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Analysis of vertical drifts in the post sunset equatorial F-region during geomagnetically quiet and disturbed periods

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This paper reports the HF Doppler Radar measured post sunset F-region vertical drift (V_d) over Trivandrum (8.5°N, 77°E, 0.5°N dip latitude) during quiet and disturbed periods. In general, V_d showed significant day-to-day variability, both in the overall trend and the nature of short period oscillations present. Analysis based on the simultaneous measurements of equatorial electrojet (EEJ) induced surface magnetic field (ΔH) and interplanetary magnetic field (IMF) revealed that the V_d, on geomagnetically quiet days, exhibit oscillations of periodicity 15-20 minutes; whereas on disturbed days, it exhibit a dominant oscillation of ~ 45 minutes periodicity, similar to the one present in the IMF. Overall, the vertical drifts during quiet days seemed to be controlled by gravity waves of lower atmospheric origin. On the other hand, during disturbed time, the vertical drift is controlled by the interplanetary medium through the coupled electric field. It has also been observed that whenever post sunset V_d showed enhanced oscillation of 15-20 minutes periodicity, the equatorial spread-F occurred.

Keywords: Equatorial ionosphere, Equatorial electrojet (EEJ), Vertical drift, Equatorial magnetic field, Interplanetary magnetic field (IMF), Auroral electrojet

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1 Introduction

The plasma drifts and electric fields over equatorial/low latitude ionosphere are controlled by the complex E and F-region electrodynamical processes. In fact, the electron density distribution over the entire low latitude region is controlled by such processes over the dip equator. Due to the high electrical conductivity of the equatorial ionosphere, the electric field variations near the magnetic equator are very sensitive to the changes in the electric field imposed on it and any change in the electric field of the equatorial ionosphere will have an immediate effect on the plasma drift in the ionosphere[1-3.]

It is known that over the dip equator, upward propagating tides lead to the generation of a global electric field through the E-region dynamo. Recent studies have shown that upward propagating tides modulate the E-region dynamo electric field and hence, the vertical F-region plasma drifts over the dip equator[4,5.] Therefore, the formation of the dynamo electric field is controlled by the variability of upward propagating tides. In contrast, the tides themselves are also known to be modulated by the gravity waves and planetary waves of different periodicities. In fact, the equatorial electric fields and currents are found to exhibit fluctuations with quasi-periods ranging from a few minutes to few tens of minutes. A detailed description of such short period fluctuations in the ionospheric wind dynamo system was given by Richmond[6]. The quasi-periodic variations with periods of 5 to 60 minutes are believed to be due to zonal electric field perturbations associated with atmospheric gravity waves[7]. The longer period (> 4 hours) quiet-time perturbations and irregular day-to-day variations are generally associated with the variability of tidal forcing and the planetary wave activity[6].

Apart from those generated in the lower atmosphere, the ionosphere can support a variety of waves, which are generated by different sources. One such source is the auroral zone, which can produce waves in connection with the interplanetary disturbances and geomagnetic storms[8]. During geomagnetically disturbed periods, significant perturbations occur over the higher latitude ionosphere. The fluctuations in the electric fields over equatorial F-region during such conditions are thought to be due to the perturbation of the interplanetary electric field which penetrates into the low latitude ionosphere[1,9-12]. Similarly, a wide spectrum of gravity waves can be produced both at E and F-region of the ionosphere during solar eclipses[7,13].

It has been found that short period fluctuations in the range 5-33 minutes are very common over the equatorial ionosphere[14]. Reddy & Devasia[15] have reported short-period fluctuations of ~25 minutes periodicity in the EEJ (as inferred from the magnetic field measurements at surface) during geomagnetically quiet periods. It is known that the fluctuations in the E-region electric field could affect the F-region of the ionosphere through modified E×B drift. The spectral analysis of the east-west electric field at F-region during post sunset period over the magnetic equator revealed that periods of a few minutes to several tens of minutes are very common in the F-region also[7]. The response of such fluctuations in the vertical drift (V_d) in the equatorial F-region has been reported by Nayar *et al.*[1]. Similarly, using HF Doppler radar, George *et al.*[16] studied a spectrum of vertical plasma drift velocity over the geomagnetic equator. Also, Sastri *et al.*[17] have noticed that the fluctuations in the F-region vertical drift are coherent with the variations in the B_z component of the interplanetary magnetic field.

The information about the F-region drifts is typically obtained by a variety of methods, like observing the motion of the F-layer using an ionosonde; analyzing the Doppler spectra from HF Doppler radar and/or using the measurements from an incoherent scatter radar[18-20]. Similarly, the F-region drift can also be measured using coherent backscatter radar and spaced receiver technique. Such observations have provided a wealth of information, especially on the diurnal, seasonal and solar activity dependence of the F-region electric fields. However, in general, it is difficult to characterize the nature of short-period oscillations in the plasma motion with good time resolution. This is mainly because the incoherent scatter technique generally involves signal integration of the order of 5 minutes[21] and ionosondes are usually operated at 15 minute time intervals. In this context, the HF Doppler Radar operated at University of Kerala, Trivandrum surmounted this difficulty by providing high time resolution (1 minute) data on multiple probing frequencies (2.5, 3.5 and 4.5 MHz).

In the present work, the vertical drift measurements using the aforementioned radar, the EEJ induced magnetic field at surface and the interplanetary magnetic field have been analyzed to characterize the nature of oscillations present in these parameters on both during quiet and disturbed periods. The motivation behind extending the analysis during quiet days is the short-period fluctuations in electrojet reported by Reddy & Devasia[15]. It has been observed that on geomagnetically quiet days, V_d during the post-sunset periods shows a dominant oscillations of periodicity 15-20 minutes, whereas on disturbed days they exhibit an oscillation of periodicity ~ 45 minutes. These aspects are discussed in terms of the prevailing dynamics/electrodynamics over the geomagnetic equator.

2 Data and Method of analysis

The F-region vertical drift (V_d) measured using the HF Doppler Radar at the University of Kerala, Trivandrum, on a few quiet and disturbed days during the years 2004 and 2005 have been used to investigate the nature of short period fluctuations present. The radar is capable of operating at three frequencies, namely 2.5, 3.5 and 4.5 MHz. The recorded Doppler data corresponding to these frequencies are then subjected to Fourier analysis to get the prominent Doppler frequency (f_D) corresponding to up or down movement of the F-region. The vertical plasma drift velocity is calculated using the relation, $V_d = -(f_D \times \lambda)/2$, where, λ, is the sounding wavelength. It must be mentioned that the measured drift velocity is apparent as it includes the contribution from chemical loss induced by recombination reactions. The velocity due to chemical loss amounts to about 1-2 ms^{-1} and is subtracted from the measured drift velocity to get the actual vertical electrodynamic drift. Main limitations of the present radar system are: (i) only three frequencies are available; and (ii) the manual changing of the frequency settings. It is expected that the radar with additional frequencies below 2.5 MHz can provide better sounding results. Similarly, during day time, to probe the F-region, frequency higher than 4.5 MHz is required. The errors in the measurement of vertical drifts corresponding to frequencies 2.5, 3.5 and 4.5 MHz are 0.25, 0.18 and 0.14 ms^{-1}, respectively[20].

