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Key Points:
- Nine and thirteen day periodicities in density and TEC during deep solar minimum
- Good correlation between solar wind and ionospheric parameters
- Nonexistence of such periods in MLT/OLR data during this period

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The response of the equatorial ionosphere to fast stream solar coronal holes during 2008 deep solar minimum over Indian region

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Abstract In this paper, we report ionospheric response to fast stream solar coronal holes during 2008 deep solar minimum year using ground-based multi-instruments over Indian region. To examine this, we analyzed f_oF_2 (MHz) and h_pF_2(km) from Canadian Advanced Digital Ionosonde and total electron content (TEC) from GPS receiver over Tirunelveli (8.73°N, 77.70°E; dip 0.5°N) along with equatorial electrojet (EEJ) strength. Our analysis shows good correlation between solar wind and f_oF_2/TEC, while h_pF_2 is poorly correlated. However, moderate correlation exists between solar wind and EEJ strength. When we performed periodogram analysis, we observed 9 and 13 day periods as dominant periods in f_oF_2 and TEC. Interestingly, the occurrence pattern of plasma irregularities also resembles these periodic oscillations. Since it is believed that lower atmospheric waves are dominant forces for ionospheric variabilities during deep solar minimum, we examined the mesosphere/lower thermosphere region temperature using Thermosphere Ionosphere Mesosphere Energetics and Dynamics Sounding of the Atmosphere using Broadband Emission Radiometry and winds using medium frequency radar along with outgoing longwave radiation in the troposphere altitudes to rule out the sources for these periodic oscillations in the lower atmosphere. Using cross-wavelet and cross-coherence spectra of both solar wind and ionospheric/atmospheric parameters, we suggest that ionospheric periodicities are similar to that of solar wind. Based on these results, we suggest that while the periodic oscillations are associated with the disturbance dynamo winds/electric fields that are propagated to equatorial latitudes, the differences in their temporal/seasonal variations are attributed to the variations in the composition/recombination changes.

1. Introduction

The ionosphere is a coupled system wherein it experiences forces originating from both solar and lower atmosphere [e.g., *Forbes et al.*, 2000; *Rishbeth and Mendillo*, 2001; *Mukhtarov and Pancheva*, 2012]. Under steady state condition, ionosphere does not vary much and may behave quietly. However, due to variabilities in the forcing from both below and above, the response of the ionosphere varies significantly. While long-term variabilities of the ionosphere have been studied extensively, short-term variabilities such as day-to-day and intraday variability are not yet understood properly due to lack of observations. The variability of the F_2 layer density (N_mF_2) is studied quantitatively using ionosonde f_oF_2 data by *Forbes et al.* [2000]. Their study indicates that small-scale variabilities might account for ~30% at higher frequencies and ~20% at lower frequencies at all latitudes under geomagnetic quiet time conditions. Further, they suggested that if we consider geomagnetic storms into consideration, these numbers may be even larger and it will have latitudinal variation. *Altadill and Apostolov* [2003] have suggested that geomagnetic activity plays significant role in driving the periodic oscillations in the ionosphere in addition to the planetary wave activity in the mesosphere/lower thermosphere (MLT). Since it is believed that radio wave communication especially GPS signals over equatorial and low latitude gets corrupted due to these variabilities, it is important that we understand them thoroughly. It may be noted that understanding the influence of these solar and atmospheric forcings independently is very difficult as they are coupled. To delineate this issue, many investigators have chosen to study one forcing when other is in quiet condition. During recent solar minimum, many investigations have been made to study the forcing from below as the dominant forcing in comparison to the solar forcing as it is believed that forcing due to solar origin is negligible during deep solar minimum. However, recently, some studies have shown that recurrent geomagnetic activity is the dominant forcing during low solar activity period and are believed to be responsible for the periodic oscillations in the electron density and thermospheric neutral density [e.g., *Lei et al.*, 2008a, 2008b, 2011; *Sojka et al.,* 2009; *Thayer et al.*, 2008; *Tulasi Ram et al.*, 2010a; *Qian et al.*, 2010; *Solomon et al.*, 2012].

Recent studies have shown that thermospheric neutral density oscillations have analogous periods as that of solar wind speed and *Kp* index whose variations are related to the variations of the coronal holes on the Sun's chromosphere. The coronal holes are the regions of low-density plasma on the Sun that have open magnetic field into the heliosphere. Due to their low density, these coronal holes extend to the outer solar atmosphere where ionized atoms and electrons flow along the open magnetic fields to form the high-speed solar wind. There are large coronal holes that cover the north and south polar caps of the Sun during low solar activity periods. It is believed that high-speed wind streams in the coronal holes are responsible for some of the major geomagnetic storms during low solar activity periods [e.g., *Tsurutani et al.*, 2006]. The association between coronal holes and corotating interacting regions (CIR) in the solar winds is well known. Initially, it is felt that CIR events do not produce major storms, and so they are not part of major space weather events. But, recently it is realized that ionosphere/thermosphere system do respond to CIR events in a significant way than it was felt. So, it is important that we understand their effects [*Tsurutani et al.*, 2006; *Sojka et al.*, 2009]. The coronal hole (CH) disturbances can lead to variations in the geomagnetic activity in a periodic manner [*Temmer et al.*, 2007]. There is a good correlation between rotating solar coronal holes and mass density variations in the Earth's thermosphere where it is shown that thermospheric mass density measured at 400 km using CHAMP satellite correlate well with both the solar wind speed and *Kp* index [e.g., *Lei et al.*, 2008a, 2008b; *Thayer et al.*, 2008]. Since ionosphere is coupled through thermospheric mass density, composition, neutral winds, and electrodynamics, variability in thermospheric mass density can contribute significantly to the ionospheric variability [e.g., *Crowley et al.*, 2008]. In addition, a 9 day periodicity observed in infrared cooling over mesospheric altitudes is suggested to be a direct coupling between the solar variability and the lower thermosphere [*Mlynczak et al.*, 2008]. The local time response of the 9 day periodicity in both total electron content (TEC) and electron densities measured at the altitude of ~350 km have been investigated by *Pedatella et al.* [2010]. They showed that the largest oscillations occur in the daytime TEC at midlatitudes with increase of ±25% of background levels. Their findings suggests that ionospheric response is symmetric about the geomagnetic equator with out of phase variation between high and low latitudes during daytime, but at night the high-latitude Northern Hemisphere is in phase with low latitudes but is out of phase with the high-latitude Southern Hemisphere. Using these findings, they suggested that combination of enhanced equatorward neutral winds and changes in neutral composition are important factors that are responsible for the observed periodicities in the ionosphere. In addition, it is suggested that the magnitude and orientation of interplanetary magnetic fields (IMF) B_z plays vital role in causing periodic variations in the ionosphere apart from solar wind speed [*Zhang et al.*, 2013]. *Tulasi Ram et al.* [2010b] showed the latitudinal and altitudinal variation of ionospheric response to the recurrent geomagnetic activity using Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) density profiles from 2008. They showed that while topside ionospheric response appears to be dominated by changes in the plasma temperature and/or scale height and exhibits simultaneous enhancements with the oscillations in geomagnetic activity, the ionospheric response at lower altitudes is dominated by changes in the neutral composition and show latitudinal, local time, and seasonal variations.

