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ORIGINAL RESEARCH

RESPONSE OF F2- REGION MAXIMUM ELECTRON DENSITY (NmF2/foF2) TO SOLAR ACTIVITY USING PEARSON PRODUCT MOMENT CORRELATION

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Abstract:

Introduction: The ionosphere owes its origin primarily to ultraviolet radiation from the Sun. The ionosphere is an essential part of the Earth's upper atmosphere. It is ionized by solar radiation and influences transionospheric radio wave propagation. Maximum electron density of the F2- layer (NmF2) is an important parameter for studying the ionosphere. The ionospheric F2-region maximum electron density (NmF2) depends strongly on solar activity, it also suffers temporal and spatial variations.

Aims: The aim of this paper is to investigate the response of NmF2 to solar activity during high solar activity (HSA), moderate solar activity (MSA) and low solar activity (LSA) years using correlation analysis.

Materials and Methods: The data used in this work are the hourly NmF2 values derived from foF2 data observed at Jicamarca (Lat.11.9 ^{o}S, Long.76.8 ^{o}W) and Puerto Rico (Lat.18.5 ^{o}N, Long.67.2 ^{o}W) during high solar activity HSA (2001), moderate solar activity MSA (2011) and low solar activity LSA (2006) years. The NmF2 data were evaluated using the relation in equation 1

$$NmF2 = 1.24 \times 10^{10} (foF2)^2 \qquad (1)$$

Where NmF2 is in el/m^3 and foF2 is in MHz. Pearson Product Moment Correlation (PPMC) equation was used to further analyse the NmF2 data.

Results: Our results revealed two unequal NmF2 peaks. The NmF2 peaks values at Jicamarca (60 - 240; 63 - 204) x 10^{10} el/m^3 are observed to be higher in values than those at Puerto Rico (63 - 187; 57 - 164) x 10^{10} el/m^3. The highest NmF2 peak values of 240 and 187 x 10^{10} el/m^3 occurred during March equinox at 09:00 and 14:00 hours at Jicamarca and Puerto Rico, respectively, during HSA year.

Conclusion: Correlation analysis for the three epochs of solar activity revealed that NmF2 showed positive correlation with sunspot number with highest correlation coefficient values of 0.904 and 0.976 at Jicamarca and Puerto Rico stations respectively during MSA year.

Keywords: Maximum electron density, Sunspot, solar activity, F2 layer.

All co-authors agreed to have their names listed as authors.

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1. INTRODUCTION

The ionosphere owes its origin primarily to ultraviolet radiation from the Sun. The ionosphere is an essential part of the Earth's upper atmosphere. It is ionized by solar radiation and influences trans-ionospheric radio wave propagation. Maximum electron density of the F2- layer (NmF2) is an important parameter for studying the ionosphere. The ionospheric F2-region maximum electron density (NmF2) depends strongly on solar activity, it suffers temporal and spatial variations. It is related to the critical frequency of the F2 layer by the relation shown in section two of this paper. A number of studies have been made to divulge any trends of these F2-layer characteristics as a function of local time, season, and solar/geomagnetic activity. Some of these studies include those of ([11]; [8]; [21]; [12]; [3]; [5]; [2]; [15]; [19]; [23]) had investigated ionospheric variability of the F2 layer critical frequency (foF2) at equatorial and low latitude during high, moderate and low solar activity periods. They reported that equatorial foF2 variability increases with decreasing solar activity. [17]; [16]; [13]; [14]; [3]; [10]; [2]; [9]; [22]; [1]; [6]; [15]; [16]) had examined ionospheric parameters (foF2, hmF2 and NmF2) in correlation with solar indices and their results documented. In most of the work NmF2/foF2 show strong dependence on solar indices like sunspot number (Rz) and solar radio flux on 10.7 cm wavelength (F10.7 cm) used as solar proxy. In this present work the Zurich sunspot number (Rz) was used because it has direct relation with the level of solar activity.

