Study of disturbance dynamo effects at nighttime equatorial F region in Indian longitude

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[1] Post sunset height of F layer may significantly increase or decrease as compared to their monthly quiet time pattern due to superimposed disturbed time electric field associated with either disturbance dynamo (DD) or prompt penetration (PP) or combination of both DD and PP. In this paper, the effects associated with disturbed time eastward electric field causing upward movement of F layer in the post sunset hours are investigated. Ionosonde data recorded at dip equatorial station Trivandrum for the period of 1990–2003 are scaled to obtain the variation of $h'F$ from 17-31LT. Effect of magnetic activity on $h'F$ (ΔH) is obtained by subtracting monthly quiet time average of $h'F$ from disturbed time $h'F$. The maximum enhancement seen in $h'F$ i.e $\Delta H_{\max}$ provides the quantitative estimate of maximum effect of magnetic activity at equatorial F region. Here 97 magnetically disturbed days with $\Delta H_{\max} \geq 80$ km are studied. Geomagnetic activity index *ap* is used along with *AE* and attempt has been made to identify the effects associated with short and long term DD electric field. It is found that the duration of short and long term DD effects seen at equatorial F region decreases with increase in solar flux. However this dependence is not applicable close to early morning hours ($\geq$ 05LT). Time delays required to produce maximum effect at equatorial F region during high solar flux are found to be 16–23 hrs (0.5–4 hrs) for long (short) term DD effects studied here.

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1. Introduction

[2] A large amount of energy gets deposited in the high latitude ionosphere during periods of strong geomagnetic activity. Enhancement of electric field and electrical conductivity in the high latitude ionosphere results in intense current which give rise to increased Joule heating during periods of high magnetic activity. Thus the neutrals get heated and a disturbance dynamo is set up by the changed neutral wind at high latitudes [*Blanc and Richmond*, 1980]. During periods of high magnetic activity, disturbance dynamo (DD) and prompt penetration (PP) of magnetospheric electric field are the sources for modulation of equatorial ionospheric electric field and hence plays an important role in the dynamics of equatorial ionosphere. It is known from past observations that the equatorial ionosphere shows highly variable responses during magnetically active periods [*Fejer and Scherliess*, 1997; *Abdu et al.*, 1998; *Sastri et al.*, 2000; *Basu et al.*, 2001; *Bhattacharyya et al.*, 2002]. The effect of magnetic activity observed at a given local time (LT) in equatorial ionosphere may be associated with either DD or PP electric field alone or it may be a combined effect of both [*Fejer et al.*, 1991; *Maruyama et al.*, 2005; *Kakad et al.*, 2007].

[3] Earlier studies have suggested that sudden change in polar cap potential may cause prompt penetration of electric field, when there is no sufficient shielding effect [*Peymirat et al.*, 2000]. These PP electric fields (i) have short time duration (1 hr), (ii) can reverse the direction of the normal electric field during periods of rapid decrease in polar cap potential (iii) its effects are often observed simultaneously at all longitudes [*Spiro et al.*, 1988; *Fejer et al.*, 1990; *Forbes et al.*, 1995; *Fejer and Scherliess*, 1997; *Scherliess and Fejer*, 1997]. However, recent study suggests that the effects of PP electric field can be seen for longer duration during intense geomagnetic storm [*Basu et al.*, 2005]. On the other hand the altered neutral wind resulting from enhanced Joule energy at high latitudes during periods of strong geomagnetic activity takes some time to set up the DD. As a result DD associated perturbations in the equatorial ionosphere are observed with some time delays after the enhancement in magnetic activity.

[4] Recent simulation study has shown that PP electric field considerably modulates the existing DD electric field and hence its associated effects at equatorial F region [*Maruyama et al.*, 2005]. But how PP electric field alters the existing DD electric field and to what extent is not well understood yet. The modulated ionospheric electric field associated with either DD or PP or DD + PP may increase or decrease the height of equatorial F layer considerably depending on the direction and strength of magnetically

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disturbed time electric field, which is superposed on ambient ionospheric electric field. The duration and strength of the effect of magnetic disturbances on equatorial F region height ($h'F$) is found to be different for different magnetically disturbed days. This may be attributed to differences in the magnetic activity level on those days and hence in the Joule energy, in the starting time and duration of magnetic activity and in the ambient ionospheric conditions.

[5] Many studies addressing the effect of DD electric field on zonal/vertical plasma drifts and associated time delays have been carried out extensively using Jicamarca radar observations. *Fejer et al.* [2005] suggest that DD electric field, with dominant time delay of about 3-15 hrs after a period of increased magnetic activity largely accounts for disturbed time zonal plasma drifts. They also found that geomagnetic activity effect on zonal plasma drifts are season and solar flux dependent. *Scherliess and Fejer* [1997] have studied disturbed time F region vertical plasma drifts using Jicamarca radar observations and proposed two dynamo processes with time delays of 1–12 and 22–28 hrs. In their study it is suggested that the long term DD effects may be resulted from storm-driven compositional/conductivity changes which occurs approximately a day later the enhancement in high latitude disturbance current. Whereas short term DD effects may be associated with fast traveling atmospheric disturbances (TADs), which reach equatorial latitude few hours after enhancement in high latitude disturbance current. Recently, *Huang and Chen* [2008] used NACR/TIEGCM model and examined the solar flux dependence of perturbed zonal electric field resulted from DD for March and June months. Nevertheless, the effect of solar flux on duration of DD effects observed at equatorial F region is not yet addressed.

[6] In the present study attempt is made to separate the effects associated with short and long term DD. The influence of solar flux on duration of DD (short/long) effects observed at equatorial F region is investigated. Also time delays associated with DD effects at nighttime equatorial F region are estimated for high solar flux period. Time delays linked with DD effects during low solar flux are not computed due to less number of days in that category. Here, LT variation of base height of F layer ($h'F$) in the post sunset hours is obtained by manual scaling of ionosonde data recorded at Trivandrum during 1990–2003. Total 97 magnetically disturbed days, which shows significant enhancement in $h'F$ as compared to their monthly quiet time variability, in the post sunset hours due to magnetically disturbed time eastward electric field are considered.

[7] Data and method used to get quantitative estimates of magnetic disturbance effects on $h'F$ in post sunset hours are given in section 2. Separation of quiet and disturbed days using three hourly geomagnetic activity index *ap* and categorization of magnetically disturbed days are briefed in sections 3 and 4 respectively. Joule energy computation is described in section 5. Results are discussed in section 6. The present work is summarized and concluded in section 7.

2. Data Used and Quantitative Estimate of Magnetic Activity

[8] In the present study ionosonde data acquired at Trivandrum (77°E, 8.5°N, dip 0.5°N) for the period of January 1993- February 2003 are used along with the data of March-April during 1990–1992. *AE* indices data from http://wdc.kugi.kyoto-u.ac.jp/ and IMF B_Z, OMNI data from http://cdaweb.gsfc.nasa.gov/ for magnetically disturbed days studied here, are also utilized. All together 126 months of data are available during 1990–2003. These data are scaled for all available dates to obtain the variation of base height of F layer, $h'F$ from 17–31 LT for each day. Here 31 LT implies 07 LT of the next day. $h'F$ is not scaled for the time intervals when base height of the F layer is not clearly visible in ionogram due to strong range spread.

