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Effect of solar cycle on topside ion temperature measured by SROSS C2 and ROCSAT 1 over the Indian equatorial and low latitudes

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Abstract. The effect of solar activity on the diurnal, seasonal and latitudinal variations of ion temperature T_i and its relationship with corresponding ion density N_i over the Indian low and equatorial topside ionosphere within 17.5° S to 22.5° N magnetic latitudes are being investigated, combining the data from SROSS C2 and ROCSAT 1 for the 9-year period from 1995 to 2003 during solar cycle 23. T_i varies between 800 K and 1100 K during nighttime and rises to peak values of ∼1800 K in the post sunrise hours. Daytime T_i varies from 1000 K to 1500 K. The time of occurrence, magnitude and duration of the morning enhancement show distinct seasonal bias. For example, in the June solstice, T_i increases to ∼1650 K at ∼06:00 h and exhibits a daytime plateau till 17:00 LT. In the equinoxes, enhanced ion temperature is observed for a longer duration in the morning. There is also a latitudinal asymmetry in the ion temperature distribution. In the equinoxes, the daytime T_i is higher at off equatorial latitudes and lower over the Equator, while in the solstices, T_i exhibits a north–south gradient during daytime. Nighttime T_i is found to be higher over the Equator. Daytime ion temperature exhibits insignificant positive correlation with $F_{10.7}$ cm solar flux, while nighttime ion temperature decreases with increase in solar flux. Daytime ion temperature and ion density are negatively correlated during solar minimum, while nighttime T_i does not exhibit any correlation. However, during high solar activity, significant positive correlation of T_i with N_i has been observed over the Equator, while at 10° S and 10° N temperature and density exhibit significant negative correlation. The neutral temperature T_n derived from the MSISE 90 model is found to be higher than measured T_i during nighttime, while daytime T_i is higher than model T_n.

Keywords. Ionosphere (Plasma temperature and density)

1 Introduction

In the ionospheric F-region, the photo electrons produced by the solar ionizing radiations are hotter than the neutral atoms. This results in intense heating of the sunlit upper ionosphere. The excess energy of the photoelectrons is gradually shared with the positive ions. Heat transfer to the neutrals is slow and less efficient. As a result of this redistribution, the plasma temperature is higher than that of the neutrals, and within the plasma the electrons are hotter than the ions. Both electron and ion temperature exhibit marked diurnal and altitude variations. These changes in temperature strongly influence the F-region plasma density distribution. Higher temperature results in greater scale height for the plasma, which spreads to higher altitudes where the loss rate is smaller and persists for longer duration (Hargreaves, 1995). At higher altitudes, the ionosphere is coupled to the protonosphere through the O^+–H^+ charge exchange reaction, which reverts during the evening to maintain the nighttime ionosphere. The electron–ion loss and transport processes are similarly affected by a series of cyclic chain reactions involving density, composition and temperature of all the ionospheric constituents. Normally the ion temperature is an intermediate between electron and neutral temperature. Study of the ion or electron temperature of the F-region thus helps understand the dynamics of the ionosphere thermosphere system.

Ion temperature studies of the F-region have been carried out using satellites, rockets and incoherent scatter radars. McClure et al. (1973) compared electron and ion temperature measurements of OGO 6 with those from incoherent scatter radars. Rishbeth et al. (1977) further studied the ion temperature measurements from OGO 6 satellite at equatorial and low latitudes. Schunk and Nagy (1978) had reviewed the local time, altitude and latitudinal variation of the electron and ion temperature in the F-region. Some interesting features of the low latitude ionosphere such as the morning and afternoon enhancement, the temperature and wind anomaly, latitudinal asymmetry, and short and long term periodicities have been observed and extensively studied (Brace and Theis, 1981; Oyama et al., 1996; Watanabe et al., 1995; Balan et al., 1997; Bhuyan et al., 2002a, b, 2004; Prabhakaran Nayar et al., 2004). Brace and Theis (1981) used Atmospheric Explorer C satellite data to derive a model of electron temperature and found low nighttime temperature followed by a morning peak, a daytime plateau and a secondary evening enhancement. Oyama et al. (1996) examined the seasonal, local time and longitude variation of electron temperature at 600 km in the low latitude region using Hinotori satellite data for high solar activity years of 1981–1982 and observed that T_e shows a steep rise in the morning, a daytime decrease and another increase around dusk. Significant seasonal and latitudinal/longitudinal asymmetries have been observed, particularly during the period of morning enhancement. The electron temperature, measured by the SROSS C2 satellite over the Indian sector during the low solar activity period of 1995–1996, varied from 800–900 K during nighttime, rose sharply to 3000 K and then fell to a daytime average of 1500 K (Bhuyan et al., 2002a). They also found T_i to be less than T_e in all seasons. Bhuyan et al. (2004) further examined the diurnal, seasonal and latitudinal variation of ion temperature at 500 km and reported latitudinal gradients in T_i during the period of morning and afternoon enhancement. Prabhakaran Nayar et al. (2004) using SROSS C2 data for the period 1995–2000 examined the periodicities in electron and ion temperature and found periodicities ranging from 14 days (short) to 1.3 years (long) in both T_e and T_i. Zhang and Holt (2004) have studied the climatology of plasma temperature and the relationship between T_e and N_e from the long term data base of the Millstone Hill radar. The daytime T_e in the F2 layer is found to increase with the increasing solar activity in summer and to decrease in winter. The inverse relationship between T_e and N_e prevails in summer and equinox but is not discernible in summer. The vertical temperature profiles (Fig. 2, Zhang and Holt, 2004) shows that between 500–600 km the ion temperature is higher at solar minimum than that at solar maximum, while the reverse is true for electron temperature. Further, at these altitudes, midday ion temperature is about 1000–1500 K less than the electron temperature.

