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Variability in Ionospheric Ion Temperature and Density with Varying Solar Activity over Low Latitude F2 Region

Geeta Rana[1], M K Yadav[1] and D K Sharma[2]
[1]*Department of Humanities & Applied sciences, YMCA University of Science & Technology, Faridabad*
[2]*Department of Physics, Manav Rachna University, Faridabad-121001,*
Email: geetikarana72@gmail.com

Abstract-The ionospheric parameters (ion temperature - Ti and total ion density - Ni) as measured by SROSS-C2 satellite have been studied and compared with predicted values of IRI-2012 model over low latitude F2 region during low (year 1995, F10.7 = 77) and high (year 2000, F10.7 = 177) solar activity. The study region encompasses over 5°-35°N Geog. latitude and 65°-95°E Geog. Longitude and ~500 km altitude. Ni increases by the factor of 10^2 with increase of solar activity and Ti varies from ~ 650K – 1500K and 900K- 1300K during low and high solar activity years respectively. Ni and Ti are minima just before the sunrise. During sunrise, Ti increases rapidly owing to the low density of Ni. During evening sector PRE (pre-reversal enhancement) is evident in Ni during high solar activity and in Ti during low solar activity. The relative variation shows that IRI-2012 and SROSS-C2 Ti values are in good agreement with each other during low and high solar activity, except for nighttime of low solar activity. Ni values, as obtained from SROSS-C2 and IRI-2012 show asymmetrical behaviour during both high and low solar activity. IRI overestimates Ni values during low solar activity and underestimates during high solar activity. Further, the relationship between Ni and Ti show weak /poor co-relation. Correlation factor is weaker in low solar activity compared to high solar activity. The co-relation factor R^2 values are similar during high solar activity and differ during low solar activity with IRI-2012 model values.

Index Terms-Low latitude, F2 region, Ionospheric parameters, IRI model

1. INTRODUCTION

Satellite navigation and communication system have become an integral part of today's world. This dependence necessitates the study and forecasting of changes in F2 region ionosphere. The incoming solar flux is a predominant factor of ionization. However, other dynamical process like electrodynamic drifts, transport mechanisms diffusion etc. also determines the variability and structure of ionosphere. These ionospheric variabilities are still not well understood. Thus the variations in ionospheric or plasma parameters (Ne, Te, Ti, Ni, and icon composition) are partially understood. These parameters change on diurnal, annual seasonal, latitudinal, longitudinal and attitudinal scales. Hence, analyzing its complexity and prediction of their behaviour has become extremely important for forecasting ionospheric weather and improvement of existing ionospheric models.

It is well known that the ionosphere is primarily ionized by incoming solar radiation flux. These solar radiation and flux change over the temporal and spatial scales thereby inducing variations in the ionospheric / plasma parameters [1, 2]. The variation in ionospheric parameters is most noticeable due to the solar cycle [3, 4]. The solar cycle modulates the ionospheric parameters significantly on 11-year scale [5, 6].

The structure and variability of low latitude ionosphere are significantly different from high and mid-latitude ionosphere. The effect of geomagnetic field lines on ionospheric plasma changes and spatial scales over the low latitudes, the geomagnetic field lines actually give birth to various unique physical features such as electro dynamical drifts, equatorial electrojet and equatorial ionization anomaly (EIA) etc. Owing to these unique features like EIA, E × B drifts, the low latitude ionosphere has been studied in detail [7, 8]. The features like equatorial plasma fountain, equatorial ionization anomaly, EEJ etc. have been analyzed [9, 10 and 11]. These reports indicate that the ionospheric structure depends predominately over the E × B drift over F region of low latitude ionosphere. This drift further gets modified due to seasons, solar cycle and level of geomagnetic activity etc. [8].

O^+ ions produced during the daytime diffuses to the topside ionosphere, thereby increases the expected O^+ - H^+ transition height. The zonal and meridional components of neutral winds also play a significant role in increasing or decreasing the O^+ - H^+ transition height [12]. Using satellite measurement from AE-C, OGO-6 and IK-24 effect of solar activity on topside ion density on global scale for a period from 1960's to1990's has been explained [13]. Effect of high and low solar activity on ion composition over

Indian region using SROSS-C2 measurements have been also studied [14].

Ion density/composition studies are much more composed of ionospheric temperature studies [15]. However, few comprehensive and detailed studies on ionospheric temperatures can be found reported in the literature [9, 16, 17, 18, and 19]. Ion and electron temperatures are determined by energy flow as well as heating and cooling of ionospheric plasma [20]. Various researchers have studied the variability of ionospheric temperatures with solar cycles & seasons over low latitude using SCROSS C2 satellite [18, 19, and 15].