[9] Generally, in the post sunset hours the daytime eastward electric field enhances rapidly before turning to westward which is known as pre-reversal enhancement (PRE) [*Woodman*, 1970]. Thus in the post sunset hours F layer moves upward rapidly and then comes down due to decay of this PRE associated eastward electric field. It is noticed that PRE varies considerably from day-to-day and it also depends on season, solar flux and longitude [*Abdu et al.*, 1981; *Batista et al.*, 1986; *Hari and Krishna Murthy*, 1995; *Fejer and Scherliess*, 2001; *Oyekola et al.*, 2007]. As a result the post sunset height of F layer varies considerably from day to day for magnetically quiet periods, which gets reflected in the monthly quiet time pattern of apparent base height of F layer $h'F$. Despite of these day-to-day variability in the post sunset hours $h'F$ generally follow a well defined pattern for magnetically quiet days of a given month.

[10] A monthly quiet time average of $h'F$ ($\langle h'F_Q \rangle$) is obtained by taking 15 min average from 17LT to 07LT of following day for magnetically quiet days of a month. The method used to select magnetically quiet and disturbed days is described in section 3. For each magnetically disturbed day, effect of magnetic disturbance at equatorial F region (ΔH) is obtained by subtracting $\langle h'F_Q \rangle$ from disturbed time $h'F$ ($h'F_D$). Figure 1a shows the LT variation of (i) monthly quiet time average of $h'F$ ($\langle h'F_Q \rangle$) along with standard deviation as error bar for July 1999 and (ii) $h'F$ for magnetically disturbed day 2 July 1999. Figure 1b shows LT variation of $\Delta H = h'F_D - \langle h'F_Q \rangle$ for 2 July 1999. It is clearly seen that during the night of disturbed day 2 July 1999, F layer moves upward considerably as compared to its monthly quiet time average of $h'F$ and maximum increase of $\sim$156 km is seen around 01.7LT (i.e 01.7LT on 3 July 1999). Maximum of ΔH is taken as quantitative measure of maximum effect of magnetic activity on $h'F$ resulted from disturbed time eastward electric field that is superimposed on usual ambient quiet time electric field in the post sunset hours and its time of occurrence is considered as the time of maximum effect of magnetic disturbance, T_m.

[11] It should be noted that during night of 2 July 1999, $h'F_D$ starts deviating from its monthly quiet time average pattern from $\sim$23LT and after showing maximum effect of magnetic activity at $\sim T_m$ = 01.7LT it again tend to follow the monthly quiet time pattern around 05LT. One can say that the effect of magnetic disturbance is observed between 23-05LT. The portion of $h'F_D$ that is affected by the magnetic activity is fitted with 6th order polynomial ($h'F_{DF}$) and its first time derivative is computed to get the vertical drift of base height of F layer on disturbed day. For 2 July 1999, the $h'F$ between $\sim$22-05LT is fitted with 6th order polynomial which is shown by black dots in Figure 1a and its

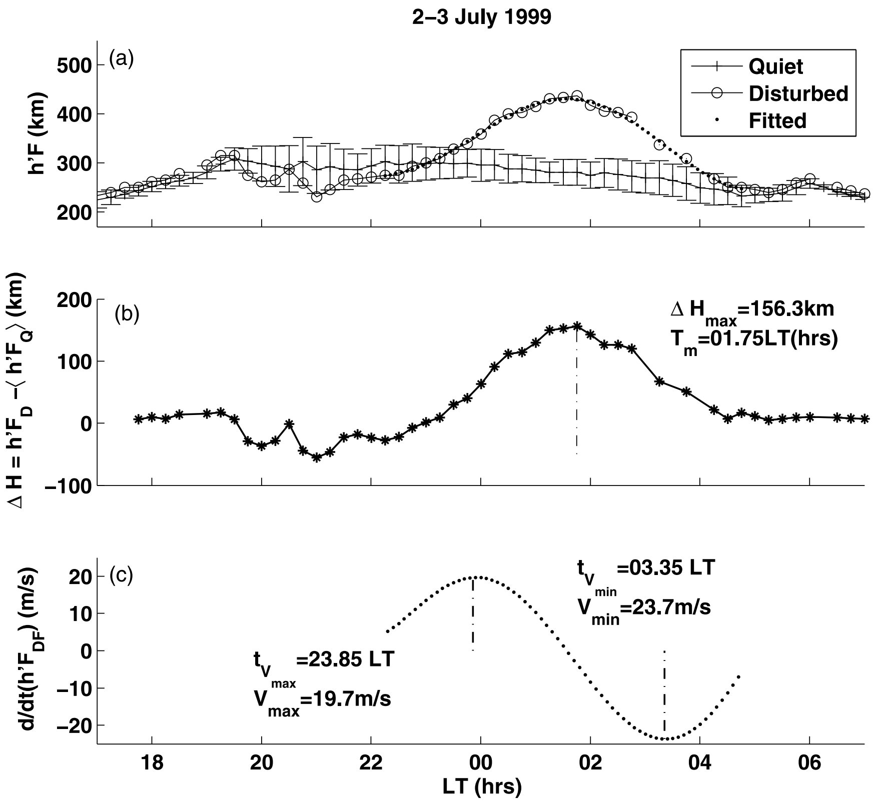

Figure 1. LT variation of (a) quiet time average of $h'F$ for a month of July 1999 superimposed with disturbed time (i) actual $h'F$ and (ii) $h'F$ fitted with 6th order polynomial for 2–3 July 1999. (b) ΔH and (c) first order time derivative of disturbed time fitted $h'F$ ($h'F_{DF}$) for 2–3 July 1999.

first time derivative is shown in Figure 1c. $V = \frac{d\left(h'F_{DF}\right)}{dt}$ provides the estimate of apparent vertical drift of base height of F layer. The maximum rate of upward(downward) movement of $h'F_D$, $V_{\max}(V_{\min})$ is estimated by taking maximum(minimum) of V along with their occurrence time $t_{V_{\max}}(t_{V_{\min}})$.

[12] In many investigations the rate of change of $h'F$ is used to get the vertical drift of base height of F layer [*Goel et al.*, 1990; *Subbarao and Krishna Murthy*, 1994; *Oyekola*, 2009]. However the vertical apparent drift obtained from $h'F$ measurements deviate considerably from true vertical $\mathbf{E} \times \mathbf{B}$ drift during early and late evening hours due to effects of chemical recombination. It should be noted that eastward electric field and recombination of molecular species at the bottom side of F layer contributes to apparent upward movement of equatorial F layer in the post sunset hours, whereas apparent downward movement is solely controlled by electric field. In earlier studies it is reported that apparent vertical drift estimated above 300 km are close to the real vertical drift as at this altitude the chemical loss on vertical drift are negligible during 18-22LT hours [*Bittencourt and Abdu*, 1981; *Krishna Murthy et al.*, 1990]. Hence the apparent $V_{\max}$ and $V_{\min}$ obtained from first time derivative of $h'F_{DF}$ in the early and late evening hours are close to true vertical drift only if they are estimated at an altitude >300km. After 22LT when molecular recombination at the bottom side of F layer is considerably reduced the observed increase in $h'F_D$ as compared to its monthly quiet time pattern is associated with magnetically disturbed time eastward electric field alone. So the apparent $V_{\max}$ and $V_{\min}$ obtained from first time derivative of $h'F_{DF}$ during ~22-04LT hours can be considered as a proxy of true vertical drift of base height of equatorial F layer.

