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Morphology of *F*-region vertical *E*×*B* drifts in the African sector using ionosonde measurements

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Abstract
F-region vertical velocities are derived from the ground-based ionosonde data for Ibadan (7.4°N, 3.9°E; dip 6°S: an equatorial station in the African zone), to study the general characteristics of electrodynamics of equatorial ionosphere, such as their variation with season, solar cycle, and magnetic activity at different local time sectors. The results show profound seasonal and geomagnetic effects. Except for equinoctial period, there is an excellent consistency in the magnitudes (nearly 20 m/s) and patterns of upward daytime *F*-region drifts at low and high solar activity periods. Evening *F*-region exhibits strong motion with absolute mean value for quiet-time (15 m/s) greater than on disturbed-time (10 m/s). The average downward quiet midnight-early morning hours sector value is well below than 10 m/s. The evening reversal time is earliest and latest during solstitial periods. Prereversal peak is season dependent and varies strongly with magnetic activity. We show that prereversal peak, daytime, and nighttime maximum drifts saturate at particular values of *F*10.7 cm solar radio flux index, effects not noticed with corresponding sunspot number. Our observations confirm several previous results from other equatorial sites utilizing different experimental techniques.

Key words *equatorial* F*-region – ionospheric variability – ionospheric modelling – ionosonde observations – ionospheric dynamics*

1. Introduction

The nature of ionospheric plasma motions in the *F*-region at the magnetic equator is such that they are driven by the neutral air wind along the Earth's magnetic field and by the electric field in the plane perpendicular to it. Accordingly, measurements of vertical plasma drifts in the equatorial *F*-region are a valuable means of deriving information on the electric field. The plasma drifts, however, in the equatorial zone significantly affect the morphology of the equatorial *F*-region, the evolution of the Appleton anomaly, the latitudinal variation of thermospheric neutral winds, and the low-latitude protonospheric ion composition (Fejer and Scherliess, 1997). Furthermore, equatorial *E*×*B* drift velocities are significant input parameters that go into many ionospheric models, because they help describe vertical plasma motion near the magnetic equator. In the evening sector, vertical drifts are of particular significance as they are the major drivers for the generation of Equatorial Spread *F* (ESF) (Fejer *et al.*, 1999; Martinis *et al.*, 2005).

The quiet time low-latitude plasma drifts are driven by a complex interaction of *E*- and *F*-region electrodynamic processes (Richmond, 1995). The relative efficiency of these dynamo mechanisms varies significantly with the time of day, from day to day, and also with season, solar cycle, and longitude. Theoretical and numerical

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models that explain the low-latitude dynamo electric fields and currents are plentiful (Rishbeth, 1971; Heelis *et al.*,1974; Richmond *et al.*, 1976; Anderson and Mendillo, 1983; Takeda and Maeda, 1983; Farley *et al.*, 1986; Takeda and Yamada, 1987; Kelley, 1989; Haerendel and Eccles, 1992; Eccles, 1998). During geomagnetic active conditions magnetospheric and disturbance dynamo effects can dramatically affect the low-latitude drifts (Fejer and Scherliess, 1997, and references therein; Scherliess and Fejer, 1997; Kelley *et al.*, 2003).

A prereversal peak in the upward velocity in the dusk sector is the most common feature during solar cycle maximum years (Woodman, 1970). This phenomenon occurs just before the *F*-region vertical plasma drift reverses from upward (positive) to downward (negative) direction. Prereversal velocity enhancement is believed to be caused by the very rapid decrease in the *E*-region conductivity after sunset compared to that of the *F*-region (Farley *et al.*, 1986). The evening upward velocity enhancement is responsible for the rapid rise of the equatorial *F*-layer after sunset, which plays an important role in the generation of *E*- and *F*-region plasma instabilities (Fejer and Kelley, 1980; Fesen *et al.*, 2000).

Nevertheless, on the basis of extensive data from various experimental observation techniques, climatological regional models of the equatorial plasma drifts in the Peruvian, Brazilian, and Indian sectors have been developed. Global empirical models for the quiet time *F*-region equatorial vertical drifts have been reported (Richmond *et al.*, 1980; Scherliess and Fejer, 1999). Additionally, a study carried out by Anderson *et al.* (2002) showed that daytime measurement of the difference between the horizontal component of the magnetic field at an equatorial and a slightly off-equatorial station can be used to infer the equatorial vertical $E \times B$ drift (eastward electric field). Thus, equatorial and low-latitude studies indicate that under quiet magnetic conditions, to first order, the *F*-region electrodynamic plasma drifts are upward and westward during the day and downward and eastward at night. However, these probing techniques for investigating the bottomside ionospheric plasma give generally consistent equatorial vertical drift velocities, but often contradictory patterns are reported.

Unfortunately, most of these experimental observations of *F*-region plasma drifts described above are available only from a few locations at limited times in the African sector of the equatorial ionosphere. This remarkably sparse database in the African region is a major deficiency in global low latitude ionospheric modeling studies.

This study used ground-based ionosonde data obtained near the magnetic equatorial station in Africa (7.4°N, 3.9°E, dip. lat. 6°S) to investigate the general characteristics of *F*-region vertical plasma drifts, such as variation with local time, season, solar cycle, and magnetic activity.

