© JAN 2026 | IRE Journals | Volume 9 Issue 7 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I7-1713231

Morphology of M(3000)F2 At an African Equatorial Sector

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Abstract- This study examined the morphology of the ionospheric propagation factor M(3000)F2 over an African equatorial sector using long-term ionosonde observations from Korhogo, Ivory Coast. Existing published datasets covering the period from January 1993 to December 2000 were analyzed to investigate the diurnal, seasonal, and interannual characteristics of M(3000)F2. Hourly values were averaged to obtain monthly and seasonal mean profiles, and the data were classified into equinoctial and solstitial seasons to highlight systematic morphological patterns. The results showed that M(3000)F2 exhibited pronounced diurnal variability characterized by sharp post-sunrise maxima, extended daytime minima, prominent post-sunset enhancements, and sustained nighttime peaks across all seasons. Seasonally, higher M(3000)F2 values were consistently observed during the equinoxes compared to the solstices, indicating enhanced equatorial electrodynamic activity during equinoctial periods. Interannual analysis revealed that M(3000)F2 values were generally higher during years of low solar activity and reduced during years of elevated solar activity, although the fundamental diurnal structure remained largely invariant throughout the study period. These findings demonstrated that the morphology of M(3000)F2 at the African equatorial sector was primarily controlled by equatorial electrodynamic processes, including vertical plasma drifts and pre-reversal enhancement, with solar cycle conditions modulating the magnitude of variability. The study provided valuable observational evidence from a data-sparse region and contributed to improved understanding of equatorial ionospheric behavior relevant to high-frequency radio propagation and ionospheric modeling.

Keywords: M(3000)F2; Equatorial Ionosphere; Diurnal And Seasonal Variation; HF Radio Propagation; African Sector

I. INTRODUCTION

The ionosphere constitutes a critical region of the Earth's upper atmosphere in which solar radiation ionizes neutral particles, producing free electrons that strongly influence radio wave propagation. Among the ionospheric layers, the F2 layer is of paramount importance because it persists both day and night and supports long-distance high-frequency (HF) radio communication (Davies, 1990; Rishbeth & Mendillo, 2001). The variability of this layer introduces uncertainty into communication systems, navigation applications, and space-weather-sensitive technologies.

A widely adopted parameter for assessing HF propagation conditions is the propagation factor M(3000)F2, defined as the ratio of the maximum usable frequency (MUF) for a 3000 km radio path to the critical frequency of the F2 layer (foF2). Unlike foF2, which depends mainly on peak electron density, M(3000)F2 incorporates information about the height, curvature, and effective thickness of the F2 layer, making it a sensitive indicator of ionospheric morphology (Davies, 1990; Zolesi & Cander, 2014).

$$M\ (3000)F2 = \frac{MUF\ (3000)}{foF2} \qquad (1)$$

Equatorial ionospheric regions exhibit particularly complex behavior due to the dominance of electrodynamic processes such as the equatorial electrojet (EEJ), vertical E × B plasma drifts, the equatorial ionization anomaly (EIA), and pre-reversal enhancement (PRE) of the zonal electric field (Fejer et al., 1999; Anderson et al., 2004; Kelley, 2009). These mechanisms produce pronounced diurnal and seasonal variations in F2-layer height and structure, which are directly reflected in the morphology of M(3000)F2. Despite the scientific and operational importance of equatorial ionospheric studies, the African equatorial sector remains comparatively under-represented in long-term observational analyses (Bilitza, 2018). Most existing empirical models rely heavily on data from American and Asian longitude sectors, often leading to reduced accuracy when applied to Africa (Adebesin et al., 2013; Arowolo & Adeniyi, 2016). This study therefore focuses on the morphology of M(3000)F_2 over Korhogo, Ivory Coast, an equatorial station located within the West African ionospheric belt, using long-term ionosonde observations.