In this paper, attempts have been made to study the response of the equatorial ionosphere to these periodic forcings during the recent solar minimum period of 2008 using ground-based ionosonde, geomagnetic data, and GPS TEC over Indian region so as to understand the coupling from Sun to aurora and to equatorial latitudes. We also use lower atmospheric winds/temperature/outgoing longwave radiation (OLR) observations to study the lower atmospheric forcing. While the mechanism responsible for these periodic oscillations are suggested to be due to energy deposition by fast stream solar wind that produces Joule heating in the auroral latitudes which ultimately causes disturbed winds to propagate to low latitudes and causes periodic oscillations through disturbance dynamo effect, but it needs to be examined thoroughly using observations. Since disturbed winds are propagated to middle and low latitudes, electrodynamics of the low latitudes will be disturbed. Also, it is not clear why they impact only during low solar activity periods. Hence, it is important that we examine their impact on the low-latitude ionosphere which may be useful for space weather applications. Since recent studies have suggested that the response of the ionosphere to these coronal holes varies with altitude and latitude, it is important to see how the different parts of the ionosphere behave in the ground-based observations. In addition, attempts have been made in this paper to study these periodic forcings in terms of solar vis-à-vis atmospheric waves so as to identify their sources.

2. Data

To address the relationship between solar, auroral, and equatorial ionosphere during the deep solar minimum of 2008, various solar, auroral, and ionospheric data sets are analyzed. Also analyzed are the daily outgoing longwave radiation (OLR) and mesosphere/lower thermosphere (MLT) temperature to rule out any atmospheric variations that is coming from the vertical coupling. Here we use hourly averaged solar wind speed data which are obtained from the Goddard Space Flight Center (GSFC)/Space Physics Data Facility (SPDF) OMNIWeb interface as observed by the ACE satellite located at the L1 point. Similarly, *Kp* index which is a 3-hourly planetary magnetic activity index obtained from WDC Kyoto University website is used in this study.

The Canadian Advanced Digital Ionosonde (CADI) is a modern digital ionosonde developed for both routine monitoring and scientific research by Scientific Instrumentation Lab, Canada [e.g., *MacDougall et al.*, 1995]. Its frequency range is from 1 to 20 MHz. The CADI is operated as vertical incidence sounder (VIS). A complete ionogram requires from a few seconds (at low-frequency resolutions) to several minutes (at high-frequency resolutions). Delta-type transmitting antenna with four colocated receivers arranged in magnetic N-S and E-W directions are used to receive the returned echo. The transmitter uses 13 bit Barker code pulse compression technique to increase the signal strength. The peak transmitter power of the system is 600 W. Amplifier units are all solid state devices. CADI can probe from 90 km to height of 512 km (1020 km) with either 3 or 6 km resolutions. The transmitter and receivers are synchronized to a reference oscillator at 50 MHz using Direct Digital Synthesizer unit. We analyzed ionospheric parameters such as f_oF_2 (MHz) (F layer critical frequency), virtual height (km), and h_pF_2 (km) (virtual height at which ordinary wave mode frequency equals to 0.834 f_oF_2) for the entire 2008. It may be mentioned that there may be some errors in height estimates in ionosonde mainly from (a) pulse distortion of transmit pulse of the order of ~1 km as well as manual scaling which may be of the order of ~6 km (resolution of the height). In order to reduce manual scaling errors, we scaled the whole 2008 year data by same person only. The data were scaled at every 15/10/5 min interval depending up on the experiment. It may be mentioned that due to low-density plasma and poor sensitivity of the CADI system to such low densities during 2008, quality of the ionograms where extremely poor during late nights especially during 03–06 LT on many of the days. On average, ~ 10% of total data shows such blank ionograms. However, it does not have any major impact on the results.

We also used collocated GPS TEC observations from Scintillation Network Decision Aid (SCINDA) GPS receiver at Tirunelveli. From this receiver, slant TEC (STEC) is obtained. The vertical TEC (VTEC) from slant TEC (STEC) is obtained using appropriate mapping function, $S_f = \cos\chi$, i.e., VTEC = STEC* $\cos\chi$, where $\chi = \sin^{-1}[R_E \cos\alpha/(R_E + h)]$, α is the elevation angle at ionospheric penetration point, $R_E = 6378$ km, and $h = 350$ km.

SABER (Sounding of the Atmosphere using Broadband Emission Radiometry) data are obtained from its website. These payloads are launched using Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite on 7 December 2001 [*Christensen et al.*, 2003]. The satellite is orbiting in a circular orbit at 630 km altitude with inclination of 74.1°. SABER provides altitude variation of temperature in the MLT region. The orbit processes at a rate of 3° per day. In this paper, mean temperature over 90–100 km altitude range over Indian longitude (75–85°E) with latitude average of 5–10°N with local solar time of 09–15 h are examined along with ground-based observations.

The MF radar also known as partial reflection (PR) radar is operating at 1.98 MHz over Tirunelveli is similar to the one installed at Christmas Island. This system is operated routinely for measuring winds in the mesosphere. For technical details, readers are referred to *Vincent and Lesicar* [1991]. While it routinely measures winds in the mesospheric altitude range of 60–98 km during daytime, it measures winds from 70 km during nighttime. Good quality data are recorded at heights of 80–90 km during both day and night. Here winds are recorded every 2 min at every 2 km height intervals using full correlation analysis. As the radar has been operated continuously, we have data which is relatively free from data gaps at most of the times. However, there exist data gaps mainly due to instrumental issues. The 2 min raw data for the observation period from January 2008 to December 2008 are binned into hourly data.

The hourly values of the horizontal variations in the H component (ΔH) of the geomagnetic field as obtained from the difference between Tirunelveli (8.7°N, 77.8°E, dip latitude: 0.4°N) and Alibag (18.5°N, 72.9°E, dip latitude: 13.0°N) for the year 2008 are used to calculate the equatorial electrojet (EEJ) strength as given by