[13] Quantitative measure of maximum effect of magnetic disturbance $\Delta H_{\max}$ along with its occurrence time T_m, maximum apparent vertical $V_{\max}$ and downward $V_{\min}$ drift speed of $h'F_D$ together with their occurrence time $t_{V_{\max}}$, $t_{V_{\min}}$ are computed for each magnetically disturbed day. The error in 6th order polynomial fitting of portion of $h'F_D$ affected by magnetic activity is <25 km for all magnetically disturbed days under consideration. The standard deviation of monthly quiet time averages of $h'F$ varies from ~10–60 km for all months considered in the present study. Depending on the strength and direction of disturbed time electric field F layer moves upward or downward considerably as compared to their monthly quiet time average of $h'F$ [*Sastri*, 1985; *Forbes et al.*, 1988; *Sobral et al.*, 2001; *Tulasi Ram et al.*, 2007]. Sometimes more than one increase or decrease are observed in $h'F$ at different LT as a result of magnetic activity. However days which shows significant upward movement (i.e $\Delta H_{\max} \geq 80$ km) as compared to their monthly quiet time average of $h'F$, due to disturbed time eastward electric field in the post sunset hours, are only considered here. This assures that observed $\Delta H_{\max}$ is substantial as compared to the quiet time variability of $h'F$. The days which shows considerable decrease in $h'F$ (i.e $\Delta H_{\min} \leq -80$ km) in the post sunset hours

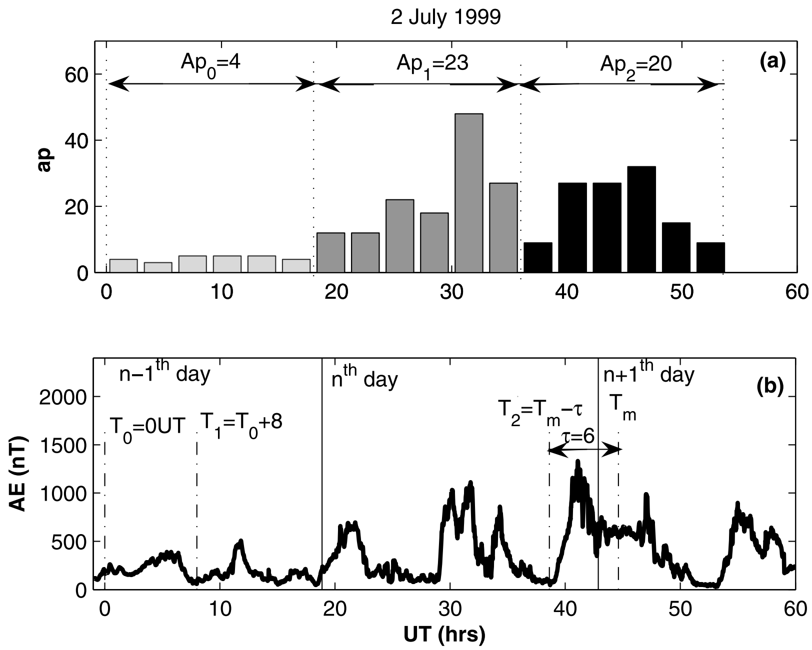

Figure 2. Variation of (a) *ap* and (b) *AE* for 2 July 1999 starting from 00UT of previous day till 06UT of following day.

resulted from superimposed westward electric field associated with magnetic activity, shall be taken up as a separate study.

3. Separation of Quiet and Disturbed Days

[14] It is known from past study that effect of magnetic disturbance can be sometimes seen on a following day [*Scherliess and Fejer*, 1997]. Here the effects of magnetic activity on *h'F* are studied in the post sunset hours from 17LT to 07LT of next day. Thus for each magnetically disturbed day the *ap* variation from 00UT of previous day to 06UT of next day is considered. This *ap* variation for 54 hrs is divided in three windows of equal time length such that the last window approximately covers the time when the effect of magnetic activity are studied i.e from 17-31LT. Each window contains the 6 *ap* values and Ap_0, Ap_1 and Ap_2 respectively indicates the average geomagnetic activity for these three windows. Thus, for each nth day Ap_0, Ap_1, and Ap_2 reflect the average geomagnetic activity between 00-18UT (i.e 5.13-23.13LT of n-1th day), 18-36UT (i.e 23.13LT of n-1th day to 17.13LT of nth day) and 36-54UT (i.e 17.13LT of nth day to 11.13LT of n + 1th day) respectively. These indices are used to separate the magnetically quiet and disturbed periods.

[15] Figure 2a shows the *ap* values for 2 July 1999 starting from 00UT of previous day till 06UT of following day, along with the estimates of Ap_0, Ap_1 and Ap_2 for 2 July 1999. For the site of observation, Trivandrum the local time, LT = UT + 5.13. Ap_0 and Ap_1 unitedly indicate the average magnetic activity for 36 hrs prior to 17.13LT of nth day. Whereas Ap_2 indicate the average magnetic activity during the period when effect of magnetic disturbance on *h'F* are identified. Generally periods with $Kp \geq 3+$ or $ap \geq 18$ are considered as magnetically disturbed [*Bartels*, 1957; *Menvielle and Berthelier*, 1991]. Sometimes the effect of magnetic activity may be seen on the following day of magnetically disturbed day. Hence the days with $Ap_0 < 18$ and $Ap_1 < 18$ and $Ap_2 < 18$ are considered as magnetically quiet. This condition is chosen to confirm that the duration when effect of magnetic disturbance on *h'F* are investigated and 36 hrs prior to ~17LT of a day under consideration are magnetically quiet. The days with $Ap_0 \geq 18$ or $Ap_1 \geq 18$ or $Ap_2 \geq 18$ are considered as magnetically disturbed. This condition is chosen so that the effect of magnetic activity occurring (i) throughout the night (i.e 17-07LT) and (ii) 36 hrs prior to ~17LT of the day under consideration are both taken into account while investigating the effects of magnetic activity on *h'F* in post sunset hours.

4. Categorization of Magnetically Disturbed Days

[16] The effect of magnetic disturbance on *h'F* observed at a given LT may be associated with DD or PP or combination of DD and PP both depending on the time and nature of magnetic disturbance occurring prior to the time T_m when maximum effect on *h'F* is observed. Generally the DD effects at equatorial ionosphere are observed after 1-12 hrs and 20-22 hrs after the enhancement in high latitude disturbance currents [*Scherliess and Fejer*, 1997]. In order to separate the short and long term DD effects the maximum *AE* (AE_m) before T_m and its time of occurrence (t_{AEm}) is noted for each disturbed day. $T_{ef} = T_m - T_{AEm}$ is the measure of duration, when the maximum enhancement in high latitude disturbed time currents is observed prior to time T_m. It should be noted that T_m and T_{AEm} are expressed in UT hours. Here Ap_0, Ap_1, Ap_2 described in previous section are used along with T_{ef} and AE_m to separate the magnetically disturbed days in three categories, which are listed in Table 1.