II. STATEMENT OF THE PROBLEM

Accurate characterization of the ionospheric F2 layer is fundamental to reliable high-frequency (HF) radio communication, satellite operations, and space-weather forecasting. One of the most important propagation parameters used in this regard is the ionospheric propagation factor M(3000)F2, which reflects not only the peak electron density of the F2 layer but also its effective height and curvature, thereby providing a more comprehensive measure of HF propagation capability than foF2 alone (Davies, 1990; Zolesi & Cander, 2014). However, the equatorial ionosphere is known to exhibit highly complex and nonlinear behavior driven by electrodynamic processes such as vertical E × B plasma drifts, equatorial electrojet activity, and pre-reversal enhancement, all of which introduce substantial temporal variability into M(3000)F2 (Fejer et al., 1999; Kelley, 2009; Abdu, 2016).

Despite its scientific and operational importance, the morphology of M(3000)F2 at equatorial latitudes remains insufficiently documented, particularly within the African longitude sector. Most existing empirical and climatological studies of M(3000)F2 have been concentrated in the American, European, and Asian sectors, where long-term ionosonde datasets are readily available (Rishbeth & Mendillo, 2001; Liu et al., 2006). Consequently, global ionospheric models and prediction tools often rely on geographically biased datasets, leading to significant uncertainties when applied to African equatorial conditions (Bilitza, 2018; Adebesin et al., 2013).

Furthermore, previous ionospheric investigations in Africa have predominantly emphasized electron density parameters such as foF2 and total electron content (TEC), while propagation-oriented parameters like M(3000)F2 have received comparatively little attention (Adeniyi, 1996; Oyekola, 2013). This imbalance has limited the understanding of HF propagation behavior over Africa, where communication systems are particularly sensitive to ionospheric variability. The absence of detailed long-term morphological studies of M(3000)F2 has also constrained the validation and regional adaptation of global ionospheric models for African equatorial environments (Obrou et al., 2009; Bilitza et al., 2020).

As a result, there exists a clear scientific gap in the comprehensive characterization of the diurnal, seasonal, and interannual morphology of M(3000)F2 over African equatorial stations using long-term observational data. Addressing this gap is essential for improving the physical understanding of equatorial ionospheric dynamics, enhancing the reliability of HF radio propagation predictions, and strengthening the representation of the African sector in global ionospheric modeling and space-weather research.

III. LITERATURE REVIEW

Early investigations into ionospheric radio propagation established the propagation factor M(3000)F2 as a fundamental parameter for estimating maximum usable frequency over long-distance HF radio paths. Davies (1990) provided one of the most comprehensive treatments of ionospheric propagation parameters, demonstrating that M(3000)F2 is strongly influenced by the height and shape of the F2 layer rather than electron density alone. Subsequent studies emphasized that variations in M(3000)F2 reflect changes in thermospheric composition, neutral winds, and electric fields, making it a sensitive diagnostic of ionospheric structure (Rawer, 1993; Zolesi & Cander, 2014).

At low and equatorial latitudes, ionospheric morphology is dominated by electrodynamic processes that differ significantly from mid-latitude mechanisms. Rishbeth and Mendillo (2001) showed that vertical E × B plasma drifts play a central role in controlling F2-layer height and thickness near the magnetic equator, thereby strongly modulating M(3000)F2. Fejer et al. (1999), using incoherent scatter radar and satellite observations, demonstrated that diurnal variations in zonal electric fields produce characteristic daytime minima and post-sunset enhancements in F_2-layer parameters, features that are consistently reflected in M(3000)F2 behavior.

Several global and regional studies have documented the diurnal morphology of M(3000)F2, revealing persistent sunrise peaks, daytime troughs, and nighttime maxima. Liu et al. (2006) analyzed long-term ionosonde data from multiple low-latitude stations and reported that M(3000)F2 typically decreases during periods of enhanced solar activity due to compression of the F2 layer. Danilov and Lastovicka (2012) further confirmed that solar cycle effects primarily modulate the amplitude of M(3000)F2, while its diurnal structure remains relatively stable across solar conditions. Seasonal variations of M(3000)F2 have also been widely reported, particularly the equinoctial enhancement observed at equatorial and low-latitude stations. Rishbeth (2000) attributed this phenomenon to changes in solar zenith angle and thermospheric wind circulation that enhance upward plasma transport during equinoxes. Stolle et al. (2008) reinforced this interpretation by linking equinoctial maxima in ionospheric parameters to increased symmetry in hemispheric conductivity and intensified electrodynamic coupling, effects that directly influence M(3000)F2 morphology.

