Journal of Atmospheric and Solar-Terrestrial Physics 182 (2019) 25–30

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Dynamics of sunspot cycle ascending and descending phases asymmetry in equatorial ionospheric variability

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ARTICLE INFO

Keywords:
Equatorial ionosphere
foF2 variability
Sunspot cycle asymmetry
African sector

ABSTRACT

Ionospheric variation from the climatological mean has been extensively studied due to its effect on ionospheric high frequency radio propagation. This work reports foF2 variation at Ouagadougou (geogr. 12°N, 1.8°W, dip ~3°), complementing works that have been done at this station. Nighttime variability is higher than daytime and varies with season but with no consistent pattern. There is an earlier post-midnight peak variability in June solstice (around 0100LT) and occurred between 0400 and 0500LT in other seasons for all sunspot classifications except solar maxima. In this study, we have paid attention to features in the ascending/decending phase of the sunspot cycle and we observed that nighttime ionospheric variability may not always decrease with increasing sunspot number, particularly in the ascending phase. The mechanisms for the difference between observations in the ascending and descending phases could not be identified.

1. Introduction

The subject of the variability of the ionosphere, particularly the quantitative description of deviation from its average behavior, has been the focus of a good number of researches. Ionospheric variation poses challenges to high frequency (HF) propagation, radar surveillance, navigation, and other satellite applications. Modulation of ionospheric photochemistry and electrodynamics by solar activity and geomagnetic disturbance can cause significant deviation of the ionosphere from its climatological mean. Several literature have focused on the subject of ionospheric variability due to the intractable problem it poses to high frequency radio wave propagation (Rishbeth and Mendillo, 2001; Kouris and Fotiadis, 2002a). The role played by the occurrence irregularity and varying intensities of geomagnetic disturbance intensity makes it a continuous field of research. According to Rishbeth and Mendillo (2001), geomagnetic activity complimented by sources from lower atmospheric layers plays a dominant role in the day-to-day variability of the ionosphere/thermosphere system. Literature abound on case studies of low latitude ionospheric variations during geomagnetic storms in the African sector (Adebesin et al. 2013; Adebiyi et al. 2014; Olawepo and Adeniyi, 2012).

Due to the importance of the practical and efficient use of the ionosphere for radio wave propagation, several variability studies has been undertaken at different latitudes and has employed several ionospheric parameters (Jayachandran et al. 1995; Forbes et al. 2000; Rishbeth and Mendillo, 2001; Kouris and Fotiadis, 2002b; Fotiadis et al. 2004; Bilitza et al. 2004). Specific studies on the equatorial ionosphere in the African sector include Bilitza et al. (2004), Adeniyi et al. (2007), Akala et al. (2010a,b) and Abe et al. (2013), as well as in the Asian, American, and Australian sectors (Akala et al., 2011; Khoobchandani et al., 2017).

Several ionospheric parameters from several stations within and outside the Equatorial Ionization Anomaly (EIA) region have been employed for this type of study. It is known that ionospheric variability is highest around the bottomside peak (Oladipo et al., 2008), therefore it is a major contributor to the variability in total electron content. There may be two nighttime variability peaks - the sunrise/postmidnight and sunset peaks (Bilitza et al., 2004; Akala et al., 2010b, 2011) due to the steep density gradient caused by the onset and turnoff of solar ionization (Bilitza et al., 2004). Akala et al. (2010a) observed the post-sunset and post-midnight peaks in June solstice and September equinox, but only the post-midnight peak in March equinox and December solstice. Adebesin et al. (2014) also observed the post-sunset peaks only across all seasons. Some of the general results that have emerged from these studies include higher ionospheric F2-peak variability at nighttime than daytime irrespective of the season, increase in nighttime variability as sunspot activity decrease, annual asymmetry in variability (with solsticial variability higher in December than June),

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https://doi.org/10.1016/j.jastp.2018.10.017
Received 10 February 2018; Received in revised form 4 August 2018; Accepted 25 October 2018
Available online 26 October 2018
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and higher variability at high/subauroral and low latitudes than at mid-latitudes (Aravindan and Iyer, 1990; Kouris and Fotiadis, 2002b, Bilitza et al. 2004; Adeniyi et al. 2007; Akala et al., 2010a; b, 2011; Abe et al. 2013). Greater nighttime variability has been attributed to enhanced energy input into the low latitude ionosphere at night, lack of strong photochemical control (Rishbeth and Mendillo, 2001) and lower electron density (Rishbeth and Mendillo, 2001; Bilitza et al., 2004).

