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Variability of ionospheric parameters during solar minimum and maximum activity and assessment of IRI model

D.K. Sharma [a,*], Malini Aggarwal [b], Ananna Bardhan [a]

[a] Department of Physics, Manav Rachna University, Faridabad 121001, India
[b] Indian Institute of Geomagnetism, Mumbai 410206, India

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Abstract

The ionospheric parameters (electron and ion plasma temperatures (Te and Ti) and total ion density, Ni) as obtained by the Indian SROSS-C2 satellite (altitude ~500 km) have been investigated during low (year 1995, $F_{10.7} \sim 77$ sfu) and high (year 2000, $F_{10.7} \sim 177$ sfu) solar activity periods. The region under study spans over 5°S-30°N geomag. latitude and 60–100°E geog. longitude over the Indian sector. The observations are compared with the modelled values using IRI-2007 and IRI-2012 versions to assess model predictability. We found that minimum plasma temperatures (Te and Ti) in nighttime gets twice hotter whereas maximum temperatures in early morning gets reduced by half (cooler) when the solar flux gets doubled indicating a direct relation of Te and Ti with solar flux, F10.7 in nighttime but inverse in the morning hours. The ion density (Ni) exhibits solar activity dependence throughout the day and increases by one order when solar activity gets doubled. The modelled Te and Ti are found in agreement to the observed values for high solar activity over both the regions. Whereas the discrepancy exists during low solar activity period over both the regions with over-/under-estimated values in nighttime/morning and noontime respectively. The latest IRI-2012 model improves the nighttime Te and Ti whereas the modelled Ni is found in complete agreement to the observations.

Keywords: Electron temperature; Ion temperature; Ion density; SROSS-C2 satellite; IRI-2007; IRI-2012 model

1. Introduction

The F2 region (>150 km) of the Earth's ionosphere is a complex and important region owing to the society's technological dependence on satellite's communication and navigation systems. Thus, understanding, forecasting and monitoring of the changes in the ionosphere has become extremely important to suggest the corrections for precise measurements. It is also well known that the ionosphere responds in a complex manner to the geophysical conditions like solar flux, electro-dynamic drifts, etc., with a lot of variability and hence various ionospheric parameters (like electron/ion densities, total electron content (TEC), electron and ion temperatures) behave partly in regular and irregular manner exhibiting daily, seasonal, annual, latitudinal and solar cycle variations (e.g. Kawamura et al., 2002; Sharma et al., 2005, 2010; Aggarwal et al., 2007, 2009 and more). Thus understanding of its complexity and forecasting has become an important field of present day research to suggest improvements also in the existing ionospheric models.

Most of the ionospheric studies are mainly based on the electron density and TEC observations whereas lesser exists for ionospheric plasma temperatures which is because of a fewer ground (radar)- and satellite-based measurements (Hinotori, OGO-2, AE-C, AE-E and IK-24,

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

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SROSS C2, FORMOSAT-1 and DEMETER) to understand the ionospheric behaviour (for eg., Balan et al., 1997; Aggarwal et al., 2007, 2009; Sharma et al., 2010; Borgohain and Bhuyan, 2010; Slominska and Rothkaehl, 2013; Bardhan et al., 2015 and more). And the database over equatorial and low latitudes is even sparse, particularly over the Indian subcontinent where the morphology and dynamics of equatorial/low latitude ionosphere is also considered notably different from that of mid and high latitude. This is because either the orbits of satellite are very high (300–3000 km) or is highly elliptical. However, the SROSS-C2 mission is considered an opportunity for studies where the orbit is just above the F-region peak (∼400–500 km altitude) and the orbit ellipticity is also much less (Garg and Das, 1995).

The plasma temperatures (electron, Te and ion, Ti) similar to electron density in the upper ionosphere have been found to demonstrate solar activity dependence and also exhibits diurnal, seasonal, altitudinal and latitudinal variations (Kohnlein, 1986; Bilitza, 1991; Oyama et al., 1996; Prabhakaran Nayar et al., 2004). Kohnlein (1986) using observations from six satellites (AE-C, AE-D, AE-E, ISIS-1, ISIS-2, OGO-6), five incoherent scatter stations (Arecibo, Chatanika, Jicamarca, Millstone Hill, St Santin) and rocket measurements found that above up to 1500 km, the Te is on average higher than Ti and above ∼2000 km, Te is equal to Ti. Bilitza (1991) using various radar and satellite measurements of ionospheric temperatures presented the shortcomings and needs of future data for the model. An interesting feature in Te called as "morning overshoot" and "evening overshoot" was found by Oyama et al. (1996) using the Hinotori observations (∼600 km). This morning overshoot in Te was observed during winter in high solar activity whereas evening overshoot was found at higher latitudes in all seasons with more enhancements in winter. These phenomenon also showed longitudinal differences. Using Indian satellite: SROSS C2, Prabhakaran Nayar et al. (2004) found morning and evening enhancements in both Te and Ti which evolved with season, altitude, latitude and solar activity respectively. The global studies of topside ion densities (O^+, H^+, He^+ and N^+) obtained by ACTIVE mission, AE and OGO-5 satellites data made by Truhlik et al. (2005) found these ions to be a linear function of solar activity whereas the upper transition height to be a non-linear function of F10.7 respectively. An interesting feature of strong equinoctial asymmetry in daytime O^+ during solar minimum is found by Bardhan et al. (2014) using SROSS C2 data over Indian region. Recent studies reported by Bardhan et al. (2015) based on the temperature ratios of plasmas and neutrals (Te, Ti and Tn) during different seasons with varying solar activities (year 1995–2000) found an equilibrium between Te, Ti and Tn and plasma cooling faster than neutrals in the nighttime.