In contrast to the extensive literature from American and Asian longitude sectors, studies focusing on Africa remain limited. Adeniyi (1996) provided one of the earliest detailed analyses of ionospheric parameters over West Africa, highlighting strong diurnal and seasonal variability associated with equatorial electrodynamics. Obrou et al. (2003, 2009) examined F2-layer characteristics over equatorial stations in Côte d'Ivoire and Burkina Faso, reporting pronounced post-sunset enhancements and equinoctial maxima consistent with global equatorial behavior. However, these studies primarily emphasized foF2 and hmF2, with limited attention given to propagation-specific parameters such as M(3000)F2.

More recent African studies have attempted to address this gap. Oyekola (2013) analyzed ionosonde observations from Nigerian stations and showed that M(3000)F2 exhibits clear seasonal dependence, with higher values during equinoxes and reduced values during solstices. Adebesin et al. (2013) further demonstrated that global ionospheric models often underestimate African equatorial ionospheric parameters due to insufficient regional data input. Bilitza (2018) and Bilitza et al. (2020) emphasized that improving the representation of African ionospheric observations is critical for enhancing the performance of empirical models such as IRI.

Regression-based and modeling studies have also explored the relationship between M(3000)F2 and solar activity. Tukhashvili et al. (2003) applied regression techniques to model M(3000)F2 variations and found a generally inverse relationship between M(3000)F2 and solar flux indices. Similar conclusions were reported by Abdu (2016), who noted that increased solar EUV radiation tends to lower the effective reflection height of the F_2 layer, thereby reducing M(3000)F2 values, particularly during daytime hours. Overall, the existing literature demonstrates that while the general morphology of M(3000)F2 is reasonably well understood at global and low-latitude scales, significant gaps remain in the African equatorial sector. Most prior African studies have focused on electron density parameters, leaving propagation-oriented metrics underexplored. Consequently, there is a clear need for long-term, morphology-focused investigations of M(3000)F2 using African ionosonde data to strengthen regional understanding and improve global ionospheric modeling accuracy.

IV. METHODOLOGY AND RESULTS

Data and Analysis Procedure

The analysis utilized ionosonde-derived M(3000)F2 data obtained from the Korhogo ionosonde station (9.33°N, 5.42°W). Existing published datasets covering January 1993 to December 2000 were employed. This period spans moderate to high solar activity conditions and provides adequate temporal coverage for identifying persistent morphological features. Hourly values of M(3000)F2 were averaged to obtain monthly and seasonal means. The seasons were classified into March equinox, June solstice, September equinox, and December solstice, following standard ionospheric practice (Rishbeth & Mendillo, 2001; Obrou et al., 2009). This approach minimized short-term variability and highlighted systematic diurnal and seasonal structures.

