Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 56 (2015) 2117–2129

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Electron–ion–neutral temperatures and their ratio comparisons over low latitude ionosphere

Ananna Bardhan [a], D.K. Sharma [b,*], M.S. Khurana [b], M. Aggarwal [c], S. Kumar [a]

[a] *Department of Physics, FET, Manav Rachna International University, Faridabad 121001, India*

[b] *Department of Physics, Manav Rachna University, Faridabad 121001, India*

[c] *Indian Institute of Geomagnetism, Mumbai 410206, India*

Received 5 December 2014; received in revised form 26 August 2015; accepted 28 August 2015
Available online 4 September 2015

Abstract

Annual variations in temperatures of plasma (electron–Te, ion–Ti) using SROSS-C2 satellite and neutral (Tn) using NRLMSIS-00 (neutral atmospheric model); have been investigated and their ratios have been compared over half solar cycle (year 1995–2000, F10.7 ~ 72–190). The region under consideration spans over 5–35°N geog. latitude and 65–95°E geog. longitude in the Indian sector, at an average altitude of 500 km. Te and Ti exhibit similar, while Tn show completely different diurnal features. During nighttime Te, Ti and Tn attain equilibrium with each other, but plasma cools faster than neutrals. Magnitude of Te and Ti reduces, while that of Tn increases with increasing solar activity. Ratio comparisons (Te/Tn, Ti/Tn and Te/Ti) show higher sensitivity of electrons compared to ions and neutrals. Te/Tn, Ti/Tn exhibits linear/direct relationship with solar flux, while Te/Ti doesn't. The deviation of Te, Ti and Tn from equilibrium temperature decreases with increasing solar activity.

Keywords: Plasma temperatures (Te and Ti); Neutral temperature (Tn); Ionospheric temperature ratios (Te/Tn, Ti/Tn and Te/Ti); SROSS-C2 satellite; Neutral atmospheric model – NRLMSIS-00 and low latitude F2 region

1. Introduction

The lower regions of the atmosphere above the Earth's surface have been studied intensively by meteorologists as the seat of weather phenomena. It is comparatively in the recent times that the comprehensive study of upper region atmosphere–ionosphere, has become extremely important, owing to society's technological dependence on satellite communication and navigation. Thus, understanding, forecasting and monitoring changes in ionosphere has become extremely important.

As the Earth is embedded in the outer atmosphere of the Sun, the effects of its radiations affect the thermospheric dynamics of F region ionosphere. Ionospheric parameters modulate with solar cycle, geomagnetic conditions, seasons and local time. Extensive studies using ground and space born facilities have been carried to understand and forecast changes in ionosphere. Greatest bulk of research is concentrated on ion composition and electron densities. Although examples of comprehensive reports on ionospheric temperatures were provided by Balan et al. (1997), Watanabe et al. (1995), Titheridge (1998), Schunk et al. (2003), Bhuyan et al. (2002), Aggarwal et al. (2007), Sharma et al. (2010) and many more, still, studies focused on global distribution of ionospheric temperatures are less rich (Slominska and Rothkaehl, 2013). Ionospheric temperatures in F region are determined by heating, cooling and

* Corresponding author.
E-mail addresses: dksphses@rediffmail.com, jointcoe@mru.edu.in (D.K. Sharma).

http://dx.doi.org/10.1016/j.asr.2015.08.031
0273-1177/

energy flow (Schunk and Nagy, 1978). The solar radiation reaching the earth's atmosphere cause ionization of neutral atoms and produce photoelectrons. The energetic photoelectrons lose their energy by sharing it with the ambient electrons causing a rise in electron temperatures. The increase in electron temperature is higher during early morning as the electron density is low (Sharma et al., 2003). However, as the day progresses, more and more electrons are produced and energy share of each electron decreases. Thus, the electron temperature reaches a maximum in the early morning, decreases and then attains a steady value by the afternoon. The ion temperature also shows similar enhancement during sunrise hour, however, the peak in ion temperature is delayed as compared to electron temperature (Aggarwal et al., 2007; Sharma et al., 2010).

The morphology and dynamics of equatorial ionosphere is notably different from that of mid and high latitude. In low latitudes, magnetic field lines become nearly horizontal with insignificant vertical component, giving birth to a different dynamics. Equatorial/low latitudes exhibit unique features such as equatorial electrojet, vertical $E \times B$ drift, etc. The region under consideration for present study is over Indian subcontinent (low latitude). Electron and ion temperatures in the upper ionosphere over the Indian subcontinent have been studied in detail by various researchers based on the SROSS C2 satellite data (Bhuyan et al., 2002, 2004, 2006; Aggarwal et al., 2007, 2009). The studies are based on diurnal, seasonal and latitudinal variations of ionospheric parameters. Bhuyan et al. (2002) have studied the diurnal and seasonal variation of electron and ion temperatures along with electron density during 1995–96. Both the electron and ion temperature show an enhancement during sunrise hours, although; the ion temperatures were found to be less than electron temperatures in all seasons and latitudes under study. Nayar et al. (2004) have used the same satellite data to make a direct comparison of electron and ion temperatures at the low-latitude topside ionosphere. They observe d that electron and ion temperatures exhibit similar diurnal features with morning and evening enhancements. Characteristics of these enhancements were found to evolve with season, altitude, latitude and solar activity. Aggarwal et al. (2009) have studied electron and ion temperatures at 500 km altitude during the sunrise. They studied the solar dependence of the electron and ion temperatures during early morning hours and observed seasonal variations in the temperature with the varying solar activity. Sharma et al. (2010) made a similar study using the SROSS C2 electron and ion temperature data to study the diurnal, seasonal and latitudinal variations of electron and ion temperatures, during periods of minimum to maximum solar activity. Sharma et al. (2005) also made a study of the seasonal variation of electron and ion temperature ratios for the period 1995–1999 for low solar activity period (1995–1997; $F10.7 < 50$) and high solar activity period (1998–1999; $F10.7 > 50$).

Present work analyses the diurnal variability of plasma temperatures (Te and Ti) obtained from SROSS-C2 satellite according to latitude and different seasons – summer (May, June, July, August), winter (November, December, January, February) and equinox (March, April, September, October) with varying solar activity. For the first time, the present study brings out comparison of diurnal behaviour of neutral temperatures with electron and ion temperatures during half solar cycle (1995–2000) over low latitude region (Indian subcontinent). We have used the SROSS-C2 satellite data and Neutral model NRLMSIS-00 to study the annual hourly variation of electron, ion and neutral temperature ratios with varying solar activity. Current study is different from earlier studies as it provides a detailed investigation of electron ion temperature ratios for each year from 1995 to 2000 i.e. half of the solar cycle, instead of binning them into low and high solar activity periods (Sharma et al., 2005) or low, moderate and high activity periods (Aggarwal et al., 2009). Also the study is not confined to specific hours of a day and has been carried for both morning and quiet hours. We believe that detailed treatment of the Te, Ti and Tn ratios would give a better understanding of the variation of ionospheric temperature ratios with the varying solar activity and help in improving the existing ionospheric models.

2. Data used

2.1. SROSS-C2 data

To investigate the diurnal behaviour of Te, Ti and ratios of Te and Ti over half solar cycle (1995–2000), data of ionospheric temperatures from RPA (Retarding Potential Analyser), aboard SROSS-C2 satellite, have been used. The region considered for present study spans over the Indian subcontinent/ low latitude (5–35°N geog. Lat., 65–95°E geog. Long.) at an average altitude of ~500 km/F2 region.

The detail description of SROSS-C2 mission and the procedure for retrieval of plasma parameters have been given by Garg and Das (1995). The ionospheric parameters (Te, Ti, $O+$ and $H+$) are obtained using a Retarded Potential Analyser (RPA) payload aboard the SROSS-C2 satellite, which was launched by Indian Space Research Organization (ISRO) on May 4, 1994 around 420×620 km altitude. The RPA payload consisted of two sensors, (i.e. electron and ion sensors) and associated electronics (Garg and Das, 1995). In addition, a spherical Langmuir probe was included which acted as a probe to estimate the spacecraft potential as the satellite spin. The electron and ion sensors had a planar geometry and consisted of multi-grid Faraday cups with a collector electrode. The mechanically identical sensors were mounted on the top deck; and move in the cartwheel mode perpendicular to the spin axis of the spacecraft. Both sensors had different grid voltages which was suitable for the collection of electrons and ions in the earth's ionosphere. The temperature data (Te and Ti) was obtained by analysing one complete electron and ion *I–V* plot through linear and non-linear curve fitting techniques, respectively. The ion density (O+, O2+, H+, He+) was obtained by the curve fitting to a composite I-V curve using a non linear curve method of iteration to the observed characteristics.