It has been observed that in general, the V_d exhibits significant oscillations in its temporal variation and also exhibits large day-to-day variability. In order to quantify these periodicities, the data have been subjected to wavelet analysis[22] and the power spectra are obtained. To study the relationship between the oscillations in the interplanetary medium, the interplanetary magnetic field (IMF) obtained from Advanced Composition Explorer (ACE) satellite during the post sunset hours have also been analysed. The magnetic field values obtained from Indian Institute of Geomagnetism have been used to analyse the variability of EEJ current. The difference between the night level subtracted values of Tirunelveli (ΔH_{TIR}) and Alibag (ΔH_{ALB}) is taken as a proxy of the EEJ strength and hereafter referred as ΔH. The total number of days presented in the paper is very limited mainly due to the unavailability of HF radar data due to various operational difficulties. Nevertheless, extensive analysis including the analysis of additional data set is called for in future to characterize the nature of the oscillation and its causative mechanisms better.

3 Observations

In order to characterize the nature of oscillations present in equatorial magnetic field ΔH, vertical drift (V_d) and north-south component of interplanetary magnetic field (IMF Bz), the time evolution of these parameters during evening hours for 3 quiet days ($Ap \leq 19$) and 3 disturbed days (Ap indices 50, 140 and 119) during the year 2004 have been analyzed. Figure 1 shows the time variation of the IMF Bz, ΔH and V_d for three quiet days, i.e. 11 January, 24 February and 06 November 2004, respectively. It is clear from the figure that the parameters do not exhibit significant changes during these days. IMF Bz is more or less steady during the time interval considered and varies ± 5 nT. The V_d on 24 February and 06 November exhibits the signatures of pre-reversal enhancement (PRE) with short period oscillations. To get a better picture about the amplitudes of the small oscillations present, the data have been de-trended (e.g. 11 January 2004) and depicted in Fig. 2. It is clear from the figure that V_d shows dominant oscillations that varies ± 5 ms^{-1}. Similarly, ΔH and IMF Bz shows short period oscillations in the range ±3 nT and ±7 nT, respectively. In order to find out the nature of these oscillations, the parameters are subjected to wavelet analysis and the periodograms are depicted in Fig. 3. It is clear from the figure that V_d on all these days exhibit oscillations of periodicity 0.4 - 0.5 h (24-30 min), which is more prominent on 24 February. However, the amplitudes of the oscillations are very small during 11 January and 06 November. These oscillations are believed to be due to the gravity waves, which originate in lower atmosphere since they are totally absent in IMF Bz.

In other words, it indicates that V_d during quiet days are controlled mainly by the waves, which are lower atmospheric in origin. On 24 February and 06 November 2004, equatorial spread-F (ESF) occurred from 19:30 and 20:00 hrs IST, respectively. So, the vertical drift measurements after that may not be correct and the periodicities are considered till that time on such days.

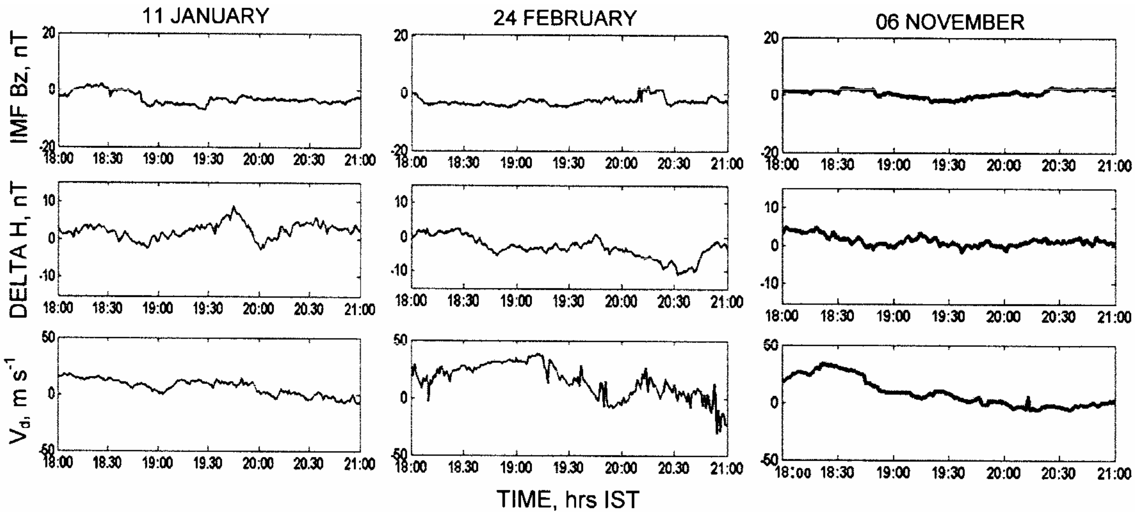

Fig. 1 — Time variation of vertical drift (V_d), equatorial magnetic field (ΔH) and interplanetary magnetic field (IMF Bz) at surface for three quiet days during 2004

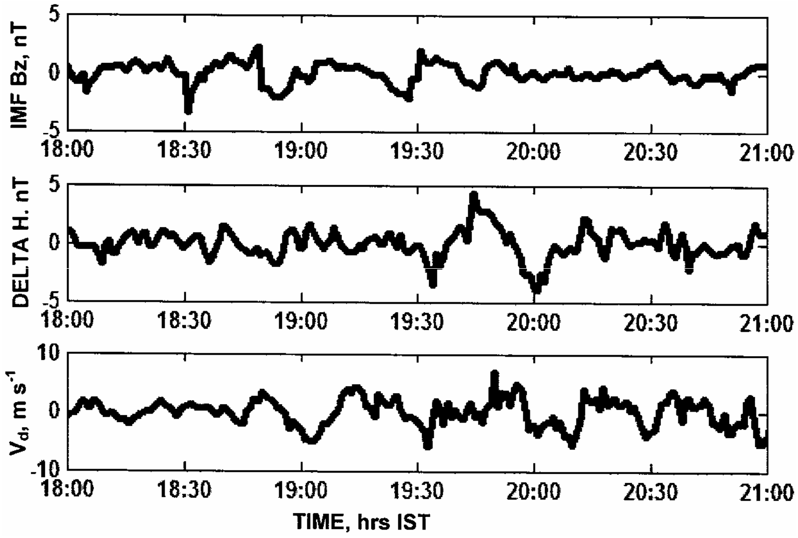

Fig. 2 — De-trended plots for vertical drift (V_d), equatorial magnetic field (ΔH) and interplanetary magnetic field (IMF Bz) for a quiet day (11 January 2004)