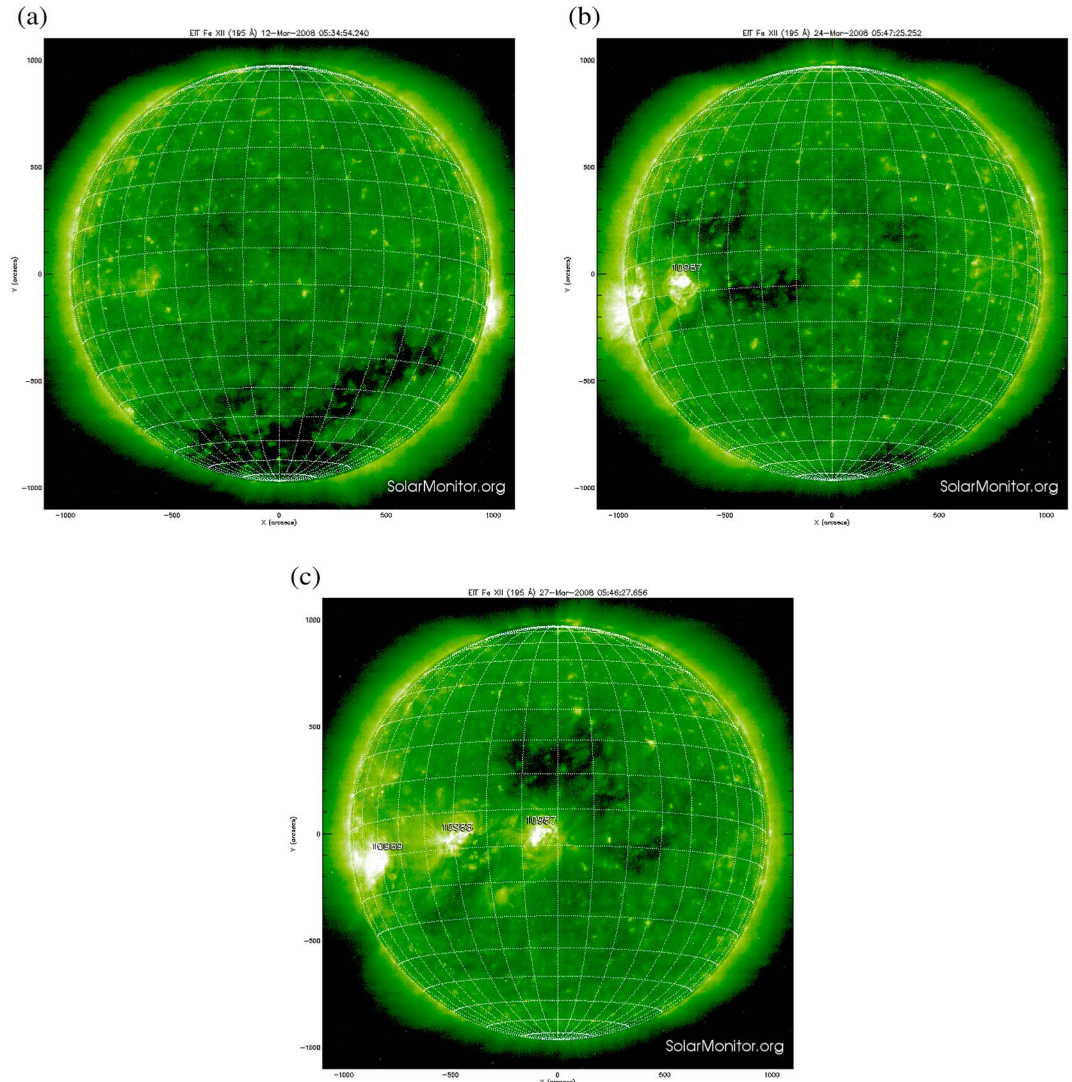

Figure 1. (a–c) The images of solar Fe XII (195 Å) over three different days, namely, 12 March, 25 March, and 27 March 2008.

$\Delta H = (\Delta H)_{\text{Tirunelveli}} - (\Delta H)_{\text{Alibag}}$ [*Rastogi and Klobuchar*, 1990]. In addition, daily mean outgoing longwave radiation (OLR) close to Tirunelveli as obtained from the National Centers for Environmental Prediction is used as tracers of lower atmospheric forcing.

3. Data Analysis and Results

Figures 1a–1c shows the images of solar Fe XII (195 Å) showing the coronal holes over three different days, namely, 12 March, 24 March, and 27 March 2008. From the figures, it can be noticed that the dark patches on both sides of the Sun close to equator and as time elapses these dark patches are found to corotate with the Sun longitudinally. The coronal holes were seen near the Sun's equator facing the Earth on all these days (Figures 1a–1c).

Figures 2a–2j show the daily mean variation of various solar, auroral, ionospheric, and atmospheric parameters during the year 2008, namely, (a) solar wind, (b) *Kp* Index, (c) $F_{10.7}$ solar flux, (d) EEJ strength, (e) GPS TEC over Tirunelveli, (f) CADI h_pF_2, (g) CADI f_oF_2, (h) zonal/meridional winds over MLT region over Tirunelveli using Medium Frequency (MF) radar, (i) mean zonal average of MLT temperature in the latitude range of 5–10° during 12–14 UT from SABER over altitude range of 95–100 km, and (j) outgoing longwave radiation (OLR) at 5°N latitude and 80°E longitude. The blank spaces in f_oF_2 (MHz), h_pF_2 (km), and SABER

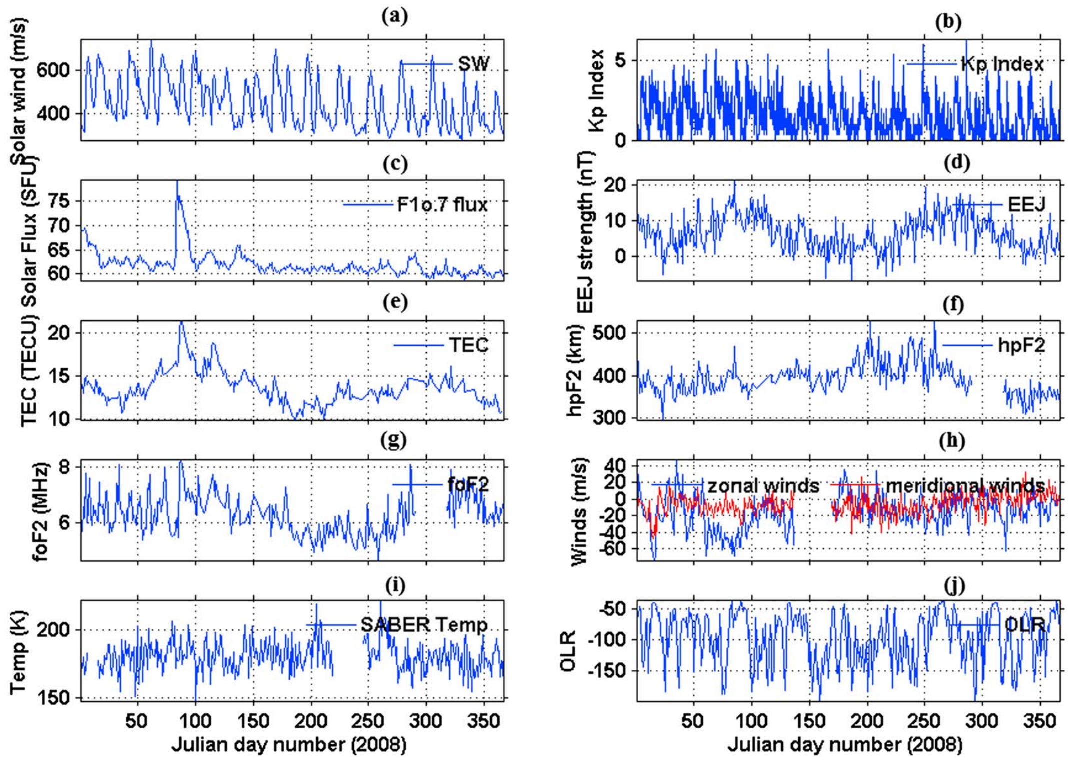

Figure 2. The daily mean variation of various solar, auroral, and ionospheric and atmospheric parameters during the year 2008, namely, (a) solar wind, (b) *Kp* index, (c) $F_{10.7}$ solar flux, (d) EEJ strength, (e) GPS TEC, (f) CADI h_pF_2, (g) CADI f_oF_2, (h) MF radar zonal/meridional winds at 90 km, (i) zonal mean MLT temperature in the latitude range of 5–10°N during 12–14 UT from SABER, and (j) outgoing longwave radiation (OLR) at 5°N latitude and 80°E longitude.