Table 1: Typical sample of M(3000)F2 data

KORHOGO CARACTERISTIQUE: 03 M(3000)F2

JANVIER 1996

	0000	0100	0200	0300	0400	0500	0600	0700	0800	0900	1000	1100
1	U330F	327	335	304F	L	L	L	F	324	285	264R	U238H
2	U332F	324S	332	317S	326	341	348	310	293	286	264G	269G
3	L	L	L	L	336F	L	L	331	306	U278R	U256R	255G
4	L	336S	F	L	347F	F	361	326	329	307R	286R	272
5	U325F	341	332	348	340	326	F	331	310	279H	260	260
6	338	F	L	320F	L	340F	362	326	311	268	266	252G
7	L	L	F	338	324	F	341	324	302	277	283	264
8	L	L	L	L	L	E	E	326	307	274R	273R	238
9	L	L	F	L	F	L	S	357	316	U285R	259R	276G
10	L	L	L	L	L	L	E	347	314	269R	276	250G
11	L	L	L	F	L	E	E	328	303	272	262	249G
12	L	L	318S	298	336	348F	E	348	327	294S	C	C
13	L	349F	L	F	L	S	E	348	336	331	318	300
14	325	317	308S	269	269	275	326	322	327	312	304	273
15	296	320	F	288S	272	295	309S	314	316	U301R	304	277R
16	302	L	L	L	311L	335	352	332	294	276	283	265
17	341	344F	337	L	F	293	326	337	330	307R	U256R	263G
18	340	347	341	319	330	363	E	352	367	351	326	285
19	L	L	357	343	F	U344S	E	332	322	284	231G	252G
20	L	L	L	L	341	S	C	C	C	C	C	C
21	323S	L	F	323	L	E	S	319	289	280	263	272G
22	L	L	F	F	330F	E	E	319	282	290	252	262G
23	C	C	C	C	C	C	C	C	290	284	273	271G
24	F	F	L	F	345	S	E	348	323	U276R	276	230
25	F	L	F	L	L	S	E	341	348	319R	U269R	253G
26	347S	350	328	310	320	U333S	E	327	315	266	257G	263G
27	335	338	L	L	L	L	A	347	336	313	U272R	238
28	323	337	F	F	L	341	E	341	329	314	265	257G
29	329S	S	F	L	A	326F	U329S	337	352	326R	U287R	U262R
30	326	349	351	333	317	323	343	333	331	324	297R	252H
31	L	L	341F	L	309	L	345	329	307	281	266	267G
M	329	338	335	319	328	334	343	332	316	285	269	262G
B	15	13	11	13	16	14	11	28	30	30	29	29

_E
_(s10H

Diurnal Morphology of M(3000)F2

The diurnal variation of M(3000)F2 over Korhogo displayed a remarkably consistent structure across all years and seasons. A sharp enhancement was observed shortly after sunrise, typically between 0500 and 0700 LT. This early-morning peak reflects the rapid onset of photoionization as solar radiation penetrates the upper atmosphere, leading to a sudden increase in electron density and effective F_2-layer height (Chapman, 1931; Rishbeth & Mendillo, 2001). Following the sunrise peak, M(3000)F2 decreased steadily toward a pronounced daytime minimum extending from late morning to late afternoon. This daytime trough is characteristic of equatorial ionospheric behavior and has been reported at several African and low-latitude stations (Adeniyi, 1996; Oyekola, 2013). During this period, vertical plasma drifts are relatively weak, and the F2 layer stabilizes at lower altitudes, reducing the MUF and hence M(3000)F2.

A prominent post-sunset enhancement was observed around 1800–2000 LT, corresponding to the pre-reversal enhancement (PRE) of the zonal electric field. PRE produces strong upward plasma drifts that lift the F2 layer to higher altitudes, decreasing recombination rates and increasing the effective propagation height (Fejer et al., 1999; Anderson et al., 2004). Similar evening enhancements in M(3000)F2 have been documented at other equatorial stations in West Africa (Obrou et al., 2003; Adeniyi et al., 2014). During nighttime hours, M(3000)F2 values remained relatively high, forming a broad nocturnal maximum. This behavior reflects reduced ion-neutral collision frequencies and sustained elevated F2-layer heights after sunset, consistent with established equatorial ionospheric theory (Kelley, 2009).

