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Ionospheric Virtual Height ($h'F2$) Response and its Vertical Ion Drifts Characteristics at an Equatorial Station

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ABSTRACT

The Ionospheric virtual heights ($h^{'}F2$) obtained from the DPS-4.2 Version of the GIRO's site, as a computing parameter for vertical E × B ion drifts in this present study using the international quiet days (IQDs) is engaged. Vertical ion drifts (v_z') computed from virtual heights was studied over Ilorin (lat. 8.31°N, long. 4.34°E, dip lat. 2.95°) during a solar minimum (SM), a station situated at the equatorial dip. The hourly averages of vertical ion drifts, v_z' were computed from 10-international quiet days (IQDs) hourly $h^{'}F2$ averages for the four seasonal months adopted. Seasonally, v_z' was having same behavourial patterns of pre-noon and post-noon peaks, but in $h^{'}F2$, it had noontime, post-sunset and pre-sunrise peaks occurred in all seasons. The v_z' pre-noon peaks magnitudes are 6.8, 14.4 and 15.0 m/s in June Solsticial, Equinoctial and December Solsticial respectively; and its post-noon peaks magnitudes are 0.8, 7.4 and 7.9 m/s in December and June Solsticials, and Equinoctial seasons respectively. The $h^{'}F2$ noontime peaks magnitudes are (321–410) km, post-sunset peaks magnitudes are (253–329) km and pre-sunrise peaks magnitudes are (228–318) km in all seasons. Also, v_z' depicted pre-reversal enhancement (PRE) night peaks in all seasons. The PRE peaks magnitudes are [(-4.0)–(-13.4)] m/s at 2000 LT, [(-4.9)–(-9.3)] m/s between 2200 LT and 2300 LT in all seasons. Similar phenomenal observations occurred in the $h^{'}F2$ and v_z' annual patterns plots. In general, the $h^{'}F2$ and v_z' magnitudes were greatest in Solsticial seasons and least in Equinoctial season. The $h^{'}F2$ and v_z' stable and continual descent indicates generally that the electrons briskly drifting away from the equator triggered by solar ionization in the equatorial region. As well, seasonal peaks occurred in general are assumed to be controlled by the enhanced vertical E × B ion drifts upsurge, which adapts with former aftermaths at some stations in the West African sector during closely related solar activity.

Keywords:
Virtual Heights,
Ion Drifts,
Pre-noon peak,
Noontime peak,
Post-Sunset peak,
Pre-Sunrise peak.

INTRODUCTION

The Morphology of the F2-region vertical E × B ion drifts in the equatorial latitude had been broadly studied using different observational methods and measuring instrument at different equatorial regions of the world to obtained experimental models. Investigations from Jicamarca Ionospheric Station had frolicked the most leading role for the modelling of ion drifts by these numerous investigators (Fejer *et al*., 1995; Fejer, 1997; Scherliess and Fejer, 1999; Woodman *et al*., 2006). Furthermore, (Fejer *et al*, 1991; Luhr *et al*., 2008; Fejer *et al*, 2008; Kil *et al*., 2009), using observational avenues of measuring instruments and satellites [e.g. Ions Drift Meter (IDM), CHAllenging Minisatellite Payload-SATellite (CHAMP-SAT), and Republic Of China SATellite 1 (ROCSAT-1)] to investigate vertical E × B ion drifts at equatorial regions. The two-measuring techniques (IDM and SAT) has caused the evolving investigations of the universal model for the determinations of F2-region vertical E × B ion drifts.

The ionospheric virtual-time data from Ionosondes, as suggested by Reinisch *et al*. (2005) are truly treasurable parameters in the probing of the ionosphere. Digisondes data obtainable from ionospheric F2-region can be used to compute the drifts of vertical E × B ions. An early trepidation was stumbled upon concerning the data-worth derived from ionograms during the automatic scaling of its echo traces as described by Reinisch *et al*. (1998). However, according to Reinisch *et al*. (2005), a designed algorithm program called 'ARTIST' used as an auto-scaling in the ionograms has been inputted in the digisondes. This is inculcated into Digisondes to ensure that the now scaled-out data are trustworthy and beneficial for models predicting in the ionosphere.