temperature plots indicate data gap due to instrumental problem. While solar wind varied from 300 to 700 km/s, *Kp* index varied from 0 to 5. The mean solar flux varied in the range of 60–65 solar flux unit (sfu), while it rose to 75 sfu for a while in the month of March/April 2008 period. The mean TEC varied between 5 and 25 total electron content unit, 1 TECU = 10^{16} el m^{-2} (TECU) during this period. CADI density varied in the range of 4–8 MHz, while h_pF_2 varied from 220 to 400 km. The SABER temperature data shows that it varied in the mean range of 180 K. The EEJ strength plot suggests that it shows higher values during equinox period with small fluctuations. More number of counter electrojet events can be seen during summer and winter periods. The mean EEJ strength varied between −20 nT and 50 nT. These plots become base plots for subsequent analysis as shown in the next plots.

Figures 3a–3f show the correlation of solar wind with (a) f_oF_2 (MHz), (b) h_pF_2 (km), (c) GPS TEC (TECU), (d) EEJ strength (nT), (e) MLT zonal winds, and (f) MLT meridional winds during the year 2008. The correlation coefficient is shown on the top of the each subplot. From the observations, it is clear that solar wind positively correlates with f_oF_2, TEC, and EEJ strength, while it poorly correlates with h_pF_2 and MLT winds.

Now, we perform the periodogram analysis on these data sets using Lomb-Scargle (L-S) method. Lomb-Scargle (L-S) periodogram analysis is used here rather than fast Fourier transform due to the fact that this method can be applied to unevenly spaced data and is equivalent to least squares fitting of sine waves [*Lomb*, 1976]. This method is known to be a powerful tool to identify weak periodic signals. This technique is widely used in astronomy. Now this technique is also widely used in atmospheric/ionospheric studies. Figures 4a–4f shows the L-S periodogram of (a) solar wind, (b) EEJ strength, (c) TEC, (d) CADI h_pF_2, (e) CADI f_oF_2, and (f) MLT zonal/meridional winds at 90 km altitude along with SABER mean temperature at 97 km altitude, respectively, as mentioned above for the year 2008. From the plots, one can notice that solar wind and *Kp* index show the periodic oscillations at 9, ~13, and 27 day periods. When we look the ionospheric and atmospheric parameters, it shows that except MLT winds/temperature and OLR data, all other parameters show the 9 day and 13 day periodicity. However, 27 day periodicity which is of solar rotation is seen in all

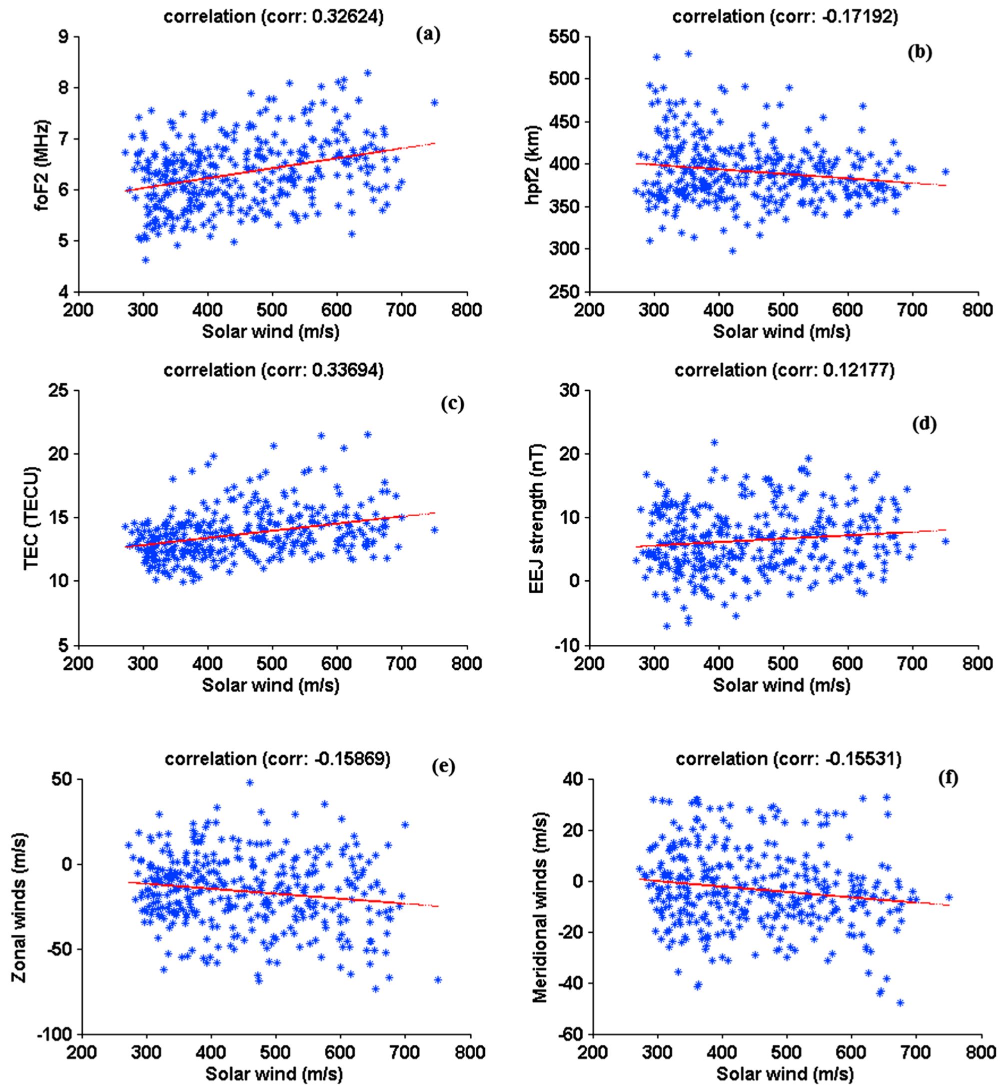

Figure 3. The correlation of solar wind with (a) f_oF_2 (MHz), (b) h_pF_2 (km), (c) GPS TEC (TECU), (d) EEJ strength (nT), (e) MLT zonal winds, and (f) MLT meridional winds during the year 2008.

the parameters. The 9 day period appears to be predominant than 13 day period in our analysis. In MLT zonal winds, however, there exists a 16 day period during Julian day number from 1 to 50 which could be of lower atmospheric origin. We have analyzed the level of auroral activity during 2008 as represented by auroral hemispheric power (HP) which is the total energy flux of precipitating electrons over one hemisphere (not shown here). The L-S periodogram of HP also suggests that it has periodicity of ~13 and 9 day apart from 27 day period which follows quite similar to that of solar wind.

