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Equinoctial asymmetry in the occurrence of equatorial spread-F over Indian longitudes during moderate to low solar activity period 2004-2007

G Manju[1,$,*], M K Madhav Haridas[1], Sudha Ravindran[1], Tarun Kumar Pant[1] & S Tulasi Ram[2]

[1]Space Physics Laboratory, Vikram Sarabhai Space Centre, Trivandrum 695 022, India

[2]Research Institute for Sustainable Humanosphere (RISH), Kyoto University, Uji, Japan

[$]E-mail: manju_spl@vssc.gov.in

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The seasonal pattern of equatorial spread-F (ESF) was observed at the magnetic equatorial station Trivandrum and low latitude station SHAR in the Indian sector using ionosonde data. A clearly higher ESF occurrence percentage is observed during vernal equinox compared to autumnal equinox at both locations. Post-sunset vertical drift velocities were observed to be nearly comparable at Trivandrum indicating the comparable electrodynamical forcing on the post-sunset F-layer during the two equinoxes. At the off equatorial station SHAR, post-sunset vertical drift exhibits clear asymmetric pattern, with higher values in the vernal equinox, indicating the possible role of meridional neutral winds in modulating the layer height. The meridional winds estimated during the period just prior to ESF at the two equinoxes reveal much larger poleward winds to be prevalent during autumnal equinox compared to that in vernal equinox. Large neutral winds are shown to be related directly to asymmetry factor of the equatorial ionisation anomaly (EIA) derived from single station Coherent Radio Beacon Experiment (CRABEX) data. The larger neutral winds in autumnal equinox, results in an increase in off equatorial E-region conductivity, thereby, inhibiting or weakening the F-region dynamo. This study, thus, focuses on the role of neutral dynamics, as one possible candidate producing the asymmetric occurrence pattern of ESF, during the two equinoxes over Indian longitudes.

Keywords: Equinoctial asymmetry, Equatorial spread-F (ESF), Equatorial ionisation anomaly, Meridional wind

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1 Introduction

The seasonal and solar activity variability of equatorial spread-F has been investigated by a number of researchers (e.g. Sreeja *et al.*[1]). They have shown that for high solar activity during equinoctial period, the ESF occurrence is nearly 100% with the ESF duration being much above 400 min, whereas for low solar activity period, ESF occurrence is substantially reduced with duration generally below 400 min.

Maruyama & Matuura[2] found that a symmetric ionization distribution on either side of magnetic equator is favourable for occurrence of ESF and proposed that trans-equatorial neutral wind is capable of suppressing the Rayleigh Taylor (RT) instability which is known to be primarily responsible for the triggering of ESF. Maruyama[3], through numerical simulations, showed the role of winds in increasing the Pedersen conductivity and thereby, reducing the growth rate of RT instability. Devasia *et al.*[4] showed that converging/diverging thermospheric meridional winds become significant with the equatorward wind being present when h'F was below a threshold height (h'F_c) for the RT instability to get triggered. Above the critical height, the polarity did not matter. Raghavarao *et al.*[5] conjectured that such equatorward winds could be produced as a result of the pressure bulges associated with equatorial temperature and wind anomaly (ETWA). Valladares *et al.*[6,7] compared the plasma bubble occurrence and total electron contents (TECs) measured by a chain of receivers along the western coast of South America. They did not find any significant north-south asymmetry of TECs associated with plasma bubble occurrence. Lee *et al.*[8] concluded that smaller north-south asymmetry and larger zonal electric fields are favourable conditions for plasma bubble development. Abdu *et al.*[9] analyzed ionograms from two ionosonde stations, one near the magnetic equator and the other at the low latitude and found that meridional neutral wind could adversely affect plasma bubble development. Thampi *et al.*[10,11] have shown that the north/south asymmetry of total electron content at the equatorial anomaly crests could be related to the absence of ESF, although the asymmetry alone does not suffice to make a deterministic forecast for ESF on a given day. Aspects related to equinoctial asymmetry of ESF occurrence have been investigated in the Indonesian sector[12,13]. Sripathi *et al.*[14] have investigated the equinoctial asymmetry in scintillation occurrence over Indian regions and suggested that the asymmetry in the electron density distribution and that in the meridional winds could be responsible for the same. Dasgupta *et al.*[15] have studied the equinoctial asymmetry in F-region ionization over equatorial and low-latitude regions and attributed it to changes in neutral composition. Several other researchers have also investigated the equinoctial asymmetric behaviour of the ionosphere[16-20].