The aim of present study is to examine the ionospheric behaviour using various ionospheric parameters (electron and ion temperatures (Te, Ti) and ion densities, Ni) as obtained by Indian SROSS C2 satellite and examine the relation between plasma temperatures and ion densities during a solar minimum (1995, F10.7 ∼ 77) and maximum (2000, F10.7 ∼ 177) year for equatorial and low-latitude regions respectively. As the latest ionospheric model: IRI-2012 has been recently released, the observations have also been compared with the modelled values to assess and validate the model. Here, Section 2 gives the introduction of data used and model followed by Results in Section 3 and Discussion in Section 4. Finally, Conclusions are presented in Section 5.

2. Data used

2.1. SROSS-C2 data

The ionospheric parameters: electron and ion temperatures (Te, Ti) and ion densities, Ni are obtained using a Retarded Potential Analyser (RPA) payload aboard the SROSS-C2 satellite, as launched by Indian Space Research Organization (ISRO) on May 4, 1994 around 420 × 620 km altitude. The detailed description of the SROSS-C2 mission and the procedure for retrieval of plasma parameters have been illustrated by Garg and Das (1995). The ionospheric plasma parameters (Te, Ti and Ni = sum of O^+, O_2^+, H^+, He^+) are obtained at an average altitude of ∼500 km over the Indian region (∼5–35°N geog. Lat., ∼60–100°E geog. Long.). The hourly observed parameters are grouped into bins of 1 degree latitude to obtain the contour plots without any longitudinal selection. If there were more than one satellite pass for a given local time in a season then the averaged values are considered. The ionospheric region of study is above the F2-peak (>350 km) for solar minimum (year 1995) and maximum (2000) period respectively.

2.2. IRI (International Reference Ionosphere)

The study of ionospheric variability results in the improvement and development of ionospheric models serving a large number of users ranging from radio operators to satellite/rocket instrument designers to operators of Earth observing satellites. One of the most widely used ionospheric model is the International Reference Ionosphere (IRI), which describes the monthly median values of electron density, electron temperature, ion composition (percentage of O^+, H^+, He^+, N^+, NO^+, O_2^+ and Cluster ions), ion temperature, ionospheric electron content up to a specified upper height limit, ion drift at magnetic equator, spread-F occurrence probability, and auroral boundaries. These parameters are expressed as functions of height, latitude, longitude, time of day (LT or UT), and date (Bilitza et al., 2014). The major data sources include the worldwide network of ionosondes, the powerful incoherent scatter radars (Jicamarca, Arecibo, Millstone Hill, Malvern, St. Santin), the ISIS and Alouette topside sounders, and in situ instruments on several satellites and rockets. The

IRI model requires specification of 6 parameters – latitude, longitude, twelve months running average Zurich sunspot number representing solar activity (R_{z12}) or solar flux, $F_{10.7}$, month, hour (UT or LT), and altitude. Over the years testing and modifications of IRI has led to improvements through several versions (IRI-80, IRI-86, IRI-90, IRI-95, IRI-2000, IRI-2007, IRI-2012). The detail description of latest model: IRI 2012 is reported in Bilitza et al., (2014).

In the present study the SROSS-C2 satellite observations over Indian region have been compared with the modelled values obtained by using previous IRI-2007 and latest IRI-2012 models to assess the predictions and suggest corrections in the model. The modelled values of ionospheric plasma temperatures (electron and ion temperatures – Te and Ti) and electron density (Ne, assuming Ne ~ Ni, ion density) have been obtained using IRI – 2007 (http://ccmc.gsfc.nasa.gov/modelweb/models/iri_vitmo.php) and IRI-2012 (http://omniweb.gsfc.nasa.gov/vitmo/iri2012_vitmo.html) models respectively. The modelled values of Te, Ti and Ne have been obtained using averaged monthly values of F10.7 for each month (January - December) at an average altitude of ~500 km for equatorial (0° geomag latitude) and low-latitude (15° geomag latitude) and 77°E longitude using URSI for F peak model, NeQuick for Ne topside and TBT-2012 for topside Te options respectively The yearly ionospheric variability of modelled Te, Ti and Ni is obtained for low (year - 1995) and high (year - 2000) solar activity years by averaging the values from January to December months for same local time (0–24 h) during each year (1995 and 2000) respectively.

3. Results

3.1. Variability of plasma temperatures (electron (Te) and ion (Ti)) and total ion density (Ni)

The radio flux F10.7 was 77 sfu (solar flux unit, 10^{-22} $W/m^2/Hz$) in year 1995 (solar minimum) which is more than doubled to 177 sfu in year 2000 (solar maximum) respectively. The variability of observed Te, Ti and Ni varying with local time and geomagnetic latitude in 5°S to 30°N obtained for solar minimum (1995) and maximum (2000) period is represented in Fig. 1. Here the contours are hourly values of Te, Ti and Ni with 1 degree latitude bins when the satellite visibility occurs (~7–12 min) during daytime and nighttime over Indian region (Aggarwal et al., 2007). Note lesser data is available above 20°N magnetic latitude.

During solar minimum, after sunset the Te is minimum ~600–800 K in nighttime which does not varies much in the period 1800–0400 LT over both equatorial and low latitudes but start rising sharply around ~0500 LT with peak around ~0700 LT (~4000–4400 K). This higher Te is observed up to 20°N latitude in morning hours but intense over equatorial regions. After ~0800 LT, the Te decreases and becomes stable in noontime to evening-time up to ~1900 LT after which the electron plasma rapidly cools to minimum values. An evening enhancement in Te is observed (~2200 K) around 1800 LT. During solar maximum, the similar general trend is observed for Te, but the magnitudes are different. After sunset, higher Te (~1200 K) is observed with lower in morning and daytime Te (~3200 K, ~1600 K) in solar maximum than solar minimum period respectively. We found the Te to be inversely related with solar flux during the daytime. A higher increase of Te is observed above 20°N latitudes during noontime in both solar activities. These observations represent the general trend of Te exhibiting a sharp morning enhancement, a daytime trough, an evening enhancement and stable nighttime values. During early morning hours, the high Te occurs due to the photoelectrons heating the low density species in the morning (Schunk et al., 2000). This morning peak is prominent at the low latitude ionosphere due to the downward vertical EXB plasma drift which decreases the electron density followed by an increase in Te (Su et al., 1996; Balan et al., 1997). Within an hour or two, the electron densities increases and cause electron cooling and restore Te to a lower equilibrium value. A secondary maximum is also observed before sunset (Otsuka et al., 1998; Bhuyan et al., 2002). Afternoon enhancement in Te at the low-latitude region is observed to be strongly affected by both the EXB drift and the neutral wind (Oyama et al., 1996).