To study the temporal variation of these periodic oscillations in solar wind, TEC, h_pF_2, f_oF_2, EEJ strength, and MLT winds during 2008, we applied the Morlet wavelet analysis to (a) solar wind, (b) EEJ strength, (c) GPS TEC, (d) CADI h_pF_2, (e) CADI f_oF_2, and (f) MLT zonal winds, using the method described in *Torrence and Compo* [1998] which are plotted as subplots in Figures 5a–5f. From these subplots in Figures 5a–5f, it can be seen that 9 and ~13 day periods are dominant in solar wind. While 9 day period is almost visible on several days throughout the year, ~13 day period is mostly noticed significantly during 50–100 days, 150–200 days, and weak 220–230 days. When we examined the ionospheric and atmospheric parameters, it is seen that the same periods exist in TEC, h_pF_2, f_oF_2, and EEJ strength also. But MLT zonal winds data suggest that weak 9 day and 16 day periods exist which are not clearly seen except during the first 1–50 Julian day period.

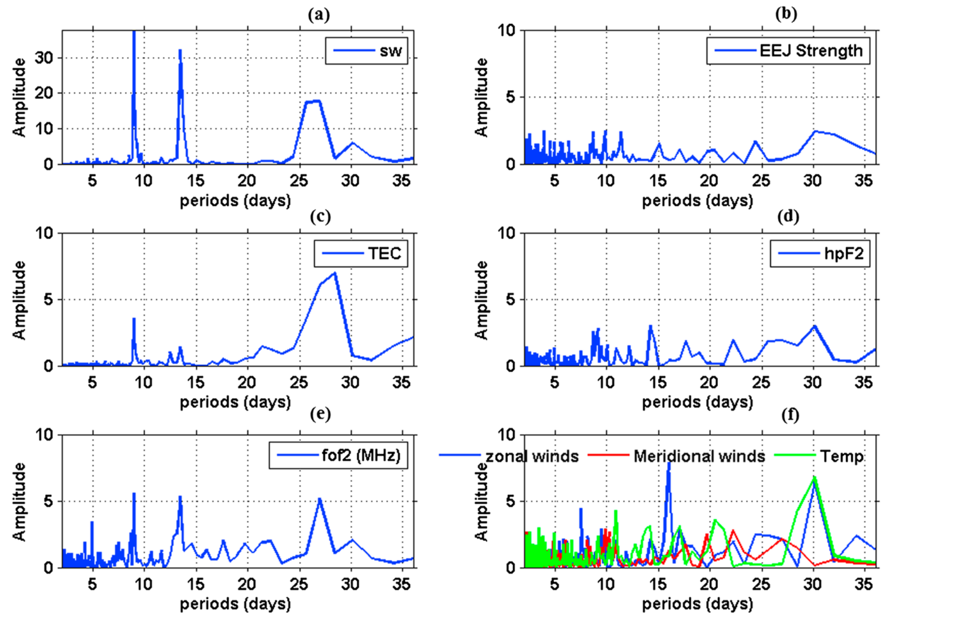

Figure 4. The Lomb-Scargle (L-S) periodogram of (a) solar wind, (b) EEJ strength, (c) TEC, (d) CADI h_pF_2, (e) CADI f_oF_2, and (f) MLT zonal/meridional winds at 90 km altitude along with SABER mean temperature at 97 km altitude, respectively, during the year 2008.

Figures 6a–6d show the 9 day band-pass-filtered data from (a) TEC, (b) f_oF_2, (c) h_pF_2, and (d) EEJ strength with filter half-power points at 6 and 12 days as was done by *Lei et al.* [2008a]. The same filtering conditions are applied for *Kp* index which is plotted on the right axis of the plot for comparison. From the figure, it can be seen that on many occasions TEC, f_oF_2 data very nicely match with the *Kp* index. However, phase of the h_pF_2 match well on some days but does not match well on other days. Similarly, EEJ strength plot shows that it does match on some days but not on some other days. Over all, it shows that f_oF_2 and TEC very well match with the *Kp* index, while moderate to poor correlation exists between other parameters.

In order to examine further whether the ionospheric/atmospheric parameters are correlated with solar or geomagnetic variabilities for the year 2008, we applied the cross wavelet (Morlet) and wavelet coherence between solar wind and (a) EEJ strength, (b) GPS TEC, (c) h_pF_2, (d) f_oF_2, (e) MLT zonal winds, and (f) MLT meridional winds which are obtained from various ionospheric/atmospheric parameters as shown in Figures 7a–7l. While Figures 7a, 7c, 7e, 7g, 7i, and 7k show the cross-wavelet spectra, Figures 7b, 7d, 7f, 7h, 7j, 7l show the wavelet coherence spectra during the year 2008. The cross wavelet and wavelet coherence are plotted using the method described in *Grinsted et al.* [2004]. Using cross wavelet and wavelet coherence, it is possible to identify the correlations at different times and the temporal variation of their coherence. From the figure, it can be noticed that we do not see any significant correlation between MLT winds and ionospheric parameters. It may be mentioned that even though there is some correlation of solar wind with MLT winds in cross wavelet, but their wavelet coherence suggests that their coherence is very low. Also, it may be mentioned that they are poorly correlated with solar wind as can be seen in Figure 3.

Figures 8a and 8b shows the daily temporal variation of (a) virtual height (*h′F* (km)) during 18:00–28:00 LT which include prereversal enhancement (PRE) hours along with superposed daily variation of solar wind speed (blue color) on the right-hand side of the figure for comparison and (b) ESF durations as recorded in the ionograms as well as L band scintillations as observed in GPS receiver over Tirunelveli during the Julian day numbers from 1 to 200 days for the year 2008. The white spaces in the Figure 8a indicate blank ionograms either due to low signal noise ratio during night times or due to ionosonde system was down on that particular day during 2008. We have chosen this time window here because we had relatively good simultaneous CADI and scintillations data than other periods. The observations show that PRE height varies in a periodic manner for which the scintillations/ESF durations also shows similar periodic resemblance in their occurrence. The solar wind plot also suggests that these periodic variations are associated with solar wind speed. It may be mentioned that while ESF is seen on many occasions in ionograms; however, L band scintillations are rarely seen in GPS receivers.

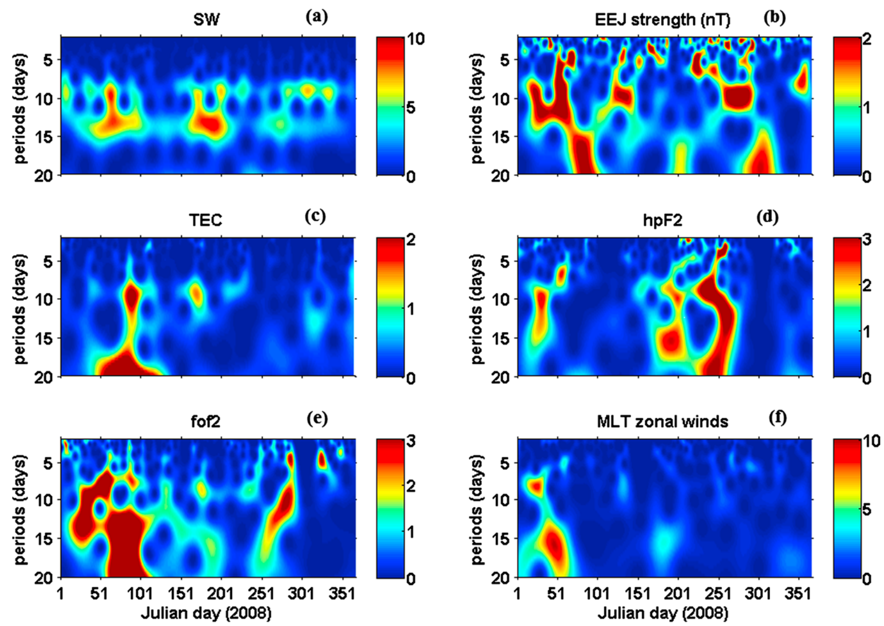

Figure 5. The Morlet wavelet analysis performed on (a) solar wind, (b) EEJ strength, (c) GPS TEC, (d) CADI h_pF_2, (e) CADI f_oF_2, and (f) MLT zonal winds.