[17] For Cat I, the criteria chosen (i) $Ap_2 < 18$ assures that the average magnetic activity during the period when effects

Table 1. Three Categories of Magnetically Disturbed Days

Category	Condition	Number of Days With $\Delta H_{max} \geq 80$ km	Observed Effects Are Associated With
I	($Ap_0 \geq 18$ or $Ap_1 \geq 18$) and ($Ap_2 < 18$) and $AE_m > 500nT$ and $T_{ef} > 17$hrs	17	long term DD
II	($Ap_0 < 18$ and $Ap_1 < 18$) and ($Ap_2 \geq 18$) and $AE_m > 500nT$ and $T_{ef} < 15$hrs	22	Short term DD/PP/Short term DD+PP
III	($Ap_0 \geq 18$ or $Ap_1 \geq 18$) and ($Ap_2 \geq 18$) and $AE_m > 500nT$	58	PP/DD/DD+PP

of magnetic activity on $h'F$ are investigated (i.e 17-07LT) is magnetically inactive and (ii) $Ap_0 \geq 18$ or $Ap_1 \geq 18$ ensures that magnetic activity has occurred any time during 36 hrs prior to 17LT of magnetically disturbed day under consideration. Also for all days considered under this category the maximum enhancement in the AE is observed prior to 17 hrs and $\langle T_{ef} \rangle = 26 \pm 5$hrs. Thus combining these two conditions safely one can attribute the effects seen on $h'F$ to long term DD electric field alone, for days falling in Cat I.

[18] Cat II is chosen such that the time, when effect of magnetic activity, is investigated is magnetically active (i.e $Ap_2 \geq 18$) and magnetically quiet conditions prevail for 36 hrs prior to 17LT of that magnetically disturbed day. Also T_{ef} is < 15hrs for all days considered under this category and $\langle T_{ef} \rangle = 4.5 \pm 2.9$ hrs. So, for Cat II, the observed effect on $h'F$ may be associated with short term DD or PP or combination of short term DD and PP. IMF B_Z component averaged over 30 min is considered for magnetically disturbed day of Cat II, in order to identify the PP. Any N-S/S-N turning of IMF B_Z of more than 15nT/30 min during $T_m - 5$ to T_m are identified as PP cases. There are 5 such days in Cat II out of which, 4 days are associated with $V_{max} > 50$m/s. Thus the days under Cat II with $dB_Z/dt < 15$nT/30 min are chosen to study short term DD effects. For Cat I, no sudden turning of IMF B_Z component is noticed and dB_Z/dt during $T_m - 5$ to T_m found to vary in the range of 1-9nT/30 min. Hence Cat I days are considered to study long term DD effects.

[19] In Cat III, the magnetic disturbance is active during the time when effects of magnetic activity is investigated (i.e $Ap_2 \geq 18$) and also during the period of 36 hrs before 17LT of the magnetically disturbed day under consideration (i.e either $Ap_0 \geq 18$ or $Ap1 \geq 18$. For Cat III, T_{ef} found to vary in the range of 0.5-39 hrs and the observed effect of magnetic activity on $h'F$ may be attributed to combined effects of interaction between DD and PP electric fields. Figures 3a–3c show LT variation of ΔH for one magnetically disturbed day falling under Cat I, II and III, with their corresponding variation of ap starting from 00UT of previous day of magnetically disturbed day under consideration in Figures 3d–3f, respectively. Mass plot of variation of ap indices starting from 00UT of previous day of magnetically disturbed day is shown for all days studied under Cat I, II and III in Figure 4, separately for (i) $S_a > 150$ and (ii) $S_a \leq 150$. Vertical line shown in Figure 4 corresponds to time T_m when maximum effect is observed on $h'F$, in UT hours.

5. Joule Energy Computation

[20] DD effects are linked with the modified neutral winds resulted from enhanced energy input at high latitude ionosphere during magnetically disturbed periods. Thus for each

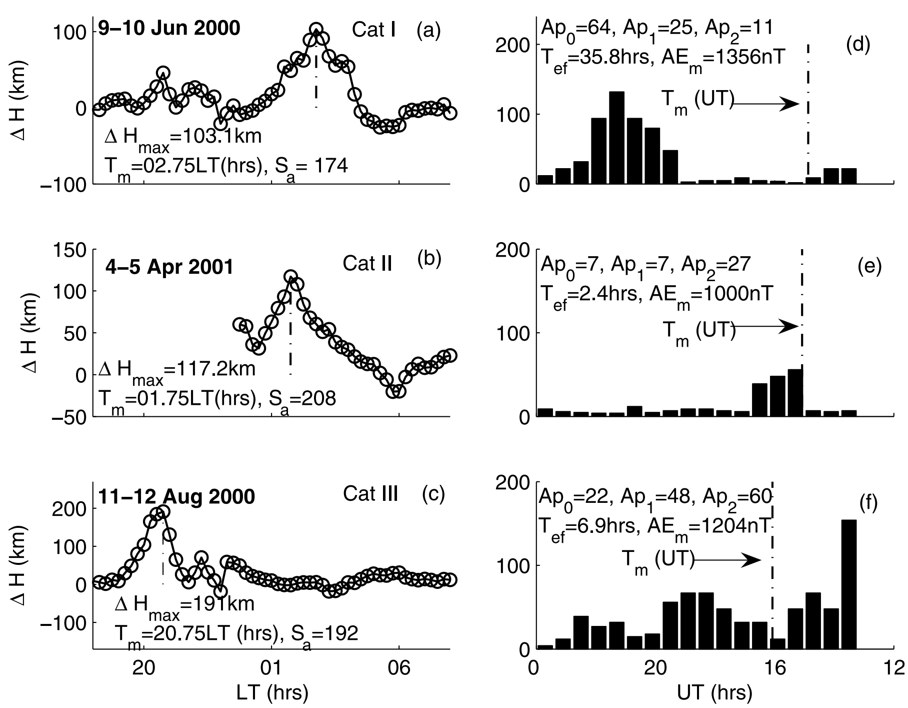

Figure 3. (a–c) LT variation of ΔH for one day falling in Cat I, II and III respectively. (d–f) Variation of ap starting from 00UT of previous day for corresponding days.

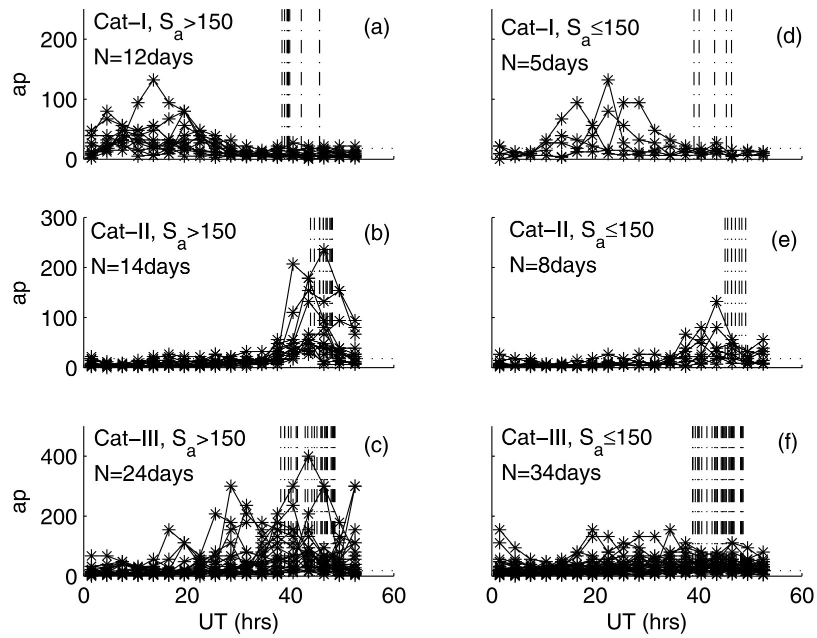

Figure 4. (a–c) Combined plot of variation *ap* starting from 00UT of previous day of magnetically disturbed day considered under Cat I, II and III, respectively, for $S_a > 150$. (d–f) Similar plots for $S_a \leq 150$.

