Low latitude topside ionospheric response to magnetic storms from in-situ satellite measurements

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Abstract. During the last 40 years or so a number of satellites have been launched to measure various characteristics of the ionospheric charged particle population. To study ionospheric departures during magnetic storms it is necessary to have the satellite in orbit for a considerable number of years and this is possible only if the orbit is in the topside ionosphere and thus most of the good data sets for this topic relate to topside ionosphere only. Starting from the earliest satellite TIROS VII which gave global coverage of electron density at 640 km to the more recent SROSS C2 satellite also around the same altitude several excellent results have been published. While it is true that storms of similar magnitude produce widely varying responses depending on latitude, local time and season, there are certain consistent features which require special attention. Some of the salient features for low latitudes include simultaneous enhancements in electron density (N_e) and electron temperatures (T_e) particularly during nighttime. This result has been observed consistently from several satellite measurements and has been subjected to critical interpretation. Possible explanation could be precipitation of neutral particles through charge exchange processes of ring current ions. Another outstanding feature noticed is the daytime T_e enhancement around 600 km in low latitudes which has been partly attributed to a bottleneck in cooling due to increased neutral densities.

Index Terms. Electron density and temperature variations, low latitude, magnetic storm, topside ionosphere.

1. Introduction

Geomagnetic storms and auroral phenomena represent the two most spectacular consequences of solar-terrestrial interactions that have engaged the scientists for several decades now. While ground-based observations from ionosondes and incoherent radars have thrown light on the general morphology of the ionospheric behaviour during storms, it was only after the advent of certain dedicated satellites that ionospheric responses to magnetic storms could be studied quantitatively. The earliest results of this nature were reported by Willmore and Henderson (1965) using Ariel satellites and by Reddy et al. (1967, 1969) from TIROS VII and Explorer 22 satellites. The low latitude ionosphere has but received only scant attention partly because the results of storm response as viewed from ground based observations was spectacular only in mid and high latitudes. However, it is relevant to mention here that occasionally the storm time departures may not be so benign even at equatorial and low latitudes (Lakshmi et al., 1997). Also, because of the modification of the equatorial electrojet during magnetic storms the equatorial anomaly peaks in the F region electron densities undergo steep temporal and spatial changes that cause severe problems in HF communications as well as in GPS dependent systems. As storm response studies require some degree of longevity for the satellite missions, it was possible to study only the topside ionosphere with in situ measurements.

By way of illustration certain representative storms were taken for which satellite data of electron density (N_e) and electron temperature (T_e) is available right from the year, 1963 (TIROS VII) and upto 1998 (SROSS C2) to study salient features of low latitude ionospheric response to magnetic storms.

2. Data

Early reports on global behaviour of topside ionosphere during magnetic storms has come primarily from insitu measurements of ionospheric parameters from TIROS VII and Explorer 22 satellites (Reddy et al., 1967; Reddy et al., 1969; and Lakshmi et al., 1970). TIROS VII was launched in June 1963 with a perigee and apogee altitudes of 625 km and 660 km respectively and an inclination of 58º. It carried an electrostatic Langmuir probe of cylindrical type design for insitu measurements of both electron densities and temperatures; however it was found that electron temperature data lacked the required resolution and was not useful. Explorer 22 satellite was launched in October, 1964 into an 80º inclination direct orbit in a nearly circular orbit at an altitude of 1000 km. This satellite also carried two electrostatic probes for insitu measurements of electron densities and temperatures at 1000 km.

These early satellite missions were later followed by several missions such as OGO, ISIS, ISS, Dynamic Explorer, Atmospheric Explorer series with on-board ionospheric experiments to measure topside ionospheric parameters globally, but availability of high resolution insitu measurements over equatorial and low latitudes was rather limited. However, the Japanese HINOTORI satellite launched in February 1981 with an inclination of 31º carrying on-board two plasma probes one for electron density and another for electron temperature has provided excellent high resolution data suitable to study ionospheric behaviour both during quiet and disturbed periods over low latitudes. The perigee and apogee of the satellite were 576 and 643 respectively and the latitude coverage was from 30 S to 30 N (Oya and Morika, 1975).

The Indian satellite SROSS C2 was launched in May 1994 with an inclination of 46º and provided data sets to study ionospheric behaviour exclusively over Indian longitudes. The perigee and apogee altitudes were around 430 km and 630 km respectively. It carried on-board ion and electron Retarding Potential Analyzer (RPA) payloads and a spherical Langmuir probe. SROSS C2 provided information on ion densities, ion temperatures and ion composition. The spatial resolution for plasma density is 170 m and for temperature measurements it is 10 km. The latitude coverage of this satellite was from 10 S to 30 N (geomagnetic). One major limitation of SROSS C2 data is local time coverage with the data coming from only two passes per day, one during day time and another during the night (Garg and Das, 1995).