With respect to solar activity effect on variability, most of these past works had employed years in the descending phase of the solar cycle for moderate solar activity while few others employed moderate solar activity years in the ascending phase. However, review of literature revealed that observations may be quiet different if the ascending phase is considered. For example, post-midnight peak in nighttime variability at Dakar (dip: 11.4°N) is higher in 1978 (in the ascending phase of solar cycle 21, with Rz = 98) than in 1973 (in the descending phase of solar cycle 20, with Rz = 38) (Akala et al., 2010a). Likewise at Korhogo (dip: 0.67°S), the post-midnight variability peak is higher in 1998 (in the ascending phase of solar cycle 23, with Rz = 64) than in 1995 (a year of low solar activity between solar cycles 22 and 23, with Rz = 18) (Bilitza et al., 2004). Therefore, there seems to be some asymmetry in foF2 variability characteristics in the descending and ascending phases for similar solar activity levels. As highlighted in this section, observations from past studies have been biased towards MSA years in the descending phase of different sunspot cycles. Some works (Bilitza et al. 2004; Adebesin et al. 2014) have suggested that observations may be quiet different in the ascending phase. Therefore, this work focuses on the descending/ascending phase asymmetry in the nighttime variability around the magnetic equator.

2. Data and methodology

This study was carried out with data from the ionsonde located at Ouagadougou, Burkina-Faso (geogr. 12°N, 1.8°W, dip ~3°). Several works in the African sector employed the same set of data used for this work. These include Bilitza et al. (2004), Adeniyi et al. (2007). Ikubanni and Adeniyi (2016) commented on Ouagadougou data as an additional information. The sounder is an analogue vertical type called the Ionospheric Prediction Service (IPS-42). The data are products manually scaled ionograms produced by the sounder. The quality of the data has been validated with the International Reference Ionosphere (IRI); however, some missing data has been attributed to spread-F occurrence (Adeniyi and Radicella, 1998). The years used and the corresponding sunspot number are presented in Table 1. The years were classified into four epochs according to Ouattara and Amory-Mazaudier (2012). The year of solar maximum used is a good representation of very high solar activity. Adeniyi and Ikubanni (2013) had earlier shown that for the station used for this work, differences in ionospheric response to moderate and high solar activity is substantial when the radio solar flux of 10.7 cm wavelength (F10.7) is ~155 solar flux unit (sfu) and above. This is an equivalent Rz of approximately 110 (https://spawx.nwra.com/spawx/comp.html; Accessed: April 6, 2017). The months in each year were classified into four seasons as follows: March Equinox (Febraury, March, April), June Solstice (May, June, July), September Equinox (August, September, October) and December Solstice (November, December, January). Variability of different ionospheric parameters have been studied adopting different approaches. A summary of several statistics that have been used for variability studies include: the upper (q_{75}) and lower quartiles (q_{25}), median quartiles (q_{50}), and/or deciles (q_{10} , q_{90}), inter-quartile range fraction of the median ($q_{75} - q_{25}$/median) (Kouris and Fotiadis, 2002b; Fotiadis et al., 2004; Ezquer et al., 2004), and relative deviations from the monthly median (Kouris and Fotiadis, 2002a; Mitic and Cander, 2008).