The aim of this study is to examine the response of NmF2 to solar activity during high solar activity (HSA), moderate solar activity (MSA) and low solar activity (LSA) years using Pearson Product moment correlation analysis in two equatorial stations (Jicamarca and Puerto Rico) both in the American sector. This study is significant because the results will be of assistant to radio expert in understanding the trends of NmF2 response to solar activity in equatorial ionosphere in Puerto Rico in particular where such work is still inadequate. In this paper, the second section presents the data and methods of analysis used. The third section treats our ~~our~~ results and discussions. Section four gives the conclusion of the paper.

2. MATERIAL AND METHODS

The data used for this work are the hourly NmF2 values derived from foF2 data observed at Jicamarca (Lat. 11.9°S, Long.76.8°W) and Puerto Rico (Lat 18.5°N, Long. 67.2°W) during high solar activity HSA (2001), moderate solar activity MSA (2011) and low solar activity LSA (2006) years. The NmF2 data were evaluated using the relation in equation 1

$$\mathrm{NmF2} = 1.24 \times 10^{10} (\mathrm{foF2})^2 \qquad (1)$$

where NmF2 is in el/m^3 and foF2 is in MHz
All the available foF2 data from 2001- 2011 where obtained at the local time of these stations from the National Geophysical Data Centre (NGDC) website (https://www.ngdc.noaa.gov). Zurich sunspot data for the same period used as solar activity proxy in this work were also obtained from NGDC. The 12 month running mean Zurich sunspot number Rz12 was used as solar index to define solar activity level for each of the month and year. Seasonal grouping was done by combining the mean monthly hourly values of NmF2 for all days of the months of November, December and January; February, March and April; May, June and July; and August, September and October to represent December Solstice, March Equinox, June Solstice and September Equinox, respectively. Correlation analysis between NmF2 and sunspot number for the three epochs of solar activity was carried out using the Pearson Product Moment Correlation Coefficient (PPMCC) denoted with r given by equation 2

$$r = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{\sqrt{\left(n\sum x_i^2 - (\sum x_i)^2\right)\left(n\sum y_i^2 - (\sum y_i)^2\right)}} \qquad (2)$$

where x_i and y_i represent the two variables and n is the number of available data ([20]; [10]; [16]). In this study x_i is the monthly mean value of sunspot number (Rz) and y_i is the mean monthly hourly values of NmF2. Correlation coefficient (r) is a single number that describe the degree of relationship (comparison) between two variables. It shows how strongly pairs of variables are related. The variables are not designated as dependent and independent. The value of a correlation coefficient varies from -1 to +1 only. A minus one correlation value indicates a perfect negative relationship while a plus one indicates a perfect positive relationship. A correlation of zero means there is no relationship between the two variables [20].

The diurnal variation of the correlation coefficient of NmF2 with Rz for year of maximum solar activity (2001), year of moderate solar activity (2011) and year of minimum solar activity (2006) were investigated by plotting the correlation coefficient values against the hours of the day. Three typical years of different solar activity level were chosen for the study: (i) a year of high solar activity – 2001; (ii) a year of moderate solar activity – 2011; and (iii) a year of low solar activity – 2006. These three typical years were choosen after plotting and studying the graph of Zurich sunspot number (Rz12) over a solar cycle and for different solar epochs as presented in Figure. 1

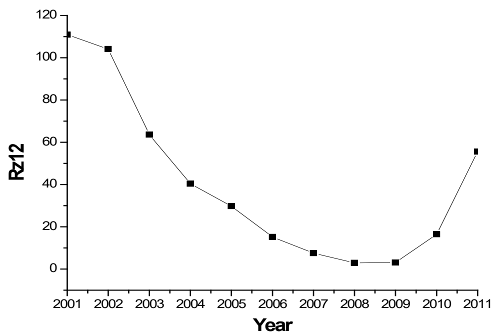


Figure 1: A plot of twelve-months running mean sunspot number (R12) over a solar cycle (2001 – 2011)

3. RESULTS AND DISCUSSION

Figure 1 shows the plot of twelve-month Zurich sunspot number (Rz12) over a solar cycle (2001 – 2011). It was observed that the Rz12 values were high between 2001 and 2002. Thereafter, there was rapid decrease in values of Rz12 after 2002 to 2003 representing descending phase of solar activity. The decrease continues till 2008 where there was comparative equilibrium between 2008 and 2009 representing a period of very low values of Rz12 (low solar activity). After this low solar activity period, there was rapid increase of Rz12 values between 2010 and 2011 representing a period of moderate values of Rz12 (moderate solar activity).

