

Dynamics of ionospheric irregularities in increasing phase of 24th solar cycle at Kolhapur [16.4°N, 74.2°E]

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Abstract

In this paper we have focused on drift of irregularities using amplitude scintillations for period January 2011 to December 2015. The data of VHF amplitude scintillations and all sky imager at Kolhapur has been used to obtain the drift of ionospheric irregularities. The drift is compared with velocities of thermospheric wind obtained by HWM-07 (Horizontal Wind Model-07) and of EPBs (Equatorial Plasma Bubbles). The results are in good agreement with model data. Also, the pattern of drift in scintillation data matches well with velocity of EPBs, mainly during equinoctial months. To examine the possible effect of magnetospheric disturbance on the dynamics of the irregularities we have compared the drift on magnetically disturbed nights with the monthly averaged quiet nights drift. Zonal velocity pattern on magnetically disturbed nights shows reversal in the direction of eastward zonal drift around midnight. The deviation of plasma drift on disturbed nights from monthly averaged quiet night drift shows maximum effect of magnetic activity around midnight. The monthly averaged peaks of the zonal drift increases with increasing 10.7 cm solar flux.

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1. Introduction

Neutral wind, electric field, pressure gradients, magnetic field and thermospheric temperature play very important role in the dynamics of ionosphere. The dynamics of plasma in the ionosphere is affected greatly by the electromagnetic forces (Hunsucker and Hargreaves, 2003; Kelley, 2009; Nayak et al., 2014). The electromagnetic forces acting on the charged particles produce electric currents, which are responsible for the electric field and electrical conductivity. The role of neutral wind in the formation of electric field and the electric currents in the presence of

magnetic field has been recently discussed by many authors (Brekke, 2013; Chapagain, 2011; Martinis et al., 2001).

During the periods of high geomagnetic activity, the equatorial ionosphere shows very high variable response to both disturbance dynamo electric fields and prompt penetrating electric fields from high to low latitude ionosphere and electric fields generated in the ionosphere by disturbance dynamo (Blanc and Richmond, 1980; Singh et al., 2013). Electric field plays very important role in the dynamics of ionosphere and therefore the study of dynamics of the ionosphere is needed to get information about the generation of electric field and changes in it. The electric field at different altitudes can be measured by in-situ experiments. The zonal, meridional and vertical drifts of the plasma are related to electric field as,

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$$\mathbf{V} = \mathbf{E} \times \mathbf{B}/B^2$$

At nighttime the electric field is downward causing an eastward motion of the plasma. This has been observed by various techniques by many authors (Basu et al., 1986; Bhattacharyya et al., 1989; Chapagain, 2011; Fejer, 1991). A large database of equatorial F region plasma drift velocities, obtained from radar observations at the Jicamarca observatory, has been used to model the behavior of the equatorial electric fields during storms. It also has been used to show the contributions from electric fields generated at the time of magnetic activity (Fejer and Scherliess, 1997; Scherliess and Fejer, 1999).

Nightglow emissions at (¹D) OI 630.0 nm are governed by dissociative recombination of O₂⁺ that is responsible for maximum ions at height of about 250–280 km (Terra et al., 2004). The studies made by the Challenging Minisatellite Payload (CHAMP) showed that equatorial plasma bubble (EPBs) occur at apex height of 250–600 km in the equatorial region (Xiong et al., 2012). The equatorial spreads F (ESFs) have scale size ranging from few centimeters to hundreds of kilometers. Large scale ESFs in (kilometer range) are considered as EPBs—the regions of deep plasma depletions (Chapagain, 2011; Kelley et al., 2011). The EPBs have altitudinal range from 90 km to 1000 km and above. Drift of the EPBs has been studied by many authors (Pimenta et al., 2001; Sharma et al., 2014; Taylor, 1997) using all sky imager which is useful to study the dynamics of large scale irregularities. The velocity of plasma bubbles also can be calculated by correlating TEC structures observed at two VHF polarimeter sites (Abdu et al., 1985). Kil et al., 2002; Kriegel et al., 2017 studied drift of plasma irregularities by monitoring the GPS signal using spaced receivers system. The intermediate scale sizes within these bubbles affects the VHF scintillations (Bhattacharyya et al., 2014). Bhattacharyya et al., 2001 used VHF scintillations (spaced receiver system) to study the drift velocity of plasma irregularities in the F region. Similar method has been used to study the effect of magnetic activity on the equatorial F region plasma drift by (Engavale et al., 2006). Therefore, it is useful to study the dynamics of the ionosphere simultaneously by VHF scintillation and EPBs observations.

In this paper we have examined the drift of ionospheric irregularities using both techniques. The Horizontal Wind Model data has been used to compare it with drift obtained by VHF scintillation data. This drift is also then compared with the drift of EPBs obtained by all sky imager. The behavior of drift of the irregularities has been studied for the five years (2011–2015). The effects of magnetic activities on drift of the irregularities have also been discussed in this paper.

2. Method of data analysis

Observations of amplitude scintillation of 251 MHz signal transmitted by geostationary satellite situated at 71.2°E

were made. For these observations two identical receivers with eleven element Yagi-Uda antennae separated by ~300 m in magnetic east-west direction are installed in Shivaji University, Kolhapur [16.4°N, 74.2°E, 10.6° dip. lat.] by Indian Institute of Geomagnetism (IIG), Navi Mumbai. The ionospheric amplitude scintillations are digitally recorded at 20 Hz sampling rate. The data used in this paper is from January 2011 to December 2015 which is increasing phase of 24th solar cycle.

