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A test of the efficacy of sporadic E layer ionization at the magnetic equatorial region

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Abstract

Numerical models generated by solving equations of continuity for electron density have been used to study the variability of E_{sq} horizontal winds at an African magnetic equatorial station, Ibadan – Nigeria. The behavioural trends of the composite results from the models tend to exhibit fluctuating solar flux dependence. The mean annual E_{sq} value during the period of high solar flux index seems to outperform the corresponding value for the period of low solar flux index, if the horizontal length scale is set at 200km. The results are compared with similar experiments carried out within the vicinity of the magnetic equator - in the process revealing salient insights into sporadic E-electromagnetic dynamics.

1.0 Introduction

The earth's ionosphere is a region of the upper atmosphere from about 85km to 600km attitude and includes the thermosphere and parts of the mesosphere and exosphere. The peculiarity of the region lies in the fact that it is ionized by solar UV radiation.

The interactions of the ionosphere, thermosphere, exosphere and the near-horizontal magnetic field in the region provide some of the most scintillating and remarkable features at the equatorial zone, particularly the plasma structuring of the E and F layers, widely regarded as the equatorial electrojet (EEJ) irregularities and the equatorial spread-F (ESF) [1, 2, 3].

The E-layer, as an intermediate layer between about 90km and 120km above the earth's surface is primarily determined by the competing effects of ionization and recombination. The region may reflect radiowaves at oblique incidence, probably at frequencies lower than 10 MH_Z. It may also have some contributory effects to radiowave absorption on frequencies above 10 MH_Z.

Occasionally however, sudden high value radio frequencies / electron densities greater than usually expected, are observed within the normal E-region. This phenomenon is referred to, as 'sporadic' E (Es). It is a region of intense ionization density embedded in the E-layer and has the capacity to reflect high radio frequencies. It is assumed that the layer has strongly ionized clouds in the lower part of the E-region. While its thickness may be of the order of 1km, its lateral extent could be up to a few 100km. The phenomenon should not be part of the normal E-layer but exists within the same altitude [4]. The mechanism for its detection is backscatter instead of reflection.

Occurrences of the different types of Es depend on the latitude of interest but the type peculiar to the magnetic equator (and hence to Ibadan) is the equatorial sporadic E-layer (E_{sq}) [5]. Esq is a plasma irregularity layer which occurs due to irregularities in the electrojet equatorial (EEJ) current [6], causing **E x B** plasma gradient instability at the base of the E region.

E_{sq} is strongly linked to the equatorial electrojet current which flows along the magnetic equator [7]. Review of available data at Ibadan shows that, nighttime existence of E_{sq} may occur, just for some few minutes but its daytime occurrence usually exceeds several hours. Daytime occurrence of E_{sq} has been investigated by some workers [8,9,10] over the past few decades.

Basic types of sporadic E layer signatories recognized include the equatorial type which is transparent and occurs within $\pm 6^0$ of the magnetic equator, the temperate type and the auroral type. There is also a blanketing type that is opaque to low F-region frequencies. It is widely accepted that a mechanism based on wind shear may be mainly responsible for Esq although particle dumping can contribute in the case of auroral Es [11].

The normal E-layer electron density profile follows the Chapman layer variation of the form:

$$N_m E \ \alpha \ (Cos\ x)^2{}_{\rho}$$

where x N_mE is the maximum value of election density and χ the sun's zenith angle; ρ is an index generally in the neighbourhood of 0.25 at sunspot maximum and 0.32 at sunspot minimum.

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Aside the dependence on solar zenith angle, N_iE is also believed to show regular solar cycle variations. In this vein, situations where sporadic E signatures are visible, it could also exhibit similar dependence on sunspot indices as in the case of the normal E layer. In order to test the efficacy of the phenomenon, we may subject the variations of sporadic E signature profiles to the well-known basic equation for electron density but re-defined in the present study as:

$$N_{sq} = 1.24 \times 10^{4} (f_oE_{sq})^{2}\ \text{cm}^{-3}$$

where f_oE_{sq} is the equatorial sporadic-E critical frequency measured in MHz and N_{sq} is the corresponding electron density.