During solar minimum, throughout nighttime Ti is lowest (~400–700 K) and increases slowly in early morning hours up to ~2400 K in 0–20°N latitudes. During daytime (0900–1800 LT), the Ti is almost stable (~1000–1400 K). Whereas in solar maximum year, the nighttime Ti is higher (~800–1000 K) than solar minimum and is almost constant (~1200–1400 K) throughout the daytime. An evening enhancement in Ti is also observed (~1400 K) around 1800 LT in solar minimum year. Similar to Te, the Ti is found to be dependent on solar flux in nighttime but directly related during the daytime.

The Ni is represented as Log Ni for a better picture in the same frame. The general diurnal characteristics of Ni is minimum during nighttime, gradual increase during sunrise as photoionization initiates, day time peak, then again gradual decrement till the nighttime minimum due to higher rate of recombination is achieved. During solar minimum, as expected the Ni is lower after post-sunset ($10^{10.2}$–$10^{10.4}$ m^{-3}) and becomes minimum in post-midnight hours (up to $10^{9.4}$ m^{-3}) up to 0600 LT. After this time, it start enhancing and becomes maximum during noontime (1100–1700 LT) up to $10^{11.6}$ m^{-3} in 5°S to 10°N latitudes respectively. At other latitudes the Ni is slightly lower in noontime, up to $10^{11.2}$ m^{-3}. During solar maximum, the Ni is lower ($10^{11.4}$-$10^{11.6}$ m^{-3}) during post-sunset period and is lowest ($10^{10.8}$–$10^{11.2}$ m^{-3}) during early morning hours (0300–0600 LT) which increases and becomes stable for the whole day (0800–2000 LT, up to ~$10^{12.6}$ m^{-3}). An interesting post-sunset enhancement (1900–2200 LT) is observed during solar maximum in the equatorial regions

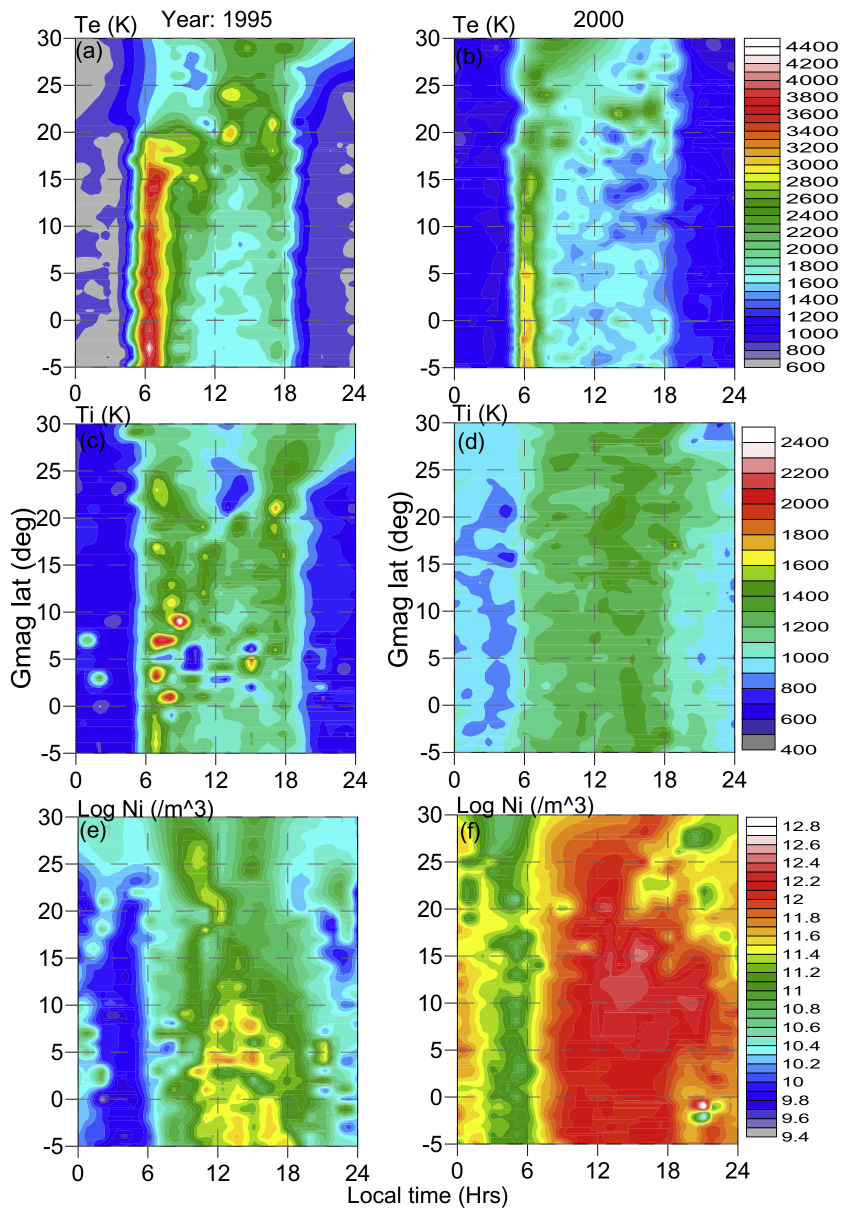

Fig. 1. (First column) Annual variability for observed ionospheric plasma temperatures (electron, Te, (a) and ion, Ti, (c)) and total ion density (Ni, (e)) with local time and geomagnetic latitude (5°S to 30°N) during solar minimum (1995) period respectively. (Second column) Same as first column but for solar maximum (2000) respectively.

and an early decrease of Ni is observed above 20°N latitudes. A clear solar activity dependence of Ni is observed throughout the day. We found here that the equatorial ionization anomaly in Ni is absent in the yearly variation at ~500 km altitude which is in agreement to Hinotori satellite observations (Bhuyan and Chamua, 2002) and the EIA have been reported to be stronger in equinoxes but weaker in solstices using SROSS C2 measurements (Bhuyan et al., 2003) respectively.

