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Variations of ion density and temperature as measured by ROCSAT-1satellite over the Indian region and comparison with IRI-2016 model

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Abstract -Topside ionospheric parameters-total ion density (Ni) and ion temperature(Ti) have been analysed at low latitude region with changing solar activity (years 1999 to 2003).The Ni and Ti data collected from ROCSAT-1 satellite has been compared with the estimated values of IRI-2016 model. The annual diurnal features observed for Ni (measured by ROCSAT-1) are: a minimum value just before local sunrise (~04:00/05:00 LT), a day-time peak (~13:00/14:00 LT) and then a gradual decrement throughout the evening and nighttime. The annual diurnal variation of Ti (measured by ROCSAT-1) shows that Ti exhibits a morning peak (morning overshoot, ~07:00 LT), a day-time trough, a secondary peak (evening enhancement) followed by nighttime minima and a minimum value before the sunrise. The distinct annual diurnal feature observed by the IRI model is the presence of a secondary evening peak in Ni which is absent in Ti, which is exactly opposite to the trend measured by ROCSAT-1. Some other discrepancies observed in the model are:overestimation of Ni during all the years, specifically in the morning and evening time; overestimation of Ti, during the entire day except in the morning peak hours of the year 1999, 2000 and 2003.For each year, the hourly averaged ROCSAT-1 measured value of Ni and Ti has been correlated with the estimated value of IRI-2016 model. The correlation coefficient factor R^2 is ~ 0.8 for Ni and ~ 0.9 for Ti respectively. The variations of Ni and Ti with changing solar flux have also been studied. The ionospheric parameters are found positively and linearly correlated with solar-flux (F10.7). The correlation coefficient factor R^2 for Ni and Ti with F10.7 is ~ 0.8 and ~ 0.9 respectively.

Keywords- Topside ionosphere, ion density, ion temperature, solar flux, solar activity, IRI model

1. Introduction

The solar radiations are the primary cause of ionization of the Earth's atmosphere. Specifically, the X-ray and extreme ultraviolet radiations are the basic drivers at the base of the plasma density distribution in the ionosphere. It is well known that ionospheric plasma and temperature varies with respect to the latitude, altitude, season, geomagnetic and solar activities [Fejer 1997, and Otsuka et al.1998]. The morphology and dynamics of equatorial and low latitude regions is different compared to the mid and high latitude ones.This is because in the low latitude and equatorial regions there occur some unique phenomenon such as equatorial ionization anomaly (EIA), equatorial electrojet (EEJ), plasma fountain, equatorial spread-F (ESF), equatorial wind and temperature [Bhuyan et al. 2002, Prabhakaran Nayar et al. 2004].The EIA is an important characteristic of low latitude ionosphere, which is basically a trough in plasma density at magnetic equator and two crests at around ±15° on both sides of the equator. The theory at the base of EIA was proposed by Martyn[1947], who said that the action of the eastward electric field generated perpendicular to the geomagnetic field linesuplifts (E×B drift) the plasma to altitudes greater than 800km. The uplifted plasma thereafter diffuses along the geomagnetic field lines to the north and south of the equator under the action of gravity and pressure gradient [Hanson and Moffett 1966, Ren et al. 2008]. Hence, forming the ionization trough at the equator. The prereversal enhancement (PRE) phenomenon is also a significant featureof low latitudes. Near the sunset, the eastward electric field shows a strong enhancement just before reverting to westward. This phenomenon causes a sudden rise in the height of F-layer in the evening.

In order to understand the really complex dynamics of low latitude ionosphere, the coupling between the topside ionosphere and protonosphere and all related processes, many researchers have worked to study the variations of low latitude ionospheric parameters [Balan et al. 1997, Bhuyan et al. 2002,Watanabe and Oyama 1996, Zhang and Holt 2004, Liu et al. 2007a]. For example, the electron density and temperature at height of ~ 600 km has been investigated with the help of Hinotori satellite which shows that the electron temperature rises sharply in the morning (known as morning overshoot), declines after that and increases again in the evening (known as evening overshoot) [Watanabe and Oyama 1996]. By utilising Millstone Hill radar data, the daytime increment of electron temperature is found more prominent in summer with increasing solar activity than in winter, while the ion temperature is higher during decreasing solar activity [Zhang and Holt 2004]. Again with the Hinotori satellite measurements in the low latitudes, a strong annual anomaly of plasma density has been observed by Su et al. [1998], Bailey et al. [2000], while an electron density semi-annual anomaly has been observed by using Japanese middle and upper atmosphere (MU) radar [Balan et al.2000]. The features of total ion density in the topside ionosphere (840 km) were also observed through the Defence Meteorological Satellite Program (DMSP) and they have reported an annual asymmetry in the rising and declining phases of solar activity [Liu et al. 2007a].The ion density distribution at low latitudes during solar minimum equinoctial conditions has been simulated by using a time dependent model based on the solution of the plasma continuity equation and the results were compared with the observations made by SROSS-C2 satellite [Bhuyan and Kakoty2001, Bhuyan et al. 2002].The variations in electron and ion temperature and density within a region of ±30º latitude and 200-1000 km of altitude, have been studied by using the time-dependent three-dimensional simulation technique by Watanabe et al. [1995] and they showed a strong effect of plasma drift in the equatorial F-region. At low latitudes, the variations in plasma temperature under equinoctial conditions for low, medium and high solar activity have been studied by Balan et al. [1997]. They made a comparison between values of plasma temperature, modelled by the Sheffield University Plasmasphere Ionosphere model (SUPIM), and ones measured by the Hinotori satellite and found an anomalous variation in temperature from evening to pre-mid night.The atmospheric neutral winds along with the ionospheric dynamics are considered the dominant factors for perturbing the behaviour of plasma density and temperature [Liu et al. 2007b, Rishbeth and Muller-Wodarg 2006, Zou et al. 2000, Mendillo et al. 2005].