2.0 Presentation of data and model fundamentals.

Data used for the study were compiled from ionospheric bulletins published at the University of Ibadan, Nigeria for the International Geophysical Year (IGY) and the International Geophysical Quiet Year (IGQY) periods majorly under geomagnetically quiet conditions. The ionospheric station at Ibadan was equipped with a Union Radio Mark II ionosonde, developed at the Radio Research Station at Slough. The transmitter and receiver are kept in tune by a frequency sensitive servo system, as the transmitter frequency is swept over the range 0.7 and 25 MHz, in 5mm duration. Details of the ionosonde are given by Somoye [12]. The ionospheric bulletins were also published for over three decades, thus serving as part of major research instruments for the African equatorial sector, particularly at Ibadan.

In line with the basic procedures adopted in earlier studies for the African equatorial region (e.g. [13], data used are also grouped into 4-month seasonal periods as follows:

Summer (June Solstice) May, June, July and August),
Equinoxes (March – April; September – October).
Winter (December Solstice) [November, December, January, February].

In addition, correlations between solar indices and the ionospheric parameters suited to a 12-month running mean analyses were utilized. We also adopt the continuity equation for electron density in our analysis, but redefined subsequently to connote sporadic E-electron density variability at the ionospheric height near 100km.

Basically, the electron (or ion) number density continuity equation may be put in the form:

$$\frac{\partial N}{\partial t} = q - L\,(N) - M \tag{1}$$

where q is the electron production term, L(N) is the electron loss term and M is a movement or transport term, which analysis would be considered in due course.

The continuity equation may thus be reframed to take into cognizance, a new version sorely for an atmosphere where sporadic – E signatures are visible. In this case, the remodeled version of the continuity equation for electrons in a sporadic – E domicile atmosphere may take the form:

$$\frac{\partial N_{sq}}{\partial t} = q - L\left(N_{sq}\right) - M \tag{2}$$

where N_{eq} represents electron density for sporadic E layer signatures.

Hence,

$$\frac{\partial N_{sq}}{\partial t} = q - L\left(N_{sq}\right) - \nabla.\left(N_{sq}\bar{v}\right) \tag{3}$$

where $\nabla.\left(N_{sq}\bar{v}\right)$ represents a sporadic E layer divergence function with the composite wind vector, $\bar{v}$.

Therefore,

$$\frac{\partial N_{sq}}{\partial t} = q - L\left(N_{sq}\right) - \bar{v}.\nabla N_{sq} - N_{sq}\left(\nabla.\bar{v}\right) \tag{4}$$

$$\frac{\partial N_{sq}}{\partial t} + \bar{v}.\nabla N_{sq} = \frac{dN_{sq}}{dt} = q - L\left(N_{sq}\right) - N_{sq}\left(\nabla.\bar{v}\right) \tag{5}$$

Write $\bar{v} = \overline{\infty} + \overline{w}$ (5a)

$(\overline{\infty} \rightarrow \textit{horizontal wind vector}; \overline{w} \rightarrow \textit{vertical wind vector}),$

and set $\bar{v}.\nabla\ N_{sq} = O,$ in equation (5) such that

$$\frac{\partial N_{sq}}{\partial t} = \frac{dN_{sq}}{dt} = q - L\left(N_{sq}\right) - N_{sq}\left(\nabla.\bar{v}\right) \tag{6}$$

In a horizontally stratified atmosphere, w vanishes in comparison with ω For the photochemically active E-region, the electron density continuity equation of the form:

$$\frac{\partial N_{sq}}{\partial t} = q - L\left(N_{sq}\right) - N_{sq}\left(\frac{\partial \overline{\infty}}{\partial h} + \frac{\partial \overline{w}}{\partial D}\right) \qquad (7)$$

should therefore prevail.

In equation (7), h is the ionospheric height associated with the vertical component of the drift of electrons and D is the horizontal length scale over which ω varies).

Note that $\overline{w} >> \overline{\infty},\ but\ \frac{\partial w}{\partial h} >> \frac{\partial \overline{\infty}}{\partial h}.$

If $\overline{w} \to O,$ in equation (7), then

$$\frac{aN_{sq}}{\partial t} = q - L\left(N_{sq}\right) - N_{sq}\,\frac{\partial \overline{w}}{\partial D} \qquad (8)$$

We also deduce therefrom that when ion flow is assumed incompressible, only w would seemingly be estimated from electron density gradient in the vertical (upward) direction.