The objective of the present study is to look into the equinoctial asymmetry in occurrence of ESF at the magnetic equatorial station, Trivandrum and low latitude station SHAR in the Indian sector and the role of neutral winds as one plausible causative mechanism for the same.

2 Data and Methodology

Ionosonde data from Trivandrum (8.5ºN, 77ºE) (for 2004-2007) and SHAR (12.5ºN, 80ºE) (2004-2005) and Coherent Radio Beacon Experiment (CRABEX) data from Trivandrum (2005) have been used for this study. Ionosonde data at 15 min intervals have been used for meridional wind estimation. CRABEX data corresponding to satellite passes between 1600-1800 hrs IST is used for the study.

2.1 CRABEX data

The CRABEX receiver located at Trivandrum receives the two phase coherent signals 150 and 400 MHz transmissions from the Low Earth Orbiting Satellites (LEOS) and measures the differential Doppler between them. LEOS were part of the Navy-navigational satellite system (NNSS), which is presently known as the Navy Ionospheric Monitoring System (NIMS). LEOS, which are polar orbiting satellites with orbital heights ~1000 km, scan from horizon to horizon within a fraction of an hour and provide the ‘snap-shot’ picture of the ionosphere. The conversion of the measured relative phase to the latitudinal profiles of relative vertical TEC up to 1000 km is already reported[21].

2.1.1 Asymmetry factor estimation

Thampi *et al.*[11] formulated a new parameter using single station relative TEC measurements at Trivandrum (TRV), which incorporates the effects of the equatorial ionization anomaly (EIA) strength and asymmetry and predicts the occurrence/non-occurrence of ESF as early as 1600 hrs IST. TRV being the trough of the EIA, the northern and southern gradients at TRV station represents the EIA gradients. This parameter seeks to define the state of the background ionosphere conducive for the generation of ESF irregularities much prior to its onset. When the asymmetry of EIA is greater than zero, this parameter has the form:

$$\mathrm{C} = \sqrt{\frac{S_F}{abs(A_F)}}$$

where, $S_F = \left(\frac{N+S}{2}\right)$, represents the strength of the EIA; $A_F = \frac{N-S}{S_F}$, represents the asymmetry of EIA; N and *S,* the northern and southern gradients of the EIA, with reference to the trough, estimated from relative TEC measurements. Here, the strength parameter is assumed to represent the electrodynamical effect on the EIA which is expected to be symmetric at both hemispheres, while the asymmetry parameter is assumed to represent the deviation from the symmetry of the crests produced as a result of the meridional wind effects. The asymmetry factor is estimated in the present study for understanding its variations during the two equinoxes and consequent implications for occurrence of ESF.

2.2 Meridional wind estimation

The meridional wind estimation is made using ionosonde data from TRV and SHAR. The method given by Krishna Murthy *et al.*[22] is used for estimating the meridional winds. Here, the vertical drift of the F-layer is estimated for the two stations (TRV and SHAR) after taking into account the effects due to recombination and diffusion. The F-region vertical drift at the magnetic equatorial region over Trivandrum is purely electrodynamical in nature while that at a low-latitude station like SHAR has contribution from the meridional winds (U) in addition to diffusion along the magnetic field lines. The observed vertical drift velocities (V_o) are initially derived from the rate of change of h’F (d[h’F]/dt). The true vertical drift is obtained from $V_d = V_o - \beta H$, where β, is the effective recombination coefficient; H, the scale height given by $H = (1/N\ dN/dh)^{-1}$; N, the electron density; and βH, the correction due to recombination. The actual meridional wind for the period of study is estimated from the equations for the vertical drift at the two stations as:

$$U = [2 (V_D \cos I - V) / \sin 2I] - W_D \tan I \quad \ldots (2)$$

where, V_D and V, are the vertical drifts over Trivandrum and SHAR, respectively; I, the dip angle at SHAR; and W_D, the plasma drift velocity due to plasma diffusion and is given by g/υ_{in}, where g, is the acceleration due to gravity; and υ_{in}, the ion-neutral collision frequency. The error in the meridional wind, using this method, is estimated to be about ~ 25 m s^{-1} (Ref. 22). This method is used, generally, for estimating meridional winds at night time in the absence of production.