2.2. Other data used

To analyse the diurnal behaviour of neutral's temperature and its ratio comparisons with Te and Ti for the above said region, the neutral atmospheric model NRLMSIS-00 is used for ~500 km altitude, 77°E longitude and averaged latitude range for 5–35°N (http://ccmc.gsfc.nasa.gov/modelweb/models/nrlmsise00.php). NRLMSIS-00 is newer version, which considers drag and accelerometer data as well as SMM UV occultation data. The model is majorly upgraded from its old MSISE-90 model. NRLMSIS-00 includes neutral temperatures from incoherent scatter radar (ISR). Picone et al. (2002) report statistical comparisons and scientific issues related to NRLMSIS-00.

To study the effect of solar flux on ionospheric temperature ratios, the values for F10.7 have been obtained from Omniweb NSSDC site for year 1995–2000. The F10.7 correlates well with the sunspot number as well as a number of Ultra Violet (UV) and visible solar irradiance records. The Extreme Ultra Violet (EUV) emissions that impact the ionosphere and modify the upper atmosphere also track well with the F10.7 index, thus, we have used it as an indicator of solar activity for our analysis.

3. Results and discussions

Fig. 1 represents data count of Te, Ti for which SROSS-C2 satellite has been used and solar Flux (F10.7) during each year over half solar cycle (1995–2000). F10.7 increases with each successive year. However, the value of F10.7 during 1996 is slightly lesser than 1995. The values of Tn have been obtained from NRLMSIS-00 neutral atmospheric model, thus the count of Tn has not been included in Fig. 1.

3.1. Electron–ion temperatures: diurnal; seasonal and latitudinal variability

Figs. 2, 3 and 4 are show the temporal and spatial variations in plasma temperatures as measured by SROSS-C2 satellite during different seasons – summer (May, June, July, August), winter (November, December, January, February) and equinox (March, April, September, October) with varying solar activity: low (1995–1996; F10.7 ~ 74.5), moderate (1997–1998; F10.7 ~ 99.5) and high (1999–2000; F10.7 ~ 166).

In 3.1.1 and 3.1.2 sections, spatial behaviour of plasma temperatures (Te and Ti respectively) with time has been studied. Number of data points (Te and Ti from SROSS-C2 satellite) in the latitude range of 30–35° geographic N is not appreciable and hence the region is not included in the study. Section 3.1.3 investigates temporal variability according to different seasons and solar activity.

3.1.1. Electron temperatures:- latitudinal and seasonal variability of diurnal trend

Contour plots showing temporal and spatial variability in diurnal pattern of electron temperature (Te) during low (1995–1996; $F_{10.7} \sim 74.5$, upper panel), moderate (1997–1998; $F_{10.7} \sim 99.5$, middle panel) and high (1999–2000; $F_{10.7} \sim 166$, lower panel) solar activity periods for different seasons (summer-left column; winter – middle column and equinox – right column) is represented in Fig. 2.

During low solar activity years, in summers; after sunset, the observed electron temperature is almost ~800 K from 20.00–04:00 LT and doesn't vary much in latitude range of 5–30° geographic N. The electron temperature

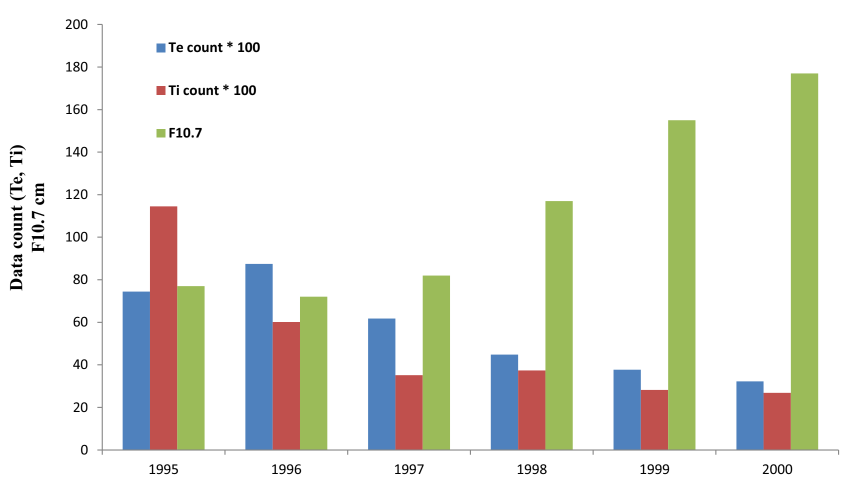

Fig. 1. Representation of ionospheric temperature data count – electron temperature (Te-blue), ion temperature (Ti-Red) and $F_{10.7}$ (Green) during each year (1995–2000). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

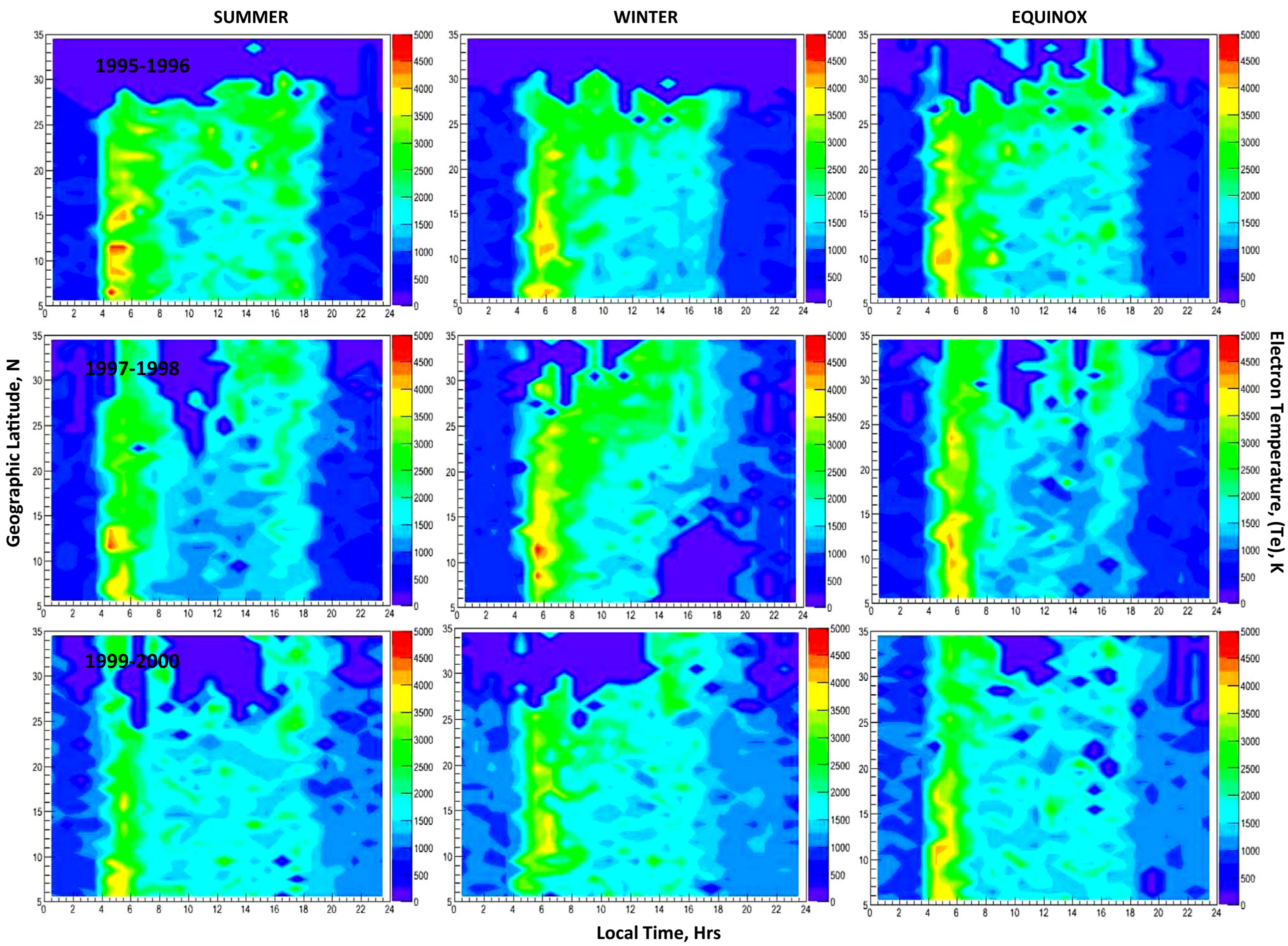

Fig. 2. Diurnal and seasonal variability of electron (Te-blue) and ion (Ti-red) temperatures during low (1995–1996; $F_{10.7} \sim 74.5$, upper panel), moderate (1997–1998; $F_{10.7} \sim 99.5$, middle panel) and high (1999–2000; $F_{10.7} \sim 166$, lower panel) solar activity years. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