The studies on relationship of electron/ion densities with their corresponding temperatures are less. In literature, one can find many studies related to electron density and its temperature with the help of satellite measurements [10, 21, 22, 23, 24, and 25]. It is widely accepted that the electron density is negatively correlated to electron temperature. However, some positive correlations have been found reported at the time of high solar activity [26, 27]. The relationship between Te and Ne and climatology of ionospheric temperatures using Milestone Hill radar data has been studied [28]. They found that electron temperature increases in the summers and decreases in winters during high solar activity in the F2 region.

The present study aims to statistically analyze the behaviour and relationship of total ion density Ni with ion temperature Ti during high and low solar activity using SROSS-C2 satellite data and compare it with IRI-2012 model data. The region under consideration extends over 5º-35ºN geog. latitude and 65º-95ºE geog. longitude at an average altitude of ~ 500 km. The relationship of Ni and Ti using SROSS-C2 measured values and its comparison with the IRI-2012 model has not been attempted as per our knowledge. The relative study of Ni and Ti as obtained from SROSS-C2 and as estimated by IRI-2012 brings out symmetry/asymmetry variations in the two sources of data. The co-relation between the Ni and Ti and its comparison with IRI-2012 model data further helps in understanding their behaviour. These studies also help in the improvement of existing ionospheric models.

2. DATA USED

The data of ionospheric parameters (ion temperature and density – Ti, Ni) used in the present study have been taken from retarding potential analyzer (RPA) of the SROSS-C2 satellite. The region selected for present work spans from 5-35˚Geog. N and 65-95˚ Geog. E. The study has been carried over low latitude and at an average altitude of ~ 500 Km. Detailed aeronomy, data retrieval and associated electronics of SROSS-C2 mission can be found reported in literature [29].

The diurnal pattern of ion temperature and density measured by SROSS-C2 satellite has been compared with the international ionosphere reference model IRI-2012 data. The IRI-2012 model data has been obtained online from OMNIWEB NASA site. The IRI model, its collaborative partners, data estimation processes, simulation techniques is discussed in literature [30]. To study the effect of solar activity on ion temperature and density, the data of solar flux - F10.7 have been retrieved from Omniweb NSSDC site for year 1995 and 2000.

3. Results and Discussions

Fig 1 shows the data count of ion density (Ni) and ion temperature (Ti) for which SROSS-C2 satellite has been used and solar flux (F10.7) during year low (1995) and high (2000) solar activity years. The solar flux F10.7 is around ~77 in year 1995 and ~177 in the year 2000. As IRI-2012 gives the estimated modelled values, the data counts have not been included in fig 1.

3.1 Variation of total ion density, Ni and ion temperature Ti

Fig 2 represents the diurnal variation of total ion density, Ni (a - SROSS and b - IRI) and ion temperatures (c – SROSS and d - IRI) during low (1995) and high (2000) solar activity years. As EUV flux coming from the Sun is the main source of ionization, it is important to understand the distribution of this energy which is expended in heating and ionizing the ions. Diurnal variation of Ni and Ti as measured by SROSS – C2 data has been compared with IRI - 2012 modelled data for low (1995) and high (2000) solar activity years.

During low solar activity year – 1995 (fig 2 - a); the diurnal features of total ion density are as follows, the minimum magnitude of density during nighttime, gradual increase during sunrise, day time peak, then gradual decrement of density until night time minimum is achieved. Ni varies from ~$2.5*10^{11}$ to $4.5*10^{10}/\ m^3$ during day time maximum to nighttime minimum. Total ion density is minimal just before the sunrise at 04.00 LT during the year 1995. Thereafter during sunrise, photoelectron production begins in the ionosphere. These photoelectrons ionize the neutral particles and density of ions gradually begins to increase which attains maxima/ peak at 12 LT. As the sun sets, ion density decreases gradually. Density keeps decreasing all through the evening sector till nearly constant value is achieved during nighttime. The major cause of this temporal pattern of Ni during low solar activity is photo-ionization due to solar EUV flux.

During high solar activity year – 2000 (fig 2 -b); the diurnal features exhibited by total ion density are the minimum magnitude of density during nighttime, steeper increase during sunrise, day time peak, secondary or evening peak during, and then gradual decrement of density till night time minimum is achieved. Ni varies from ~$2*10^{12}$ to $1.5*10^{11}$/ m^3 during day time maximum to nighttime minimum. Ion density is minimal just before the sunrise at 05 LT during year 2000. Thereafter during sunrise, through ionization of neutral particles, Ni steeply begins to increase and attains maxima/ peak at 15 LT. As sunsets , a secondary/ evening enhancement during 21 LT is observed. Thereafter gradual decrease in ion density can be observed. Density keeps on decreasing all through the evening sector till nearly constant value is achieved during nighttime.

