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Equatorial Ionospheric Anomaly (EIA) and comparison with IRI model during descending phase of solar activity (2005– 2009)

Sanjay Kumar^{1,2*}, A. K. Singh³, Jiyun Lee⁴

¹Aryabhata Research Institute of Observational Sciences (ARIES),
Nainital-263129, India.

²School of EEE, Nanyang Technological University,
Singapore-639798.

³Atmospheric Research Lab.,
Department of Physics,
Banaras Hindu University,
Varanasi- 221005, India.
Email: abhay_s@rediffmail.com

⁴Dept. of Aerospace Engineering,
Korea Advanced Institute of Science and Technology,
Deajeon, Republic of Korea.
Email: jiyunlee@kaist.ac.kr

* Corresponding Author

Dr. Sanjay Kumar
School of EEE,
Nanyang Technological University
Singapore-639798.
Tel: +65-67906527
Email: sanjay.skitvns@gmail.com

Abstract

The ionospheric variability at equatorial and low latitude region is known to be extreme as compared to mid latitude region. In this study the ionospheric total electron content (TEC), is derived by analyzing dual frequency Global Positioning System (GPS) data recorded at two stations separated by 325 km near the Indian equatorial anomaly region, Varanasi (Geog latitude 25° , $16'$ N, longitude 82° , $59'$ E, Geomagnetic latitude 16° , $08'$ N) and Kanpur (Geog latitude 26° , $18'$ N, longitude 80° , $12'$ E, Geomagnetic latitude 17° , $18'$ N). Specifically, we studied monthly, seasonal and annual variations as well as solar and geomagnetic effects on the equatorial ionospheric anomaly (EIA) during the descending phase of solar activity from 2005 to 2009. It is found that the maximum TEC (EIA) near equatorial anomaly crest yield their maximum values during the equinox months and their minimum values during the summer. Using monthly averaged peak magnitude of TEC, a clear semi-annual variation is seen with two maxima occurring in both spring and autumn. Results also showed the presence of winter anomaly or seasonal anomaly in the EIA crest throughout the period 2005-2009 only except during the deep solar minimum year 2007-2008. The correlation analysis indicate that the variation of EIA crest is more affected by solar activity compared to geomagnetic activity with maximum dependence on the solar EUV flux, which is attributed to direct link of EUV flux on the formation of ionosphere and main agent of the ionization. The statistical mean occurrence of EIA crest in TEC during the year from 2005 to 2009 is found to around 12:54 LT hour and at 21.12° N geographic latitude. The crest of EIA shifts towards lower latitudes and the rate of shift of the crest latitude during this period is found to be 0.87° N/per year. The comparison between IRI models with observation during this period has been made and comparison is poor with increasing solar activity with maximum difference during the year 2005.

Keywords: Equatorial ionization anomaly (EIA); Global Positioning System (GPS), IRI-model, Solar activity.

1. Introduction

The temporal and spatial variation of Total Electron Contents (TEC) at the equatorial and low latitude regions are significant compared to mid latitude regions owing to its dynamic nature due to well known phenomenon equatorial ionization anomaly (EIA) associated with it and is a challenging problem even today to model it (Sridharan et al., 1994; Kumar and Singh, 2009; Aggrawal et al., 2011). The equatorial ionospheric anomaly (EIA) is characterized, in terms of latitudinal distribution of ionization, showing a trough at the magnetic equator and crests at about $\pm 17^\circ$ magnetic latitude (Appleton, 1946). Many theories, like the diffusion theory (Mitra, 1946; Rishbeth et al., 1963) and the electrodynamic drift theory (Martyn, 1955; Duncan, 1960; Bramley and Peart, 1965; Moffett and Hanson, 1965) have been known to explain the anomaly crest. Although Mitra (1946) suggested role of diffusion, but correct explanation was given after Martyn's electromagnetic drift theory (upward plasma drift followed by diffusion). The fountain effect and associated anomaly can cover more than 30° latitudes on either side of the magnetic equator. The perseverance of the EIA into the nighttime hours depending on the season and solar activity is known to be produced by the post-sunset enhancement in the eastward electric field produced by the F-region dynamo action. This dynamo action, in turn, results from the eastward component of the thermospheric wind blowing in the region of the decreasing dawn-to-dusk E-layer Pedersen conductivity distribution (Heelis, 2004). Balan and Bailey (1995) further studied the plasma fountain including neutral wind also and shown that the plasma velocity turning more poleward in that hemisphere, where the wind is pole-ward. The first signal of the significant role of EIA in the initiation of ESF was discussed by Raghavarao et al. (1988) and they showed that the large crest to trough ratio of EIA in the 270–300 km altitude range between 17:00 and 19:00 LT favored the occurrence of post sunset ESF. A similar relationship between EIA and ESF has also been discussed in some later studies (Sridharan et al., 1994; Rama Rao et al., 1997; Thampi et al., 2008). The EIA is responsible for the global maximum values of the TEC over tropical latitude that affects the most, UHF radio propagation range determinations based on GPS satellite signals. It also contributes to the enhanced ionospheric scintillations effects produced by