Previous studies have shown that for low latitudes sufficient theories and observations are available for total electron content TEC and electron density but there is a gap concerning the ion density and the ion temperature. The present study focuses on the variations of total ion density (Ni) and ion temperature (Ti), in the low latitude topside ionosphere, for different solar activities, as recorded by ROCSAT-1between 1999 and 2003; a comparative study with the output of the IRI-2016 model has been also performed. Although the IRI model has been continuously improved [Bilitiza et al. 2017], it still shows some shortcoming at equatorial and low latitude regions. Hence, the present analysis is then an additional contribute for testing and understanding advantages and disadvantages of the IRI model.

2. Data Analysis

The ion density and ion temperature data used in the present study have been taken from the ionospheric plasma electrodynamics instrument (IPEI) onboard ROCSAT-1 satellite. The selected region for the analysis lies between 5-35ºGeo.N to 65-95°Geo. E in the altitude range of around 600±50 km.

The ROCSAT-1 satellite was launched in 1999 and its mission ended in 2004. It had a circular orbit at an average altitude of around 600 km with an orbit inclination angle of 35°[Su et al. 1999, Chang et al. 1999].The instrument IPEI onboard the satellite had four sensors and made measurements for ion density, ion temperature, ion composition and drift velocity. The detailed information about IPEI is given in Yeh et al. [1999 a, b].

The IRI-2016 model data has been obtained online from https://ccmc.gsfc.nasa.gov/modelweb/models/iri2016_vitmo.php. It is an empirical model which, for a specified time, date and location, provides monthly average values of electron temperature, ion composition, ion temperature, equatorial vertical ion drift and vertical ionospheric electron content in the ionospheric altitude range of 50-2000 km [Bilitza, 1991, Bilitza et al. 2017, Bilitza, 2000].

3. Results and Discussion

The solar flux index (F10.7) data has been retrieved from the website https://omniweb.gsfc.nasa.gov/form/dx1.html. Based upon the strength of yearly solar flux magnitude F10.7, the years (1999-2003) have been categorized as rising, higher and declining phases of solar activity. The year 1999 (F10.7~153.9 sfu),-is considered as a rising phase of solar activity; the year 2000 (F10.7~180 sfu), 2001(F10.7~ 181.1 sfu) and 2002(F10.7~179.4 sfu) as high solar activity years; the year 2003(F10.7~128.4 sfu) as the declining phase of solar activity. Figure 1 represents the variation of F10.7 flux during the years 1999-2003(upper panel) and yearly averaged data count from 1999-2003 as measured by ROCSAT-1 satellite (lower panel).

3.1. Annual–Diurnal variation of total ion density, Ni

Figure 2, represents the annual variation of hourly averaged total ion density measured by ROCSAT-1 satellite (red coloured triangles) and estimated by IRI-2016 (black coloured circles), during different solar activity phases. The calculations for the IRI model have been made for each month and thereafter the monthly values were averaged for every year. The diurnal features shown by Ni as measured by ROCSAT-1 satellite during the year1999-2003 are: a daytime peak; nighttime minima; an absolute minimum just before the local sunrise.

During the rising (1999) and declining (2003) phases of solar activity, Ni shows a minimum of ~4.16E+04 and ~2.94E+04 cm^{-3} respectively during pre-sunrise hours (~04:00/05:00 LT). Analysis by using Stretched Rohini Satellite Series (SROSS-C2) data measurements has also shown a minimum density of Ni just before local sunrise [Bardhan et al. 2014]. Thereafter, Ni increases gradually due to photoionization of the neutral particles and attains a maximum value of 5.08E+05 to ~3.62E+05 cm^{-3}during the day time (~14:00 /15.00 LT). Ni then starts decreasing continuously through the evening and nighttime hours.

During high solar activity years 2000, 2001and 2002 the minimum values of Ni observed during pre-sunrise hours (~04:00/05:00 LT) are ~6.16E+04, 6.66E+04and 6.30E+04 cm^{-3} respectively. The peak value of Ni observed in the afternoon hours (~ 13.00/14.00 LT) is 6.96E+05, 7.28E+05 and 8.16E+05 cm^{-3}during 2000, 2001 and 2002 respectively.

According to the IRI model, the diurnal features shown by Ni are: a daytime relative maximum; a secondary absolute maximum during late evening hours; nighttime minima with an absolute minimum during pre-sunrise hours. During the years 1999 and 2003, Ni shows an absolute minimum of ~6.5E+04 cm^{-3} and ~4.39E+04cm^{-3} respectively at ~05:00 LT; the daytime peaks as 3.8E+05 cm^{-3} and~2.8E+05 cm^{-3} respectively at ~14:00 LT. The secondary absolute peak during 1999 is 3.78E+05 cm^{-3}at ~19:00 LT whereas, in the year 2003 there is no secondary peak, so the daytime maximum becomes the absolute one.