3.2. Comparison of observed parameters with model: IRI-2007 and IRI-2012

The observed parameters (Te, Ti and Ni) are extracted for equatorial (5°S-5°N geomag.) and low-latitudinal (10–20°N geomag.) regions for both solar activities as represented in first column of Fig. 2. These observed values of ionospheric parameters are then compared with the IRI models: 2007 and 2012 versions (column: second and third in Fig. 2) for 0° and 15°N geomagnetic latitude respectively. The derived Te, Ti and Ni are obtained along 77° E meridian and ~500 km altitude for each month and averaged for yearly variability. For accessing the model quantitatively, we obtained the relative hourly values (modelled/observed) of these parameters for both models as shown in the last two columns (Fig. 2). Here the line at ratio 1 represents the complete agreement in observed and modelled values whereas higher/lower than 1 represents the over-/under-estimation of predicted modelled values respectively.

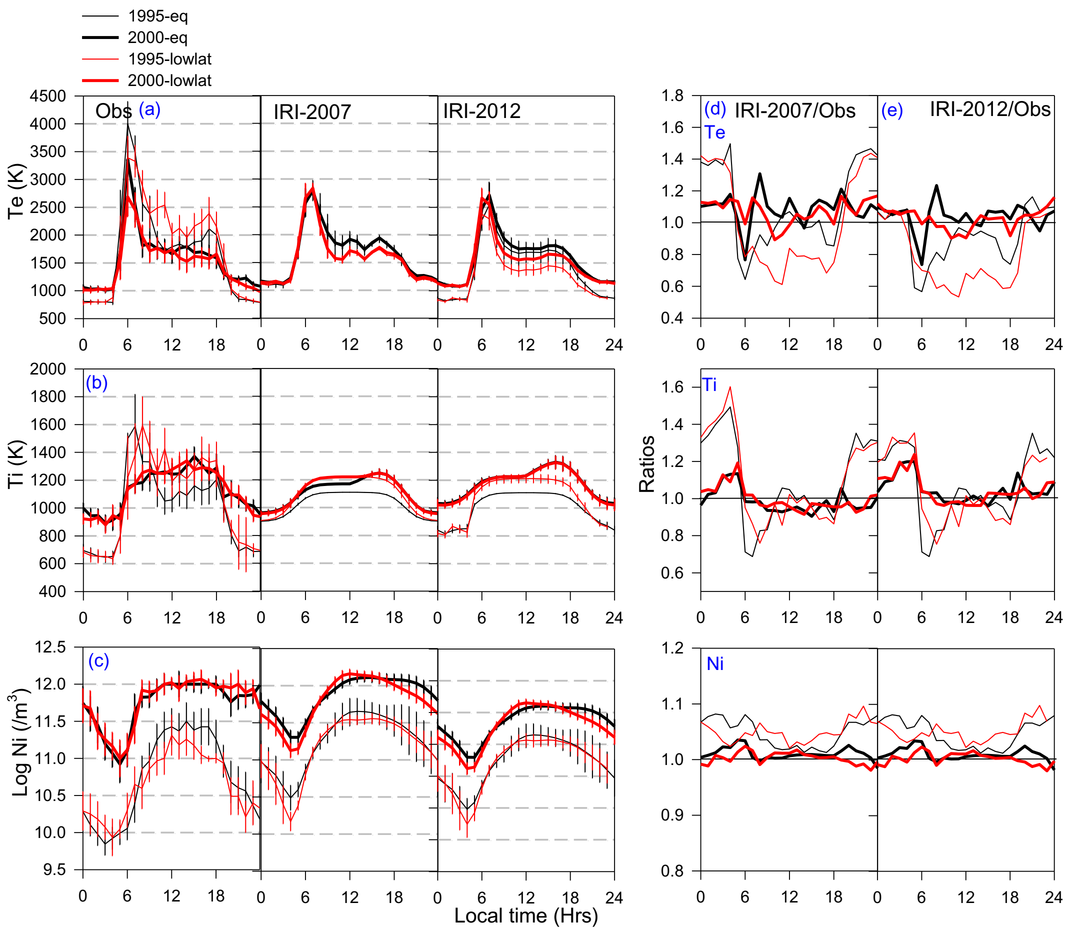

Fig. 2. Diurnal variation of observed (first column) and modelled (IRI-2007, second column and IRI-2012, third column) values for (a) Te, (b) Ti and (c) Ni and the ratio of observed and modelled ((d) IRI-2007 and (e) IRI-2012, last two columns) of corresponding parameters for both equatorial and low latitude regions during low (1995, thin-line) and high (2000, thick-line) solar activity period respectively. Here the ratio 1 represents equal observed and modelled values whereas above/below 1 represents the higher/lower modelled values respectively.

During both solar activity periods, the observed Te exhibits a diurnal feature: minimum in nighttime and sudden increase during early hours and then a daytime stable decrease. From Fig. 2(a), over equator the nighttime Te is found to be higher and daytime Te lower during solar maximum than solar minimum respectively. Over the low-latitude regions, the nighttime Te exhibit behaviour similar to equatorial region for both solar activities but the morning Te is much lower (~2600–3400 K) and daytime Te is higher (~2200–2600 K) during solar minimum than the equatorial region. In short, during nighttime, the Te behaviour is similar for both latitudes and solar activities (direct) whereas during daytime, inverse relation with solar activity is more clear over low-latitude than equator as the difference in Te of two solar activities is also higher over low-latitudes. A secondary enhancement is also observed in Te during noontime for solar minimum over low-latitudes. This afternoon enhancement in Te at low-latitude region is found to be strongly affected by both the EXB drift and the neutral wind (Oyama et al., 1996). The evening enhancement in observed Te is found during solar minimum for both regions (higher over low latitude) respectively.