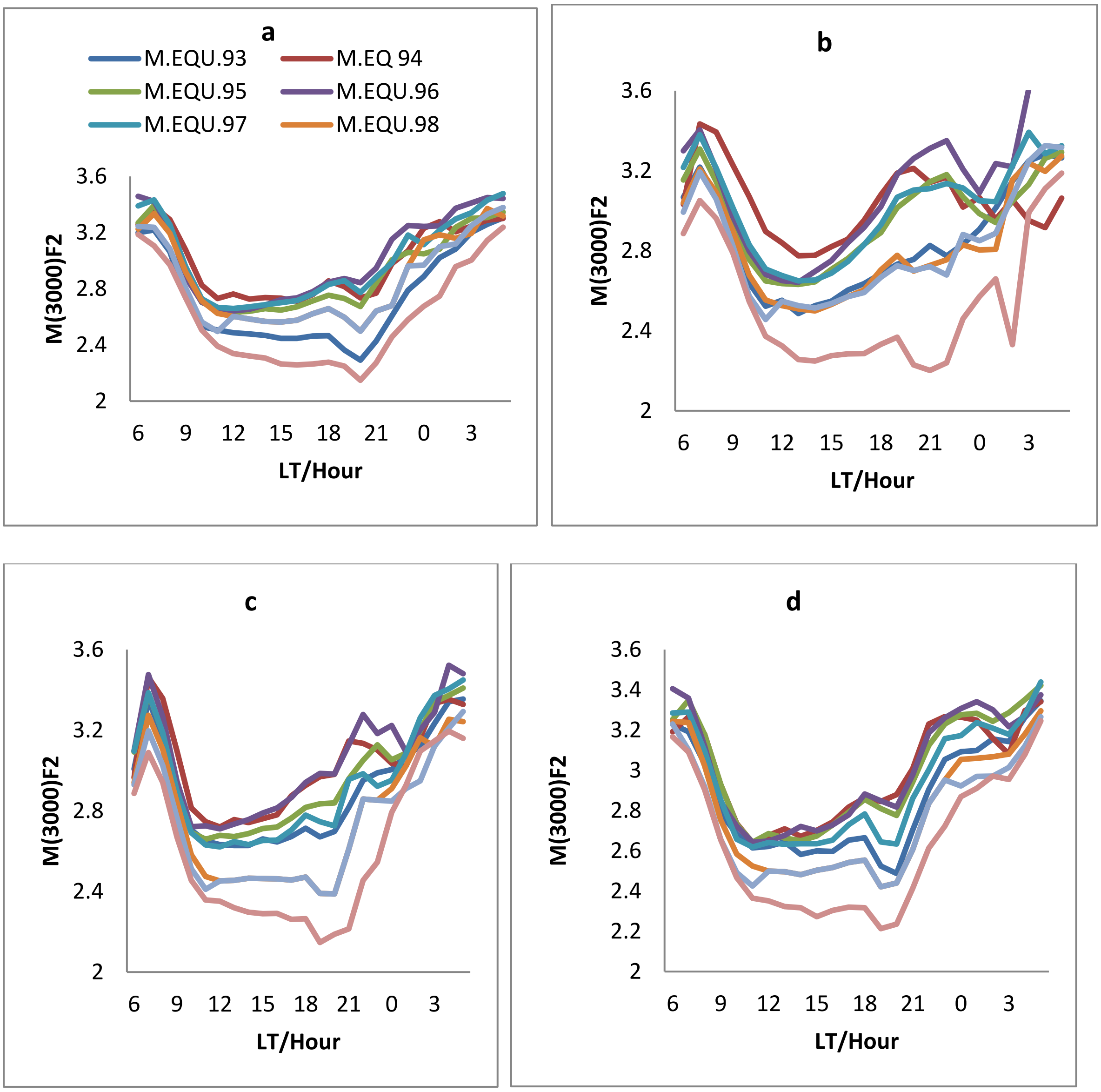

Figure 1: The diurnal plot of M(3000)F2 for (a) March equinox, (b) June solstice, (c) September equinox , and (d) December solstice over the years of study, 1993 - 2000

Seasonal Morphology of M(3000)F2

Seasonal analysis revealed that M(3000)F2 values were consistently higher during equinoxes than during solstices. This equinoctial enhancement is a well-known feature of equatorial ionospheric behavior and is attributed to symmetric solar illumination of both hemispheres, which strengthens the plasma fountain effect and enhances vertical plasma transport (Rishbeth, 2000; Stolle et al., 2008). The June solstice exhibited the lowest M(3000)F2 values, particularly during daytime and early evening hours. This reduction has been linked to seasonal changes in thermospheric wind circulation that suppress upward plasma drifts during this period (Fejer et al., 1999; Obrou et al., 2009). The December solstice showed intermediate values, indicating partial recovery of electrodynamic activity.