2.3 FORMOSAT-3: COSMIC data

The FORMOSAT-3, the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC), in short F3/C, is a constellation of six microsatellites, designed to monitor weather and space weather with its major payload, GPS radio occultation experiment (GOX) instruments, performing the radio occultation observations in both the troposphere and the ionosphere. Each microsatellite also has a triband beacon (TBB) transmitter to perform ionospheric tomography and an ionospheric photometer (TIP) to observe the nighttime ionospheric airglow emissions. In the present study, the vertical electron density observations from the GOX payload for the year 2007 have been used. Each microsatellite orbits at around 800 km altitude, 72º inclination angle, and 30º separations in the longitude between two satellite orbits[23]. Detailed description of the inversion technique applied to invert the F3/C occultation soundings to ionospheric electron density profiles is already reported[24,25]. The details of the validation of F3/C radio occultation observations are presented by Schreiner *et al.*[26]

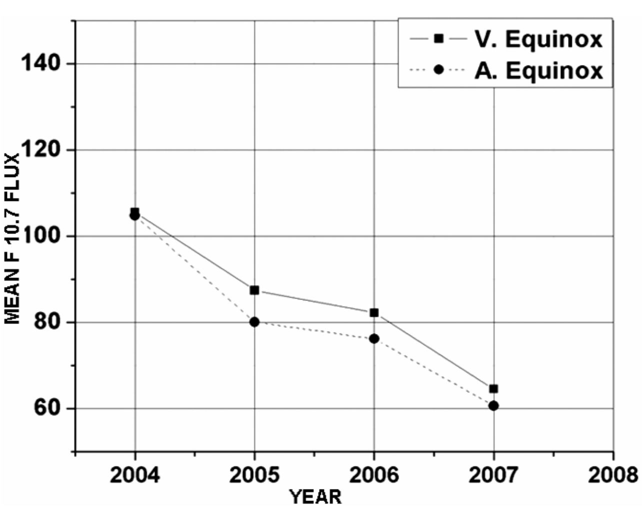

Fig. 1 — Temporal evolution of yearly mean solar flux for the two equinoxes during 2004-2007

3 Results

The observations pertaining to the asymmetric occurrence of ESF and related aspects, during the period covering moderate solar activity to deep solar minimum, are presented here. Figure 1 shows the temporal evolution of yearly mean solar flux for the two equinoxes during this period. For both autumnal and vernal equinox, there is a steady decrease in mean yearly solar flux from around 100 in 2004 to around 60 in 2007.

3.1 Seasonal pattern of mean vertical drift at TRV and SHAR

The post-sunset vertical drift (V_d) is represented by dh'F/dt, where, dh'F (at 2.5 MHz) is the difference between maximum post-sunset height of F-layer and the height at 1800 hrs LT; and dt, the time difference between the time of occurrence of maximum height and 1800 hrs LT.

The seasonal mean pattern of ESF occurrence during vernal and autumnal equinoxes for the stations of Trivandrum (magnetic equator) and SHAR (low latitude) in the Indian sector during the period of 2004-2007 is illustrated in Fig. 2. The interesting aspect is that the occurrence percentage during the vernal equinox is much higher than during autumnal equinox at both the locations, for all the four years examined, indicating an equinoctial asymmetry in ESF occurrence pattern. Another aspect, that is evident, is the steady decrease in percentage occurrence of ESF as solar flux decreases.