During the high solar activity years 2000, 2001 and 2002 the absolute minimum values of Ni observed at ~5:00 LT is ~ 9.48E+04, 9.13E+04 and 8.77E+04 cm^{-3} respectively; the day time peaks at ~14:00 LT is 5.21E+05, 4.97E+05 and 4.72E+05 cm^{-3} respectively; the evening absolute maximum is modelled at ~19:00 LT as 5.71E+05, 5.30E+05 and 4.86E+05 cm^{-3}.The results of Figure 2 show that during high solar activity years higher day-time peaks of Ni are attained as compared to the rising and declining phases of solar activity. Hence, photoionization can be considered as the primary cause of daytime peaks. Moreover, this figure also shows that during all the investigated years (1999-2003), if compared to measurements made by ROCSAT -1, the IRI model predicts higher values of Ni in the pre-sunrise hours and lower values of Ni during daytime. A further feature is that the IRI model shows evening enhancement that are not been observed by ROCSAT-1.

3.2. Annual –Diurnal variation of ion temperature, Ti

The annual variation of hourly averaged ion temperature measured by ROCSAT-1(red coloured triangles) and estimated by IRI-2016 (black coloured circles) during different phases of solar activity is represented in Figure 3.The study region for Ti is around 600 km which is not the isothermal region of the ionosphere because the temperature is found to increase in the topside ionosphere [Farley et al.1967].

The diurnal features observed by ROCSAT-1 measurements for Ti during years1999-2003 shows that Ti presents a minimum value during pre-sunrise hours and as the sun progresses, the Ti exhibits a sharp increment known as the morning overshoot [Aggarwal et al. 2007, Sharma et al. 2010].Owing to photoionization, photoelectrons gain higher energy which they share with the surrounding electrons and ions through coulomb-collision; consequently, because of lesser electron/ion density in early morning hours, ion temperature starts increasing rapidly and attains a maximum/peak value at ~07:00 LT [Balan et al. 1996, Su et al. 1995, Bardhan et al. 2015, Oyama et al. 1996]. After attainment the morning peak, Ti experiences a daytime trough, and then, due to the pre-reversal enhancement phenomenon [Balan et al. 1997], it shows an evening enhancement followed by a nighttime decrease.

During the years 1999 and 2003, at ~ 07:00 LT, Ti shows morning peaks of ~1565 K and ~1491K respectively, while secondary peaks present values of ~1348 K and ~1292 K respectively at ~ 17/18:00 LT. During the high solar activity years, 2000, 2001 and 2002, the morning peaks are 1525K, 1504 K and 1457 K (at 07:00 LT), whereas the secondary peaks are ~1400K, 1394 K and 1370K respectively at 16/17:00 LT. The nighttime Ti values are also observed to be higher during high solar activity years (~950 K) as compared to those of rising and declining solar activity years (~850 K). This may be due to the adiabatic expansion and compression of the plasma, flowing across the equator and along the field lines [Hanson et al. 1973]. The same nighttime plasma features have been observed with the help of the Orbiting Geophysical Observatory satellite (OGO-6) at an altitude of 500 km [Bailey et al. 1973].

According to the IRI model, the diurnal features shown by Ti are typical diurnal ones, with higher values during daytime and lower values during nighttime. For years 1999 and 2003, the morning peaks of Ti are observed as ~1475K and 1449 K respectively at ~ 07:00 LT. For years 2000-2002, the morning peaks of Ti are of higher magnitude i.e. ~1500K.The secondary peak of Ti visible in ROCSAT-1 measurements is not represented by IRI-2016 model.

The annual-diurnal behaviours of Ni and Ti show a different variation pattern. Specifically, during daytime, when Ti presents a trough, Ni shows a peak value. For the topside ionosphere over India, also Borgohain and Bhuyan [2012] investigated Ni and Ti and they observed a positive correlation between them during high solar activity and a negative correlation during low solar activity.

3.3 Assessment of IRI-2016 model estimations with ROCSAT-1 measurements

3.3.1 Relative variation of Ni

To perform an analysis of the relative variation of Ni as measured by ROCSAT-1 and calculated by IRI-2016 model, the ratios (Ni_{ROCSAT}/Ni_{IRI}) have been plotted in Figure 4 (upper panels).This figure shows that during the whole investigated period (1999-2003) the IRI model overestimates the Ni measurements by ROCSAT-1 during nighttime and pre-sunrise hours, whereas underestimates them during daytime. Largest differences of ratios are obtained during 12-14:00 LT and 22-04:00 LT where values vary from 0.4 (lower side; year 1999) to 1.7(upper side; year 2002). Only during the local time ~09-11:00 and ~17-18:00 LT the ratio is equal to ~1, which means that the Ni value measured by ROCSAT-1is similar to that modelled by IRI.

Anyhow, Figure 2 shows that the diurnal pattern of Ni as measured by ROCSAT-1 and estimated by IRI are similar. With regard to this issue, Figure 4 (lower panels) shows the scatterplots between the two data sets (measured and estimated), along with the corresponding linear fit and the value of the correlation coefficient R^2. R^2 for 1999 and 2003 is found to be 0.84 and 0.89 respectively, while during high solar activity years (2000-2002) is found to vary from 0.73-0.85.