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DOI: https://doi.org/10.64388/IREV9I7-1713231

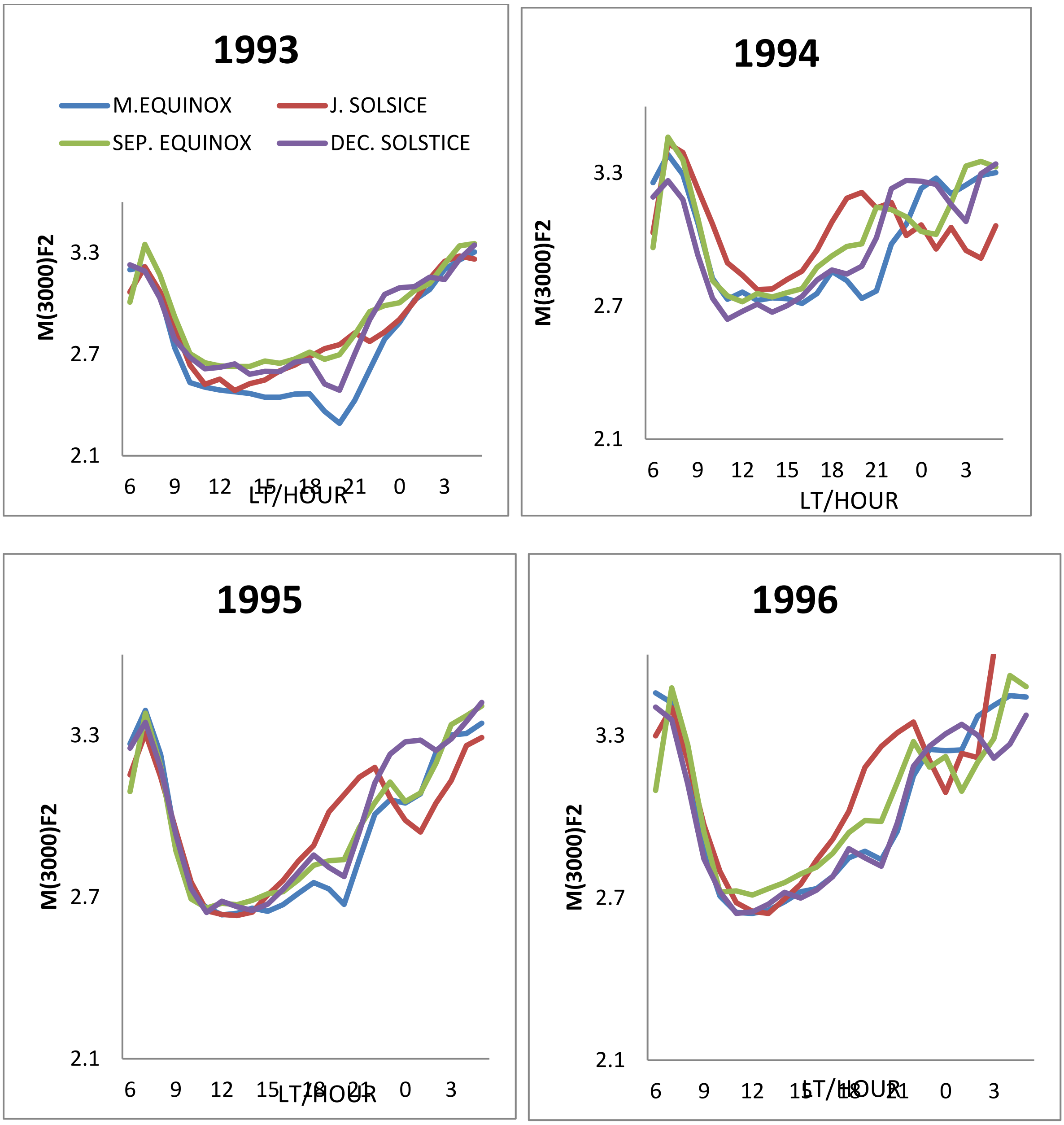

Figure 2: Diurnal plot of seasonal average of M(3000)F2 for the four seasons over the years (a) 1993 , (b) 1994 , (c) 1995, (d) 1996 (e) 1997, (f) 1998, (g) 1999, and (h) 2000

V. DISCUSSION

The present study has provided a detailed morphological characterization of the ionospheric propagation factor M(3000)F2 over an African equatorial sector using long-term ionosonde observations from Korhogo. The observed diurnal, seasonal, and interannual patterns are discussed here in relation to established ionospheric theory and previous empirical findings, with particular emphasis on equatorial electrodynamic processes.