The scintillation in the incoming amplitude signal is calculated using a parameter called scintillation index (S₄), which is the root mean squared standard deviation of normalized intensity variations of the signal. S₄ indicates the strength of intensity scintillation (Wernik et al., 2004).

$$S_4^2 = [\langle I^2 \rangle - \langle I \rangle^2] / \langle I \rangle^2 \quad (1)$$

where I is the intensity of the signal. S₄ index of each three minute interval has been determined. To minimize the effect of noise in the signal, we have used data intervals with S₄ > 0.15, such intervals are considered as scintillation events (Bhattacharyya et al., 2001; Kakad et al., 2007).

According to cross correlation technique, the space time correlation function of the intensity scintillation pattern received by two spaced receivers on ground is of the form (Briggs, 1984),

$$C_I(x, t) = f[(x_o - V_o t)^2 + V_c^2 t^2] \quad (2)$$

Here, x_o is the distance between two receivers, V_o is zonal drift of the irregularity patterns across the propagation of VHF signal and V_c is the measure of spatial and temporal changes in the irregularity which is evolving randomly (Bhattacharyya et al., 2003). The method to calculate V_o and V_c explained by Bhattacharyya et al., 2003; Kakad, 2007 is given below: f is monotonically decreasing function of space and time with $f(0) = 1$. When correlation is greater than or equal to 0.5, the assumed functional form of f specified in Eq. (2) has greater validity at a time $t = t_m$ where, t_m is the time at which cross correlation is maximum. Therefore, using scintillation events which have cross-correlation, $C_I(x_o, t_m) \geq 0.5$ and the following boundary conditions,

$$\left. \frac{\partial C_I}{\partial t} \right|_{t=t_m} = 0 \text{ and } \left. \frac{\partial^2 C_I}{\partial t^2} \right|_{t=t_m} < 0 \quad (3)$$

we get,

$$t_m = V_o x_o / (V_o^2 + V_c^2) \quad (4)$$

Considering the time t_p , the time when auto-correlation function has same value as maximum cross-correlation function, then we have:

$$C_I(x_o, t_m) = C_I(0, t_p) \quad (5)$$

Using Eqs. (4) and (5) we can get the equations for V_o and V_c as, $V_o = x_o t_m / t_m^2 + t_p^2$ and $V_c = x_o t_m / t_m^2 + t_p^2$.

These equations are used to calculate V_o and V_c .

By taking vertical drift, V_z into account, the zonal velocity is given as,

$$V_0 = V_E - V_z \tan \theta \sin \phi \quad (6)$$

where θ and ϕ are zenith angle and azimuth angle measured eastward from north (Bhattacharyya et al., 2001). The geometry of the receiver site at Kolhapur yields zenith and azimuth angle as, $\theta = 3^\circ$ and $\phi = 100^\circ$ which gives, $V_0 = V_E - 0.01 * V_z$, therefore, contributions to the zonal drift is only from V_E and negligible from vertical drift V_z . V_0 is considered as the true drift of the irregularities.

The thermospheric horizontal wind model (HWM-07) provides a statistical representation of the horizontal wind fields of the Earth's atmosphere from the ground to the exosphere (0–500 km). It estimates atmospheric wind using satellite, rocket, and ground-based wind measurement's data of over 50 years (Drob et al., 2008). HWM-07 model has been run in Fortran 90 subroutine for height of 350 km.

The zonal drift of EPBs has been calculated by comparing their positions in consecutive images to find the longitudinal offset and using time difference (Makela et al., 2005; Makela and Kelley, 2003). Pimenta et al., 2001 proposed the “scanning method” to calculate drift of EPBs from OI 630.0 nm images. In this method, each image of OI 630.0 nm is scanned through the zenith from east to west to obtain a cross-section of the depletion for each EPB. The linearized images with an appropriate geographic coordinate system have been used to compare the east–west intensity variations in consecutive images (Garcia et al., 1997; Pimenta et al., 2001). Here the zonal drift of EPBs in OI 630.0 nm has been calculated using fast image analysis technique developed by Sharma et al., 2014. In this technique, the position of Eastern wall, Western wall and centre of EPB in each image is recorded. By taking time difference between successive images the velocity is determined. The comparison between the F region zonal plasma drift with EPBs velocities and zonal neutral wind was done by Chapagain et al., 2013. These results of the nighttime temporal variations of the zonal velocities of EPBs and plasma drifts correlate well with each other and also with the zonal neutral winds. The plasma drift pattern using GPS scintillations compared with drift of EPBs by Wiens et al., 2006 also shows similar behavior.

3. Results and discussion

3.1. Zonal and random velocity during night

Onset of the drift is around 20 LT, it starts to increase from 50 to 75 m/s then it reaches a peak around 21 LT and then decreases continuously throughout the night. In the generation phase (post sunset period) of the ESF irregularities, because of random changes in the vertical electric field, zonal velocity V_0 results into the random fluctuations. This can be seen in pattern of all quiet nights of September 2012. Sample of such data as shown in Fig. 1(a).

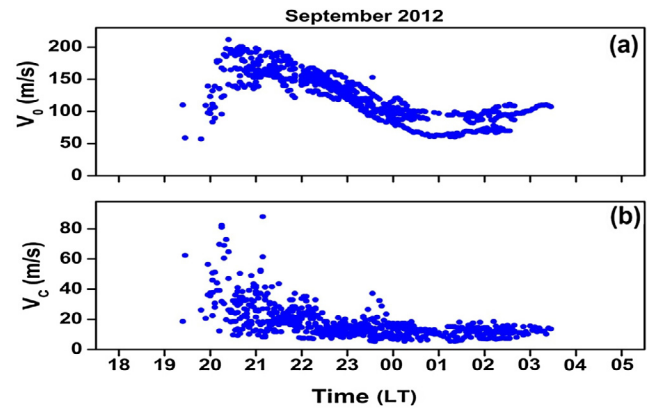


Fig. 1. Zonal velocity V_0 (upper panel) and Random velocity V_c (lower panel) of all quiet days.