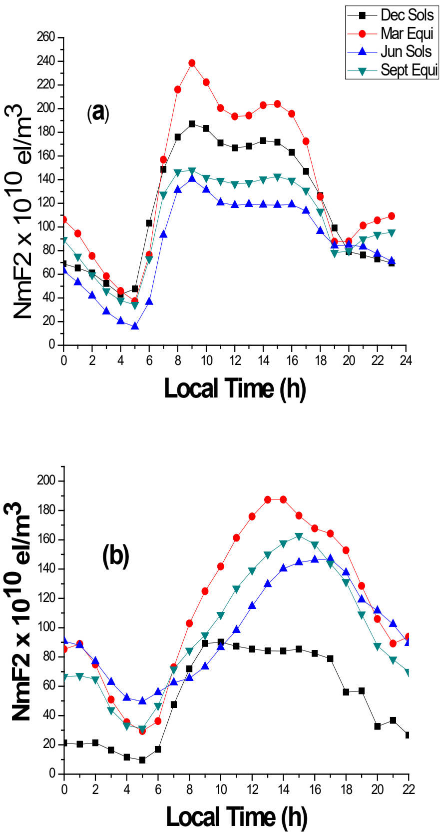


Figure 2: Diurnal variation of equatorial NmF2 values for all seasons during the HSA year (2001) at (a) Jicamarca, and (b) Puerto Rico

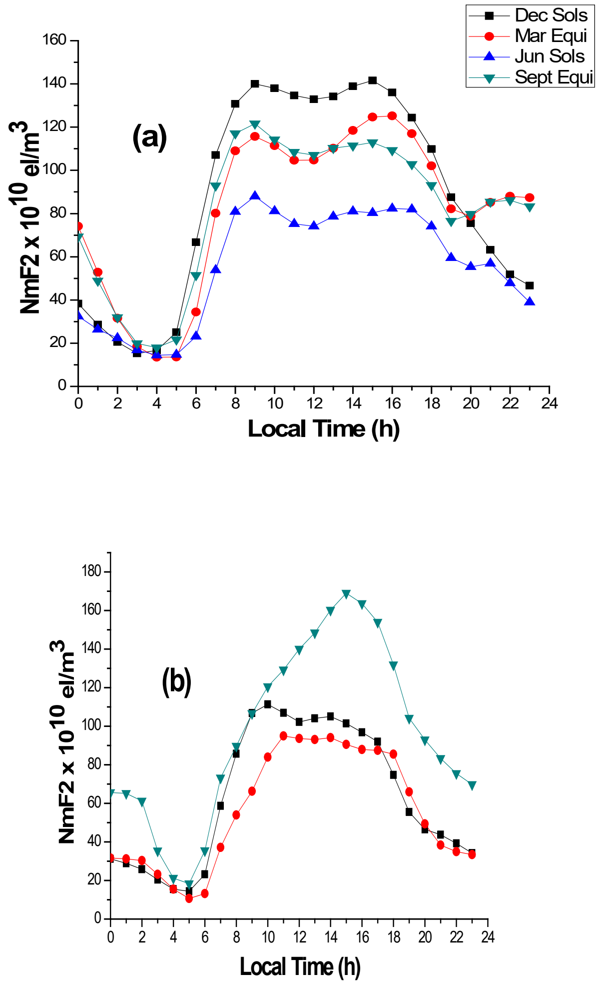
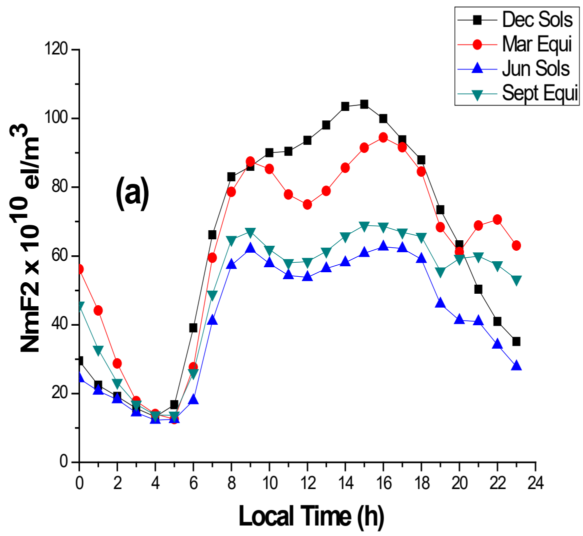


