Occurrence characteristics of ionospheric irregularities over Indian low-latitude region Varanasi during ascending phase of solar cycle 24

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ABSTRACT
Ionospheric irregularities degrade the performance of radio technological system by producing fluctuations in amplitude and phase of signal passing through them, a phenomenon which is known as scintillation. This study presents diurnal and seasonal variations of ionospheric irregularities during ascending phase of solar activity from 2009 to 2014 by using the amplitude scintillation index S4 computed from a dual frequency GPS receiver installed at the low-latitude station of Varanasi (Lat. 25.31° N, Long. 82.97° E). Scintillation occurrences are found to be higher during nighttime hours (1930-0130 LT), and characterized by an equinoctial maximum throughout the years 2009-2014, except for the peculiar solar minimum year 2009. Gravity wave seed perturbation from lower atmosphere and pre-reversal enhancement (PRE) in zonal electric field have been considered to explain the observed seasonal occurrences, which have been also compared with previous results obtained from observations and model. Influence of solar activity on scintillation occurrence has also been studied, and it was found that there is linear dependence between the solar activity and scintillation occurrence, which is seasonally variable.

1. Introduction

Ionospheric irregularities are responsible for generating scintillation in electromagnetic signals passing through them. When the electromagnetic signal propagates through the irregular ionosphere, it gets distorted in terms of phase and amplitude, a phenomenon which is known as phase and amplitude scintillation respectively [Aarons et al. 1980, Béniguel et al. 2004]. Severe scintillations can cause problems such as signal power fading, phase cycle slips, and receiver loss of lock and can thus degrade the quality of satellite-based communication and navigation systems. Main source of ionospheric irregularities is structuring and dynamics of ionosphere at equatorial and high latitudes. Equatorial spread F (ESF) irregularities are mainly generated during the post sunset hours due to plasma interchange instability process driven by the Rayleigh-Taylor (R-T) instability mechanism. This mechanism initiates at the bottom side of ionosphere and causes plasma depletion, which rises to the topside ionosphere in the form of plasma-depleted flux tubes with the nonlinear growth of the instability which gives rise to equatorial plasma bubbles (EPBs) [Groves et al. 1997]. During their evolution, the EPBs generally drift eastward. Secondary instabilities develop at the steepening gradient regions of the rising bubbles in a cascading process leading to hierarchy of irregularities with decreasing scale sizes [Haerendel 1973].

To study the ionospheric irregularities, ionosonde [Rastogi 1980, Abdu 2001], topside sounders [Maruyama and Matuura 1984], scintillation receivers [Basu and Basu 1985, Aarons 1993, Iyer et al. 2006, Singh et al. 2006], air glow observations [Mendillo and Baumgardner 1982] and satellite measurements [Huang et al. 2011] were used in past years. The different signal wavelengths used in different techniques are susceptible to irregularities of different scale sizes [Kintner et al. 2004]. Therefore, each kind of technique measures ionospheric irregularities of different dimensions. In the beginning, ionospheric scintillations mainly focused on VHF and UHF radio bands. Climatology of scintillation in equatorial and polar regions first reported by Aarons [1982] was performed by organizing the amplitude and phase scintillation of radio beacons observed from 40 to 3000 MHz, but nowadays Global Navigation Satellite System (GNSS) (whose working frequencies are 1.57542 GHz and

1.22760 GHz) has become an important tool to study the ionospheric irregularities because of its growing application in civilian and military applications [Rama Rao et al. 2006].

Rama Rao et al. [2006] studied the spatial and temporal characteristics of scintillations during a solar minimum period over the Indian low-latitude regions. It has been noticed that in equinox months the occurrence of scintillation was maximum in the pre-midnight hours, and the intensity of the scintillation activity was stronger around the equatorial ionization anomaly (EIA) region. Using GPS ionospheric scintillation and ROTI measurements, Li et al. [2007] showed a statistical analysis of the ionospheric scintillation and transverse drift velocities of irregularities over Wuhan and Sanya in China. Their results revealed that amplitude scintillations mainly occur from post sunset to near midnight or later. The occurrence rate and intensity of scintillation were enhanced in equinox months and reduced in winter and summer months. Jiao et al. [2014] have made a comparative study of high and low-latitude ionospheric scintillation characteristics using GPS signals. Their results revealed that scintillation is more frequent during nighttime, and almost all low-latitude scintillation events occur within six hours after local sunset.

A number of studies have been done in African, Chinese and Indian low-latitude regions related to ionospheric irregularities during geomagnetic storms and specific solar activity conditions [Straus et al. 2003, Singh et al. 2004, Nishioka et al. 2008, Béniguel et al. 2009, Muella et al. 2009, Spogli et al. 2009, Seemala and Valladares 2011, Alfonsi et al. 2011, Brahmanandam et al. 2012, Seif et al. 2012, Carter et al. 2013, Oron et al. 2013, Deng et al. 2013, Tanna et al. 2013, Spogli et al. 2016]. All above studies of ionospheric irregularities over different regions have been reported so far but study for a recent solar minimum period mainly in equatorial and low-latitude regions is lacking.