The random velocity V_c for quiet nights of same month is plotted simultaneously in Fig. 1(b). Very high V_c , about 80–100 m/s, in pre-midnight period, indicates fluctuations in drift velocity at that time. This may be the effect of pre-reversal enhancement in post sunset period. In this period increase in eastward electric field which is responsible for prereversal enhancement lifts the F region peak to higher heights resulting in of ESF irregularities. Then it decreases to lower values up to 5 m/s. It shows steadiness in drift velocity followed by decrease in height of F region in post midnight and decay of ESF irregularities.

3.2. Comparison of zonal plasma drift velocity with horizontal wind model (HWM-07)

Zonal drift of night time is averaged for each one hour interval for the magnetically quiet ($A_p \leq 18$) days. Averaged quiet day pattern, for each month, is obtained by averaging drifts of all quiet days in a month. Six months only (of 2012) have sufficient number of data points. The drift of irregularities of these months is then plotted with monthly averaged thermospheric wind velocities obtained by horizontal wind model (HWM-07). In Fig. 2 the drifts calculated from amplitude scintillation data and using HWM-07 are plotted simultaneously. Vertical lines indicate standard deviations. In equinoctial months of March and September peaks of monthly averaged drift nearly matches with the peaks of wind model data. In these months, peak values of drift of irregularities are 159 m/s and 163 m/s respectively are higher than the corresponding peak values 150 m/s and 160 m/s obtained from the wind model. On the contrary, in equinoctial month of October the drift is 143 m/s which is lower than the corresponding value 170 m/s obtained from the wind model. Peak time for all the equinoctial months is around 21 LT. Peak values of drift in all other three winter solstice months of January, November and December, are about 140 m/s, which are lower than 170 m/s obtained by HWM-07 wind model. It is worth noting that for these months peaks were shifted towards midnight. These values are smaller than that of

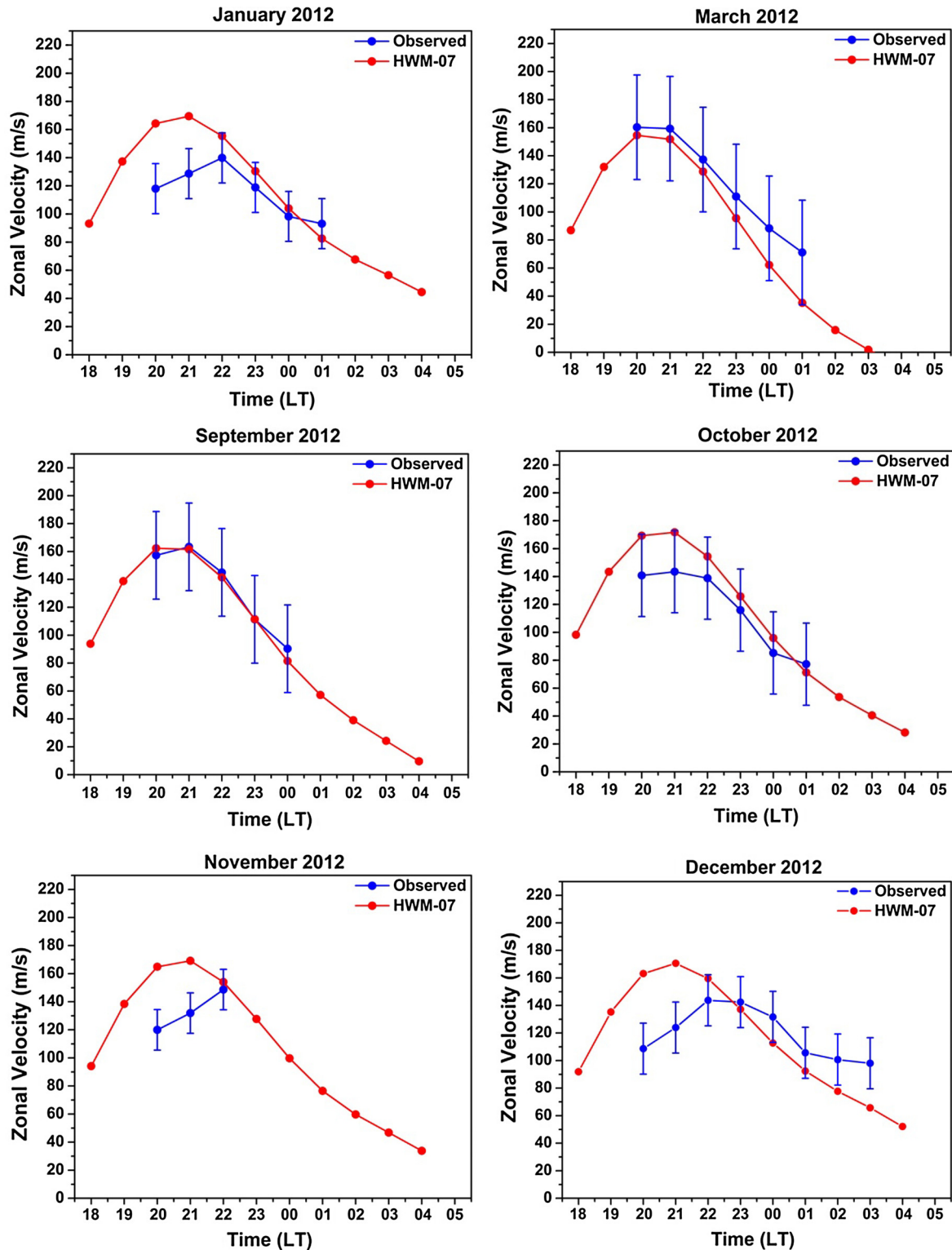


Fig. 2. Zonal plasma drift obtained using amplitude scintillation and wind velocity using HWM-07 model.

the equinoctial months. Peak time for all the solstice months is about 22 LT.