3.3.2 Relative variation of Ti

To perform an analysis of the relative variation of Ti as measured by ROCSAT-1 and measured by IRI-2016 model, the ratios (Ti_{ROCSAT}/Ti_{IRI}) have been plotted in Figure 5 (upper panels).

From the graphs, it can be seen that during all the years (1999-2003) the ratio values are below 1, which means overestimated values of Ti modelled by the IRI model except during few morning peak hours in years 1999, 2000 and 2003.

Figure5 (lower panels) shows scatter plots between modelled and measured data, along with the corresponding linear fit and the value of correlation factor R^2. R^2 is found to be 0.86 during years 1999 and 2003, while, during high solar activity years 2000-2002, is found to vary from 0.87-0.90.

3.4. Relationship of Ni and Ti with Solar flux index (F10.7)

The solar flux, F10.7 is very often used as an index to monitor the solar activity. Since the solar radio emission takes place from the chromosphere and corona, it indicates variations occurring in the Sun during different phases of solar activity [Tapping 2013]. Figure 6 shows scatter plots of Ni vs F10.7 and Ti vs. F10.7. To plot this figure, yearly averaged values of F10.7, Ni and Ti during the daytime (10:00-16:00 LT) have been utilized. The correlation coefficient R^2 between Ni and F10.7 is found to be 0.83 for ROCSAT measured values (Fig 6a) and 0.97 between IRI estimated values and F10.7 (Fig 6b).This shows that photoionization via extreme ultraviolet radiation remains a major source of ionization in our selected region of study. This confirms what found by Bardhan et al. [2014] who observed higher photoionization during high solar activity in the year 2000 compared to that of the low solar activity in the year 1995, using SROSS-C2 satellite data.

Instead, the correlation coefficient R^2 between Ti and F10.7 is found to be 0.97 for ROCSAT measured values (Fig 6c) and 0.94 for IRI estimated values (Fig 6d). Both R^2 values are pretty similar to each other during years 1999-2003, which indicates that Ti data during daytime (10:00-16:00 LT) is in good agreement with the solar flux index.

4.Conclusions

In the present study, we have examined the variation of topside ionospheric parameters, specifically the total ion density, Ni and the ion temperature, Ti, at low latitudes during different phases of solar activity (1999-2003). The Ni and Ti data has been obtained from ROCSAT-1 satellite and then a comparison is made with the estimations of the IRI-2016 model. The findings of the present analysis can be summarized in the following points.

1. The annual diurnal analysis of Ni (measured by ROCSAT-1) shows a minimum value just before local sunrise (~04:00/05:00 LT), a daytime peak (~13:00/14:00 LT) and then a gradual decrement through the evening and nighttime.
2. During high solar activity years, measured Ni data exhibited steeper enhancements with a higher magnitude of the peak density as compared to those during the rising and declining phases of solar activity. This shows a direct dependency of the ion density on solar flux.
3. During all the considered years (1999-2003), IRI-2016 model overestimates Ni data, specifically in the nighttime and pre-sunrise hours. On the contrary, the model underestimates Ni during daytime. Also, the IRI model predicts evening enhancements in Ni which are not observed in ROCSAT-1 measurements.
4. The annual diurnal analysis of Ti (measured by ROCSAT) shows that Ti exhibits a morning peak (morning overshoot, ~07:00 LT), a daytime trough and a secondary peak (evening enhancement) followed by nighttime minima and a minimum before the sunrise.
5. According to ROCSAT-1 measurements, secondary peaks of Ti are of higher magnitude (~1500K) for years 2000-2002 as compared to year 1999 and 2003 (~1400K). On the contrary, the IRI-model cannot model the Ti secondary peaks measured by ROCSAT-1.
6. For each year scatter plots between Ni data measured by ROCSAT-1 and those estimated by the IRI model for years 1999-2003 have been generated; they indicate R^2 value ranging from 0.7-0.8. Analogous scatter plots for Ti show R^2 values ranging from 0.8-0.9.
7. We have found that Ni and Ti are strongly positively correlated with solar-flux (F10.7). In this case, the correlation coefficient factor R^2 obtained for Ni and Ti during daytime (10:00-16:00 LT) was ~ 0.8 and ~ 0.9 respectively.

At last, it can be concluded that an overall evaluation demonstrates a moderate agreement between the IRI-2016 model's estimations and ROCSAT-1 measurements. However, the model still requires some improvements to be done, left as a scope for future work.

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Figure captions

Figure 1:Variation of Solar Flux (F10.7, sfu) (upper panel) and yearly averaged data count as measured by ROCSAT-1 satellite (lower panel), foryears 1999-2003.

Figure 2: Annual variation of Ni (cm^{-3}) measured by ROCSAT-1 (red color) and estimated by IRI-2016 model (black color) for years 1999-2003.

Figure 3: Annual variation of Ti (K) measured by ROCSAT-1 (red color) and estimated by IRI-2016 (black color) for years 1999-2003.

Figure 4: Variation of Ni measured by ROCSAT-1 relative to Ni estimated by IRI-2016 on a diurnal scale for years 1999-2003(upper panels). Scatter plots of two data sets, along with the corresponding linear fits and correlation coefficient values obtained for hourly averaged daytime values (10-16 LT) of Ni (lower panels).