However, long term study of the temporal and spatial variation of topside ion temperature over the Indian low and equatorial latitudes has not been attempted thus far to our knowledge. In this study, diurnal, seasonal, solar activity and latitudinal variations of ion temperature, and its relationship with corresponding ion density over the Indian low and equatorial topside ionosphere, are being investigated – combining the data from SROSS C2 and ROCSAT 1 for the 9 year period from 1995 to 2003 during solar cycle 23. The temperature of the neutral gas at the average height 550 km of the two satellites is derived from the Mass Spectrometer Incoherent Scatter (MSISE 90) model for the corresponding period and compared with the measured ion temperature.

2 Data

Ion temperature data from the Indian satellite SROSS C2 and Taiwanese satellite ROCSAT 1 are used for the present study, which covers the ascending and descending phase of the solar cycle 23. Simultaneous data from the two satellites are available for the high solar activity years 1999 and 2000. The combined data from the two satellites provide a unique opportunity to study the effect of solar activity on the diurnal, seasonal and latitudinal variation of ion temperature during solar cycle 23. Borgohain and Bhuyan (2010) have reported the diurnal, seasonal and latitudinal variation of O^+, H^+, He^+, O_2^+ ion densities for the 1995–2003 period over the Indian low and equatorial latitudes, combining measurements from the SROSS C2 and ROCSAT 1.

2.1 SROSS C2

The Indian satellite SROSS C2 was launched on 4 May 1994 into an orbit of 46° inclination and 930-km apogee with 430-km perigee. In July 1994, the orbit of the satellite was trimmed to 630 km by 430 km. Two Retarding Potential Analyzer (RPA) sensors were on board the satellite to measure electrons and ions separately. The electron and ion RPA sensors consist of four grids and a collector electrode, which are mechanically identical but provided with different grid voltages suitable for collection of ions and electrons. The collector current versus retarding bias voltage generate characteristic curves separately for electrons and ions, which are used to derive total ion density N_i, ion compositions, ion temperature T_i and electron temperature T_e (Garg et al., 2003). The maximum error in T_e and T_i measurement is $\pm 5\,\%$ within the limits 500 K to 5000 K. SROSS C2 RPA data are available from 1994–2001 within the latitude belt $\pm 34°$ and longitude belt 40–100° E at an average altitude 500 km. The standard deviation of the data from the mean used in this analysis varied from a minimum of 111 K to a maximum of 470 K considering all latitudes and local time. Details of the procedure for retrieval of ion temperature from the SROSS C2 RPA are given in Bhuyan et al. (2004).

2.2 ROCSAT-1

ROCSAT-1 had a circular orbit at a mean altitude of 600 km with an inclination of 35°. The Ionospheric Plasma and Electrodynamics Instrument (IPEI) on board ROCSAT-1 made in situ measurements of ion density, temperature, ion composition and drift velocity. The measurement started from 1 March 1999 and ended on 14 June 2004. Details of the IPEI are given in Yeh et al. (1999). The satellite took about 25 days

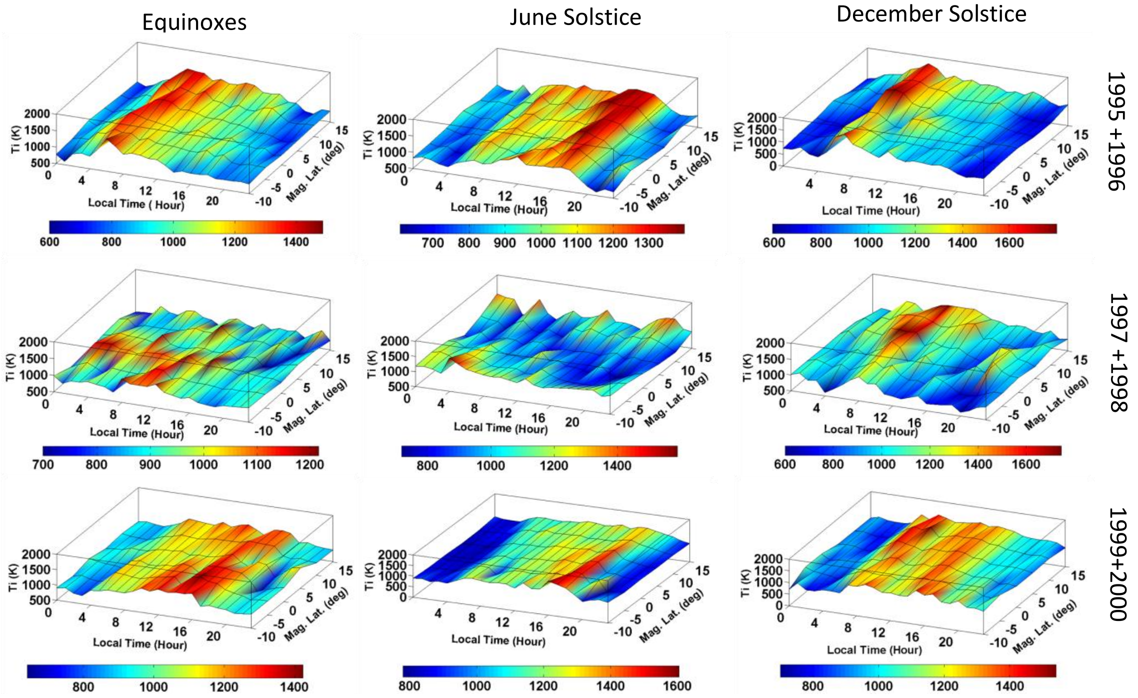

Fig. 1. Three-dimensional plots showing seasonal average ion temperature as a function of magnetic latitude and local time measured by SROCC C2 at 500 km altitude in equinox, June and December solstice (from left to right) for the low (1995 and 1996), moderate (1997 and 1998) and high (1999 and 2000) solar activity (top to bottom).

for a full coverage of the local time at a fixed longitude in low latitudes. The longitudinal extent of the ROCSAT 1 data is restricted to ±30° of 70° E to match the spatial coverage of SROSS C2. Further, the ROCSAT 1 measured T_i are normalized to 500 km altitude using the International Reference Ionosphere (IRI 2007) ion temperature vertical profiles for the corresponding periods to study the effect of solar cycle.

