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Review

Thermospheric Neutral Wind Measurements and Investigations across the African Region—A Review

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Abstract: This paper briefly reviews studies of thermospheric neutral wind dynamics over the African region. The literature includes a review of the observations of neutral winds over five African locations using the Fabry–Perot Interferometer (FPI), and the comparison between the FPI observations and predictions of the horizontal wind model (HWM-14). So far, there are reports of FPI thermospheric wind measurements in South Africa and Morocco representing the mid-latitude regions in the southern and northern hemispheres, respectively. Within the low latitudes, FPI instruments are installed in the Ivory Coast, Ethiopia, and Nigeria. For the literature reviewed, the years covered in the FPI data are 2018–2019 (South Africa), 2016–2017 (Nigeria), 2015–2016 (Ethiopia), 2013–2016 (Morocco), and 1994–1995 (Ivory Coast). Overall, the HWM-14 reproduces the climatological behavior of the meridional and zonal winds, with varying levels of fidelity for the different regions. The HWM-14 is more accurate in the stations located in the northern hemisphere of the African region; a result attributed to the presence of data during the development of this empirical model.

Keywords: Fabry–Perot Interferometer; neutral wind; thermosphere; meridional; zonal; HWM; FPI

1. Introduction

The thermosphere lies roughly between the altitudes of about 85 km to 700 km in the Earth's atmosphere, immediately above the mesosphere and beneath the exosphere. This region of the atmosphere comprises substantial amounts of both neutral and charged particles, whose dynamics and interactions (mainly in the form of winds and drifts, respectively) dominate the atmospheric effects on space-based technologies, such as satellite communication and navigation. Neutral winds are of interest in this study. Neutral winds are mainly generated by pressure gradients, but there are other forces that also play roles in creating the winds [1,2].

The importance of studying thermospheric neutral winds was first established decades ago. For example, it was from the work of Delinger (1939) [3] that we began to understand that the complex behavior of ionospheric currents and electric fields during quiet and magnetically active periods are partly affected by thermospheric neutral winds [4]. Thermospheric neutral winds were established to play vital roles in the dynamics of the ionosphere and in the generation of the evening anomalies of electron concentrations [5–7]. The configuration of the equatorial ionization anomaly (EIA), for instance, can be significantly modulated by thermospheric neutral winds [8–10]. Thermospheric neutral winds were also shown to play important roles in determining the thermospheric composition (e.g., [11]). Despite this importance, thermospheric neutral winds are generally inadequately studied globally. This is obviously due to the general paucity of thermospheric neutral wind measurements. Neutral winds are difficult to measure remotely and space-based measurements are also hard to come by. However, with recent advances in imaging technologies, the ability to field robust and reliable wind-measuring instruments has allowed for easier and more reliable deployments.

Fabry–Perot Interferometers (FPIs) are commonly used to measure thermospheric neutral winds (e.g., [12–17]). They monitor the Doppler shift and the broadening of thermospheric nightglow emissions, from which the neutral wind and temperatures are deduced [18]. Ground-based FPIs typically make observations of nightglow emissions (usually at 630 nm wavelength) in different alternating directions, and the observations are analyzed individually to estimate the Doppler shift (neutral wind) and Doppler broadening (neutral temperature) [4,19] along the line of sight of the observation. The nighttime 630.0 nm redline emissions are naturally produced through the dissociative recombination of ${O_2}^+$ at altitudes of ~250 km. However, the instrumentations that can provide thermospheric wind information remain scarce in a number of regions including in Africa, and especially in the southern hemisphere. As a result, data-driven modelling approaches such as the horizontal wind model, HWM [20–22] can be challenged to accurately specify thermospheric winds [4,13,23] and additional measurements are needed.

This review focuses on reports of FPI measurements of the thermospheric neutral winds across the African region. In Africa, few FPI measurements of the thermospheric neutral winds were reported. Five installations of FPI were reported across the region, as indicated in Table 1 and in Figure 1. The red line in Figure 1 represents the geomagnetic equator. In the next section, we present summaries/highlights of research reports on FPI measurements of thermospheric neutral winds across the region. Sections 3 and 4 review the meridional and zonal wind magnitudes and directions, respectively. Section 5 reviews comparisons of the FPI measurements with the HWM predictions.