spread-F/plasma bubbles (depleted electron density region) irregularities on trans-ionospheric radio wave (GPS signal) propagations (Abdu, 2005).

The formation of the EIA is seen in the total electron content (TEC), which is the integral of electron number density along the line of sight from satellite to receiver and can vary dramatically from day-to-day (Huang et al., 1989; Rastogi and Klobuchar, 1990; Bagiya et al., 2009; Aggrawal, 2011). The latitudinal variation of daily TEC was found to correlate with strength of the electrojet current (Rastogi and Klobuchar, 1990; Rama Rao et al., 2006). On the other hand long-term averages of TEC do have seasonal variations. The strength of monthly anomaly crest increases with solar activity and shows a winter anomaly with the winter strength larger than the summer strength for all solar activity levels (Huang and Cheng, 1996). The strength of equatorial anomaly shows semiannual variations. In the Indian sector, the diurnal variation in TEC was reported by Rama Rao et al. (2006) who showed that at EIA crest, day maximum in TEC occurs between 13:00 and 16:00 LT and a short lived day minimum occurs between 05:00 to 06:00 LT. He further showed that in the Indian sector the EIA crest is found to occur in the latitude zone of 15° to 25° N geographic latitudes. Rastogi and Klobuchar (1990), using ATS-6 phase II TEC measurements from India, have shown a large day to day variability in the location of the anomaly crest in the Indian sector and its dependence on the equatorial electrojet and counter electrojet. several individual measurements of TEC at various locations in India have been made using the available low earth orbiting satellites as well as geostationary satellites (Rastogi and Sharma, 1971; Rama Rao et al., 1977; Davies et al., 1979). All these studies have shown the characteristic features of the TEC for the Indian region.

The seasonal and geomagnetic effects on the equatorial ionospheric anomaly crest by analyzing TEC data acquired from a chain of nine ground GPS stations at and in the neighborhood of Taiwan during the solar minimum period between September 1996 and August 1997, was studied by Wu et al. (2004). They found that the surveyed data indicates semiannual variation in TEC, with maxima at equinoxes. They further demonstrated that the monthly EIA was well correlated with Dst and weakly correlated with $F_{10.7}$. Huang and Cheng (1996) studied solar cycle variations of the equatorial

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4 anomaly in TEC received by single ground station of Lumping (25.00⁰ N, 12.17⁰ E).
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6 They found that the winter crest appears larger and earlier than the summer crest and the
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8 summer crest appears lower in latitude than during other seasons. They attributed these
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10 seasonal effects to the daytime meridional wind. Kumar and Singh (2009) studied
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12 variation of EIA crest at Varanasi, India during low solar activity period from May 2007
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14 to April 2008 and showed EIA is found to be highly correlated by Kp-index and very
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16 poorly correlated by the solar activity parameters (SSN and F_{10.7}).