In this paper a comparative study of ionospheric responses to magnetic storms over low latitudes has been made using data from different satellites namely TIROS VII, Explorer 22, HINOTORI and SROSS C2. Magnetic storm events chosen for this study pertain to different solar epochs, seasons and are of different severity. The details of these magnetic events are given in later sections where the results are discussed.

3. Topside ionospheric responses to magnetic storms

i) Early Results from TIROS VII and Explorer 22 satellite measurements.

Reddy et al. (1967) reported for the first time from insitu satellite measurements the global behaviour of topside ionosphere during magnetically disturbed periods using TIROS VII data. Three specific disturbed events during 4 to 9 July 1963 were chosen for their study. Fig.1 presents relative enhancements in N_e over the background quiet time separately for these three magnetically disturbed events as observed from TIROS VII for daytime (0700 to 1100 LT). The disturbed values $N_e(d)$ correspond to the most disturbed pass and quiet values $N_e(Q)$ are averaged values for quiet time. As we are essentially discussing ionospheric responses over equatorial and low latitudes ($\pm$ 30^o), our observations from the figure will be restricted to these latitudes. It is obvious from the figure that disturbed-time N_e variations around equatorial latitudes are only marginal and a modest depression in ionization can occur around the equator (±10^o) especially under severely disturbed conditions during day time (Event 2 with a_p 67). However, beyond 10^o a very substantial increase in N_e can be seen from the figure.

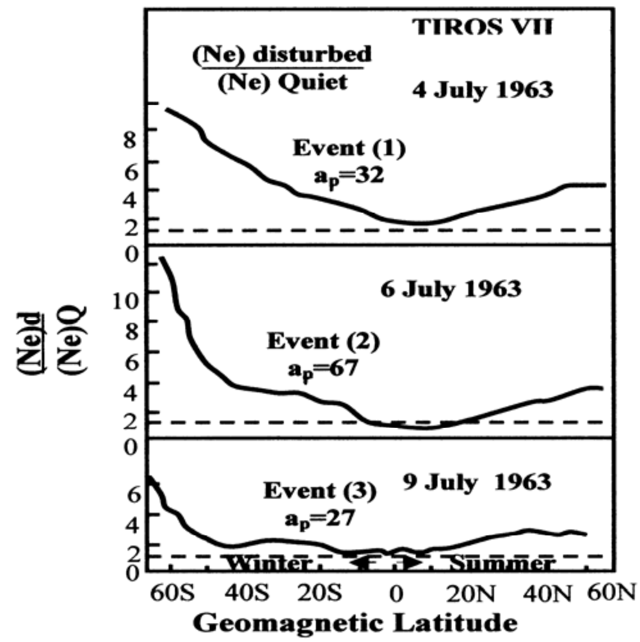

Fig. 1. The relative enhancements in N_e over the background quiet time distribution during day time for the three events (after Reddy et al., 1967).

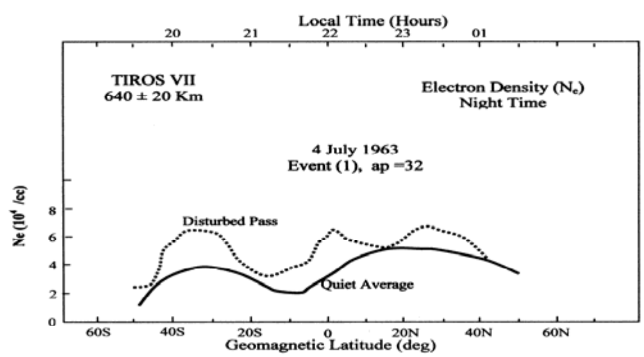

Fig. 2. Shows latitudinal variation of N_e during night time for Event 1 and also quiet time average (after Reddy et al., 1967).

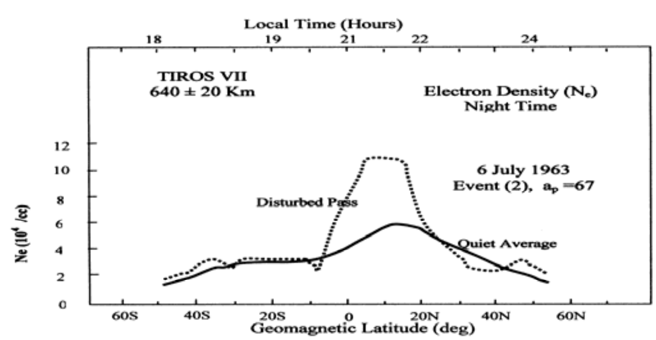

Fig. 3. Shows latitudinal variation of N_e during night time for Event 2 and also quiet time average (after Reddy et al., 1967).

The nighttime behaviour at 640 km during the disturbed event 1 and event 2 considered for daytime study is presented in Figs. 2 and 3 respectively. The most important feature to be noticed here is the large N_e enhancements during nighttime around equator, the increase being spectacularly large by almost 100% in case of Event 2 with maximum a_p of 67. In fact, the nighttime data for disturbed periods shown in these figures belong to the same pass which is a continuation of the most disturbed dayside pass.