To understand the possible role of the post-sunset F-layer vertical drift in producing the above

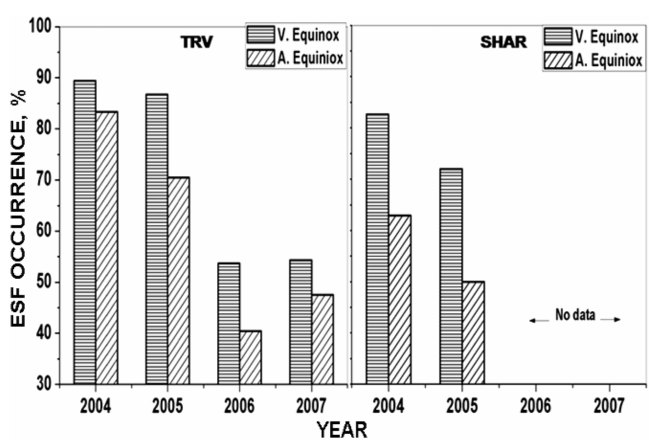

Fig. 2 — Seasonal mean occurrence pattern of ESF during vernal and autumnal equinoxes at TRV (left panel) and SHAR (right panel) in the Indian sector

asymmetric occurrence of ESF, the variation of the former at TRV and SHAR between the two equinoxes is examined. Figure 3 depicts this seasonal mean pattern of V_d during the period 2004-2007 for TRV and 2004-2005 for SHAR. It is evident from the figure that V_d is nearly comparable for the two equinoxes at TRV, while at SHAR, it is significantly higher during vernal equinox compared to autumnal equinox. The nearly symmetric pattern of V_d at TRV, a magnetic equatorial station, where the post-sunset F-layer movement is controlled by electrodynamics alone indicates that electrodynamics is not the factor responsible for the observed equinoctial asymmetry in ESF occurrence. But for a low-latitude station like SHAR, the F-layer movement is controlled by meridional wind in addition to electric field. Hence, it seems that the asymmetric pattern of V_d at SHAR is probably a meridional wind related modulation of the F-layer. In the light of this observation, it is conjectured that neutral dynamical effects are probably responsible for the equinoctial asymmetry in ESF occurrence. Hence, the mean meridional winds, during the post-sunset hours (1800-1900 hrs IST) prior to triggering of ESF, are estimated from the ionosonde data of TRV and SHAR for 2004 and 2005. From the estimated meridional winds depicted in Fig. 4, it can be seen that larger poleward winds are prevalent in the post sunset hours of autumnal equinox compared to vernal equinox.

3.2 Dependence of asymmetry of EIA on the meridional wind

The C parameter quantifies the effect of electrodynamics and neutral dynamics through the strength and asymmetry, respectively of the EIA. Strength is directly related to the post-sunset height of the F-region and asymmetry is inversely related to the same. It is the combined effect of the two, which decides the post-sunset height of the F-layer and it is represented by C parameter. There is a threshold value of C parameter above which ESF occurs for a given season[10,11]. As is evident from the above, the asymmetry factor is obtained from single station CRABEX data at Trivandrum and is a proxy for the meridional wind effects on the post-sunset F-layer.

Figure 5 illustrates the variation of asymmetry factor obtained from CRABEX data with the actual estimated meridional wind from ionosonde data for different days in 2005. Here, the limited number of days with simultaneous CRABEX satellite passes and ionosonde data are used to generate the figure. It is seen that higher poleward winds result in larger asymmetry factor.

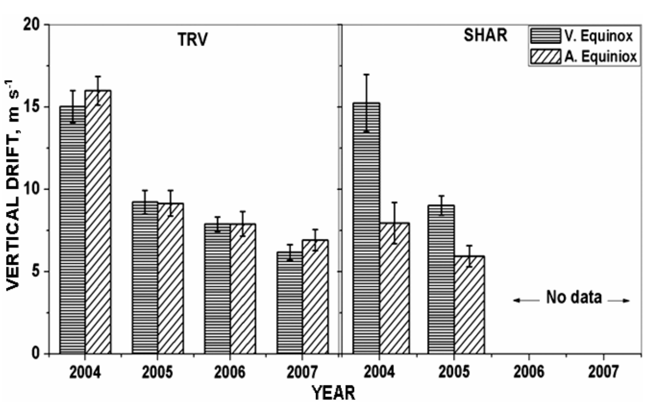

Fig. 3 — Seasonal mean pattern of post-sunset vertical drift during vernal and autumnal equinoxes at TRV (left pane) and SHAR (right panel) in the Indian sector