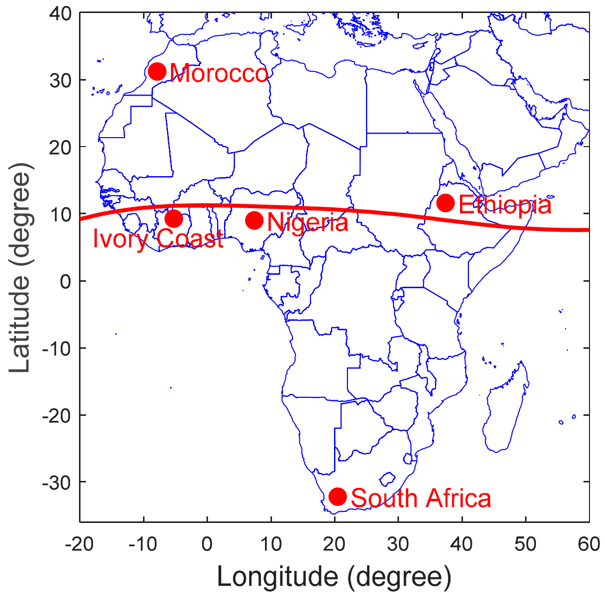

Figure 1. Map of Africa showing locations where the Fabry–Perot Interferometer studies of thermospheric neutral winds were conducted. The red line represents the geomagnetic equator.

Table 1. List of locations in Africa where FPI studies of thermospheric neutral winds were conducted, and comparisons of maximum thermospheric winds observed. The maximum winds presented are maximum magnitudes, not signed directions.

Country	Location	Coordinates	References and FPI Data Coverage	Max Meridional Wind (m/s)	Max Zonal Wind (m/s)
Ivory Coast	Korhogo Observatory, Korhogo	Geographic: 9.25° N, 5.26° W; Geomagnetic: 2.5° S	Vila et al. (1998) [24] (November 1994 to March 1995)	100	100
Morocco	Oukaimeden Observatory, Oukaimeden	Geographic: 31.2° N, 7.87° W; Geomagnetic: 22.84° N	Fisher et al. (2015) [17] (November 2013 to December 2014); Kaab et al. (2017) [23] (January 2014 to February 2016); Malki et al. (2018) [25] (24 February to 1 March 2014); Loutfi et al. (2020) [26] (2014 to 2016)	120	100
Ethiopia	Bahir Dar University, Bahir Dar	Geographic: 11.6° N, 37.4° E; Geomagnetic: 3.7° N	Tesema et al. (2017) [27] (November 2015 to April 2016)	100	90
Nigeria	Space Environment Research Laboratory, Abuja	Geographic: 8.99° N, 7.39° E; Geomagnetic: 1.60° S	Rabiu et al. (2021) [4] (March 2016 to January 2018); Okoh et al. (2021) [7] (4 April 4 2016 to 23 November 2017)	95	160
South Africa	South African Astronomical Observatory, Sutherland	Geographic: 32.2° S, 20.48° E; Geomagnetic: 40.7° S	Ojo et al. (2022) [13] (February 2018 to January 2019)	100	150

2. Highlights on Reports of Thermospheric Neutral Wind Measurements across Africa

This section of the paper provides highlights from the reports which are detailed in subsequent sections of the paper. Additional details and synthesis between the studies are contained in Section 3 (meridional winds), Section 4 (zonal winds), and Section 5 (wind comparisons with the HWM-14 predictions) of the paper. It is also important to highlight here that the general conventions used for the winds are as follows: Positive meridional winds are northwards, while negative ones are southwards (in the northern hemisphere, positive meridional winds are therefore poleward, while negative ones are equatorward. The reverse is the case in the southern hemisphere; positive meridional winds are equatorward, while negative ones are poleward). Positive zonal winds are eastward, while negative ones are westward.