The annual mean $F_{10.7}$ cm solar flux for 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002 and 2003 are ∼77, ∼71, ∼78, ∼115, ∼154, ∼181, ∼184, ∼180 and ∼129, respectively. For studying seasonal variations, three seasons are considered: June solstice (May, June, July, August), December solstice (November, December, January, February), and equinoxes (March, April, September, October).

3 Results and discussion

3.1 Temporal and latitudinal variations

Figure 1 shows the three-dimensional view of the temporal and spatial variation of ion temperature measured by the SROSS C2 from 1995 to 2000 within 12.5° S to 17.5° N magnetic latitude. The data are grouped into three periods of solar activity: low (1995 and 1996), moderate (1997 and 1998), and high (1999 and 2000), with bins of ±2.5° at 5° latitude intervals for each hour of local time. Ion temperature at the altitude of 500 km during the ascending half of solar cycle 23 shows morning and afternoon enhancement and a daytime low value. It is seen from the figure that in low solar activity, equinox enhancement in T_i up to ∼1400 K occurs in the sunrise hours (05:00–07:00 LT) at latitudes away from the Equator. After the morning peak, the T_i averages ∼1100 K between 08:00–12:00 LT, after which it gradually drops and reaches the nighttime (22:00–04:00 LT) average temperature of ∼800 K. In summer, on the other hand, T_i gradually increases from its nighttime low of ∼800 K during morning hours to ∼1100 K. The post sunrise increase continues through the morning and midday until it reaches the diurnal maximum of 1300–1400 K at around 16:00–17:00 LT. The daytime ion temperature in this season is found to be higher towards northern latitudes. During December solstice, T_i reaches its diurnal maximum value of ∼1700 K within 06:00–07:00 LT. From the diurnal maximum, T_i reduces sharply to ∼1300 K within the next couple of hours. Daytime (10:00–14:00 LT) average temperature is ∼1100 K and nighttime average temperature is ∼700 K. A temperature gradient, positive towards north, has been observed during daytime.

During the moderately active period of 1997–1998, in the equinoxes the nighttime T_i varies from 850 K to 900 K. The pre-sunrise ion temperature is higher towards south. The morning T_i is higher at about 1100 K near the Equator and lower at ∼900 K for off equatorial latitudes. There is a temperature gradient from south to north in the mean daytime