Methodology with same approaches adopted by some early investigators at different sectors of the world was looked into. Investigators (Richmond *et al*., 1980; Batista *et al*., 1996; Buonsanto and Witasse, 1999; Kelley *et al*., 2009) carried out their studies on the South America sector; also, (Sastri, 1996; Dabas *et al*., 2003; Liu *et al*., 2004; Araujo-Pradere *et al*., 2010) concentrated their studies in the Indian sector. For the Africa sector, various studies were investigated by some investigators, such as, Adebesin *et al*. (2015), Adeniyi *et al*. (2014a, b), Oyekola and Kolawole (2010), Oyekola (2009), Oyekola and Oluwafemi (2007), Obrou *et al*. (2003), Radicella and Adeniyi (1999). The data adopted for this our present study were auto-scaled data extracted from Ilorin Ionospheric Observatory (8.5°N, 4.68°E, dip 2.96°N) of GIRO site for the months of April (Sunspot number (SSN), $R_z = 7$) stands for March equinoctial, July (Sunspot number (SSN), $R_z = 15$) representing June solsticial, October (Sunspot number (SSN), $R_z = 21$) stands for September equinoctial and November (Sunspot number (SSN), $R_z = 21$) used for December solsticial during 2010 – a year of solar minimum (SM).

In computing the ion drifts variation over Ilorin, the time-rate of change of F2-region virtual height, *h'F2* were obtained and calculated. However, some previous studies have shown a development by the peak height at some particular frequencies (say, 3, 4 or 5 MHz) as well as calculating the means at such selected frequencies, e.g., Abdu *et al*. (2004); other works have revealed the ion drifts computed from the F2-region virtual heights of reflection, *h'F2*, e.g., Lee *et al*. (2005), Araujo-Pradere *et al*. (2010) and Ehinlafa *et al*. (2023). Liu *et al*. (2011) depict notable equatorial changes in the virtual height patterns (*h'F2*), which controls the effect of solar activity in the equatorial regions, and also, the purpose of adopting it as a computing parameter in this work. Drifts of vertical E × B ion computed from *h'F2* indicates a well statistical representation of the enhanced ionization upsurging with pre-noon/post-noon peaks during the daytime, and also, a better illustration of the pre-reversal enhancement of vertical ion drifts with night peaks showcasing between 1900 LT and 0500 LT. Hence, this is the main purpose for embracing the virtual heights, *h'F2* as a computing parameter for drifts of vertical E × B ion in this our present work using the international quiet days (IQDs). In essence, this present work aimed to investigate the virtual heights, *h'F2* variation patterns; to compute the vertical E × B ion drifts from virtual heights, *h'F2*; and finally, to study the computed drifts patterns of the F2-region. This is done as a proof to the earlier outcomes obtained by Bittencourt and Abdu (1981) and Adeniyi *et al.* (2014b).

MATERIALS AND METHODS

The major parameter adopted for this present work is the auto-scaled F2-region virtual heights of reflection (*h'F2*) extracted from the Digisonde Portable Sounder (DPS-4.2 Version) situated at Ilorin Ionospheric Observatory (Geo. Lat. 8.50°N, Long. 4.68°E, dip Lat. 2.95°N) on GIRO's site, an equatorial station in the Nigeria North central of West Africa sector. The hourly data of F2-region virtual heights (*h'F2*) were obtained from the DPS-4.2 Version of the GIRO's web address (https://giro.uml.edu/didbase/scaled.php). The algorithm program, developed by Huang and Reinisch (1996), known as the Calculated Average Representative Profile (CARP) inversion, was engaged for auto-scaling of data in the digisonde. The engaging data period is 2010, a year of solar minimum (Sunspot number (SSN), $R_z = 16$; which is also the mean of the four-month sunspot numbers adopted here, and Solar (F10.7) flux (SF), $\phi_z = 81$). The international quiet days (IQDs) data from world data centre (wdc), (2020) is determined at an interval of one-hour local time (LT). The F2-region virtual heights, *h'F2* data extracted is analysed by computing the monthly mean over ten international quiet days (IQDs) for each month considered except five international quiet days (IQDs) were used in December Solsticial due to the availability of scanty data. From these hourly monthly mean values, the drifts of vertical ion, according to Adeniyi *et al*. (2014b), were computed by calculating the time-rate of change of F2-region virtual heights:

$$v_z' = \left[{d(h'F2)}/{dt} \right] \quad (1)$$

For the seasonal variation of vertical ion drifts pattern, v_z' from the virtual heights (*h'F2*) are computed by determining the means for the adopted months across each hourly local time. Similarly, the annual pattern of v_z' variation is determined by finding the annual mean of the four months across each hour for a better presentation.

