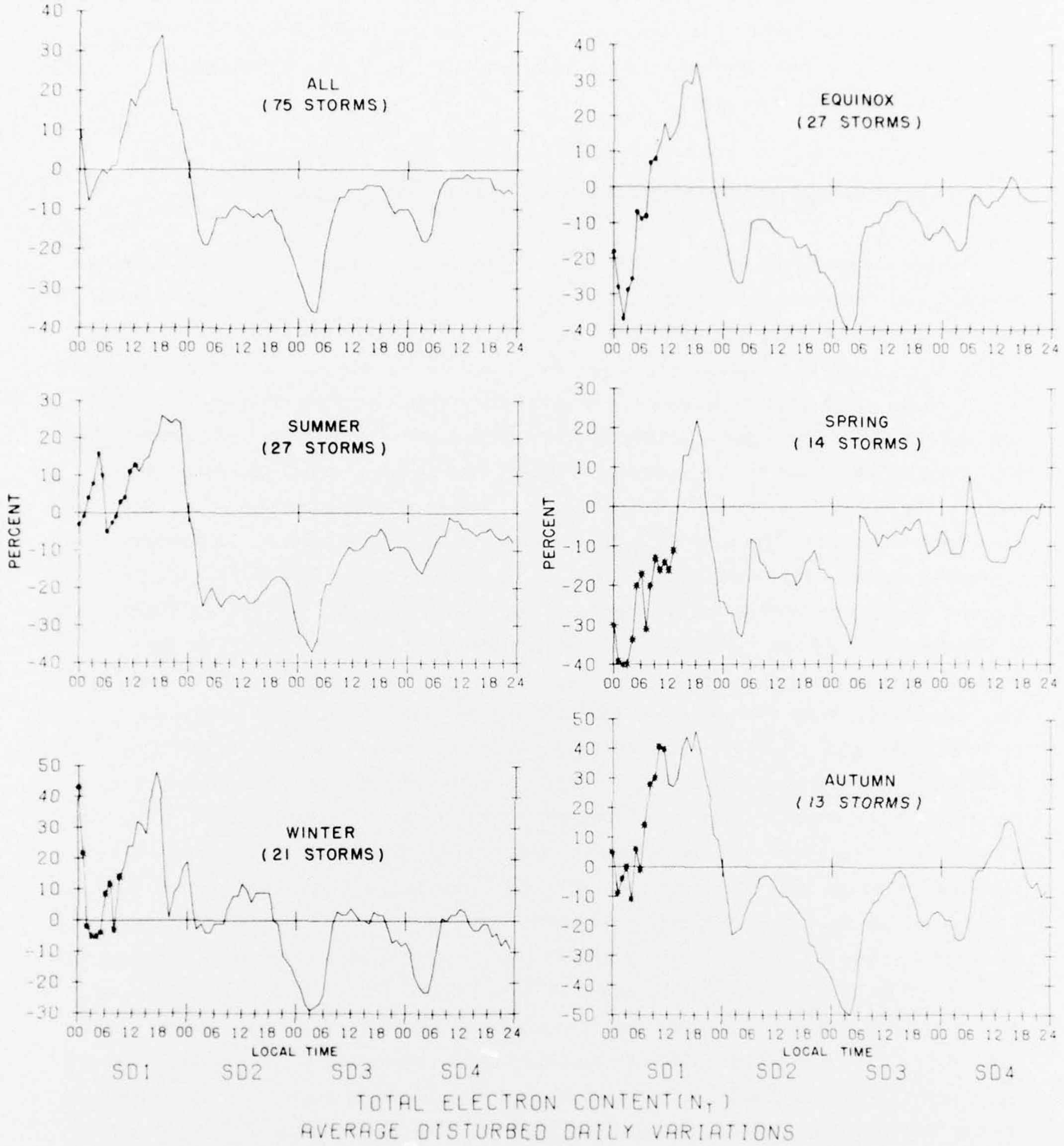

Figure 9. Average Local Time Behavior of TEC During Magnetic Storms for Each Season