As sun transverses from low to high activity phase, there is a huge increment in the magnitude of ion density (indicating higher EUV flux) via photo-ionization which is the main cause of diurnal distribution of ion density. However, others factors - plasma movement due to E × B drift in low latitude F-region also comes into play. The secondary enhancement during late evening hours during high solar activity years is due to the movement of E × B drift in F- region. The typical 24 hours diurnal variation states that the magnitude of the velocity of vertical F-region E × B drift increases till day time peak velocity is attained thereafter decreases till sunset. During post-sunset drift velocity suddenly increases, then reverses and increases in reverse direction during night time [9]. Thus attainment of secondary peak during solar high activity period is completely attributed to the movement of E X B drift and is known as a pre-reversal enhancement (PRE).

Fig 2-b represents the diurnal variation of total ion density, Ni as estimated by IRI model during low (1995) and high (2000) solar activity years. IRI model underestimates the day time Ni value during high solar activity year – 2000. During night time RPA measured values are almost similar to IRI estimated values. During low solar activity year, the diurnal features and magnitude value of Ni as measured by SROSS-C2 satellite are in fair agreement with IRI estimated values. Diurnal features as estimated by model data are minimum magnitude of density during nighttime; which is minimal just before the sunrise, gradual increase during sunrise, day time peak, then gradual decrement of density till night time minimum is achieved. Magnitude values of Ni as estimated by IRI in the year 1995 remains lower than 2000, which is in agreement with SROSS-C2 values; however, the typical diurnal feature of evening enhancement in year 2000 can’t be observed in IRI plot.

Diurnal features of Ti exhibited by fig 2 - c are minimum magnitude of temperatures during nighttime, morning peak during sunrise, day time trough and evening enhancement during low solar activity year (1995). However, in high activity year – 2000 the secondary or evening enhancement is negligibly observable. Ti varies from ~ 650K – 1500K and 900K- 1300K during low and high solar activity years respectively. Ti is minimal just before the sunrise at 4 and 5LT during year 1995 and 2000 respectively.

It is found that – as ion density decreases, ion temperature increases and vice versa during the daytime. During sunrise, when ion density is less, ion temperature (Ti) shoots up. It is called morning overshoot [18, 19]. At sunrise, the photoelectrons production begins in the ionosphere through the ionization of neutrals. As the photoelectrons share their high energy with ambient electrons, the electron temperature rises [21]. These electrons further increase the temperature of ions and similar kind of observations in Ti is expected as electron energy gets transferred via elastic electron-ion collision [15]. This increase is rapid in the early morning due to low ion density. 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 Ti is observed. During this daytime peak in Ni (total ion density) is observed. This process is much pronounced during low solar activity year. The evening enhancement of Te is attributed to vertical E x B drift [10]. 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.

The daytime magnitude value and diurnal features of Ti as measured by SROSS-C2 are higher and differ from IRI model value and pattern during low solar activity year -1995. During high solar activity year, the daytime diurnal/ temporal pattern and magnitude value of model and the measured data are almost similar. However, during nighttime the IRI model data overestimates Ti magnitude value than SROSS-C2 measured value by a moderately higher value. Magnitude values of Ti as estimated by IRI in year 1995 remains lower than 2000. However, SROSS-C2 Ti values are higher during morning and evening enhancements in year 1995 compared to year 2000.

3.2 *Relative variation of total ion density Ni and temperature Ti*

To understand the relative variation of Ni and Ti values as measured by SROSS-C2 and as predicted by IRI-21012 model, their ratios are studied. Fig 3 represents the variation of ion temperature Ti (a); Ni (b) as measured by SROSS-C2 satellite, relative to Ti (a); Ni (b) as estimated by IRI – 2012 model on the diurnal scale during year 1995 and 2000. Here value 1 represents no asymmetry in SROSS-C2 and IRI model values. Below one indicates IRI overestimated the values and higher than one indicates underestimation compared to SROSS-C2 values. During low solar activity year, 1995 (a-blue), in night (23 – 4 LT) overestimation of Ti values by IRI is observed by a factor of ~ 0.8. During sunrise, the measured Ti values by SROSS-C2 are much higher than IRI values by almost ~1.2 times. Day time values show an equilibrium value of nearly approaching to one, indicating similar daytime values. Again during evening sector asymmetry in both the values (SROSS-C2 and IRI) is observed. During high solar activity year - 2000 (a-red) IRI estimated values are in good agreement with SROSS-C2 measured values. During sunrise, day and evening time value is almost ~1, thus both the values -model and measured are in agreement with each other. Only during night time, a little variation or asymmetry is observed.