increases rapidly during sunrise hours. Te is appreciably high ~4000 to 5000 K in latitude range of 5–15°N, whereas in 15–30°N region Te varies from ~2500 to 4000 K. This indicates that Te increases the most near geomagnetic equator region during morning enhancement. During day time electron temperature varies as ~1700 K and ~3000 K in 5–20°N and 20–30°N regions respectively. During sunset Te again increases to almost ~ 2800 K on an average and varies from ~1500 to 3000 K over entire latitude range and thereafter decreases to attain nighttime minimum. The contour profile of equinoxes is similar to that of summers except for the fact that Te is higher in 20–30°N compared to 5–20°N during evening/sunset time. During winters, sunrise hours register analogous behaviour as in other seasons. During day time Te varies from 800 to 1500 K in 5–20°N and ~2500 to 3000 K in 20–30°N regions. There is no considerable evening enhancement during winters. Te decreases faster than in summers and equinoxes, after sunset; and acquires ~800 K value from 18 LT to 4 LT. It is interesting to note that in latitude range of 20–30°N there is no appreciable variations in Te and it remains almost constant ~2500 to 3000 K during all the seasons at sunrise, day and sunset timings.

During moderate years of solar activity, Te in all the seasons experience similar kind of variation (Te ~800 K) during nighttime as experienced in low activity period. Summers, winters and equinoxes observe morning overshoot over the entire latitude region under consideration. Te is ~ 4500 to 5000 K around 8–12°N and in other latitude regions under consideration, Te varies from ~2500 to 4000 K. During daytime in summers and equinoxes Te varies from 1000 to 1500 K over 5–30°N and sporadically, Te's variation from 1500 to 2000 K can be observed over some latitudinal regions. During winters Te varies from 1500 to 3000 K in day time. Te is higher in higher latitudes during daytime. During 14:00–17:00 LT from 5–10°N Te is lesser (~500 or less than 500 K), which could be due to lesser number of data points. Late afternoon enhancement is evident in all the seasons. Te varies from ~2000 to 3000 K and is higher at higher latitudes during sunset time. Evening enhancement is more pronounced in latitudes away from geomagnetic equator.

During high solar activity years, nighttime Te is little higher in magnitude (Te ~1000 K) for all seasons compared to low and mid solar activity years. Morning overshoot is noticed during all the seasons and over entire latitude range

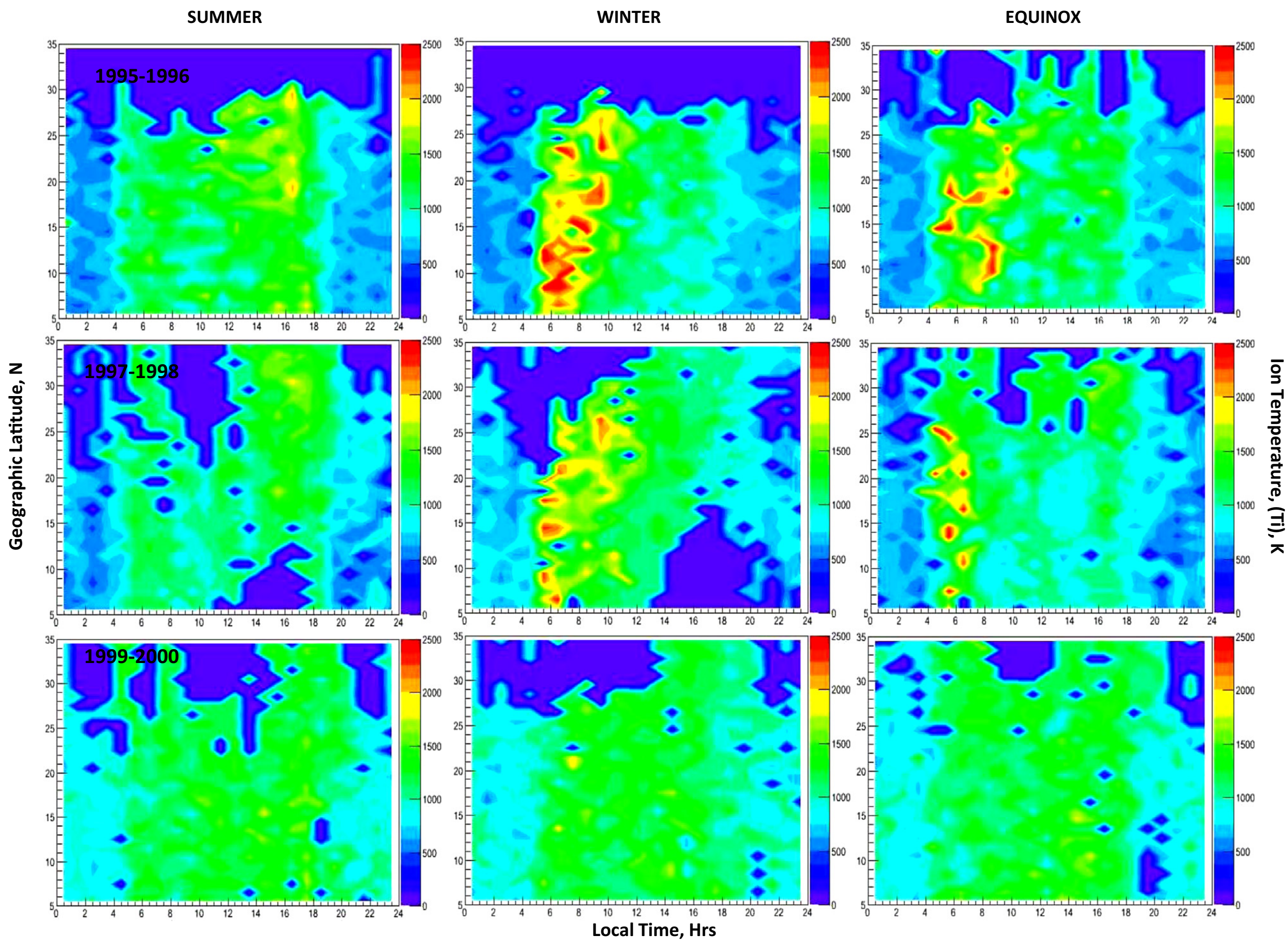

Fig. 3. Diurnal, latitudinal and seasonal (summer-left column; winter – middle column and equinox – right column) variations of electron temperature (Te) during low (1995–1996; $F_{10.7} \sim 74.5$, upper panel), moderate (1997–1998; $F_{10.7} \sim 99.5$, middle panel) and high (1999–2000; $F_{10.7} \sim 166$, lower panel) solar activity periods.

under consideration. During sunrise hours Te varies from ~3000 to 4000 K, however Te is lower; compared to low and moderate solar activity years. During day and sunset time, Te ranges from 1500 to 2500 K during all the seasons. Evening enhancement is not observed in any season during high solar activity years. Te starts decreasing around 18 LT and reaches its minimum during nighttime.

3.1.2. Ion temperatures:- latitudinal and seasonal variability of diurnal trend

Fig. 3 represents contours showing temporal and spatial variability in diurnal pattern of ion temperature (Ti) during low (1995–1996; $F_{10.7} \sim 74.5$, upper panel), moderate (1997–1998; $F_{10.7} \sim 99.5$, middle panel) and high (1999–2000; $F_{10.7} \sim 166$, lower panel) solar activity periods for different seasons (summer-left column; winter – middle column and equinox – right column).

During low solar activity years; Ti attains almost a constant and same value (Ti ~ 700 K) during nighttime (20.00–04.00 LT). During summers; Ti varies ~ from 900 K to 1600 K at sunrise hours, followed by a day time trough (Ti ~ 1100 K) which peaks up during sunset (Ti ~ 900 K to 1500 K) and attains a nighttime minimum. The behaviour is consistent over entire latitude range considered for study. During equinoxes, Ti varies from 1700 to 2500 K during sunrise hours showing morning overshoot; thereafter daytime observes Ti ~ 900 to 1500 K over 5–30°N. During sunset Ti shows evening enhancement around ~1500 K over 5–30°N, then attains nighttime minimum (Ti ~ 700 K). Winters, during sunrise time; show maximum enhancement in Ti, compared to summers and equinoxes. Ti varies from 1800 K to 2500 K over entire latitude range during sunrise time. During daytime, Ti varies from 1000 K to 1500 K and decreases through sunset till nighttime least is achieved. Ti is higher in 20–30°N compared to over 5–20°N during day and evening time during all the seasons.