2.1 General solution of the continuity equation for electrons at the sporadic E-region

The general application and solution of the continuity equation for electrons at the sporadic E-region of the equatorial ionosphere has been very sparse. In order to find solutions to the problem, we limit ourselves in the first instance to the case involving vertical transport of electrons in the continuity equation and then write,

$$\frac{\mathrm{dN_{sq}}}{\mathrm{dt}} = \mathrm{q_o}\,\mathrm{Cos}\,\chi - \alpha\,\mathrm{N_{sq}} - \beta\mathrm{N_{sq}} - \frac{\partial w}{\partial \mathrm{h}}\left(\mathrm{N_{sq}}\right) \qquad (9)$$

where q the election production term equals $L\left(N_{sq}\right) = \left\lfloor \alpha\ N_{sq}{}^{2} + \beta N_{sq} \right\rfloor.$

In furtherance of the treatment of the equation, we follow Appleton and Lyon [14] postulation but appropriately redefine the statement in the form:

$$\frac{\mathrm{dN_{sq}}}{\mathrm{dt}} = \mathrm{q_o}\,\mathrm{Cos}\,\chi - \alpha\,\mathrm{N_{sq}}{}^{2} - \beta\mathrm{N_{sq}} - \frac{dw}{dz}\left(\mathrm{N_{sq}}\right) \qquad (10)$$

where $q_o =$ maximum electron production rate for overhead sun, χ = zenith distance of the sun and z= reduced height in the vertical coordinate.

An estimation of the vertical plasma digit may be assumed if we set at

equilibrium, $$\frac{d}{dz}\left(N_{sq}w\right) \approx \frac{wdN_{sq}\left(h,t\right)}{dz} \approx \frac{wN_{sq}\left(h,t\right)}{Hp\left(h\right)} \qquad (11)$$

where $H_p(h)$ is the plasma scale height.

Hence

$$\frac{dN_{sq}}{dt} = q_o\ Cos\ \chi - \alpha\ N^{2}{}_{sq} - \beta N_{sq} - \frac{wN_{sq}\left(h,t\right)}{H_p\left(h\right)} \qquad (12)$$

or

$$\frac{wN_{sq}}{H_p} = q_o Cos\chi - \alpha\ N_{sq}{}^{2} - \beta N_{sq} \qquad (13)$$

where $\frac{\mathrm{dN_{sq}}}{\mathrm{dt}}$ is negligible, following similar reasoning adopted in the works of Iheonu and Oyekola, [13] and Picquenard [15], for daytime.

Thus, the vertical component of wind speed for sporadic E- layer becomes:

$$w = \frac{\mathrm{Hp}}{\mathrm{N_{sq}}}\left(\mathrm{q_0 \, Cos}\,\chi - \alpha\,\mathrm{N_{sq}}^2 - \beta\mathrm{N_{sq}}\right) \qquad (14)$$

where H_p is taken as 10km approximately [12].

Next, we consider the treatment involving the horizontal wind component such that the continuity equation changes to:

$$\frac{\mathrm{dN_{sq}}}{\mathrm{dt}} = \mathrm{q_0 \, Cos}\,\chi - \alpha\,\mathrm{N_{sq}}^2 - \beta\mathrm{N_{sq}} - \mathrm{N_{sq}}\left(\frac{\mathrm{dw}}{\mathrm{dD}}\right) \qquad (15)$$

For mathematical expediency, we may take that

$$\frac{dw}{dD} \text{ tends to } \frac{w}{D} \qquad (16)$$

Hence,

$$\frac{dN_{sq}}{dt} = q_o Cos\ \chi - \alpha\ N_{sq}{}^2 - \beta N_{sq} - \frac{wN_{sq}}{D} \qquad (17)$$

Therefore,

$$\frac{wN_{sq}}{D} = q_o\ Cos\chi - \alpha\ N_{sq}{}^2 - \beta Nm \qquad (18)$$

where for similar reasons as above, $\frac{dN_{sq}}{dt} \approx 0$

The horizontal component of wind speed is thus defined by the expression:

$$w = \frac{D}{N_{sq}}\left(q_o\ Cos\ \chi - \alpha N_{sq}{}^2 - \beta N_{sq}\right) \qquad (19)$$

where α and β are respectively, $1.0 \times 10^{-8}\mathrm{sec}^{-1}$ and $1.0 \times 10^{-4}\ \mathrm{sec}^{-1}$.