The use of standard deviation (σ) as the measure of the variability of foF2 is appropriate for characterizing the average deviation from the monthly mean, if the data follows Gaussian distribution (Snedecor and Cochran, 1989). Ouagadougou data distribution closely follows Gaussian distribution and there is at least a 0.68 probability that at least 63% the observed foF2 data lie within the range $\mu \pm \sigma$ (where μ is the statistical mean) (Adeniyi et al., 2007). However, results with σ may be more difficult to interpret in terms of probability than some other parameters (e.g. q_{75}, q_{25}, q_{50}, and/or q_{10}, q_{90}) that may disregard a reasonably portion of dataset (Bilitza et al., 2004). The relative standard deviation (rather than the absolute) expressed as percentage ratio of σ to μ is adopted as the variability index for this work. This is to help achieve one of the objectives of this work, which is to achieve fair comparison with previous works form the EIA region and to investage the asymmetry in the sunspot activity dependence of nighttime ionospheric variability during years of MSA in the ascending and descending phase of a sunspot cycle, and compare with past works. The adopted variability index was coined variability ratio (VR) by Bilitza et al. (2004) and coefficient of variability (CV) by Akala et al. (2010a,b; 2011). This is expressed mathematically as:

$$CV\ (\%) = \left(\sigma/\mu\right)*100$$

Ouagadougou is an equatorial station near the EIA trough. During the period the data was collected (solar cycle 22: 1985–1993), its geomagnetic latitude varied between 0.73°N and 0.59°N (http://www.ukssdc.ac.uk/cgi-bin/wdcc1/coordcnv.pl). Hence, it falls within the equatorial electrojet (EEJ) belt. Therefore, observations reported here are good representations of EIA trough region. The adoption of CV (or VR) for several works in the equatorial station is evident in literature and appropriate (Adeniyi et al., 2007). For other latitudinal classifications, investigations of the data distribution types could assist with identifying the appropriate statistical tools for variability studies (Ikubanni and Adeniyi, 2017). The monthly mean values calculated using the entire data set for the month were employed as the reference monthly average. Ikubanni and Adeniyi (2017) had shown that likely differences in either adopting monthly mean or median are negligible. Likewise, estimating monthly mean with data that corresponds to quiet-time conditions only is inconsequential around the EIA trough.

3. Result and discussion

3.1. Seasonal observations

Fig. 1 presents the diurnal seasonal plot of foF2 variability for each of the classes of solar activity. The figure contained the diurnal plot of CV for the **four** seasonal classifications in each phase of solar activity, which include: a year of low solar activity (LSA) – top-left panel; a year of moderate solar activity in the ascending phase (aMSA) – top-right panel; a year of moderate solar activity in the descending phase (dMSA) – bottom-left panel; and a year of solar maximum (HSA) – bottom-right panel.

The general features are: Lower daytime variability which has been attributed to higher foF2 average values (Bilitza et al., 2004), gravity waves (Akala et al., 2011) and strong photochemical control of the daytime ionosphere (Rishbeth and Mendillo, 2001). Photochemical processes in the daytime ionosphere is driven by solar activity which is nearly constant for a short time (that is, from day-to-day) and changes over a long period (that is, year-to-year); thus a very low daytime

Table 1
Employed years in the different solar activity phases epochs and their respective sunspot numbers (Rz).

YEAR	Rz	PHASE
1985	18	Minimum
1987	29	Ascending Phase
1993	55	Descending Phase
1989	158	Maximum