RESULTS AND DISCUSSION

Variation of Seasonal Virtual Heights (h'F2) Patterns

Figure 1 shows the variation of seasonal mean patterns of the F2-region virtual heights of reflection (*h'F2*) during solar minimum over Ilorin.

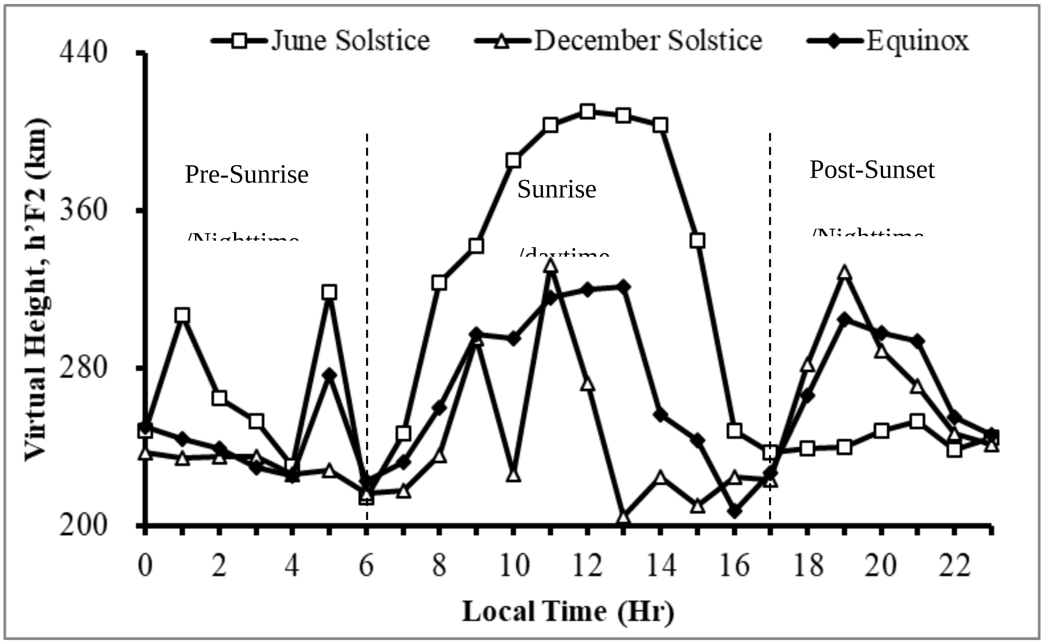

Figure 1: Hourly seasonal mean virtual height (*h'F2)* during solar minimum period

h'F2 variations depict a stable and continuous thrust in the seasons of December Solsticial and Equinoctial, and also, a rapid upthrow in the season of June Solsticial between 0600 LT and 1600 LT sunrise period. In the daytime observations, noontime peaks occurred between 1100 LT and 1300 LT having magnitudes of (321–410) km in all seasons. The noontime peak magnitudes of virtual height, *h'F2* occurred was least in Equinoctial (321 km) around 1300 LT, then next in December Solsticial (333 km) around 1100 LT and greatest in June Solsticial (410 km) around 1200 LT, during solar minimum period. This is attributed that the rapidly drifting of electrons to higher heights as observed in virtual height, *h'F2* of June Solsticial season where the loss rate due to recombination becomes much feebler; the electrons found in higher heights therefore has a lengthier lifetime, and thereby yielding a higher magnitude in June Solsticial, which is in harmony with Chen *et al*. (2008) and Ehinlafa *et al*. (2023). Also, during the time-interval between 0800 LT and 1600 LT, slight dips are created in virtual heights, *h'F2* observational patterns in all seasons. The dips magnitudes created are greatest in Equinoctial (347 km) around 1100 LT, followed by another in December Solsticial (340 km) around 1300 LT and least in June Solsticial (310 km) around 1100 LT.