One of the earliest reports of thermospheric neutral wind measurements in Africa using the FPI was presented by Vila et al. (1998) [24]. The study presented some night-time observations of neutral wind measurements made by an FPI installed at Korhogo (Geographic: 9.25° N, 5.26° W, Geomagnetic: 2.5° S). Their study used FPI measurements from November 1994 to March 1995, and the results revealed persistent eastward flows of the zonal winds, and frequent intervals of southward meridional winds, with velocities typically in the range of 50 to 100 m/s. The time resolution of measurements for this FPI is larger (~1 h) than for more recent deployments (<20 min).Therefore, the FPI measurements are relatively fewer per observation night. The authors also reported that the procedure for their measurement was not perfect, as there was a need to update the ‘zero-wind velocity’ reference, using both zenith wind and a calibration lamp.

Fisher et al. (2015) [17] presented one of the first results from FPI measurements in the African region made this century. The study presented the climatology of the quiet time thermospheric winds and temperatures estimated from FPI measurements of the 630.0 nm airglow emission for three locations: north-eastern Brazil; USA; and Morocco (the African station; Geographic: 31.2° N, 7.87° W; Geomagnetic: 22.84° N). They discussed the day-to-day, seasonal, and solar cycle variations of thermospheric meridional winds, zonal winds, neutral temperatures, and, for the first time, vertical winds. Kaab et al. (2017) [23] took the study further by concentrating on measurements from the Morocco FPI. They presented the first multi-year results of the climatology of meridional and zonal winds obtained during the period from January 2014 to February 2016 (648 nights' observations). Their results showed that the wind climatology followed the pattern reported in Loufti et al. (2022) [28] and Tesema (2017) [29], such that the wind starts with a strong eastward speed during the early evening, and ends with a weak eastward, or even westward, speed towards sunrise. The zonal winds were strongly eastward in the early evenings just after sunset, with speeds of about 50 to 100 m/s decreasing in magnitude, and then reversing directions in the local summer months, as sunrise was approached. The meridional winds were slightly poleward in the early evening during the local winter, and reversed directions around 21:00 LT. During local summer, the meridional winds were predominantly equatorward throughout the nights, reaching a maximum equatorward speeds of ~75 m/s. Similar to the work of Fisher et al. (2015) [17], they also compared the FPI wind climatology to that of the Horizontal Wind Model (HWM-14), with the aim of validating the model's predictions of the thermospheric wind patterns in the region. Their results showed that the model climatology was mostly similar to that of the FPI. The major difference between the two sources was in their zonal wind values, during local summer; the FPI maximum eastward wind occurred ~4 h later than predicted by the HWM-14.

Soon after the report of Kaab et al. (2017) [23], Tesema et al. (2017) [27] reported the first measurements of the FPI in Ethiopia (in the East African region; Geographic: 11.6° N, 37.4° E; Geomagnetic: 3.7° N). The measurements covered a period of six months between November 2015 and April 2016, with 53 nights of useable data. Their results showed that the monthly-averaged zonal winds were predominantly eastward between 19:00 and 21:00 LT, and that the zonal wind magnitudes were mostly within the range of 70 to 90 m/s. In the early evenings, during local winter, the meridional winds were about 30 to 50 m/s in the poleward (northward) direction. Similar to Kaab et al. (2017) [23], Tesema et al. (2017) [27] compared the FPI observations to predictions of the HWM-14. They noted that the HWM-14 generally predicted the zonal wind observations accurately, except for some over-estimations during winter.

Malki et al. (2018) [25] used the measurements from the FPI in Morocco to investigate the ionospheric and thermospheric responses to the geomagnetic storm of 27–28 February 2014. This study represented the first study in which measurements from an FPI in the African region were used to investigate geomagnetic storm effects on the neutral wind. Their results showed that during the storm there was a clear departure of the neutral winds from their seasonal behavior; the meridional wind speeds increased steeply towards the equator, and the zonal wind reversed to westward. Wind-induced Travelling Atmospheric Disturbance (TAD) circulation was dominant, including a trans-equatorial TAD. By making use of an all-sky imager tracking plasma bubbles, they established a correlation between the plasma drift velocities and the zonal winds, making clear the ionosphere/thermosphere coupling during geomagnetic storms. Neutral wind transport was found to dominate over the plasma electrodynamics. Loutfi et al. (2020) [26] further investigated the geomagnetic activity effect on the thermospheric neutral winds using measurements of the FPI in Morocco. They characterized the neutral wind variability and dependence on the solar cycle, during both quiet and disturbed conditions. By analyzing the storms that occurred during a 3-year period covering 2014–2016, they also established the statistics of the storm-induced circulation in different storm phases. In an earlier total electron content modelling study, Uwamahoro et al. (2018) [9] showed that the meridional wind velocity (obtained from the HWM), when included as input, led to improvements in the prediction accuracy of their model in the African region.