magnetically disturbed day Joule energy deposited at high latitude is computed using empirical relation given by *Akasofu* [1981]. These estimates of Joule energy are used to compute the delay time required to show the maximum effect of DD at equatorial F region. Joule energy is calculated from integration over time of the power given by equation (1):

$$P_{Joule,Akasofu} = 2 * \left(2 * AE * 10^8\right) W \tag{1}$$

A factor of 2 accounts for the energy from both hemispheres. Let T_1 and T_2 be start and end time for integration. The maximum effect of magnetic activity on *h'F* is observed at time T_m and this effect is a manifestation of energy deposited in the high latitude ionosphere over a period of time prior to this time T_m. Let T_0 is the start time considered for integration i.e 00UT. T_1 is allowed to change from T_0 to $T_0 + 40$ in steps of 2 hrs. The end time T_2 is considered as $T_m - \tau$, where τ is the minimum time lag for the high latitude disturbances to have an effect on the equatorial F region and allowed to change from 0, 1, 2…15 hrs. Figure 2b shows the variation of *AE* index for 2 July 1999 starting from previous day 00UT, with different (i) start time T_1 and (ii) time lags τ used for the computation of Joule energy deposited at high latitudes. Vertical black solid lines in Figure 2b indicate the start of 2 July 1999 and 3 July 1999 at corresponding to 00LT hours. For each magnetically disturbed day the Joule energy estimates are available for different combination of T_1 and τ.

[21] So, for all days considered to study (i) short term (ii) long term DD effects, $\Delta H_{\max}$ is compared with Joule energy estimates for different combination of T_1 and τ separately. The correlation coefficient (R) between $\Delta H_{\max}$ and Joule energy is estimated for each combination of T_1 and τ. The combination of T_1 and τ which gives the best correlation is considered for calculating time delays associated with DD (short/long) effects at equatorial F region. τ gives minimum delay time and $\langle T_m \rangle - T_1$ gives the maximum delay time. Here $\langle T_m \rangle$ is the average time of occurrence of $\Delta H_{\max}$ for all the days under consideration in UT hours.

6. Results and Discussion

6.1. Occurrence Pattern of $\Delta H_{\max}$

[22] Cat I, II and III, which are discussed in section 4 are having the magnitude of $\Delta H_{\max}(V_{\max})$ in the range of 80–280 km (8–56 m/s), 83–339 km (10–118 m/s) and 81–257 km (2–110 m/s) respectively. For Cat I, II and III the local time distribution of percentage of occurrence of $\Delta H_{\max}$ is calculated separately for days with $S_a > 150$ and $S_a \leq 150$ and displayed in Figure 5. A clear difference in the occurrence of $\Delta H_{\max}$ is seen for all three categories. It should be noted that for days in Cat I, the effect of DD is mostly seen in pre-midnight hours ($\langle T_m \rangle = 21.2 \pm 0.98$ hrs) during $S_a > 150$, whereas for $S_a \leq 150$ it is difficult to draw any conclusions due to fewer (5 days) data points. For Cat II the effect of magnetic disturbance is predominantly seen around 02-06LT hours for both $S_a > 150$ and $S_a \leq 150$. Magnetically disturbed days falling in Cat III shows effect of magnetic activity mainly at (i) post midnight hours for $S_a > 150$ and (ii) both pre- and post-midnight hours for $S_a \leq 150$.

[23] It is observed that 68(29) out of 97 magnetically disturbed days show the effect of magnetic activity in post- (pre-) midnight hours. Studies by *Richmond et al.* [2003] and *Huang et al.* [2005] have shown that the LT for reversal of DD electric field from westward to eastward is close to local midnight near Indian longitudes. So the occurrence of $\Delta H_{\max}$ in post midnight hours for ~70% of magnetically disturbed days is in agreement with these results. However, *Huang et al.* [2005] have also shown that the PRE height of

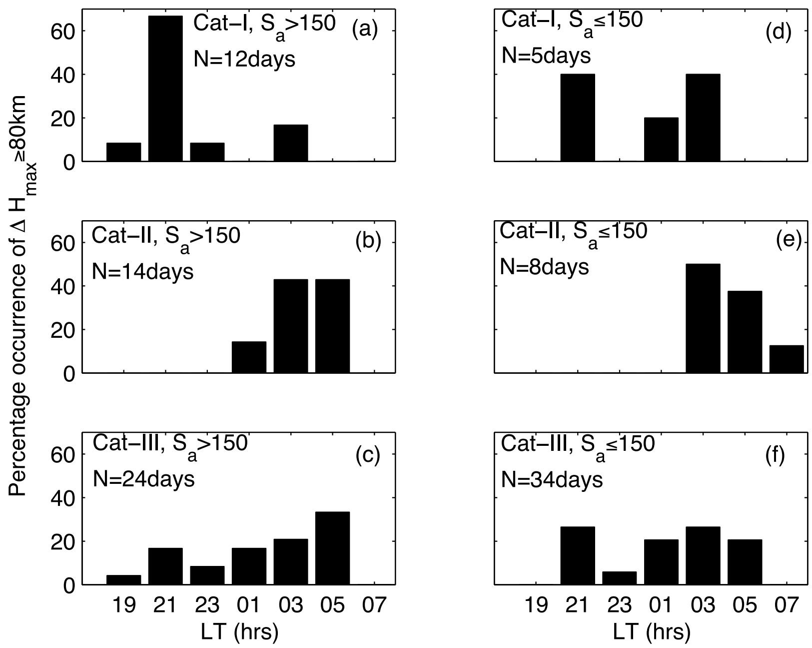

Figure 5. LT distribution of percentage occurrence of $\Delta H_{\max}$ is shown for magnetically disturbed days falling in Cat I, II and III separately for (a–c) S_a > 150 and (d–f) $S_a \leq 150$.

the F layer is reduced due to effect of DD electric field. For Cat I, the enhancement in *h'F* due to DD eastward electric field is mainly observed close to 21LT, which does not agree with the reduction in PRE due to DD electric field reported by *Huang et al.* [2005]. It should be noted that the enhancement observed in *h'F* for Cat I is linked with long term DD effects only, which might be causing this disagreement in result observed close 21LT.

6.2. Solar Flux Influence on Duration of DD Effects

[24] The difference between time of occurrence of minimum and maximum vertical drift $\Delta t = t_{V_{\min}} - t_{V_{\max}}$ of disturbed time *h'F* is considered as the proxy of time duration for which effect of magnetic activity persist at equatorial F region. As mentioned in section 4, the magnetically disturbed days of Cat II having dB_Z/dt < 15nT/30 min during T_m-5 to T_m (17 days) are considered to study the short duration DD effects, whereas Cat I (17 days) is used to study the long term DD effects. Δt is plotted as a function of 10.7 cm solar flux S_a in Figure 6a together for days considered under (i) long term DD and (ii) short term DD. Similar plot is made for Cat III and shown in Figure 6b.