Mid activity years experience increase in Ti (~800 K) over all the seasons, compared to low activity years; during nighttime over 5–30°N. In summers there is negligible morning enhancement and temperature varies from 1000 to 1500 K over 5–30°N. Daytime ion temperature is slightly lower in magnitude than sunrise hours. In equinoxes, Ti ranges from 1500 K to 2500 K and morning enhancement is observed over 5–30°N. During daytime and sunset hours; Ti is higher in 20–30°N compared to

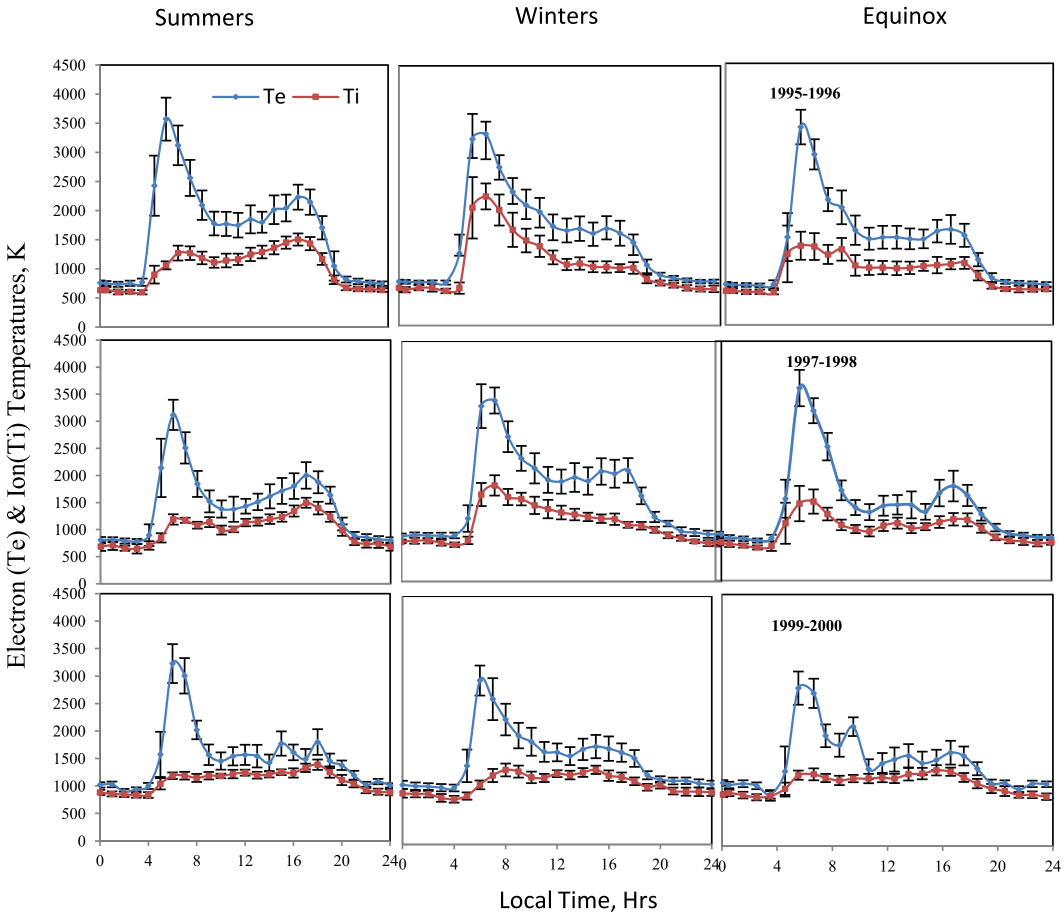

Fig. 4. Diurnal, latitudinal and seasonal (summer-left column; winter – middle column and equinox – right column) variations of ion temperature (Ti) during low (1995–1996; $F_{10.7} \sim 74.5$, upper panel), moderate (1997–1998; $F_{10.7} \sim 99.5$, middle panel) and high (1999–2000; $F_{10.7} \sim 166$, lower panel) solar activity periods.

5–20°N and varies from 800 K to 1500 K. Evening enhancement is marginal and thereafter Ti minimises to attain nighttime low. Winter's Ti register morning overshoot ~2000 K over 5–25°N latitude range, while Ti in 25–30° N is lesser. During daytime Ti is ~1000 K to 1500 K. There is no evening enhancement and Ti gradually decreases till nighttime over 5–30°N.

During high solar activity years, the diurnal pattern is lost over entire latitude range under consideration, during all the seasons. There are no morning and evening enhancements. Ti (~1000 K) takes up little higher value during sunrise, day and evening time till it attains nighttime low during all the seasons over entire latitude range.

A spatial analysis of plasma temperatures reveals that the latitude range 5–20°N is more dynamic in nature is compared to higher latitudes under consideration. Morphology during sunrise and sunset time are more complex compared to day and nighttimes. During sunrise, photoelectron production begins in the ionosphere through ionization of neutral particles. As these photoelectrons share their high energy with ambient electrons; electron temperature increases; this increase is very rapid owing to low electron concentration resulting in morning overshoot (Da Rosa, 1966). Present study indicates Te is higher in magnitude near geomagnetic equator region as compared to higher latitudes. During sunrise, Te in lower latitudes (5–20°N) is higher in magnitude than in higher latitudes (20–30°N), whereas during evening/sunset time higher latitudes (20–30°N) are at higher temperatures. Whereas no such significant distribution is observed in Ti contours.

3.1.3. Electron – ion temperatures: diurnal and seasonal variability

Fig. 4 represents the diurnal variability of hourly averaged electron (Te-blue) and ion (Ti-red) temperatures during low (1995–1996; F10.7 ~ 74.5, upper panel), moderate (1997–1998; F10.7 ~ 99.5, middle panel) and high (1999–2000; F10.7 ~ 166, lower panel) solar activity years for summers (left column), winters (middle column) and equinox (right column). Te and Ti have been averaged over 5–35°N geog. Lat. and 65–95°E geog. Long.

During low solar activity, in summers; the enhancement in Te and in Ti is up to ~4000 K and ~1300 K respectively during the sunrise hours (05:00–07:00 LT). After morning enhancement, plasma temperatures (Te and Ti) decrease; follows a daytime trough where Te and Ti vary from

~ 1700 to 1900/2000 K and 1100 to 1250 K respectively. Secondary/evening enhancement is observed in both the plasma (Te and Ti) and peaks up at 17 LT (Te ~ 2230 K and Ti ~ 1300 K). After sunset, during nighttime (20.00–04.00 LT), Te and Ti attain almost a constant and same value (Te ~ 800 K and Ti ~ 700 K). Similar kind of behaviour is observed during equinoxes. Sunrise overshoot in Te and in Ti is up to ~4000 K and ~1500 K respectively at 06:00 LT. Unlike, daytime trough in summers, equinox experience almost a constant value of Te ~ 1600 K and Ti ~ 1100 K. Evening enhancement is observed for Te ~ 1800 K at 17 LT and Ti ~ 1200 K at 18 LT. During nighttime, plasma attains non varying value (Te ~ 800 K and Ti ~ 700 K). In winters, Te attains a morning peak ~3500 K, while Ti shows much higher magnitude (Ti ~ 2200 K at 7 LT) compared to morning peak of Ti in summers and equinoxes. After morning overshoot, plasma cools gradually (Te ~ 1600 K and Ti 1000 K). There is no significant evening enhancement in Te and Ti during sunset. Thereafter, Te steeply and Ti gradually decreases and attains nighttime minimum.

