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The F-Region Equatorial Ionospheric Electrodynamics Drifts

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Abstract

The ionospheric plasma drift is one of the most essential parameters for understanding the dynamics of ionospheric F-region. F-region electromagnetic drifts are calculated for three seasonal conditions from ionosonde observations acquired during quiet period of a typical year of high and low solar activity at Ibadan (7.4^{o}N, 3.9^{o}E, dip 6^{o}S), Nigeria. The vertical plasma drifts derived from h' (f) ionosonde data are compared with vertical drifts obtained by incoherent scatter radar and AE-E satellite measurements during nighttime periods under similar solar and geomagnetic conditions. We find comparable variability among the ionosonde drifts at Ibadan, Jicamarca VHF radar drifts, and AE-E satellite drifts during high solar flux and geomagnetic quiet conditions at equinox and solstices periods. The equinoctial average evening upward drifts enhancements by the three methods are roughly similar and occur at the same local time (19 LT) for all the seasons. Additionally, the evening reversal time from upward daytime to downward nighttime does not vary much except during the winter months; and occurs earliest in summer and equinox, but least during winter period. Also the data indicate asymmetry of evening reversal times about the dip-equator between the Peruvian, Indian, and the African equatorial regions. Our observations are in conformity with some results obtained at other equatorial ionospheric stations

Keywords: equatorial-ionosphere; Plasma-drift; F-region; Ionospheric-variability; Solar-activity

1.0 Introduction
1.1 Background

The altitudinal variation of the ionospheric plasma density is strongly affected by vertical plasma motions [Fejer and Scherliess, 2001]. Also, ionospheric electric fields and plasma drifts play essential roles on the dynamics of the equatorial and low-latitude thermosphere. In the evening period, the vertical plasma drifts are of particular significance, as they appear to have a direct bearing on the occurrence of Equatorial Spread F (ESF) [Fejer, 1997]. The understanding of the variability of ionospheric plasma drifts is fundamental for the development of realistic ionospheric and thermospheric models. However, at the magnetic equator, plasma motions are controlled by the vertical and zonal electric fields arising from the low-latitude dynamo current system [Matsushita, 1969]. The global-scale motion of winds across the magnetic field lines generates a dynamo system formed by currents and polarization electric fields. The E-region dynamo fields are created by tidal winds in the E-layer, and are coupled to the F-region by equipotential magnetic lines. F-region dynamo fields are driven by F-region winds. During daytime the latter are largely reduced by the conductivity of E-region, but are important at night [Kelley, 1989; Fejer, 1991]. The intense E-region east-west electric field at 100-110 km [Richmond, 1973] induces a vertical plasma motion throughout the equatorial F-region at a **E** x **B** velocity, where **E** and **B** are the electric field and the magnetic field, respectively.

1.2 Measurement techniques for F-region vertical plasma drifts

Observations of plasma drifts in the equatorial and low-latitude regions have been widely studied using satellite and ground-based techniques. Measurements of F-region plasma drifts have been reported extensively from the equatorial station Jicamarca (12°S, 76.8°W, dip latitude 2°N) using the incoherent scatter radar (ISR) technique [Basley and Woodman, 1969; Woodman 1970, 1972; Fejer et al., 1979, 1985, 1989, 1991; Gonzalez et al., 1979] and the general characteristics of plasma drifts and ionospheric electric fields with their dependence on season, solar cycle, and magnetic activity were determined [Fejer et al., 1979]. Ionosonde observations have been made in the Peruvian, Brazilian, and Indian equatorial F-region vertical drifts [e.g., Abdu et al., 1981; Sastri, 1996; Batista et al., 1986). Although the ionosonde drifts have well known limitations, they have long shown clear indications of large longitudinal variations of the F-region vertical plasma drifts. This has been attributed to the displacement of the geomagnetic and geographic equators and the large differences in the magnetic declination angles and magnetic field strength along the geomagnetic equator. Valladares et al. [1996] presented results of the zonal drifts of equatorial F-region irregularities obtained by spaced-antenna satellite radio beacon (SRB) measurements of scintillation of 250 MHz signals from a geo-stationary satellite. These measurements were performed in 1994 at Ancon, Peru (11.8°S, 77.18°W, dip latitude 0.9°N). Multifrequency high-resolution HF Doppler systems have also been used to take measurement of bottomside F-region plasma drifts at equatorial and low-latitude stations [e.g. Balan et al. 1992; Jayachandran et al., 1993, Subbarao and Krishna Murthy, 1994; Blanc and Houngninou, 1998]. The HF radar method, however, is often limited to the evening period when the F-region bottom altitude raises beyond 300 km. The importance of the recombination and profile changes is then lower and the apparent vertical displacement velocity is about the same as the vertical **E**x**B** plasma drift velocity [Bittencourt and Abdu, 1981].