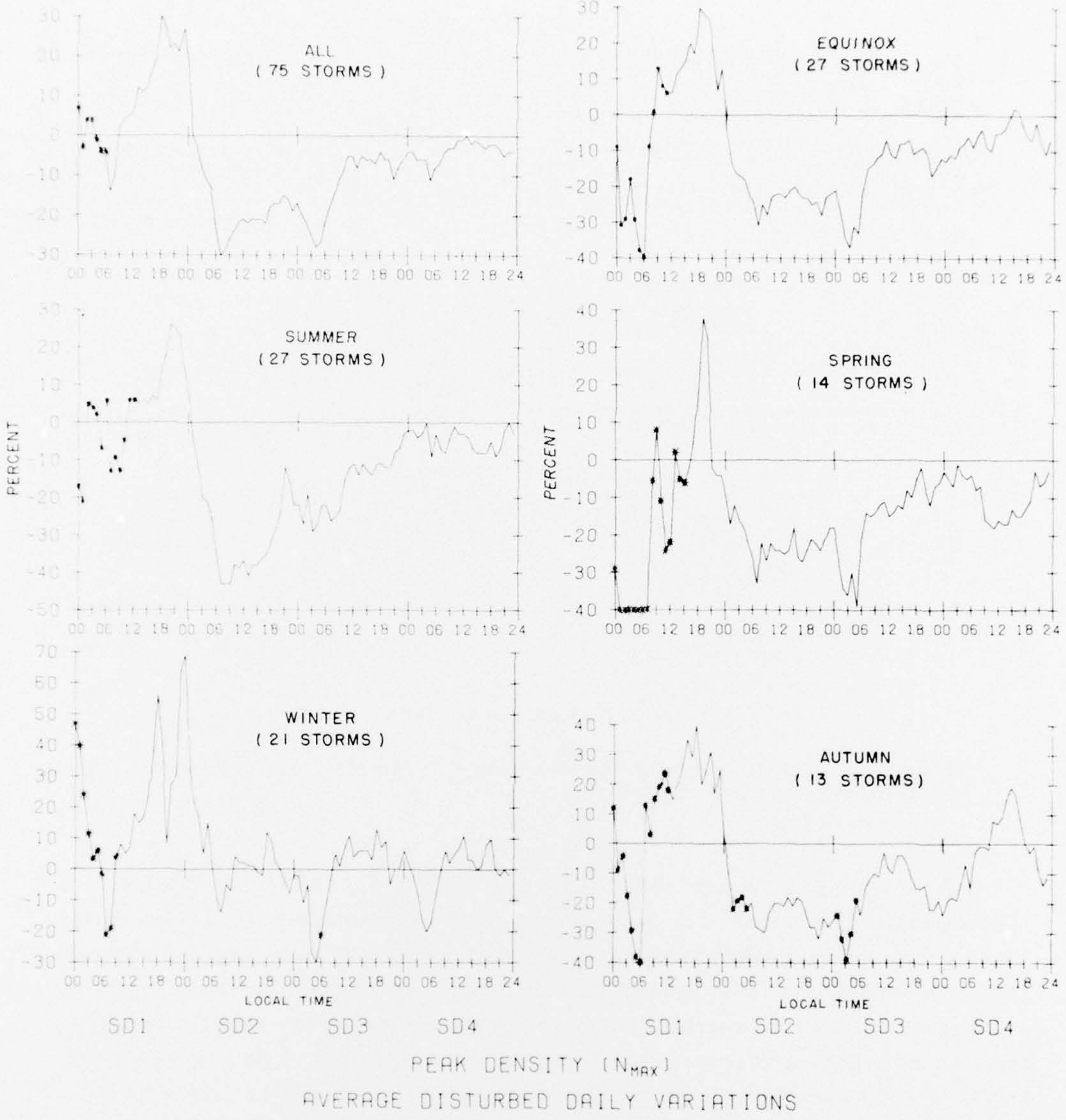

Figure 10. Average Local Time Behavior of Peak Density, N$_{max}$ *During* Magnetic Storms for Each Season