At the E-region height, it is often appropriate to assume that ion cloud move with the neutral wind. Using the interferometry estimate of the cross-beam motion, the temporal duration of the sporadic E patches in both the ionosonde and radar data information suggests a horizontal scale size of 50-150km [16]. If inference is made from the electron density profile due to the authors, then it is possible to suggest that the ideal value of the horizontal length scale could probably exceed the upper boundary limit suggested above.

For numerical estimations of this nature and magnitude, and making inference from deductions derived herein, it appears appropriate for thermally driven winds requiring a definite statement, for the horizontal length scale to be set at 200km numerically, for the perturbed ionospheric E-region at Ibadan.

Solar activity may be represented either by daily values of solar flux density at wavelength, 10.7cm ($S_{10.7}$) or by the daily values of Zurich sunspot number $\overline{R}_z$. $\overline{R}_z$ has been used formally in several studies (eg [13]) and hence would be adopted in this study.

Following Ratcliffe and Weakes [17], the equation for peak electron production rate is given by:

$$q_o = 250\left[1 + 16\ x\,10^{-3}\,\overline{R}_z\right] cm^{-3}\,\mathrm{sec}^{-1}. \qquad (20)$$

Here,

$q_o = 620\ cm^{-3}\ \mathrm{sec}^{-1}$, for a typical period of high solar activity and

$q_o = 270 cm^{-3}\ \mathrm{sec}^{-1}$, for a typical period of low solar activity.

At the higher F_2 region near about 250km however, the assumed ‘plane earth’ approximation in the first paper developed by Chapman [18] becomes invalid and has to be replaced by a more robust function to incorporate the effect due to the earth’s sphericity.

We thus compute the composite horizontal winds at the equatorial station of Ibadan, using equations (14), (19), and (5a) inclusively.

3.0 Results and discussion

Equations (14) and (19) aside the nomenclatures, are by implication also applicable to the normal E-layer and hence subject to all implied conditions adopted in this study.

We have plotted the composite electron density profiles for the sporadic E layer and compared with the normal E layer for periods of high and low solar flux indices (see figures 1 and 2). It is observed that there is no significant difference in the bahavioural trends of the two plots, except for the wider departure of sporadic E layer critical frequencies and hence the electron densities from those of the normal E-layer. The diurnal behaviours of the two plots suggest good agreement with Chapman theory, with particular reference to the peak electron density occurrence around mid-day, hitherto associated with the normal E-layer curve [19]. The dip in value of electron density for the sporadic E layer signature profile for low solar flux index (see Figure 2) before midday however, is somewhat a key characteristic feature of the F_2 – region of the equatorial ionosphere.

Plots of the diurnal variations of the sporadic E-layer signatures are shown in figure 3. We found out that the composite annual sporadic E-horizontal wind speed (E_{sq}) has a mean value of $138\pm16ms^{-1}$, compared to a normal E-layer value of $55\pm17ms^{-1}$, observed during the period of high sunspot index ($\bar{R}_z \approx 186$). On the other hand, the composite annual E_{sq} during the period of low sunspot index ($\bar{R}_z \approx 10$) has a value of $69\pm6ms^{-1}$, in comparison with a value of $45\pm21ms^{-1}$, observed for the normal E-layer.

The results during the period of low solar flux index for both sporadic E and the normal E layers are fairly comparable but the discrepancy in values obtained for the period of high solar flux index appears to be on a higher pedestal; by a factor in the neighbourhood of 2.

Kent [8] and Oyinloye [9] had made some measurements of E_{sq} drift velocity at Ibadan. While Kent obtained a mean E_{sq} value of $80ms^{-1}$ for the period of low sunspot index period ($\bar{R}_z \approx 19$), Oyinloye obtained a mean E_{sq} value of $80\pm9ms^{-1}$, for the moderate sunspot index ($\bar{R}_z \approx 70$).

The above results tend to suggest that sporadic E mean velocities at Ibadan do not distinctly show solar cycle dependence, contrary to the findings of Misra et al [20], that sporadic E-region drift irregularities at Thumba (magnetic latitude, 0.3^0S) India, decrease with increasing sunspot number. A critical appraisal of the results in the present study however indicates solar activity dependence of the composite sporadic E signature profiles at Ibadan.