Over the last years, satellite observations have been increasingly been used to investigate the global distribution of equatorial F-region plasma drifts and, in particular, their longitudinal variability [e.g. Coley and Heelis, 1989; Coley et al., 1990; Fejer et al., 1995; Maynard et al., 1995]. Nevertheless, on the basis of these extensive data accumulated for several years with various experimental techniques enumerated above, climotological regional models of the equatorial and low-latitude plasma drifts in the Peruvian, Brazilian, Indian, and Japanese sectors have been developed [e.g., Blanc and Amayenc et al., 1979; Richmond et al. 1980; Buonsanto and Witasse, 1999; Scherliess and Fejer, 1999; Zhang et al., 2001]. In spite of the well-known longitudinal variations, these empirical models have been widely used as input parameters for global low-latitude modeling studies [e.g., Anderson et al., 1987; Bailey et al., 1993]. These equatorial and low-latitude studies have shown the general properties of F-region plasma drifts and electric fields. The measurements indicated that F-region electrodynamic plasma drifts are upward and westward during the day and downward and eastward at night under quiet magnetic conditions. Regrettably, the situation at the equatorial region of the African continent is, however, different entirely. There is an acute shortage of ionospheric stations to carry out these measurements. The quite few locations have stopped data recordings many years due to the breakdown of equipment coupled with economic problems of most African countries. The lack of extensive studies in the African region is a major obstacle in global ionospheric modeling effort.

The main purpose of this paper is to use available data at Ibadan and compare the seasonal equatorial vertical plasma drifts during low solar activity of 1964 and high solar activity of 1958 during magnetic quiet condition. We also compare vertical velocities inferred from ionosonde observations in the nighttime sectors with incoherent scatter radar and AE - E satellite drifts at three different seasons.

2. 0 Theory

A really satisfactory self-consistent model of the equatorial ionosphere has yet to be made; it would present quite a computational challenge owning to the many coupled processes operating in a complicated geometrical situation. In addition, equatorial ionosphere is constantly subjected to several competing forces [e.g. *Rishbeth*, 1981]. However, the most general fundamental equation is the equilibrium form of the continuity equation given by

$$q(h,\chi) - \beta N(h,t) - \nabla \bullet (N(h,t)\vec{V}) = 0 \qquad (2.1)$$

where $q(h,\chi)$ is the rate of electron production per unit volume and so is a function of both height and solar zenith distance, χ . β is the loss coefficient, a function of height, N is electron or ion density at height h and time t , $\vec{V}$ is the drift velocity vector. The velocity $\vec{V}$ may be that of either the ions or electrons, $\vec{V}_i$ or $\vec{V}_e$ without assuming these to be the same. Mass of electron (m_e) is negligibly small compared with mass of ion (m_i), so that we actually obtain appropriate equation of motion for ion, which is generally accepted to be sufficiently accurate in F-region.

The equation of motion is given by the expression $-\frac{1}{N_i}\nabla N_i k_B T_i + m_i\vec{g} + e(\vec{E}+\vec{V}_i\times\vec{B}) - m_i\upsilon_{in}(\vec{V}_i-\vec{U}) = 0$

(2.2)

where $\frac{1}{N_i}\nabla N_i k_B T_i =$ Pressure gradient, N_i = Ion density, $k_B =$ Boltzmann constant, $T_i =$ Ion temperature, $m_i\vec{g}$ = Gravity, $m_i =$ the mean ion mass, $\vec{g} =$ Acceleration due to gravity, $e\vec{E}$ = Electric field, e = the unit charge, $\vec{E}$ = Electric field intensity, $e(\vec{V}_i\times\vec{B}) =$ Lorentz, $\vec{V}_i$ = Ion velocity, $\vec{B}$ = Geomagnetic flux density, $m_i\upsilon_{in}(\vec{V}_i-\vec{U})$ = Collisions with neutral particles, υ_{in} = Collision frequency of ion with neutral particle, $\vec{U}$ = Velocity of neutral air.