Fig 3-b discusses relative variation of ion density Ni. During year 1995 (blue), it can be seen that all though diurnal time scale (0-24 hrs), the values are below 1, indicating an overestimation by IRI-2012. During year 2000 (red), the values are generally above 1, pointing underestimation by IRI. Only during 5 -10 LT, IRI overestimates the SROSS-C2 values. Ni values as measured by SOSS-C2 and IRI-2012 are highly asymmetrical. The asymmetry varies from 0.2(lower side) to 0.9 (upper side) in year 1995 and from 0.6 (lower side) to 1.7 (upper side) in year 2000 respectively.

3.3 Correlation of total ion density Ni with temperature Ti

Generally, as temperature increases the density decreases and vice-versa, over low latitude F2 regions. This trend can be observed from many reports [10, 21, 22 and many more]. This kind of observation indicates a poor or negative co-relation between these two ionospheric parameters. The negative/ 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 [26] and also in the equatorial area at sunset in December [27]. It would be interesting to understand how they (Ni and Ti) are co-related and their comparison with IRI values would further help in improvising the model. IRI is revised periodically and any small parameter's statistical variation/ asymmetry with measured values would help in improving it. Fig 4 represents, Ni Vs Ti during 1995 and 2000 as measured by SROSS-C2 satellite and IRI-2012 model over 0-24 hrs diurnal scale. During year 1995, the Ni and Ti are weakly/ poorly co-related - R^2 = 0.22 as measured by SROSS-C2, and R^2 = 0.599 as estimated by IRI-2012 respectively. The co-relation factor R^2 shows lot of dissimilarity during low solar activity year, 1995. During year 2000, the Ni and Ti are weakly/ poorly co-related - R^2 = 0.41 as measured by SROSS-C2, and R^2 = 0.48 as estimated by IRI-2012 respectively, which shows variation of Ni with Ti as estimated values by IRI and measured by SROSS-C2 are symmetrical. Thus the nature of interaction and their behaviours also coincide. Few researchers have also reported weak/negative co-relation [31]. The whole diurnal temporal scale of 24 hrs includes highly dynamic times – sunrise and evening time. Thus it would be interesting to understand Ni Vs Ti relationship in rather quite times (day and night time). Figure 6, shows Ni Vs Ti during 1995 and 2000 as measured by SROSS-C2 satellite and IRI-2012 model during day and night time. The daytime is considered from 10-14LT and night time from 22-04 LT in this section. During the daytime in year 1995, the Ni and Ti are poorly co-related having a correlation factor of - R^2 = 0.39 as measured by SROSS-C2, and R^2 = 0.16 as estimated by IRI-2012 respectively. It shows moderate variation in both the R^2 values. During daytime in year 2000, the Ni and Ti are poorly co-related by a correlation factor of - R^2 = 0.2 as measured by SROSS-C2, and R^2 = 0.27 as estimated by IRI-2012 respectively. R^2 values are almost same indicating similar kind of interactions as assumed by IRI model and as actually measured values by SROSS-C2 satellite. During night time in year 2000, the Ni and Ti are poorly co-related by a correlation factor of - R^2 = 0.49 as measured by SROSS-C2, and R^2 = 0.007 as estimated by IRI-2012 respectively, showing a large deviation in both the values. In year 2000, the Ni and Ti are poorly co-related by a correlation factor of - R^2 = 0.69 as measured by SROSS-C2, and R^2 = 0.38 as estimated by IRI-2012 respectively during night time. Thus during night time both the years show appreciable variations in R^2 values.

4. CONCLUSIONS

The behaviour of ionospheric ion parameters (total ion density - Ni and ion temperature - Ti) as measured by SROSS-C2 satellite have been analyzed and compared with estimated IRI – 2012 model values at an average altitude of ~ 500 km during low (year 1995, $F_{10.7}$ = 77) and high (year 2000, $F_{10.7}$ = 177) solar activity over 5°-35°N geog. latitude and 65°-95°E geog. longitude. From the present study, following can be concluded.