Figure 5: Variation of Ti measured by ROCSAT-1 relative to Ti estimated by IRI-2016 on a diurnal scale for years 1999-2003 (upper panels). Scatter plots of two data sets, along with the corresponding linear fits and correlation coefficient values obtained for hourly averaged daytime values (10-16 LT) of Ti (lower panels).

Figure 6: Scatter plots between yearly averaged values of (left panels) Ni, cm^{-3} and solar flux F10.7, sfu, and between averaged values of (right panels) Ti (K) and solar flux F10.7, sfu, for (upper panels) ROCSAT-1 and (lower panels) IRI-2016, for years 1999-2003.

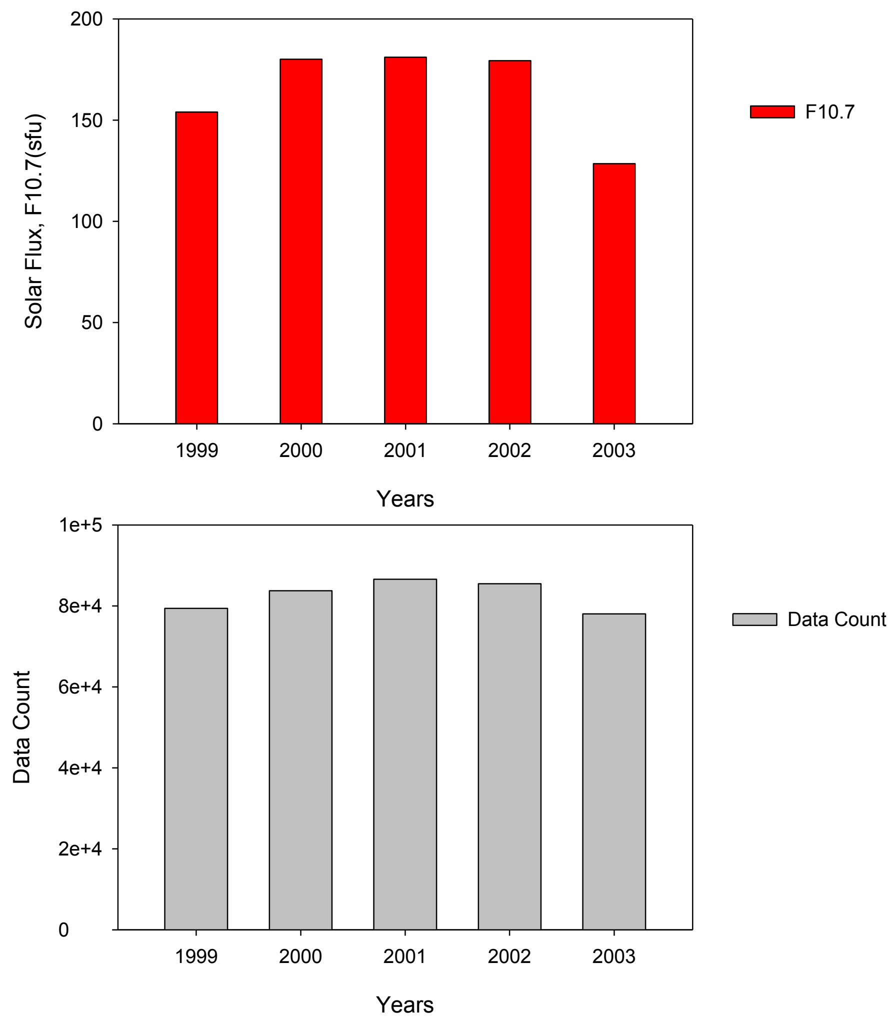


Figure 1: Variation of Solar Flux (F10.7, sfu) (upper panel) and yearly averaged data count as measured by ROCSAT-1 satellite (lower panel), between years 1999-2003.