Reddy et al. (1969) studied simultaneous variations in N_e and T_e during magnetic storms using Explorer 22 measurements for daytime. Figs. 4 and 5 show latitudinal variation in N_e and T_e respectively for daytime (1500 LT) during a moderate storm that began with a SC at 0203 UT on 20 January 1966. Fig. 4 also shows a_p values for the storm period. The continuous curve represents pre-storm conditions and the dashed curve corresponds to the most disturbed conditions. While N_e shows a slight decrease around the equator during disturbed conditions (Fig. 4), T_e measurements made simultaneously show spectacularly large increases by as much as 600 K when compared to pre-storm conditions (Fig. 5). The nighttime behaviour of N_e and T_e during this storm was studied separately by Lakshmi et al. (1970). Figs. 6 and 7 show latitudinal variations in N_e and T_e respectively for nighttime (0300 LT) for 20 January 1966 storm. Large increases in N_e accompanied by significant increases in T_e (100 K to 200 K) seem to characterize the nighttime response to the storm.

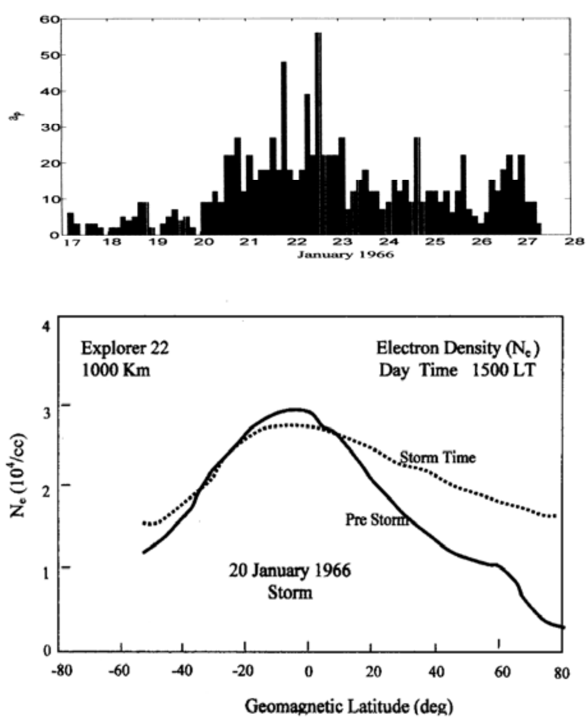

Fig. 4. Electron Density Vs Geomagnetic Latitude for 20 January 1966 storm for daytime. a_p values for the storm are also shown at the top (after Reddy et al. ,1969).

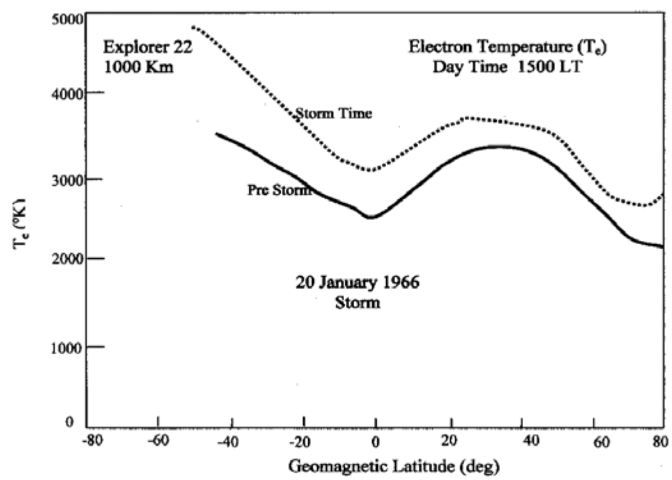

Fig. 5. Electron Temperature Vs Geomagnetic Latitude for 20 January 1966 storm for daytime. (after Reddy et al., 1969).

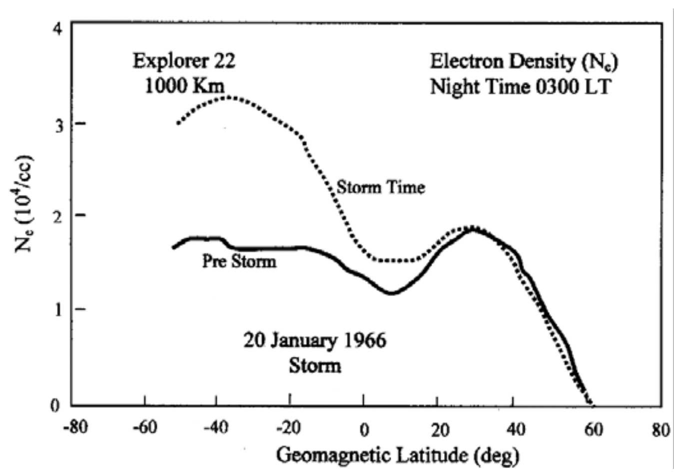

Fig. 6. Electron Density Vs Geomagnetic Latitude for 20 January 1966 storm for nighttime (after Lakshmi and Reddy, 1970).