[25] The correlation coefficient between Δt and S_a comes out to be −0.51 for Cat I. The decreasing tendency of Δt with increasing solar flux is clearly seen for long term DD effects, however there are two outlier points. For short term DD effects, it is noticed that the decreasing tendency of Δt with increasing solar flux is clearly visible, when the magnetically disturbed days with $T_m \leq 05LT$ (13 days) are taken into account and it gives a correlation coefficient of −0.68. The correlation coefficient between Δt and S_a comes out to be −0.70, when days of long term DD excluding 2 outlier points are considered together with days of short term DD having $T_m \leq 05LT$. The least square fitting of Δt with S_a for these 28 days gives; $\Delta t = -\ 1.09\text{e-}2{*}S_a + 4.1$. For magnetically disturbed days of Cat III no dependence of Δt on solar flux is established. Also, it is noticed that magnetically disturbed days of Cat I, II and III are mostly having smaller values of Δt (<1.5 hrs) when $T_m > 05LT$.

[26] This result suggests that the effect of magnetic activity associated with either short/long term DD electric field sustain for longer duration during low solar flux periods. Studies by *Hysell and Burcham* [2002] have shown that the ambient westward electric field in the post sunset hours are stronger during high solar flux as compared to low solar flux. This causes rapid downward movement of F layer during the descending phase of PRE for high solar flux as compared to low solar flux. Thus we conclude that decay of DD associated eastward electric field that is imposed on quiet time ambient equatorial F region electric field is mainly controlled by background ionospheric conditions which are considerably different during high and low solar flux periods. Nevertheless this dependence does not hold during periods close to early morning hours (>05LT). Shorting of DD electric field due to enhancement in E region conductivity close to early morning hours results in rapid downward movement of F layer, which is likely to produce small values of Δt. Thus the decreasing tendency of Δt with increasing S_a is not seen close to early morning hours and it is mainly associated with smaller values.

[27] For Cat III the observed effect $\Delta H_{\max}$ might be associated with short/long term DD or PP or combination of both DD and PP. Studies by *Maruyama et al.* [2005] suggest that directly penetrated electric field preferentially at night are sufficient to alter the subsequent development of the disturbance dynamo. Also recent numerical simulations shows that the disturbance electric field is reduced due to previous magnetic activity, which is attributed to the residual disturbance dynamo effect and preconditioning of the magnetospheric plasmas [*Maruyama et al.*, 2011]. Hence it is suggested that the unseen tendency of decreasing Δt with increasing S_a for Cat III is mainly arising due to mixed

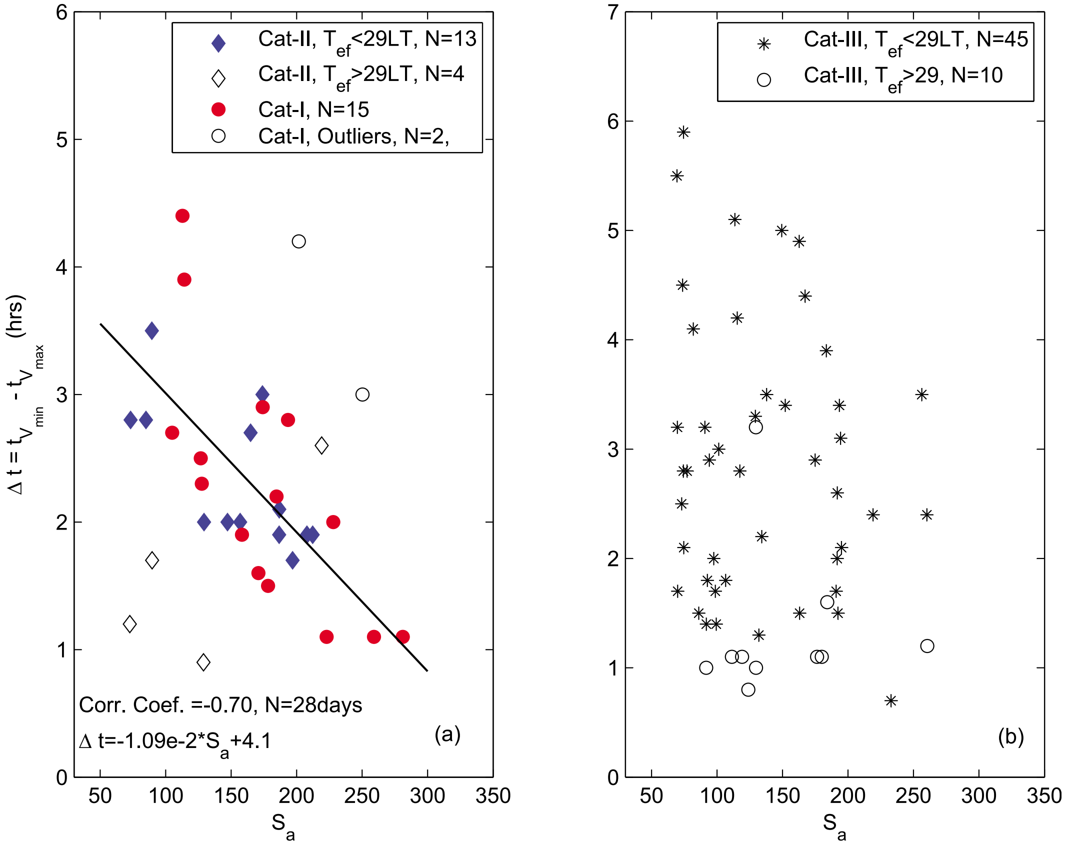

Figure 6. $\Delta t = t_{V_{\min}} - t_{V_{\max}}$ is plotted as a function of 10.7 cm solar flux S_a for (a) Cat I and II together and (b) Cat III.

effects of PP and DD electric fields at equatorial F region. These DD and PP electric field may not have same dependence on solar flux.

6.3. Time Delay Linked With Short and Long Term DD Effects

[28] It is noticed that long term DD effects occurs mainly during pre-midnight hours for $S_a > 150$. These events (10 days) are used to estimate the time delays associated with long term DD effects. Similarly magnetically disturbed days associated with short term DD effects with $S_a > 150$ (8 days) are chosen to get the estimates of time delay associated with short term DD effects. Time delays associated with short and long term DD effects are not estimated for the periods of $S_a \leq 150$ due to less number of events in that category. In order to estimate the time delays associated with long/short term DD effects the $|\Delta H_{\max}|$ is compared with estimates of Joule energy for the days considered under respective groups for different combination of T_1 and τ. So for each combination of T_1 and τ the correlation coefficient between $|\Delta H_{\max}|$ and Joule energy is estimated. Figures 7a and 7b show the plot of correlation coefficient R as a function of τ for (i) long and (ii) short term DD for $S_a > 150$. The dotted horizontal line shows the minimum value of correlation coefficient to get the 95% confidence limit. It should be noted that while estimating time delays for short term DD effects τ is changed in steps of 0.5 hrs.