Equation (2.2) can be rewritten in the form given as

$$-\frac{1}{N_i m_i \upsilon_{in}}\nabla N_i k_B T_i + \frac{\vec{g}}{\upsilon_{in}} + \frac{e}{m_i\upsilon_{in}}\vec{E} + \vec{U} + \frac{\Omega_i}{\upsilon_{in}}(\vec{V}_i\times\hat{b}) - \vec{V}_i = 0 \qquad (2.3)$$

where $\Omega_i = \frac{e\vec{B}}{m_i}$ = Ion Gyrofrequency, $\hat{b}$ = Unit vector of $\vec{B}$

From Equation (2.3), velocity independent forces are put together by the following expression

$$\vec{F} = -\frac{1}{N_i m_i \upsilon_{in}}\nabla N_i k_B T_i + \frac{1}{\upsilon_{in}}\vec{g} + \frac{e}{m_i\upsilon_{in}}\vec{E} + \vec{U} \qquad (2.4)$$

Furthermore, ion velocity $\vec{V}_i$ can be decomposed into component parallel ($\vec{V}_i^{\,ll}$) and perpendicular ($\vec{V}_i^{\perp}$) to the geomagnetic field.

$$\vec{V}_i = \vec{V}_i^{\,ll} + \vec{V}_i^{\perp} \qquad (2.5)$$

The component of ion velocity $\vec{V}_i^{\perp}$ perpendicular to the magnetic field may be obtained by direct solution of equation (2.2); it is given by

$$\vec{V}_i^{\perp} = \frac{1}{1+(\frac{\Omega_i}{\upsilon_{in}})^2}[\vec{F} + \frac{\Omega_i}{\upsilon_{in}}(\vec{F}_i^{\perp}\times\hat{b})] \qquad (2.6)$$

whenever $\frac{\Omega_i}{\upsilon_{in}} < 1$, $\vec{V}_i^{\perp} \approx \vec{F}^{\perp}$, and $\vec{V}_i^{ll} = \vec{F}_i^{ll}$, where $\vec{F}_i^{ll}$ is the component parallel to the magnetic field. In the F-region, $\frac{\Omega_i}{\upsilon_{in}} > 1$, that is, Hall motion predominates, and so equation (2.6) reduces to

$$\vec{V}_i^{\perp} \approx \frac{\upsilon_{in}}{\Omega_i}(\vec{F}^{\perp}\times\hat{b}) \qquad (2.7)$$

If we neglect the mechanical part of $\vec{F}_i^{\perp}$, the final perpendicular component of ion velocity is simply

$$\vec{V}_i^{\perp} = \frac{\vec{E}\times\vec{B}}{B^2} \qquad (2.8)$$

4.0 Data and discussion

The study is for an equatorial station in the African sector. We used ground-based ionosonde observations acquired at Ibadan, Nigeria (7.4°N, 3.9°E, dip latitude 6°S). We ensured that the data chosen were good enough to be scaled, and magnetic storm days were avoided. Five international quiet days ionograms from each month of the year were picked for the study. The records were manually analyzed using a ten-point *Kelso* [1952] technique to obtain electron density profiles at hourly interval during the daytime from 07 to 17 LT sector. Theoretical model calculations obtained by simplifying electron density continuity equation, proposed by Iheonu and Oyekola [2006] were used to obtain the vertical *E* x *B* drifts in the daytime period. The simple model calculation is valid away from the peak of the F-layer. In order to investigate solar cycle effects, data from 1958 IGY period (yearly average F10.7 cm = 208 in units of 10^{-22} W/m^2/Hz, and R_z = 185), a year of high solar activity, and 1964 (yearly average F10.7 cm = 72 in solar flux units, and R_z = 10.2), a year of low solar activity, were selected for this study. In the nighttime period F-region vertical drifts were derived from ionosonde measurements by determining the time rate of change of virtual height (h'F) of the bottomside of the F-region, Δh'F/Δt., the technique that has been well accepted and has been used for several years to estimate vertical motion of the equatorial ionosphere in the American and Indian sectors [e.g. *Abdu et al.*, 1981; *Batista et al*., 1986; Hari *and Krisna Murthy*, 1995]. The months of the year were grouped into 4-month seasonal periods as follow: summer (November, December, January, and February), equinox (March, April, September, October), winter (May, June, July, August).