Diurnal Morphology and Equatorial Electrodynamics

The pronounced diurnal pattern of M(3000)F2 observed in this study characterized by early morning maxima, extended daytime minima, post-sunset enhancements, and sustained nighttime peaks is consistent with classical descriptions of equatorial F2-layer behavior. The sharp increase in M(3000)F2 shortly after sunrise reflects the rapid onset of photoionization and the associated increase in electron density and effective F2-layer height, as previously reported by Chapman (1931), Davies (1990), and Rishbeth and Mendillo (2001). At equatorial latitudes, this morning enhancement is further amplified by upward vertical plasma drifts driven by the eastward electric field.

The broad daytime minimum in M(3000)F2 aligns with reduced vertical plasma drift velocities and a relative stabilization of the F_2-layer height during periods of intense solar illumination. Similar daytime depressions in M(3000)F2 have been reported at equatorial and low-latitude stations by Adeniyi (1996), Obrou et al. (2003), and Oyekola (2013). This behavior suggests a balance between ion production and recombination processes, with the F2 layer residing at lower altitudes where recombination rates are higher, thereby reducing the effective propagation factor. The post-sunset enhancement observed in the evening hours is a defining feature of equatorial ionospheric morphology and is directly linked to the pre-reversal enhancement (PRE) of the zonal electric field. PRE-driven upward E × B plasma drifts lift the F2 layer to higher altitudes, decreasing ion-neutral collision frequencies and increasing M(3000)F2 values. This mechanism has been extensively documented by Fejer et al. (1999), Anderson et al. (2004), and Kelley (2009), and its clear manifestation in the Korhogo data confirms the dominant role of equatorial electrodynamics in shaping nighttime propagation conditions over West Africa. The persistence of elevated nighttime M(3000)F2 values further reflects sustained high F_2-layer altitudes after sunset, a feature commonly observed in equatorial regions (Abdu, 2016). The consistency of this nocturnal behavior across seasons and years underscores the robustness of the underlying physical processes governing equatorial ionospheric morphology.

Seasonal Dependence of M(3000)F2
The seasonal analysis revealed systematically higher M(3000)F2 values during equinoctial months compared to solstitial periods, a result that agrees strongly with previous equatorial and low-latitude studies. The equinoctial enhancement has been widely attributed to increased symmetry in solar illumination between hemispheres, which strengthens the equatorial plasma fountain effect and enhances upward plasma transport (Rishbeth, 2000; Stolle et al., 2008).

The relatively suppressed M(3000)F2 values observed during the June solstice are consistent with earlier findings by Obrou et al. (2009) and Oyekola (2013), who reported reduced vertical plasma drifts during this season due to changes in thermospheric wind circulation and conductivity gradients. These conditions limit the uplift of the F2 layer, resulting in lower effective propagation heights and reduced M(3000)F2. The December solstice exhibited intermediate behavior, reflecting partial recovery of equatorial electrodynamic activity. This seasonal asymmetry highlights the sensitivity of M(3000)F2 to changes in solar declination and neutral wind dynamics, further confirming that seasonal morphology at equatorial latitudes is governed primarily by electrodynamic rather than photochemical processes.

Interannual Variability and Solar Cycle Modulation
Interannual analysis demonstrated that M(3000)F2 values were generally higher during years of lower solar activity and reduced during years of elevated solar activity. This inverse relationship has been reported in several earlier studies and is commonly attributed to solar-cycle-driven changes in thermospheric composition and scale height (Liu et al., 2006; Danilov & Lastovicka, 2012). Increased solar EUV radiation during high solar activity leads to enhanced ionization but also increases thermospheric temperatures, causing compression of the F2 layer and a reduction in its effective reflection height, thereby lowering M(3000)F2.