In the West African equatorial region, Rabiu et al. (2021) [4] examined the variability of the night-time equatorial thermospheric meridional and zonal wind speeds, using the FPI located in Abuja, Nigeria (Geographic: 8.99° N, 7.39° E; Geomagnetic: 1.60° S). They used

FPI measurements for 9 months (including 139 nights of usable data) obtained between the months of March to June 2016 and September 2017 to January 2018. Their results showed that the hourly zonal wind speeds were between −124 and 163 m/s, and that the meridional winds were between −70 and 95 m/s. Similar to most of the prior work in other parts of the region, the FPI measurements were compared to predictions of the HWM-14. The results showed that the HWM-14 most often reproduced the post-midnight meridional component better than for the pre-midnight component. There was good agreement between the FPI zonal wind measurements and corresponding HWM-14 predictions during the month of January 2018, but the model typically underestimated the FPI zonal wind speeds for the months in 2016 (March to June). A new feature of their study involved periodicity analysis of the daily maximum neutral wind speeds. The results revealed modal periods which are quasi 27 days and quasi-terannual, for both the zonal and meridional winds.

Okoh et al. (2021) [7] explored neutral wind and ionized plasma coupling by using 11 nights of coincident neutral wind measurements and EPB (equatorial plasma bubble) speed measurements. Zonal neutral wind measurements were obtained from the Abuja FPI, while corresponding EPB speeds were derived from airglow observations of a co-located optical all-sky imager. This is one of the few studies in the African region that reported simultaneous measurements of thermospheric neutral winds and corresponding EPB speeds. Their results showed that the magnitudes of instantaneous zonal neutral wind speeds were between 30 and 300 m/s, while the zonal EPB speeds were between 15 and 400 m/s. They generally observed that both the neutral winds and the EPBs were faster during the early evening hours than towards the midnight hours. Their comparison of the neutral wind and EPB speeds showed a mixture of scenarios in which both speeds were comparable in some instances, the neutral winds were faster than the EPBs in other instances, and the EPBs were faster than the neutral winds in other instances.

In the South African mid-latitude region, Ojo et al. (2022) [13] presented a climatology of night-time thermospheric neutral winds using FPI measurements from Sutherland, South Africa (Geographic: 32.2° S, 20.48° E; Geomagnetic: 40.7° S), obtained between the months of February 2018 and January 2019. Their results show that the annual meridional and zonal winds varied between −100 and 120 m/s, and that the wind measurements exhibited typical midlatitude nocturnal and seasonal variations. The meridional winds were mostly equatorward (northward) from dusk to predawn during summer (December-February), while during the winter (July–August), the meridional winds were poleward (southward) from dusk, then turned equatorward around midnight. They noted that the zonal winds were typically eastward during the evenings until just before the midnights, and that they became westward after midnight. A comparison of the FPI measurements with corresponding predictions from the HWM-14 showed that the model predictions of the meridional winds were in better agreement with corresponding FPI measurements, compared to the zonal components. They also noted, from the monthly averages, that the HWM-14 zonal wind predictions always peaked about 3 h before the FPI zonal wind measurements. The eastward-to-westward transition times for the HWM-14 predictions happened about 2 h earlier during the months of November to January. They attributed this temporal discrepancy to the difference in the phase shift of the terdiurnal tide in the model.

3. Measurements of Meridional Wind Magnitudes and Directions

The typical scenario of the meridional winds reported is that the winds are poleward in the early evening hours. The directions switch to the equatorward direction towards midnight. This reversal often happens between 20:00 and 22:00 LT. Then the peak of the equatorward wind is attained around local midnight and the equatorward magnitude decreases thereafter, even returning to the poleward direction for some nights. This pattern is consistently reported in the works of [4,7,13,17,23–27].

There are, however, some exceptions to this pattern. For example, in the Nigerian region [4], the early evening winds were sometimes observed to be equatorward with small and decreasing magnitudes, then turning poleward within 1–3 h of sunset. This pattern was observed in the months of March–June and September, whereas the early evening poleward winds were observed in the months of October to January.