Figure 3: Diurnal Variation of equatorial NmF2 values for all seasons during the MSA year (2011) at (a) Jicamarca, and (b) Puerto Rico



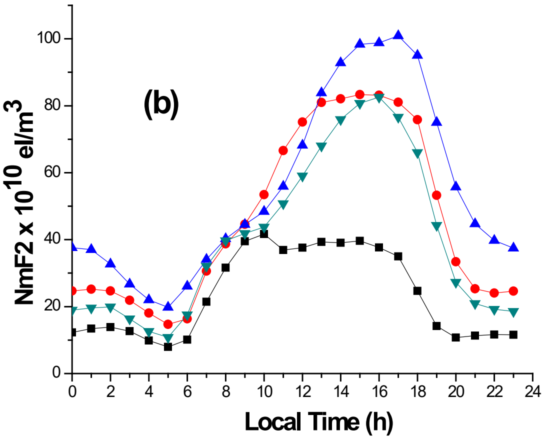


Figure 4: Diurnal Variation of equatorial NmF2 values for all seasons during the LSA year (2006) at (a) Jicamarca, and (b) Puerto Rico

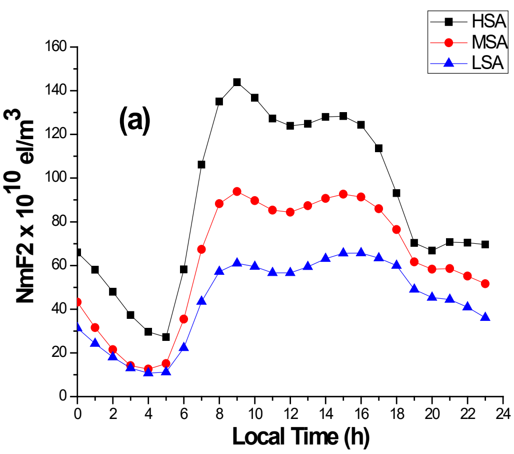
3.1 Diurnal and Seasonal variation of NmF2 with solar activity

Depicted in Figures 2, 3 and 4 (a) – (b) are the diurnal plots of monthly mean values of NmF2 x 10^{10} el/m^3 on seasonal scales against local time (LT) during HSA, MSA and LSA years respectively for the two stations under study. On general consideration, all the plots followed the same trend and were characterized by similar diurnal features, that is low mean values during the night time (1800 - 0500h) with typical post midnight minimum and post sunset minimum, and high mean NmF2 values during the daytime (06:00 - 1800h) with typical maximum occurring before and after noon at both stations. Observation from the plots revealed two typical peaks; pre- sunrise and post - sunset peaks that are more pronounced at Jicarmaca station than at Puerto Rico station due to difference in their latitudinal locations at the equatorial region. The former is located the southern hemisphere a little below the peak of equatorial anomaly (lat. 11.9°S) while the later is located the northern hemisphere a little above the peak of equatorial anomaly (lat. 18.5°N).