Figure 1 shows diurnal and seasonal variation of vertical component of the equatorial F-region plasma drifts obtained by ionosonde method for the period of 1964 (upper panel), and 1958 (bottom panel). We calculated the vertical drifts around 300 km height for both solar epochs

Figure 1 indicates the classical behaviors for the vertical component of the equatorial F-region plasma drift velocity. It is upward during the daytime for both low and high solar activity periods. As can be seen, there is a strong seasonal variation in vertical drifts over Ibadan during both low and high solar period. During low solar activity period the lowest seasonal effect are seen in summer (~11 m/s), intermediate in the winter condition (~12.6 m/s) and the strongest effect in equinox (~16.7 m/s). The magnitude of the overall variation during the low solar activity period is about 14 m/s with a standard deviation of nearly 6.9 m/s. At high solar activity (the bottom panel) the values of vertical drifts are, as expected, much higher than at low solar activity and their variation are found to be similar to those at low solar activity. The drift decreases gradually and systematically until about noon, afterward increases noticeably till about 17 LT for all seasons. Here, the estimated seasonal values are approximately 17 m/s, 19 m/s, and 22 m/s in winter, summer, and equinox, respectively. The overall average is fairly less than 20 m/s. Figure 2 presents nighttime diurnal variations of ionosonde, radar, and AE-E vertical drifts for equatorial stations. For a more detailed comparison, ionosonde, incoherent scatter, and satellite F region vertical drift results are plotted together for three different seasons. The VHF radar and satellite data were inferred from the work of *Fejer et al*., [1995]. They used two years of data from January 1978 and December 1979 to examine the longitudinal (±5^o dip latitude) dependence of the satellite-observed drifts during moderate to high solar flux. The results were compared with corresponding Jicamarca drift measurements. The average solar flux indices were in the range 160-180 (in units of 10^{-22} W/m^2/Hz). The mean sunspot number, R_{12} for 1978 = 86.9; and 1979, with average R_{12} = 146. The observational results presented here are for quiet geomagnetic condition**.**

Generally, the vertical drifts are characterized with an evening upward enhancements followed by a downward reversal. As can be seen, the equinoctial peak velocities are about 36 m/s and 35 m/s, for ionosonde and satellite drifts, respectively. Jicamarca equinoctial peak velocity is less than 30 m/s. The evening peak velocities all occur at around 19 LT. After 19 LT the velocities are negative (downward), followed by large hour-to-hour variations even during quiet magnetic condition and eventually to a reversal in the drift direction at about 06 LT except radar drifts. Notice that the drifts are predominately downward between about 20-05 hr LT sector. Also, the nighttime downward drift velocities particularly from 21-05 LT at Ibadan are generally significantly smaller in magnitudes than Jicamarca and AE-E vertical drifts. Detailed analysis shows that ionosonde drifts are lower than satellite and radar drifts by a factor of about 2 and 3, respectively, during the equinox. During the summer, however, the magnitude of ionosonde drifts are about more than a factor of 2 smaller than both radar and satellite drifts. On the other hand, the values of ionosonde and satellite winter drifts are found to be consistent; while ionosonde drifts are about a factor of 2 lower than Jicamarca data. It is as well observed that ionosonde evening reversal times are different by about 3 and 2 hours than Jicamarca and AE-E evening reversal times, respectively. But the morning reversal times agree quite well for all the techniques. Figure 3 compares the inferred evening reversal times from ionosonde data from Ibadan (dip lat 6^{o}S) and Trivandrum (dip lat. 0.3^{o}S) and the reversal times determined from the Jicamarca (dip lat 2^{o}N) drift observations all for solar maximum. Figure 3 indicates that ionosonde records can be effectively used to determine the evening reversal times. Also, the reversal times in the Peruvian, Indian and African equatorial regions have similar annual variations but are shifted by 6 months. The reason for the shift is probably the location of Peruvian, Indian, and African stations in the southern and northern hemisphere, respectively.

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 [Fejer and Scherliess, 2001]. Richmond [1994] pointed out that quiet-time ionospheric variability is probably associated with irregular day-to-day variations 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. 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 HF 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. In recent times, the best experimental evidence for seeding of an ionospheric bottomside *E* x *B* plasma drift instability is presented by Nicolls and Kelley [2005].