During moderate solar activity years, similar kind of diurnal pattern is observed as during low solar activity period. During nighttime (20.00–04.00 LT), plasma attains steady value (Te ~ 800 K and Ti ~ 700 K) in all the seasons. In summers Te and Ti show a morning/sunrise peak of ~3000 K and ~1200 K respectively at 06:00 LT. There is gradual increase in daytime values of Te (1300–1700 K) and Ti (1000–1300 K) till evening peak is registered at 17 LT (Te ~ 2000 K and Ti ~ 1500 K). Plasma, thereafter; decreases steeply till nighttime. In equinoxes, the morning peaks are observed in Te (~3600 K) at 6 LT and Ti (~1500 K) at 7 LT and are higher than in summers. During daytime, Te and Ti experience fluctuations in temperature magnitudes. Thereafter, Te and Ti increase to attain secondary enhancement (Te ~ 1800 K and Ti ~ 1200 K) at 17 LT, then decrease gradually till nighttime. During winter the sunrise overshoot is observed at 7 LT (Te ~ 3300 K and Ti ~ 1800 K). Winters behave differently from other seasons. During daytime Te attains a constant value and increases during sunset and peaks at 17 LT (Te ~ 2100 K), then decreases till nighttime. However, there is no evening enhancement in Ti. After morning overshoot; Ti decreases gradually all through the day and evening time till it attains almost a constant and minimum value at nighttime.

During high solar activity years, nighttime behaviour is similar to moderate and low activity years. However, there is small increment in average values of Te ~ 1050 K and Ti ~ 900 K for all the seasons. Morning enhancement in Te during sunrise hours, is observable during all the seasons in (~3200 K during summers; ~3000 K during winters; 2800 K during equinoxes) and it peaks up at 6 LT. After morning overshoot, the diurnal trend is distorted and bumpy till nighttime. During all the seasons, Ti doesn't show any diurnal feature as shown during low and moderate activity years. It shows gradual daytime increase, then decrease till nighttime. There is no morning and evening enhancement in Ti for all the seasons.

During morning and evening sectors, Te undergoes rapid changes, while during day and nighttime changes are smaller. Te increases rapidly due to low electron density during sunrise hours (Aggarwal et al., 2009). Morning enhancement in Te is more distinct in summers and equinoxes as compared to winters. The typical 24 h diurnal variation of vertical E × B drift states that the magnitude velocities of the upward vertical F-region E × B drift increases until daytime peak velocity is attained, thereafter it decreases till sunset. Post sunset, drift velocity suddenly increases to an evening maximum known as evening enhancement, thereafter reverses and increases in reverse direction. Finally, downward E × B drift movement again reverses to upward direction till nighttime minimum is achieved (Fejer, 1991; Balan and Bailey, 1995). Thus, attainment of a secondary peak during the evening sector is completely attributed to the movement of the E × B drift. However, evening enhancement is more evident during low and moderate solar activity years. Energy due to heating of electrons gets transmitted via elastic collisions to ions. Thus Te and Ti show analogous diurnal trend except for the fact that Ti is much lesser in magnitude than Te. Plasma temperatures show morning enhancement during sunrise, day time trough, secondary/evening enhancement during sunset and nighttime quite and constant behaviour. However, this diurnal trend is lost with increase in solar activity.

3.2. Diurnal variability of electron–ion–neutral temperatures

Fig 5 represents the diurnal variability of electron (Te-red), ion (Ti-blue) and neutral (Tn-green) temperatures over half solar cycle (1995–2000). Te and Ti exhibit similar diurnal features with minimum magnitude of temperatures during nighttime, morning peak during sunrise, day time trough and evening enhancement. Te varies from ~700–4000 K and 1000–3000 K during low and high solar activity years respectively. The daytime electron temperature strongly depends on electron heating and loss rates which further arises from electron density (Brace, 1975). During low solar activity period, Ti follows almost similar diurnal trend as that of Te, except for the fact that magnitude of Ti is much lower than Te. But as solar activity increases the diurnal pattern of Ti gets distorted and becomes almost constant throughout the day. Bardhan et al. (2014) have also reported similar kind of observations.

Morning peak and secondary enhancement can be observed in Te and Ti, however the morning overshoot and secondary enhancement during evening time ~~is~~ are more pronounced during low solar activity years. During sunrise (05.00–07.00 LT) Te and Ne (electron density) changes rapidly as heat loss is very less owing to lower electron density (Aggarwal et al., 2007; Sharma et al., 2005). The evening enhancement of Te is attributed to vertical

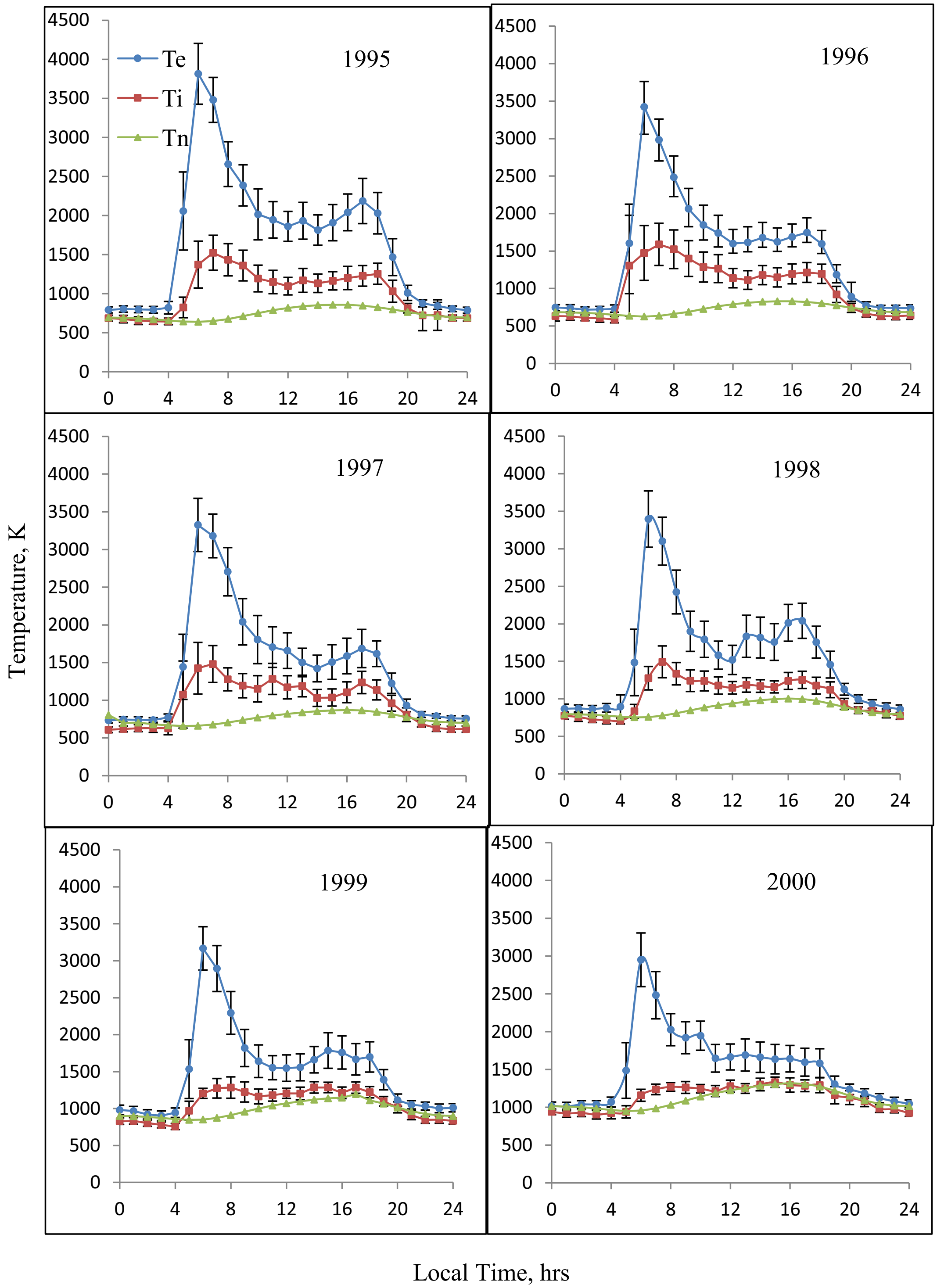

Fig. 5. Diurnal variation of electron (Te-red), ion (Ti-blue) and neutral (Tn-green) temperatures over half solar cycle (1995–2000). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

E × B drift (Balan et al., 1997). Similar kind of observations in Ti is expected as electron energy gets transferred via elastic electron–ion collision (Banks, 1967). During nighttime (20.00–04.00 LT) in absence of solar flux – UV and EUV emissions, Te and Ti decrease gradually and attain almost a constant value.