1. As solar activity increases, total ion density Ni also increases by the factor of 10^2 emphasising the main source of ionization as solar flux. Ti varies from ~ 650K – 1500K and 900K- 1300K during low and high solar activity years respectively. Ni and Ti are minima just before the sunrise. During sunrise, Ti increases rapidly owing to the low density of Ni, known as morning overshoot. During the evening sector, PRE (pre-reversal enhancement) is evident in Ni during high solar activity and in Ti during low solar activity. Thus highlighting the role of E × B drift in determining the spatio-temporal structure of ionospheric ion parameters over the low latitude.
2. Relative variation shows that IRI-2012 and SROSS-C2 Ti values are in good agreement with each other during low and high solar activity years. However, during nighttime of year 1995 (low solar activity) show asymmetry. Ni values as obtained from SROSS-C2 and IRI-2012 show asymmetrical behaviour during both high and low solar activity

years. IRI overestimates Ni values during low solar activity and underestimates during high solar activity.

3. The relationship between Ni and Ti shows weak /poor co-relation. Correlation factor is weaker in low solar activity compared to high solar activity. The R^2 values as obtained from SROSS-C2 are similar during high solar activity and differ during low solar activity with IRI-2012 modelled values.

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FIGURES

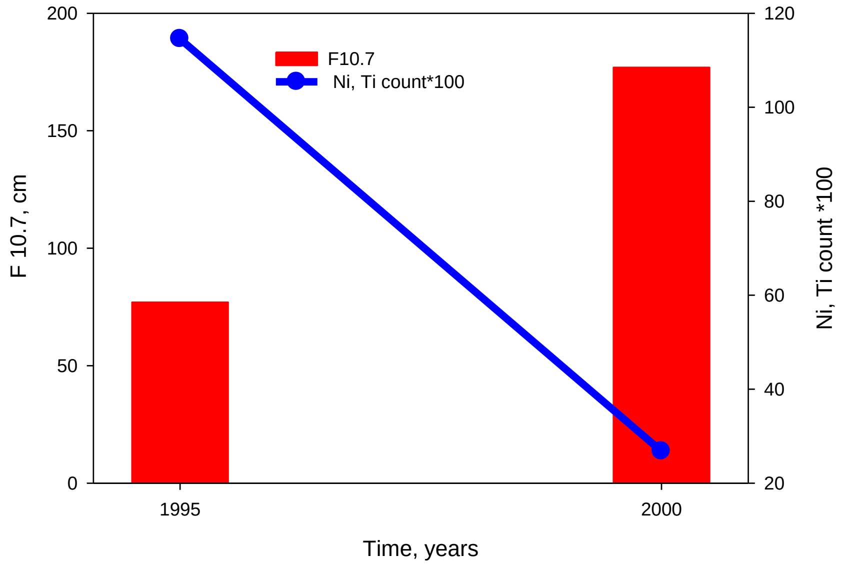

FIGURE 1 Representation of ionospheric ion density - Ni and temperature - Ti data count (blue line) - and F10.7 (red) during low (1995) and high (2000) solar activity years.