In the equatorial region of Brazil (geographic: 6.87° S, 38.56° W; geomagnetic: 5.73° S and geographic: 7.38° S, 36.52° W; geomagnetic: 6.81° S), the results of Fisher et al. (2015) [17] showed similar results, but during contrasting months. The cases of early evening equatorward winds were observed around the months of October to January, while the early evening poleward winds were conspicuous around the months of April to August. The reason for the contrasting months can be explained to be as a consequence of the equatorial location of both stations but in opposite hemispheres. The Nigerian and Brazilian stations are both located in the equatorial region, but the Nigerian station is in the northern hemisphere, while the Brazilian station is in the southern hemisphere. The reason is that the trans-equatorial winds which are observed as equatorward in Nigeria will be observed as poleward in Brazil, and vice versa.

During the geomagnetic storm of 27–28 February 2014, the results of Malki et al. (2018) [25] also indicated an early evening equatorward wind, which mostly remained equatorward until 2 h after local midnight.

Clear seasonality can be seen in the reports of Morocco and South Africa because these are mid-latitude stations. Figures 2–4 represent some of the plots of the meridional winds in Morocco, South Africa, and Nigeria, respectively. The equatorward winds are faster in summer than in winter [13,17,26]. Morocco (South Africa) is in the Northern (Southern) hemisphere, and so local summer occurs during the months of June–August (November–January), while winter occurs during November–January (June–August). In Morocco, the peak equatorward magnitude is slightly greater than 100 m/s during summer, but the equatorward magnitudes are reduced or non-existent during winter [17,23]. In South Africa, the peak equatorward magnitudes grow to ~100 m/s during both winter and summer. The difference between winter and summer, however, is that the winds are predominantly equatorward (in terms of duration) during local summer [13].

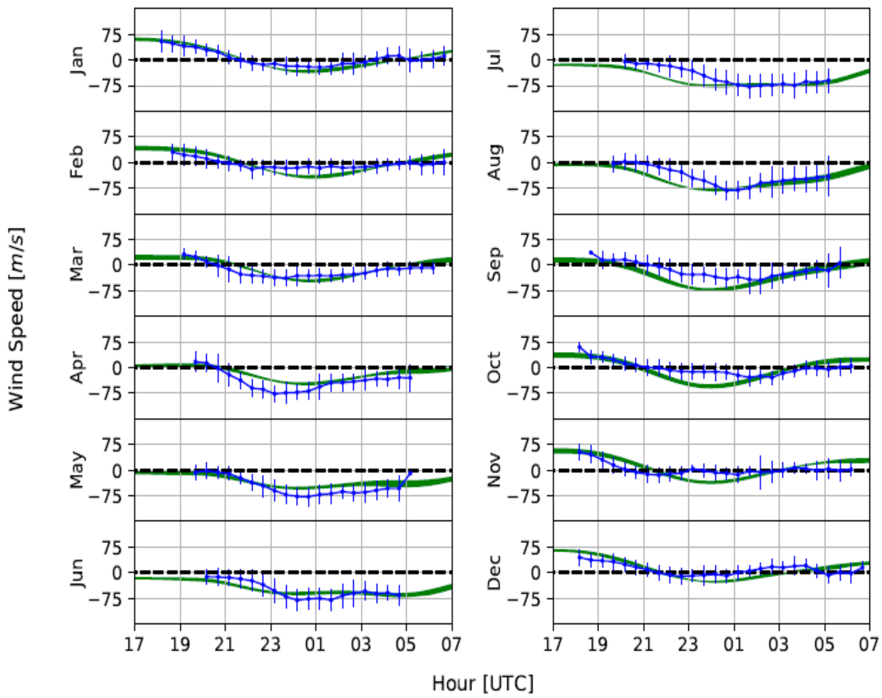

Figure 2. Meridional winds in Morocco for January 2014 to February 2016. The blue plots represent the FPI measurements, while the green plots represent corresponding HWM-14 predictions. The vertical error bars indicate the standard deviations of the observations. Adapted with permission from Ref. [23]. 2017, Kaab et al.