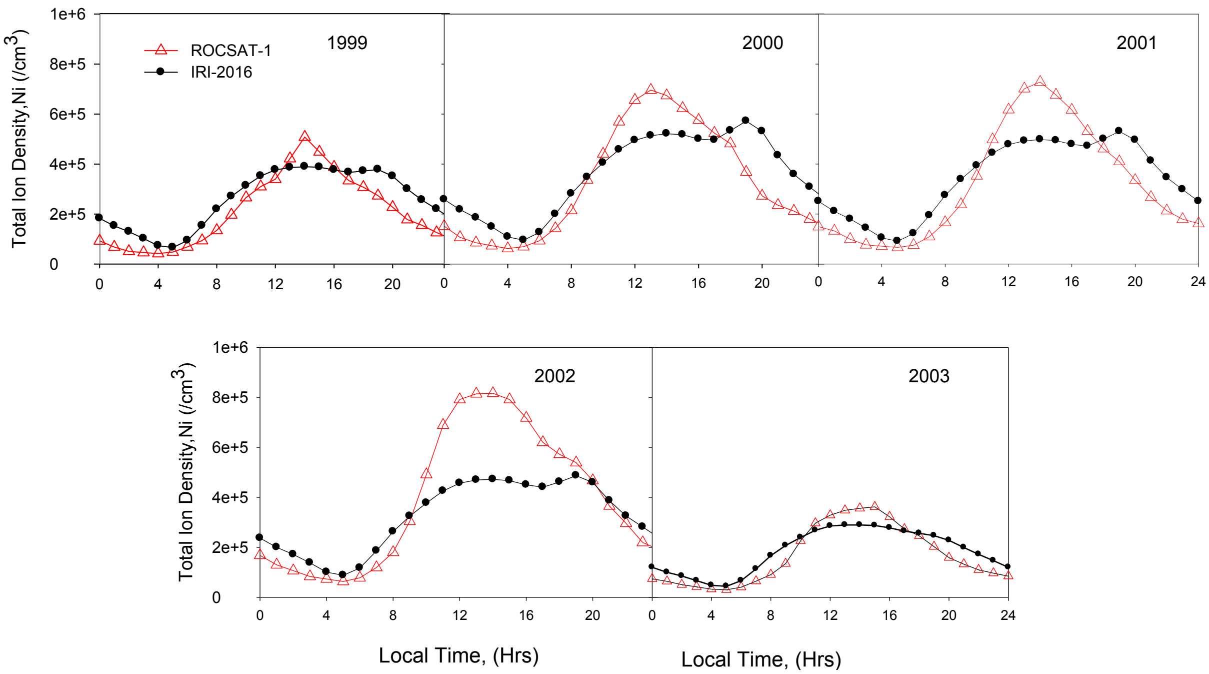


Figure 2: Annual variation of Ni (cm^{-3}) measured by ROCSAT-1 (red color) and estimated by IRI-2016 model (black color) for years 1999-2003.

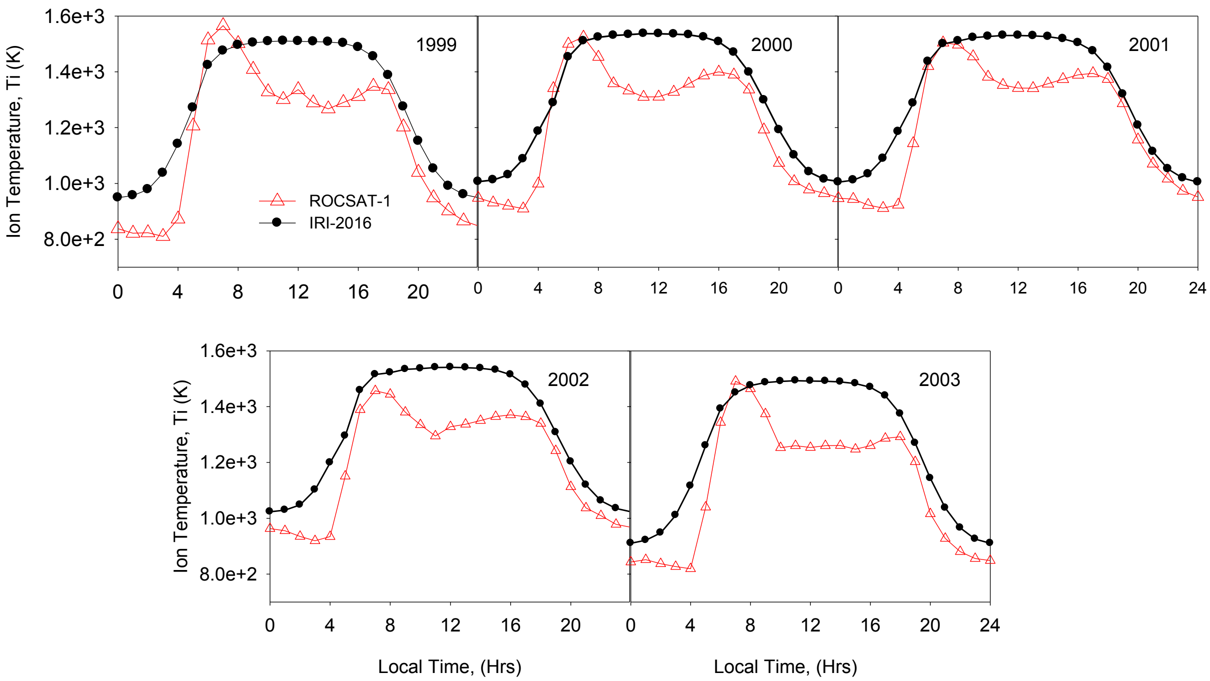


Figure 3: Annual variation of Ti (K) measured by ROCSAT-1 (red color) and estimated by IRI-2016 (black color) for years 1999-2003.