Despite these amplitude changes, the fundamental diurnal morphology of M(3000)F_2 remained remarkably stable throughout the study period. This observation supports the findings of Tukhashvili et al. (2003) and Bilitza (2018), who noted that solar activity primarily modulates the magnitude of ionospheric parameters while leaving their basic temporal structure largely intact. The stability of the diurnal pattern further emphasizes the dominant control exerted by equatorial electrodynamic processes.

Implications for African Equatorial Ionospheric Studies
The consistency between the present results and earlier studies from other longitude sectors confirms that the African equatorial ionosphere exhibits morphological features similar to those observed globally. However, the clear manifestation of these features in Korhogo data also highlights the importance of incorporating African observations into global ionospheric databases. Previous studies have shown that global ionospheric models often

underperform over Africa due to limited regional data input (Adebesin et al., 2013; Bilitza et al., 2020).

By providing a long-term morphological assessment of M(3000)F2 from an African equatorial station, this study contributes valuable empirical evidence that can be used to improve the regional accuracy of ionospheric models and HF propagation predictions. The findings are particularly relevant for communication and navigation systems operating in West Africa, where ionospheric variability remains a significant operational challenge. Overall, the results of this study reinforce the established understanding that M(3000)F2 is a reliable indicator of equatorial ionospheric structure and propagation conditions. The observed diurnal, seasonal, and interannual patterns are consistent with theoretical expectations and previous empirical findings, while also addressing a critical data gap in the African equatorial sector. The strong agreement between the present observations and existing literature validates the use of Korhogo ionosonde data for regional and global ionospheric research.

VI. CONCLUSION

This study has presented a comprehensive morphological analysis of the ionospheric propagation factor M(3000)F2 over an African equatorial sector using long-term ionosonde observations from Korhogo, Ivory Coast, covering the period January 1993 to December 2000. The analysis revealed well-defined diurnal, seasonal, and interannual patterns that are characteristic of equatorial ionospheric behavior. The diurnal morphology of M(3000)F2 was dominated by pronounced post-sunrise enhancements, extended daytime minima, distinct post-sunset peaks, and sustained nighttime maxima. These features were found to be closely associated with equatorial electrodynamic processes, particularly vertical E × B plasma drifts and the pre-reversal enhancement of the zonal electric field. Seasonally, higher M(3000)F2 values were consistently observed during equinoctial periods compared to solstitial seasons, reflecting enhanced plasma transport under symmetric solar illumination. Interannual variations showed that M(3000)F2 values were generally higher during periods of low solar activity and reduced during high solar activity, although the fundamental diurnal structure remained largely invariant across the study interval. Overall, the findings demonstrated that the morphology of M(3000)F2 at the African equatorial sector is primarily governed by equatorial electrodynamic processes, with solar cycle conditions modulating the magnitude of variability. The results provided important empirical evidence from a data-sparse region and contributed to improved understanding of equatorial ionospheric structure and HF propagation conditions in West Africa.

VII. RECOMMENDATIONS

Based on the findings of this study, the following recommendations are made:

1. Expansion of Equatorial Ionospheric Observations in Africa: Additional ionosonde stations should be established across the African equatorial region to improve spatial coverage and enable comparative morphological studies of M(3000)F2.
2. Integration of Multi-Instrument Measurements: Future studies should combine ionosonde observations with GNSS-derived Total Electron Content (TEC), magnetometer data, and satellite measurements to provide a more comprehensive understanding of equatorial ionospheric dynamics.
3. Improvement of Regional Ionospheric Models: The morphological characteristics identified in this study should be incorporated into regional and global ionospheric models, such as IRI, to enhance their predictive accuracy over African equatorial latitudes.
4. Application to HF Communication Planning: HF communication and navigation systems operating in West Africa should incorporate seasonal and diurnal variability of M(3000)F2 into frequency management strategies to improve reliability.
5. Preservation and Digitization of Historical Ionospheric Data: Efforts should be intensified to digitize and preserve historical ionosonde records in Africa to support long-term climatological studies and facilitate future ionospheric research.

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