2. Date sets and method of analysis

The first data set consists of a half-hourly data record (called ionogram) obtained during the daytime from 07:30-18:30 LT sector. Five international quiet day ionograms from each month of the year were picked for the investigation. We ensured that the data chosen were good enough to be scaled, and magnetic storm days were avoided. The records were manually analysed using a ten-point Kelso (1952) method to obtain electron density profiles at half a hour intervals. Results of comparisons between automatically and manually scaled data have been reported to be in excellent agreement (Renisch and Huang, 1983; Pezzopane and Scotto, 2004, 2005). Already, Iheonu and Oyekola (2006) have proposed a model description, obtained from a simplified electron continuity equation, for estimating daytime vertical $E \times B$ drift velocities in the equatorial *F*-region ionosphere. The model calculation is valid away from the peak of the *F*-layer, the formula is expressed as

$$V_z = \frac{H_p(h)\, q(h,\chi)}{N_e(t,h)} - H_p(h)\beta(h) \qquad (2.1)$$

where $H_p(h)$ represents plasma scale height, a function of height, $q(h, \chi)$ represents the rate of ionization production per unit volume and so is a function of both height and solar zenith distance, χ. The production rate is estimated from the

«Chapman Theory» (Chapman, 1931). $N_e(t,h)$ represents electron density at altitude, h and time t, obtained from $N_e(h)$ profiles. $\beta(h)$ is the loss coefficients, a function of height, calculated from the expression given by Ratcliffe and Weeks (1960). The product $H_p(h)\beta(h)$ is the apparent vertical drift velocity due to chemical recombination. Thus, we use eq. (2.1) to compute the vertical velocities during the daytime. Accordingly, the vertical plasma drifts are divided into 2 solar activity, and 3 seasonal divisions under quiet geomagnetic condition during the daytime. January through December 1958 (era of International Geophysical Year, IGY) comprises solar maximum with the averaged yearly $F10.7$ radio flux value of 208 (in units of 10^{-22} W/m^2/Hz) and the mean yearly sunspot number of 185. January to December 1964 comprises solar minimum with averaged yearly decimentric solar flux of 65 and the mean annual sunspot number of 9.3.

F-region vertical drifts are also estimated from the $h'F$ variations for the equatorial station Ibadan from one year of data during 1958 period, which comprises the second dataset. This method has been used for several years to calculate vertical motion of the equatorial ionosphere in the Peruvian, Brazilian, and Indian sectors (*e.g.*, Abdu *et al.*, 1981; Bittencourt, 1986; Sastri *et al.*, 1995), but such estimate has not been carried out at Ibadan longitude sector. The technique is often limited to the evening hours when the F-region bottomside altitude rises beyond 300 km (Fejer *et al.*, 1989; Jayachandran *et al.*, 1993; Subbarao and Krishna Murthy, 1994). In this case, our data are divided, according to 4 seasonal and 2 geomagnetic activity divisions at solar maximum. The months of the year are grouped as follows: March equinox (January, February, March), June solstice (April, May, June), September equinox (July, August, September), and December solstice (October, November, December). $Kp \leq 3$ comprises quiet geomagnetic conditions and $Kp > 3$ comprises disturbed condition.

3. Results

Seasonal averages of the vertical component of the equatorial F-region plasma drifts as derived from ionosonde data at Ibadan during January to December 1964 (solar minimum), and January to December 1958 (solar maximum) under quiet magnetic conditions are plotted in fig. 1. Standard deviations are shown as error bars on the two data sets in each panel. $F10.7$ index (the solar radio flux at a wavelength of 10.7 cm at Earth's orbit) are in the range 62-65, and 184-224 (in flux units) during low and high solar epoch, respectively. Figure 1 indicates the classical behaviour for the vertical component of the equatorial F-region plasma drift velocity. It is upward during the daytime for low and high solar activity periods. As can be seen, except for equinoctial periods, there is an excellent consistency in the variability pattern of upward daytime F-region drifts during low and high solar flux conditions. The average value of upward daytime F-region plasma drifts for solar minimum equinox (top panel) (~18.6 m/s) is smaller than that of solar maximum equinox

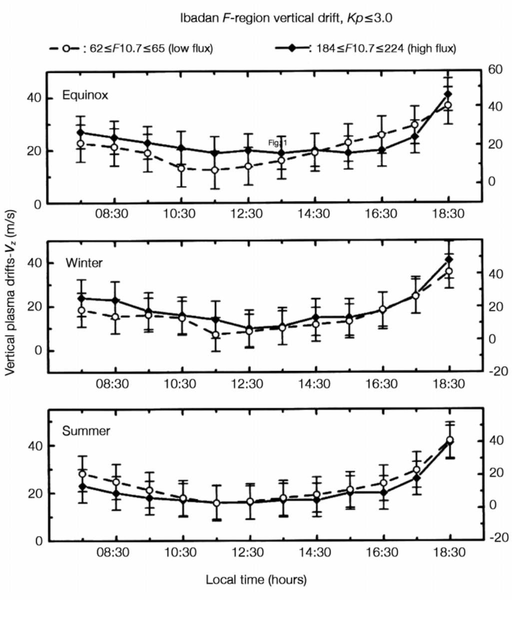

Fig. 1. Average daytime F-region vertical plasma drifts obtained for three different seasons from Ibadan ionosonde data during 1964 low solar activity (right verical axis) and 1958 high solar activity (left vertical axis) under quiet magnetic condition. The vertical bar indicates the standard deviation about the mean.