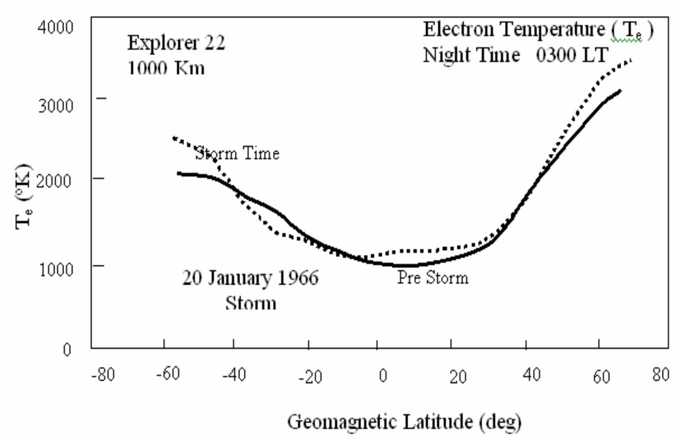

Fig. 7. Electron Temperature Vs Geomagnetic Latitude for 20 January 1966 storm for nighttime (after Lakshmi and Reddy, 1970).

A similar study was also conducted on N_e and T_e variations for the severe storm of 25 May 1966 which began with an SC at 2330 UT. The storm time variations for the above storm in both N_e and T_e during day time (1000 LT) are in contrast to those seen for 20 January 1966 storm. While electron densities show modest enhancements in the summer hemisphere for this 25 May storm the electron temperatures show slight decrease for the same latitudes (Figs. 8 and 9). Fig.8 also shows a_p values for the storm period. However, during nighttime variations in both N_e and T_e are similar to those for 20 January 1966 storm (Figs. 10 and 11). A point to be noticed regarding the 20 January 1966 storm and 25 May 1966 storm is while there is a good agreement in both N_e and T_e variations during nighttime, there is no such agreement especially in Te variations during daytime. It may also be mentioned here that in case of 20 January 1966 storm the local time is 1500 Hrs and it is 1000 Hrs for the 25 May 1966 storm.

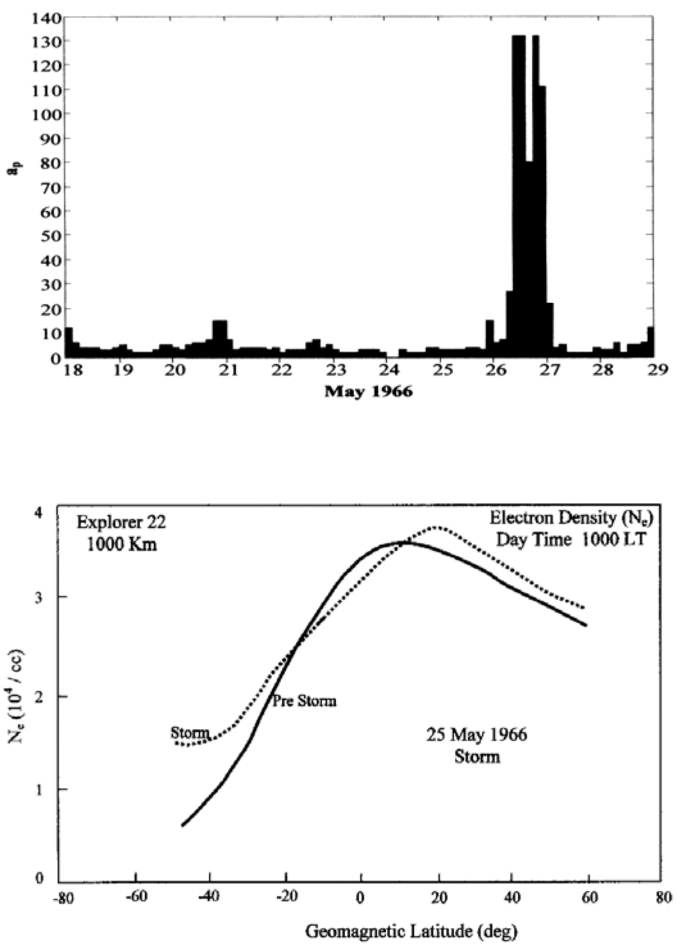

Fig. 8. Electron Density Vs Geomagnetic Latitude for 25 May 1966 storm for day time. a_p values are shown. (after Reddy et al., 1969).