Nighttime E_{sq} profiles (though very short in duration) were also observed at Ibadan. The E_{sq} ionization occurrence may be low during nighttime due primarily to decay of ionization. An average value probably less than 25% nighttime occurrences of E_{sq} during the two epochs of solar activity may not be due to the immense decay of ionization alone but also its relatively less variability across the seasons. It should be emphasized here that the occurrence of nighttime E_{sq} may not be very significant when compared to those of its daytime values particularly towards the physical appreciation of the contributions to knowledge and impact on radio science.

4.0 Conclusion

Electron density profiles of the sporadic E-layer of the equatorial ionosphere at Ibadan, Nigeria have been estimated and compared with those of the normal E-layer. Appreciable degree of symmetry about midday were established for the two quantities for both periods of solar activity, but the large departure of electron density profiles for sporadic E, far outweigh the corresponding profiles for the normal E-layer during daytime.

The mean E_{sq} drift at the station has values of $136\pm16ms^{-1}$ and $69\pm6ms^{-1}$, for the periods of high solar flux and low solar flux indices, respectively. The mean composite value of E_{sq} drift based on this study during high solar flux condition thus seems to be at a higher level when compared with results from either moderate or low solar flux conditions observed in similar experiments carried out in the vicinity of the magnetic equator.

The physical limitations due sorely to the minimal occurrences of nighttime sporadic E electron density variability at the equatorial ionosphere across the seasons make its applicability highly subdued in the field of radio science.

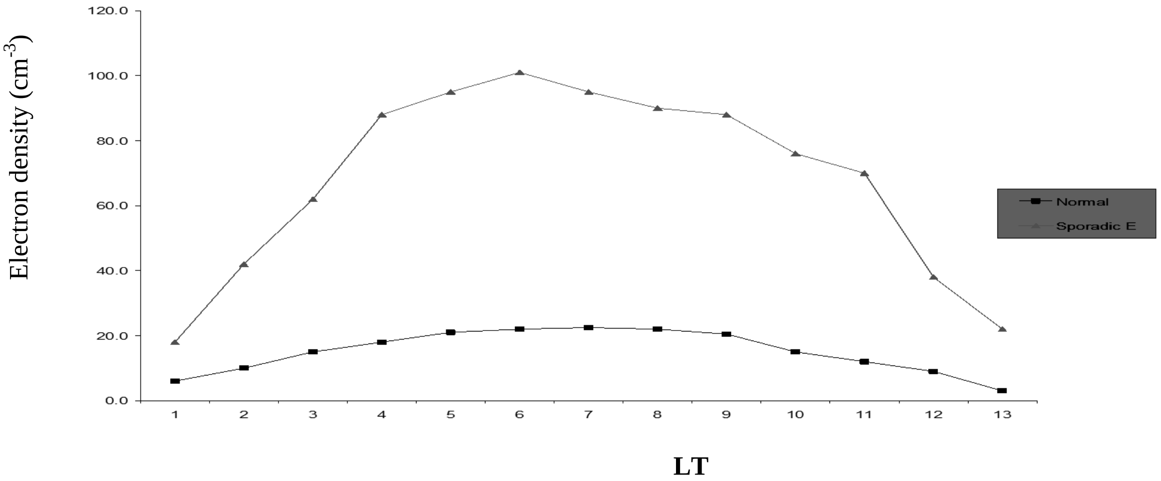

Figure 1: Electron density profile at Ibadan for high solar flux index.