In the nighttime observations, almost at sunset, another rapid upthrow of virtual height, *h'F2* occurred between 1600 LT and 1900 LT in all seasons to attain a second peak (post-sunset peak) with magnitudes occurring in Equinoctial (305 km) and December Solsticial (329 km) as the greatest *h'F2* both around 1900 LT, except in June Solsticial, where a steady decline is maintained with a slightly significant post-sunset peak (253 km) occurred around 2100 LT as the least *h'F2* magnitude during solar minimum. According to Adeniyi *et al.* (2014a, b) and Ehinlafa *et al.* (2023), the sudden electrons movement caused by the triggering of the solar ionization onset and turn-off, and also, the Spread-F superimposition on the virtual height (*h'F2*) of reflection between 1600 LT and 1900 LT may be of benefit in the virtual height, *h'F2* post-sunset peak illustration here. Immediately after the periodic time between 1900 LT and 0400 LT, a continual stable reduction occurred in the *h'F2* patterns of diurnal variation in all seasons. However, around 0500 LT, a *h'F2* pre-sunrise peaks occurred with magnitudes of (228–318) km in all seasons during the period of solar minimum. The magnitudes differences of pre-sunrise peaks are less and considerably distinct compared with the post-sunset peaks in all seasons.

Shown in Figure 2 is the hourly annual mean of F2-region virtual heights, *h'F2* depicted the same as the Figure 1.

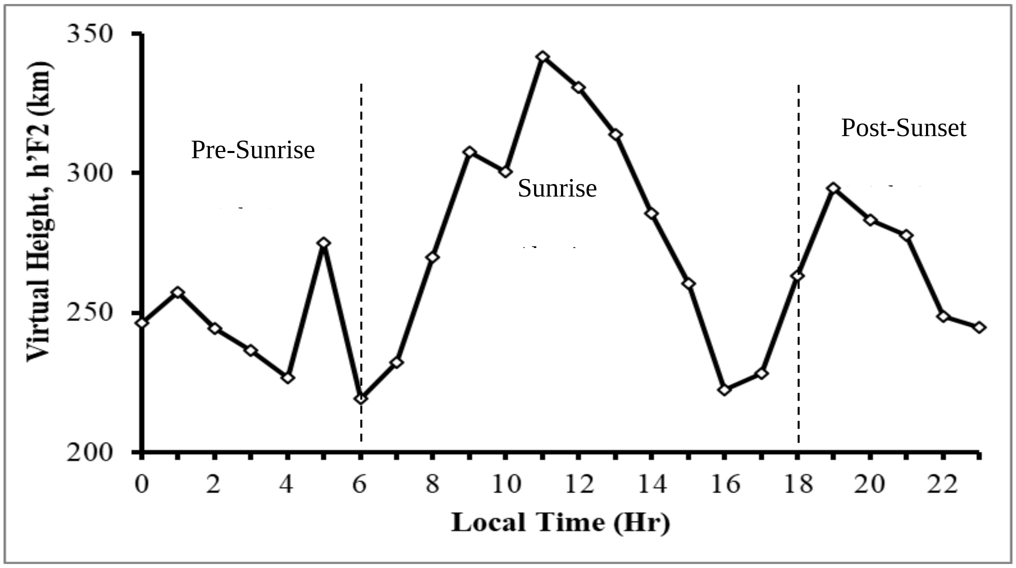

Figure 2: Hourly annual mean plot of virtual height, *h'F2* during period of solar minimum

In the daytime, *h'F2* annual pattern experienced a continual steady surge between 0600 LT and 1100 LT by attaining a noontime peak having mean magnitude of 345 km around 1100 LT. However, a slight dip occurred between 0900 LT and 1100 LT with a mean magnitude of 300 km around 1000 LT. This result obtained is in treaty with the general theory that above 300 km height, the apparent vertical drift is about the same as the vertical E × B ion drift Bittencourt and Abdu (1981). Hence, our result stated here validates the fact that during sunrise period, the *h'F2* displays rapid surge. The result further suggests that between 0900 LT and 1900 LT just before sunset, the general theory that vertical drifts obtained by digisonde measurements only matches the E × B drifts if the F2-region is greater than 300 km, is reliable.