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18 The TEC in EIA region is a subject of considerable day-to-day variability and is a
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20 crucial challenge for the complicated models of the upper ionosphere (e.g., Huang et al.
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22 1989; Rastogi and Klobuchar 1990). Considering this, numerous ionospheric models
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24 have been developed like IRI, Bent, NeQuick (Add References). Out of these, the
25
26 International Reference Ionosphere (IRI) model is one of the most extensively used
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28 which is regularly being improved and updated by the scientific committee. After many
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30 years of up gradation, the current version of IRI: IRI-2007 is released with many
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32 improved features. The validation of IRI for equatorial and low latitude regions is
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34 important because of its growing application in diverse areas of ionospheric investigation
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36 with wide varieties of objectives such as communication and navigation. Costa et al.
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38 (2004) from a low latitude [stations](#) found that IRI-95 overestimates GPS-TEC for all
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40 seasons. Recently, Mukherjee et al. (2010) also compared GPS-TEC observations with
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42 IRI-2001 and observed a higher variability on quiet days as compared to disturbed days
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44 throughout the day. Chauhan and Singh (2010) compared GPS-TEC at Agra near an
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46 anomaly station with the latest IRI-2007 and they found a good agreement between GPS
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48 and IRI TEC. Using electron density data from CHAMP, Liu et al. (2007) concluded that
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50 IRI-2001 reproduces the EIA around noon time quite well for all levels of solar flux. It
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52 appears that IRI simulation of ionospheric parameters needs improvement for the
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54 equatorial and low latitude regions, mainly, at the equatorial anomaly crest region. In this
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56 regard, an investigation is required to study the variability of GPS-TEC at different EIA
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58 region during different solar and geomagnetic conditions.

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60 In this paper, we studied monthly and seasonal variation of equatorial
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62 ionospheric anomaly (EIA) in TEC with the help of GPS-based measurement at Indian
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64 low latitude station Varanasi and Kanpur (these two stations are laying very close to each
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other) during the descending phase of solar activity (2005-2009). To study the effect of solar and geomagnetic activity effects on EIA, we have taken Dst-index and Kp-index, Smoothed Sunspot Number (SSN) data, solar flux $F_{10.7}$ and EUV flux data and compared with our EIA crest variations. We have also studied latitudinal migration of EIA with decreasing phase of solar activity which was not reported by earlier workers. During this period the EIA crest estimated from GPS has been compared to those from IRI model TEC and impact of solar activity on the accuracy of IRI model has also been discussed. We described experimental observation of TEC measurement using GPS in section 2. Our main results are given in section 3 which describes the monthly as well as seasonal variation of EIA crest, effect of solar and magnetic activity on it, latitudinal gradient of EIA, and comparison of GPS-estimated EIA with those from IRI model. The discussions of these results are presented in section 4. The last section 5 summarizes the results.

2. Experimental Observation of TEC

The slant total electron content (STEC) estimated from GPS data recorded in RINEX format (Trimble 5700 receiver) with a time resolution of 30 s at the low latitude stations Varanasi and Kanpur is converted into vertical total electron content (VTEC) according to the relation (Rama Rao et al. 2006; Kumar and Singh, 2009)

$$VTEC = (STEC - [b_R + b_S]) / S(\theta_{el}) \quad (1)$$

where b_R and b_S are receivers and satellite biases respectively, θ_{el} is the elevation angle of the satellite in degrees, $S(\theta_{el})$ is the obliquity factor with zenith angle ψ at the ionospheric pierce point (IPP) and VTEC is the vertical TEC at the IPP. The satellite bias is corrected using the differential code bias (DCB) file provided by IGS code website (<ftp://ftp.unibe.ch/aiub/CODE>). The receiver bias has been estimated using the Kalman Filter technique (Sardon et al., 1994). The obliquity factor $S(\theta_{el})$ (or mapping function) is defined as

$$S(\theta_{el}) = \frac{1}{\cos(\psi)} = \left\{ 1 - \left(\frac{R_E \cos(\theta_{el})}{R_E + h_{\max}} \right)^2 \right\}^{-0.5} \quad (2)$$

where R_E is the mean Earth's radius in km, $h_{\max}$ is the height of the ionospheric shell above the Earth's surface, ψ is the zenith angle and θ_{el} is the elevation angle of satellite in degree. The error in TEC measurements is very large for lower elevation angle (due to multipath effect and tropo-scatter, due to water vapor). So in order to minimize this error we have taken satellite elevation angle greater than 30° . In order to minimize such errors the spatial averaging ($8^\circ \times 10^\circ$ grid averaging) has been made of observed TEC and used for determination of crest latitude. The procedure of grid averaging in details was discussed by Rama Rao et al. (2006). The latitudes and longitudes of the ionospheric pierce points (IPPs) have been calculated from the RINEX navigation message data by using standard coordinate transformation formulae and corrections in satellite orbits (Hofmann-Wellenhof et al., 2001). The VTECs derived from a GPS receiver (Trimble 5700) installed at Varanasi, and Kanpur lying 325 km apart during the period, 2005 to 2009 are used to quantify the equatorial anomaly in the present paper. The GPS over Varanasi has been operated since January 2007. Therefore in this study; GPS data over Kanpur during 2005 to 2006 and over Varanasi during 2007 to 2009 has been analyzed to study the EIA characteristics during the period 2005-2009. These two stations are lying very close to each other so ionospheric variability at these two locations is expected to be almost similar.