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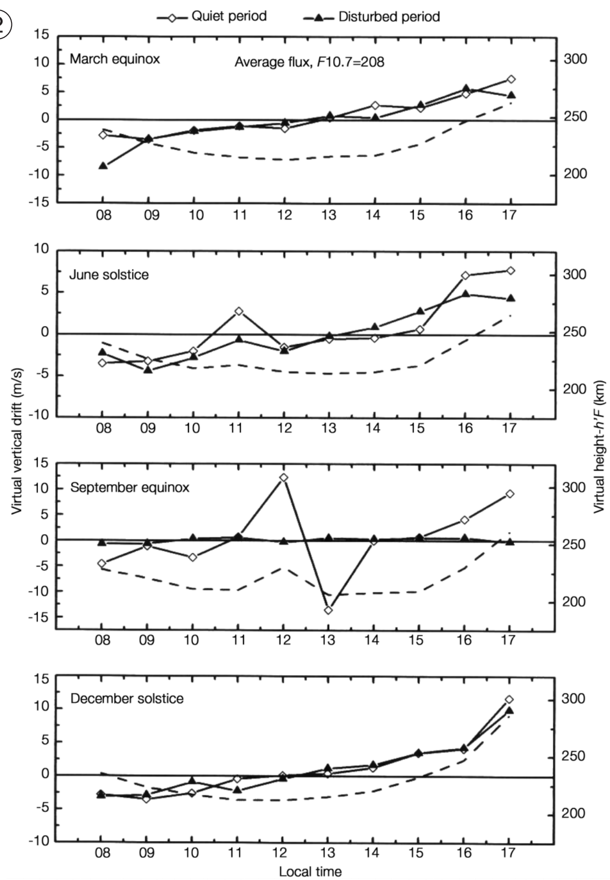

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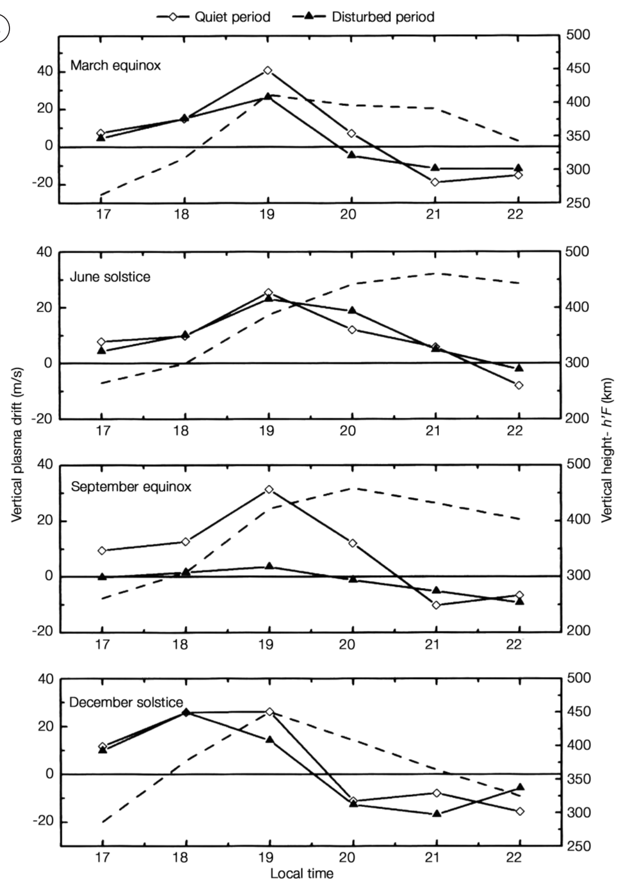


Fig. 2. Examples of diurnal and seasonal variations of vertical virtual velocity deduced from ionosonde data at Ibadan in the *F*-region during daytime high solar flux conditions for quiet and disturbed periods. 1957/1958 International Geophysical Year (IGY) data was used. The dashed curve (right verical axis) gives the mean variation of the reflecting (*h'F*) layer.

Fig. 3. Ibadan evening *F*-region average vertical plasma drifts derived from ionosonde observations for the three-month seasonal periods during undisturbed and disturbed high solar activity conditions. 1957/1958 International Geophysical Year (IGY) data are used. The dashed curve (right vertical axis) gives the mean variation of the reflecting (*h'F*) layer.

(~23.3 m/s). Solar minimum winter data (middle panel) (~15 m/s) is also notably lower than solar maximum winter value (~19.1 m/s). On the other hand, low solar flux summer (bottom panel) magnitude (~13.8 m/s) is much lower than high solar flux summer (~20.9 m/s). The average daytime upward vertical drift velocity is nearly 16 m/s and 20 m/s during low and high solar activity, respectively.

Figure 2 shows 3-month seasonal periods of daytime *F*-region averaged virtual vertical velocities deduced from the virtual height changes in the time during quiet and disturbed geomagnetic conditions. The dashed curve on the right vertical axis gives the mean variation of the height of reflecting layer. The figures show that except for disturbed September equinox drift, which is about zero drift (~0 m/s) throughout the daytime and short fluctuations between 11:00-14:00 LT in the corresponding quiet September equinox vertical velocity; the average virtual vertical velocities exhibit similar morphological pattern of variability. The variation appears as negative velocities (downward) in the morning sector and increases gradually until the drift reverses direction gently at about 13:00 LT in all seasons. Notice that the velocity does not exceed 5 m/s either downward or upward from 08:00-16:00 LT. These weak velocities were observed by Blanc and Houngninou (1998) during the International Equatorial Electrojet Year (1993-1994) in Africa (Korhogo: 9.24°N, 5.4°W, dip. 4°S), Ivory-Coast, using high resolution multi-frequency *HF* Doppler radar measurements in the upper *F*-region during daytime on 21, 27, 30 May 1993.