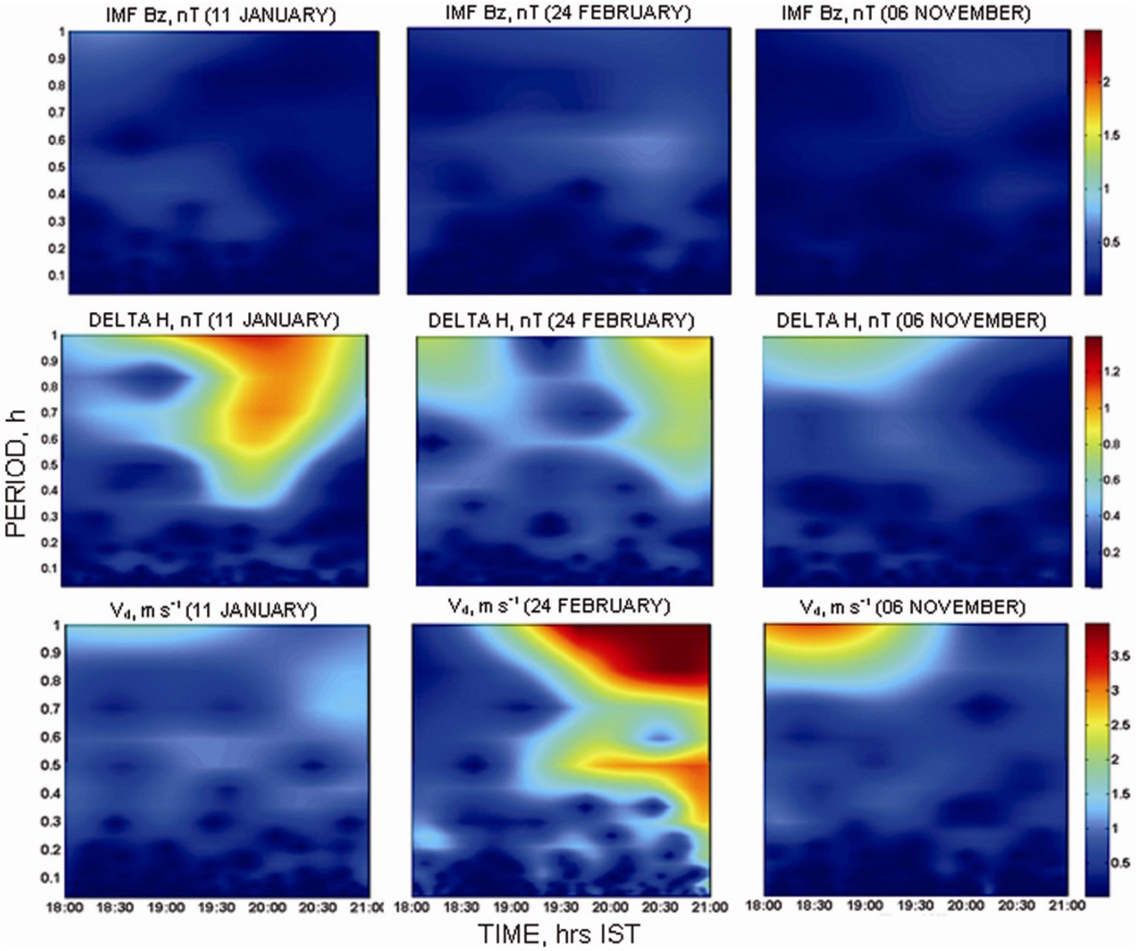

Fig. 3 — Wavelet periodograms of vertical drift (V_d), equatorial magnetic field (ΔH) and interplanetary magnetic field (IMF Bz) at surface for three quiet days during 2004

For characterizing the behaviour of V_d during disturbed days, the variability of the aforesaid parameters during three disturbed days have been looked into and depicted in Fig. 4. As it is seen, the IMF Bz shows significant fluctuations on these days. On 07 November 2004 (Ap = 50), the IMF Bz varied between -20 nT and +20 nT, whereas on 08 November (Ap = 140), it varied between -10 nT and +10 nT and on 09 November (Ap = 119), it fluctuated between -8 nT and +10 nT. The PRE was present on 07 November 2004 with peak value of about 40 ms^{-1}. But on 08 and 09 November [recovery phase of the geomagnetic storm (07-09 November are storm days)], PRE is absent or inhibited. However, compared to that on the quiet days, the fluctuations present in V_d are amplified on the magnetically active days, with a maximum amplitude of ~20 ms^{-1} and ~40 ms^{-1} on 07 and 09 November, respectively. In order to bring out the nature of these oscillations, the data has been subjected to wavelet analysis and Fig. 5 shows the periodograms for the disturbed days. It is clear from the figure that the dominant period present in all the three parameters are those of 30-48 min (0.6-0.8 h). The amplification of this periodicity in all the three parameters is found to be nearly simultaneous. It is interesting to note that the short period oscillation of 12-18 min as seen during the quiet days are totally absent on these disturbed days.

In order to check the consistency of this behaviour, the IMF Bz, ΔH and V_d during the year 2005 have also been analyzed. It has been observed that the same observation holds good in the year 2005 too. Figure 6 shows the time variation of the IMF Bz, ΔH and V_d for two quiet days, 10 January and 11 February 2005, respectively. It is clear from the figure that IMF Bz does not vary significantly on these days. However, a closer look reveals the presence of short scale fluctuation in V_d similar to the quiet days during the year 2004. The wavelet periodograms as depicted in Fig. 7 shows the presence of short period waves ranging from 0.2 to 0.4 h in V_d and this is found to be absent in IMF Bz.

This observation, further, confirms the lower atmospheric control of V_d during geomagnetically quiet periods. On the other hand, during disturbed days (17 January, and 07 February), all the free parameters exhibit significant variability as evident from Fig. 8. 17 January, the IMF Bz shows large fluctuations, which varies between - 10 nT and + 30 nT, whereas on 07 February, it fluctuates between - 10 nT and + 10 nT. The V_d also exhibits significant short-scale fluctuations during these days. The wavelet periodogram as shown in Fig. 9 reveals that IMF Bz, ΔH and V_d exhibit similar periodicities during disturbed days. In general, it is clear from these observations that the fluctuations in V_d during quiet periods are mainly controlled by the gravity wave activity while on disturbed days, they are controlled by the oscillation in interplanetary medium. During the year 2005, spread was present on 07 February and 11 February with occurrence time from 19:30 and 20:00 hrs IST, respectively. So, the drift measurements after the occurrence of ESF may be incorrect.