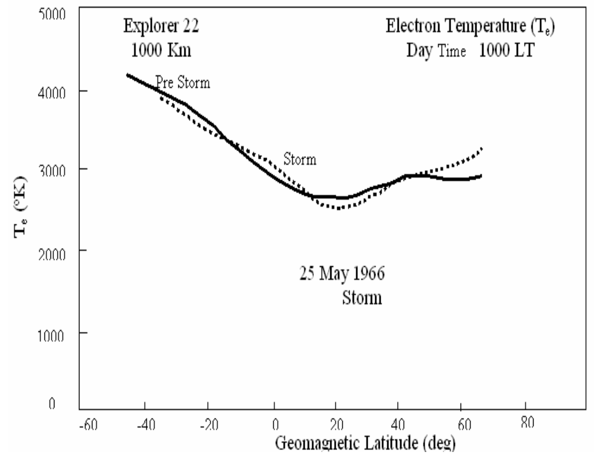

Fig. 9. Electron Temperature Vs Geomagnetic Latitude for 25 May 1966 storm for day time (after Reddy et al., 1969).

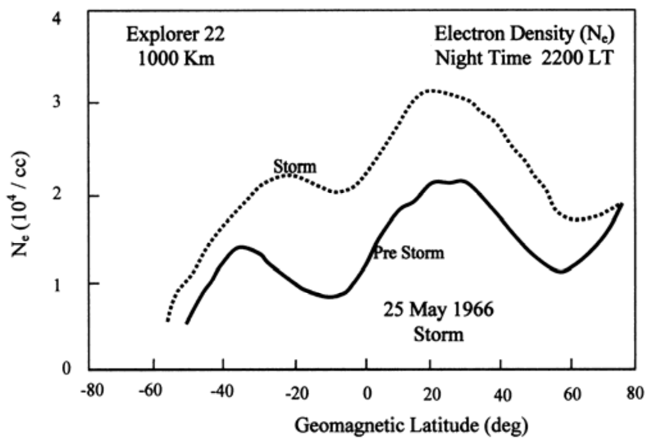

Fig. 10. Electron Density Vs Geomagnetic Latitude for 25 May 1966 storm for nighttime (after Lakshmi and Reddy, 1970).

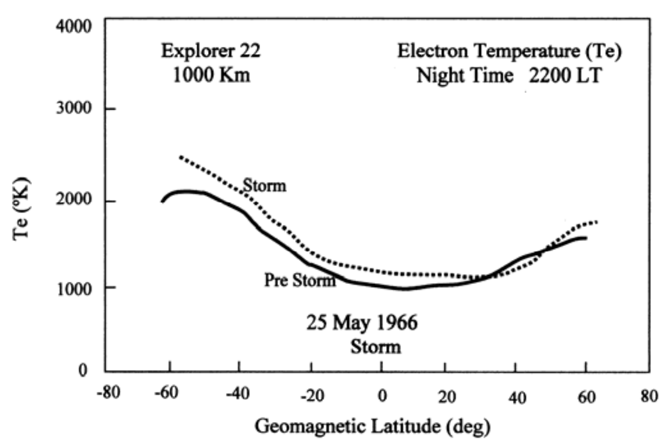

Fig. 11. Electron Temperature Vs Geomagnetic Latitude for 25 May 1966 storm for nighttime (after Lakshmi and Reddy, 1970).

ii) Results from HINOTORI observations

HINOTORI satellite launched in near circular orbit in February 1981 at the height of 600 km with an orbital inclination of 31º provided excellent high resolution data until July 1982 in the latitude range of 30 S to 30 N. Recently, Oyama et al. (2005) published for the first time results on low latitude ionospheric responses to magnetic storms at 600 km using HINOTORI data. They studied in detail N_e and T_e variations during the moderately severe storm of 1 March 1982 with SC at 1138 UT. Fig.12 shows data from HINOTORI (pass no. 5578, 5589, 5590, 5591 and 5605) for the period 1 to 6 May 1982. The black lines in the figure represent average quiet time conditions and the red lines show the values during a particular pass. The Dst variations for the storm period are also shown at the top of the figure. The most important results of their study as can be seen from pass nos. 5589 and 5590 are large storm time enhancements in T_e during 0800 to 1200 LT in the low latitude region with N_e showing little variation with respect to quiet time values. Another important observation is regarding nighttime behaviour where large storm time increases in N_e were seen during (2000 to 0600 LT) accompanied by significant increases in T_e by 200 K to 300 K as compared to quiet time values. Oyama et al. (2005) also analyzed T_e data for a large number of storms and have shown that the nocturnal T_e enhancements are well correlated with magnitudes of storm intensities.