In the present paper diurnal and seasonal variation of ionospheric irregularities over a low-latitude region Varanasi (Lat. 25.3° N, Long. 83.0° E, Magnetic dip Lat. 16.2° N) during an ascending phase of solar activity from January 2009 to December 2014, by using S_4 amplitude scintillation index computed from dual frequency GPS receiver has been studied. Effect of solar activity on occurrences of scintillations has also been analyzed. The seasonal occurrences of scintillation have been discussed with reference to observations and modeling results. The method of data analysis is presented in section 2, results and discussion in section 3 and summary of the results in section 4.

2. Data and Method of Analysis

In this study, amplitude scintillations recorded over Varanasi using GPS measurements have been used. A dual-frequency GPS receiver NovAtel GSV4004B (L1 of frequency 1.57542 GHz and L2 of frequency 1.22760 GHz) with choke ring antenna was installed at Varanasi (Lat. 25.31° N, Long. 82.97° E, Magnetic dip Lat. 16.2° N) India. The amplitude scintillations, as indicated by the S_4 index, are estimated by the receiver at 60s intervals. The amplitude scintillation index S_4 is the standard deviation of the received signal intensity (SI) divided by its mean value which, is calculated every 60s using 3000 points of detrended signal intensity measurements. This produces the S_{4T} index, which includes the effects of ambient noise. The signal intensity is actually received as signal power. Detrended signal intensity is obtained by filtering the intensity measurements in a low-pass filter. S_4 and S_{4T} indices stored in the GSV4004B receiver's data log is defined as follows [Van. Dierendonck and Hua 2001]:

$$S_4 = \sqrt{S_{4T}^2 - S_{4N}^2} \quad (1)$$

$$S_{4T} = \sqrt{\frac{\langle SI^2 \rangle - \langle SI \rangle^2}{\langle SI \rangle^2}} \quad (2)$$

where SI shows the signal intensity. S_{4T} is the total S_4 measuring fluctuations due to any cause and S_{4N} is a measure of amplitude functions due to ambient noise described in more detail by Van Dierendonck and Hua, [2001] as:

$$S_{4N} = \sqrt{\frac{100}{\frac{S}{N_o}}\left[1 + \frac{500}{19\frac{S}{N_o}}\right]} \quad (3)$$

where S/N_0 is the signal to noise ratio.

To obtain consistent statistics, following two criteria have been used in the present analysis: (a) in order to minimize the effects of the multipath on the observations, measurements with a satellite's elevation angle greater than 20 deg are taken into account and (b) the analysis is limited to measurements made from satellites that are locked on for greater than 4 min (240 s) to allow the GSV4004B receiver's de-trending filter to stabilize, as it has to be reinitialized whenever the lock to the carrier phase is lost. In this analysis only cases with $S_4 > 0.15$ are considered. Values of S_4 index between 0.15 and 0.5 are usually used for weak scintillations and > 0.5 for strong scintillations [Hlubek et al. 2014]. IPPs (Ionospheric pierce points)