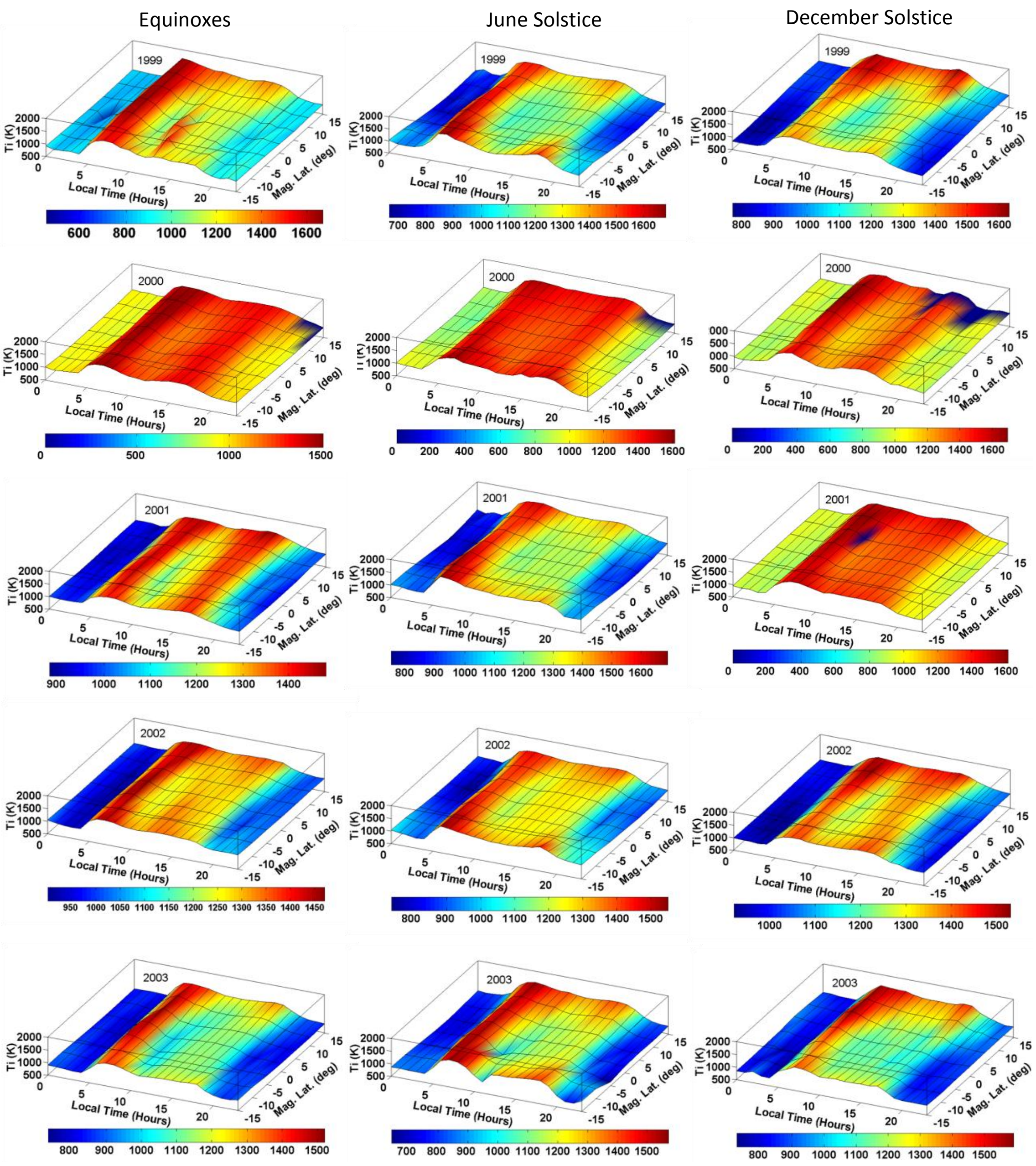

Fig. 2. Three-dimensional plots showing seasonal mean ion temperature as a function of magnetic latitude and local time measured by the ROCSAT 1 at 600 km in equinox, June and December solstice (left to right) for the period 1999 to 2003 (top to bottom).

temperature that varies between 1000 K and 900 K. In the June solstice, on the other hand, nighttime T_i varies from a very low ∼800 K to 1300–1400 K away from the Equator in the Northern Hemisphere and between 1000 K–1150 K in the Southern Hemisphere, thus forming a nighttime equatorial trough in ion temperature in this season. In the post sunrise hours (06:00–07:00 LT), the T_i shows significant variation from ∼900 K to ∼1500 K between the Northern and Southern Hemispheres. Daytime average T_i varies between 1000 K to 1100 K. In the afternoon, there is a secondary increase in T_i to about 1300 K. Nighttime ion temperature in the December solstice exhibits an equatorial crest with high values around 1250 K, while away from the Equator it varies within 900–1000 K. Ion temperature then increases to a late post sunrise peak of ∼1700 K around 10:00 LT. The daytime T_i varies between 1000 K–1700 K during 10:00–11:00 LT with a positive gradient towards north.

At the peak of the solar cycle 23, i.e. in 1999 and 2000, in equinox the nighttime T_i varies from 850–900 K. The temperature gradually increases in the post sunrise hours and through midday to a high of ∼1300 K in the afternoon. During daytime, temperature near the Equator is less than that at off equatorial latitudes, forming a trough at the Equator. In the June solstice, nighttime T_i also remains within 850–950 K. During 06:00–07:00 LT the T_i rises to 1100–1200 K, the higher temperature being over southern latitudes. During the daytime till about 14:00 LT, T_i averages ∼1200 K. From the daytime 1200 K, there is an enhancement again in the afternoon to ∼1500 K, which is the diurnal maximum temperature in this season. In the December solstice, nighttime temperature is high at ∼900 K over the Equator and low at ∼700 K away from the Equator. It then increases to 1400 K around 10:00 LT. In the afternoon, T_i again rises to ∼1300 K from the midday value of about 1000 K. The afternoon peak is higher towards Southern Hemisphere and morning peak is higher towards Northern Hemisphere.

In Fig. 2, 3-D plots of total ion temperature measured by the ROCSAT 1 versus local time and magnetic latitude from 12.5° S to 17.5° N at 5° latitude intervals are shown from the peak of the solar cycle 23 through its descending phase 1999 to 2003. The data for each latitude interval are grouped within ±2.5° in latitude. When all latitude and local time are considered, the standard deviation of T_i from the mean varied from 165 K to 460 K. The figure shows that in the equinoxes, in 1999 the daytime and nighttime average T_i varies between 1100–1300 K and 800–900 K, respectively. A morning high of 1650 K around 07:00 LT has been observed. The daytime temperature shows an equatorial tough. At the peak of the solar cycle in 2000, the daytime T_i averages 1200 K with an equatorial dip of 100 K. Nighttime T_i varies between 900–1000 K. During post sunrise period, ion temperature reaches a high of 1500 K. There is also a secondary afternoon enhancement to 1350 K. In the year 2001, the ion temperatures remain nearly at the same level as in the year 2000 both during day and nighttime, including the time of morning and afternoon enhancement. In 2002, the solar activity is nearly at the same high level as in 2000 and 2001; therefore, the ion temperatures show similar variations as in the previous years. In the morning hours between 07:00–08:00 LT, T_i reaches ∼1450 K at all latitudes, while daytime T_i is about 1300 K. No latitudinal gradient is seen in these hours. In the afternoon hours, T_i rises by about 50 K from the daytime average level. In the moderate solar activity year 2003, ion temperature shows a nighttime dip around the Equator. The morning enhancement is slightly higher as compared to high solar activity years and reaches ∼1500 K. The daytime average T_i is 1100 K. The ion temperature falls gradually from the daytime level to the nighttime average of ∼850 K.

The ion temperature in the June solstice of 1999 varied between 800–1000 K at night, the temperature being lower near the Equator. The post sunrise T_i is ∼1550 K. During daytime, temperature varied from 1150 K at 10° S to 1500 K at 15° N. There is also a late afternoon secondary enhancement during which T_i can rise to about 1400 K. In the year 2000, nighttime temperature varied from 800 K at the Equator to 1000 K away from the Equator. In the morning the T_i rises from its nighttime value to 1450–1550 K. The equatorial trough continues till the morning hours also. During the daytime, T_i varies from 1350 K to 1450 K, it being higher in the Northern Hemisphere. There is also a secondary late afternoon enhancement to about 1400 K at latitudes away from the Equator. The nighttime T_i in 2001 varied from a minimum of 800–1000 K, with a dip near the Equator. In the morning, T_i rises to a high value of 1600–1700 K, while during daytime the mean temperature is ∼1250 K above the Equator and ∼1350 K away from the Equator. Afternoon T_i also similarly varied from 1250 K at the Equator to ∼1400 K at northern and southern anomaly latitudes. In the following year 2002, the solar activity level being nearly same, the temporal and latitudinal variations are more or less similar to that in 2001. But in the year 2003, the solar activity reduced to moderate levels and accordingly the ion temperatures have been found to decrease. Nighttime temperature is 700–850 K while daytime average temperature varied from 1100 K to 1300 K. The equatorial trough is prominent during daytime. Post sunrise T_i rises to ∼1500 K almost uniformly across all latitudes. The T_i increases to another secondary peak in the afternoon.