[29] It is clearly seen that the maximum correlation coefficient of 0.66(0.85) is obtained for $T_1 = 16$ and $\tau = 16$ hrs ($T_1 = 42$ and $\tau = 0.5$ hrs) for long(short) term DD. These values of maximum correlation ($R_{\max}$) lies well above the 95% confidence limit and hence can be used to compute the time delays. As discussed in section 5, the maximum delay time is calculated using $\langle T_m \rangle - T_1$ and minimum delay time is given by τ. Here $\langle T_m \rangle$ and T_1 are expressed in UT hours and 24 hrs are added to $\langle T_m \rangle$ as T_1 starts from 00UT of previous day. The average T_m is 21.2±1.0 and 27.5±0.8 LT hours for long term and short term DD events considered here respectively. Thus the time delays associated with long(short) term DD effects are found to be 16–23.7 hrs (0.5–4 hrs) for an average solar flux of 214±41 (185±20). The delays linked with long term DD effects are found to be in agreement with the time delays reported by *Scherliess and Fejer* [1997] using Jicamarca radar observations.

[30] Whereas the time delay of 4 hrs obtained for short term DD events is small as compared to time delay of 12 hrs reported by these authors. It should be noted that 8 events that are used to compute time delay linked with short term DD effects are having $\langle T_{ef} \rangle = 3.2 \pm 1.3$ hrs. Thus, the maximum enhancement in the high latitude disturbed currents is seen ~3.2 hrs prior to time T_m, which may be giving rise to these small time delays for short term DD events considered here.

[31] It should be noted that, in the present study the time delay associated with long and short term DD effects are estimated by considering the time of maximum enhancement in $h'F$ during disturbed time. On the other hand, *Scherliess and Fejer* [1997] have considered the time of perturbations

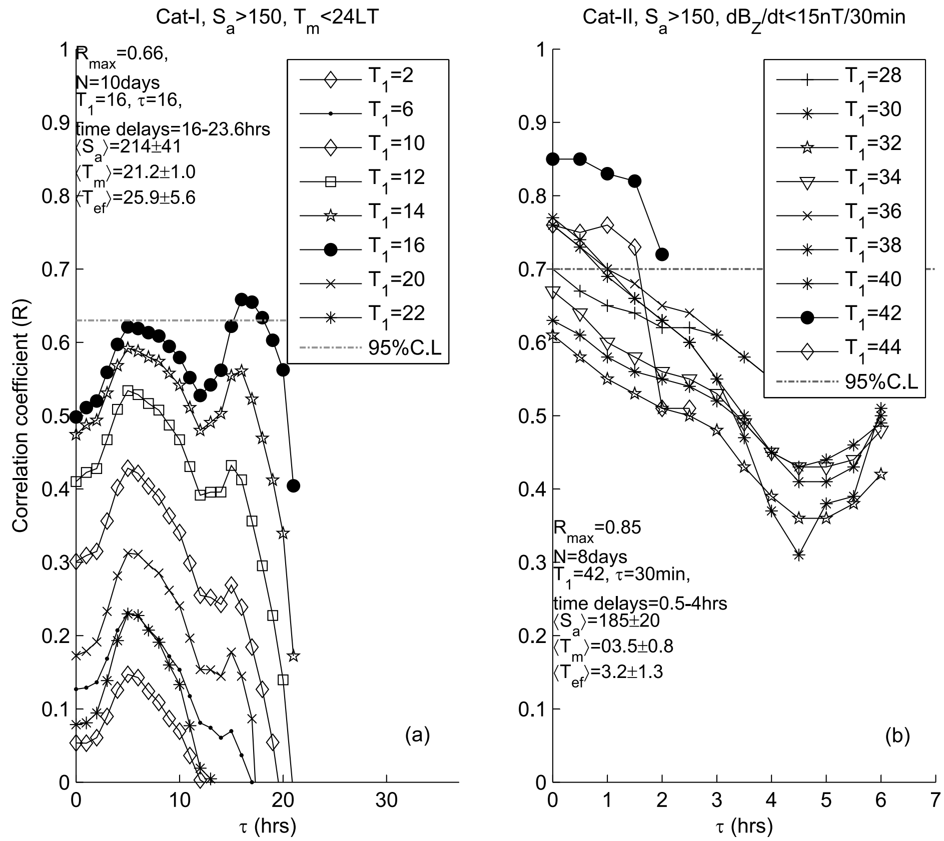

Figure 7. Correlation coefficient R is plotted as a function of τ for different starting time T_1 for magnetically disturbed days with (a) Cat I, $S_a > 150$, $T_m < 24$hrs, and (b) Cat II, $dB_Z/dT < 15$nT/30 min, $S_a > 150$, $T_m < 29$hrs.

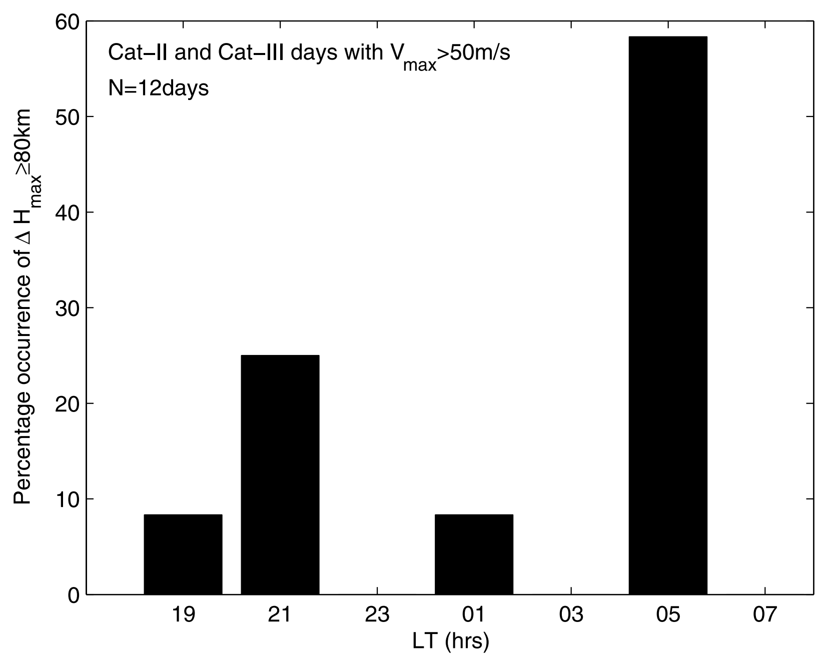

Figure 8. LT distribution of percentage occurrence of $\Delta H_{\max}$ is shown for magnetically disturbed days with $V_{\max} > 50$ m/s falling in Cat-II and III.