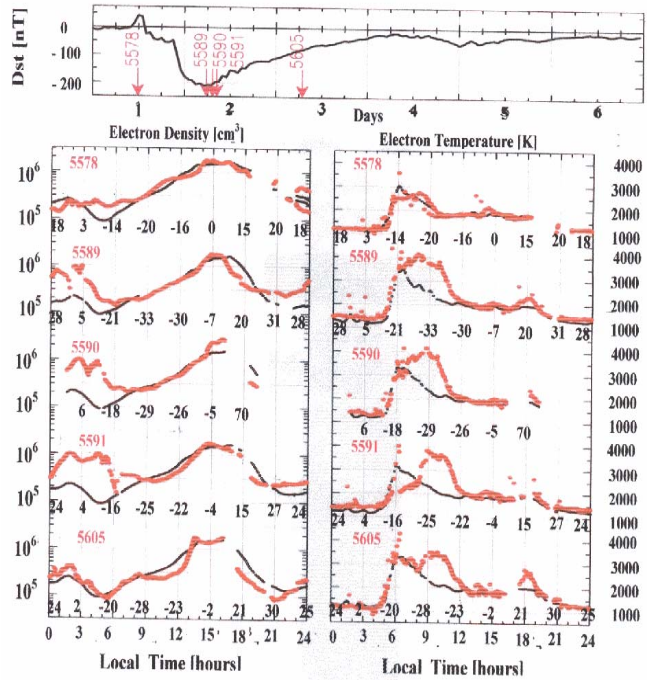

Fig. 12. Shows observed Electron density and Electron temperature values (red lines) for HINOTORI passes 5578, 5589, 5590, 5591 and 5605 during 1-6 March 1982 along with average quiet time values (black lines). Geomagnetic latitude is also shown separately for each of the passes in the figure. Dst variation for the same period is shown in the top panel with pass positions marked on time axis (after Oyama et al., 2005).

iii) SROSS C2 results

In the light of above mentioned results the ion (electron) density (N_i) and electron temperature (T_e) data obtained from SROSS C2 satellite during 1 to 5 May 1998 over Indian longitudes has been analyzed to study the storm time variation in N_i and T_e. This period is marked by two sudden commencement storms, the first one beginning on 1 May 1998 at 2156 UT and the second at 1744 UT on 3 May 1998 when the earlier storm was still in the recovery phase. Fig.13 shows the Dst values for the period 1 to 5 May 1998. Fig.14a shows latitudinal plots of ion densities (O^+) separately for each day for the period 1 to 5 May 1998 for the daytime (1300 to 1500 LT). The latitudinal density variation for 1 May 1998 here represents pre-storm quiet conditions. While latitudinal plots for 2 and 3 May 1998 correspond to the main phase and recovery phase of 1 May storm respectively. The plots for 4 and 5 May correspond to the recovery phase of the severe storm of 3 May 1998. The main phase of 3 May 1998 storm was of very short duration and no satellite pass was available during that period. From a comparison of the data for 2, 3 and 4 May with pre- storm data of 1 May it is obvious that there is a decrease in plasma densities during storm days, the decrease being very marked beyond 15 N (3 May).

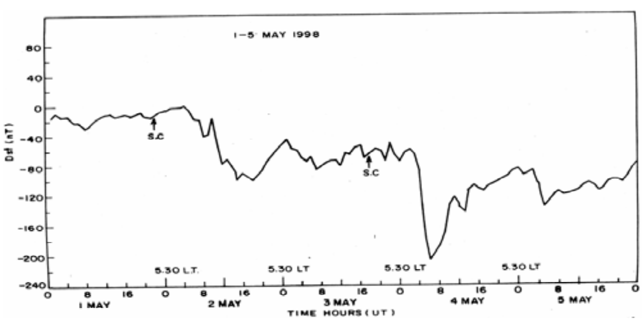

Fig. 13. Shows Dst values for 1-5 May 1998 a period marked by two SC magnetic storms.

Fig. 14b shows latitudinal variations of T_e (1300 to 1500 LT). It is obvious that electron temperature in general show increases during disturbed days as compared to pre- storm (1 May) values by 300 K to 400 K in 0 to 10º latitude range. An interesting feature however is the spectacular increase in T_e seen on 3 May 1998 beyond 20 N latitude the increase being by almost 1500 K. This steep increase in electron temperature is associated with a similar steep decrease in electron densities (Fig. 14a) during day time and it can be due to decreased collisional cooling. The inverse relationship between plasma densities and temperatures is well known (Brace et al., 1969). It appears T_e values on 5 May 1998 are approaching the pre-storm values as the storm is recovering.

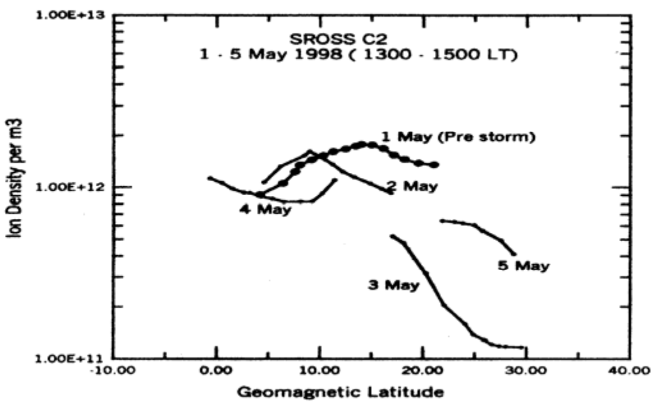

Fig. 14a. Latitudinal variation of ion density (O^+) for daytime (1300 to 1500 LT) during 1–5 May 1998.