In the nighttime, the post-sunset peak with mean magnitude 295 km around 1900 LT, which is distinctly greater than the pre-sunrise peak with a mean magnitude of 275 km around 0500 LT occurred in figure 2 for the *h'F2* annual pattern during the solar minimum condition. Also, a continuous steady depression occurred around 1900 LT, and the depression moves-on until a pre-sunrise minimum period around 0400 LT occurred during the nighttime. This results obey the steadily downward depression in the electrons rapidly relocating away from the equator caused by solar ionization due to low recombination in the equatorial latitude ascribed to Bai *et al.* (2020) and Ehinlafa *et al.* (2023).

Seasonal Vertical Ion Drifts (v_z') Variation

Figure 3 revealed the hourly diurnal mean patterns of vertical E × B ion drifts in all seasons as computed at Ilorin for the period of 2010.

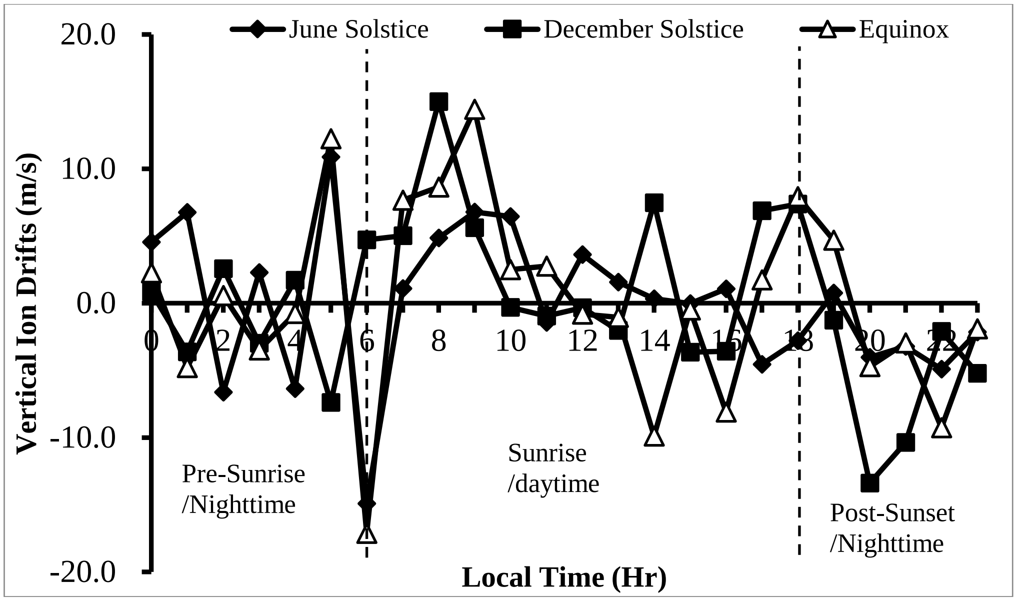

Figure 3: Hourly diurnal mean of vertical ion drifts (v_z) in all seasons during the SM period

The figure above displayed that the seasonal vertical ion drifts (v_z') variation of ionospheric F2-region accomplished dynamical equilibrium by the sources of recombination process and enhanced uplifting by the solar ionization, that respectively produces the processes of loss rate and production rate. In the daytime, the signs of upheaval and decline processes of the vertical ion drifts, v_z' occurred in this our present work during the solar minimum were well discussed here. The experienced drift, v_z' upsurges which commenced from 0600 LT to 0900 LT, attaining high-pitched (pre-noon) peaks of ion drifts between the local time periods of 0800 LT and 0900 LT in all seasons. The v_z' least pre-noon peak magnitude occurred in June Solsticial (6.8 m/s) around 0900 LT, then next occurred in Equinoctial (14.4 m/s) around 0900 LT and the greatest pre-noon peak magnitude occurred in December Solsticial (15.0 m/s) around 0800 LT during the solar minimum period. This resulted occurrence conforms with Oyekola (2009) and Oyekola and Oluwafemi (2007) daytime drifts peak outcomes of 15.0 m/s and 18.6 m/s for Solsticial and Equinoctial seasons respectively over another equatorial region in West Africa sector. Afterward, a swift downward declining of v_z' occurred by attaining below zero and trifling above zero drifts of the vertical ion in all seasons between time-interval of 1000 LT and 1600 LT. However, a v_z' slight-transitory spike enhancing occurred around noontime of 1200 LT having magnitudes in seasonal order of December Solsticial (-0.3 m/s) being the least, then next with Equinoctial (-0.8 m/s) and June Solsticial (3.6 m/s) as the greatest. Another enhanced v_z' transitory spike (post-noon peak) greater than the first one occurred around evening time between 1800 LT and 1900 LT with magnitudes in order of least in December (0.8 m/s) and then in June (7.4 m/s) Solsticials, and greatest in Equinoctial (7.9 m/s) seasons. These daytime occurrences of a continual swift and downward fall to below zero and trifling above zero of the drifts of vertical ion beyond 0800 LT and 0900 LT in all seasons noticed, explain that the ionospheric F2-region is declined by the advancement of vertical ion drifts over the equatorial dip along the magnetic field lines of the Earth. This is realized by effecting ion reduction about the equatorial dip generating a-twin allocating equatorial stooped (EIA) on each side of the magnetic equator. The EIA generated with the production of peaks near the equatorial dip between 0800 LT and 0900 LT, and also, advances in strength by the ion motion towards both poles. The upward surge in virtual height, *h'F2* that is generated from the consolidating of peaks produced, thereby building up the vertical ion drifts of pre-noon peaks between 0800 LT and 0900 LT in all seasons. These noticed occurrences agree with observed occurrences in Adeniyi *et al*. (2014b) and Adebesin *et al*. (2015) in all season during the sunrise period.