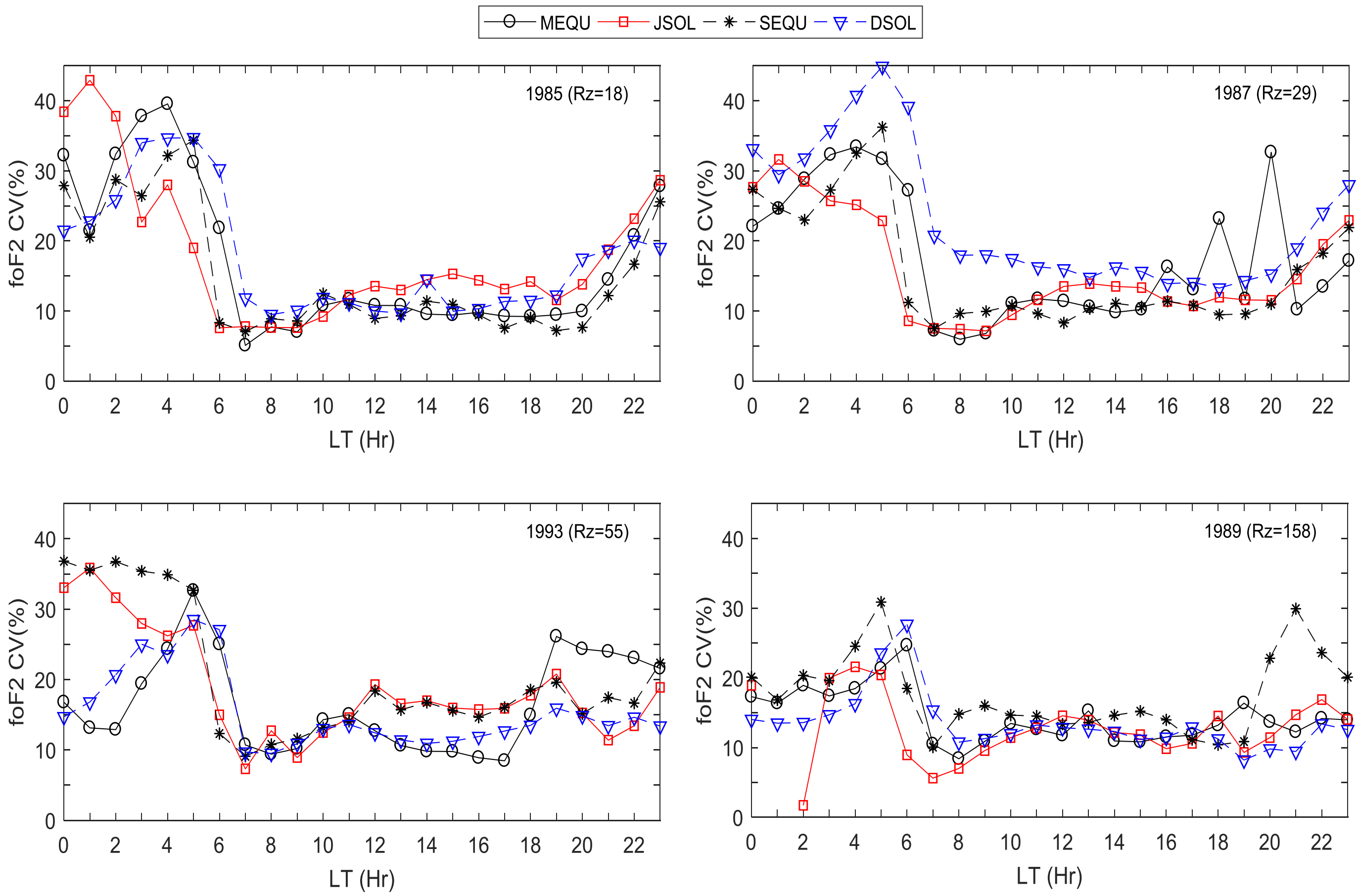

Fig. 1. The diurnal variation of foF2 coefficient of variability for all seasons in (i) 1985 – a year of low solar activity/solar minimum (top-left), (ii) 1987 – a year of moderate solar activity in the ascending phase (top-right), (iii) 1993 – a year of moderate solar activity in the descending phase (bottom-left), and (iv) 1989 – a year of high solar activity/solar maximum (bottom-right). Rz is the yearly mean sunspot number.

variability. The higher variability during the nighttime is due to lack of strong solar activity influence. It has been noted that, transport and recombination are the major processes that sustains the nighttime ionosphere. Sharp rise and drop in variability after sunset and around sunrise respectively has been attributed to turnoff and onset of solar radiation (Bilitza et al., 2004), and similar daytime variability across all solar epochs considered. It is worth mentioning that postmidnight variability is higher in December solstice than in June solstice in aMSA and lower in dMSA.