5.0 Summary

Ionosonde measurements obtained at Ibadan were used to determine the variation of the equatorial vertical plasma drifts with season, solar cycle, under quiet magnetic activity. Profound similar seasonal trends were found during quiet daytime low and high solar activity. The magnitude of upward daytime during low solar flux is substantially lower (about 14 m/s) than that of high solar flux (nearly 20 m/s). The F-region drifts show largest variation in the evening hours. In the nighttime sector, we find comparable variability pattern among the three techniques. The equinoctial average evening upward drifts enhancements by the three methods are very nearly equal and occur at the same local time (19 LT) for all seasons. Additionally, the evening reversal time from upward daytime to downward nighttime does not vary much except during the winter months; and occurs earliest in summer and equinox, but least during winter period. Also, Also the results show asymmetry of evening reversal times about the dip-equator between the Peruvian, Indian, and the African equatorial sectors. The observations presented in this paper are in conformity with some results obtained at other equatorial and low-latitude stations [e.g. Balan et al., 1992; Fejer et al., 1995; Fejer, 1997; Scherliess and Fejer, 1999].

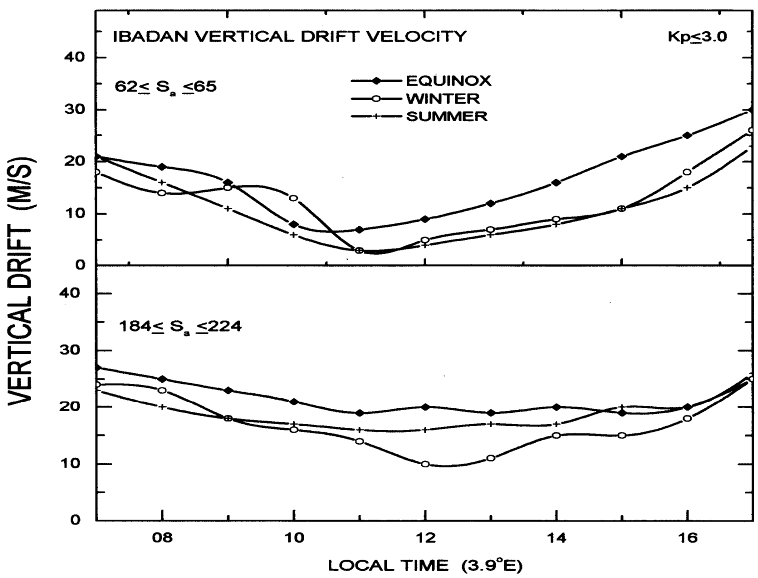

Figure 1. Average daytime F-region vertical plasma drifts obtained for three different seasons from Ibadan ionosonde data during 1964 low solar activity (top panel) and 1958 high solar activity (bottom panel) under quiet magnetic condition. Here S_a denotes decimetric solar flux index.