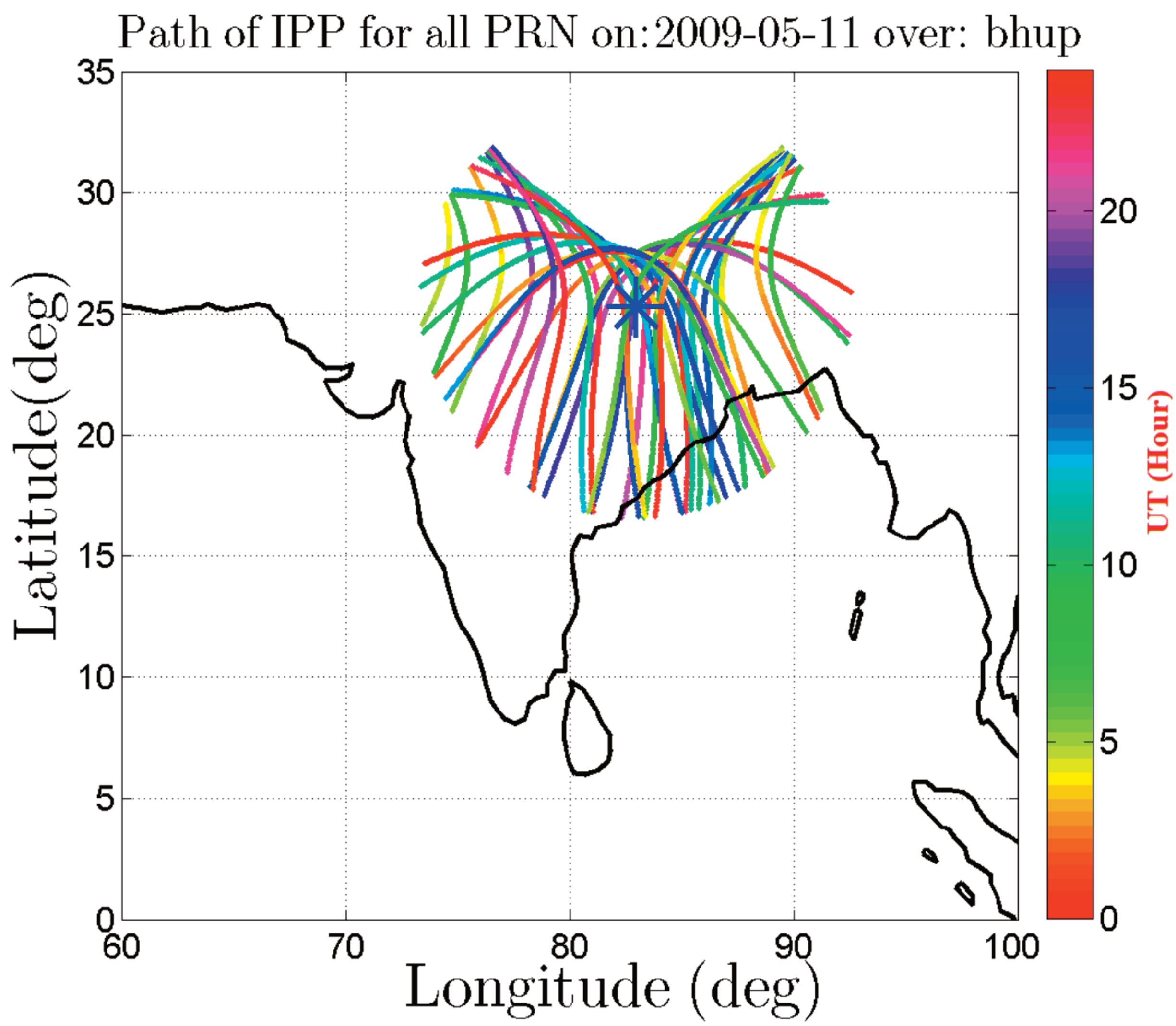

Figure 1. Map showing spatial coverage, in terms of IPP, of all GPS satellite with elevation greater than 20 deg observed from the GPS station installed at Varanasi (blue star) on 11 May 2009, a quiet day. Satellites have a coverage 17°-32° N in latitude and 74°-93° E in longitude.

geometry of all GPS satellites observed from Varanasi station is shown in Figure 1 for a typical day, the 29 February 2012. This figure shows that satellites have a good spatial coverage 17°- 32° N in latitude and 74°- 93° E in longitude.

To understand whether the occurrence of scintillations is affected by the solar activity, SSN (Sun Spot Number) and $F_{10.7}$ (solar radio flux at 10.7 cm) indices were considered. Corresponding values have been downloaded from websites: http://sidc.be/silso/home and http://www.swpc.noaa.gov respectively.

To perform the analysis, a year is grouped into four seasons: March equinox (February to April), June solstice (May to July), September equinox (August to October) and December solstice (November to January). To study the diurnal, monthly, and seasonal occurrences only geomagnetic quiet days ($Kp \leq 4$) during the period from 2009 - 2014, have been considered for further analysis.

3. Results and Discussion

3.1 Diurnal variation of scintillation occurrences

The variation of hourly percentage occurrence of scintillation as a function of LT during 2009-2014 over Varanasi has been analyzed and shown in Figure 2. For a particular year, percentage diurnal occurrence of the scintillation during an hour interval of day has been computed against total number of scintillation occurrences observed during whole day (00:00-24:00 hour). Normally, scintillation occurrences are higher during nighttime hours (1930-0130 LT) than during daytime through over the years 2009-2014. Moreover, the occurrences show the maximum values during the years 2010, 2011 and 2012. It can be easily seen in Figure 2 that the percentage occurrence of scintillation increases with solar activity. Apart from the nighttime scintillation occurrences, the daytime scintillation occurrences have also been observed all through the period 2009-2014