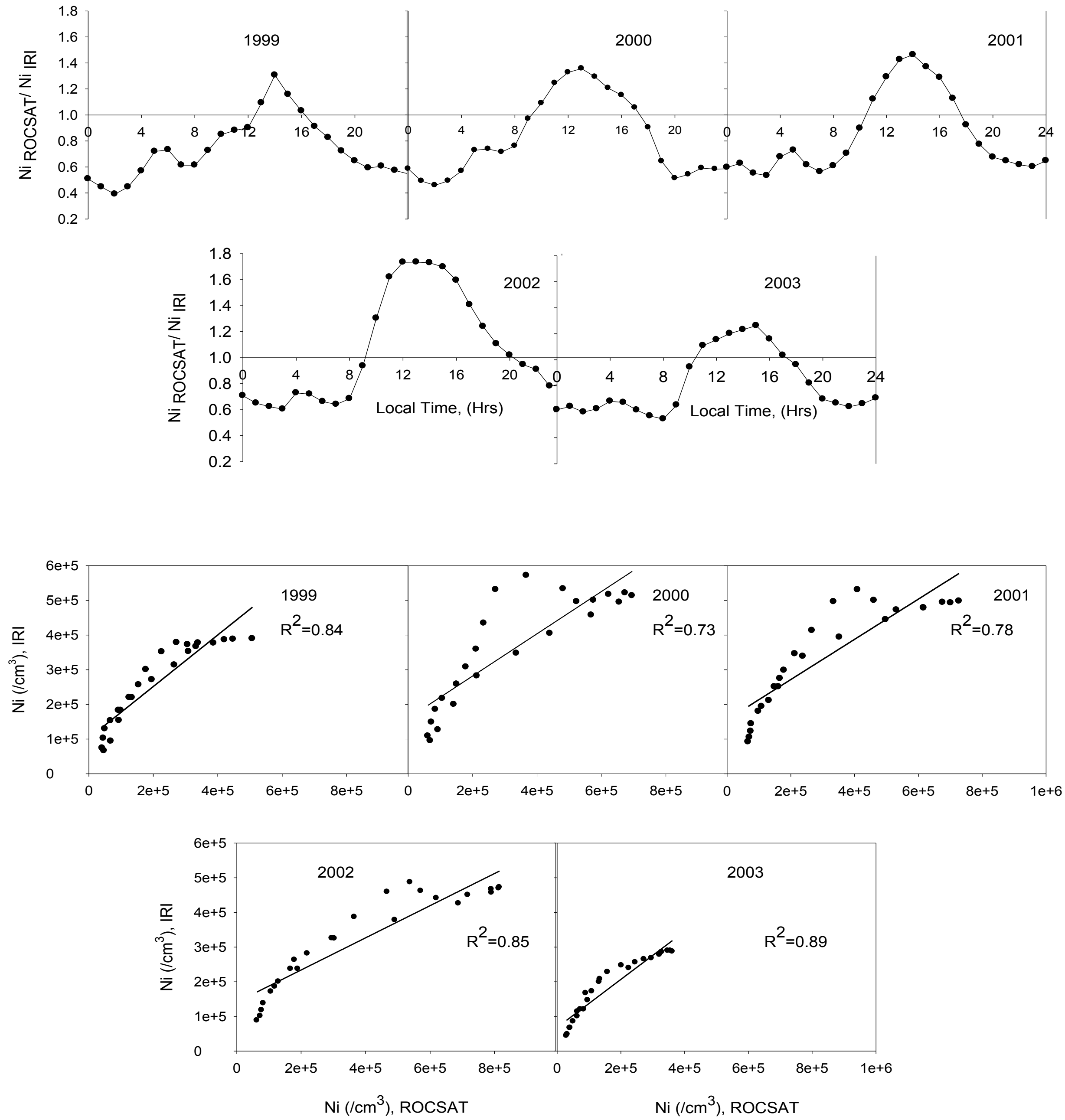
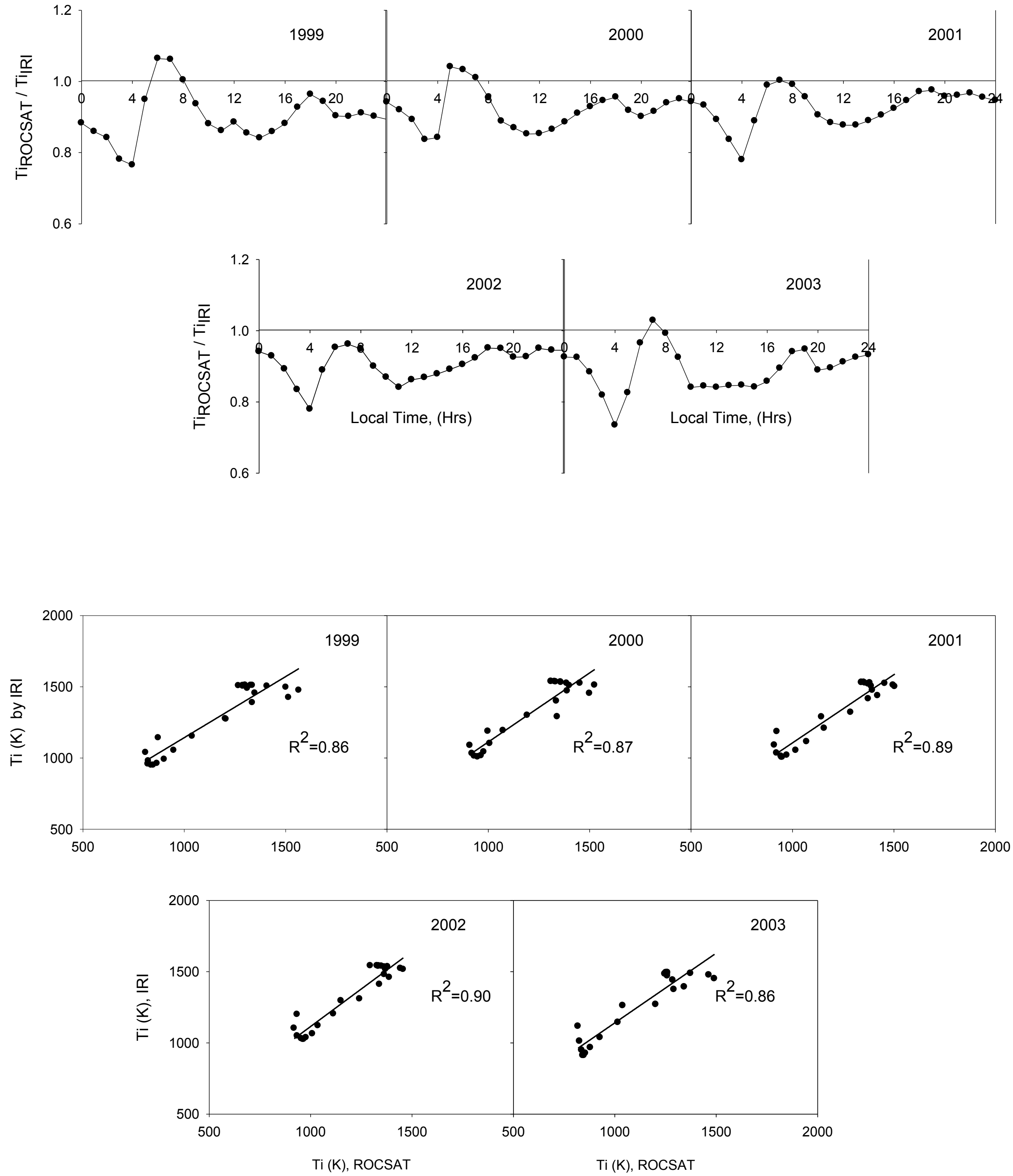