The results on diurnal, seasonal, and magnetic variations in the vertical drifts are presented in fig. 3. The dashed curve on the right vertical axis gives the mean variation of reflecting layer. Again, apart from disturbed September equinox vertical drifts, which ~0 m/s throughout the entire period; the trends for both datasets in each season are similar. Figure 3 shows that the vertical drifts on all the seasons are characterized by upward enhancement followed by a downward reversal. The enhancements have peak velocity in the range 25-40 m/s and occur at around 19:00 LT during quiet period. The average quiet evening prereversal peak *E*×*B* drift is typically 30 m/s and occurs at 19:00 LT. Conversely, the values of prereversal peak velocity during disturbed March equinox and June solstice are 26 m/s and 23 m/s, respectively; whereas for September equinox, it is absolutely insignificant, while December solstice it is much smaller than 20 m/s. Figure 3 also indicates that geomagnetic activity effect (as determined by the *Kp* index) on the vertical plasma drifts show a noticeable season dependency. The late afternoon to evening sector seasonal average values for magnetically quiet periods are consistently larger than on disturbed periods. The estimated mean magnitude of the drifts for quiet periods are ~17.4 m/s, ~11.5 m/s, ~13.7 m/s, and ~16.4 m/s for March equinox, June solstice, September equinox, and December solstice, respectively, while the absolute average values for disturbed March equinox, June solstice, September equinox, and December solstice drifts are 12.4 m/s, 10.6 m/s, 3.5 m/s, and 14.2 m/s, in that order. The reversal time is latest during the June solstice months for quiet and disturbed drifts and earliest in all other seasons. The most regular feature of all the curves is the gradual reversal of drifts. It is noteworthy to see that the vertical drifts reverse direction during the periods of high *F*-layer heights. The average virtual height of the bottomside *F*-layer (*h'F*) is lifted as high as 412 km at 19:00 LT (March equinox), 461 km at 21:00 LT (June solstice), 459 km at 20:00 LT (September equinox), and 450 km at 19:00 LT (December solstice). Certainly, we can say that the post-sunset heights observed here appear to be meaningful threshold values needed to seed ESF.

Figure 4 illustrates the behaviors of vertical drifts data in the midnight to early morning sector. The vertical bars are calculated standard deviations about the mean. The dashed curve yet again (right vertical axis) gives the mean variation of the height of reflecting layer. Figure 4 indicates noticeable variability in the occurrence patterns of vertical plasma drifts even between equinoctial and solstitial seasonal periods. Generally, quiet and disturbed vertical drift velocities are characterized by variations in the downward direction during the entire period until the drifts reverse to upward direction at about 05:00 LT, except June solstice drift data, which reverse upward at 23:00 LT followed by

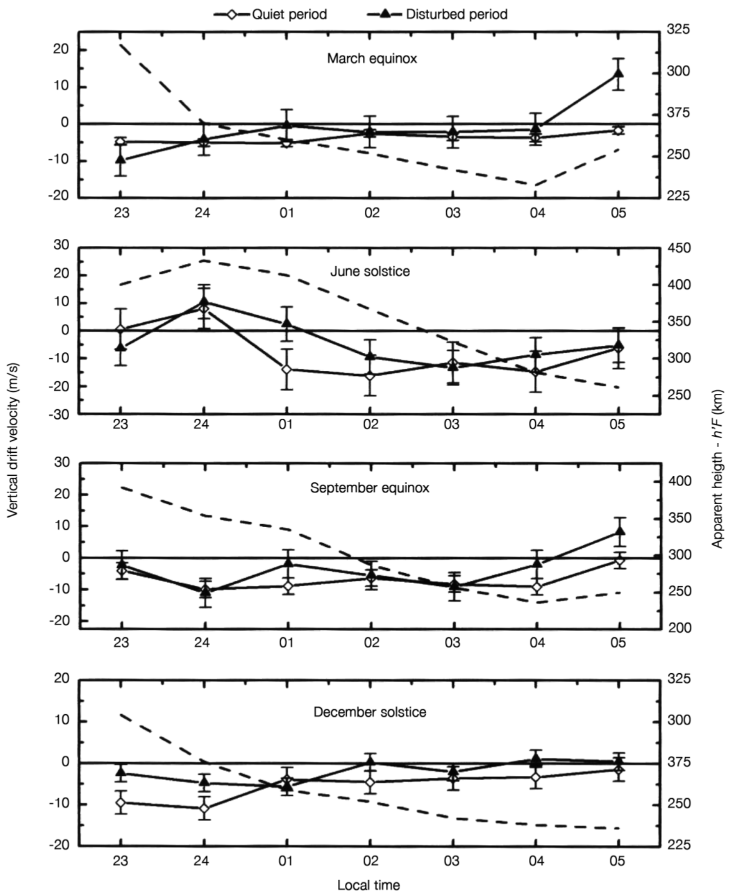
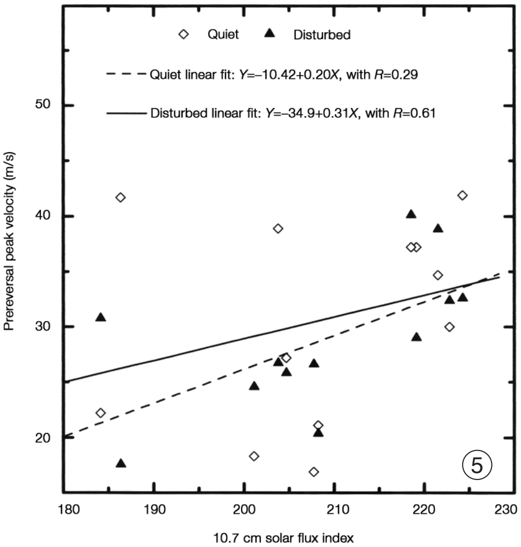


Fig. 4. Ibadan nighttime *F*-region average vertical plasma drifts derived from ionosonde observations for the three-month seasonal periods during undisturbed and disturbed high solar activity periods. The vertical bars are calculated absolute standard deviations about the mean. The dashed curve (right vertical axis) gives the mean variation of reflecting layer. 1957/1958 IGY data are used.

a gentle downward reversal at midnight. Magnetic activity effects are also apparent on the vertical plasma drift velocity, particularly between midnight to 02:00 LT in June solstice. The average downward nighttime drift velocity is as low as ~4 m/s (March equinox) and as high as ~12 m/s (June solstice) during quiet period.