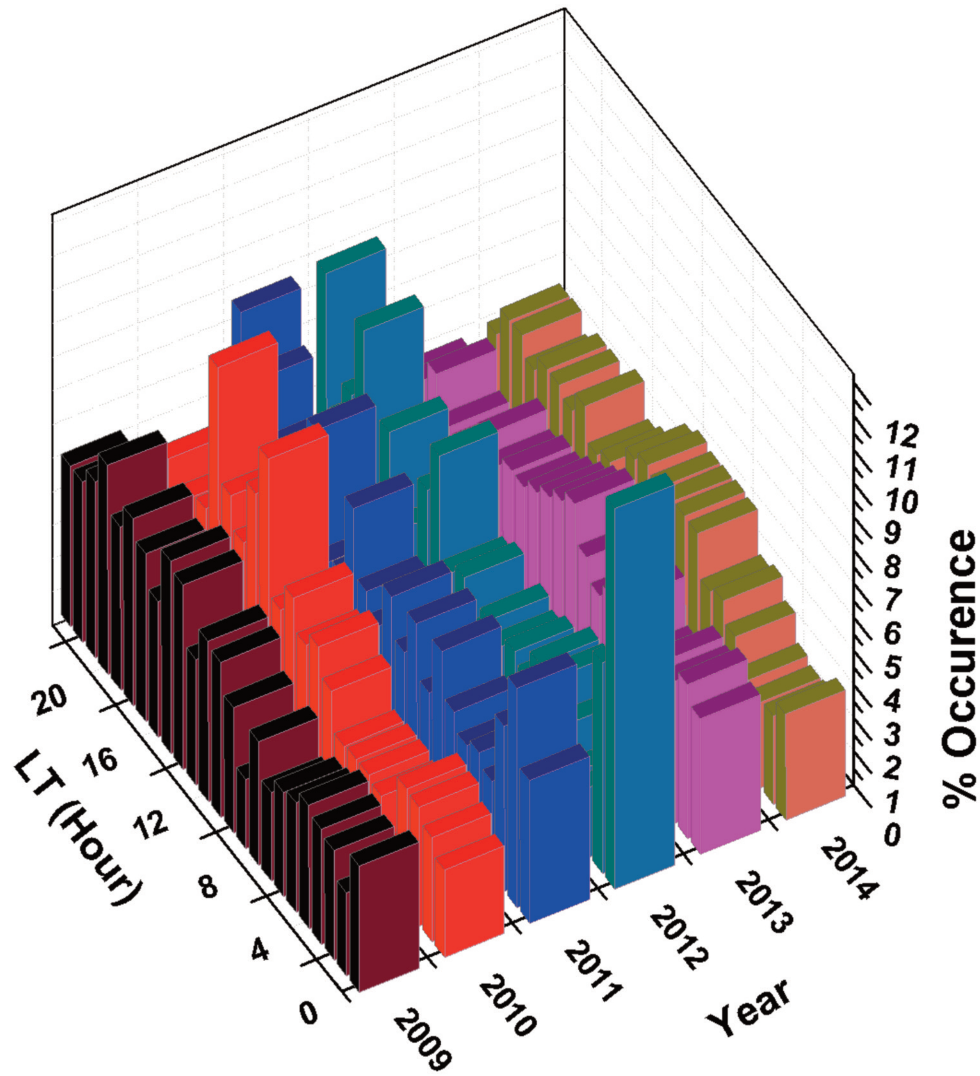

Figure 2. Diurnal percentage occurrences of amplitude scintillation (S4-index) against LT during the years 2009-2014.

with relatively small values as compared to nighttime. Similar diurnal occurrences of irregularities were reported by previous workers [Rama Rao et al. 2006, Nishioka et al. 2008, Singh et al. 2016, Kumar et al. 2016]. The development of post sunset irregularities is governed by mainly two parameters: evening F-layer drift as well as precursor gravity waves in seeding the instability. These two parameters further produce perturbations in density and polarization electric fields [Abdu 2012].

Daytime scintillations are expected to be caused by the irregularities associated with the sporadic E (Es) layers [Patel et al. 2009, Patra et al. 2012, Chatterjee and Chakraborty 2013, Alfonsi et al. 2013], whereas nighttime is associated with spread-F irregularities. Through statistical analysis, earlier studies focused on the existence of daytime irregularities depicted the favourable conditions for its occurrences to be: (a) at early morning, (b) at low-latitude, (c) at high altitude or (d) during geomagnetic storms. Generally, daytime EPBs prefer higher altitude because of two factors: (i) daytime EPBs are leftover of nighttime / pre-sunrise (ii) EPBs at higher altitude are protected from the refilling due to daytime photo-ionization [Huang et al. 2013]. Li et al. [2011] have reported the diurnal occurrences of plasma bubbles. Their results show that during the June solstice months of low solar activity years, normally the majority of the EPBs are formed at post-midnight sector. However, these EPBs are mainly initiated by gravity wave perturbation at around the midnight and survive for several hours until the sunrise (or late in daytime).

3.2 Seasonal occurrences

Figure 3 shows *Pi* diagram of seasonal occurrences of scintillation during the years 2009-2014 over Varanasi. It is easily noticed that the occurrences are found to be minimum during solstice months. Scintillation occurrences are found to show equinoctial maximum throughout the years 2009-2014 only excluding the