It is to be mentioned here that wavelet periodogram of equatorial magnetic field ΔH for all disturbed

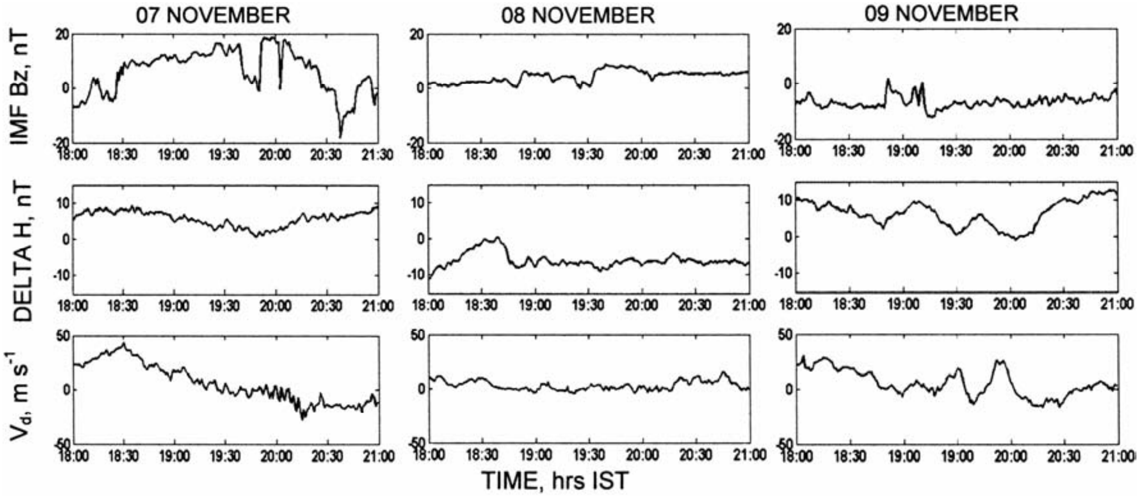

Fig. 4 — Time variation of vertical drift (V_d), equatorial magnetic field (ΔH) and interplanetary magnetic field (IMF Bz) at surface for three disturbed days during 2004

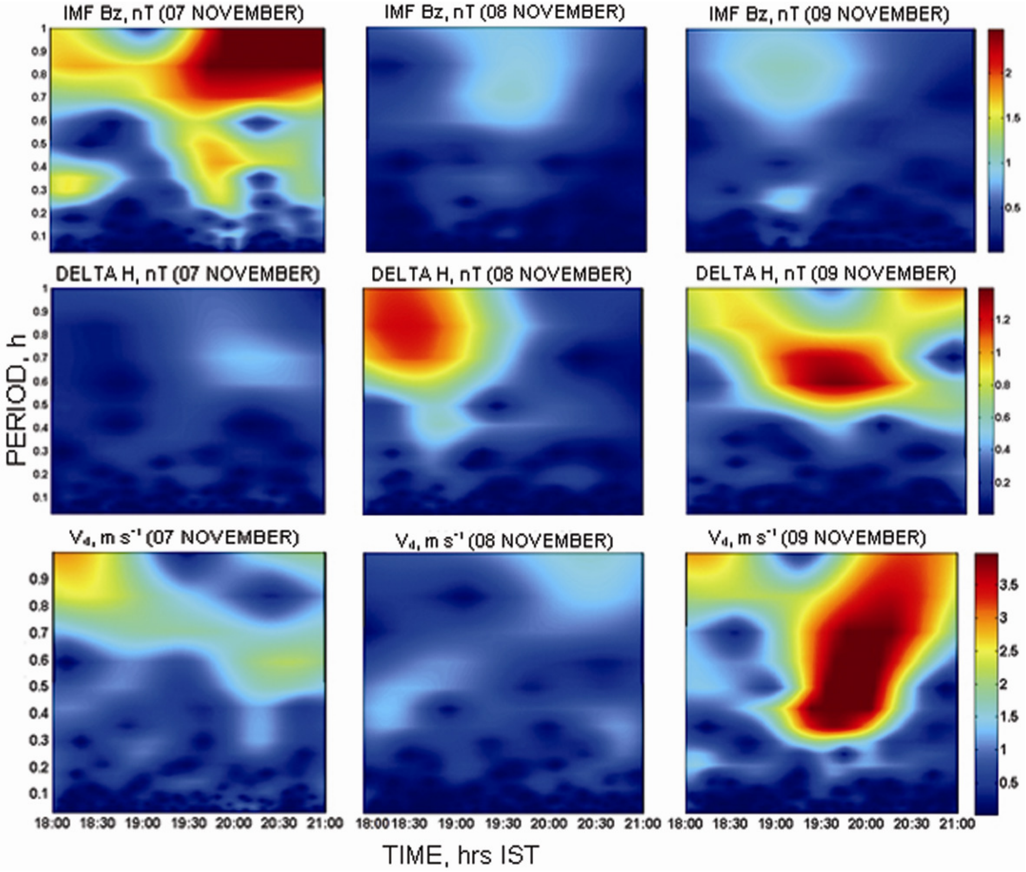

Fig. 5 — Wavelet periodograms of vertical drift (V_d), equatorial magnetic field (ΔH) and interplanetary magnetic field (IMF Bz) at surface for three disturbed days during 2004