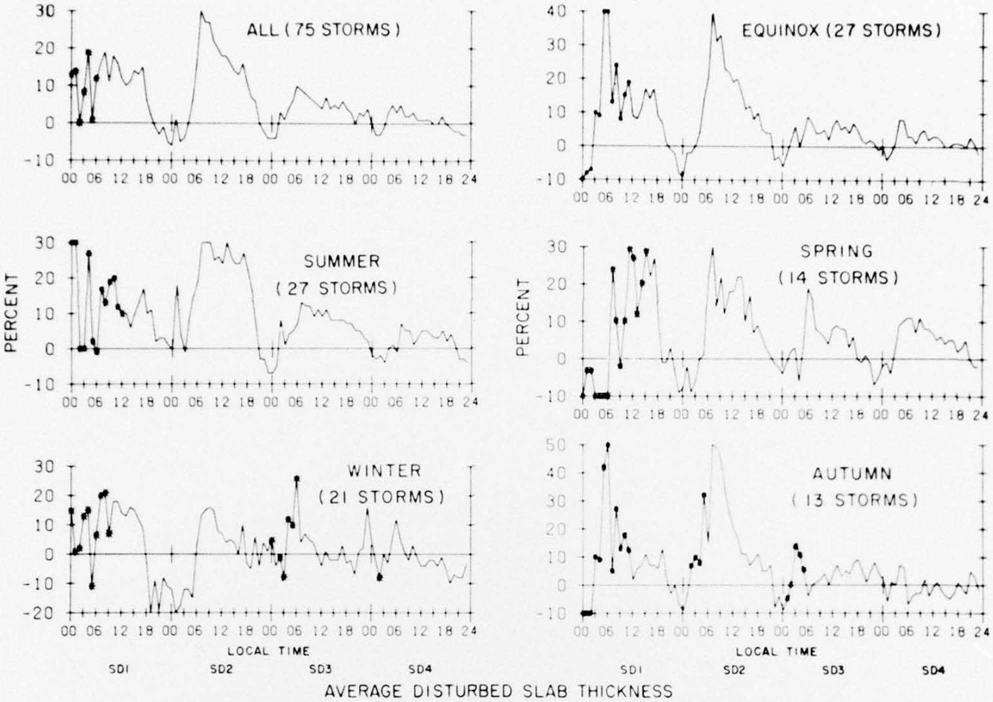

Figure 11. Average Local Time Behavior of Equivalent Slab Thickness During Magnetic Storms for Each Season

The changes observed at midlatitudes in TEC, N_{max}, and in slab thickness have been extensively studied. The large enhancement in content and N_{max} seen during the afternoon of the initial storm day has been described as being due to an increase in F_2-region height where the loss is much lower. This height increase, probably at least 50 km from the normal height, can be due to strong equatorward winds, from an auroral heat source, which force ionization upwards along magnetic field lines, or can be due to an enhanced poleward electric field which slows down the co-rotation of plasma, thereby causing a pile-up of ionization in the dusk sector. The depletion in TEC and in N_{max}, which occur on the second storm day and the days following, are generally recognized to be due to the thermal heating and expansion of the atmosphere during magnetic storms. In the winter season this heating is less, and the available N_2, thus, is also less. Consequently, the negative phase of geomagnetic storms in winter is shorter and smaller.

8. CONCLUSIONS

The diurnal, seasonal, and solar-cycle behavior of the ionospheric Total Electron Content and slab thickness has been described. Also, the mean changes in TEC, N_{max}, and slab thickness during magnetic storms have been summarized. The potential of a slab-thickness relation to determine neutral temperature has been tested against actual T_N values and found to differ by a large factor. Other changes in TEC, such as sudden increases during large solar flares, SITECs, effects of solar eclipses, and the response of the ionosphere to the SKYLAB rocket launch, have also been studied from data taken at Hamilton, Mass., but the results of these rare, or one-time-only, events have not been summarized here. Also, various engineering models of TEC and slab thickness have been constructed from these data, but are not included in this summary report.

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1. Hawkins, G.S., and Klobuchar, J.A. (1974) *Seasonal and Diurnal Variations in the Total Electron Content of the Ionosphere at Invariant Latitude 54 Degrees*, AFCRL-TR-74-0294.
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