In equinoctial months after 21 LT drift decreases steadily up to smallest values 70–80 m/s during 01–02 LT. Similar is the case with wind model drift values. In November

available data are less. In January drift decreases with wind model drift values. But the drift value during 01 to 02 LT is about 90 m/s which is higher than corresponding equinoctial drift. In December drift decreases smoothly, remains almost higher than that of wind model drift throughout

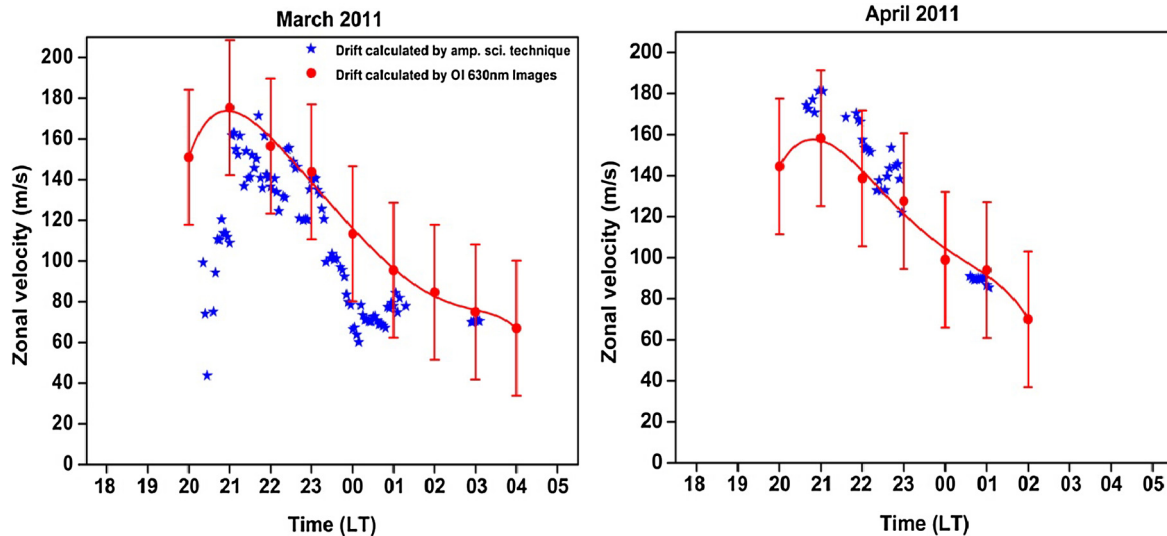


Fig. 3. Monthly averaged plasma drift obtained using amplitude scintillation plotted with drift of EPBs using OI 630 nm images in equinoctial period.

the night and has value about 100 m/s during 01 to 02 LT. The drift attained after midnight in equinox is smaller than in solstice months. These results are in agreement with that of Pathan and Rao, 1996; Pimenta et al., 2003. From Fig. 2 it is clear that the monthly averaged zonal drift pattern matches well with HWM-07 wind model during March and September.

3.3. Comparison of zonal plasma drift calculated using techniques of scintillation and all sky imager

Monthly averaged quiet day plasma drift obtained by amplitude scintillations of VHF signal and the drift of EPBs observed in OI 630.0 nm images of all sky images are plotted in Fig. 3. Both observations are made from Kolhapur. 4th order polynomial fit for drift of EPBs is shown as red¹ curve in Fig. 3. The vertical bars indicate the standard deviations. Monthly averaged quiet day drift of March 2011 of ground scintillation pattern of VHF signal starts at 2030 LT then maximizes at 2130 LT and then decreases throughout the night, while in April 2011 it starts at 21 LT with maximum and then decreases throughout the night. Similarly, for both months March and April, the drift of EPBs starts at 20 LT, then maximizes at 21 LT and then it decreases throughout the remaining night. Eastward drift obtained from amplitude scintillation data falls within the standard deviation. Therefore, it is clear that the averaged zonal drift at the F region peak and zonal drift of plasma bubbles have similar pattern with smaller velocities of EPBs in March 2011 and higher in April 2011. Since the pattern of both is same and the velocity data points of EPBs fall within the standard deviations of the averaged zonal drift at the F region peak, it can be concluded that the dynamics of both phenomena have a significant correlation.

3.4. Seasonal behavior of plasma drift

Fig. 4 shows the mass plot of monthly averaged zonal drift values of equinoctial and winter months in five years (2011–2015). In equinoctial months zonal drift is in the range ~50 to 180 m/s during the times of onset 19–21 LT. But in winter onset time lags to that of equinox by few minutes and at the times of onset zonal drift is above 80 m/s. Maximum value of drift also has shifted forward for winter during 22–23 LT with average of 170 m/s. It is less than the average peak value of 180 m/s in equinox. Value of drift decreases after midnight but remains greater than 80 m/s in winter and in equinox value of drift decreases to 75 m/s. This indicates that the downward electric field remains higher throughout the night in winter season (Manju et al., 2007).