Evening *F*-region prereversal upward velocity peaks as a function of *F*10.7 cm solar flux index for both quiet and disturbed magnetic activity is displayed in fig. 5. The best fits to the data are also shown. The drifts values correspond to monthly averaged values of *F*10.7 cm. The slopes relating prereversal peak velocity to *F*10.7 during quiet period are about 36% smaller than during disturbed magnetic activity, but the correlation coefficient value is also approximately 52% smaller during quiet period than disturbed time. Furthermore, the prereversal peak velocity appears to saturate around 185, 205, and 220 (in solar flux units). Figure 6 further illustrates the dependence of prereversal peak $E{\times}B$ drift on solar and magnetic activity. Here, the slopes connecting the evening *F*-region prereversal upward



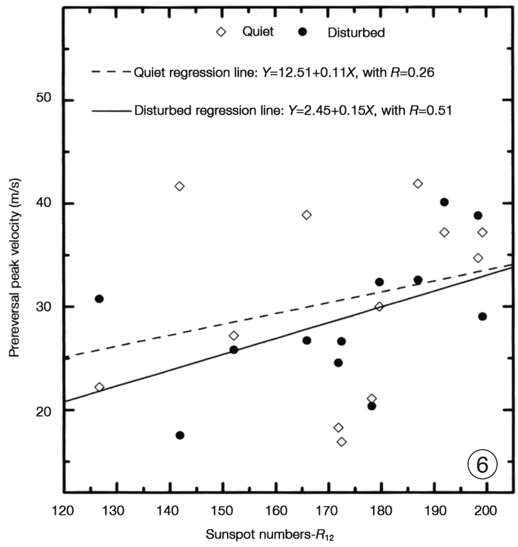


Fig. 5. Evening *F*-region prereversal upward velocity peaks as a function of solar flux for both quiet and disturbed magnetic activity. The monthly values of velocity peaks correspond to the monthly mean values of solar flux. Linear fits to the data are shown.

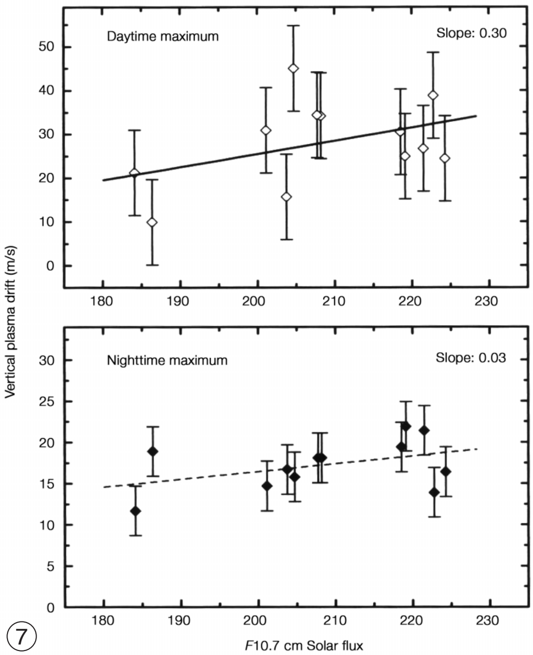
Fig. 6. Evening *F*-region prereversal upward velocity peaks as a function of sunspot numbers for both quiet and disturbed magnetic activity using the same format as in fig. 5.

velocity peaks to monthly averaged sunspot number (R_{12}) during magnetically quiet period is just about 27% smaller than during magnetically active period, while the regression coefficient is nearly 49% lower in value during quiet time than disturbed time.

Figure 7 compares peak upward daytime (upper panel) and peak downward nighttime (bottom panel) vertical velocity patterns *versus* *F*10.7 solar flux index during quiet magnetic conditions. Notice that the monthly values of maximum velocities correspond to the monthly average values of solar index. The first feature to note in fig. 7 is that the vertical drifts saturate around the *F*10.7 values mentioned for fig. 5 during both the daytime and nighttime periods. The slopes of the lines are different by about 90%. Such a much larger discrepancy clearly points to a reasonable confirmation of solar influence on maximum upward daytime *F*-region plasma drifts variability. Maximum upward daytime and downward nighttime vertical drifts *versus* sunspot numbers using the format as in fig. 7 are shown in fig. 8. The situation is rather different, however, from the variability pattern of maximum vertical drifts obtained with solar flux. Vertical plasma drifts vary around their monthly averaged upward daytime value of approximately 28 m/s (±9.76 m/s) (the upper panel), while peak downward nighttime drifts vary about their monthly mean magnitude of nearly 18.7 m/s (±5 m/s) (the bottom panel), where the values in the brackets indicate standard deviations of the mean. The slopes relating maximum vertical drifts with sunspot numbers during daytime and nighttime periods are consistent at ~0.1.