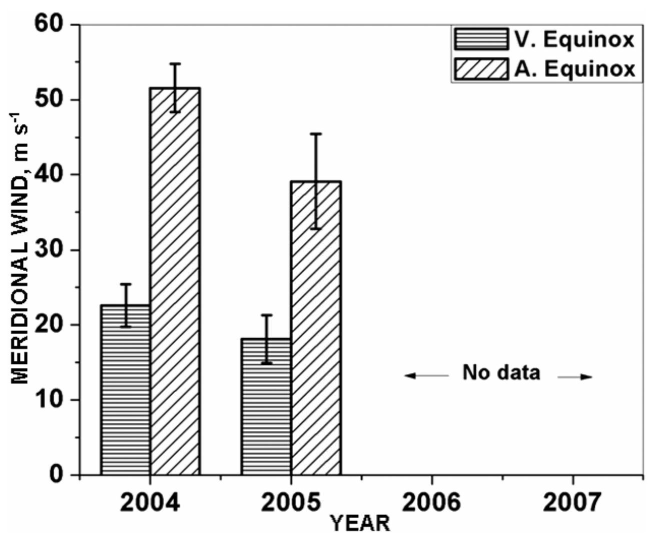

Fig. 4 — Seasonal mean pattern of post-sunset thermospheric meridional wind during vernal and autumnal equinoxes over Indian low-latitude regions

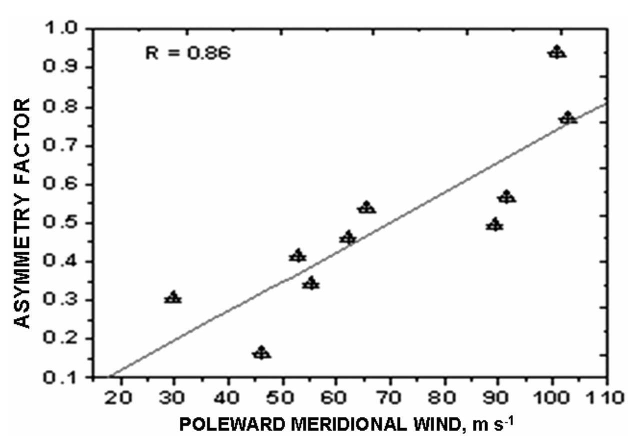

Fig. 5 — Scatter plot of post-sunset meridional neutral winds and EIA asymmetry factor for low solar activity period 2005

3.3 Variation of the EIA asymmetry during vernal and autumnal equinoxes from COSMIC data

The pattern of asymmetry of the EIA during the two equinoxes is examined using COSMIC radio occultation data in the 75-85ºE longitude belt and during 1800-1900 hrs IST. The observed pattern of the EIA asymmetry in the autumnal (top panel) and vernal (bottom panel) equinoxes of 2007 are shown in Fig. 6. There is COSMIC data only for 2007 and the pattern is expected to be same during the other years also except for possible changes in the magnitude of the effects. The significantly higher asymmetry of the anomaly in the autumnal equinox season is evident from the figure.

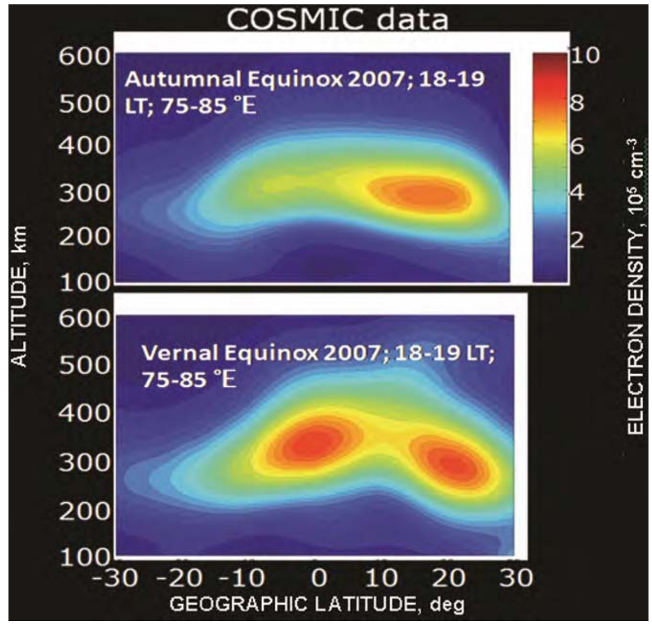

Fig. 6—Seasonal mean EIA ionization distribution for the vernal and autumnal equinoxes of the year 2007