3. Results

To study the monthly, seasonal and annual variation of EIA, and the effect of geomagnetic activity and solar activity on their variation, we have chosen daily peak value of TEC observed at Varanasi and Kanpur (a station situated near EIA crest, in Indian region) as the daily anomaly crest value and are used to estimate monthly mean value of EIA crest. The value of daily anomaly crest was identified for each of 365 days of each year from 2005 to 2009 as a function of local time and latitudes and from these daily values of EIA monthly mean has been estimated. To investigate the effect of geomagnetic activity on the variation of EIA crest value, we have taken hourly Dst-index (<http://swdcwww.kugi.kyoto-u.ac.jp>) and then daily and monthly average has been calculated. Three hourly Kp-index data have also been used (<http://swdcwww.kugi.kyoto-u.ac.jp>) and average is estimated in similar manner as applied for Dst-index. Further to

study the impact of solar activity, sunspot number (SSN), EUV flux and solar flux $F_{10.7}$ data have been taken (<http://www.ngdc.noaa.gov>) for period 2005 to 2009.

The EUV flux Measurements are available from several space-based experiments, including the Solar EUV Monitor (SEM) (Judge et al., 1998) on the Solar and Heliospheric Observatory (SOHO) (<http://sohowww.nascom.nasa.gov/data/data.html>). The IRI model is the recent ionospheric model accepted globally. In order to check the accuracy of the IRI model we have also compared EIA estimated from GPS and IRI model over both the stations Varanasi and Kanpur. The monthly, seasonal and annual variation of EIA and its dependence of solar and geomagnetic parameter are discussed in the following subsection.

3.1 Monthly, Seasonal and Annual Variation of EIA Crest

The variation of monthly mean EIA during the period 2005-2009 is shown in figure 1. Here vertical bar indicates the standard deviation in the estimated mean data. As reflected from this figure the variation in EIA crest shows semiannual variation with two maxima in equinox months (October and April) and two minima in winter (December) and summer (July) for each year. Figure 1 also shows the equinoctial asymmetry during 2005-2009, with EIA crest at March equinox being greater than September equinox. It is reflected from this figure that there is data gap from July-December during year 2005 which is due to technical problem in the operation of GPS receiver over Kanpur during this period. During the period 2005-2009, the EIA crest during winter is greater than the summer value except during the deep solar minimum year 2007-2008 which is indicating the appearance winter anomaly or seasonal anomaly. The TEC during the nighttime (figure not shown) for each year is found to be largest (~10-13 TECu) during summer solstice. To study dependence of EIA crest on solar and geomagnetic activity, we have plotted the monthly mean Dst-index, Kp index, solar flux $F_{10.7}$, EIA crest TEC respectively from top to bottom, for the period from 2005 to 2009, which is shown in Figure 2. Here vertical bar indicates the standard deviation in the mean data. From Figure 2 the continuous decrease in solar activity parameter shows descending phase of solar activity from 2005 to 2009. During this period from 2005-2009 the EIA also shows decreasing trends. The variation in EIA crests (i) data do not show exact variation and (ii)

ionospheric variation at the long deep solar minimum has been reported to have less dependence on solar activity as seen in F10.7 (or SSN) than at higher levels of solar activity. The geomagnetic activity indices (Kp) also shows decreasing trends except only Dst-indices which in general shows constant effect from 2005 to 2009. To study the effect of solar and geomagnetic activity on the variation of anomaly crest in more details the correlation analysis between EIA and solar as well as geomagnetic parameters has been carried out which is shown in figure 3. Figure 3 shows high correlation of EIA crest with F10.7 during 2005-2009 while the year wise correlation is poor and negative in some years (Table 1); similar for SSN also.