4. Discussion

The data presented above clearly described the general patterns of *F*-region vertical plasma drifts at different local time sectors, seasons, so-



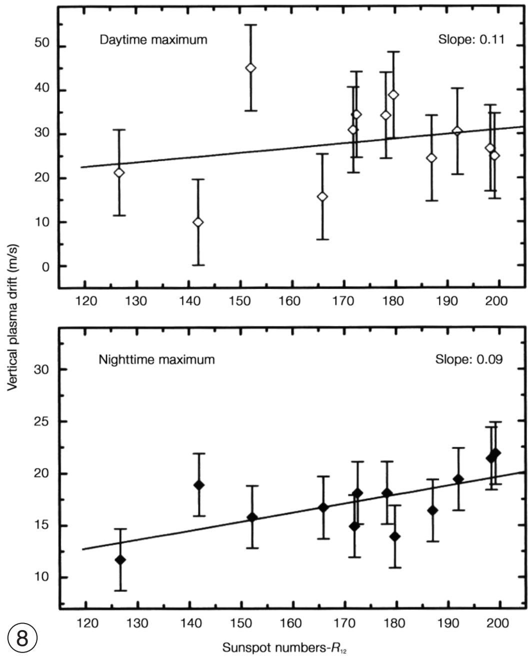


Fig. 7. Dependence of the peak upward daytime (upper panel) and peak downward nighttime (bottom panel) vertical velocity on the 10.7 cm solar flux during quiet magnetic condition. Notice that the monthly values of velocity peaks correspond to the monthly mean.

Fig. 8. Maximum upward daytime and downward nighttime vertical drifts *versus* sunspot numbers using the same format as in fig. 7.

lar activity, and geomagnetic activity periods. The study considered vertical drifts as the key parameter determining the dynamics of ionospheric *F*-region, and of course the occurrence of ESF. Indeed, earlier results cited in Section 1 have pointed out a clear relation between the magnitude of the prereversal enhancement and occurrence of postsunset ESF: irregularities are more likely to develop when a strong prereversal enhancement is present. The strength will depend on the prevailing geophysical conditions, *e.g.*, at solar maximum, a threshold level of ~50 m/s is required, while during solar minimum it is reduced to ~20 m/s (Fejer *et al.*, 1999). Subbarao and Krishna Murthy (1994) using coherent *HF* radar data covering 28 days of observation spread over the period 1973-1976 during the late afternoon-early evening sector in the India equatorial region, reported that the mean value of peak velocity on nights with spread *F* (34.4 m/s) is rather greater than on nights without spread *F* (29.2 m/s). In their study, solar activity (*F*10.7 cm flux) was in the range 75-107 (in solar flux units), representative of low solar activity period. In the present study, a vertical plasma drift of ~30 m/s seems to be a meaningful threshold value needed to trigger ESF. A careful comparison of values of the enhancement peak drifts quoted above, instantly discloses that solar activity appears not to have important effect on the threshold value of vertical plasma drift required for the onset of ESF.

Moreover, during geomagnetically quiet periods, the equatorial vertical plasma drifts result from the combined effects of *E*- and *F*-region magnetic field line-integrated thermospheric winds weighted by the integrated Pedersen conductivity. Richmond (1994) pointed out that quiet-time ionospheric variability is probably associated with irregular day-to-day variation due to short term changes in tidal forcing, the effects of planetary waves and irregular winds in the dynamo region, and changes in the dynamic conditions at the base of the thermosphere. Different types of upward coupling from neutral atmosphere dynamics are perhaps the major sources yet unknown of quiet-time *F*-region vertical drift variability. However, at magnetically disturbed times, two major sources of drift perturbations are found in the magnetospheric and ionospheric disturbance dynamo. Electrodynamical mechanisms of magnetospheric dynamo processes are found in the work of Martinis *et al.* (2005, and the references therein).

The ionospheric disturbance dynamo, on the other hand, results from thermospheric disturbance wind generated by Joule heating at auroral latitudes during periods of high magnetic activity (Blanc and Richmond, 1980; Richmond *et al.*, 2003). These disturbance winds affect the low-latitude region several hours after the increase in magnetic activity. These winds are equatoward of region 2 current and any electric fields they generate are not shielded from the low-latitude ionosphere. They produce changes in the ionospheric dynamo (long lived effects) that are more persistent than those associated with the magnetospheric dynamo (prompt effects).

The high latitude electric field should penetrate most efficiently into the equatorial ionosphere near dusk and in the post midnight to early morning hours (Fejer *et al.*, 1989). The most frequent and largest equatorial drift perturbations are downward during the day and upward at night (Gonzales *et al.*, 1979; Fejer 1986). At equatorial latitudes, gravity waves have been found to play an important role in the formation of the equatorial spread *F* (Hysell *et al.*, 1990). Blanc and Houngninou (1998), using high-resolution *FH* radar during the 1993-1994 International Equatorial Electrojet Year (IEEY), found that the amplitude of gravity wave is variable from day-to-day and does not depend on the magnetic conditions. The wave activity was even strong on magnetic quiet conditions. They reported that the wave characteristics are periods in the range 5-30 min, and a downward phase velocity (during the daytime) of the order of 80 m/s at altitudes of 240-280 km, appearing as a phase delay at lower radar frequencies, hence at lower altitudes. Millard *et al.* (2001), using a Coupled Thermosphere-Ionosphere-Plasmasphere (CTIP) model showed the importance of lower thermospheric tidal forcing on the daytime vertical ion drifts.