4 Discussions

Burke *et al.*[27] generated a comprehensive global distribution map (longitude *vs* season) of equatorial ionospheric irregularities on the basis of the Defense Meteorological Satellite Program (DMSP) *in situ* observations. The map indicates high occurrence probabilities along two lines around the equinox seasons, where the sunset terminator aligns with the magnetic meridional plane. Another feature noted in the map is the equinoctial asymmetry although it is not as prominent as the seasonal and longitudinal effects. In the Indian and Pacific longitudes, the maximum occurrence probability around the March equinox is higher than that around the September equinox. The meridional wind control on the asymmetric occurrence of ESF during equinoxes is shown over Indonesian sector by Maruyama *et al.*[12]. Numerical simulations have also been presented by them, which demonstrate that the growth rate of the RT instability is halved when the meridional wind velocity changed from 10-40 m s^{-1}. In their study, they have used data for one month in each season for a single year. In the present study, the evolution of the equinoctial asymmetry in the occurrence of ESF over the magnetic equatorial station TRV has been examined using four years (2004-2007) data covering the period from moderate solar activity to deep solar minimum. Further, the equinoctial asymmetry in ESF occurrence at low-latitude station SHAR is also presented and discussed.

The occurrence of ESF is steadily found to reduce as solar activity decreases for both seasons at TRV and SHAR. The asymmetry in ESF occurrence is less for moderate solar activity year 2004 compared to the other years. It is seen that for solar maximum years, the ESF occurrence percentage is near 100 for the equinoxes during post-sunset hours because the post-sunset height rise of F-layer is very high[28], which is indicative of absence of significant asymmetry. Hence, it is logical to expect less asymmetry during moderate solar activity years compared to low solar activity years, as observed in the present study. In the case of low latitude station SHAR, ESF occurrence is significantly asymmetric for moderate solar activity year 2004 and low solar activity year 2005.

The pattern of V_d at TRV does not show asymmetry for any year in the period 2004-2007 but at SHAR, V_d shows significant asymmetry for both 2004 and 2005. This is indicative of the role of strong meridional neutral winds in modulating the layer height at low-latitude regions and lack of significant differences in the factors affecting post-sunset vertical drift over magnetic equatorial regions. In agreement with the behaviour of the V_d at SHAR, the meridional winds are clearly much higher there for autumnal equinox season.

Thampi *et al.*[10] have shown that asymmetric EIA has an inhibiting effect on ESF. They have estimated the asymmetry factor from the TEC gradients and suggested that these are representative of the neutral wind related modulations of the background ionosphere prior to ESF occurrence. In the present study, it has been actually shown that the asymmetry factor is directly related to the poleward meridional winds in the EIA in the post-sunset period providing direct confirmation that the neutral dynamical effects are incorporated in the asymmetry factor. The larger asymmetry factor is observed to occur for higher poleward winds. Hence, during autumnal equinox season when the meridional winds are stronger as is brought out in this study, the asymmetry is also larger. Larger meridional winds in autumnal equinox means the vertical winds associated with the ETWA related circulation cell[29] will also be larger. These larger vertical winds are inhibiting for RT instability[30,31]. These winds can significantly contribute to the observed asymmetric pattern of ESF in the two equinoxes at magnetic equatorial station TRV. At SHAR, the meridional neutral winds seem to be inhibiting the ESF significantly, thereby, causing substantial inhibition of ESF as wind magnitude increases.

In addition to the role of neutral winds, the possible contribution from other factors like seed perturbations are not considered in this study.