3.5. Effect of magnetic activities on ionosphere

Equatorial F region during night is affected by magnetic disturbances (Basu et al., 2001; Dymond et al., 2004; Sastri et al., 2000). The effect of magnetic activities on ionospheric irregularities crossing the signal can be identified through cross correlation, $C_I(x, t)$. For this we accept maximum value of $C_I(x_0, t_m)$ or C_I . It correlates the signal received at two antennae separated by 300 m in East-West direction. The ESF irregularities generated as a result of magnetic activity cause scintillations to incoming radio signal. On quiet days in the generation phase of irregularities the values of cross correlation are smaller than 1 up to 22 LT and then it is saturated towards 1. If values of C_I have large deviation from 1 (less than 0.5) after 22 LT then it may be considered that irregularities are generated newly in this period. Therefore, the quantity C_I can be used as the parameter to identify the freshly generated irregularities. The freshly generated irregularities are said to be present if C_I is less than 0.5. Such days can be considered as

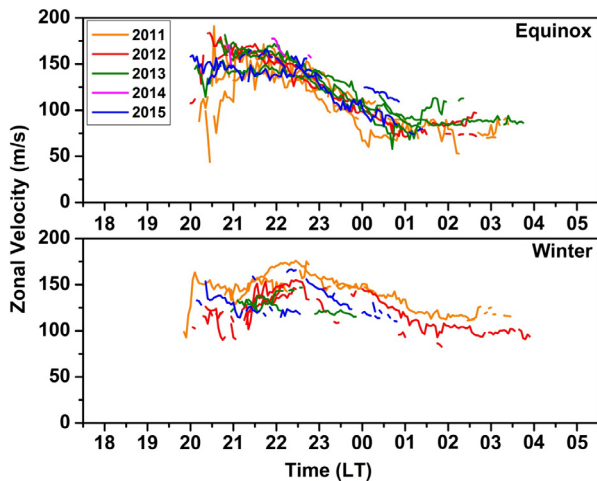


Fig. 4. Mass plot of monthly averaged zonal plasma drift of equinoctial period and winter period for five years (2011–2015).

magnetically disturbed (Bhattacharyya et al., 2002). Kakad et al., 2007 studied occurrence pattern of freshly generated EPBs, during night for different seasons using the estimates of C_I by spaced receiver VHF scintillations. We have used data of the magnetically disturbed days for which $A_p \geq 18$.

The C_I is plotted in Fig. 5 for six magnetically disturbed nights, 06–07 April 2011, 15–16 March 2012, 01–02 November 2012, 14–15 October 2013, 12–13 September 2014 and 01–02 March 2015. The three hour A_p values of corresponding nights are also shown in purple color on the x-axis of Fig. 5. On 06–07 April 2011 when $A_p = 48$ and 39 in pre midnight period causes C_I to attains smaller values at midnight and then reaches to about one in post midnight period and similar behavior can be seen on 12–13 September 2014 and 01–02 March 2015. C_I reaches nearly zero in pre-midnight and remains below 0.5 throughout the night when A_p is very high ($A_p = 39$ and 94) in pre midnight period of 15–16 March 2012. This implies that small values of A_p do not appreciably affect the C_I as compared to that on 15–16 March 2012 where A_p is very high in pre-midnight period and therefore C_I is very low throughout the night. On 01–02 November 2012 and 14–15 October 2013, C_I appears to fall below 0.8–0.9 but not less than 0.5. On 01–02 November 2012 it shows small depression at midnight and again decrease towards 0.5 after midnight. This shows fresh generation of irregularities at and after midnight even when $A_p = 18$ and $A_p = 39$ are comparably small. On 14–15 October 2013 scintillation do not occur after midnight so the data points of C_I are also less but, depression in C_I can be seen after 22 LT which is the indication of fresh generation of irregularities even when A_p is comparably small ($A_p = 18$ and 32).

Six magnetically disturbed night observations show that the irregularities are probably freshly generated during midnight and post-midnight periods. For higher A_p , values

of C_I are very small. Therefore, it can be concluded that the value of A_p affects the depression in C_I but, the time of appearance of freshly generated irregularities cannot be predicted on the basis of level of A_p . This can be seen in Fig. 5(a and b) where A_p throughout the night is high and large number of data points have C_I less than 0.5. While in Fig. 5(c and d) where A_p is small and very less data points have C_I less than 0.5. But in both the cases irregularities are generated freshly at midnight and post midnight period.

3.6. Variation in zonal drift on magnetically disturbed nights

The eastward plasma drift (V_0) estimated from spaced receiver system can be used to study the effect of magnetic disturbance on the F region electric field which is responsible for the eastward motion of the plasma and the F region nocturnal dynamics. This can be done by superimposing zonal drift velocity of particular night on monthly averaged quiet day pattern of corresponding month. The monthly averaged zonal drift pattern is considered as the ambient plasma drift. The six disturbed days mentioned in above Section 3.5 are considered here for the study, three hour A_p for all six days is given in Fig. 5. Fig. 6 is the plot of night time eastward zonal drift velocity for each disturbed day superimposed with quiet day nocturnal ambient plasma drift pattern of corresponding month. Zonal drift before 21 LT has high fluctuations, due to the generation phase of the irregularities. Because of day to day variability before 21 LT the magnetically disturbed day pattern in this period cannot be used. So to estimate the effect of magnetic disturbance, only pattern after 21 LT has been considered.

Eastward drift on 06–07 April 2011 is largely affected at 2230 LT due to magnetic disturbance as in Fig. 6(a). On this day eastward drift is drastically decreased from 140 to 15 m/s during 21–22 LT, this is the turning of eastward velocity of irregularities to westward. Here eastward velocity do not completely turn to west but decreases to very smaller values, continue to for about one hour, then increases and shows two maxima after 01 LT. This increase in zonal drift in post midnight period is due to the uplifting of the F region which may be attributed to magnetic activity on this day. This can also be seen in the peaks of random velocity as in Fig. 7(a). The downward to upward turning of electric field on magnetically disturbed night is responsible for decrease in eastward drift of the plasma. This may be due to electric field produced by the ionospheric disturbance dynamo. On 15–16 March 2012 magnetic disturbance is very high which shows very low C_I on this period.