Neutral temperature (Tn) exhibits a completely different diurnal pattern compared to Te and Ti. Tn increases from about 07 LT to 18 LT and then decreases till 21 LT, then becomes almost constant and minimum during nighttime. During low (1995, 1996), mid (1997, 1998) and high (1999, 2000) solar activity years, Tn varies from 700 to

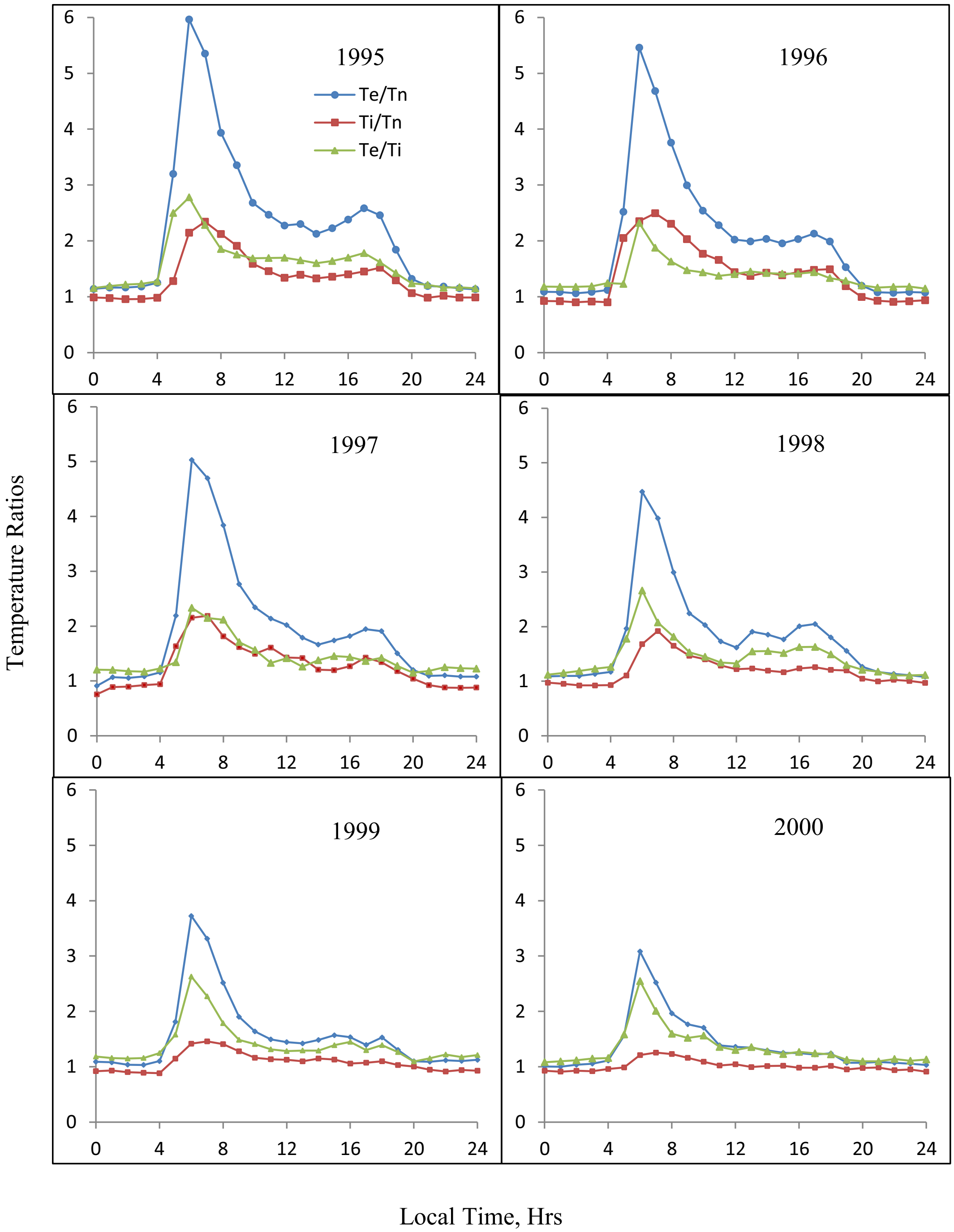

Fig. 6. Diurnal variation of Te:Tn (blue), Ti:Tn (red) and Te:Ti (green) over half a solar cycle (1995–2000). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

850 K, 900 to 1100 K and 1000 to 1300 K respectively. Thus, the magnitude enhancement in Tn increases with increasing solar activity. There are very few reporting on Neutral temperature. McClure (1969) using Thomson scatter Te and Ti profiles from Jicamarca; Peru, deduced that Tn increases at an almost constant rate of 16 K/h from 08 to 16 h then decreases rapidly near sunset. Thereafter, the decrease is constant, at a rate of about 10 K/h from 21 h to sunrise.

During nighttime, Te; Ti and Tn attain almost an equilibrium state with each other. As solar activity increases, diurnal trend of Ti is lost and merges with Tn values. Another interesting observation to be considered here is – Tn surpasses Ti at nighttime; during almost all the years but becomes more evident in high solar activity years. At low latitudes the electron temperature is controlled by local heating and cooling process (Slominska and Rothkaehl, 2013). And electrons transfers energy to ions which further increases Ti via elastic collisions (Brace, 1975). The same process – i.e. via inelastic collision with electrons (electrons) transfer heat to neutrals, can be expected (Kholodny-Ivanov and Mikhailov, 2012). Thus Tn should be lower than Te and Ti. But during nighttime, Tn ~ Te. Truhlik et al. (2009) also observed, that Te ~ Tn during nighttime.

3.3. Diurnal variability of electron–ion–neutral temperature ratios

Fig. 6 represents diurnal variation of Te/Tn (blue), Ti/Tn (red) and Te/Ti (green) over half a solar cycle (1995–2000). Diurnal characteristics of Te/Tn, Ti/Tn and Te/Ti are morning peak during sunrise, then daytime trough/almost constant value, secondary enhancement during sunset, thereafter minimum and almost constant value during nighttime till sunrise. However, as solar activity increases this diurnal trend gets distorted and amplitude of secondary enhancement reduces and merges with daytime values. The morning peak of Te/Tn and Te/Ti is attained at 06.00 LT, while that of Ti/Tn is observed at 07.00 LT. The values of morning peak for Te/Tn, Ti/Tn and Te/Ti varies from (5.9–3), (2.3–1.3) and (2.8–2.3) respectively over half solar cycle (1995–2000). This peak for Te/Tn, Ti/Tn decreases with increasing solar activity, however for Te/Ti the value first decreases and thereafter increases with increasing solar activity. The morning peaks infer that electron is relatively sensitive than ion and neutrals. The secondary enhancement observed for Te/Tn, Ti/Tn and Te/Ti occurs during sunset/evening time (16–18 LT). The evening enhancement is much lesser in amplitude compared to morning peak and is more pronounced during low solar activity years. The evening enhancement for Te/Tn is maximum in amplitude, clear and distinct during low (1995, 1996) and mid (1997, 1998) solar activity years, but merges with Ti/Tn and Te/Ti during high solar activity years (1999, 2000). On the other hand evening peak for Ti/Tn and Te/Ti are almost same during 1995–1997, but Te/Ti reduces in magnitude and flattens during 1998–2000.

During the quiet hours/ nighttime Te, Ti and Tn attains ~ constant value and exhibits a uniform behaviour. In the absence of solar flux, which plays key role in determining the thermospheric dynamics; Te, Ti and Tn attain equilibrium with each other. Thus, the ratios for Te/Tn, Ti/Tn and Te/Ti during nighttime remain within the range 1–1.3. The ratios show almost uniform behaviour during night hours as the electron temperature is almost constant during night time, thus, temperature difference between electrons and neutrals become almost negligible. Truhlik et al. (2009) have also reported that electrons and neutrals are in thermal equilibrium, during nighttime.

During daytime (10.00–16.00 LT), when solar flux becomes almost steady due to constant solar Zenith angle; Te/Tn, Ti/Tn and Te/Ti show a slight trough/steady state in diurnal pattern. The values are almost similar for each ratio curve during day time. Thus, the average during daytime has been obtained for Te/Tn, Ti/Tn and Te/Ti. To analyse the effect of increasing solar activity over half solar cycle, the day time averages have been analysed with respect to $F_{10.7}$ (solar flux). Fig. 7, represents variation of daytime averages of Te/Tn, Ti/Tn and Te/Ti with corresponding $F_{10.7}$ during each year (1995–2000). It is interesting to note that Te/Tn, and Ti/Tn show a linearly inverse trend with yearly $F_{10.7}$ values during daytime with good co-relation coefficient, but Te/Ti does not appreciably depend linearly on $F_{10.7}$. Te/Ti shows nearly linear relation similar to Te/Tn and Ti/Tn, although the increasing rate with solar activity is very small. This indicates that during daytime Te/Tn and Ti/Tn strongly get affected by solar flux, Te/Ti gets modulated not only by solar flux but other factors like plasma drifts through electric and magnetic field interactions, alignment of geomagnetic lines etc also affects it.