In the nighttime, an enhanced upthrow of the ion drifts, v_z' occurred firstly at 1900 LT having positive drift, v_z' peaks magnitudes with greatest in Equinoctial (4.9 m/s), followed by December Solsticial (1.3 m/s) and the least in June Solsticial (0.8 m/s), and also, the second one occurred at 0000 LT with positive drift, v_z' peaks magnitudes of (0.8–4.5) m/s in all seasons. Afterward, a downward enhanced reversal was observed. The downward enhanced reversal occurred at two separate periods of local time thereby giving pre-reversal enhancement (PRE) occurrence of negative drift, v_z' peaks: the first one occurred at 2000 LT recording negative drift peak magnitudes with least in December Solsticial (-13.4 m/s), then the Equinoctial (-4.7 m/s) and the greatest in June Solstice (-4.0 m/s) and, the second between 2200 LT and 2300 LT having negative drift, v_z' peak magnitudes of [(-4.9)–(-9.3)] m/s in all seasons. Occurred similarly of night pre-reversal enhancement (PRE) negative drift, v_z' peaks firstly between 0100 LT and 0200 LT with magnitudes of [(-3.6)–(6.6)] m/s in all seasons, and secondly, between 0300 LT and 0400 LT having magnitudes recorded with least in June Solsticial (-6.4 m/s), followed by the Equinoctial (-3.5 m/s) and the greatest in December Solstice (-3.0 m/s). This depicts seasonal dependent of the vertical E × B ion drift, and also, the observed occurrences agree with the noticed observations of Adeniyi *et al*. (2014a) and Adebesin *et al*. (2015) during the nighttime in all seasons.

Revealed in Figure 4 is the hourly annual mean patterns of the F2-region vertical E × B ion drifts shown similar to Figure 2.