5 Conclusions

From the above, it is concluded that:

1. Significant equinoctial asymmetry in occurrence of ESF at magnetic equatorial regions. The extent of asymmetry reduces with solar activity.
2. Significant equinoctial asymmetry in occurrence of ESF at low-latitude station SHAR which persists even as solar activity decreases.
3. The possible role of neutral dynamics as one candidate contributing to the equinoctial asymmetry in the occurrence of ESF at magnetic equatorial and low-latitude regions is highlighted.

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References

1 Sreeja V, Devasia C V, Ravindran Sudha & Sridharan R, The persistence of equatorial spread F – an analysis on seasonal, solar activity and geomagnetic activity aspects, *Ann Geophys (Germany)*, 27 (2009) pp 1–8.

2 Maruyama T & Matura N, Longitudinal variability of annual changes in activity of ESF and plasma depletions, *J Geophys Res (USA)*, 89 (1984) pp 10903-10912.

3 Maruyama T, A diagnostic model for equatorial spread-F Pt 1: Model description and applications to the electric field and neutral wind effects, *J Geophys Res (USA)*, 93 (1988) pp 14611-14622.

4 Devasia C V, Jyoti N, Viswanathan K S, Subbarao K S V, Tiwari D & Sridharan R, On the plausible linkage of thermospheric meridional winds with equatorial spread-F, *J Atmos Sol-Terr Phys (UK)*, 64 (2002) pp 1-12.

5 Raghavarao R, Hoegy W R, Spencer N W & Wharton L, Neutral temperature anomaly in the equatorial thermosphere-A source of vertical winds, *Geophys Res Lett (USA)*, 20 (1993) pp 1023-1026.

6 Valladares C E, Basu S, Groves K, Hagan M P, Hysell D, Mazzella Jr A J & Sheehan R E, Measurement of the latitudinal distributions of total electron content during equatorial spread F events, *J Geophys Res (USA)*, 106 (2001) pp 29133–29152.

7 Valladares C E, Villalobos J, Sheehan R & Hagan M P, Latitudinal extension of low-latitude scintillations measured with a network of GPS receivers, *Ann Geophys (Germany)*, 22 (2004 pp 3155–3175, http://www.ann-geophys.net/22/3155/2004/.

8 Lee C C, Liu J Y, Reinisch B W, Chen W S & Chiu F D, The effects of the pre-reversal drift, EIA asymmetry and magnetic activity on ESF during solar minimum, *Ann Geophys (Germany)*, 23 (2005) pp 745-751.

9 Abdu M A, Iyer K N, de Mederios R T, Batista I S & Sobral J H A, Thermospheric meridional wind control of equatorial spread-F and evening prereversal electric field, *Geophys Res Lett (USA)*, 33 (2006) L07106, doi: 10.1029/2005GL024835.

10 Thampi S V, Ravindran S, Pant T K, Devasia C V & Sridharan R, Seasonal dependence of the forecast parameter based on the EIA characteristics for the prediction of Equatorial Spread-F (ESF), *Ann Geophys (USA)*, 26 (2008) pp 1751–1757, http://www.ann-geophys.net/26/1751/2008/.

11 Thampi S V, Ravindran Sudha, Pant Tarun Kumar, Devasia C V, Sreelatha P & Sridharan R, Deterministic prediction of post-sunset ESF based on the strength and asymmetry of EIA from ground based TEC measurements – Preliminary results, *Geophys Res Lett (USA)*, 33 (2006) L13103, doi: 10.1029/2006GL026376.

12 Maruyama T, Saito S, Kawamura M, Nozaki K, Krall J & Huba J D, Equinoctial asymmetry of a low-latitude ionosphere-thermosphere system and equatorial irregularities: Evidence for meridional wind control, *Ann Geophys (Germany)*, 27 (2009) pp 2027–2034.

13 Otsuka Y, Shiokawa K & Ogawa T, Equatorial ionospheric scintillations and zonal irregularity drifts observed with closely spaced GPS receivers in Indonesia, *J Meteorol Soc Jpn (Japan)*, 84A (2006) pp 343–351, doi: 10.2151/jmsj.84A.343.

14 Sripathi S, Kakad B & Bhattacharyya A, Study of equinoctial asymmetry in the Equatorial Spread F (ESF) irregularities over Indian region using multi-instrument observations in the descending phase of solar cycle 23, *J Geophys Res (USA)*, 116 (2011) A11302, doi: 10.1029/2011JA016625.