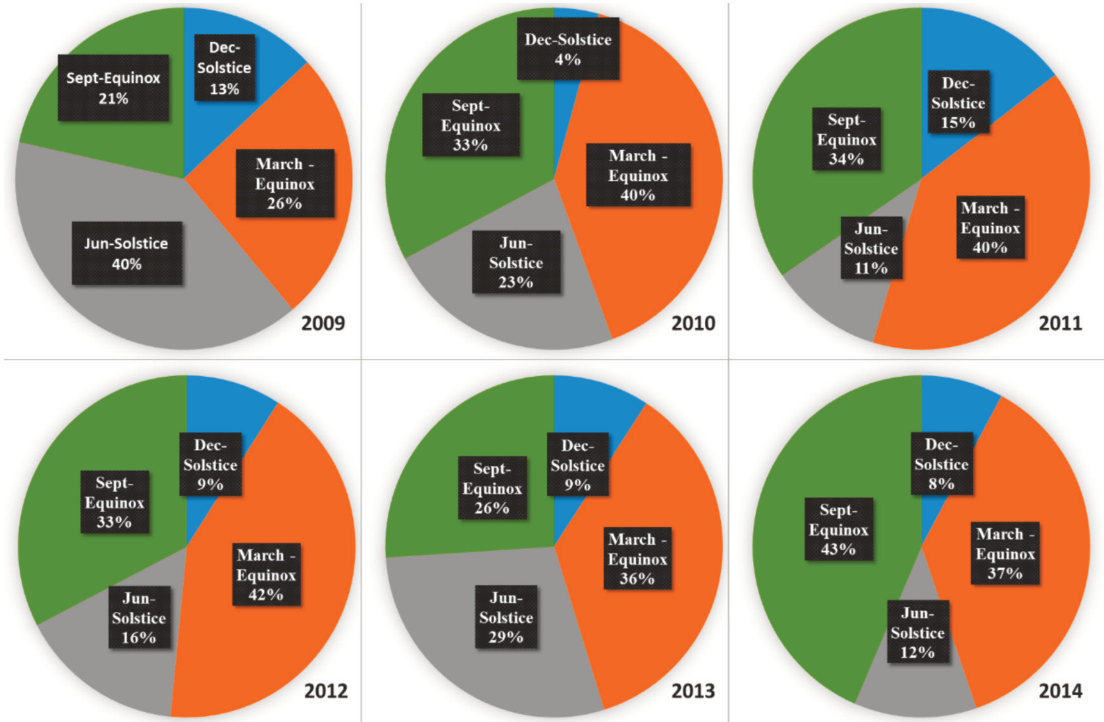

Figure 3. Pi diagram showing seasonal distribution of percentage scintillation occurrences during the years 2009-2014.

solar minimum year 2009. The seasonal maximum occurrences of ionospheric irregularities can be mainly controlled by two parameters: (i) one is post-sunset rise of F-layer (or vertical drift) due to pre-reversal enhancement (PRE) and (ii) other is seed perturbation in plasma density induced by gravity waves (GWs) which is originated from troposphere [Tsunoda 2010, Kumar et al. 2016, Kumar 2017]. During solar minimum period, the vertical drift due to PRE is less significant and seed perturbation can play significant role to manage the seasonal variation of ionospheric irregularities. Therefore GWs seed perturbation could be responsible for occurrences to be maximized during solstice months for solar minimum year 2009 [Tsunoda 2010].

In addition to seasonal maximum during equinox, scintillation occurrences also show equinoctial asymmetry throughout the years 2009-2014. The EPB occurrences may be affected by inter-hemispheric neutral winds (meridional winds) blowing from summer hemisphere to winter hemisphere. Using the numerical simulation, [Maruyama 1988] showed that the role of inter-hemispheric neutral winds, which is directed from summer hemisphere to winter hemisphere, is to increase the Pedersen conductivity and thereby reducing the growth rate of the R-T instability. This asymmetry is expected to arise by the difference in inter-hemispheric neutral winds strength during two equinoxes [Nishioka et al. 2008, Maruyama et al. 2009, Mungufeni et al. 2016, Kumar et al. 2016]. The results reported over Indonesia indicated that, asymmetric meridional winds during vernal and autumn equinox periods over Indonesia may provide asymmetric growth of the irregularity and leading to the equinoctial asymmetry [Maruyama et al. 2009].

3.3 Effect of solar activity

To study the effect of solar activity on scintillation occurrences, S_4 occurrences are plotted along with SSN and $F_{10.7}$. Figure 4 shows seasonal scintillation occurrence number with SSN (in left panel) and with $F_{10.7}$ (in right panel) over Varanasi during the years 2009-2014. Our analysis is divided into three seasons: summer (May, June, July, August), winter (Nov, Dec, Jan, Feb) and equinox (Mar, Apr, Sep, Oct). The scintillation trend is similar to that of solar activity indices (SSN and $F_{10.7}$) throughout the years 2009-2014. Scintillation occurrences show highest values during the years 2013 and 2014. In contrast to this percentage diurnal occurrences show maximum values during 2010, 2011 and 2012 (Figure 2). To quantify the influence of solar activity on scintillations, a correlation analysis between scintillation occurrence numbers and solar indices has been made. Figure 5 shows the seasonal correlation between scintillation occurrence number and with both solar indices, SSN and $F_{10.7}$, during the years 2009-2014. The correlation between two parameters is