The observed Ti (Fig. 2(b)) exhibits similar behaviour as Te in nighttime for both the regions. During solar minimum over both latitudes, a rise in early morning Ti (up to 1600 K, 0700 LT) is observed and becomes stable in daytime (1100–1800 LT). During solar maximum, the morning rapid rise of Ti is not observed, but the Ti increases slowly and becomes stable during daytime. The solar activity dependence in Ti is observed over both the regions during daytime and higher/lower Ti corresponds to high/low solar activity respectively. The observed Ni (Fig. 2(c)) over both the regions exhibits similar diurnal feature and Ni is highly dependent on solar flux (higher the F10.7-higher the Ni).

Both model values (second and third columns in Fig. 2) also exhibits similar diurnal pattern to the observations for all three parameters (Te, Ti and Ni) over both regions and solar activities except the Ti during solar minimum over both the regions. The model Te by IRI-2007 exhibits similar behaviour for solar minimum and maximum throughout the day for both regions but represents difference during daytime for equatorial (~2000 K) and low latitude (~1800 K) regions respectively. The modelled Te by IRI-2012 exhibits higher values throughout the day in solar maximum than minimum with lower values over low-latitude than equator showing clear solar activity dependence (direct) throughout the day. The modelled Ti by IRI-2007 is lower for both regions during solar minimum than maximum throughout the day with lower values for equatorial than low-latitude during daytime whereas the modelled Ti by IRI-2012 exhibits also a solar dependence throughout the day and the values are higher over low-latitudes in solar minimum but similar in solar maximum over both regions. The modelled Ni values by both models are higher for solar maximum than minimum year and similar for both the regions respectively.

The relative Te (Fig. 2(d) and (e)) represents that both model versions and regions are in agreement for high solar activity. For the low-solar activity, over the low-latitude higher discrepancy existed throughout the day (over-/under-estimated in nighttime (by IRI-2007)/morning hours and noontime) respectively and over the equator, predicted Te by both the models are closer during noontime but over-/under-estimated in nighttime/morning hours respectively. The latest IRI2012 model exhibits nighttime Te closer to the observations.

Similar to Te, over the low-latitudes the modelled Ti is in agreement for both solar activity throughout the day whereas over equator, the modelled Ti is in agreement in noontime but discrepancy existed (higher/lower in nighttime/morning hours) at other times for both solar activity. However the typical diurnal feature of noontime enhancement in year 1995 over low-latitudes is not observed by IRI. Again the nighttime modelled Ti values are improved in the latest IRI-2012 version. The modelled Ni values are found closer to the observed values indicating a good agreement over both the latitudes.

3.3. Correlation of plasma temperatures (Te and Ti) with total ion density (Ni)

As the plasma temperatures are related with plasma densities, the correlations of Te and Ti with Ni (Ni ≈ Ne, electron density) for both observed and modelled values during (a) whole day (0000–2400 LT), (b) daytime (1000–1600 LT) and (c) nighttime (2200–0400 LT) for both solar activities are investigated as represented in Fig. 3. Throughout the day (Fig. 3(a)), though the correlation between Te and Ni is poor for both observed and modelled but the observed Te ~~is~~ moderately correlates (~0.54) during solar minimum (1995) for low latitude. The Ti correlates well (both observed and model, moderate to strong, 0.5–0.75) during both solar activities and regions.

During the daytime (Fig. 3(b)), both observed Te and Ti are inversely (moderate: 0.45–0.5, equator to strong: 0.7–0.9, low latitude) related with Ni during solar minimum. During solar maximum, no relation exists of both observed and modelled Ti with Ni for both locations except the direct relation of IRI modelled Ti (moderate: 0.65–0.7, year 2000 over equator). During nighttime (Fig. 3(c)), except observed Te for low-latitudes during year 1995 (moderate and inverse) and 2000 (no relation), the observed Te and

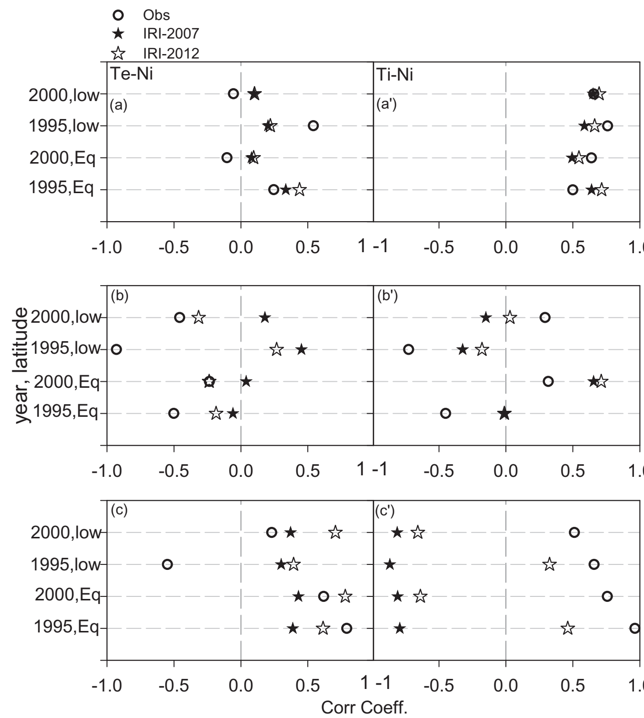

Fig. 3. Correlation of Te (left-column) and Ti (second-column) with Ni for both observed and modelled values throughout the (a, a′) whole-day, (b, b′) daytime (1000–1600 LT) and (c, c′) nighttime (2200–0400 LT) during low (1995) and high (2000) solar activity years for both the latitudinal regions respectively.

