CHAPTER IV

LATITUDINAL DEPENDENCE OF DAY-TO-DAY VARIABILITY AND STORM-TIME RESPONSE OF TEC

4.1. Introduction 100
4.2. Data and Method of Analysis 101
4.3. Results and Discussion 102
4.3.1. Day-to-day variability in TEC 102
4.3.2. TEC response to geomagnetic storms at low, mid and high latitudes 113
4.4. Conclusions 122
4.4.1. Conclusions on day-to-day variability in TEC 122
4.4.2. Conclusions on storm-time response of TEC 123
4.1. Introduction

One of the important aspects of TEC study from the standpoint of application oriented models, is the day-to-day variability. This has been studied at different latitudes for various geophysical conditions by a number of investigators (eg., Yuen and Roelofs, 1966; Tyagi, 1974; Kane, 1975, 1980; McNamara and Smith, 1982; Dabas et al., 1984; Soicher, 1986, 1988; Rastogi and Alex, 1987). The earlier studies were limited mostly to single stations and/or restricted solar activity conditions. No attempt has yet been made to study the variation for a wide range of latitudes and geophysical conditions. In this chapter we present the results from a comprehensive study of the day-to-day variability of TEC using the simultaneous data collected from low, mid and high latitudes in the roughly constant longitude of about $290^\circ E$, during the solar maximum and minimum years of the last (21) solar cycle. The low, mid and high latitudes are respectively represented by Ramey, Sagamore Hill and Goose Bay.

The second aspect that is presented in this chapter addresses to the latitudinal dependence of the storm-time response of TEC. The global storm-time response of TEC is one of the complex aspects of TEC variations. Although a number of studies have been conducted on the
storm-time response of TEC, a clear picture has not emerged for the TEC behaviour under disturbed conditions. Accordingly, it has not been possible to develop consistent TEC models for magnetically disturbed conditions. The reason for the complexity of the storm-time response is that it depends on a number of variables such as the location, time of occurrence, season, solar activity and the type of the storm. In this chapter we present the storm-time TEC response from the case studies of two SC storms, one occurring around local midnight and the other around local noon during the equinoctial period of the solar maximum year 1981. The results are presented for the low, mid and high latitudes represented by the same three stations as mentioned above.

4.2. Data and Method of Analysis

Faraday rotation data collected by using geostationary satellites during the years 1981 and 1985 at the three stations of Ramey, Sagamore Hill and Goose Bay form the data base of the present study. The satellites used along with the co-ordinates of the sub-ionospheric points corresponding to the three stations and other details of analysis are the same as given in chapter III, section 2.
4.3. Results and Discussion

4.3.1. Day-to-day variability in TEC

In this sub-section, the diurnal, seasonal and solar activity variations of the day-to-day variability in TEC for the three stations are presented first. This is followed by an attempt to compare the TECmax variabilities at the three latitudes during the two solar phases to the corresponding variabilities in Sl0.7 solar flux values. The variability curves of Sl0.7 and TECmax are Fourier analysed to obtain the power spectra and the prominent periodicities present are compared for the three stations during both the solar phases. A discussion of the observed results is also given at the end.

Diurnal, seasonal and solar activity variations of the day-to-day variability: The day-to-day variability in TEC at any location is best described by the ratio of the standard deviation to the mean TEC value as a function of time. Such ratios in percentage are plotted in figure 4.1 for the three seasons corresponding to the solar maximum and minimum years for the three stations. The mean daytime (0600 - 1800 LT) and mean nighttime (1900 - 0500 LT) variabilities computed are shown in table 4.1.
Figure 4.1. Mean diurnal variations of percent standard deviations of TEC (σ-TEC) for the three stations in winter (Nov - Dec), summer (Jun - Jul) and equinox (Mar - Apr) during the solar maximum (1981) and minimum (1985) years.
Table 4.1. Mean percentage standard deviations of TEC during daytime (0600-1800 LT) and nighttime (1900-0500 LT) for the three stations corresponding to the solar maximum (1981) and solar minimum (1985) years