3.2 Effect of Solar and Geomagnetic activity on EIA Crest

To study the effect of solar and geomagnetic activity on EIA we have studied correlation analysis of EIA with these indices which is shown in figure 3. The variation in monthly average EIA crest in TEC is very similar to variation in monthly average solar indices (Fig 2). The correlation coefficient between monthly average EIA crest and monthly average solar and geomagnetic indices from 2005 to 2009 is found to be 0.63, -0.68, 0.79, 0.86 and 0.81 with Kp-index, Dst-index, F10.7 and SSN respectively. The year wise correlation between EIA with solar and geomagnetic indices is listed in table 1. Thus during 2005-2009 EIA has highest dependence on solar indices in comparison to geomagnetic indices. It is clear from table 1 that during the year 2005 EIA shows very poor correlation with solar and geomagnetic indices while during 2006 EIA shows highest correlation with SSN (0.42). During the period from 2007-2009 the EIA is found to be highly correlated with the Kp-index. Thus it is found that during 2005-2009 EIA has highest dependence on solar indices in comparison to geomagnetic indices. We have also estimated correlation between annual mean EIA and solar and geomagnetic indices which is also listed in table 1. The correlation coefficient between annual mean EIA crest and annual mean solar and geomagnetic indices from 2005 to 2009 is found to be 0.87, -0.94, 0.99, 0.99 and 0.99 with Kp-index, Dst-index, F10.7, EUV and SSN respectively. Thus the annual mean correlation of EIA with solar and geomagnetic indices is higher than the monthly mean and EIA. This shows that EIA is found to vary with solar activity (F10.7 and SSN) effectively in long term basis except with EUV flux (2006-2008). The

EIA shows dependence on EUV flux in long term as well as short term basis. From 2005-2009 the EIA development is more affected by EUV flux compared to other solar activity parameters F10.7 and SSN.

3.3 Latitudinal Gradient of EIA Crest

Figure 4 (a) shows the occurrence of daily EIA crest in TEC in terms of local time. The daily EIA crest in TEC occurred over wide range of local time (10:00 to 16:00 LT). We fit the histogram by a Gaussian function, $a_0 \exp(-z^2/2)$ where $z = (x-a_1)/a_2$ and x stands for local time, $(a_0, a_1, a_2) = (250.20, 12.91, 2.10)$. The statistical mean location during 2005-2009 is found at 12:54 LT and the full width at half maximum (FWHM) is 3.7 h in LT. Similar statistical analysis of temporal occurrence of EIA has been made during each year from 2005 to 2009, which is tabulated in Table 2. From table 2 it is reflected that the EIA mean location is found between 13:00 and 14:00 LT hour during year 2005 to 2007 while between 12:00 and 13:00 LT hour during the year 2008-2009. Apart from temporal variability the EIA also exhibits spatial (latitudinal) variability. Therefore, in order to find out the statistical mean location of the EIA occurrence, we have also plotted the occurrence of daily EIA crest in TEC in terms of geographic latitude which is shown in figure 4b. [The latitude location of EIA has been obtained using geographic latitude of the ionospheric pierce point \(IPP\)](#). The daily EIA crest in TEC occurred over wide range of geographic latitude (16° N to 26° N). We fit the histogram by a Gaussian function, $a_0 \exp(-z^2/2)$ where $z = (x-a_1)/a_2$ and x stands for geographic latitude, $(a_0, a_1, a_2) = (211.1, 21.12, -0.60)$. The statistical mean location is 21.12° N in geographic latitude and the full width at half maximum (FWHM) is 5.11° N in latitude. In order to study the latitudinal gradient of EIA with solar activity using the same method we have computed statistical mean location of EIA for each year from 2005 to 2009, which tabulated in table 2. It is observed that moving from 2005 to 2009 the latitudinal gradient in mean location of EIA is found to be shifted towards lower latitude (from 22.75° N to 18.43° N) in each year. Thus EIA mean location in latitude is found to be decrease with decreasing solar activity. The average gradient rate of EIA during the period from 2005 to 2009 is found to be $\sim -0.87^\circ$ N/year (- sign indicates decrease in latitude with year).

3.4 Comparison of EIA with IRI model

To study the effect of solar activity on the accuracy of IRI model we have compared EIA estimated by GPS and IRI model during the period 2005-2009 which is shown in the figure 5. GPS and IRI both show the semiannual variation in EIA crest. The IRI model under-estimates the GPS-TEC and their difference between GPS and IRI model TEC is found to be solar activity dependent. The difference between GPS and IRI model during 2005-2009 is shown in figure 5(b). The difference between observation and model contributes significantly during high solar activity period (2005-2006) and becomes less significant in lowest solar activity (2008-2009). This difference is maximum in high solar activity period (~38TECu for year 2005, ~27 TECu for year 2006) and gradually decreases with decreasing solar activity (~17TECu for year 2007, ~10 TECu for year 2008, 12 TECu for year 2009). This difference during the year 2005 becomes almost four times of the difference during the year 2008. Thus the accuracy of IRI model is being degraded significantly at high solar activity compared to low solar activity.