On 01–02 November 2012, eastward velocity shows continuous decrease from 120 m/s to 40 m/s within few hours, this decrease may be due to higher A_p during 21–00 LT. In post midnight period three peaks in zonal drift can be seen in Fig. 6(c) at 0230, 0330 and 0430 LT. Random velocity during this period is higher (20 m/s) as shown in Fig. 7(c), where it is expected to decrease to about 5 m/s. The

¹ For interpretation of color in Fig. 3, the reader is referred to the web version of this article.

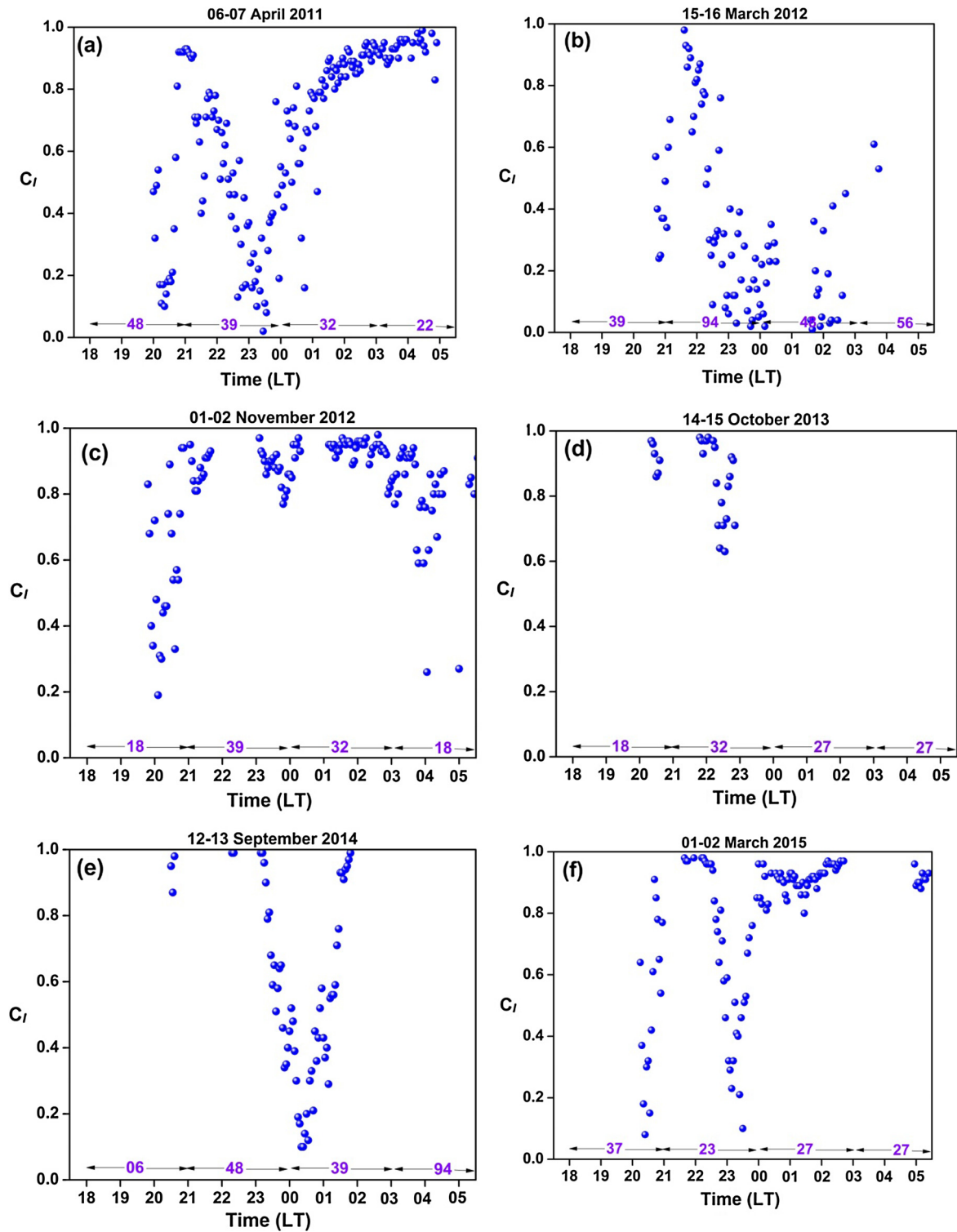


Fig. 5. Maximum cross correlation C_I during magnetically disturbed days (a-f) (three hour ap is shown by purple color). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

data points on 14–15 October 2013 after 21 LT are very less but the large deviation from ambient plasma drift is observed as shown in Fig. 6(d).