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<td>Winter</td>
<td>Equinox</td>
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<td>Ramey</td>
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<td>Day</td>
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<td>12</td>
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<tr>
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<td>Night</td>
<td>34</td>
<td>26</td>
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<tr>
<td>Goose Bay</td>
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<tr>
<td>Day</td>
<td>25</td>
<td>33</td>
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<tr>
<td>Night</td>
<td>45</td>
<td>41</td>
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</table>
It can be seen from the figure that during both solar minimum and maximum phases, the diurnal behaviour of the day-to-day variability in TEC is generally consistent. The most consistent behaviour in the variation is seen during the daytime of the low solar activity period. The variabilities assume the highest values during the pre-sunrise and post-sunset hours. From the table it can be seen that during the solar maximum the latitudinal dependence is found to be quite appreciable for both day and night during equinox and mainly during the nighttime for winter. For summer, however, there is no appreciable latitudinal dependence either during daytime or nighttime. But during the solar minimum, the mean daytime variability is found to undergo negligible variation with season and latitude. While the mean nighttime variability parameter is found to be highest at high latitude for winter and equinox, it is found to be high at both high and low latitudes during summer.

Comparison of the day-to-day variability of TECmax with that of S10.7: Figure 4.2a shows the percentage variations of the daily values of TECmax ($\Delta$TECmax) from the respective monthly mean values computed for the three stations corresponding to the solar maximum year 1981. The percentage variations of S10.7 solar flux ($\Delta$S10.7) for the solar maximum are also included in the figure (top panel) for comparison. Similar plots for TECmax at the three stations
Figure 4.2a. Percentage variations of $S_{10.7}$ ($\Delta S_{10.7}$) and TECmax ($\Delta \text{TECmax}$) from the monthly mean values for the three stations during the solar maximum year 1981.
Figure 4.2b. Same as figure 4.2a, but corresponds to the solar minimum year 1985
along with those of $S10.7$ corresponding to the solar minimum year 1985 are shown in figure 4.2b. The fluctuations in the variability of $T_{EC\text{max}}$ are found to be much rapid compared to that of $S10.7$. The mean $S10.7$ variability is found to increase by a factor of about 2 as the solar phase changes from minimum to maximum. But there is no corresponding increase in the variability of $T_{EC\text{max}}$. In fact, for the case of the low latitude station of Ramey, if anything, the mean variability is somewhat greater for the low solar activity. During the solar maximum, the mean variability at the low latitude is significantly lower compared to mid and high latitudes. For solar minimum, however, the fluctuations of $T_{EC\text{max}}$ seem to be of the same order of magnitude. During both solar phases, the variations presented for $T_{EC\text{max}}$ variability are found to be similar for the three stations and the resemblance seems to be particularly striking for mid and high latitudes.

The pattern of percentage variations of $T_{EC\text{max}}$ at the three stations with those of $S10.7$ during both solar phases are subjected to Fourier analysis to obtain the power spectra. The spectra are given in figures 4.3a and 4.3b respectively for solar maximum and minimum. During the solar maximum year the spectrum of $S10.7$ has two components of nearly equal power, the periods of which (36 and 26 days) are within the range of periods of differential rotation of the Sun. But during the solar minimum year the spectrum of
Figure 4.3a. Power spectra of $\Delta S10.7$ (%) and $\Delta TEC_{\text{max}}$ (%) corresponding to the figure 4.2a.
Figure 4.3b. Power spectra of $\Delta S_{10.7}$ (%) and $\Delta TEC_{max}$ (%) corresponding to the figure 4.2b.
S10.7 is characterised by only one component and its period (27 days) corresponds to the period of rotation of the equatorial region of the Sun. However, the corresponding spectral plots for TECmax during both solar maximum and minimum phases show significant components other than seen in S10.7. While the significant components are confined to the same spectral width for the three latitudes during solar maximum, there is evidence of narrowing of the spectra with increasing latitude during solar minimum.