From Figures 2(a) - (b), 3(a) - (b), and 4(a) - (b), diurnal variation of NmF2 values increases from sunrise around 05:00 h and reaches its first peak before noon (pre- noon peak) in most cases for all the seasons and during all epochs of solar activity. The highest pre- noon peak values of 248 x 10^{10} el/m^3 were observed during March equinox at Jicamarca and Puerto Rico, respectively, during HSA year and the least pre-noon peak magnitude of 60 x 10^{10} el/m^3 and 45 x 10^{10} el/m^3 were observed during June solstice, respectively, at Jicamarca and Puerto Rico during LSA year. [13] reported similar observation during the equinoctial months.

After that, there is a depletion in NmF2, reaching a minimum around noon, This depletion was well noticed at Jicamarca than at Puerto Rico where it appears almost absent in most cases showing a dome shape profile. This may be due to difference in their latitudinal locations at the equatorial region. The latter is geographically located at the northern hemisphere of equatorial ionization anomaly (EIA) (18.5°N.) while the former is located at the southern hemisphere of equatorial ionization anomaly (EIA) (lat. 11.9°S).

The highest depletion of 52 x 10^{10} el/m^3 was recorded in June solstice at Jicamarca while 36 x 10^{10}el/m^3 was recorded at Puerto Rico in December solstice during LSA year for both stations. A second peak (i.e. the post noon peak) was observed between 14:00 and 17:00 h for the two stations. The magnitude of the post-noon peaks were highest during March equinox for the two station during HSA year with values of 210 x10^{10} and 164 x10^{10} el/m^3, respectively, at Jicamarca and Puerto Rico. This is followed by the post-noon values during MSA year (140 x 10^{10} el/m^3 at Jicamarca during December solstice and 156 x 10^{10} el/m^3 at Puerto Rico during September equinox. The least magnitude of post-noon peaks were recorded during LSA year at both stations. For Jicamarca, the least value is about 60 x 10^{10} el/m^3 occurred during June solstice between 16:00 and 17:00 h. The least value of about 36 x 10^{10}el/m^3 was observed during December solstice between 15:00 h. and 16:00 h at Puerto Rico. The behaviour of the ionosphere over the two stations show that the ionsphere start to build up at sunrise, fully around noon and decreases thereafter, this was due to the fact that the formation of the ionosphere was primarily due to photo-ionisation of the neutral atoms in the upper atmosphere by solar radiation. Although, other factors may also contributed to the modification of the ionization, photo-ionisation was a major factor during the daytime [1]. The night-time ionosphere in this region was largely under the control of transport and loss processes. The pre-noon peak, post-noon peak, and noon time bite out (NBO), observed in electron density values at the F2 region were attributed to the vertical drift of ionisation caused by ***E*** *x* ***B*** force and neutral winds effect on the plasma at the equatorial anomaly region ([8]; [2]).



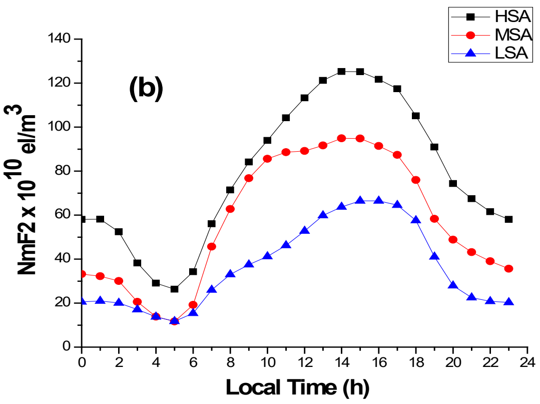
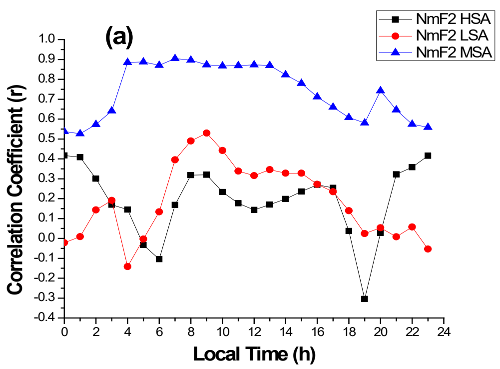