In the December solstice in the year 1999, ion temperature during the night averaged 850–950 K. T_i then rises to 1600 K in the extreme north and 1300 K in the extreme south by 07:00 LT. Daytime T_i forms a broad valley at this level, while the temperature gradient of 300 K is maintained all throughout. As the solar activity increases, the nighttime temperature increases slightly to about 1000 K. The morning T_i around 07:00–08:00 LT increases to 1650 K near the Equator and 1500 K away from the Equator, giving rise to an equatorial hump. Daytime temperature shows reversed latitudinal variation with high values of 1350 K away from the Equator and 1200 K near the Equator. Afternoon enhancement reaches ∼1400 K. In 2001, another high activity year, the ion temperature diurnal and latitudinal variations are similar to that of the previous year, with slight variation in temperature. In 2002, both morning and afternoon enhancements in T_i with higher temperature towards north have been conspicuous. In the moderate activity year 2003, the afternoon enhancement is missing and morning T_i increases to a high value of ∼1500 K in the north and 1400 K in the south. Daytime average T_i is around 1300 K, while at night it is about 950–1000 K.

The diurnal, seasonal and latitudinal variations of ion temperature for the solar minimum period of 1995–1996 using SROSS C2 data were reported by Bhuyan et al. (2004). They found that in the sunrise hours 04:00–06:00 LT, ion temperature increases from the nighttime low level of ∼700 K up to ∼3000 K. An afternoon enhancement by 200 K from the daytime level of 1000–1100 K has also been observed in summer. Latitudinal gradients in T_i during the period of morning and afternoon enhancement have also been reported. The energy lost by the electrons is the heat source for the ions, i.e. the entire ion heating is caused by elastic collisions with electrons. Therefore, the electron temperature (T_e) profile at a particular location reflects to some extent the behaviour of ion temperature. Bhuyan et al. (2006) examined the temporal variation of electron temperature measured by the SROSS C2 at ∼500 km altitude during the period of 1994–1998 and found that electron temperature varies between 700–900 K during nighttime, rises sharply in the sunrise period to reach a level of 3500–5000 K, and then falls within the next few hours to a daytime average level of 1600–2000 K. A secondary maximum in electron temperature is observed in the afternoon to early evening period in summer in all years and in the equinoxes in moderate solar activity period. The morning enhancement was found to be more pronounced in the equinoxes and between the solstices; winter enhancement was more compared to that in summer. Photoelectron productions begin at sunrise through the ionization of neutral particles. As the photoelectrons share their high energy with ambient electrons, electron temperature increases rapidly in the early morning hours due to low electron density (Schunk and Nagy, 1978). Higher electron energy results in higher ion temperature in the post sunrise period. This morning peak becomes prominent in the low latitude ionosphere due to the vertical $\boldsymbol{E} \times \boldsymbol{B}$ plasma drift, which decreases the electron density followed by an increase in T_e (Su et al., 1995, 1996; Balan et al., 1997). After sunrise, the ion temperature falls as the electron temperature also falls due to sharing of energy with more electrons. The daytime ion temperature is the result of balance between ion heating and cooling processes. The daytime electron temperature also shows a plateau. Though near noon electron heating by solar EUV is maximum, it is more than offset by electron cooling resulting from the higher noontime electron density. Afternoon enhancement in T_e at the low latitude region is observed to be strongly affected by both the $\boldsymbol{E} \times \boldsymbol{B}$ drift and the neutral wind (Oyama et al., 1996). Watanabe et al. (1995) have found from a three-dimensional computer simulation that the balance effect of plasma heating and cooling under the influence of meridional winds causes afternoon enhancement of electron temperature in midlatitudes.

Borgohain and Bhuyan (2010) examined the diurnal, seasonal, latitudinal and solar activity variation of O^+, H^+, He^+ and O_2^+ ions measured at the average altitude of 500 km by the SROSS C2 from 1995–2000 and at 600 km by ROCSAT 1 from 1999–2003 within −15° to 20° dip latitudes. The major ion O^+ density is minimum before local sunrise (04:00 LT) and reaches its peak near local noon or afternoon hours, depending on the season and solar activity. The diurnal peak occurs at 12:00 LT in summer and 14:00 LT in winter. O^+ density shows a secondary enhancement in the afternoon hours. It was also observed that in the equinoxes, the O^+ density maximizes at 15° N and 10° S and is higher in the Northern Hemisphere. In winter the ionization peak in the Southern Hemisphere is higher than that in the Northern Hemisphere. The diurnal variation of T_i observed from the present analysis is mostly explained by the inverse O^+ variations. Oyama et al. (1997) reported enhancements in T_e associated with enhancements in electron density in the crest region of equatorial anomaly. Increase in T_i with increase in density in the crest region of the Northern Hemisphere during June solstice may be attributed to higher intake of solar EUV radiations by the neutrals in this season. On the other hand, the equatorial trough in nighttime ion temperature observed in the June solstice and equinox of high solar activity years may be attributed to the increase in plasma density and adiabatic expansion of plasma.