During LSA (Rz = 18), the following features were observed (Fig. 1, top-left). Nighttime variability increases steadily from ~12% at 1900 LT in both solstices to a peak of ~43 and ~35% at 0100 LT in June and 0400 LT in December solstices respectively. It increases from ~9% around 1800 LT to a peak of ~40% at 0400 LT in March equinox and from ~8% at 2000 LT to a peak of ~34% at 0500 LT during September equinox. After the different postmidnight peaks in each season, variability decreases rapidly until sunrise. Nighttime variability peaks earlier (0100 LT) in June solstice.

During aMSA (Rz = 29), the following were observed (Fig. 1, top-right). Nighttime variability increases steadily from ~12% (at 2000 LT) in June solstice and ~13% (at 1800 LT) in December solstice. It then reached a peak of ~32 (at 0100 LT) and ~45% (at 0500 LT) in June and December solstices respectively. After the different nighttime peaks, variability then decreases rapidly until sunrise. The nighttime variability peaks earlier (0100 LT) in June solstice, compared to other seasons.

During dMSA (Rz = 55), the following were observed (Fig. 1, bottom-left). Nighttime variability increases from around sunset (~1700 LT). In March equinox, there was a sharp increase in nighttime variability (~8–~26%) that lasted about 2 h (between 1700 and 1900 LT) while it decreases steadily from ~26 to ~13% through the midnight over a period of 7 h, before increasing to a peak value of ~33% at 0500 LT. In other seasons, the nighttime variability became substantially larger than daytime after midnight, and increased to postmidnight peaks of ~36% (at 0100 LT) in June solstice, ~29% (at 0500 LT) in December solstice, and ~37% (at midnight) in September equinox, where it remained almost unchanged until 0500 LT.

During HSA (Rz = 158), the following were observed (Fig. 1, bottom-right). Nighttime variability became substantially larger than daytime after midnight in all seasosn except September equinox, where it increases sharply from 10% at 1800 LT to a peak of 30% at 2100 LT and then decreases until around 0100 LT before increasing to a postmidnight peak of ~31% at 0500 LT. In other seasons, nighttime variability inceases substantially from midnight to peaks of ~25 and ~28% (at 0600 LT) in March equinox and December solstice. The differences in the magnitude of daytime and nighttime variability is lower during solar maximum than other solar activity phases.

Generally, there is no consistent seasonal variability pattern across the four solar epochs, This is in agreement with previous works (Bilitza et al., 2004; Akala et al., 2010a; b; Akala et al., 2011). Ratovsky et al. (2014) had highlighted factors affecting seasonal pattern of variability in F2-peak electron density to be the photochemical control, geomagnetic activity, and meteorological activity. While photochemical factors dominates the mid-latitude nighttime ionosphere (Ratovsky et al., 2014), influences of geomagnetic and meteorological activity have been known to be comparable and dominant in the low-latitude due to energy input from high latitudes (Rishbeth and Mendillo, 2001).