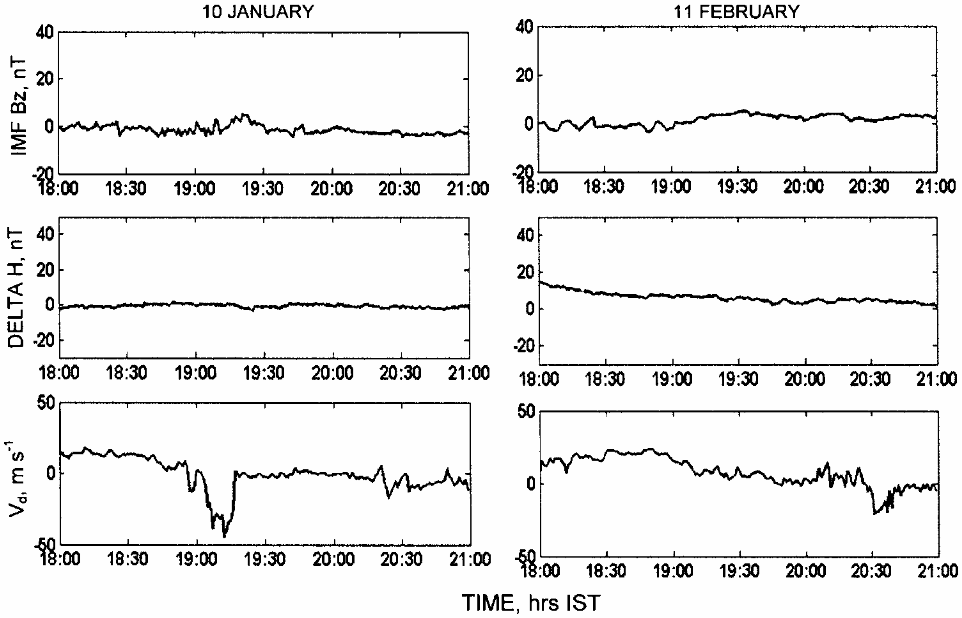

Fig. 6 — Time variation of vertical drift (V_d), equatorial magnetic field (ΔH) and interplanetary magnetic field (IMF Bz) at surface for two quiet days during 2005

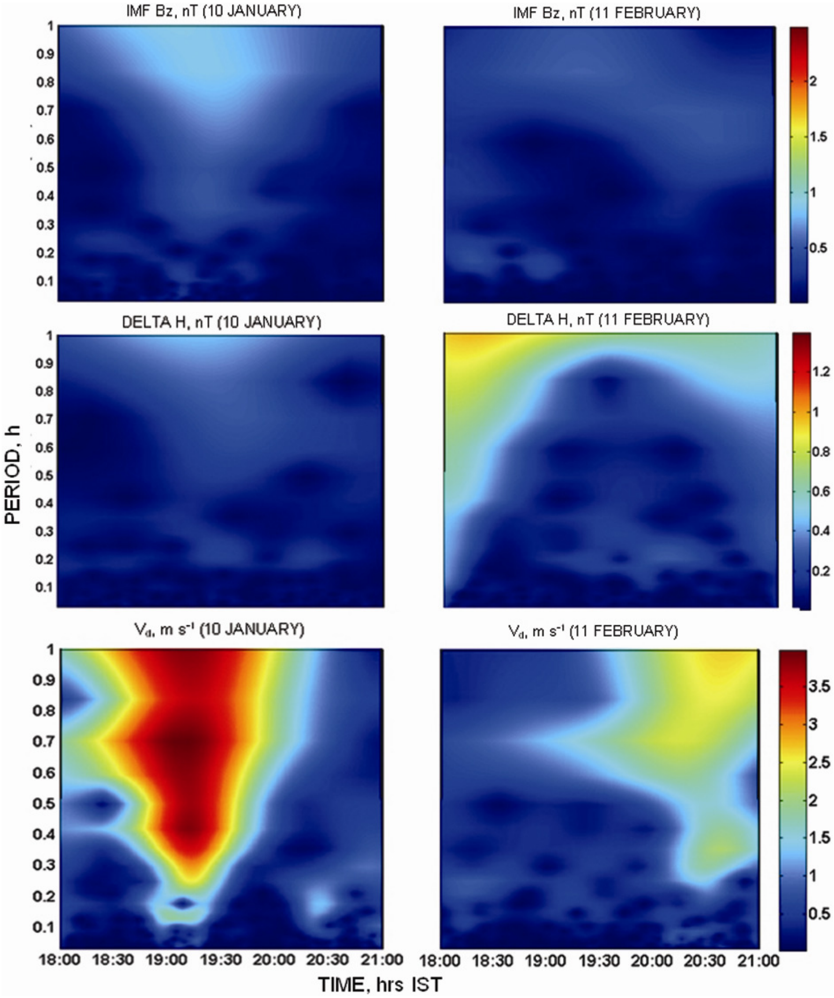

Fig. 7 — Wavelet periodograms of vertical drift (V_d), equatorial magnetic field (ΔH) and interplanetary magnetic field (IMF Bz) at surface for two quiet days during 2005

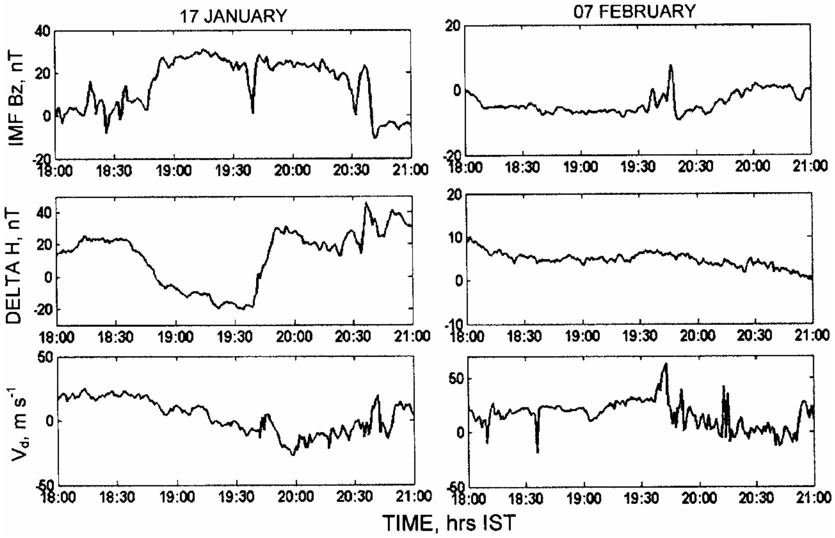

Fig. 8 — Time variation of vertical drift (V_d), equatorial magnetic field (ΔH) and interplanetary magnetic field (IMF Bz) at surface for two disturbed days during 2005