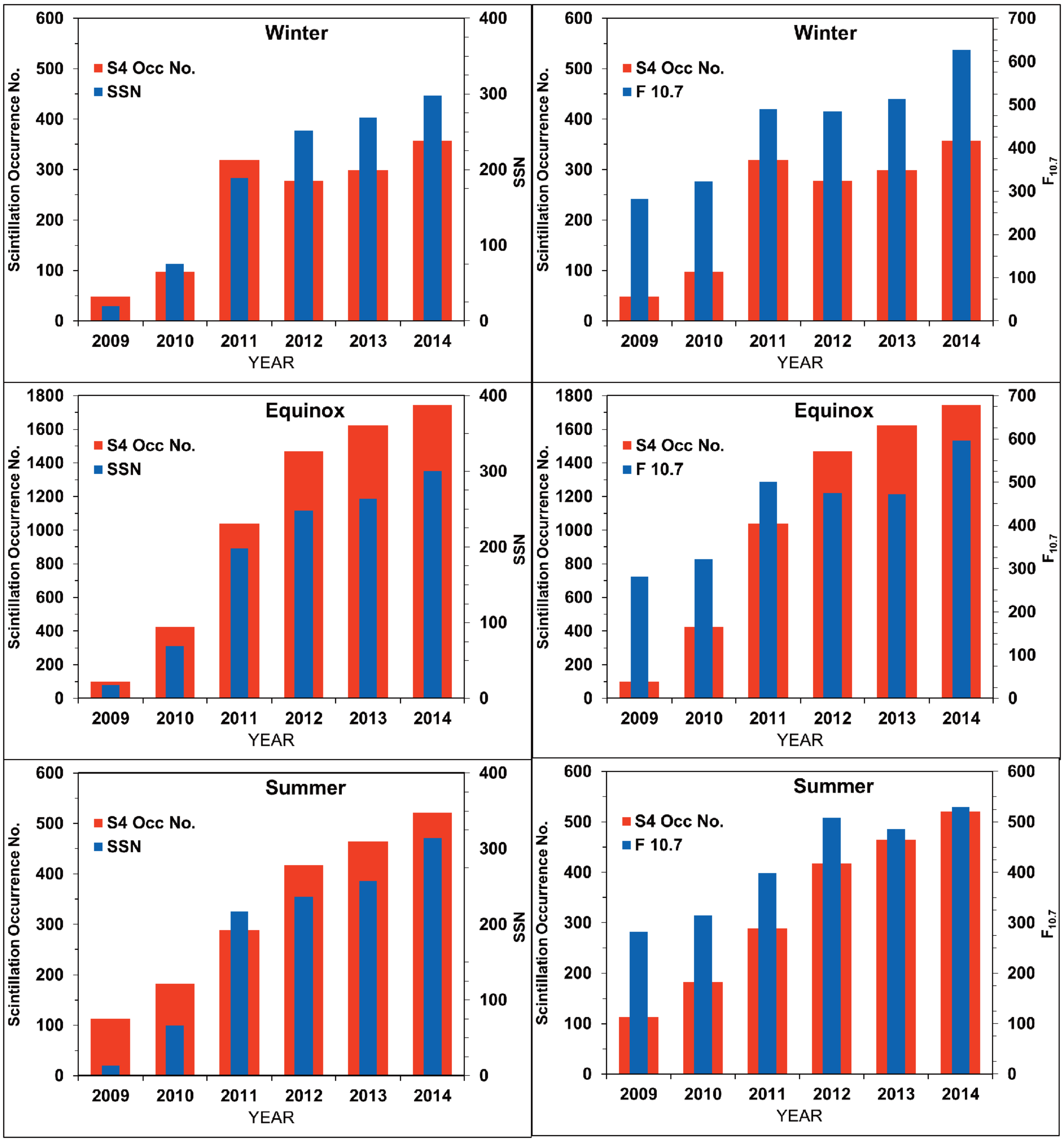

Figure 4. Seasonal scintillation occurrence number with SSN in left panel and with F10.7 in right panel for the years 2009-2014.

found to be more than 0.90 during all seasons, which indicates the influence of solar activity. Correlations are also seasonal dependent which is maximum during the equinox with SSN ($R^2 = 0.99$) and during summer with $F_{10.7}$ ($R^2 = 0.96$). Figure 6 shows annual total scintillation occurrence number along with the SSN (left-top) and the $F_{10.7}$ (right-top) annual means. Corresponding correlation analyses are shown in the bottom panels. Annual scintillation occurrences are also found to vary linearly in accordance with solar activity with annual correlation ($R^2 = 0.97$) with SSN and ($R^2 = 0.95$) with $F_{10.7}$. Annual occurrences are also maximum during the high sunspot year 2014 and minimum during low sunspot year 2009.

The solar activity plays an important role in scintillation/irregularities occurrences and more irregularities can be produced during the solar maximum years as compared to solar minimum years [Basu 2002]. Large scintillation occurrences have been observed during high solar activity and least during low solar activity years (Figures 5,6). The evening equatorial upward plasma drift due to PRE is an important factor controlling the scintillation/EPB occurrences which varies with solar activity. Specifically, higher scintillation occurrences could be expected during high solar ac-