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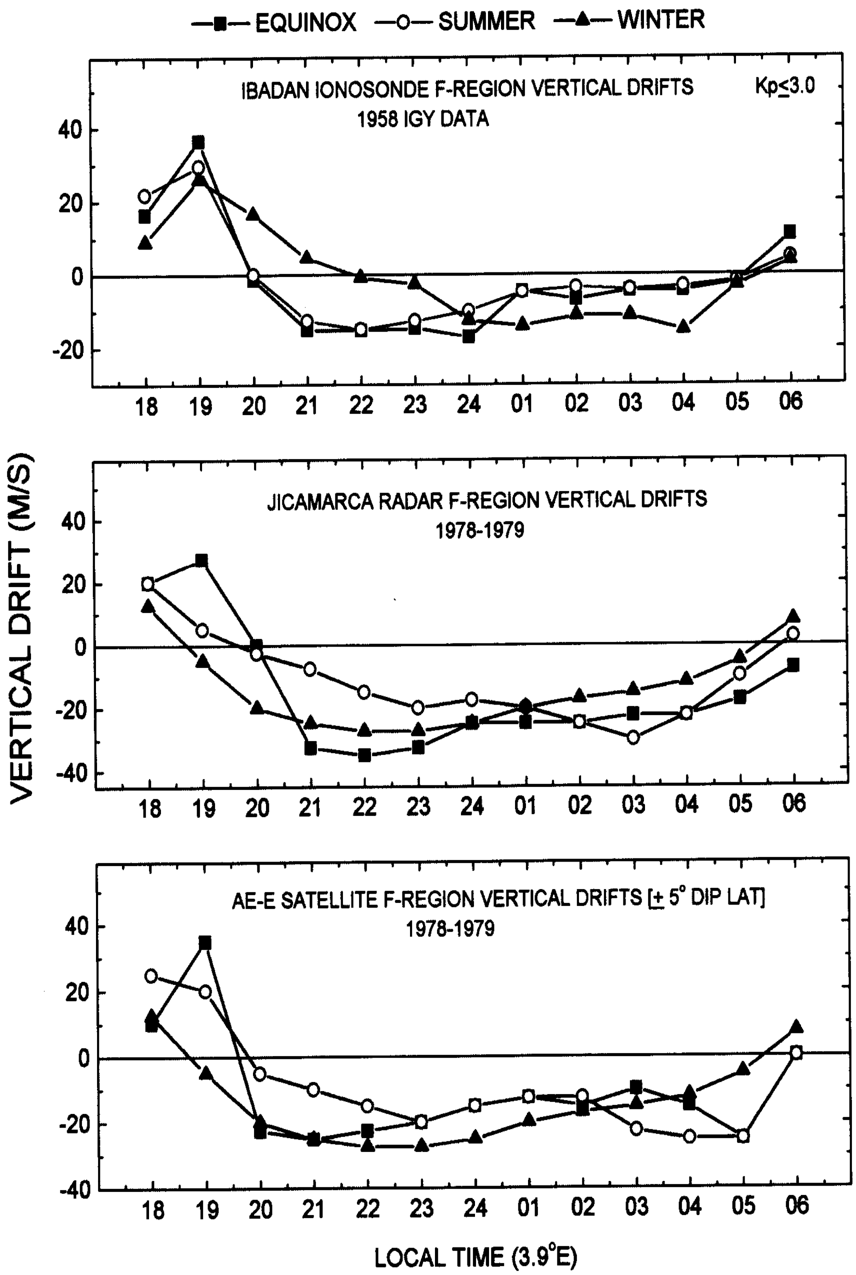

Figure 2. Nighttime variations of F-region vertical drift velocity. upper panel: calculated for Ibadan from ionosonde h'F data, middle panel: observed at Jicamarca, and bottom panel: AE-E satellite measurement for three different seasons under high solar flux and quiet geomagnetic conditions. Radar and satellite data were inferred from Fejer et al. 1995.

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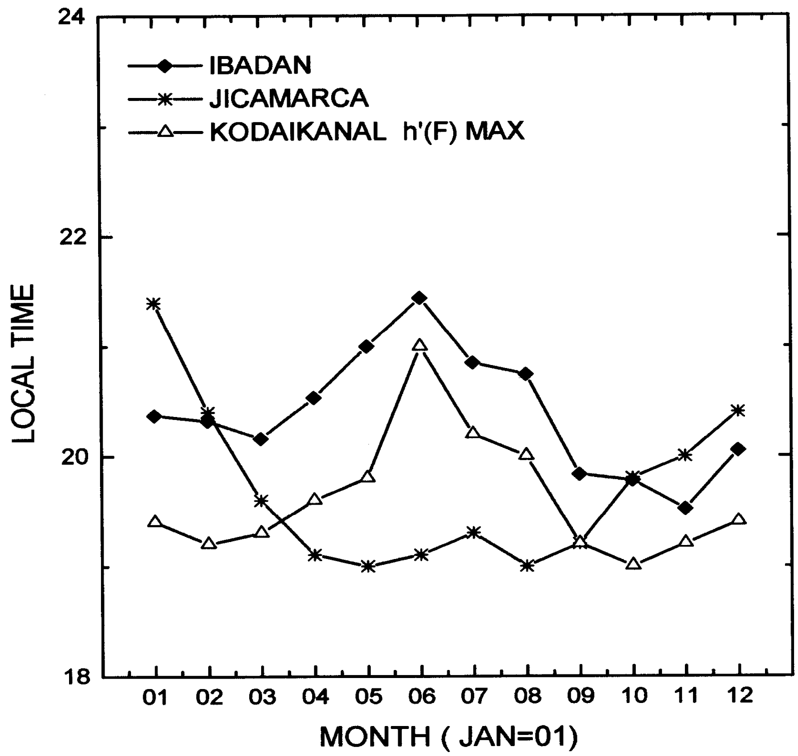

Figure 3. Comparison between the Ibadan ionosonde derived F-region vertical drift reversal times with Jicamarca reversal times and the reversal times inferred from ionogram records from Trivandrum during solar maximum.

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