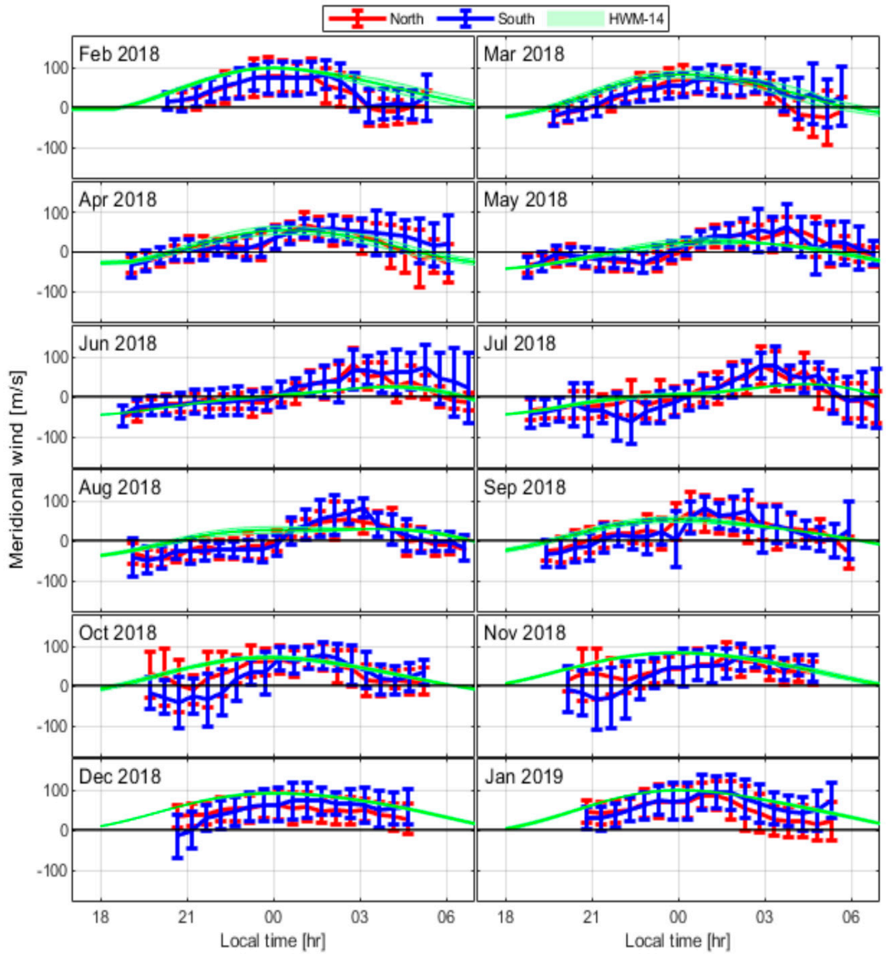

Figure 3. Meridional winds in South Africa for February 2018 to January 2019. The red and blue plots represent the FPI measurements looking in the North and South directions, respectively, while the green plots represent corresponding HWM-14 predictions. The vertical error bars indicate the standard deviations of the observations. Adapted with permission from Ref. [13]. 2022, Ojo et al.

The meridional winds are faster during periods of higher solar activity [30]. The solar activity term used here refers to the activity of the Sun which changes over ~11-year cycle, as quantified by parameters such as the sunspot number, F10.7, etc. For example, Fisher et al. (2015) [17] and Kaab et al. (2017) [23] both used data from the Morocco FPI. Their observations are both consistent with regards to the note that the equatorward winds peak around midnight during summer, but the peak magnitudes reported by Kaab et al. (2017) [23] are smaller (~75 m/s) than those reported by Fisher et al. (2015) (>100 m/s) [17]. The reason for the smaller peak magnitudes recorded by Kaab et al. (2017) [23] is likely because the measurements of Fisher et al. (2015) [17] were recorded during the peak of the solar cycle (November 2013 to December 2014), whereas the work of Kaab et al. (2017) [23] makes use of averaged measurements for the period from January 2014 to February 2016, which includes years of slightly lower solar activity. Fisher et al. (2015) [17] also demonstrated that the summer meridional wind peaks at higher velocities during greater solar activity, compared to the same summer months at lower solar activity.