15 Dasgupta A, Anderson D N & Klobuchar J A, Equatorial F-region ionization differences between March and September 1979, *Adv Space Res (UK)*, 10 (1983) pp 199-202.

16 Liu L, He M, Yue X, Ning B & Wan W, Ionosphere around equinoxes during low solar activity, *J Geophys Res (USA)*, 115 (2010) doi: 10.1029/2010JA015318.

17 Nishioka M, Saito A & Tsugawa T, Occurrence characteristics of plasma bubble derived from global groundbased GPS receiver networks, *J Geophys Res (USA)*, 113 (2008) A05301, doi: 10.1029/2007JA012605.

18 Ray S & DasGupta A, Geostationary L-band signal scintillation observations near the crest of equatorial anomaly in the Indian zone, *J Atmos Terr Phys (UK)*, 69 (2007) pp 500-514.

19 Balan N, Otsuka Y & Fukao S, New aspects in the annual variation of the ionosphere observed by the MU Radar, *Geophys Res Lett (USA)*, 24 (18) (1997) pp 2287-2290.

20 Ren Z, Wan W, Liu L, Chen Y & Le H, Equinoctial asymmetry of ionospheric vertical plasma drifts and its effect on F-region plasma density, *J Geophys Res (USA)*, 116 (2011), A02308, doi: 10.1029/2010JA016081.

21 Thampi S V, Ravindran S, Devasia C V, Pant T K, Sreelatha P & Sridharan R, First observation of topside ionization ledges using radio beacon measurements from LEOS, *Geophys Res Lett (USA)*, 32 (2005) L11104, doi: 10.1029/2005GL022883.

22 Krishna Murthy B V, Hari S S & Somayajulu V V, Nighttime equatorial hemispheric meridional winds from ionospheric h'F data, *J Geophys Res (USA),* 95 (1990) pp 4307-4310.

23 Cheng C -Z F, Kuo Y -H, Anthes R A & Wu L, Satellite constellation monitors global and space weather, *EOS Trans Am Geophys Union (USA)*, 87 (2006) 166, doi: 10.1029/2006EO170003.

24 Schreiner W S, Sokolovskiy S V & Rocken C, Analysis and validation of GPS/MET radio occultation data in the ionosphere, *Radio Sci (USA)*, 34 (1999) pp 949–966, doi: 10.1029/1999RS900034.

25 Syndergaard S, Schreiner W S, Rocken C, Hunt D C & Dymond K F, Preparing for COSMIC: Inversion and analysis of ionospheric data products, in *Atmosphere and climate: Studies by occultation methods,* edited by U Foelsche, G Kirchengast & A K Steiner (Springer, Berlin, Germany), 2006, pp 137–146.

26 Schreiner W, Rocken C, Sokolovskiy S, Syndergaard S & Hunt D, Estimates of the precision of GPS radio occultations from the COSMIC/FORMOSAT-3 mission, *Geophys Res Lett (USA)*, 34 (2007) L04808, doi: 10.1029/2006GL027557.

27 Burke W J, Huang C Y, Gentile L C & Bauer L, Seasonal/longitudinal variability of equatorial plasma bubbles, *Ann Geophys (Germany)*, 22 (2004) pp 3089–3098, http://www.ann- eophys.net/22/3089/2004/.

28 Subbarao K S V & Krishna Murthy B V, Seasonal variations of equatorial spread F, *Ann Geophys (Germany)*, 12 (1994) pp 33-39.

29 Raghavarao R, Hoegy W R, Spencer N W & Wharton L, Neutral temperature anomaly in the equatorial thermosphere: A source of vertical winds, *Geophys Res Lett (USA)*, 20 (1993) 1023.

30 Sekar R & Raghavarao R, Role of vertical winds on the Rayleigh-Taylor instabilities of the night time equatorial ionosphere, *J Atmos Terr Phys (UK)*, 49 (1987) 49, 981.

31 Kelley M C, *The Earth's ionosphere: Plasma physics and electrodynamics* (Elsevier, New York), 1989.