3.2 Solar cycle variation of ion temperature

The effect of variation of solar activity on ion temperature is studied by plotting the monthly average daytime (10:00–14:00 LT) and nighttime (22:00–02:00 LT) ion temperature over the magnetic equator, −10° and +10° against corresponding average $F_{10.7}$ cm solar flux in Fig. 3. In the figure, the data from the SROSS C2 and ROCSAT 1 are combined to study the solar cycle effect for nearly a full solar cycle, i.e. 9 years from 1995 to 2003. ROCSAT 1 ion temperature at 600 km is normalized to 500 km using the IRI-2007 topside ion temperature profiles for the corresponding period. It is seen from the figure that ion temperature shows insignificant positive correlation over all the three latitudes during daytime, while during nighttime the ion temperature is negatively correlated with solar flux. Increase in electron temperature with increase in $F_{10.7}$ cm solar flux has been reported by Bhuyan et al. (2006) from a study of the solar cycle variation of T_e measured by SROSS C2 and ROCSAT 1 from 1995 to 2003 during solar cycle 23. Similarly positive correlation between T_e and solar flux has been found by Oyama (1994) for nighttime T_e. Mahajan and Pandey (1979) found that T_e at 1000 km increased with solar activity between 1965 and 1969.

The major physical processes that control the F-region plasma temperature are (i) photoelectron heating and (ii) electron cooling or simultaneous ion heating due to loss through collisions between electron and ions. With the increase in solar activity, solar energy input increases and consequently the photoelectron production and electron heating rates increase. The increased heating rate leads to elevated electron temperature and subsequent higher ion temperature. However, increase in solar activity also results in higher ion concentration, which gives rise to increased cooling rate, resulting in decrease in T_e or T_i. Therefore, the insignificant rate of increase in T_i with solar flux during daytime may be attributed to more effective cooling of the ions than heating, while at nighttime the cooling supersedes the heating rate, resulting in negative correlation of T_i with solar flux.

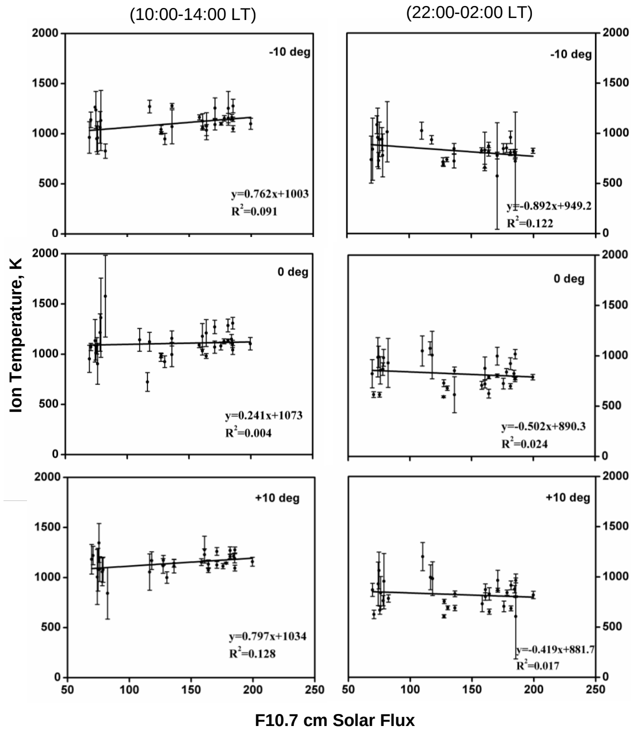

Fig. 3. Variation of monthly mean daytime and nighttime ion temperature with $F_{10.7}$ cm solar flux over −10°, 0° and 10° magnetic latitudes. The data are averaged within ±2.5° for the selected latitudes. Vertical bars about each point indicate one standard deviation from the mean.

3.3 Relationship between ion temperature and ion density

The linear plots between T_i vs. corresponding $\log_{10}(N_\mathrm{i})$ during daytime for solar minimum (1995 and 1996) for all the three seasons combined are shown in Fig. 4. Data are selected within ±2.5° of 10° S, 0° and 10° N magnetic latitudes. During daytime, significant negative correlation is observed between $\log_{10}(N_\mathrm{i})$ and corresponding T_i for at 10° N and 10° S, while insignificant negative correlation has been observed over the Equator during solar minimum (Fig. 4). During nighttime no significant correlation is observed between N_i with corresponding T_i. Nighttime correlation is apparently affected by the large scatter of the data points caused by temperatures measured much higher than the average nighttime temperature of less than 1000 K. Niranjan et al. (2006) have observed midnight temperature maximum (MTM) during low solar activity summer months using SROSS C2 satellite, ground-based night airglow intensities at 630 nm, and collocated ionosonde measurements from an Indian low latitude station Waltair (17.7° N, 83.3° E). The MTM might have contributed to the observed high values and hence the large positive scatters from the mean level during the low activity period. Ion temperature and ion density similarly grouped

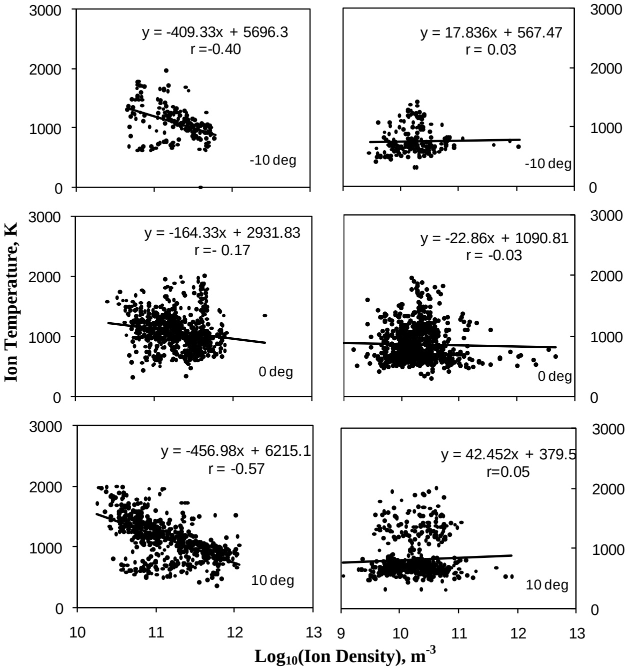

Fig. 4. Variation of daytime (left panel) and nighttime (right panel) ion temperature with corresponding ion density at −10°, 0° and 10° magnetic latitude in the Indian longitude sector during low solar activity (1995 and 1996).