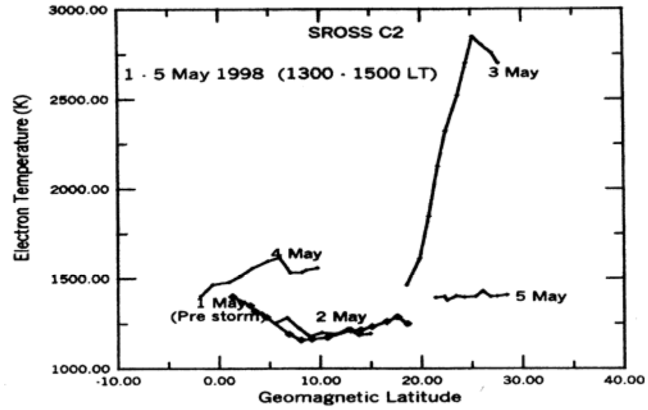

Fig. 14b. Latitudinal variation of electron temperature (T_e) for daytime (1300 to 1500 LT) during 1–5 May1998.

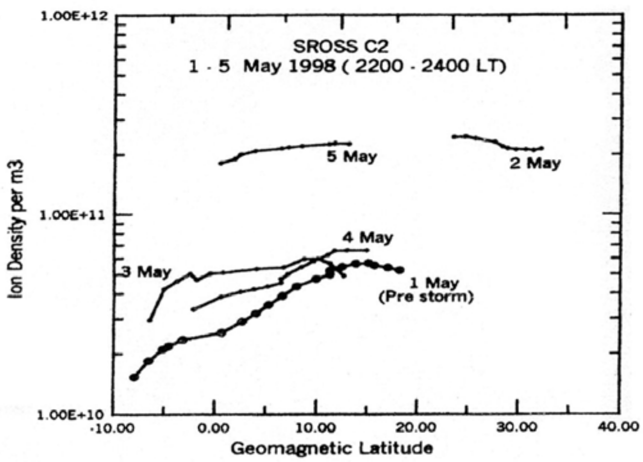

Fig. 15a. Latitudinal variation of ion density (O^+) for nighttime (2200 to 2400 LT) during 1–5 May 1998.

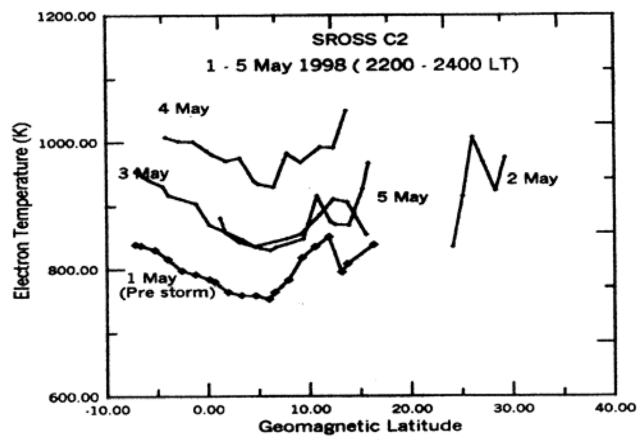

Fig. 15b. Latitudinal variation of electron temperature (T_e) for nighttime (2200 to 2400 LT) during 1-5 May 1998.

Figs.15a and 15b show N_i and T_e values respectively for nighttime (2200 to 2400 LT). It can be seen from these figures that both N_i and T_e increase during storm days as compared to quiet time in the latitude range of 5 S to 20 N. The T_e increases are in the range of 100 K to 200 K during disturbed nights. The 200 K increase occurred on the night of 4 May (Fig. 15b). It is interesting to note that 4 May is characterized by a modest increase in ion (electron) density with a very significant increase in electron temperature while for May 5, the increase in densities is spectacular accompanied by a modest increase in temperatures. This relationship is to be expected from energy considerations, as great increases in both densities and temperatures will imply an unrealistic increase in energy.

Several important and consistent features can be noted from the present study on storm time variations in electron densities and electron temperatures at equatorial and low latitudes and they are summarized below.

1) Nighttime behavior during storms is characterized in general by large increases in electron densities simultaneous with significant increases of 200 K to 300 K in electron temperatures during 2000 to 0600 LT. This feature has been observed consistently from Explorer 22 data at 1000 km, HINOTORI and SROSS C2 data at 600 km, which provided simultaneous measurements on plasma densities and temperatures. These T_e increases are found to be higher during main phase of the storm when magnetic activity is maximum. Electron density enhancements during nighttime are also seen from TIROS VII satellite data. This nighttime feature has been observed during storms belonging to different seasons and severity.