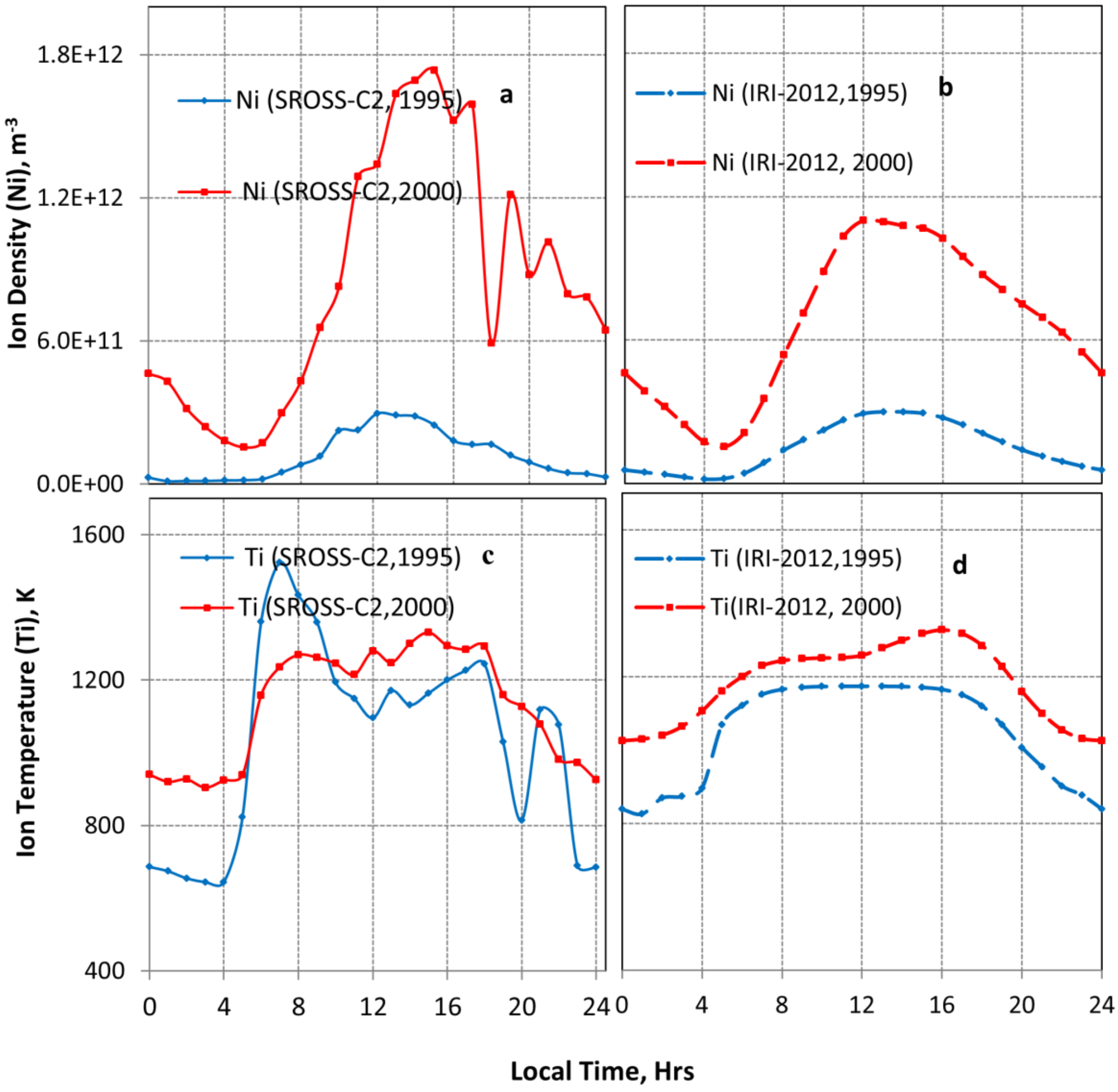

FIGURE 2 Representation of diurnal variation of total ion density, Ni (a - SROSS and b - IRI) and ion temperatures (c – SROSS and d - IRI) during low (1995) and high (2000) solar activity years.