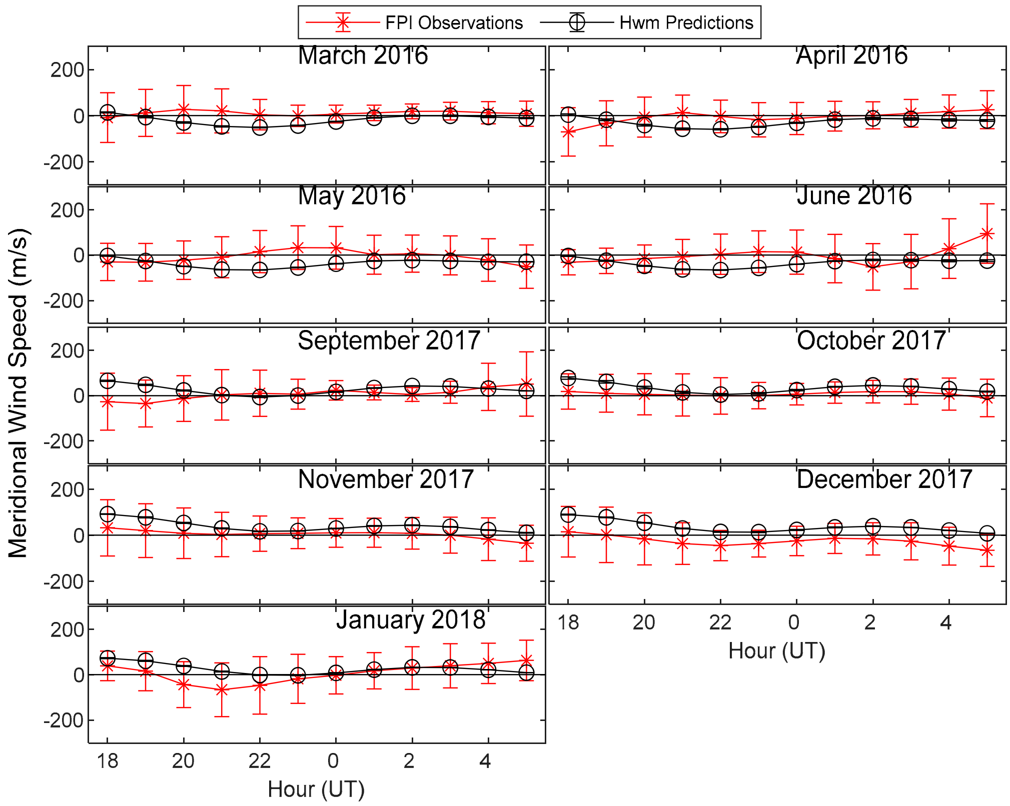

Figure 4. Meridional winds in Nigeria for March 2016 to January 2018. The red plots represent the FPI measurements, while the black plots represent corresponding HWM-14 predictions. The vertical error bars indicate the standard deviations of the observations. Adapted with permission from Ref. [4]. 2021, Rabiu et al.

4. Measurements of Zonal Wind Magnitudes and Directions

The typical scenario for the zonal thermospheric winds is that they are mostly eastward, especially before midnight. The zonal winds are generally fast in the early evening hours, and peak around ±3 h of midnight. Then they slow down thereafter, and occasionally develop weakly in the westward direction a few hours prior to sunrise. In the equatorial region of East Africa, Tesema et al. (2017) [27] reported no occurrence of westward motions of the monthly averaged winds throughout the nights for the entire periods of their study (November 2015–April 2016). In equatorial West Africa, Rabiu et al. (2021) [4] reported a few cases of westward wind motions during the months of June 2016 (05:00 to 06:00 LT) and January 2018 (06:00 LT). The westward wind magnitude in June reached ~100 m/s, while the value in January was ~20 m/s. The average monthly winds were predominantly eastward during the rest of the 9 months that they investigated.