5. Conclusions

F-region vertical plasma drift velocities derived from ionosonde observations at Ibadan have been utilized to examine the morphology of vertical plasma drifts with season, solar cycle, and magnetic activity at various local time sectors. The *F*-region drifts show the largest variations in the evening and nighttime periods. The daytime vertical plasma drift occurrence patterns during high and low solar activity periods were essentially identical, except for the equinox season. The evening reversal time from upward daytime to downward nighttime is earliest and latest during solstitial seasonal periods. Our results suggest that the daytime *F*-region drifts and, therefore, the corresponding *E*-region electric fields and neutral winds are nearly independent of solar variability. The evening prereversal enhancement, daytime and nighttime peaks drifts seem to saturate for large solar intensity values. Finally, some results (*e.g.*, Fejer *et al.*, 1989, 1991; Balan *et al.*, 1992; Hari and Krishna Murthy, 1995; Ramesh and Sastri, 1995) obtained for the equatorial region in the India and South American sectors were confirmed in this study.

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REFERENCES

ABDU, M.A., J.A. BITTENCOURT and I.S. BATISTA (1981): Magnetic declination control of the equatorial *F*-region dynamo electric field development and spread *F*, *J. Geophys. Res.*, **86**, 11443-11446.

ANDERSON, D.N. and M. MENDILLO (1983): Ionospheric conditions affecting the evolution of equatorial plasma depletion, *Geophys. Res. Lett.*, **10**, 541-544.

ANDERSON, D., A. ANGHEL, K. YUMOTO, M. ISHITSUKA and E. KUDEKI (2002): Estimating daytime vertical *E*×*B* drift velocities in the equatorial *F*-region using ground-based magnetometer observations, *Geophys. Res. Lett.*, **29** (12), 1596, doi: 10. 1029/2001GL014562.

BALAN, N., B. JAYACHANDRAN, R.B. NAIR, S.P. NAMBOOTHIRI, G.J. BAILEY and P.B. RAO (1992): *HF* Doppler observations of vector plasma drifts in the evening *F*-region at the magnetic equator, *J. Atmos. Terr. Phys.*, **54**, 1545-1554.

BITTENCOURT, J.A. (1986): Equatorial *F*-region vertical plasma drift: seasonal and longitudinal asymmetries in American sector, *J. Geophys. Res.*, **91**, 12055.

BLANC, E. and E. HOUNGHINOU (1998): Typical disturbances of the daytime equatorial *F*-region observed with a high-resolution *HF* radar, *Ann. Geophysicae*, **16**, 721-730.

BLANC, M. and A. RICHMOND (1980): The ionospheric disturbance dynamo, *J. Geophys. Res.*, **85**, 16669.

CHAPMAN, S. (1931): The absorption and dissociative or lionizing effect of monochromatic radiation in an atmosphere on a rotating Earth, *Proc. Phys. Soc.*, **43**, 26-45.

ECCLES, J.V. (1998): A simple model of low latitude electric fields, *J. Geophys. Res.*, **103** (A11), 26699-26708.

FARLEY, D.T., E. BONELLI, B.G. FEJER and M.F. LARSEN (1986): The prereversal enhancement of the zonal electric field in the equatorial ionosphere, *J. Geophys. Res.*, **91**, 13723-13728.

FEJER, B.G. (1986): Equatorial ionospheric fields associated with magnetospheric disturbances, in *Solar Wind-Magnetosphere Coupling* (Reidel, Terrapub, Tokyo), 519-545.

FEJER, B.G. and M.C. KELLEY (1980): Ionospheric irregularities, *Rev. Geophys. Space Phys.*, **18**, 401-454.

FEJER, B.G. and L. SCHERLIESS (1997): Empirical models of storm-time equatorial zonal electric fields, *J. Geophys Res.*, **102**, 24047-24056.

FEJER, B.G., E.R. DE PAULA, I.S. BATISTA, E. BONELLI and R.F. WOODMAN (1989): Equatorial *F*-region vertical plasma drifts during solar maximum, *J. Geophys. Res.*, **94**, 12049-12054.

FEJER, B., L. SCHERLIESS and E.R. DE PAULA (1999): Effects of the vertical plasma drift velocity on the generation and evolution of equatorial spread *F*, *J. Geophys. Res.*, **104** (A9), 19859-19869.

FESEN, C., G. CROWLEY, R. ROBLE, A. RICHMOND and B.G. FEJER (2000): Simulation of the prereversal enhancement in the low latitude vertical ion drifts, *Geophys. Res. Lett.*, **27** (13), 1851-1854.

GONZALES, C., M. KELLEY, B. FEJER, J.V. VICKREY and R.F. WOODMAN (1979): Equatorial electric fields during magnetically disturbed conditions: implications of simultaneous auroral and equatorial measurements, *J. Geophys. Res.*, **84**, 5803-5812.

HAERENDEL, G. and J.V. ECCLES (1992): The role of the equatorial electrojet in the evening ionosphere, *J. Geophys. Res.*, **97**, 1181-1197.

HARI, S.S. and B.V. MURTHY (1995): Equatorial nighttime *F*-region zonal electric fields, *Ann. Geophysicae*, **13**, 871-878.

HEELIS, R.A., P.C. KENDALL, R.J. MOFFELT, D.W. WINDLE and H. RISHBETH (1974): Electrical coupling of the *E*- and *F*-regions and its effects on *F*-region drifts and winds, *Planet. Space Sci.*, **22**, 743-756.

HYSELL, D.L., M.C. KELLEY, W.E. SWARTZ and R.F. WOODMAN (1990): Seeding and layering of equatorial spread *F* by gravity waves, *J. Geophys. Res.*, **95**, 17253-17260.

IHEONU, E.E. and O.S. OYEKOLA (2006): Vertical drift velocity in the daytime *F*-region at Ibadan estimated from ionosonde data, *Indian J. Radio Space Phys.*, **35**, 9-13.