4. Discussions

It is well accepted that the fountain effect is the main cause of the equatorial anomaly. Photo ionization caused by solar EUV radiation can produce more electrons and therefore enhances the background electron density (Huang and Cheng, 1996; Wu et al., 2004). The semiannual variation in EIA crest in TEC is a combined effect of the solar zenith angle and magnetic field geometry. In general, the electron population in the ionosphere is mainly controlled by solar photoionization and recombination processes; whereas localized enhancements and depletions of electrons in the ionosphere are caused by electromagnetic forcing (Wu et al., 2004). During the equinox months, the subsolar point is around the equator, where the eastward electrojet-associated electric field is often largest. Thus, in equinox months due to collocation of the peak photoelectron abundance and the most intense eastward electric field regions, one would expect that the fountain effect should be developed the most (Wu et al., 2004, 2008). On the other hand, during the solstices (winter and summer months), photoelectrons at the equator decreases

because the subsolar points moves to higher latitudes and fountain effect is expected to wane.

In the present study, we have analyzed the GPS derived TEC data to study the variation of daily EIA crest in TEC observed at Varanasi and Kanpur during the descending phase of solar activity period from 2005 to 2009. The monthly mean EIA crest (TECu) shows the seasonal and semiannual variation, having maxima in equinox (October & April) months and minima in winter (December) and summer (July). Similar type of seasonal and annual variations in EIA crest have been studied by Huang and Cheng (1996), who also analyzed TEC data from a single receiver in Taiwan and found that the winter crest appears to be larger and earlier than the summer one and the latitudinal location of the crest was lowest in summer. Wu et al. (2004) also analyzed daily characteristics in vicinity of Taiwan during 22nd solar activity minimum from September 1996 to August 1997 and observed the similar results. Thus, the smaller anomaly crest in winter and summer is found in our work is consistent with their finding that the anomaly is least developed in winter and summer. In this study TEC during night time is found largest (10-13 TECu) during summer solstice which may be due to the meridional wind blowing from one hemisphere to other. The meridional winds have been observed to be largest and equator-ward during summer solstices at mid-latitudes (Hernandez and Roble, 1976). The winds blowing towards equator-ward lift the F-layer height during the night where loss is less resulting in the enhanced value of TEC during the night time in summer solstice. Using GPS data over Rajkot, India (a station lying near the anomaly crest region) during April 2005 to March 2006, Aggarwal (2011) has shown that the observed night time TEC is largest (~10 TECu) during the summer solstice. In our study the sunspot number, SSN and solar flux $F_{10.7}$ have very little effect on EIA crest for short term duration during the year 2005, 2007 and 2009. During the long period from 2005 to 2009 the EIA is significantly affected by solar as well as geomagnetic activity (Table 1). Moreover during the period 2005-2009 the effect of EUV flux on the EIA development is more ($R^2 = 0.86$) as compared to other solar activity indices SSN ($R^2 = 0.81$) and $F_{10.7}$ ($R^2 = 0.79$) which is attributed to direct link of EUV flux with ionospheric photo ionization producing electron and ions. EUV and $F_{10.7}$ fluxes are used as a proxy of solar activity describing the variation in the solar extreme ultra-violet (EUV) irradiance

while SSN represents the state of solar activity (Chakrabarty et al., 2012). Similar impact of solar and geomagnetic activity on EIA crest at over Taiwan was studied by Wu et al. (2008) and reported correlation of EIA crest in TEC with $F_{10.7}$ ($r = -0.38$ for 1996 and $r = -0.04$ for 1999) and $r = -0.09$ for 1996-97. Kumar and Singh (2009) reported less effect of solar activity SSN ($R^2 = -0.03$) and $F_{10.7}$ ($R^2 = -0.25$) on EIA during May 2007 to April 2008 in Indian region. Using GPS data at Rajkot, India recently Bagiya et al. (2009) have studied the impact of solar activity on EIA crest during the year from 2005 to 2007 and reported high correlation ($R^2 = 0.99$) between annual mean of EIA crest and solar activity parameters (SSN and $F_{10.7}$).