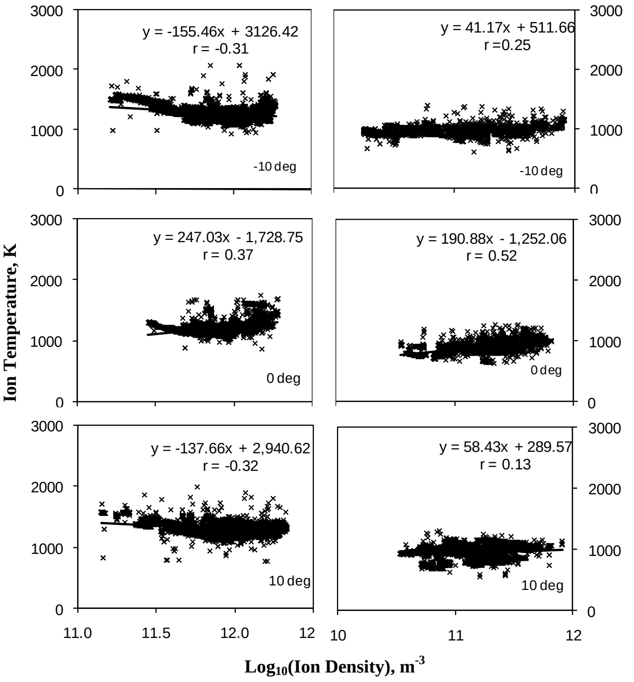

Fig. 5. Variation of daytime (left panel) and nighttime (right panel) ion temperature with corresponding ion density at −10°, 0° and 10° magnetic latitude in the Indian zone during high solar activity (2000 and 2001).

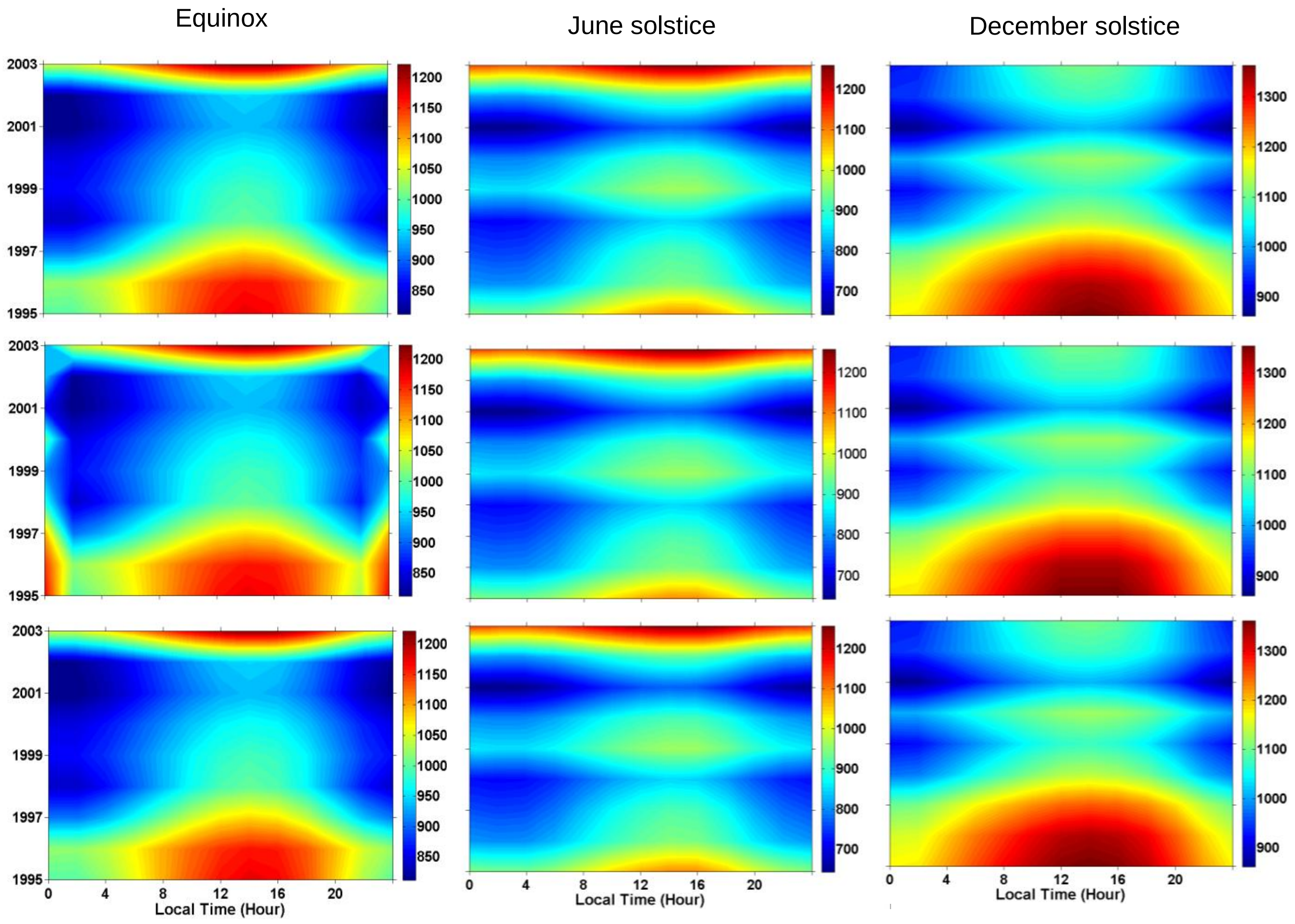

Fig. 6. Local time variation of neutral gas temperature at 550 km altitude obtained from the MSISE 90 model for the period 1995 to 2003 for −10°, 0° and 10° magnetic latitudes (from top to bottom).