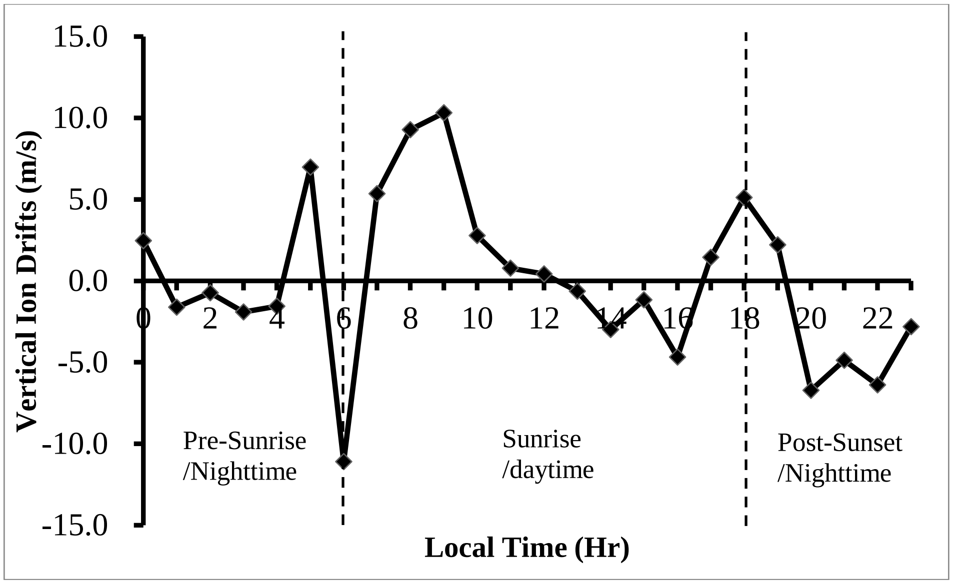

Figure 4: Annual mean pattern of vertical E × B ion drifts (v_z') during solar minimum period

During the daytime, the drift high-pitched (pre-noon) peak with mean magnitude of 10.3 m/s around 0900 LT after a sudden upsurge that started around 0600 LT occurred. Also, the continual stable and downward declining to below zero and a slight above zero drifts of the vertical ion at different local times occurred respectively having mean magnitudes as follows: 0.8 m/s at 1100 LT and [(-0.6)–(-4.7)] m/s between 1300 LT and 1600 LT. In addition, a slight-transitory enhanced spikes occurred majorly at two local times with drift mean magnitudes of 0.4 m/s at 1200 LT and -1.2 m/s at 1500 LT. An evening enhanced drift (post-noon) peak with mean magnitude of 5.1 m/s at 1800 LT occurred. These are the daytime occurrences of the annual variation of vertical ion drifts for the period of solar minimum which conforms with the same observations of Adeniyi *et al*. (2014a).

During the nighttime, an enhanced upthrow of the annual ion drift peak between 1900 LT and 2300 LT having mean magnitudes of 2.2 m/s and -2.8 m/s observed is less than that of same ion drift peak of enhanced upthrow between 0000 LT and 0500 LT with mean magnitudes of 2.5 m/s and 7.0 m/s. The night pre-reversal enhancement (PRE) negative drift peaks between 2000 LT and 2200 LT with mean magnitudes of -6.7 m/s and -6.4 m/s occurred is less than the similar PRE negative drift peaks between 0100 LT and 0400 LT having the same mean magnitudes of -1.6 m/s each. Also, a continual steady fall around 1900 LT after sunset progresses until a pre-sunrise minimum time around 0600 LT occurred in general during the nighttime. This finding of the continual downward decline in vertical ion drifts between 1900 LT and 0600 LT occurred here, which is caused by the quick electrons driving away from the equator as a result of abruptly onset and turn-off of solar ionization in F2-region. Also, the upward rise in vertical ion drifts observed between 0600 LT and 0900 LT here, which is caused by the enhanced upthrow of electrons rapidly from the equator in F2-region of ionization production due to solar radiation. These observed occurrences are noticed in the equatorial latitude of the ionosphere here (see figure 4), which is treaty with Adeniyi *et al*. (2014b) observations.

CONCLUSION

Seasonal peaks in *h'F2* occurred here are suspected to be controlled by the enhanced vertical E × B ion drifts which agrees with nearly erstwhile outcomes obtained at some stations in the West African sector during similar periods of solar activity. This is possible because of the strong relation established in computing vertical ion drifts, v_z' from virtual heights, *h'F2*. As well, it has become imperative to display the mean height profile for the entire 24-hour plot of virtual height, *h'F2* here. Also, there is worthy note in a generalized theory that a virtual height above 300 km, the superficial drift of vertical ion is nearly similar to the real drift of vertical ion, which is in treaty with our obtainable values of the mean virtual height, *h'F2*. Hence, our result promoted a fact that the virtual height, *h'F2* displays rapid surge. A steady reversal of drifts during the high periods of virtual height, *h'F2* noted here depicts that the Pre-Reversal Enhancement (PRE) is fundamentally accountable for the huge upthrow of the F2-region vertical ion drifts, and in return, the creation of the equatorial dip (EIA). In conclusion, a strong dependent expression was noticed generally with the hourly mean values computed between the corresponding virtual heights, *h'F2* and the computing enhanced vertical E × B ion drifts in each season considered here.

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