The sharp decrease of 75 m/s from quiet day pattern is observed on 12–13 September 2014 during 23 to 00 LT as in Fig. 6(e). Two sharp peaks of random velocity can be seen at 2330 LT and 0030 LT as in Fig. 7(e). Turning

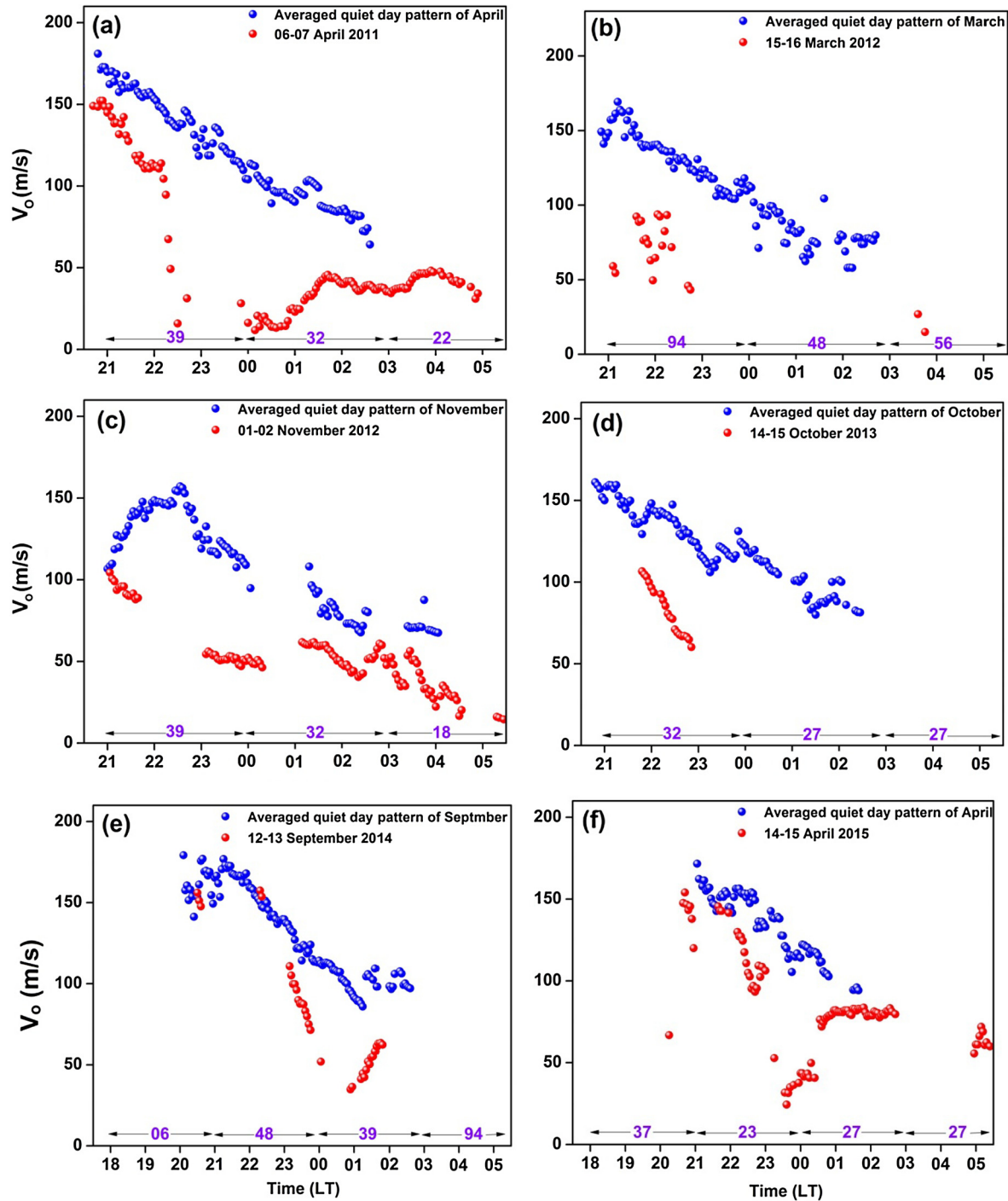


Fig. 6. Zonal velocity of each disturbed day (a–f) (date is mentioned in legend) superposed with monthly averaged quiet day pattern of zonal velocity for corresponding month.

of eastward drift to westward is maximum in Figs. 6 (f) and 7(f) for the day 14–15 April 2015 in between 23 and 0030 LT.

The large deviation of drift of each disturbed night from ambient plasma drift at midnight or in post midnight period suggests the downward to upward turning of electric field due to ionospheric disturbance dynamo electric field or due to prompt penetration of magnetospheric electric field. This is observed for all disturbed days. The sharp

decrease in the drift on 06–07 April 2011 at 2230 LT may be attributed to the polarization electric fields associated with the freshly generated irregularities or the irregularities generated before 22 LT that cross the signal on 2230 LT. The sharp peaks in V_c observed in post midnight period may be due to the increase in height of irregularities in this period. The increase in eastward electric field due to disturbance dynamo is responsible to increase height of irregularities.