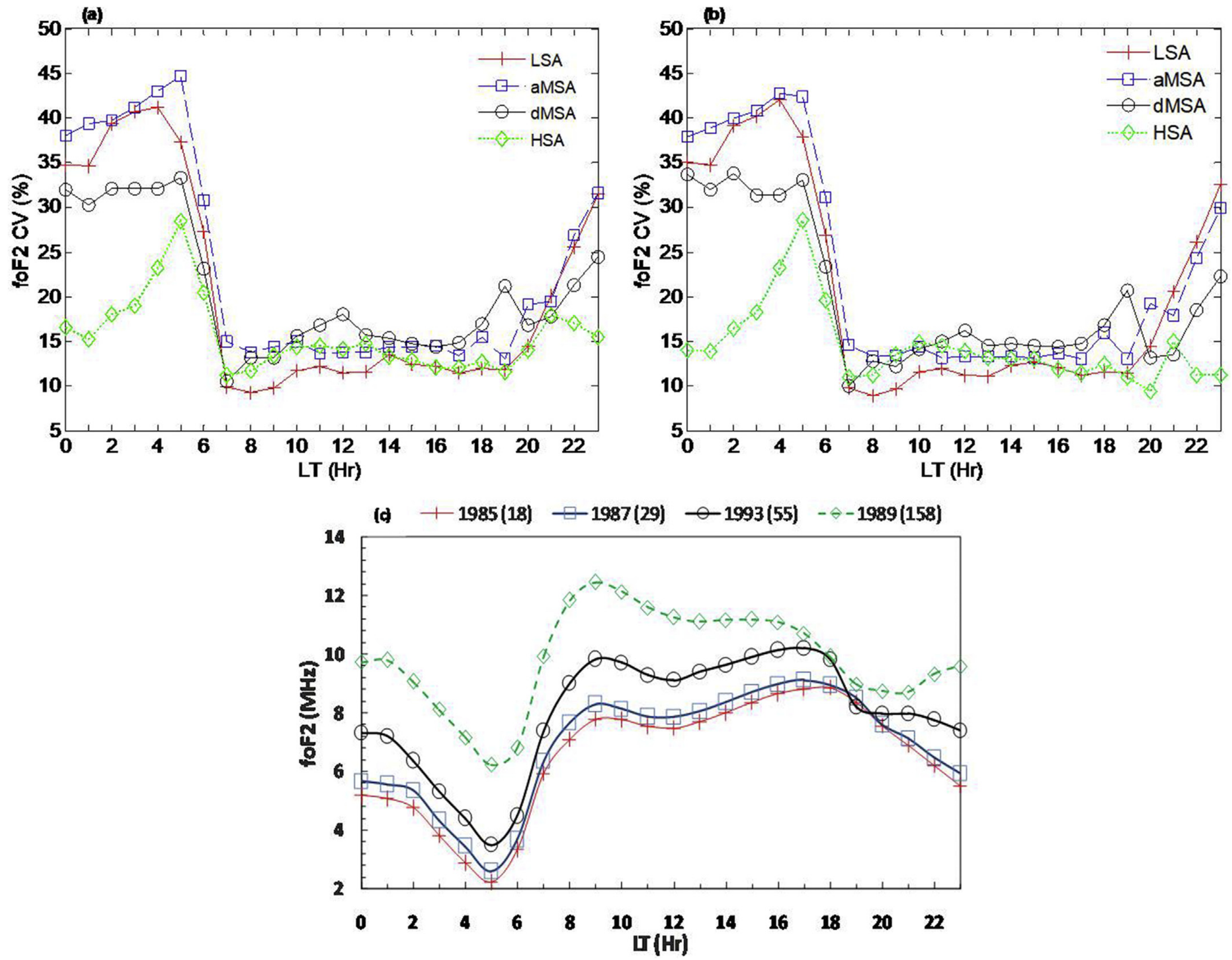

Fig. 2. Diurnal variation of foF2 coefficient of variability for the four sunspot activity phases using (a) all the available data, and (b) excluding disturbed days (days with *Ap* > 20). (c) Annual foF2 hourly mean for the four years of different solar activity with the average sunspot number in parenthesis. [LSA(cross), aMSA(square), dMSA(circle), HSA(diamond)].

3.2. Annual and solar cycle observations

Fig. 2 presents the superposed plots of coefficient of variability (panels 'a'&'b') and the foF2 annual hourly averages (panel 'c') during the different solar epochs. The CV plots in 'panel a' were obtained from all the available daily data for the years under consideration while those presented in 'panel b' were obtained from the same data set but excluding days with *Ap* > 20. Generally, nighttime variability increases at sunset through the midnight until pre-sunrise hours. It increases from ~12% (at 1900 LT) to ~41% (at 0400 LT) in solar minimum, from ~13% (at 1900 LT) to ~45% (at 0500 LT) in moderate solar activity in the ascending phase, from ~17% (at 2000 LT) to ~33% (at 0500 LT) in moderate solar activity in the descending phase (aMSA), and from ~12% (at 1900 LT) to ~28% (at 0500 LT) in solar maxima.