Ti are well directly correlated (Te: moderate, Ti: strong) with Ni for both years and regions. Similar strong inverse correlation (0.8) of modelled Ti and Ni by IRI-2007 is observed for both region and activity, but IRI-2012 model only represents the moderate correlation (0.6) that also during solar maximum over both regions which disagrees with the direct relation of observed Ti with Ni respectively.

4. Discussion

The ionospheric temperatures (both Te and Ti) in the F region are mainly controlled by heating, cooling and energy flow processes (Schunk and Nagy, 1978) whereas the production of electrons (plasma densities, assumed Ne ≈ Ni) is mainly controlled by the solar radiation, the loss by charge exchange with neutrals and the transport of electrons is dominated by the equatorial fountain effect. The neutral composition in the thermosphere also has a strong effect on electron density in the upper thermosphere, the electron production rate depends on the density of atomic oxygen, O due to direct photo-ionization of O, whereas the recombination loss rate is controlled by the density of N_2 due to recombination of O^+ and N_2. Thus, increase in the ratios of O/N_2 also enhances the equilibrium electron density.

The general diurnal trend of Te and Ti is exhibited by SROSS C2: minimum during nighttime, increases sharply during early morning hours and then have a stable daytime temperatures (Figs. 1 and 2). We found similar behaviour of Te, Ti and Ni for both solar activities over both latitudes except the Ti in solar maximum respectively (Fig. 2). The Te varied from ~600 to 4400 K during solar minimum (F10.7 ~ 77 sfu) and ~1200 to 3200 K for solar maximum (F10.7 ~ 177 sfu) throughout the day. Whereas Ti varied between ~400 and 2400 K during solar minimum and ~800 to 1400 K during solar maximum respectively. The nighttime Te behaviour is similar for both latitudes which increases with solar activities whereas the daytime Te decreases with increase in solar activity and the effect is more pronounced over low-latitude than equator. The Ni represented as Log Ni exhibits a solar activity dependence and varied as $10^{9.4}$ and $10^{11.6}$ m^{-3} during solar minimum and is increased by one order ($10^{10.8}$ and $10^{12.6}$ m^{-3}) during solar maximum throughout the day. A post-sunset enhancement (1900–2200 LT) in Ni during solar maximum is observed over equatorial regions (Fig. 1). This evening enhancement in Ni occurs due to the pre-reversal enhancement of electric field which occurs sometimes during sunset and then the plasma EXB is lifted upward where loss rate also reduces. As the EUV and X-ray solar radiation reaches the earth's upper atmosphere, it causes ionization of the neutral species and produces the photoelectrons with higher energies (temperatures). As these energetic photoelectrons collide with near-by other electrons, ions or neutrals, the energy is shared resulting in the decrease of energy of photoelectrons but other species (for eg. ions) gains energy causing a rise in their temperatures (Ti). The rapid increased rate is higher in Te during early morning when the electron density is also low (our Fig. 1) (Sharma et al., 2003; Aggarwal et al., 2009). However, as the day progresses, more and more electrons are produced (increases Ni) and energy share of each electron decreases leading to a lower Te. Thus, Te reaches a peak in the early morning, decreases and then attains a steady value by the afternoon. This sudden increase in Te during early morning hours is mainly observed in equatorial region and is called as "morning overshoot" phenomenon (Oyama et al., 1996). These electrons further increase the Ti and similar kind of observations in Ti is expected as electron energy gets transferred via elastic electron – ion collision (Banks, 1967). According to Oyama et al. (1996), the intense morning enhancement in Te observed over the equator is due to reduction in electron density caused by a downward drift of plasma, which usually occurs in the early morning hours. As electron and ion density enhances during daytime, the electrons get cooled via coulomb collisions with ions and hence Te decreases later on (Schunk and Nagy, 1978). The Ti also showed similar enhancement during sunrise hour, but peak in Ti is lower (~2400 K in solar minimum) and delayed as compared to Te as reported previously by Aggarwal et al. (2007) and Sharma et al. (2010). After sunrise, the Ti decreases as the Te also reduces due to sharing of energy with more number of electrons and ions. We found a higher enhancement of Te in morning during solar minimum (~4400 K) than maximum (~3200 K) year respectively (Figs. 1(a) and 2(a)). This is because the Ni (Fig. 1) is directly related with F10.7 and is higher for solar maximum than minimum and hence describes the lower Te in the morning hours. As the day progresses more and more ions are produced due to ionization, thus the energy shared by each ion decreases and a daytime trough in Te and Ti is observed. During the daytime, peak in Ni (total ion density) is also observed (Fig. 1) which is much pronounced during low solar activity year. Both Te and Ti rapidly begin to decrease around 1900 LT due to decrease in the photoelectron heating and enhanced vertical EXB drift and reaches a thermal equilibrium state in nighttime (Fig. 1). We also found lower daytime Te during year 2000 and is due to the high level of ambient ionisation during solar maximum (Fig. 1(f)) which induces faster cooling of the hot photoelectrons (Chandra and Herman, 1969).

We observed evening enhancement in yearly Te and Ti during solar minimum for both latitudinal regions (higher over low latitude) respectively (Fig. 1). Watanabe and Oyama (1996) also observed such an enhancement in all seasons for mid latitudes which was more pronounced in the winter hemisphere. Aggarwal et al., (2007) using SROSS observations also found such enhancements during all solar activities during summer and equinox with positive latitudinal gradient. Niranjan et al. (2003) found an evening enhancement in Te in summer, interpreted it as lesser O^+ ions existed in summer. According to Oyama et al. (1997), such an enhancement in Te is associated with enhancements in Ne in the crest region of equatorial anomaly known as the equatorial electron temperature anomaly which is found mainly in the equinoxes and rises with rise in solar activity. Dabas et al. (2000) using Hinotori observations, interpreted the enhancements in Te as of two types: one related with lower Ne (morning-hours) and other with high Ne (evening-hours). The evening enhancement of Te is attributed to vertical E x B drift (Balan et al., 1997). During nighttime (2000–0400 LT) in absence of solar flux – UV and EUV emissions, Te and Ti decrease gradually and attain almost a constant value.