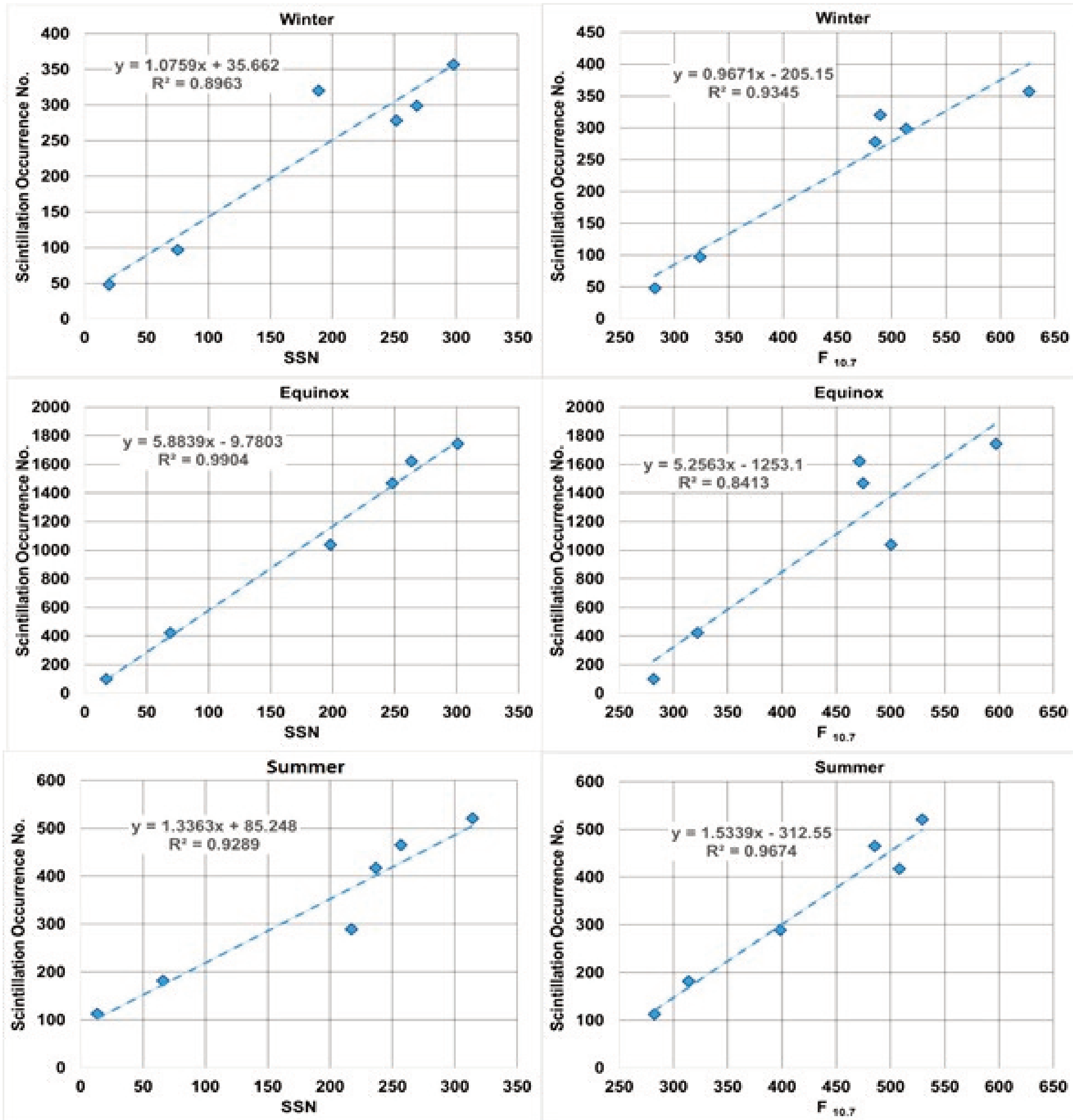

Figure 5. Seasonal correlation analysis between the scintillation occurrence number with SSN (left) and between the scintillation occurence and F10.7 (right), for the years 2009-2014.

tivity year as compared to that during low solar activity year. In support of this, using both the observation and model data, Vichare et al. [2005] and Fejer et al. [2008] have shown a linear correlation between evening equatorial upward plasma drift and solar flux level. Furthermore, Stolle et al. [2008] and Su et al. [2008] have presented global confirmation for the linear relationship between the EPB occurrences rate and the vertical plasma drift. Recently using the data from GPS based measurements, Tariku [2015] have shown that evening equatorial upward plasma drift is more prominent during the high solar activity years and almost absent during the solar minimum period.

Using network of GPS data, Nishioka et al. [2008] have shown that the influence of solar activity on irregularities/EPB occurrences depends on longitude. They reported highest correlation for African-Asian sector and a poor correlation for Atlantic sector. Their results for Atlantic sector, is in contrast to our results observed over EIA region Varanasi, India. Previous studies reported that the influences of solar activity on irregularities occurrences are further complicated by observation techniques which can cause conflicting interpretation of the irregularities climatology [Miller et al. 2010, Makela and Miller 2011]. Therefore, to resolve this issue further studies comparing solar activity influences on irregularities from different techniques are further required.