There is rapid increase in variability from after sunset until post-midnight during LSA, this results in considerable difference in the variability values between post-sunset and pre-sunrise periods during solar minimum and maximum. Likewise, our observations reveal highest nighttime variability during LSA and lowest in HSA along the descending flank of the sunspot cycle (that is, where the MSA year falls in the descending phase). This result resonates with literature (Bilitza et al., 2004; Adeniyi et al., 2007; Akala et al., 2010a; b; 2011), with nighttime variability increasing with decreasing sunspot number. On the other hand (that is, in the ascending flank), nighttime variability is highest in aMSA than the LSA and HSA. Our observations suggest that nighttime variability may not always increase with decreasing sunspot activity along the ascending flank of sunspot cycle.

Bilitza et al. (2004) and Akala et al. (2010a) related the low/high variability to high/low mean foF2 respectively. Since the index of variability employed is fraction of the mean, daytime variability is expected to be lower than nighttime variability for the same magnitude of deviation due to higher mean values in the daytime and consequentially, nighttime variability should decrease as the mean foF2 increases with increasing solar flux levels. Fig. 2, panel 'c' shows complete solar activity control of both daytime and nighttime average foF2. Panel 'c' is the hourly yearly mean foF2 for the four years considered. From the plot, the differences between the mean foF2 for each hour is clearly shown from year to year as their sunspot number increases. There seems to be insignicant difference between the plots for aMSA and dMSA.

It then follows that daytime and nighttime variability should also follow the solar cycle pattern, but this was not observed as presented in panels 'a' & 'b'. The nighttime variability is highest in 1987 (Rz = 29) followed by 1985 (Rz = 18), then 1993 (Rz = 55) and lowest in 1989 (Rz = 158). Previous results have shown that nighttime variability is higher during LSA than MSA because of increasing variability with decreasing sunspot number, as observed between 1985 (LSA) and 1993 (dMSA) in this study. The opposite was however observed between 1985 (LSA) and 1987 (aMSA), where nighttime variability was higher in the latter. This is a major difference observed between years in the descending and ascending phase.

Hysteresis effect on the Earth's magnetic field affects its upper atmosphere thereby causing asymmetry in F2-layer electron density between the ascending and descending phase of a sunspot cycle at identical magnitude of solar activity. This effect is substantial at mid-latitude, but negligible at equatorial/low and high latitude (Gopal Rao and Sambasiva Rao, 1969) and thus may not be considered in forecasting applications at low and high latitudes. Gopal Rao and Sambasiva Rao (1969) had earlier suggested geomagnetic activity, which is greater during the descending phase than the ascending phase, as the driver of hysteresis effect. Solar magnetic activity lags sunspot activity by about 2 years, leading to asymmetry in the frequency and/or intensity of magnetic activity between the rising and falling phase (Huang and Jeng, 1976). The variation of magnetic storm intensity and occurrence causes differences in foF2 at same sunspot number (Appleton and Piggott, 1955). On the other hand, Ozguc et al. (2008) reported that strength of the hysteresis effect differs for different cycles and submitted that hysteresis is a consequence of both meteorological influence and solar wind conditions. Other reported asymmetry between descending and ascending phase include: differences in the diurnal foF2 variation (Ouattara and Amory-Mazaudier, 2012), the presence of annual variation in low latitude TEC in the ascending phase of SC24 and its absence in the descending phase of SC23 (Rao et al., 2013). Ouattara and Amory-Mazaudier (2012) attributed their observations to difference in sources of geomagnetic disturbance from one phase to another. Rao et al. (2013) attributed the manifestation of annual variation to solar flux variation and/or variations of Equatorial Electrojet (EEJ) strength during different seasons.