In general, the ionospheric plasma temperatures are inversely related with the plasma densities over low latitude F2 regions. This trend has been previously reported also (for eg. Balan et al., 1997; Oyama et al., 1996; Su et al., 1996 and many more). The anti/poor–correlation in Ne or Ni (ion density) and Te during local daytime is widely accepted. Some positive correlations have been found during periods of high solar activity (Kakinami et al., 2011) and also in the equatorial area at sunset in December (Liu et al., 2007). During whole day (0000–2400 LT), we found observed Te is moderately correlated (~0.54) with Ni only for low latitude during solar minimum (1995) but independent for other regions and solar activities (Fig. 3 (a)). Whereas the Ti correlates well for both observed and model (0.5–0.75) irrespective of F10.7 and region. During daytime (1000–1600 LT) (Fig. 3(b)), both observed Te and Ti are inversely related with Ni (moderate/strong over equator/low-latitude) during solar minimum whereas independent during solar maximum except the direct relation of IRI modelled Ti with Ni in year 2000 over the equator (0.65–0.7). In nighttime (2200–0400 LT) (Fig. 3(c)), the observed Te and Ti are well correlated (Te: moderate, Ti: strong) with Ni for both years and regions except observed Te for year 1995 (moderate, negatively correlated) and 2000 (no relation) for low-latitudes respectively. Zhang and Holt (2004) studying the plasma temperature and the relationship between Te and Ne using the Millstone Hill radar found that the daytime Te in the F2 layer to increase with the increasing solar activity in summer but decrease in winter. The inverse relationship between Te and Ne prevailed in summer and equinox but was not discernible in summer. Borgohain and Bhuyan (2012) using SROSS observations also found daytime Ti and Ni to be negatively correlated during solar minimum whereas no correlation existed in nighttime. However in high solar activity, significant positive correlation of Ti with Ni has been observed over the equator, while at ±10° latitude temperature and density exhibited significant negative correlation. We found no correlation for Te but Ti exhibits a positive correlation during nighttime.

The modelled Te values by IRI-2007 exhibits similar behaviour for solar minimum and maximum throughout the day for both regions whereas IRI-2012 exhibited higher values throughout the day in solar maximum over low-latitude regions. Both modelled Ti and Ni values by both IRI versions represents lower values during solar minimum for both regions throughout the day. Using both models, the relative Te and Ti (Fig. 2(d) and (e)) exhibits agreement for high solar activity for both the regions. Whereas for low solar activity, higher discrepancy existed throughout the day (over-/under-estimated in nighttime (by IRI-2007)/morning hours and noontime) over low-latitude and similar discrepancy over the equator except the closer noontime modelled Te. The latest IRI2012 model exhibits nighttime Te closer to the observations. The previous model, IRI-90 assessed using SROSS C2 observations by Aggarwal et al. (2007) also found underestimated Te and Ti values during morning period by 50–75% in the equatorial and near-equatorial stations during all levels of solar activities. We found modelled Ni values closer to the observed Ni indicating a good agreement over both latitudes. During morning hours, IRI-2012 model has to be corrected for the equatorial and low latitude regions for Te as well as Ti. The careful observation shows that the Te and Ti obtained by both versions, IRI-2007 and 2012 of model shows the same features irrespective of the solar activity in the equatorial and near-equatorial regions with nighttime Te by IRI-2012 closer to the observations. The relative variability of modelled and observed Te, Ti and Ni obtained in this study will serve as a representative for the equatorial and low-latitude ionosphere in correcting a variability model for the IRI. In general, the model generates good results, although some improvements are still necessary especially in morning hours to implement in order to obtain better simulations for ionosphere during low solar activity respectively.

5. Conclusions

The behaviour of yearly ionospheric plasma parameters (plasma temperatures (electron, Te and ion, Ti) and total ion density, Ni) as obtained by SROSS-C2 satellite measurements have been examined during solar minimum and maximum periods. The observations are compared with predicted values of IRI-2007 and latest IRI-2012 model at an average altitude of ~500 km during low (year 1995, $F_{10.7} = 77$ sfu) and high (year 2000, $F_{10.7} = 177$ sfu) solar activity over 5°S-30°N geomagnetic latitude and 60–100°E geog. longitude respectively. From the study following conclusions are drawn:

1. The yearly Te varied from ~600 to 4400 K and ~1200 to 3200 K and Ti between ~400 to 2400 K and ~800 to 1400 K throughout the day during solar minimum (F10.7 ~ 77 sfu) and maximum (~177 sfu) respectively. Throughout the day, Ni varied as $10^{9.4}$–$10^{11.6}$ m^{-3} during solar minimum and one order higher ($10^{10.8}$–$10^{12.6}$ m^{-3}) during solar maximum respectively. A post-sunset enhancement (1900–2200 LT) in Ni is observed during solar maximum in the equatorial regions. The Te/Ti is found to be inversely/directly related with solar flux during daytime and direct in nighttime with a clear solar activity dependence of Ni is observed throughout the day.
2. During both solar activities, the modelled Te is in agreement for high solar activity throughout the day but for low solar activity is over-/under-estimated in nighttime (by IRI-2007)/morning and noontime over low-latitude but the discrepancy exists at other times and is in agreement during noontime over equator respectively. The nighttime Te over both latitudes has been corrected in latest IRI 2012 model and is closer to the observations. For both regions, the IRI modelled Ti for high solar activity is in agreement throughout the day whereas for low solar activity discrepancy exists (higher/lower in nighttime/morning hours). The modelled Ni is in agreement to the observed Ni over both the latitudes.
3. Throughout the day, only observed Te is correlated (~0.54) with Ni for low latitude during solar minimum and modelled Te values are independent of Ni. Both observed and modelled Ti correlates strongly to moderately with Ni for both solar activities and regions. During daytime, both observed Te and Ti are strong and inversely related with Ni during solar minimum whereas the observed and modelled Ti is found independent of Ni for both locations except solar maximum over the equator. In nighttime, both observed and modelled Te and Ti are observed Te for solar minimum (inverse and moderate for low-latitude) and solar maximum (no relation) respectively.