3.4. Relative variations of Te, Ti and Tn on diurnal scale

In this section authors have tried to study variation of each ionospheric temperature with respect to average/ mean of ionospheric temperatures. Fig. 8 represents diurnal variation of relative Te (blue), Ti (red) and Tn

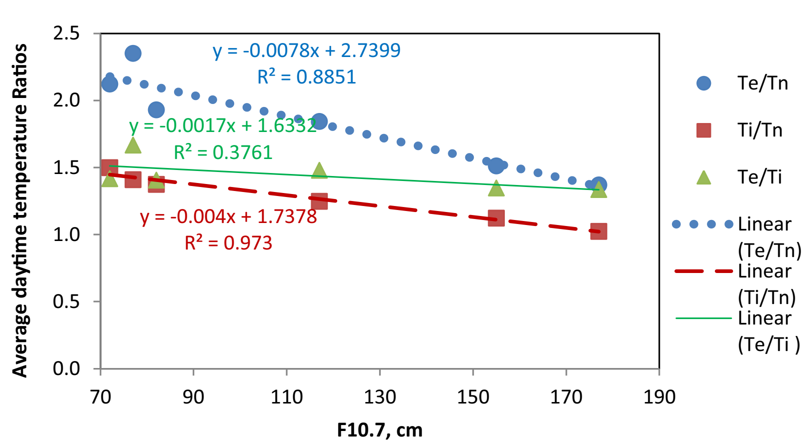

Fig. 7. Variation of daytime averages of Te:Tn, Ti:Tn and Te:Ti with corresponding $F_{10.7}$ of each year from 1995 to 2000.

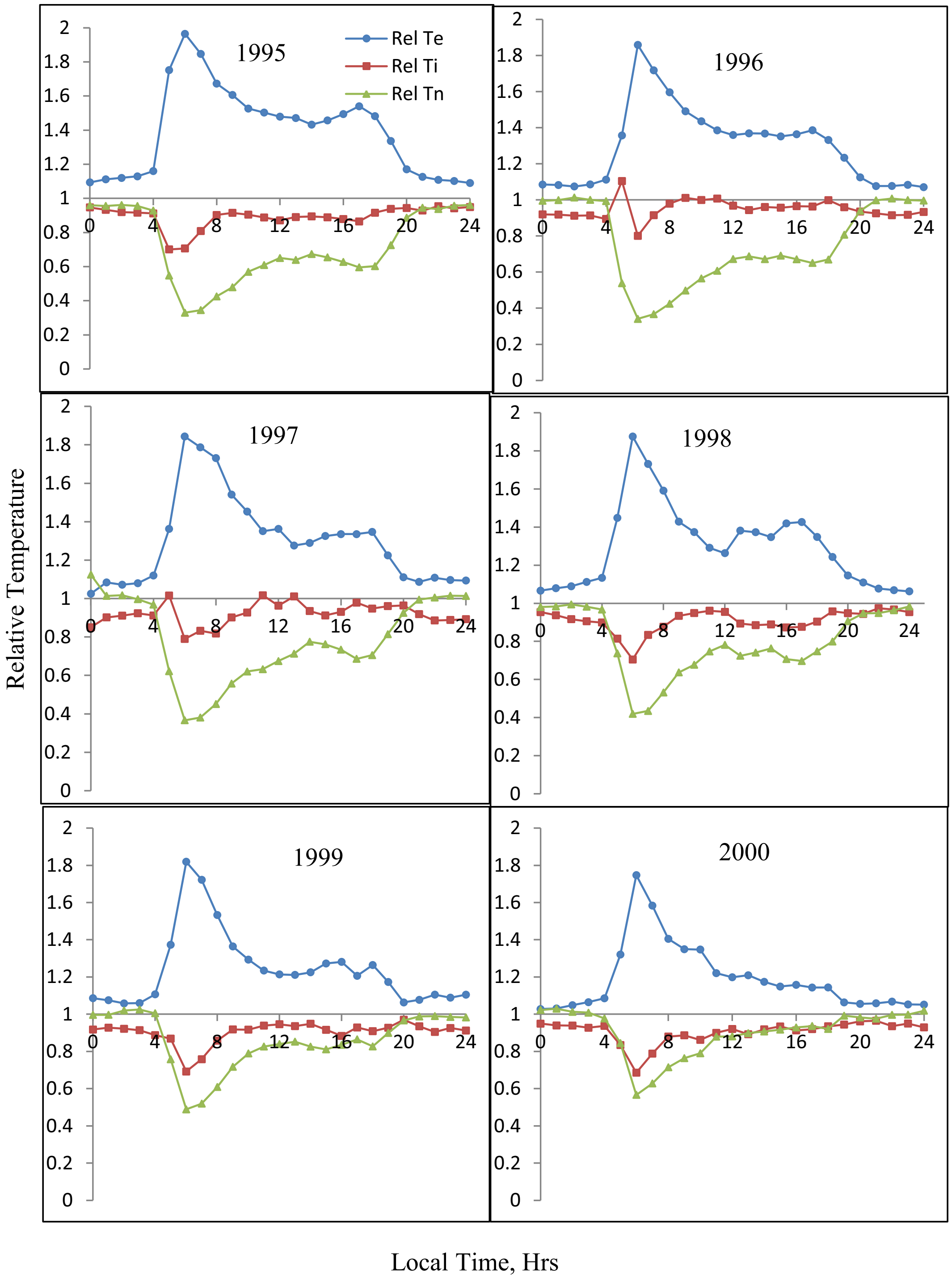

Fig. 8. Diurnal variation representation of relative Te (blue), Ti (red) and Tn (green) over half solar cycle (1995–2000). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(green) over half solar cycle (1995–2000). The equation for studying relative variation is given by - Relative Te = Te/((Te + Ti + Tn)/3), similarly Relative Ti = Ti/((Te + Ti + Tn)/3) and Relative Tn = Tn/((Te + Ti + Tn)/3). Thus if relative Te = relative Ti = relative Tn = 1; it implies that Te, Ti and Tn are in equilibrium with each other. Fig. 8, provides an excellent opportunity to understand the individual deviation of Te, Ti and Tn from average/ mean values of ionospheric temperatures.

During sunrise/morning peak the deviation is maximum, with Te showing maximum deviation on higher side, Tn on lower side and Ti lies in between on the lower side. Relative Te, during sunrise, deviates ~2–1.7 times from mean values. Tn shows maximum deviation on lower side.

Relative Tn varies from ~0.3 to 0.5, which infers that relative Tn deviates by ~1.7–1.5 times from the mean value on lower side. Ti acquires a mid range, closer to average values and attains a value of ~0.7 in all the years, during sunrise peak. It suggests that Ti is 1.3 times relative to average value on the lower side. All the deviations in ionospheric temperatures (Te, Ti and Tn) during sunrise peak decrease with increasing solar activity.

Similar kind of observations as during sunrise is registered during daytime. Relative Te and Tn show maximum deviation on higher and lower side respectively, while relative Ti acquires mid values on lower side. This observation is very evident during low (1995, 1996) and mid (1997, 1998) solar activity years. During high solar activity years (1999, 2000), the daytime difference between relative Ti and Tn decreases and becomes negligible, while Te shows positive deviation from average values. During daytime, the deviation of Te, Ti and Tn decreases with increasing solar activity.

During evening enhancement, Te and Tn show maximum deviation from average values on higher and lower side and the asymmetry reduces with increasing solar activity. However, the relative Ti attains value approaching to average values during all the years and is least deviated/affected.

Nighttime behaviour is quite interesting. During nighttime in absence of Sun, the source of photoionization, relative Te, Ti and Tn exhibit different behaviour as compared to sunrise/day/evening time. The neutral and plasma temperatures (Ti, Te and Tn) attain almost an equilibrium temperature nearing to average values, with Te slightly being on upper side and Ti on lower side and Tn attaining mid values. Ti attains higher values on lower side as compared to Tn during almost all the years (1995–2000) suggesting that plasma cools down much more rapidly than neutrals during nighttime.

From the above results and discussions we can summarize that photoionization produces photoelectrons, which act as main source of energy for thermal electrons. This energy is source of heating of electrons. The same energy via inelastic collisions gets transmitted to ions and neutrals, thus heating ions and neutrals. Although Te, Ti and Tn can be affected by several factors like alignment of geomagnetic field lines, plasma drifts, etc. (whose effects are out of the scope of present paper). The key factor in determining ionospheric temperatures remains energy transmitted via collisions through photoelectrons. At low latitudes, Te is greatly affected by local heating and cooling processes. The Te increases rapidly during sunrise owing to low electron density and cools down during daytime when photoionization increases the number density via collisions. During nighttime, in absentia of source of ionization, plasma and neutrals cool down to attain an equilibrium temperature. But, Plasma losses heat through collisions and cools down more rapidly than neutrals.