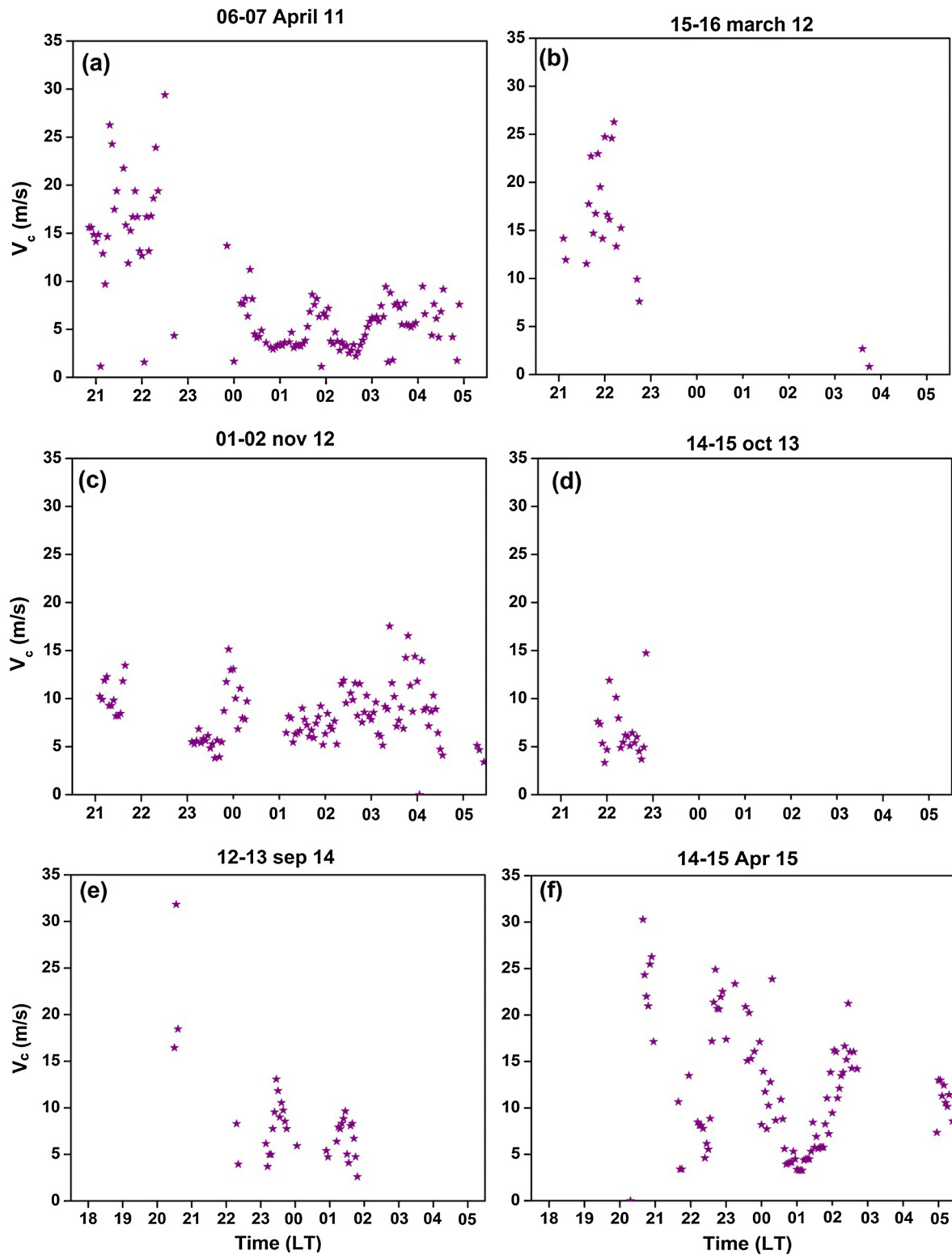


Fig. 7. Random velocity for magnetically disturbed days (a–f) ($A_p \geq 18$).

3.7. Effect of solar flux on zonal drift

Effect of season, solar and magnetic activities on irregularities have been studied extensively in equatorial region by many researchers (Muella et al., 2009; Pathan and

Rao, 1996). Fejer et al., 2005 observed that the eastward plasma drift have higher values on equinoctial and solstice period as well as it increases with increase in solar activity. Since, zonal drift shows maxima during 20–22 LT for almost all nights. The monthly averaged zonal drift during

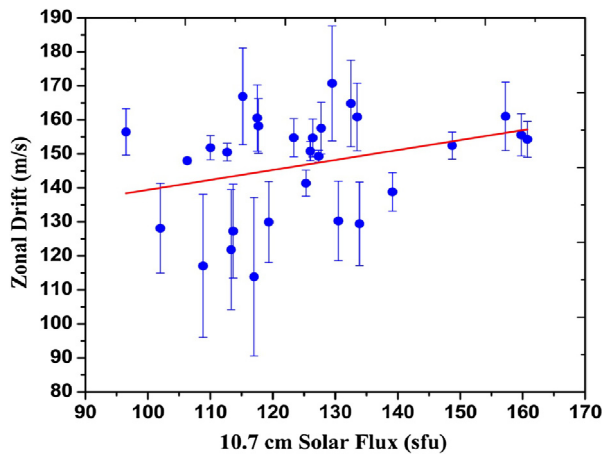


Fig. 8. Monthly averaged peak (20–22 LT) with corresponding averaged 10.7 cm solar flux. The vertical bars shows standard error.

this period is estimated and plotted with monthly averaged 10.7 cm solar flux from January 2011 to December 2015 in Fig. 8. Graph between averaged peak of zonal drift and solar activity gives slope and intercept as 0.29 and 110 respectively, which shows increase of averaged peak of zonal drift with solar activity. These results are analogous to the results of zonal drifts estimated by Fejer, 1991. It is known that the eastward electric fields produced at the time of sunset have higher values during solar maximum which in turn may be responsible for higher eastward drifts.

4. Summary and conclusions

In this paper the behavior of night time plasma drift in the F region has been investigated with respect to season, magnetic activity and solar activity. The significant results are summarized below:

- (1) Seasonal behavior of eastward plasma drift velocity for winter shows small lag to the equinoctial onset time. Values of drifts for this season are higher throughout the night than that of equinox.
- (2) The monthly averaged zonal drift pattern of F region plasma is in good agreement with that of thermospheric neutral wind obtained by Horizontal Wind Model-07 (HWM-07) for March and September.
- (3) From the comparative study of drift of EPBs with F region plasma drift obtained by scintillation technique it may be concluded that the dynamics of both phenomena have a significant correlation.
- (4) C_I on highly disturbed nights is very small around midnight. The values of a_p cause the depression in C_I . But the time of appearance of freshly generated irregularities cannot be predicted on the basis of level of a_p .
- (5) Zonal velocity pattern on magnetically disturbed nights shows reversal in the direction of eastward zonal drift around midnight.

- (6) Night time averaged peak of eastward zonal drift increase with increase in solar activity.

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