Therefore, disturbed days were identified from the data used for our analysis. Day-to-day Ap variations is a good geomagnetic disturbance indicator (Rishbeth and Mendillo, 2001). The percentage of disturbed days ($Ap > 20$) in each year are presented in order of increasing sunspot number (1985, 1987, 1993, and 1989) as 17, 16, 25, and 32% respectively. Rishbeth and Mendillo (2001) had earlier reported increase in mean Ap as sunspot number increases, however with higher mean Ap in the descending than ascending phase. The planetary geomagnetic activity index, Ap, has been identified as a good proxy for day-to-day measure of geomagnetic disturbances, since it is believed to consist measures of contributions from the equatorial ring current (Dst) and high latitude Auroral Electroject (AE) current (Fares Saba et al., 1997; Adebesin, 2016). By extracting the disturbed days and working with quiet days ($Ap \leq 20$) only, there was no noticeable change in the nighttime variability pattern (compare panels 'a' & 'b' in Fig. 2). In other words, the superposed CV plots of all four years considered (Fig. 2, panels 'a' and 'b') reveal a consistent pattern of very low variability in daytime and high variability at nighttime. This could imply relegating the influence of geomagnetic disturbance in the observed solar activity dependence of nighttime variability. Thus, it may be safe to say that the observed asymmetry between the descending and ascending phase may unlikely be due to geomagnetic factors.

Ionospheric variability is not only due to long-term mechanism, but short term and day-to-day mechanism such as the varying strength of the electric fields measured by EEJ. Dabas et al. (2006) had proposed EEJ strength as a predictor of day-to-day ionospheric variability. Rishbeth and Mendillo (2001) summarized the possible drivers of F2-layer variability as solar radiation, geomagnetic disturbances, meteorological sources from lower atmospheric layers, and electrodynamics. From the previous discussion, the unlikely role of geomagnetic disturbance and solar influx in the unexpected result of nighttime variability in aMSA has been mentioned, this leaves us with the other two classes of drivers. Meteorological influences in form of atmospheric waves and electrodynamics such as F-region neutral wind have been shown to cause large perturbations during extreme solar minimum (Liu et al., 2010). The key role of meteorology in day-to-day ionospheric variability is demonstrated recently (Liu et al., 2013).

4. Conclusion

We have investigated the diurnal, seasonal, and sunspot cycle variation of the ionospheric bottomside peak electron density (represented as foF2) over Ouagadougou, an equatorial station in the African sector. In agreement with published literature, nighttime variability is higher than daytime variability with no consistent seasonal pattern across different solar activity phases during daytime. The distinct seasonal pattern observed during the nighttime is the post-midnight variability peak, which occurred around 0100 LT in June solstice and between 0400 and 0500 LT in the other seasons besides sunspot maximum period. Nighttime variability increases with decreasing sunspot activity in the equatorial and low latitude regions, particularly when comparing years of HSA, MSA and LSA, as reported in published literature. However, critical examination of these literature suggest that this observation may be limited to MSA years that falls in the descending phase of the sunspot cycle. This work revealed that, in deviation from what has been established in previous literature, nighttime variability may be greater during MSA than either LSA and HSA, particularly in the ascending phase. Asymmetry in nighttime variability of the year in the descending and ascending phases is more pronounced in the D-season. The differences between the effect of solar activity at moderate solar activity during the ascending and descending phase of the sunspot cycle may be due to hysteresis effect in foF2. The F2-layer is highly controlled by the $E \times B$ dynamics, and magnetic field, B, is known to be prone to hysteresis. While day-to-day variability factors such as gravity waves and neutral winds may contribute to the asymmetry observed between the falling and the rising phases, the major mechanism responsible is yet to be identified.

Acknowledgments

The authors appreciate R. Hanbaba of the Centre National d'Etudes des Telecommunications, Lannion, France, for the Ouagadougou ionograms. The sunspot number was retrieved from National Oceanic and Atmospheric Administration (NOAA) (http://www.ngdc.noaa.gov/stp/space-weather/solar-data/solar-indices/sunspot-numbers/international/listings/).

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