Discussion of the results: The results of the diurnal, seasonal and solar activity variations of the day-to-day variability are in general agreement with the earlier results reported for low (eg., Rastogi and Alex, 1987; Modi and Iyer, 1988), mid (eg., Klobuchar, 1983; Soicher and Gorman, 1985; Soicher et al., 1984; Soicher, 1988) and high latitudes (eg., Soicher, 1986; Craven et al., 1988). All the investigators obtained a higher mean nighttime variability compared to the corresponding mean daytime variability which seldom exceeds a value of 30%. The higher variability during nighttime suggests that there is an irreducible ionospheric variability which upon normalization by mean TEC will be always less by day than by night. The similarities observed in the day-to-day variability curves
of TECmax for the three latitudes during both the solar phases are in agreement with the earlier spatial correlation studies of TEC variability (Da Rosa, 1974; Kane, 1975, 1982). Most of the earlier investigators, however, have not clearly brought out the types of seasonal and solar activity dependence of the day-to-day variability in TEC presented in this study.

The various characteristics of the day-to-day variability in TEC for low latitudes have been discussed at length in chapter II, section 3. Rao et al. (1970) interpreted the day to day variability at mid-latitudes due to changes in local atmospheric conditions in the thermosphere. Kane (1975) suggested the day-to-day variability at middle latitudes due to erratic equatorward neutral winds that originate in polar regions intermittently, even under quiet conditions, creating convective cells that result in ionospheric irregularities of scale length of about 3000 km and wander slowly about the globe. The influence of solar and geomagnetic activities on the day-to-day variability in TEC for mid-latitudes have also been discussed by different authors (eg., Jain et al., 1978; Kane, 1980, 1981; Dabas et al., 1984).
4.3.2. TEC response to geomagnetic storms at low, mid and high latitudes

In this sub-section initially the storm-time TEC variations for each of the two sudden commencement (SC) storms on March 5 and on May 8, 1981 are studied separately for the three stations. Following this, a comparative discussion of the storm-period responses for the two storms at the three stations together with the possible mechanisms for the observed positive and negative responses are also presented. The deviations in TEC on an hourly basis were obtained by subtracting the seven day average values prior to the storm commencement from the values of TEC during the storm-period. The deviations are considered significant only when they exceed the normal day-to-day variability of TEC. Dst is considered to represent the intensity of the storm. Figures 4.4a and 4.4b give the Dst variations together with the storm-time percent ΔTEC variations at the three latitudes for the two storms of 5th March and 8th May 1981 respectively.

Storm on 5th March 1981 (SC occurring around local midnight): This particular storm is an intense one. As shown in figure 4.4a, following SC at 0532 UT (0052 LT) on March 5, 1981, Dst reached a negative maximum of 220 nT at 1700 UT.
Figure 4.4a. Dst variations together with the average storm-time deviations in TEC (% TEC) for the three stations corresponding to the nighttime storm of March 5 - 8, 1981.
As seen from the figure the storm-time $\Delta$TEC behaviour at the low latitude is distinctly different from that at higher latitudes. The storm-time variations of TEC at the low latitude station of Ramey exhibits an oscillatory pattern which is positive during the main phase of the storm with a maximum deviation of 70% occurring at 1000 UT on the 5th March. Apart from the initial positive phase of short duration seen at Goose Bay, the responses at the mid and high latitudes exhibit negative phases which last throughout the main phase and early part of the recovery phase. The response is found to be somewhat stronger at the sub-auroral station of Goose Bay compared to the low and mid-latitudes. The maximum deviations of -55% at Sagamore Hill and -75% at Goose Bay occur respectively at 1500 UT and 2300 UT on 5th March 1981. The effect of the substorm on 7th March is found to be significant only at Goose Bay where it produces an initial positive phase followed by negative response with a maximum of -55%.