2) During daytime N_e variations in topside ionosphere are only marginal in low latitudes during storms but can decrease significantly in case of severe storms. This is apparent from TIROS VII (Event 2), HINOTORI and SROSS C2 data. Explorer 22 measurements during storms at 1000 km show both increases and decreases in electron densities.

3) Daytime electron temperatures exhibit large increases during storms. However these increases in T_e seem to be dependent on local time (Explorer 22 and HINOTORI data).

4. Discussion

The ionospheric responses to magnetic storms are governed by a number of physical processes involving chemical, kinetic and electrodynamical changes. Ionospheric storms are indeed intriguing because ionospheric responses vary from storm to storm and also one needs to invoke different sets of mechanisms to explain the changes seen at different latitudes during the same storm. Electrodynamical drifts, meridianal winds, chemical compositional changes, rapid changes in atmospheric heating and thermal expansion are some of the mechanisms that have been invoked by the various researchers to explain the storm time behaviour of F region ionosphere both in bottom and top sides (Abdu et al., 1997; Fejer et al., 1995 ; Fuller-Rowell et al., 2002; Lakshmi et al., 1997; Oyama et al., 2005; Reddy et al., 1967; Rishbeth, 1975).

At equatorial and low latitudes electrodynamical drifts (E×B drifts) play a major role in determining the distribution of F region ionization. Equatorial latitudes are unique due to the horizontal NS geomagnetic field, which in combination with the global east-west electric fields produce vertical plasma drifts. The E×B drifts are responsible for vertical transport of ionization at the geomagnetic equator with subsequent transport to latitudes upto 20º on either side along the geomagnetic field lines. During daytime when the electric field is eastward, the vertical drift is upward and the reverse is true for nighttime. The westward electric field during quiet nights causes downward drift bringing electrons to lower heights where they are lost at a faster rate. However, disturbance dynamo electric fields in general have opposite polarity to that of the quiet time dynamo electric fields and they become active over equatorial/low latitudes within 4 to 8 hours from the onset of a magnetic disturbance (Blanc and Richmond, 1980). The large increase in upward drift during post midnight/pre sunrise hours is a well-identified manifestation of a disturbance dynamo eastward electric field (Abdu, 1997; Abdu et al., 1997; Abdu et al., 2003; Fejer and Scherliess, 1995). Nocturnal enhancements in N_e seen during storms in the present study can be attributed to these storm-time electrodynamical drifts. In addition, the intensified equatorward thermospheric winds induced by energy input in the auroral region during storms can also play a major role. There is increasing evidence in recent years to show the importance of storm time equatorward winds in contributing to the observed ionization changes at equatorial and low latitudes (Fejer et al., 2000; Fesen et al., 1989; Fuller-Rowell et al., 2002). Fesen et al. (1989) have shown that thermospheric winds can blow across the magnetic equator transporting plasma along nearly horizontal field lines.

It is seen that the nighttime electron temperatures during disturbed days during main phase are significantly higher than quiet time values by 100 K to 300 K and these temperature enhancements are also associated with large enhancements in electron densities. This represents a significant heat input to low latitude ionosphere. Likely causes are (a) the strong summer time cross equatorial winds blowing towards winter hemisphere should bring in hot plasma from mid latitudes. It is established that a strong plasma temperature gradient exists in the topside ionosphere from equator to mid latitudes. (b) Energetic neutrals (hydrogen) which are produced through charge exchange with ring current protons can precipitate into mid and low latitude regions and the energy dissipation could be significant at these latitudes (Rohrbaugh et al., 1983). According to calculations by Tinsley (1979) the latitude variation of neutral particle flux maximizes at mid latitudes but with significant amount of energy input into the low latitudes down to dip equator. Tinsley et al. (1988) reported temperature increases by about 200 K from 630 nm airglow emission as measured by Fabry-Perot interferometer over Peru. It may be mentioned here that increase in neutral temperatures during storms by itself could be a significant contributor to enhanced nocturnal T_e.

The rather large enhancements in daytime T_e with almost no change in N_e as can be seen from Fig. 12 from HINOTORI data during storms is an important feature that deserves special attention. It has been discussed in detail by Oyama et al. (2005), who also brought in a new argument that it may be due to a bottleneck in electron thermal conduction from 600 km altitude to lower levels. The electron thermal conductivity is sensitive to the ratio of plasma to neutral densities. During a storm, in response to neutral heating, neutral densities are enhanced even at equatorial latitudes. This in effect decreases the electron thermal conductivity and the rate at which heat is lost to lower altitudes, and hence results in an increase in T_e at 600 km. This argument is in addition to the increased Energetic Neutral Atom (ENA) flux as a result of charge exchange with ring current ions. If these ring current ions have a pancake pitch angle distribution, then the bulk of precipitation will occur at low or equatorial latitudes (Kozyra and Magy, 1991).

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