When we analyzed the mean virtual height variation at ~2000–2030 Indian Standard Time using Lomb periodogram analysis, we find that there exists quasi 6, 13, and 16 day periods. Since 13 day period is not seen in MLT winds, it supports that this 13 day periodic oscillation could be due to coronal holes. However, 6 or 16 day periodic oscillations possibly might have come from lower atmospheric processes.

4. Discussions

The conspicuous features from the above analysis are (a) good correlation between solar wind speed and ionospheric f_oF_2/TEC but weak to poor correlation with h_pF_2/EEJ strength/MLT winds and (b) periodic oscillations at 9 and 13 day in the ionospheric f_oF_2/TEC over Indian equatorial region in 2008 which are quite similar

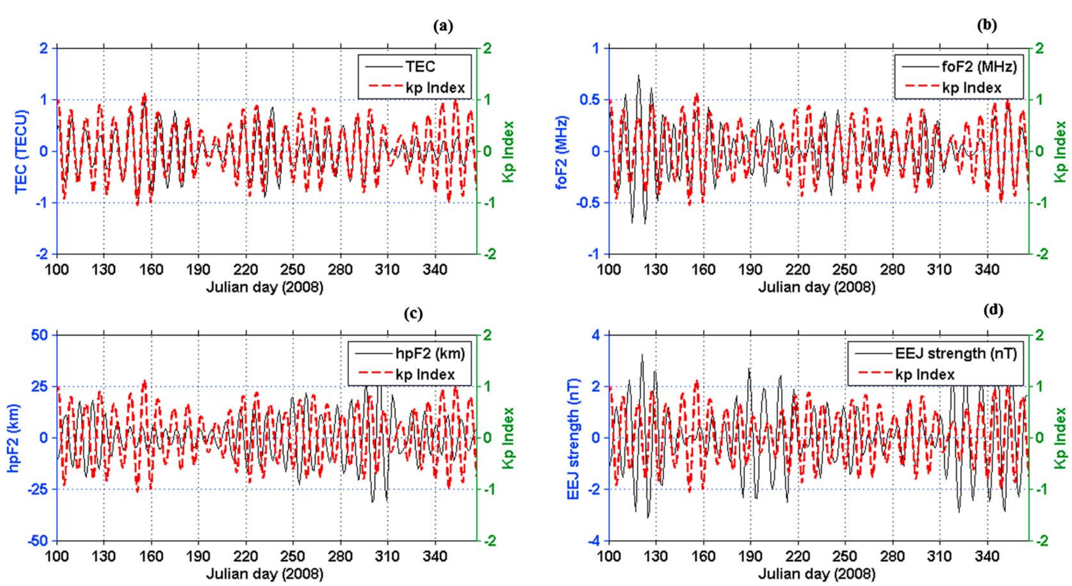

Figure 6. The 9 day band-pass-filtered data from (a) TEC, (b) f_oF_2, (c) h_pF_2, and (d) EEJ strength with filter half-power points at 6 and 12 days as was done by *Lei et al.* [2008a].

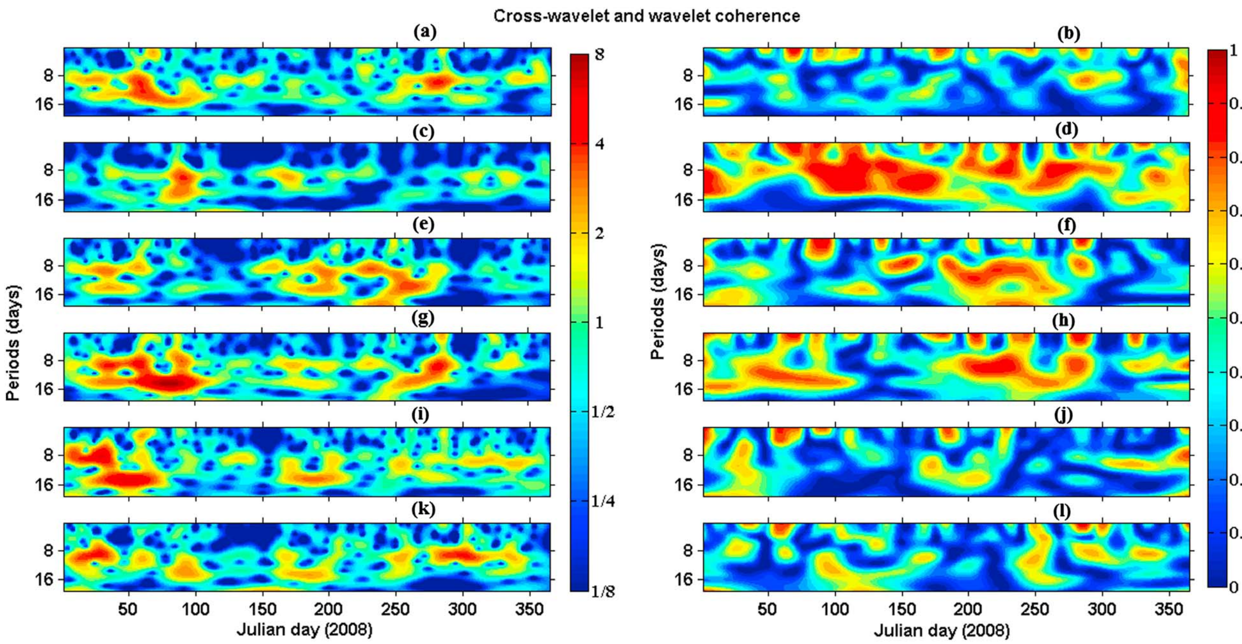

Figure 7. The (a, c, e, g, i, and k) cross wavelet (Morlet) and (b, d, f, h, j, and l) wavelet coherence between solar wind and (Figure 7a) EEJ strength, (Figure 7c) GPS TEC, (Figure 7e) h_pF_2, (Figure 7g) f_oF_2, (Figure 7i) MLT zonal winds, and (Figure 7k) MLT meridional winds during the year 2008.

to that of the periodic oscillations seen in fast streams originating from solar coronal holes. While the periodic oscillations in the density or TEC are more dominant at 9 day period than 13 day period, weak amplitudes in periodic oscillations at these periods are seen in h_pF_2 and EEJ strength. This aspect is also shown through correlation plot. We also examined the periodic oscillations in O/N_2 ratio and COSMIC density (not shown here) over Indian region which also suggests that they do represent 9 and 13 day periodic oscillations quite similar to that of f_oF_2. Apart from this, interestingly, the day to day variability in the virtual height during the prereversal enhancement (PRE) time in the ionosonde prior to the equatorial spread *F* (ESF) irregularities over Tirunelveli also indicates that the variations in the virtual height of the ionosonde and duration of the