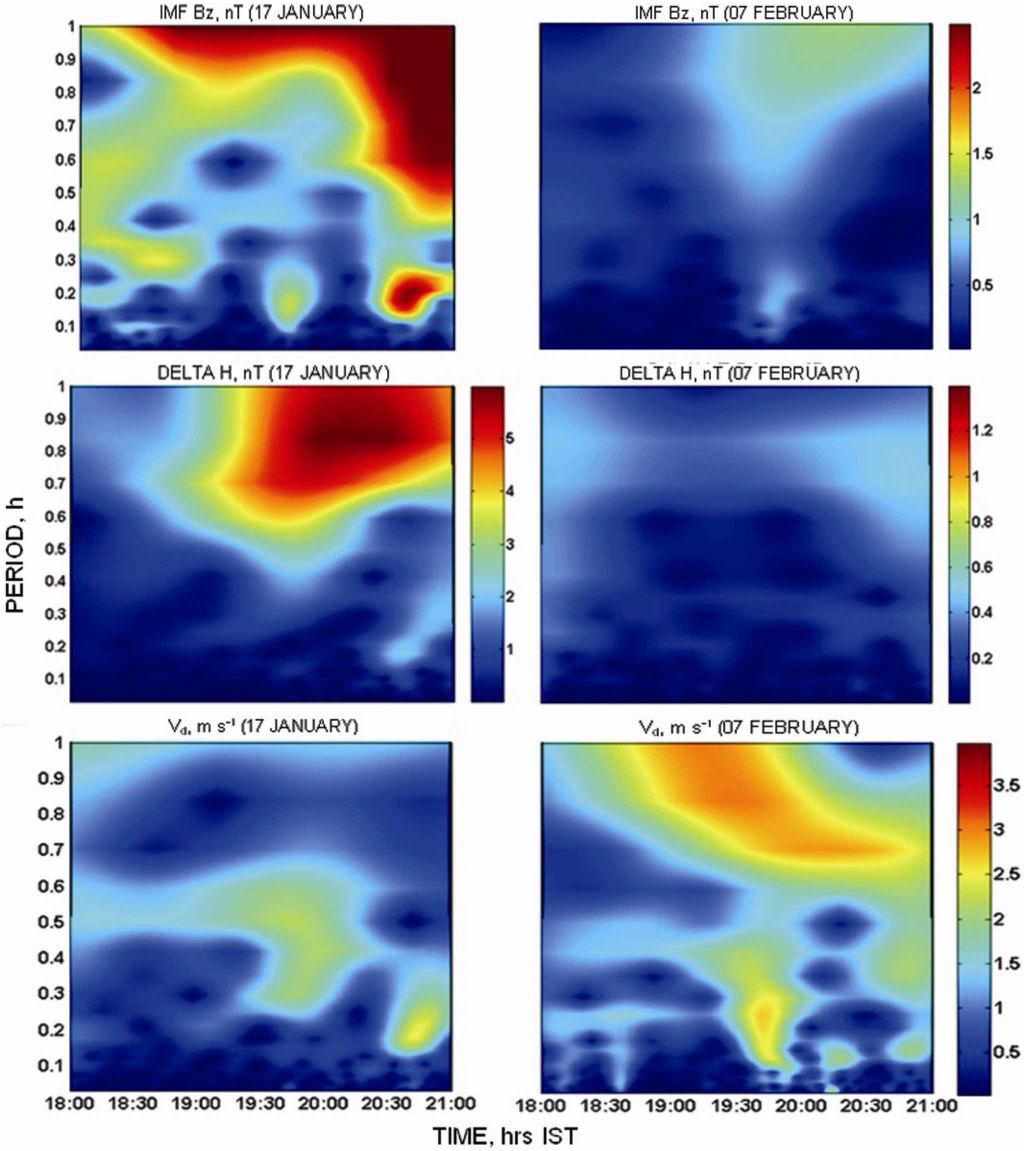

Fig. 9 — Wavelet periodograms of vertical drift (V_d), equatorial magnetic field (ΔH) and interplanetary magnetic field (IMF Bz) at surface for two disturbed days during 2005 [Note C axis is different for ΔH]

days also shows signatures of periodicity almost similar to the periodicity in V_d (Figs 5 and 9). But this is absent during quiet days except 11 January and 24 February 2004. Since IMF Bz also shows significant periodicities during disturbed days, the observed periodicity in ΔH is believed due to the solar wind influence of magnetospheric origin.

4 Discussion

4.1 Observed periodicities in V_d during quiet and disturbed days

Gravity waves (GWs) of lower atmospheric origin play a major role in controlling the day-to-day variability of the equatorial upper atmosphere/ ionosphere region. These waves exert significant drag in the middle atmosphere, which in turn affects the winds and temperatures of the Mesosphere Lower Thermosphere (MLT) region. Further, they can modify the tidal structure in the upper mesosphere region. Gavrilov *et al.*[23] first observed a correlation between the intensity of gravity waves and the tidal winds, and Fritts & Vincent[24] proposed a simple model and using that they could show the modulation of tidal winds by gravity waves. They showed that the vertical divergence of the flux of horizontal momentum associated with the dissipating gravity waves (gravity-wave drag), acted to advance the phase fronts of the tide and decrease its amplitude. McLandress & Ward[25] and Meyer[26] used parameterizations, based on the work of Lindzen[27], to study the effect of gravity-wave drag on tidal amplitudes and found the parameterized gravity-wave drag acted to decrease the amplitude of the tide and advance the tidal phase. Further, Meyer[26] showed the relative effects of parameterized gravity-wave drag and eddy diffusion on the amplitude of the diurnal tide using the Global Scale Wave Model (GSWM)[28] and demonstrated that vertical eddy diffusion significantly damps the amplitude of the diurnal tide. McLandress[29] compared the effects of several different gravity wave parameterizations in the same mechanistic tidal model and found that the diurnal tidal amplitude could be either increased or decreased depending on the parameterization used, but all were found to advance the phase of the tide by varying amounts. However, most of the time, these waves get dissipated below turbopause altitudes (~110 km) and therefore, their presence at F-region altitudes could be explained through an indirect mechanism.

At ionospheric altitudes, the GWs can modify the integrated E-region conductivities and thereby, modulate the polarization electric field, which in turn will get reflected in the vertical plasma drift of the F-region[30]. In other words, once the tidal structure in the upper mesosphere region is modified due to the activity of GWs, it will affect the zonal electric field, since the tidal wind is the major driving force behind the generation of this field. The fluctuations in electric field can be communicated to the F-region to cause fluctuations in the vertical velocity. Therefore, on quiet days when the system is not perturbed due to the external forcing, it is believed that the GWs of lower atmospheric in origin play a major role in controlling both E and F region phenomenon.

When it comes to the disturbed days, the interplanetary fields play a prominent role in the transfer of energy from solar wind to the magnetosphere. The north-south component of IMF Bz is found to be controlling the transfer of energy carried by the solar wind into the magnetosphere and thereafter, into the lower atmosphere[31,32]. This is happening, mainly, due to the influence of the variations in interplanetary electric field (IEF). Abrupt changes as well as quasi-periodic fluctuations of the IEF are known to correlate with the equatorial ionospheric electric field variations. They are called penetrating electric fields[33,34]. Eastward (westward) IEF is associated with southward (northward) IMF Bz. It has been established that during daytime, the southward excursion of IMF Bz results in an increase in normal eastward electric field, while northward turning IMF Bz leads to a decrease of this eastward field up to its reversal. During nighttime, the northward (southward) IMF Bz induces an eastward electric (westward) field in the equatorial ionosphere. Therefore, the short scale fluctuations in the IMF Bz could very well modify the equatorial electric field.