The seasonal variations of the monthly averaged values of EIA crest can be explained in terms of the composition change effect of the neutral wind (Balan et al., 1997). Due to the unequal heating of the two hemispheres, neutral constituents are transported from the summer (hot) to the winter (cold) hemisphere. As a result, an increase of the O/N₂ ratio caused by the convection of atomic oxygen is formed in the winter hemisphere as compared to summer hemisphere. Therefore, the recombination in winter hemisphere is weaker than that in the summer hemisphere, which results in the relatively higher electron concentration in winter hemisphere (Rishbeth, 1961; Johnson, 1963; Torr and Torr, 1973; Balan et al., 1997). Another possible mechanism for this seasonal anomaly is the change of direction of neutral wind. A meridional component of neutral wind blows from the summer to the winter hemisphere which can reduce the crest value during summer solstice as it blows in an opposite direction to the plasma diffusion process originating from the magnetic equator; at the equinoxes, meridional winds from equator blows pole-wards should result in a high ionization crest value. Based on this scenario, a seasonal effect on the crest should be expected with the crest maximum at the equinoxes and minimum in the summer (Bramley and Young, 1968; Stening, 1992; Wu et al., 2004, 2008).

Using the Sheffield University Plasmasphere ionosphere Model (SUPIM), Vijaya Lekshmi et al. (2008) have shown the relative effects of the main drivers of the positive ionospheric storm under penetrating daytime eastward electric field and direct and

indirect effects of equator-ward neutral wind. The modeling results show that the penetrating daytime (morning-noon) eastward electric field shifts the equatorial ionization anomaly crests in NmF2 and TEC to higher than normal latitudes and reduces their values at latitudes within the anomaly crests while the direct effects of the equator-ward wind (that reduce pole-ward plasma flow and raise the ionosphere to high altitudes of reduced chemical loss) combined with the daytime production of ionization increase NmF2 and TEC at latitudes pole-ward of the equatorial region. The down-welling (indirect) effect of the wind increases NmF2 and TEC at low latitudes while its upwelling (indirect) effect reduces NmF2 and TEC at mid-latitudes.

In this study, EIA crest has been found to show semiannual variation and equinoctial asymmetry, with the peak at March equinox being stronger compared to that at September equinox throughout 2005-2009. The equinoctial asymmetry in EIA crest may be due to equinoctial differences in neutral winds, thermospheric composition, density and electric field and studied by a number of workers (Balan et al., 1997; Mauryama et al., 2009; Chen et al., 2012). During the period 2005-2009, winter anomaly or seasonal anomaly in the EIA crest has also been observed only except during the deep solar minimum year 2007-2008. This disappearance of the winter anomaly at the deep solar minimum year may be attributed to mechanical effect of equatorward neutral wind that causes the disappearance of winter anomaly (Balan et al., 2010; 2012). This disappearance of the winter anomaly at the deep solar minimum was recently reported by other workers (Lin et al., 2007; Balan et al., 2013).

The significant result of this study is that the EIA has been found to migrate towards lower latitude from 2005 to 2009 with gradient rate $0.87^{\circ}\text{N}/\text{per year}$. To study the effect of this latitudinal gradient of EIA on the accuracy of the IRI model, the GPS-EIA has been compared with IRI model EIA during the descending phase of the solar activity from 2005 to 2009 (Figure 5). The GPS-EIA is found to over-estimate the IRI-EIA. The difference between GPS and IRI model has been found to be descending from year 2005 to 2009 with maximum difference of 37 TECu during the year 2005 and minimum difference of ~ 10 TECu during the year 2008. Thus the accuracy of the IRI model is found to be degraded significantly during high solar activity. Venkatesh et al.

(2011) compared GPS-TEC with IRI at two Indian stations Trivandrum and Waltair and have shown that IRI model TEC underestimating the GPS-TEC during day time and overestimating during nighttime at both the stations. Recently Aggrawal (2011) has compared GPS-TEC with IRI model at Rajkot, India (near northern anomaly crest region) during the year 2005-2006 and showed that the agreement between observation and IRI model TEC in the daytime sector only while underestimate in other time. Shastri et al. (1996) studied performance of IRI-model using f_0F_2 data observed from Ionosonde and reported significant the differences between observation and IRI model. The difference between observations and IRI model is attributed to longitude dependent shift in the latitudinal position of EIA towards higher latitudes that occurs with increasing solar activity (Lyon and Thomas, 1963). This property is not satisfactory included in global prediction of IRI model.