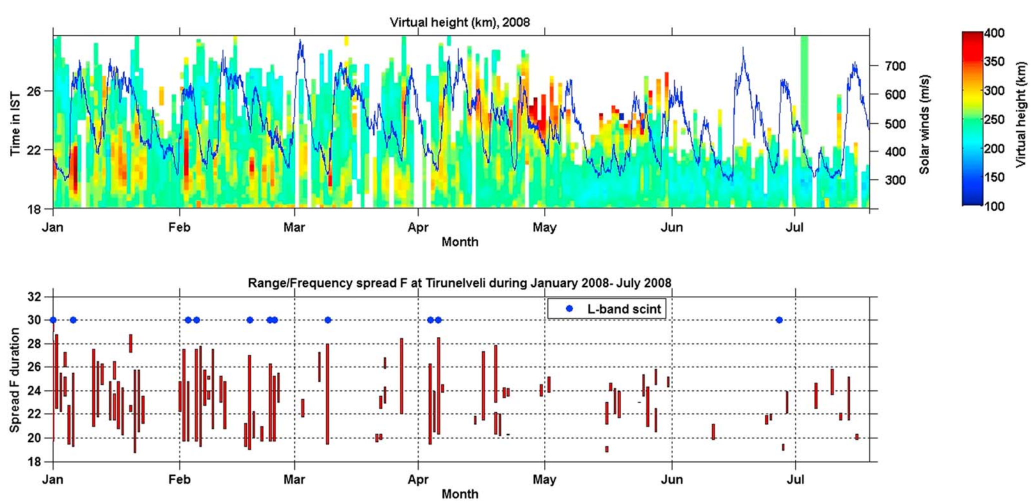

Figure 8. The daily variation of (a) prereversal enhancement (PRE) of virtual height variation along with daily variation of (b) spread *F* durations in the ionograms (red bars) along with occurrence of L band scintillations (blue filled circles) over Tirunelveli during Julian day numbers from 1 to 200 days (January–July) during the year 2008. Also shown in Figure 8a is the solar wind speed during the same period for comparison.

occurrence pattern of these irregularities are in near synchronization with that of 13 day periods as seen in solar wind or *Kp* index. Also when we analyzed the mean virtual height variation at PRE hours using Lomb periodogram analysis, we find quasi 6, 13, and 16 day periods. Since quasi 13 day period is not seen in MLT winds, we believe that this 13 day periodic oscillation could be due to coronal holes. However, we believe quasi 6 or 16 day periodic oscillations possibly have origins in the lower atmosphere. Here it may be mentioned that though we are presenting some resemblance of periodic oscillations in the occurrence of plasma irregularities based only on the virtual height oscillations, however, the occurrence of plasma irregularities are affected by gravity waves as well as atmospheric tidal forcing. So, some differences in the occurrence of plasma irregularities and virtual height as seen in Figure 8b could be due to this reason. But such periodic oscillations are not clearly visible in MLT region temperature/winds and OLR data. The cross wavelet and wavelet cross coherence analysis between ionospheric/atmospheric and solar wind parameters suggests that there exists a large correlation between ionospheric and solar parameters but moderate to weak correlation between atmospheric parameters.

Also it is not clear how the fast streams solar wind can impact the equatorial ionosphere in a periodic manner. There are several mechanisms proposed to explain the periodic oscillations in the ionosphere, namely, solar flux, atmospheric planetary waves, and magnetospheric energy. When we examined the forcing from below, our analysis of MF radar winds/SABER temperature during 2008 over Indian region suggests that these periodicities are seldom observed in the MLT altitude possibly due to proximity to the equator where its influence is reduced in the lower altitudes. At the same time, there are no periodic oscillations at 9 and 13 day period from the lower atmospheric forcing. Hence, our analysis suggests that these periods are possibly related to the solar origin and not of atmospheric origin. Even the correlation between MLT winds and solar wind suggested that they are poorly correlated. But using analysis of SABER MLT temperature data, *Chang et al.* [2009] have also shown that there is a zonally symmetric ($s = 0$) modulation in the MLT temperature field at a 9 day period which is possibly related to recurrent geomagnetic activity. However, their analysis further showed these periods are mostly seen close to poleward and not at low latitudes. Our observations of poor correlation also support this finding. So, it is evident that lower atmospheric forcing is not the cause for these oscillations. Similarly, it is clear that solar flux doesn't show any such periods. Based on these findings, it is believed that magnetic energy only can provide such periodic oscillations. However, what are the processes involved in energy transfer from this magnetosphere is of current research interest. It is believed that the energy transfers through Joule heating and particle precipitation (represented by auroral Hemispheric Power (HP)) with Joule heating being dominant mechanism. This intern depends on the IMF intensity, orientation, and solar wind speed. It is believed that variations in the Joule and particle heating at high latitudes may lead to enhancements in auroral electrojet, namely, *AE* index which induces neutral winds to oscillate as per the solar wind at the periods of 9 and 13 days. But this Joule heating at high latitudes also generates equatorward meridional winds which propagates to midlatitudes and produces disturbance dynamo process through which disturbed electric fields will be generated. Also since this equatorward disturbance winds can either push/pull the ionization to higher/lower altitudes, leading to the enhancement/decrease in density at lower latitudes. Similarly, if transequatorial winds exists which can blow across the equator, they can push ionization to lower altitudes/higher altitudes depending upon the direction of these winds where they can either enhance the ionization by reducing recombination through rising to higher altitudes or enhancing recombination through reducing density in lower altitudes. Applying this concept to DMSP satellite ion drift data, *Huang* [2012] have suggested that there is a quantitative relationship between high-speed solar winds and ion drifts over equator and suggested that disturbance dynamo as a potential source for their correlation.

The thermosphere-ionosphere-electrodynamics general circulation model modeling analysis of the response of zonal and vertical drifts also suggested that the main source for the electrodynamic response is found to be the disturbance dynamo effect [*Pedatella and Forbes*, 2011]. Further they suggested that prolonged wind perturbations have consequences not only in producing the disturbed zonal and vertical plasma drifts but also in influencing the global ionospheric current system. Our observations of occurrence of plasma density irregularities or scintillations in association with PRE height oscillations with period of 13 day indicate that they could be influenced by disturbance dynamo where depending upon the electric field/meridional wind directions plasma density irregularities may be either generated or inhibited. It is known that such possibility exists during geomagnetic storms. Even moderate correlation of EEJ strength indicates the influence of fast streams on ionospheric current system. Since geomagnetic storms prolonged for several days during the 2008 due to slow recovery during low solar activity periods, it is possible that disturbance dynamo winds and electric fields (DDEF) could have impacted the equatorial and low latitudes and could have caused periodic oscillations. Our observations of 9 and 13 day periodic oscillations in f_oF_2/TEC also may indicate that DDEF generated through the disturbance winds might cause periodic oscillations. So, these results suggest that the periodic oscillations seen in our observations could be possibly related to fast stream solar winds originating from coronal holes which are mainly associated with disturbed winds or DDEFs. But, interestingly, electric fields generated through winds also fluctuate at the same frequencies as that of neutral winds through the disturbance wind dynamo process [e.g., *Blanc and Richmond*, 1980; *Pedatella and Forbes*, 2011]. Thus, it is believed that electric fields or neutral winds which are modulated by the solar wind and geomagnetic activity at 7 and 9 or 13 day periodicities are important for these oscillations.