Figure 4: Variation of Ni measured by ROCSAT-1 relative to Ni estimated by IRI-2016 on a diurnal scale for years 1999-2003(upper panels). Scatter plots of two data sets, along with the corresponding linear fits and correlation coefficient values obtained for hourly averaged daytime values (10-16 LT) of Ni (lower panels).



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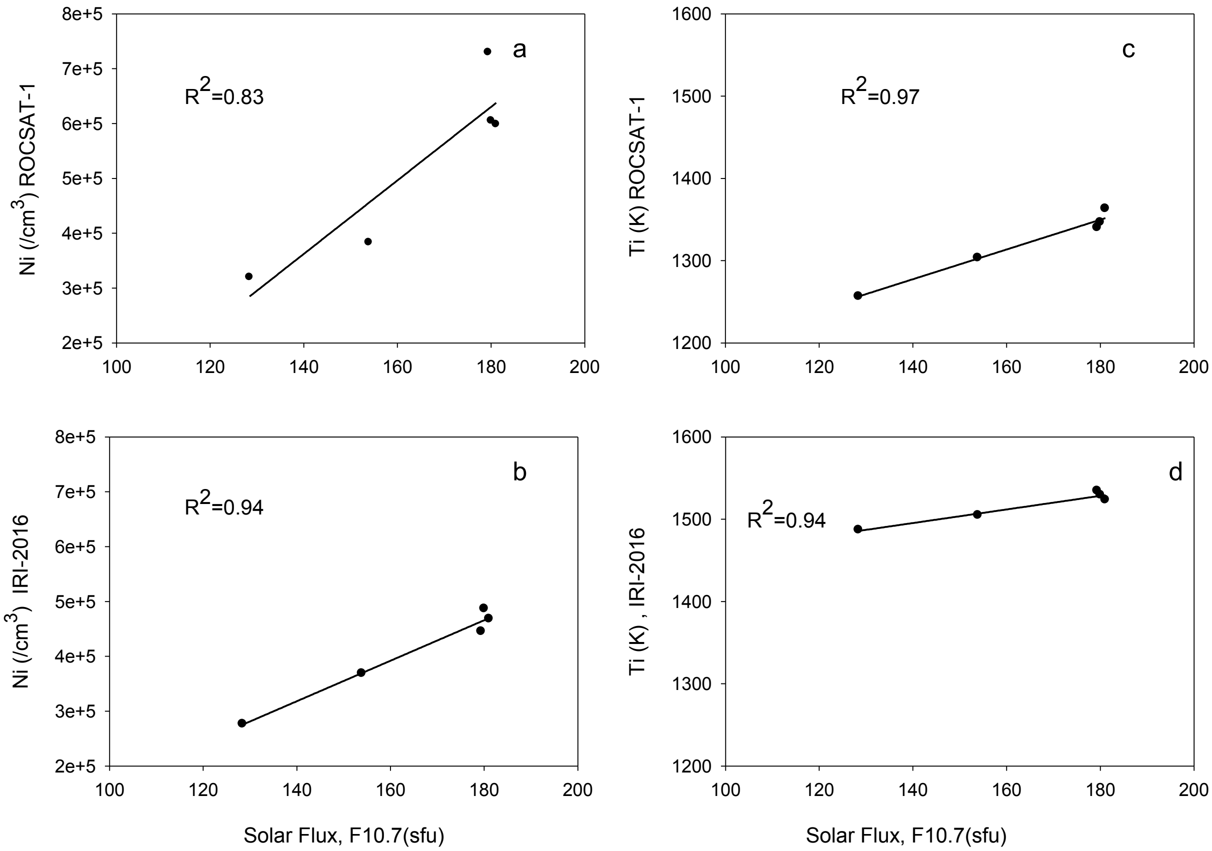

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