4. Conclusions

Annual variations in temperatures of plasma (electron–Te, ion–Ti) using SROSS-C2 satellite and neutral (Tn) using NRLMSIS-00 (neutral atmospheric model); have been investigated and their ratios have been compared during half solar cycle (year 1995–2000, $F_{10.7} \sim 72$–190) over Indian subcontinent (over 5–35°N geog. latitude and 65–95°E geog. longitude) at ~500 km altitude. From present study following can be concluded.

1. Plasma temperatures (Te and Ti) exhibit similar diurnal features like morning peak, day time trough, evening enhancement and nighttime minimum. However, neutral temperature (Tn) represent completely different features – it increases from about 07 LT to 18 LT and then decreases till 21 LT, then becomes almost constant and minimum during nighttime. Magnitude of Te and Ti including morning peak, evening enhancement, and daytime values reduces with increasing solar activity. In contrast to plasma temperatures, Tn increases with increasing solar activity.
2. During daytime Te and Ti decreases, while at nighttime Te and Ti increases as solar activity increases around the geomagnetic equator.
3. During nighttime, ionospheric temperatures show uniform behaviour and attain, almost an equilibrium temperature with each other. However, plasma losses energy/heat through collisions faster as compared to neutrals thus cools down faster.
4. The ratio (Te/Tn, Ti/Tn and Te/Ti) comparisons show higher sensitivity of electrons over ions and neutrals. The magnitude of Te/Tn, Ti/Tn including sunrise peak, daytime values and evening enhancement reduces uniformly with increasing solar activity and establish a linearly inverse relationship with solar flux ($F_{10.7}$). However, Te/Ti shows nearly linear relation similar to Te/Tn and Ti/Tn, although the increasing rate with solar activity is very small – suggesting involvement of other factors in determining its diurnal trend. During nighttime ionospheric temperatures attain equilibrium state, thus the ratios for Te/Tn, Ti/Tn and Te/Ti remains within the range 1–1.3.
5. During low solar activity years, the deviation of Te, Ti and Tn from equilibrium or mean of ionospheric temperatures is maximum and this deviation reduces with increasing solar activity.

Acknowledgments

Authors are thankful to All India Council for Technical Education (AICTE), New Delhi for financial assistance under the Research Promotional Scheme (No. 8023/RID/RPS-38). We acknowledge the online data from Omniweb NSSDC site for providing $F_{10.7,}$ and NRLMSIS-00 atmospheric model (http://ccmc.gsfc.nasa.gov/modelweb/

models/nrlmsise00.php) for providing neutral temperature values for investigating its diurnal variations and ratio comparisons. Authors are also thankful to the potential reviewers for the suggestions and comments which helped us to improve the manuscript.

References

Aggarwal, M., Joshi, H.P., Iyer, K.N., 2007. Solar activity dependence of electron and ion temperatures using SROSS-C2 RPA data and comparison with IRI model. J. Atmos. Sol. Terr. Phys. 69, 860–874.

Aggarwal, M., Joshi, H.P., Iyer, K.N., Jivani, M.N., 2009. Studies of electron and ion temperatures at 500 km altitude during sunrise using Indian SROSS C2 satellite. Adv. Space Res. 43, 273–281.

Balan, N., Bailey, G.J., 1995. Equatorial plasma foun tain and its effects: Possibility of an additional layer. J. Geophys. Res. 100, 21421–21432.

Balan, N., Oyama, K.I., Bailey, G.J., Fukao, S., Watanabe, S., Abdu, M. A., 1997. A plasma temperature anomaly in the equatorial topside ionosphere. J. Geophys. Res. 102, 7485–7492.

Banks, P.M., 1967. Ion temperature in the upper atmosphere. J. Geophys. Res. 72, 15323–15330.

Bardhan, A., Aggarwal, M., Sharma, D.K., Rai, J., 2014. Equinoctial asymmetry in low latitude ionosphere as observed by SROSS-C2 satellite. J. Atmos. Sol. Terr. Phys. 117, 101–109.

Bhuyan, P.K., Garg, S.C., Subrahmanyam, P., 2002. Electron & Ion temperature and electron density at ± 10° Magnetic Latitudes from SROSS C2 measurements over India and comparison with the IRI. Adv. Space Res. 29, 865–870.

Bhuyan, P.K., Chamua, M., Subrahmanyam, P., Garg, S.C., 2004. Diurnal, seasonal and latitudinal variations of ion temperature measured by the SROSS C2 satellite in the Indian zone equatorial and low latitude ionosphere and comparison with the IRI. J. Atmos. Sol. Terr. Phys. 66, 301–312.

Bhuyan, P.K., Chamua, M., Subrahmanyam, P., Garg, S.C., 2006. Effect of solar activity on diurnal and seasonal variations of electron temperature measured by the SROSS C2 over Indian latitudes. Adv. Space Res. 37, 885–891.

Brace, L.H., 1975. Thermal structure of the ionosphere. Rev. Geophys. 13, 882-823.

Da Rosa, A.V., 1966. The theoretical time-dependent thermal behaviour of the ionospheric electron gas. J. Geophys. Res. 71, 17.

Fejer, B.G., 1991. Low latitude electrodynamic drifts: a review. J. Atmos. Terr. Phys. 53, 677–693.

Garg, S.C., Das, U.N., 1995. Aeronomy experiment on SROSS-C2. J. Spacecraft Technol. 5, 11–15.

Kholodny-Ivanov, G.S., Mikhailov, A.V., 2012. The Prediction of Ionospheric Conditions. Springer Science and Business Media.

McClure, J.P., 1969. Diurnal variation of neutral and charged particle temperatures in the equatorial F region. J. Geophys. Res. 1, 279–291.

Nayar, S.R.P., Alexnder, L.T., Radhika, V.N., Thomas, J., Subrahmanyam, P., Chopra, P., Bahl, M., Maini, H.K., Singh, V., Singh, D., Garg, S.C., 2004. Study of the evolution of Te and Ti at the low-latitude upper ionosphere using SROSS C2 RPA observations. J. Atmos. Sol. Terr. Phys. 66, 1075–1083.

Picone, J.M., Hedin, A.E., Drob, D.P., Aikin, A.C., 2002. NRLMSISE-00 empirical model of atmosphere: Statistical comparisons and scientific issues. J. Geophys. Res. 107 (A12), 1468.

Schunk, R.W., Nagy, A.F., 1978. Electron temperatures in the F region of the ionosphere: theory and observations. Rev. Geophys. Space Phys. 16, 355–399.

Schunk, R.W., Scherliess, L., Sojka, J.J., 2003. Recent approaches to modelling ionospheric weather. Adv. Space Res. 31, 819–828.

Sharma, D.K., Rai, J., Israil, M., Shalni, P., Subrahmanyam, P., Chopra, P., Garg, S.C., 2003. Sunrise effect on ionospheric temperature as measured by SROSS-C2 satellite. J. Indian Geophys. Union 7, 117–123.

Sharma, D.K., Chand, R., Israil, M., Rai, J., 2005. Variation of electron and ion temperatures ratio over the Indian region during the period 1995–1999 as measured by SROSS-C2 satellite. J. Atmos. Sol. Terr. Phys. 67, 1443–1447.

Sharma, P.K., Pathak, P.P., Sharma, D.K., Rai, J., 2010. Variation of ionospheric electron and ion temperatures during periods of minimum to maximum solar activity by the SROSS-C2 satellite over Indian low and equatorial latitudes. Adv. Space Res. 45, 294–302.

Slominska, E., Rothkaehl, H., 2013. Mapping seasonal trends of electron temperature in the topside ionosphere based on DEMETER data. Adv. Space Res. 52, 192–204.

Titheridge, J.E., 1998. Temperature in the upper ionosphere and plasmasphere. J. Geophys. Res. 103, 2261–2277.

Truhlik, V., Bilitza, D., Triskova, L., 2009. Latitudinal variation of the topside electron temperature at different levels of solar activity. Adv. Space Res. 44, 693–700.

Watanabe, S., Oyama, K.I., Abdu, M.A., 1995. Computer simulation of electron and ion densities and temperatures in the equatorial F-region and comparison with Hinotori results. J. Geophys. Res. 100, 14581–14590.