Storm on 8th May 1981 (SC occurring around local noon): Two moderately intense storms occurred during the period of May 8-12, 1981, one immediately after the other. Unlike the storm on 5th March 1981 (discussed above), these two storms have their SCs occurring during daytime and main phase maxima occurring during nighttime. From the figure 4.4b it
Figure 4.4b. Same as figure 4.4a, but corresponds to the daytime storms of May 8-12, 1981
can be seen that following the sudden commencement at 1750 UT (1310 LT) on 8th May 1981, Dst remained positive for about 8 hours and then reached a negative maximum of -121 nT at 0700 UT on 9th May. During the recovery phase another storm occurred with SC at 2208 UT (1728 LT) on 10th May with a main phase maximum of -140 nT occurring at 0300 UT on 11th May. As seen from the ΔTEC variations, the storm-time TEC response at the low latitude is quite different from that at higher latitudes, same as has been for the nighttime storm. At the low latitude station of Ramey ΔTEC variations during the storm period are stronger and positive, though the two storms occurred during this period are less intense compared to the storm on 5th March 1981. The positive maxima of ΔTEC are found to occur around the same time as the main phase maxima of the two storms. The maximum ΔTEC variations associated with the two storms are 145% and 125% respectively. The TEC response is quite small and oscillatory as the second storm recovers to normal. The storm-time responses at mid and high latitudes are remarkably similar. The responses are found to be predominantly negative with sharp positive responses associated with the main phase maxima of the two storms. The mid and high latitude responses are much weaker compared to the low latitude response.
A comparison of the results presented above for the nighttime and daytime storms during the equinoctial period brings out the following points.

1. The general characteristic of TEC response is such that it is mostly positive for the low latitude and negative for the mid and high latitudes.

2. While the positive response drops rapidly from low to high latitudes for the daytime storms, no such systematic latitudinal dependence is noted for the nighttime storm.

3. The TEC responses to the daytime storms at the low latitude are much stronger compared to that of the nighttime storm. Such a strong difference between the daytime and nighttime storms has not been noted in the negative TEC responses observed at mid and high latitudes.

4. For the low latitude the strength of ΔTEC variations seems to be controlled by the time of occurrence of SC than by the intensity of the storm.

Discussion of the results: Earlier to this there are only few studies on the multistation observations of the storm-time TEC variations during equinox season. Klobuchar et al. (1971) studied the TEC variations during the daytime storm on 8th March 1970 for 10 stations including the same mid-
latitude and close by low latitude station as of the present study. The results reported by them are grossly in agreement with the present observations pertaining to the daytime storms during May 8-12, 1981. Lanzerotti et al. (1975) studied the storm-time TEC responses at the above two stations for 12 geomagnetic storms including 2 storms occurring in March 1970. Of these two, one is the earlier mentioned daytime storm of 8th March and the other is a nighttime storm on 31st March. This nighttime storm exhibited positive and negative responses respectively at the low and mid-latitudes, in agreement with the present observations for the nighttime storm of March 5-8, 1981. The storm-time TEC response observed at the mid-latitude during the daytime storms of May 8-12, 1981 is also found to be consistent with the average TEC response for 28 storms reported for the same station by Mendillo et al. (1972).

The possible processes which might contribute to the magnetic storm associated ionospheric variations are: (1) electrodynamic drifts associated with the storm-time electric field. (2) enhanced thermospheric circulation generated by the auroral zone heating during magnetic storms (3) compression of the plasmasphere by enhanced solar wind (4) changes in atmospheric composition due to enhanced thermospheric circulation. Since ionospheric responses to geomagnetic storms are in the form of both positive and
negative changes, the above processes may be classified according to their effects in producing either a positive or negative response.

It has been generally accepted that the negative phase of an ionospheric storm is associated with the composition changes of the neutral gas as direct evidence has been provided for this by satellite on board neutral gas mass spectrometer measurements (eg., Prolss, 1982). A large scale thermospheric circulation driven by high latitude heating associated with the geomagnetic storm results in a net transport of atomic oxygen (and other light constituents) equatorward from high and mid latitudes decreasing the ratios of O/N\textsubscript{2} and O/O\textsubscript{2} (eg., Rishbeth, 1975). Depending upon the extent of the circulation the ratios may decrease even at low latitudes (Prolss, 1987). Lower O/O\textsubscript{2} and O/N\textsubscript{2} ratios result in a higher recombination rate for atomic oxygen ions at all levels and hence lower the ionization density values and TEC.