as in Fig. 4 for the solar maximum years of 2000 and 2001 have been plotted in Fig. 5 for both day and nighttime. It is seen from the figure that ion temperature and ion density exhibit significant negative correlation at 10° N and 10° S, while good positive correlation has been observed over the magnetic equator. However, the lapse rate of T_i with N_i is slower in high solar activity as compared to that in low solar activity (Fig. 4). Nighttime density and temperature show positive and significant correlation over the Equator. The near zero growth of T_i with solar activity during the daytime is overtaken by the faster rate of growth of ion density, resulting in the observed negative correlation of T_i with N_i except over the Equator during solar maximum. It may be further mentioned that during very high solar activity years, ion density nearly saturates or the rate of growth slows down significantly. Therefore, over the Equator the increase in ion temperature could have superseded the increase in density, exhibiting a positive correlation between T_i and N_i. Mahajan (1977) reported negative correlation of electron temperature with corresponding electron density. Brace and Theis (1978) studied the relationship between electron temperature and electron density measured by the Atmospheric Explorer C satellite during December 1973 to December 1974 as a function of altitude. They found that at higher altitude, where electrons are increasingly cooled by collisions with positive ions, electron temperature and density begins to exhibit an inverse relationship. Bhuyan et al. (2002a) had also observed that electron temperature measured by the SROSS C2 satellite at 500 km altitude in the 75° E longitude sector from 10° S to 15° N geomagnetic latitudes during 1995–1996 decreases with increase in density in all seasons for temperature above the level of 1000 K. Further, Bhuyan et al. (2004) have observed that the ion temperature measured by the SROSS C2 satellite during 1995–1996 over the Indian subcontinent and combined for all latitudes decreases with increase in ion density during daytime, irrespective of season. The present study shows that the negative correlation holds both during solar minimum and maximum except over the magnetic equator. Therefore, as observed, ion temperature ought to bear a negative or insignificant positive correlation with solar activity as ion density was found to increase with $F_{10.7}$ cm solar flux (Borgohain and Bhuyan, 2010) over the Indian low latitudes at 500 km from 1995 to 2003.

3.4 Neutral temperature from the MSIS model

The temperature of the neutral gas in the ionosphere is a good indicator of the temperature of the ions and electrons as the three temperatures are roughly related by the equation $T_\mathrm{i} = (T_\mathrm{e}+T_\mathrm{n})/2$ above F peak heights. The MSISE 90 (Hedin, 1991) is a global analytical model of the atmosphere that provides neutral densities and temperature from ground to thermospheric heights. The neutral temperature T_n at 550 km derived from the MSISE 90 model for the period 1995–2003 is shown separately for the three seasons and -10, 0, $+10$ magnetic latitudes in Fig. 6. The local time variation of T_n is similar at the three selected latitudes, with a minimum at night and maximum during afternoon hours. Magnitude of T_n vary little within these latitudes. The figure also indicates that T_n is higher in low solar activity compared to that in high solar activity. For example, in the December solstice over the Equator at midnight hours, T_n is 1175 K in 1995 and 862 K in 2001. At 16:00 LT, T_n varies from a high of 1356 K in 1995 to a low of 1002 K in 2001. In the equinoxes over the Equator, maximum and minimum midnight T_n is 1175 K and 862 K, respectively, in 1995 and 2001. At 16:00 LT, neutral temperature reached 1170 K in 1995 and 937 K in 2001. In the June solstice, midnight maximum temperature of 1146 K occurred in 2003, while the temperature reached minimum value of 648 K in 2001. Similarly, T_n at 16:00 LT is 1260 K in 2003 and 767 K in 2001. It may also be noted from the figure that the daytime neutral temperature is higher in the December solstice, while nighttime T_n is comparable in all seasons. Comparison with the measured T_i for corresponding periods indicates that MSISE 90 simulated T_n is generally higher than T_i during nighttime, while the reverse is true in case of daytime average T_i and T_n. Venkatesh et al. (2011) have found that T_n computed from ionospheric slab thickness measurements for the low sunspot years 2004–2005 compare well with MSIS 90 derived temperature over Indian equatorial and low latitudes during daytime hours. A detailed comparative study of the neutral temperature predicted by the MSIS model with ion and electron temperatures measured over the Indian zone will be undertaken and reported in future.

4 Conclusions

Ion temperature over the Indian low and equatorial latitudes on either side of the magnetic equator by the SROSS C2 from 1995 to 2000 and ROCSAT 1 from 1999 to 2003 are analyzed to study the diurnal, seasonal and solar cycle variations. The availability of the two satellites for nearly a solar cycle provided an opportunity to study the effect of solar activity on ion temperature and ion density. The following conclusions are drawn:

1. T_i varies between 800 K and 1100 K during nighttime and rises to peak values of ∼1800 K in the post sunrise hours. Daytime T_i varies from 1000 K to 1500 K. An afternoon secondary enhancement has also been observed.

2. The time of occurrence, magnitude and duration of the morning enhancement show distinct seasonal bias.

3. Daytime ion temperature exhibits insignificant positive correlation over all the three latitudes, while during nighttime the ion temperature is negatively correlated with solar flux.

4. Daytime ion temperature and ion density are negatively correlated during solar minimum, while nighttime T_i does not exhibit any correlation. However, during high solar activity, significant positive correlation of T_i with N_i has been observed over the Equator, while at ±10 ° temperature and density exhibit significant negative correlation.

5. The neutral temperature T_n computed from the MSISE 90 model at 550 km altitude is found to be lower than the measured ion temperature during daytime, while at night the model temperature is higher.

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