The fluctuations in V_d up to 40 ms^{-1} are observed on the storm days, which are believed to be due to the magnetospheric effects. Similarly, the fluctuations present in the interplanetary field would get imprinted in the equatorial electric fields, which can be clearly noticed from the ΔH values. It has been shown earlier that short period fluctuations in the range of 33.5 min are the common features of V_d in the evening hours and the spectral component of 32 min is always present in the power spectrum[14]. In the present case also, the periodicity observed is somewhat similar (30-40 min). On magnetically active days, where the fluctuation in electric field is very high, it is believed that the gravity wave induced effect on the vertical drift would be masked by the electric fields fluctuations of magnetospheric in origin. In brief, this study shows that the vertical plasma drift at equatorial F-region during quiet days are controlled mainly by the gravity waves of lower atmospheric in origin and the fluctuations observed on disturbed days are the effect of induced electric fields of magnetospheric origin.

4.2 Influence of auroral electrojet on ΔH during quiet days

Looking at Fig. 3, it can be seen that periodicities in ΔH are in the range 0.4-0.7 h on 11 January and 24 February 2004, even though these days are considered as quiet according to Ap values. (On 11 January Ap=19; and on 24 February Ap=11). This periodicity is similar to the one observed in V_d. But IMF Bz doesn't show any significant variation and periodicities. Analysis of AE index (a measure of the auroral electrojet) reveals the same periodicity, which is observed in V_d (Fig. 10). This is believed to be due to the coupling from high latitude.

5 Summary

The present work discusses about the fluctuations/ periodicities present in vertical drift at dip equatorial

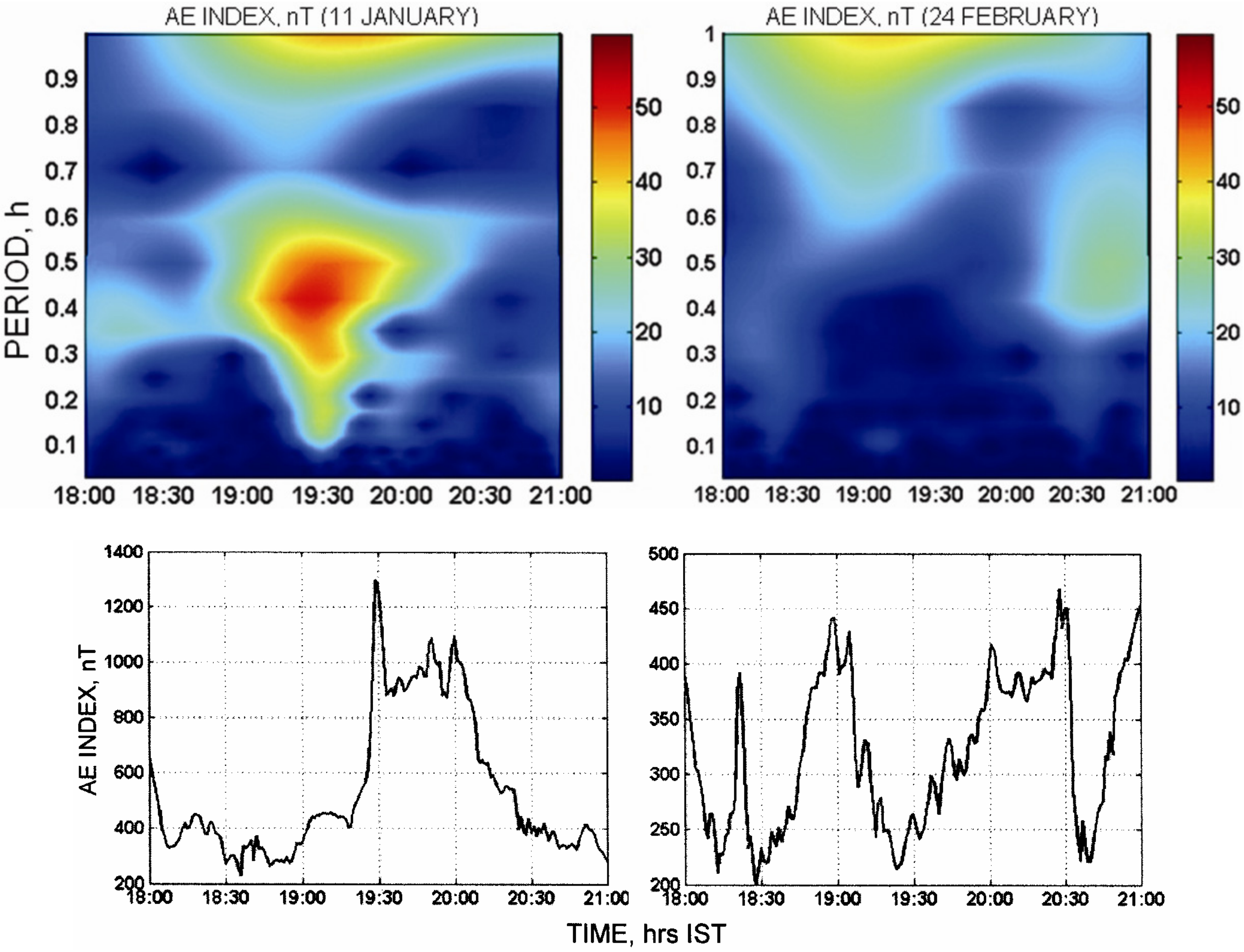

Fig. 10 — Auroral electrojet index (line plot and periodogram) for 11 January and 24 February 2004

F-region ionosphere during geomagnetically quiet and disturbed periods using the data from HF Doppler radar. The main conclusions are:

a) The oscillations in vertical drift over the dip equator during quiet days are mainly driven by the gravity waves of lower atmospheric origin.

b) During disturbed days, the vertical drifts are controlled by the changes in interplanetary medium, through the coupled electric field.

These results are very important for better understanding of the unique electrodynamical features of the equatorial ionosphere, especially, in the generation of equatorial spread-F.

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References

1 Nayar S R P, Rachel T, Bala B, Meena Varma V K & Yamini S, Response of F-region vertical drifts at the magnetic equator to the interplanetary magnetic field fluctuations, *Indian J Radio Space Phys,* 22 (1993) 338.

2 Rastogi R G & Patel V L, Effect of interplanetary magnetic field on ionosphere over the magnetic equator, *Proc Indian Acd Sci,* 82A (1975) 121.

3 Rastogi R G & Krochel H W, Interplanetary magnetic field and equatorial ionosphere, *Indian J Radio Space Phys,* 7 (1978) 84.