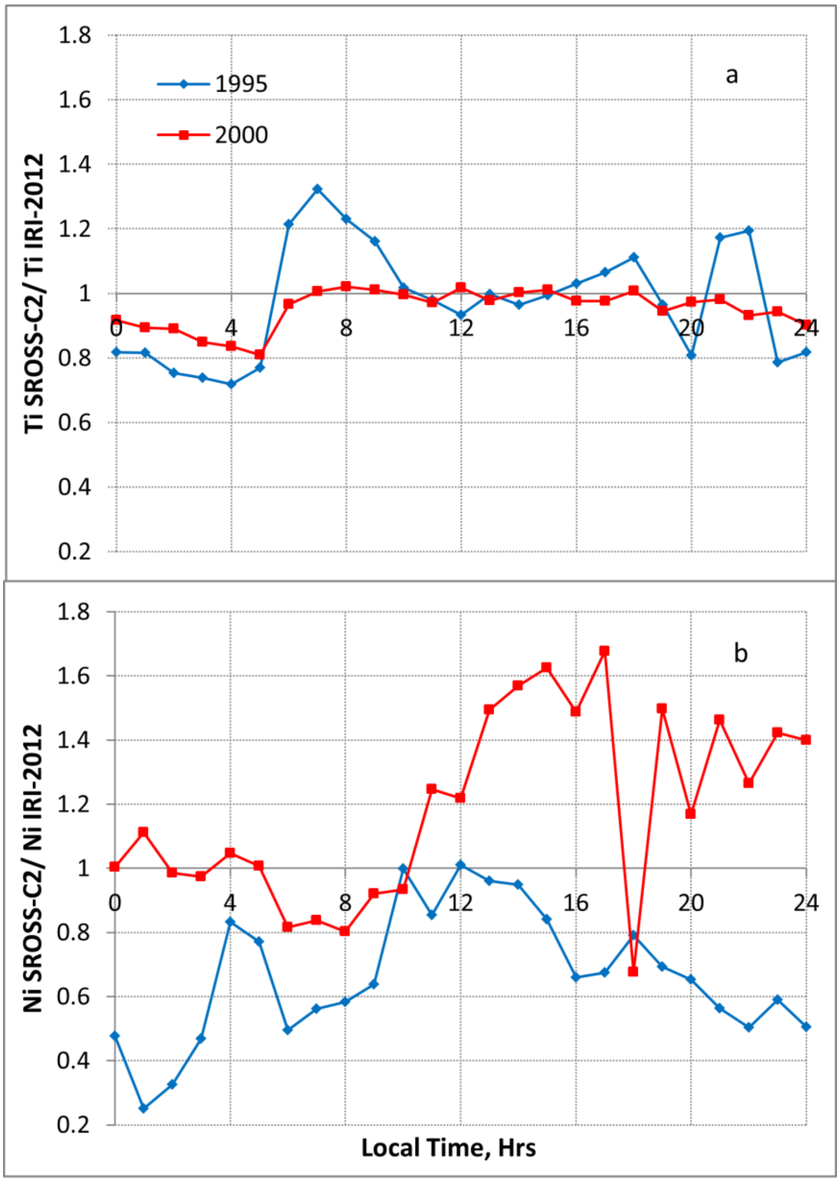

FIGURE 3 Representation of variation of ion temperature Ti (a), Ni (b) as measured by SROSS-C2 satellite relative to Ti (a), Ni (b) as estimated by IRI – 2012 model on diurnal scale during low (1995) and high (2000) solar activity years.

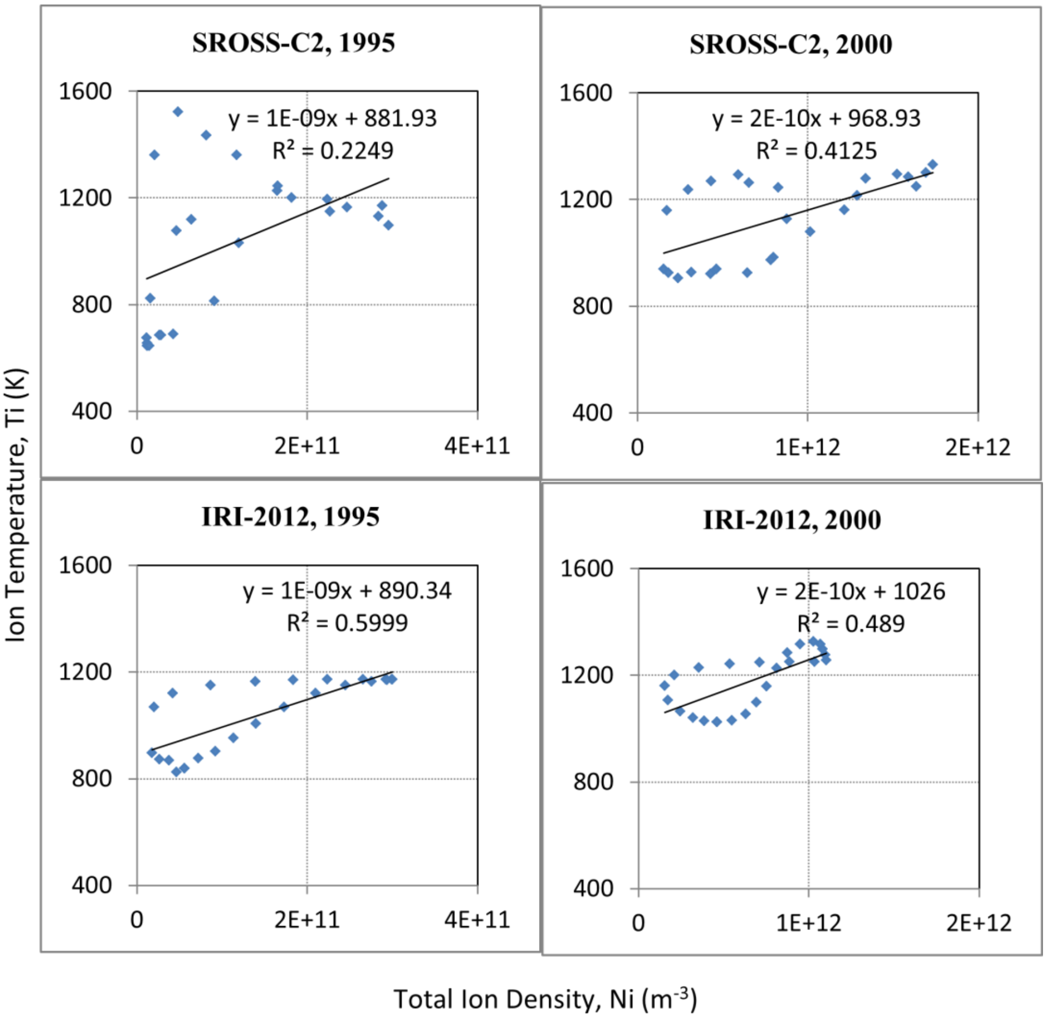

FIGURE 4 Representation of Ni Vs Ti during low (1995) and high (2000) solar activity years as measured by SROSS-C2 satellite and IRI-2012 model.