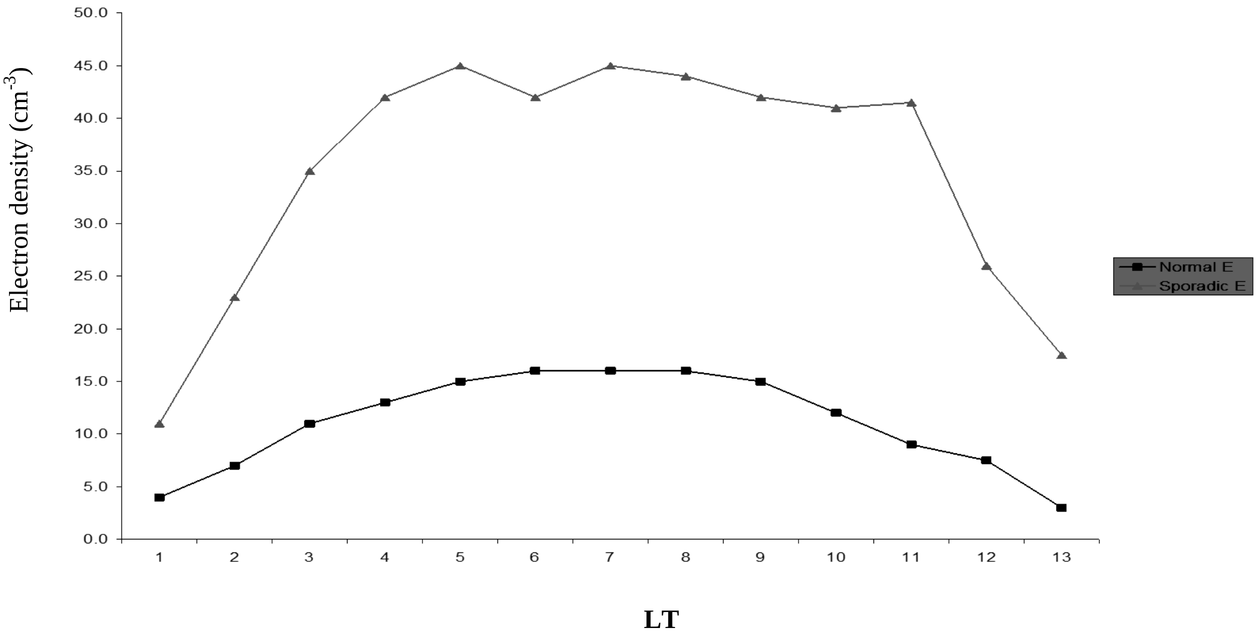

Figure 2: Same as fig.1, but for low solar flux index.

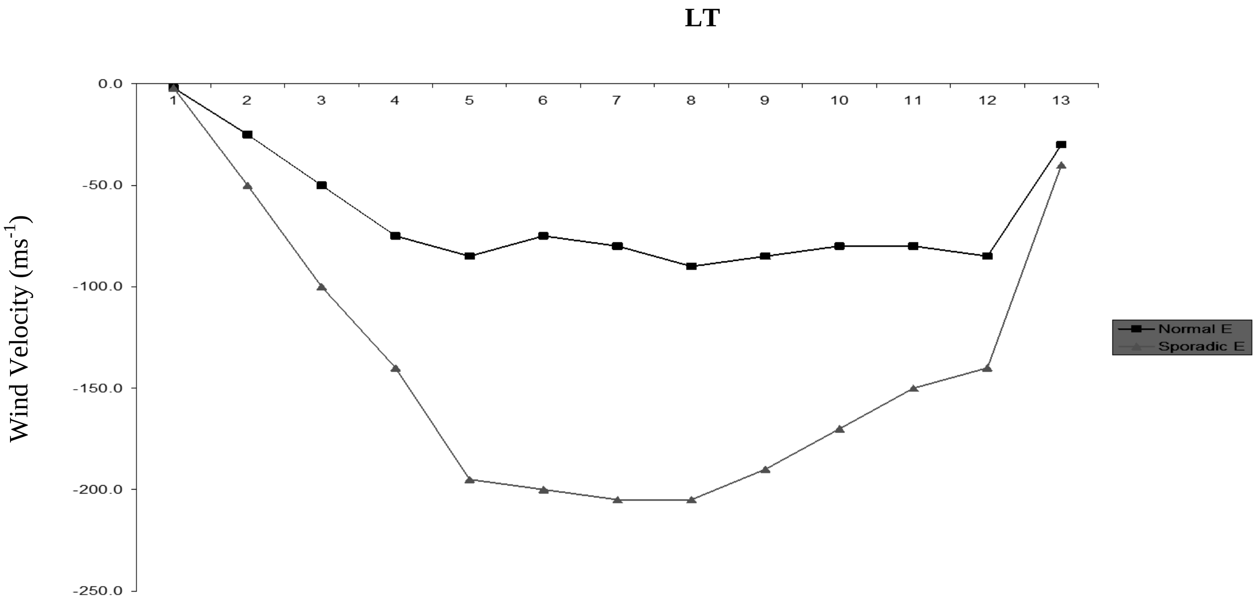

Figure 3: Diunal variation E of E-region (E_{sq}) horizontal winds at Ibadan.

Series 1: Low solar flux conditions

Series 2: High solar flux conditions

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