Figure 5: Diurnal variation of equatorial NmF2 derived from annual mean values for all seasons during HSA (2001), LSA (2006), and MSA (2011) at (a) Jicamarca, and (b) Puerto Rico

3.2 Annual variation of NmF2 with solar activity

Figures 5(a) – (b) revealed the same plots like the ones in Figures 2, 3, and 4(a) – (b) but on annual (yearly) scale during HSA (2001), MSA (2011) and LSA (2006) years. Similar trends were observed, that is all the plots followed the same pattern and were characterized by same diurnal features having low mean values during the night- time (18:00 – 05:00h) with typical post midnight minimum and post sunset minimum, and high mean NmF2 values during the daytime (06:00 – 18:00 h) with typical maximum occurring before and after noon at both stations. Observation from the plots revealed two typical peaks; pre-sunrise and post-sunset peaks that were more pronounced at Jicarmaca station than at Puerto Rico station due to difference in their geographical locations at the equatorial anomaly region as earlier explained. [7] reported that the F2 maximum was controlled by enhanced eastward electric fields (EEF) and neutral winds, and this may be supported by diffusion of super fountain plasma from the equator towards Puerto Rico in the equatorial anomaly region.



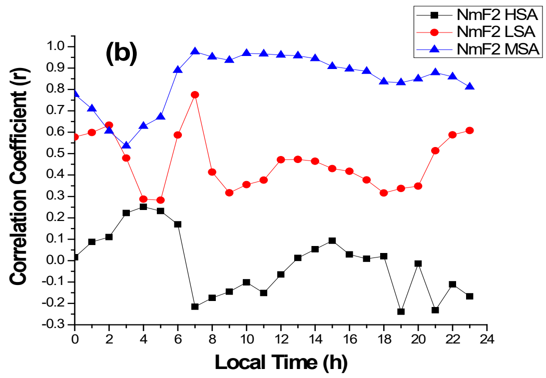


Figure 6: Diurnal variation of correlation coefficient of NmF2 with Sunspot Number Rz, for all seasons during HSA (2001), LSA (2006), and MSA (2011) at (a) Jicamarca, and (b) Puerto Rico

3.3 Diurnal variation of correlation coefficient of NmF2 with Sunspot Number Rz12 during HSA, MSA and LSA

Presented in Figure 6 (a) - (b) are the plots of the yearly correlation coefficient (r) of NmF2 with Sunspot Number (Rz12) derived from annual monthly mean values for all seasons correlated at each hour during HSA (2001), LSA (2006), and MSA (2011). Observation from the plots revealed similar pattern during MSA and LSA year at both stations, but during HSA year the pattern was different. The reason for this may be due to the fact that during HSA year the sun is highly intense, and so the ionosphere is highly disturbed with ionospheric irregularities such as solar flares and equatorial spread F (ESF) which are minima during MSA and LSA years. Also, the difference in dip angle or magnetic dip between the two stations which describe their relative position with respect to the magnetic equator and the trend sign are responsible for the difference observed [15]; [17].

The correlation coefficient (r) between NmF2 and Rz at Jicamarca during MSA year was positive for all the hours. The maximum positive values of 0.90 and 0.74 occurred at 07:00 h during the daytime and 20:00 h during the night-time, respectively. The correlation was fairly stable between 04:00 h and 13:00 h before a gradual fall was noticed till around 19:00 h. This was due to the turn-off of solar radiation while the lifting noticed at night is attributed to the pre-reversal enhancement (PRE) caused by the effect of the E x B forces at the equatorial anomaly region [4]; [7]. During LSA year, r was negative only at 04:00 h and 23:00 h and positive for the rest hours with the highest value of 0.53 and 0.06 occurring at 09:00 h during the day time and 22:00 h during the night time, respectively indicating weak relationship at night.