5. Conclusion

Seasonal and annual variations of EIA along with effect of geomagnetic and solar activity effects on it have been investigated during the descending phase of solar activity (2005-2009). The comparison of EIA crest with those from IRI-model has been made by analyzing GPS data near the EIA crest stations. The value of EIA crest in TEC shows seasonal variation (Semi-annual) with **maximum TEC** in equinox months and minimum in winter and summer, which may be due to a combined effect of the solar zenith angle and magnetic field geometry. The variation in EIA crest has been compared with solar and geomagnetic activity indices. **The correlation analysis of EIA crest with solar and geomagnetic parameter during 2005-2009 showed that on the long term basis EIA is more influenced by solar activity compared to geomagnetic activity.** The winter anomaly or seasonal anomaly in the EIA crest has also been observed only except during the deep solar minimum year 2007-2008 which is attributed to the mechanical impact of equatorward neutral winds that causes the disappearance of winter anomaly during the deep solar minimum.

The statistical mean location of EIA crest during the period 2005-2009 is found to be around 12:54 LT Hour in time and around 21.12° N in latitude. The temporal mean occurrence of EIA is found between 13:00 and 14:00 LT hour during the year from 2005-

2007 while between 12:00 and 13:00 LT hour during the year from 2008-2009, which suggest that the temporal occurrence of EIA depends on the solar activity. From 2005 to 2009 the mean location of EIA was continuously found to shift towards lower latitude, which is very important factors controlling the accuracy of IRI model. The average rate of shift of crest latitude during this period is found to be 0.87° N per year. The GPS-EIA has been compared with IRI model during the year 2005-2009. The accuracy of the IRI model is found to be degraded by solar activity. The future scope of this study is to investigate the validity IRI model with multi-instrument ground based observation data at different locations over the globe during different solar cycles.

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Caption to Figures:

Figure 1: Monthly variation of EIA crest, during the descending phase of solar activity period of 2005-2009.

Figure 2: Monthly mean variation of EIA crest in TEC, Dst index, Kp index, SSN, $F_{10.7}$ and solar EUV flux during the period 2005-2009.

Figure 3: Correlation diagram comparing monthly mean EIA with monthly mean (a) Dst-index, (b) Kp-index (c) SSN (d) $F_{10.7}$ (e) Solar EUV flux .

Figure 4: (a) Histogram of daily occurrence of EIA crest and local time during 2005-2009.

Figure 4: (b) Histogram of daily occurrence of EIA crest and geographic latitude during 2005-2009.

Figure 5: (a) Comparison of GPS derived EIA with IRI-model during 2005-2009.

(b) Variation of difference of EIA between observation (GPS) and model (IRI) during 2005-2009.

Figure: 1

Figure: 2

Figure: 3

Figure: 4

Figure 5

Table 1: Year wise correlation (2005-2009) of EIA with solar and geomagnetic indices.

Years	Correlation of monthly mean EIA with monthly mean				
	Kp-index	Dst-index	F10.7	EUV	SSN
2005	-0.71	-0.23	-0.39	-0.55	0.043
2006	-0.03	-0.01	0.23	0.56	0.42
2007	0.68	-0.12	-.09	0.37	-.21
2008	0.58	-.08	0.61	0.76	0.54
2009	0.57	-0.04	0-.14	0.08	0-.28
(2005-2009)	0.63	-0.68	0.79	0.86	0.81
	Correlation of annual mean EIA with annual mean				
Years	Kp-index	Dst -index	F10.7	EUV	SSN
(2005-2009)	0.87	-0.94	0.99	0.99	0.99

Table 2: Year wise statistical mean location of EIA (2005-2009).

S. No.	Years	Statistical mean location of EIA (Geographic Lat.)	Statistical mean location of EIA (Local Time), LT (HH:MM)
1	2005	22.75 ⁰ N	13:18
2	2006	21.56 ⁰ N	13:09
3	2007	20.78 ⁰ N	13:27
4	2008	19.62 ⁰ N	12:45
5	2009	18.43 ⁰ N	12:46
	Mean (2005-2009)	21.12⁰ N	12:54