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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., 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., Sharma, D.K., Khurana, M.S., Aggarwal, M., Kumar, S., 2015. Electron–ion–neutral temperatures and their ratio comparisons over low latitude ionosphere. Adv. Space Res. 56, 2117–2129.

Bardhan, A., Sharma, D.K., Kumar, S., Rai, J., 2014. Variation of O^+ ion density during low and high solar activity as measured by SROSS-C2 satellite. Atmosfera 27 (3), 227–237.

Bhuyan, P.K., Chamua, M., 2002. Electron density measurements in the topside F-region and its comparison with the IRI in the 75° E longitude sector. J. Atmos. Sol. Terr. Phys. 64 (1), 55–64.

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., Bhuyan, K., Subrahmanyam, P., Garg, S.C., 2003. Diurnal, seasonal and latitudinal variation of electron density in the topside F-region of the Indian zone ionosphere at solar minimum and comparison with the IRI. J. Atmos. Sol. Terr. Phys. 65 (3), 359–368.

Bilitza, D., Altadill, D., Zhang, Y., Mertens, C., Truhlik, V., Richards, P., McKinnell, L.A., Reinisch, B., 2014. The international reference ionosphere 2012 – a model of international collaboration. J. Space Weather Space Clim. 4, A07.

Bilitza, D., 1991. International reference ionosphere update. Eos. Trans. Am. Geophys. Union 72 (30), 317.

Borgohain, A., Bhuyan, P.K., 2012. Effect of solar cycle on topside ion temperature measured by SROSS C2 and ROCSAT 1 over the Indian equatorial and low latitudes. Ann. Geophys. 30, 1645–1654.

Borgohain, A., Bhuyan, P.K., 2010. Solar cycle variation of ion densities measured by SROSS-C2 and FORMOSAT-1 over Indian low and equatorial latitudes. J. Geophys. Res. 13, 115, AO 4309.

Chandra, S., Herman, J.R., 1969. F-region ionization and heating during magnetic storms. Planet. Space Sci. 17, 841–851.

Dabas, R.S., Reddy, B.M., Lakshmi, D.R., Oyama, K.I., 2000. Study of anomalous electron temperature variations in the topside ionosphere using HINOTORI satellite data. J. Atmos. Solar Terr. Phys. 62, 1351–1359.

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

Kakinami, Y., Lin, C.H., Liu, J.Y., Kamogawa, M., Watanabe, S., Parrot, M., 2011. Daytime longitudinal structures of electron density and temperature in the topside ionosphere observed by the Hinotori and DEMETER satellites. J. Geophys. Res. 116, A05316. http://dx.doi.org/10.1029/2010JA015632.

Kawamura, S., Balan, N., Otsuka, Y., Fukao, S., 2002. Annual and semiannual variations of midlatitude ionosphere under low solar activity. J. Geophys. Res. 107 (A8), 1166.

Kohnlein, A., 1986. Model of the electron and ion temperatures in the ionosphere. Planet. Space Sci. 34 (7), 609–630.

Liu, L., Zhao, B., Wan, W., Venkartraman, S., Zhang, M.L., Yue, X., 2007. Yearly variations of global plasma densities in the topside ionosphere at middle and low latitudes. J. Geophys. Res. 112 (A07303), 2007. http://dx.doi.org/10.1029/2007JA012283.

Niranjan, K., Sridhar, H.S., Rama Rao, P.V.S., Garg, S.C., Subrahmanyam, P., 2003. Evening enhancements in F-region electron temperature at subtropical latitudes during June solstice in the Indian SROSS C2 RPA data. J. Atmos. Solar Terr. Phys. 65, 813–819.

Otsuka, Y., Kawamura, S., Balan, N., Fukao, S., Bailey, G.J., 1998. Plasma temperature variations in the ionosphere over the middle and upper atmosphere radar. J. Geophys. Res. 103, 20705–20713.

Oyama, K.I., Watanabe, S., Su, Y., Takanashi, T., Hirao, K., 1996. Season, local time, and longitude variations of electron temperature at the height of −600 km in the low latitude region. Adv. Space Res. 18, 269–278.

Oyama, K.-I., Abdu, M.A., Balan, N., Bailey, G.J., Watanabe, S., Takahashi, T., de Paula, E.R., Batista, I.S., Isoda, F., Oya, H., 1997. High electron temperature associated with the prereversal enhancement in the equatorial ionosphere. J. Geophys. Res. 102, 417–424.

Prabhakaran Nayar, S.R., 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 lowlatitude upper ionosphere using SROSS C2 RPA observations. J. Atmos. Solar Terr. Phys. 66, 1075–1083.

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., 2000. 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. Ind. 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.

Su, Y.Z., Oyama, K.I., Bailey, G.J., Fukao, S., Takahashi, T., Oya, H., 1996. Longitudinal variations of the topside ionosphere at low latitudes: satellite measurements and mathematical modellings. J. Geophys. Res. 101, 17191–17205.

Truhlik, V., Trikosva, L., Smilauer, J., 2005. Manifestation of solar activity in the global topside ion composition – a study based on satellite data. Ann. Geophys. 23 (2511–2517), 2005.

Watanabe, S., Oyama, K.I., 1996. Effects of neutral wind on the electron temperature at a height of 600 km in the low latitude region. Ann. Geophys. 14, 290–296.

Zhang, S.R., Holt, J.M., 2004. Ionospheric plasma temperatures during 1976–2001 over Millstone Hill. Adv. Space Res. 33, 963–969.