Another mechanism operating at mid-latitude for producing a negative response is the compression of the plasmasphere by enhanced solar wind during geomagnetic storms. Under quiet geomagnetic conditions, the earth's plasmasphere extends to L = 4-5. During geomagnetic storms, the plasmasphere gets compressed causing the mid-latitude trough to move to lower latitudes. This could result in a
significant drop in TEC at mid-latitudes. Mendillo et al. (1974) observed five cases of large and rapid drops in TEC at Hamilton near the sunset period and are interpreted as being due to the contraction of L values less than 3.

The compression of the magnetosphere during a geomagnetic storm could also lead to a positive ionospheric response at latitudes where the trough effect discussed above is not an important factor. From simultaneous TEC and magnetic field measurements Mendillo et al. (1970) suggested that the magnetospheric compression causes the plasma to be dumped into the topside F region resulting in the observed enhancements in TEC. A decrease in the plasmaspheric content to follow an increase in the ionospheric content during geomagnetic storms has been observed by Kersley and Klobuchar (1980).

Another mechanism important for the positive responses is the vertical lifting of the ionospheric plasma to higher altitudes where the recombination losses are lower. The vertical lifting of the ionosphere occurs due to the equatorward neutral wind associated with storm-time circulation (eg., Jones and Rishbeth, 1971; Rishbeth et al., 1987) and the eastward electric field (eg., Tanaka and Hirao, 1973; Fejer et al., 1979b). The neutral wind is more effective at high latitudes and electric field at low latitudes.
The observed ionospheric response to geomagnetic storms is the relative play of the above processes as a function of time. It is possible to explain qualitatively certain gross features of the observed response by viewing the processes independent of each other as has been done above. An elaborate theoretical model taking into consideration all the processes together would be required to account for the observed features in detail.

4.4. Conclusions

The present investigation on the latitudinal dependence of day-to-day variability and storm-time response of TEC leads to the following important conclusions.

4.4.1. Conclusions on day-to-day variability in TEC

1. During both solar minimum and maximum phases, the diurnal behaviour of the day-to-day variability in TEC is seen to be generally consistent. The variability parameter, in general, assumes the highest values during the pre-sunrise and post-sunset hours.

2. During the solar maximum year, the latitudinal dependence of the mean day-to-day variability is found to be appreciable for both day and night during equinox
and mainly during the nighttime of winter and for neither daytime nor nighttime during summer.

3. During the solar minimum, the seasonal and latitudinal variations of the mean variability are seen to be significant only for the nighttime.

4. The mean S10.7 variability is found to increase by a factor of about 2 as the solar phase changes from minimum to maximum, but there is no corresponding increase in the variability of TECmax.

5. During both solar phases the variations presented for TECmax variability are found to be similar for the three latitudes, and the resemblance seems to be particularly striking for mid and high latitudes.

6. The spectra of percentage variations in TECmax during both solar maximum and minimum phases show significant components other than seen S10.7. While the significant components are confined to the same spectral width for the three latitudes during solar maximum, there is evidence of narrowing of the spectra with increasing latitude during solar minimum.

4.4.2. Conclusions on storm-time response of TEC

1. The general characteristic of TEC response is such that it is mostly positive for the low latitude and negative
for the mid and high latitudes.

2. While the positive response drops rapidly from low to high latitudes for the daytime storms, no such systematic latitudinal dependence is noted for the nighttime storm.

3. The TEC responses to the daytime storms at the low latitude are much stronger compared to the nighttime storm. Such a strong difference between the daytime and nighttime storms has not been noted in the negative TEC responses observed at mid and high latitudes.

4. For the low latitude the strength of $\Delta$TEC variations seems to be controlled more by the time of occurrence of SC than by the intensity of the storm.