4 Abdu M A & Ramkumar T K, Planetary wave signatures in the equatorial atmosphere-ionosphere system, and mesosphere-E-and F-region coupling, *J Atmos Sol-Terr Phys (UK),* 68 (2006) pp 509-522.

5 Immel T J, Sagawa E, England S L, Henderson B H, Hagan M E, Mende S B, Frey H U, Swenson C M & Paxton L J, Control of equatorial ionosphere morphology by atmospheric tides, *Geophys Res Lett (USA),* 33 (2006), doi: 10.1029/(2006)GL026161.

6 Richmond A D, The ionospheric wind dynamo: Effects of its coupling with different atmospheric regions in the upper mesosphere and lower thermosphere: A review of experiment and theory, *Geophys Monogr Ser (USA),* (1995) 87.

7 Balachandran Nair R, Balan N, Bailey G J & Rao P B, Spectra of the AC electric fields in the post-sunset F-region at the magnetic equator, *Planet Space Sci (UK),* 40 (5) (1992) pp 655–662.

8 Altadill D, Sole J G & Apostolov E M, Vertical structure of a gravity wave like oscillation in the ionosphere generated by the solar eclipse of August 11, 1999, *J Geophys Res (USA),* 106 (2001) pp 21419-21428.

9 Patel V L & Pablo Lagos, Low frequency fluctuations of the electric field in the equatorial ionosphere, *Nature (UK),* 313 (1985) 559.

10 Gonzales C A, Kelley M C, Carpenter D L, Miller T R & Wand R H, Simultaneous measurement of ionospheric and magnetospheric electric fields in the outer plasmasphere, *Geophys Res Lett (USA),* 7 (1980) pp 517-520.

11 Somayajulu V V, Reddy C A & Viswanathan K S, Penetration of magnetospheric convective electric field to the equatorial ionosphere during the substorm of March 22, 1979, *Geophys Res Lett (USA*), 14 (1987) 876.

12 Earle G D & Kelley M C, Spectral studies of the sources of ionospheric electric field, *J Geophys Res (USA),* 92 (1987) 213.

13 Chimonas G & Hines C O, Atmospheric gravity waves induced by a solar eclipse, *J Geophys Res (USA),* 75 (1970) 875.

14 Sastri J H, Short–period (5 – 33 min) variations in vertical drifts of F-region plasma near the magnetic equator, *J Geomagn Geoelectr (Japan),* 47 (1995) 1215.

15 Reddy C A & Devasia C V, Short period fluctuations of the equatorial electrojet, *Nature (UK),* 261(1976) pp 396-397, doi: 10.1038/261396a0.

16 George T M, Joymon D, Somi Sebastian, Prabhakaran Nayar S R & Revathy K, Fluctuations in vertical plasma drift and magnetic activity, *Indian J Radio Space Phys*, 27 (1998) 233.

17 Sastri J H, Luhr H, Tachihara H, Kitamura T I & Rao J V S V, Electric field fluctuations (25-35) in the midnight dip equatorial ionosphere, *Ann Geophys (France),* 18 (2000) 252.

18 Fejer B G, Farley D T, Woodman R F & Calderon C, Dependence of equatorial F-region vertical drifts on season and solar cycle, *J Geophys Res (USA),* 84 (1979) (A10) pp 5792-5796.

19 Balan N, Jayachandran B, Nair R B, Namboothiri S P, Bailey G J & Rao P B, HF Doppler observations of vector plasma drifts in the evening F-region at the magnetic equator, *J Atmos Terr Phys (UK),* 54 (1992) pp 1545-1554.

20 Nayar S R P & Sreehari C V, Investigation of height gradient in vertical plasma drift at equatorial ionosphere using multi frequency HF Doppler radar, *J Geophys Res (USA),* 109 (A12308) (2004), doi: 101029/2004JA010641.

21 Fejer B G, de Paula E R, Gonzalez S A & Woodman R F, Average vertical and zonal F-region plasma drifts over Jicamarca, *J Geophys Res (USA),* 96 (1991) (A8) pp 13901-13906.

22 Torrence C & Compo G P, A practical guide to wavelet analysis, *Bull Am Meteorol Soc (USA)*, 79 (1) (1998) pp 61-78.

23 Gavrilov N M, An algorithm for the definition of inner gravitational-wave parameters in the meteor zone, *Izv Akad Nauk SSSR Fiz Atmos Okeana (Russia)*, 17 (7) (1981) 762.

24 Fritts D C & Vincent R A, Mesospheric momentum flux studies at Adelaide, Australia: Observations and a gravity wave-tidal interactions model, *J Atmos Sci (UK*), 44 (1987) pp 605–619.

25 McLandress C & Ward W E, Tidal/gravity wave interactions and their influence on the large-scale dynamics of the middle atmosphere: Model results, *J Geophys Res (USA),* 99, (1994) pp 8139–8156.

26 Mayer C K, Gravity wave interactions with the diurnal propagating tide, *J Geophys Res (USA),* 104 (D4) (1999) pp 4223–4239.

27 Lindzen R S, Turbulance and stress due to gravity wave and tidal breakdown, *J Geophys Res (USA),* 86 (1981) pp 9707-9714.

28 Hagan M E, Burrage M D, Forbes J M, Hackney J, Randl W J & Zhang X, GSWM-98: Results for migrating solar tides, *J Geophys Res (USA),* 104 (1999) pp 6813–6828.

29 McLandress C, On the importance of gravity waves in the middle atmosphere and their parameterization in general circulation models, *J Atmos Sol-Terr Phy (UK),* 60 (1998) pp 1357-1383.

30 Pedetella N M & Forbes J M, Modulation of the equatorial F-region by the quasi-16-day planetary wave, *Geophys Res Lett (USA),* 36 (2009) L09105, doi: 10.1029/2009GL037809.

31 Nishida A, Interplanetary field effect on the magnetosphere, *Space Sci Rev (Japan),* 17 (1975) 353.

32 Kelley M C, Fejer B G & Gonzales C A, An explanation for anomalous equatorial ionospheric electric fields associated with a northward turning of the interplanetary magnetic field, *Geophy Res Lett (USA),* 6 (1979) 301.

33 Huang C S, Foster J C & Kelley M C, Long-duration penetration of the interplanetary electric field to the low-latitude ionosphere during the main phase of magnetic *storms, J Geophys Res (USA)*, 110 (2005) A11309, doi: 101029/2005JA011202.

34 Nicolls M J, Kelley M C, Chau J L, Veliz O, Anderson Dand & Anghel A, The spectral properties of low latitude daytime electric fields inferred from magnetometer observations, *J Atmos Terr Phys (UK),* 69 (10–11) (2007) pp 1160-1173.