JAYACHADRAN, B.N. BALAN, P.B. RAO, J.H SUSTRI and G.J. BAILEY (1993): *HF* Doppler and ionosonde observations on the onset conditions of equatorial spread *F*, *J. Geophys. Res.*, **98**, 13741-13750.

KELLEY, M.C. (1989): *The Earth's Ionosphere* (Academic, San Diego, Calfornia), pp. 487.

KELLEY, M.C., J.J. MAKELA, J.L. CHAU and M.J. NICOLLS (2003): Penetration of the solar wind electric field into the magnesphere/ionosphere system, *J. Geophys. Res. Lett.*, **30** (4), 1158, doi: 10.1029/2002GL016321.

KELSO, J.M (1952): A procedure for the determination of the vertical distribution of the electron density in the ionosphere, *J. Geophys. Res.*, **57**, 357-367.

MARTINIS, C.R., M.J. MENDILLO and J. AARONS (2005): Toward a synthesis of equatorial spread *F* onset and suppression during geomagnetic storms, *J. Geophys. Res.*, **110**, 7306-7319.

MILLWARD, G. H., I. C. F. MULLER-WODARG, A. D. AYLWARD, T. J. FULLER-ROWELL, A. D. RICHMOND and R.J. MOFFETT (2001): An investigation into the influence of tidal forcing on *F*-region equatorial vertical ion drift using a global ionophere-thermosphere model with coupled electrodynamics, *J. Geophys. Res.*, **106**, 24733-24744.

PEZZOPANE, M. and C. SCOTTO (2004): Software for the automatic scaling of critical frequency *foF*2 and MUF(3000)*F*2 from ionograms applied at the Ionospheric Observatory of Gibilmanna, *Ann. Geophysics*, **47** (6), 1783-1790.

PEZZOPANE, M. and C. SCOTTO (2005): The INGV software for the automatic scaling of *foF*2 and MUF(3000)*F*2 from ionograms: a performance comparison with ARTIST 4.01 from Rome data, *J. Atmos. Solar-Terr. Phys.*, **67**, 1063-1073.

RAMESH, K.B. and J.H. SASTRI (1995): Solar cycle and seasonal variation in *F*-region vertical drifts over Kodaikanal, India, *Ann. Geophysicae*, **13**, 633-638.

RATCLIFFE, J.A. and K. WEEKS (1960): *Physics of the Upper Atmosphere* (Academic, San Diego, California), pp. 586.

RENISCH, B.W. and X. HUANG (1983): Automatic calculation of electron density profiles from digital ionograms 3. Processing of bottomside ionograms, *Radio Sci.*, **18** (3), 477-492.

RICHMOND, A.D. (1994): The ionospheric wind dynamo: effects of its coupling with different atmospheric regions. in *The Upper Mesosphere and Lower Thermosphere*, edited by R.M. JOHNSON and T.L. KILLEEN (American Geophysical Union, Washington, DC).

RICHMOND, A.D. (1995): Modeling equatorial ionospheric electric fields, *J. Atmos. Terr. Phys.*, **57**, 1103-1115.

RICHMOND, A.D., S. MATSUSHITA and J.D. TARPLEY (1976): On the production mechanism of electric currents and fields in the ionosphere, *J. Geophys. Res.*, **81** (4), 547-555.

RICHMOND, A. D., M. BLANC, B. A. EMERY, R. H. WAND, B. G. FEJER, R. F. WOODMAN, S. GANGULY, P. AMAYENC, R.A. BEHNKE, C. CALDERON and J.V. EVANS (1980): An empirical model of quiet-day ionospheric electric fields at middle and low latitudes, *J. Geophys. Res.*, **85** (A9), 4658-4664.

RICHMOND, A., C. PEYMIRAT and R. ROBLE (2003): Long-lasting disturbances in the equatorial ionospheric electric field simulated with a coupled magnetosphere-ionosphere-thermosphere model, *J. Geophys. Res.*, **108** (A3), 1118, doi: 10.1029/2002JA009758.

RISHBETH, H. (1971): Polarization fields produced in the equatorial *F*-region, *Planet. Space Sci.*, **19**, 357-369.

SASTRI, J.H., V.K. MEENA VARNA and S.R. PRABHAKARAN NAYAR (1995): Height gradient of *F*-region vertical drift in the evening equatorial ionosphere, *Geophys. Res. Lett.*, **20**, 2645-2649.

SCHERLIESS, L. and B.G. FEJER (1997): Storm-time dependence of equatorial dynamo zonal electric fields, *J. Geophys. Res.*, **102**, 24037-24046.

SCHERLIESS, L. and B.G. FEJER (1999): Radar and satellite global equatorial *F*-region vertical drift model, *J. Geophys. Res.*, **104**, 6829-6842.

SUBBARAO, K.S.V. and B.V. KRISHNA MURTHY (1994): Post-sunset *F*-region vertical velocity variation at magnetic equator, *J. Atmos. Terr. Phys.*, **56**, 59-65.

TAKEDA, M. and H. MAEDA (1983): *F*-region in the evening-interpretation of equatorial *D* anomaly found by Magsat, *J. Atmos. Terr. Phys.*, **45**, 401-408.

TAKEDA, M. and Y. YAMADA (1987): Simulation of ionospheric electric fields and geomagnetic field variation by the ionospheric dynamo for different solar activity, *Ann. Geophysicae*, **5A**, 429-434.

WOODMAN, R.F. (1970): Vertical drift velocities and east-west electric fields at the magnetic equator, *J. Geophys. Res.*, **75**, 6249-6259.

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