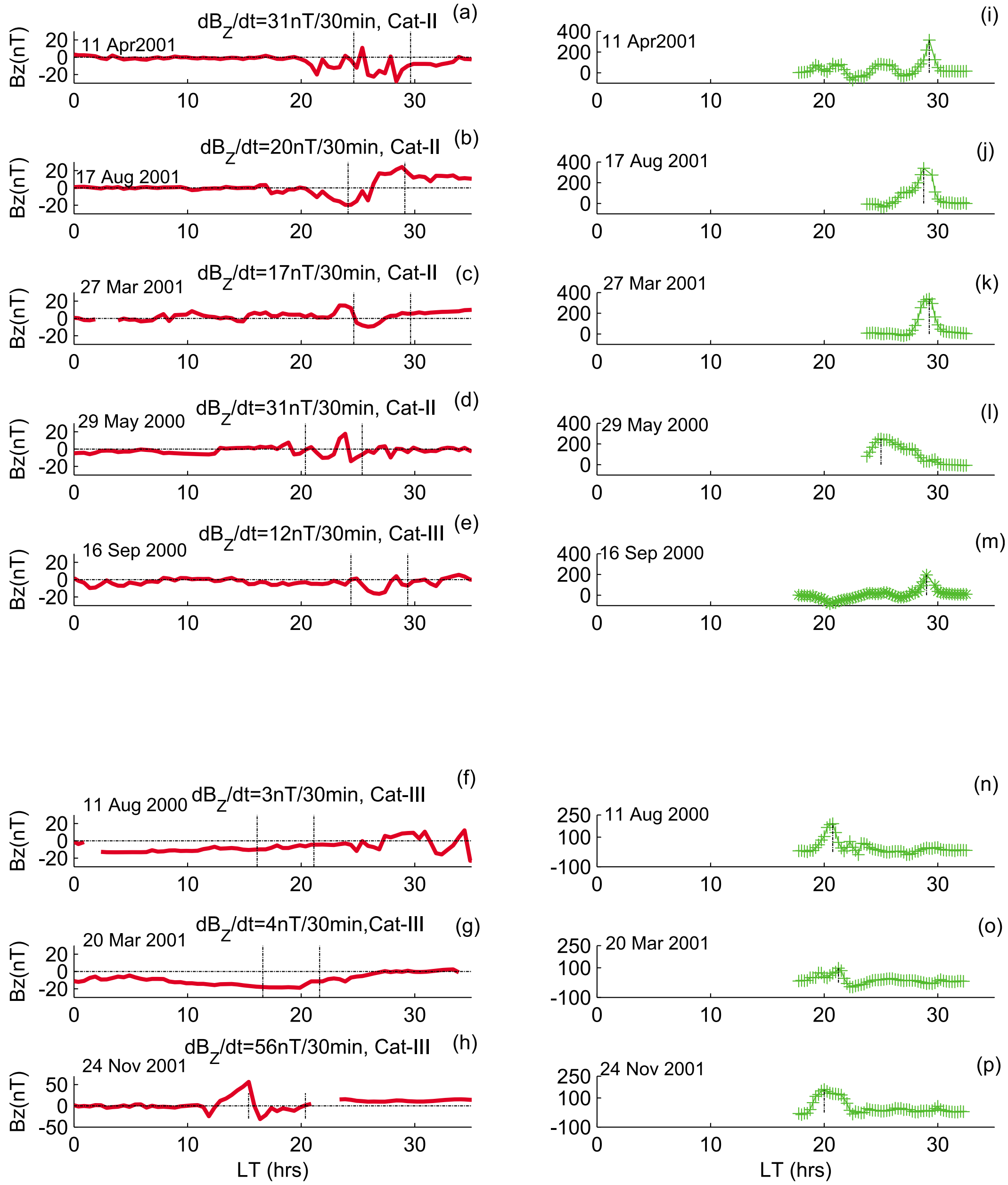

Figure 9. (left) Variation of IMF B_Z for eight magnetically disturbed days with $V_{max} > 50$ m/s of Cat-II and III and (right) corresponding ΔH, as a function of LT.

in vertical plasma drift. The enhancement in height will be seen some time later the increase in vertical drifts at equatorial F region. For the cases considered here to study short and long term DD effects, the enhancement in $h'F_D$ is observed ~1.2 ± 0.4 hrs later the time of maximum increase in vertical drift ($t_{V_{max}}$).

6.4. Magnetically Disturbed Days With V_{max} > 50 m/s

[32] As discussed earlier the effects observed in post sunset hours on $h'F$ for Cat-II and III may be associated with DD/PP/DD+PP. For these two categories, it is noticed that there are 12 days (~15%) with $V_{max} > 50$ m/s. As the maximum drift of upward movement of disturbed time $h'F$ is significantly higher, these cases are studied separately and time variation of IMF B_Z for these days are examined. For these 12 events $V_{max}(\Delta H_{max})$ varies in the range of 50–118 m/s(98–339 km). The percentage occurrence pattern of ΔH_{max} is shown in Figure 8 as a function of LT, for these 12 events. The IMF, B_Z time shifted data of OMNI are averaged over 30 min and used here. Primarily any appreciable N-S/S-N change in IMF B_Z during $T_m - 5$ to T_m hours are noted for these cases.

[33] All together 4(8) days shows maximum effect in the pre- (post-) midnight hours. There are 5 days which shows considerable southward/northward turning of IMF B_Z, which are shown in Figures 9a–9e with their corresponding LT variation of ΔH in Figures 9i–9m, respectively. Maximum effect of magnetic disturbance is seen around 01LT and 05LT for these 5 events. Out of these 5 events only 1 day is associated with northward turning of B_Z component

(Figure 9b). On 3 days the IMF B_Z is found to be southward for a long time and effects are seen during the time when IMF B_Z is gradually turning from south to north. IMF B_Z and corresponding ΔH variation for these 3 days are shown in Figures 9f–9h and Figures 9n–9p, respectively. Maximum effect of magnetic activity is observed around close to 21LT for these 3 events. For 3 days the IMF B_Z is not found to be associated with either sudden southward/northward turning during T_m-5 to T_m or long duration southward IMF B_Z. For 1 day IMF data are not available. It suggest that mainly the considerable southward turning of IMF B_Z result in PP of magnetospheric electric field to equatorial F region around 01LT and 05LT hours. Also if the IMF B_Z remains southward for a long time it might result in PP electric field around 21LT.

7. Summary

[34] In the present study ionosonde data recorded at Trivandrum for the period of 1990–2003 are used and the effects of magnetic activity on equatorial F region height in the post sunset hours (i.e 17-07LT) are investigated. The disturbed time eastward electric field that causes significant upward movement of F layer as compared to their monthly quiet time variability are identified and 97 such days are studied here. The effect of magnetic activity on $h'F$, ΔH is obtained by removing monthly quiet time average of $h'F$ from disturbed time $h'F$ and $\Delta H_{\max}$ is considered as quantitative measure of effect of magnetic activity on $h'F$. The attempt is made to identify the effects associated with short and long term DD electric field at equatorial F region using *ap* and time of maximum *AE*. Solar flux dependence of short and long term DD effect observed at equatorial F region is investigated for the first time. Main conclusions of the present work are as follows.

[35] 1. Seventy percent of magnetically disturbed days studied here shows the maximum enhancement in $h'F$, due to disturbed time eastward electric field, in post-midnight hours.

[36] 2. The effects associated with long duration DD effects are pre-dominantly seen around 21LT.

[37] 3. The duration for which short and long term DD effects are seen at equatorial F region, (Δt) is found to be longer during low solar flux as compared to high solar flux conditions. However, this dependency does not hold close to early morning hours (05LT), as DD associated electric field is shorted out due to increase in E region conductivity near sun-rise time.

[38] 4. When the effects observed at equatorial F region are linked with combined effect of interaction between DD and PP effects, Δt is not found to be dependent on solar flux.

[39] 5. Time delays associated with the long(short) term DD effects studied here are found to be 16–23 hrs(0.5–4 hrs) for an average 10.7 cm solar flux of 214$\pm$40 (185$\pm$20).

[40] 6. It is found that magnetically disturbed days with $V_{\max}$ > 50m/s occurring in post midnight hours are mostly associated with southward turning of IMF B_z. Whereas magnetically disturbed days with $V_{\max}$ > 50 m/s occurring around 21LT hours are linked with long duration gradual south-northward change in IMF B_z.

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