The correlation r during HSA year was positive at all hours except at 06:00 h and 19:00 h where it was negative as a result of electron depletion caused by other factors other than solar activity such as geomagnetic activities. The highest correlation values of 0.32 and 0.42 were recorded at 09:00 and 23:00 h, respectively, indicating weak relationship. The reason for this is that during HSA year, the sun is very active, and there are so many irregularities affecting the ionosphere.

Similarly, observation from Figure 6(b) depicted positive correlation of NmF2 with sunspot number Rz for all the hours for both MSA and LSA year. During HSA year, the correlation was observed to fluctuate between positive and negative values. Correlation coefficient was negative from 07:00 h to 12:00 h and from 19:00 to 23:00 h. it was positive for the remaining hours. The highest correlation values of 0.3 were observed at 04:00 h. During MSA, the highest correlation values of 0.98 and 0.96 were observed at 07:00 and 11:00 h, respectively, implying very strong relationship between them. For LSA year, the highest values of 0.78 and 0.61 were observed, respectively, at 07:00 h and 23:00h, indicating strong and moderate relationship. The reason for this nonlinear increase of NmF2 with increase solar activity is attributed to photo-ionisation and the fountain effect. This is because during the equinox the sun is directly above at the equator, and in terms of solar control the ionization density is expected to be maximum in that region but that was not the case. Instead, the daytime ionization density at the F2 peak shows a pronounced trough and crests at about 15°N and 15°S magnetic dip. This anomalous latitude variation of F2 ionization near the magnetic equator is known as the equatorial anomaly or *Appleton* anomaly. The equatorial anomaly is the name given to the peculiar latitude variation of the maximum electron concentration (N_m) in the ionospheric F-region (NmF2) which shows a minimum of at dip equator and two maxima on either side around 15° - 20° dip latitude as observed. This was explained in terms of fountain effect caused by vertical electrodynamic drift (***E x B*** force) at the geomagnetic field which gives rise to a vertically upward plasma motion. At higher altitudes over the equator, the plasma encounters field lines that connect to the F2 peak at 15°N and 15°S magnetic dip along which the plasma diffuses under the action of gravity waves in form of a fountain. Such plasma transport depletes the F2 ionization at the equator and increases the density at locations 15 - 20° N and 15 - 20° S [14]; [15]; [6].

According to [17] and the references therein, solar ionizing flux, meterological influences, and solar wind conditions are the origins of changes in the state of the ionosphere. All these effects are dependent on local time, season and solar cycle.

4. CONCLUSION

Diurnal analysis revealed that equatorial NmF2 respond more to solar activity during the day time than at nighttime at these stations with two characteristics peaks (pre-noon and post-noon peaks). The peaks at Jicamarca (60 - 240; 63 - 204) x 10^{10} el/m^3 are observed to be higher in values than those at Puerto Rico (63 – 187; 57 – 164) x 10^{10} el/m^3. Seasonally, the highest NmF2 peak values of 240 and 187 x 10^{10} el/m^3 occurred during March equinox at both stations in HSA year. Annual analysis showed high response of NmF2 to solar activity during HSA year at both stations during the day time. Correlation analysis for the three epochs of solar activity revealed that NmF2 showed strong positive correlation with sunspot number during MSA year and weak correlation during HSA year. Highest correlation values of 0.904 and 0.976 were observed during the day time at Jicamarca and Puerto Rico stations, respectively, during MSA year. These results for MSA period are in agreement with the results reported by other researchers. The day time high correlation indicates a strong daytime response of ionospheric NmF2 to solar activity while the night-time variation in correlation shows the effect of a stronger influence of the upper atmospheric dynamics on ionospheric F2-region.

ACKNOWLEDGEMENTS

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COMPETING INTERESTS

No competing interests exist among the authors.

AUTHORS' CONTRIBUTIONS

Eugene Onori designed the study, performed the statistical analysis, wrote the protocol and the first draft of the manuscript. Emmanuel Somoye and Ogwala Aghogho managed the analyses of the study. All authors Managed the literature searches, read and approved the final manuscript.

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