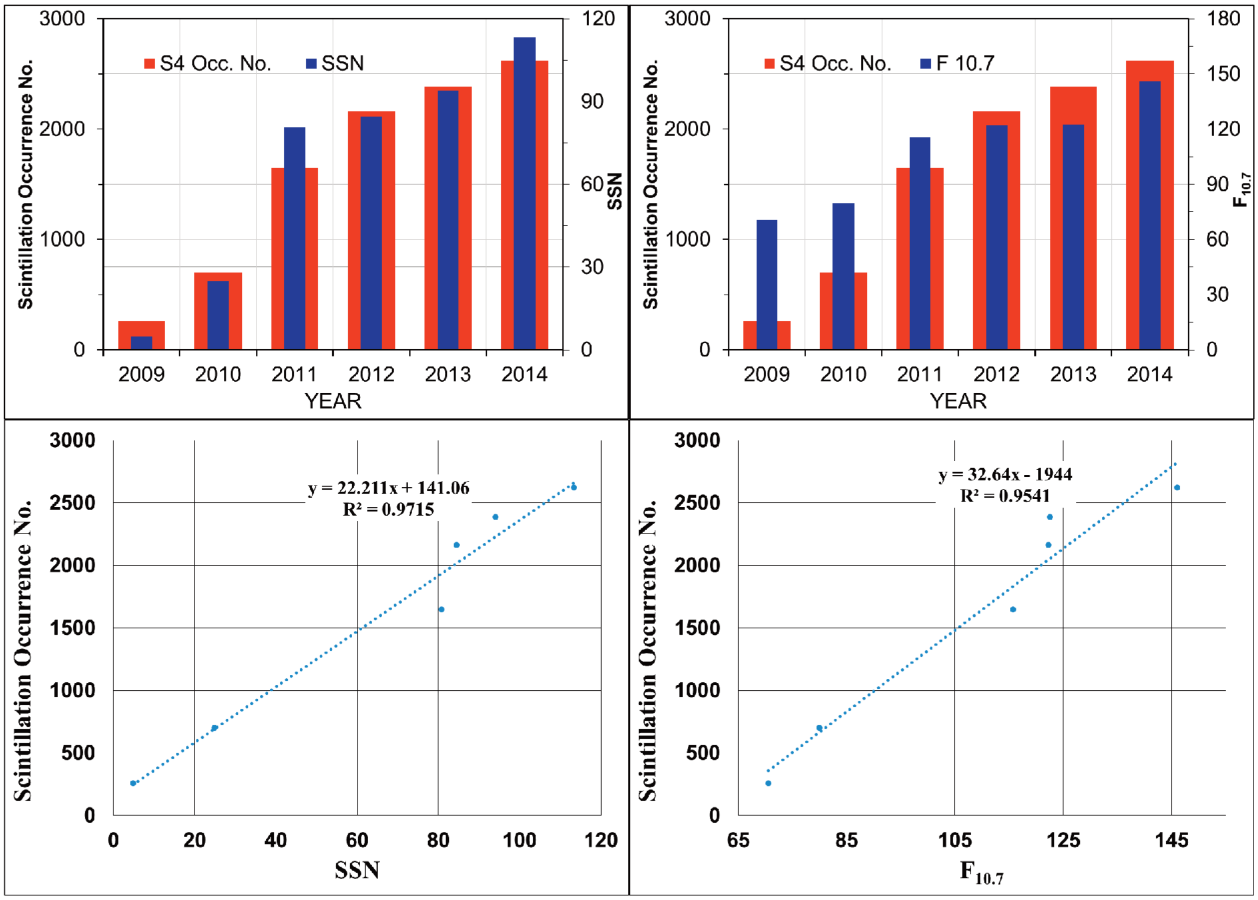

Figure 6. Annual total scintillation occurrence number along with the annual mean SSN (left-top) and of F10.7 cm flux (right-top), from 2009 to 2014. Corresponding correlation analyses are shown in the bottom panels.

4. Conclusions

In this study, the value of S_4 index greater than 0.15 is taken as a scintillation occurrence indicator. Observation data from ground station, Varanasi (India) is used to study the trend of scintillation occurrence during the years 2009-2014. Some features of scintillation occurrences are observed as follows:

- The scintillation occurrences are found to be more probable during nighttime hours (1930-0130 LT). In addition to nighttime, daytime scintillations were also observed with relatively smaller probability.
- Scintillation occurrences are found to show equinoctial maximum throughout the years 2009-2014 with the exception of the solar minimum year 2009. Gravity wave seed perturbation from lower atmosphere and pre-reversal enhancement in zonal electric field are basically two parameters to control the seasonal variations in scintillations/irregularities. During solar minimum year 2009 unusual seasonal maximum could be attributed to a predominance of gravity wave seed perturbation over pre-reversal enhancement in zonal electric field, which makes scintillations occurrences maximum during solstice months instead of equinox.
- The equinoctial asymmetry in scintillation occurrences has been observed throughout the years 2009-2014. The equinoctial asymmetry in scintillation could be caused by inter-hemispheric neutral wind which is blowing from summer to winter hemisphere [Maruyama et al. 2009].
- The influence of solar activity on scintillation occurrence has been studied by quantifying correlations with SSN and $F_{10.7}$ which are found to be different in different seasons, with a maximum in the equinox season with SSN and in summer season with $F_{10.7}$. The results agree with those previously found for the Africa-Asian sector, but they are different than those previously found for the Atlantic sector [Nishioka et al. 2008].

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