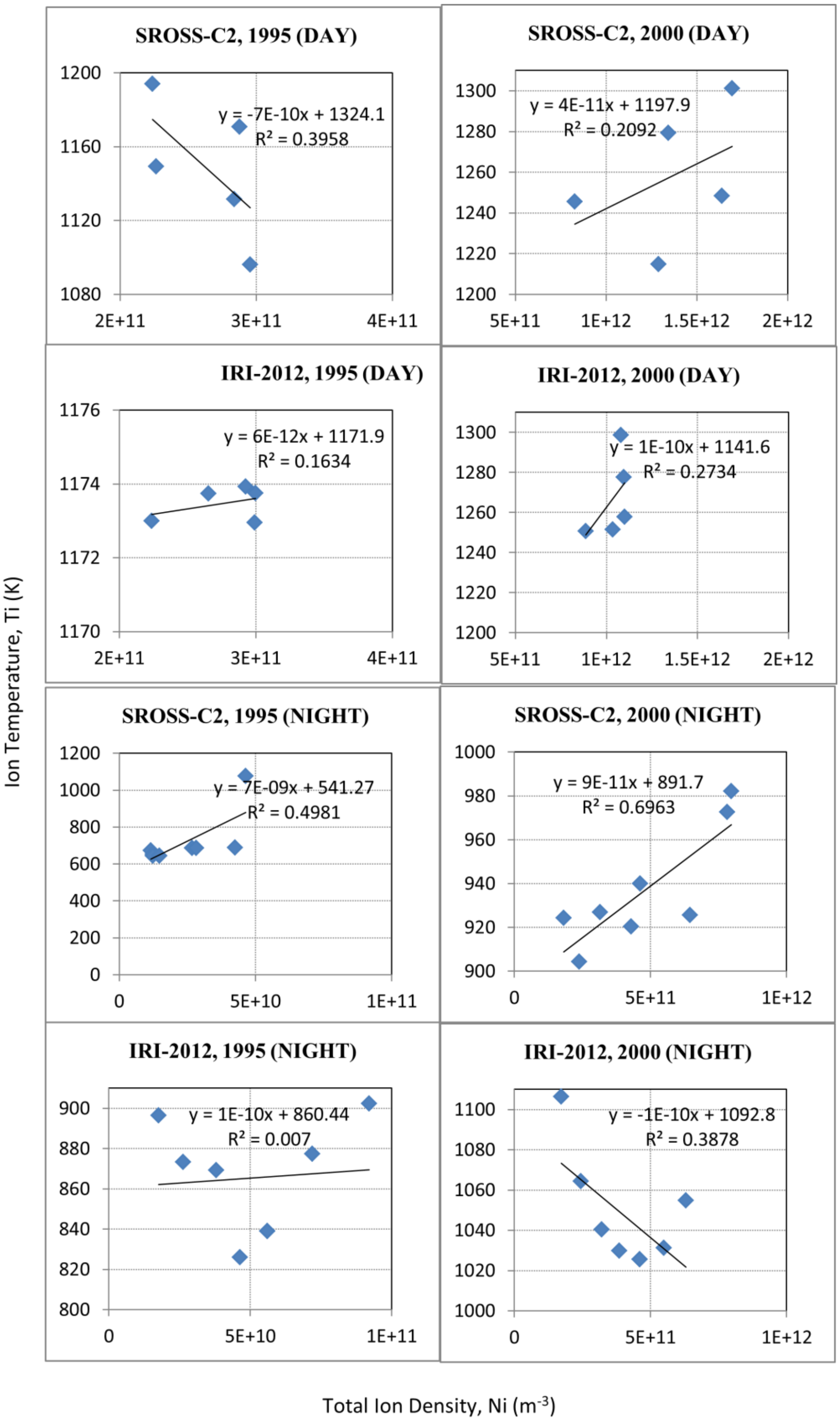

FIGURE 5 Representation of Ni Vs Ti during low (1995) and high (2000) solar activity years as measured by SROSS-C2 satellite and IRI-2012 model at day and nighttimes.