The impact of high-speed streams on the f_oF_2 and h_mF_2 at Jicamarca along with simultaneous GPS TEC near equatorial ionization anomaly region in the America sector are investigated during the recent deep solar minimum year of 2008 by *Liu et al.* [2012]. Their results also showed a prominent 9 day oscillation in the h_mF_2 and f_oF_2 at the dip equator. However, they showed that the 9 day oscillations as seen in f_oF_2 is not always correlated positively with TEC at equator, but it has nonlinear dependence on the intensity of geomagnetic disturbances. These authors have further suggested that this periodicity also could be seen in the equatorial vertical drifts as obtained from storm time empirical model of *Fejer and Scherliess* [1997] where they saw periodic oscillations in vertical drifts when disturbance dynamo electric field (DDEF) are injected but absent of such periods when prompt penetration electric fields are injected into the model. Hence, using these results, they suggested that the DDEF effects may be suitable candidate to explain these periodic oscillations but it is not sufficient to explain the observed phenomena. However, they also indicated that other mechanisms such as thermal expansion/contraction and neutral compositional changes are important.

The periodic oscillations in the neutral densities, on the other hand, are believed to be related to Joule and particle heating resulting in thermal expansion leading to the strong upward vertical winds at high latitudes [*Thayer et al.*, 2008; *Crowley et al.*, 2008]. This results in the upliftment of molecular rich air to higher altitudes and then strong trans polar winds carry the uplifted air toward the nightside of the polar cap. The outflow of air from high latitudes generates large-scale circulation system where horizontal winds converges equatorward of the auroral oval resulting in down flow. This downward flow of winds carry atomic oxygen rich air to low latitude across pressure levels thereby enhancing O/N_2 ratio at these latitudes. Based on these results, they suggested that atmosphere expands or contracts as per the solar wind speeds resulting in periodic oscillations. Similarly, *Lei et al.* [2008a] have studied the terrestrial connections between rotating solar coronal holes and thermospheric density variations in Earth's upper atmosphere using the data from the year 2005. Their findings led to an understanding that there exists a 9 day recurrence of fast streams in the solar wind due to solar coronal holes distributed in a longitude separation of ~120° which is possibly reflected in the Earth's atmosphere in terms of geomagnetic and thermospheric density oscillations as observed in accelerometer measurement on the CHAMP satellite. In an another paper by the same author during the same year investigated in a greater detail on the recurrent pperiodic oscillations at 7 and 9 days in GPS TEC and in MLT temperature and winds during 2005/2006 as measured by airglow instrument at Resolute Bay [*Lei et al.,* 2008b]. They have shown that periodic oscillations as seen in their TEC and temperature are similar to those of solar wind and *Kp* index. Since the periodicities in neutral temperature are expected to affect the electron density in the F_2 layer or TEC due to variations in the recombination and the height of the F_2 layer, they argued that these periodic oscillations could be due to solar origin. Our observations of weak correlation of MLT winds at 90 km altitude and EEJ strength representative of 100 km altitude suggests that these oscillations become weak at lower altitudes due to increasing damping.

While the periodic oscillations have been noticed in both neutral and ionized mediums, variation of these periods with altitude is not known. Recently, when *Tulasi Ram et al.* [2010b] have investigated the ionospheric response to the recurrent geomagnetic activity using COSMIC density data during 2008, it is observed that it varies with altitude and latitude. Their results showed that while the electron density response at lower altitudes is dominated by changes in the neutral composition and exhibits significant latitudinal, local time, and seasonal variations, topside ionosphere appears to be dominated by the changes in the plasma temperature and/or scale height and exhibits concurrent enhancements with the oscillations in geomagnetic activity during both day and nighttime. On the other hand, the local time and latitudinal dependence of 9 day periodicities are investigated using CHAMP in situ electron density at altitudes of ~ 350 km and GPS TEC during the year of 2005 by *Pedatella et al.* [2010] where it is shown that the largest oscillations in daytime TEC occur at mid latitudes with increase of ±25% of background levels. However, their observations are found to be more symmetric about the geomagnetic equator with anticorrelation between high and low latitudes during daytime, whereas at night the northern high latitude is in phase with low latitudes but anticorrelated with the southern high latitude. Based on these findings, they suggested that combination of enhanced equatorward neutral winds and changes in neutral composition are responsible for periodic oscillations observed in ionospheric parameters. Though our observations of periodic oscillations in ionospheric densities suggest that they may be responding to disturbed neutral winds/electric field but we cannot rule out compositional change as one of its reasons for these periods after all these two forcings are arising from the same source, i.e., auroral electrodynamics. The differences in the phase variation between solar winds and f_oF_2/TEC in our observations suggest that variations in compositional change might be playing some role in equatorial electrodynamics.

To summarize, though we have seen the periodic oscillations at 9 and 13 day in various ionospheric parameters which could be linked to disturbance dynamo effect, we also see large variations in their temporal and altitudinal variability which appears to be different from that of solar wind. This indicates that we need to investigate other aspects like thermospheric density variations, neutral wind contributions, and rate of production or recombination at different altitudes. This indicates that we need to investigate other aspects such as production and recombination while understanding geomagnetic recurrent activity using both observations and modeling. We are investigating more in this direction and will be presented in future.

5. Summary

The analysis of the ground-based observations as presented in this paper using multi-instrument observations covering different altitudes over Indian equatorial station, Tirunelveli during the deep solar minimum year of 2008 show clear periodic oscillations in ionospheric density, TEC and EEJ strength at 9 and 13 day which are quite similar to that of the periods seen in solar wind or *Kp* index. The Lomb-Scargle (L-S) periodogram shows the existence of subharmonic periods in the ionosphere. Further our observations suggest that there is an indication that the occurrence pattern of ESF irregularities is modulated by the oscillations in the solar wind/*Kp* index. However, MLT winds/temperature and OLR data suggest that these periodic oscillations are nonexistent. Using cross wavelets and wavelet coherence, we suggest that these periodic oscillations could be arising mainly from the solar origin but not due to lower atmospheric coupling. Our analysis further showed that while good correlation exists between solar wind and TEC, f_oF_2 and EEJ strength variations, poor correlation exists between solar wind and h_pF_2 and MLT winds. We attribute these periodic oscillations to disturbance dynamo winds/electric fields. However, we also observe some differences in the seasonal variation of these periods which could be possibly linked to the thermospheric neutral compositional change or recombination rate changes. Since these variations are linked to various physical and chemical properties of the ionospheric medium through which these waves propagate, the observed variabilities in these periods could be possibly due to the variabilities in the medium through which it propagates. We will examine further using long-term data composed of low, moderate, and high solar activity periods to understand its variability and its impact on the equatorial and low-latitude ionosphere.

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