In mid-latitude Morocco, Fisher et al. (2015) [17] reported westward wind motions during the months of May (02:00 to 04:00 LT), June (02:00 to 04:00 LT), July (03:00 to 05:00 LT), August (03:00 to 05:00 LT), and September (03:00 to 05:00 LT). The reported westward wind magnitudes were generally less than 50 m/s. Kaab et al. (2017) [23] and Loutfi et al. (2020) [26] reported no occurrence of the westward wind during winter, and their noticeable occurrence during summer. The averaged westward magnitudes were typically less than 50 m/s, except during 03:00 LT of the 2016 summer when the value reached ~100 m/s. These results are similar and in agreement with the report of Fisher et al. (2015) [17]. The zonal winds also show dependence on solar activity. Loutfi et al. (2020) [26] presented averaged zonal wind measurements for the years 2014, 2015, and 2016 (mean solar activity decreases in that order). The results showed that the eastward zonal winds were typically faster in 2014, slower in 2015, and slowest in 2016, indicating that the eastward zonal winds are faster during years of higher solar activity. Similar results were found by Fisher et al. (2015) [17], who showed that the monthly means of the eastward zonal winds for days with higher solar activity were greater than values of the means for days in the same months with lower solar activity. In Loutfi et al. (2020) [26], the switch from the eastward-to-westward direction of the zonal wind in summer was particularly observed to occur earlier in 2015 and 2016 (around 02:00 LT) than in 2014 (around 03:00 LT), indicating that the switch happens later for the year of higher solar activity. Figures 5–7 represent some plots of the zonal winds in Morocco, South Africa, and Nigeria, respectively.

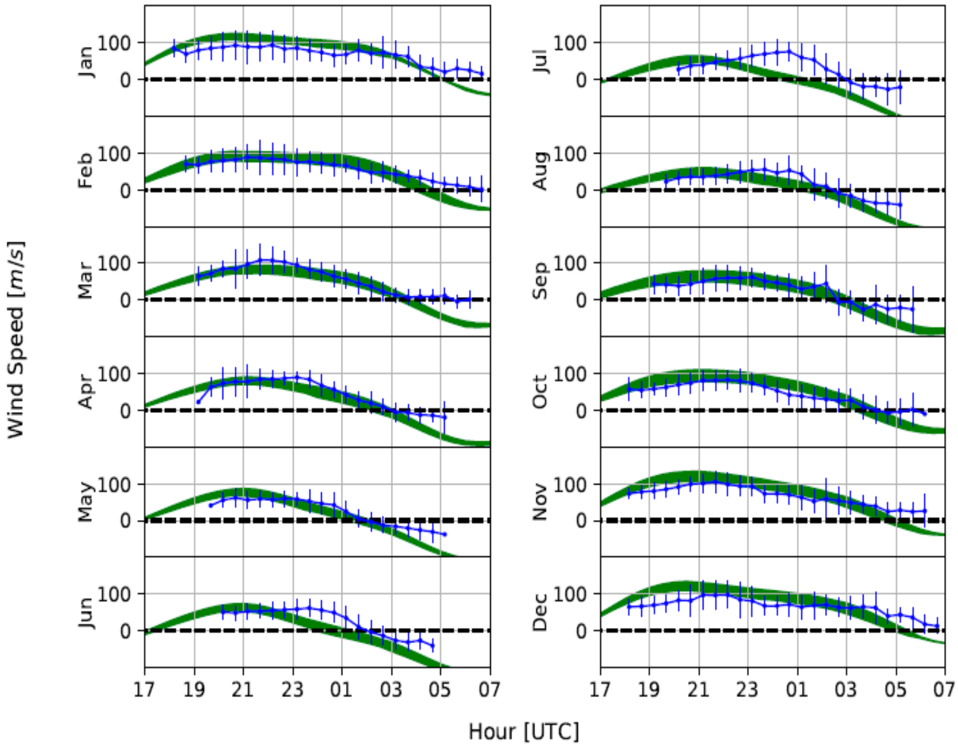

Figure 5. Zonal winds in Morocco for January 2014 to February 2016. The blue plots represent the FPI measurements, while the green plots represent corresponding HWM-14 predictions. The vertical error bars indicate the standard deviations of the observations. Adapted with permission from Ref. [23]. 2017, Kaab et al.

Geomagnetic activity can also significantly alter the climatology of wind patterns. In fact, due to high-latitude heat input, large scale storm-induced atmospheric waves that propagate to low latitudes and into the opposite hemisphere are created. As a result, the storm-induced westward zonal winds and equatorward meridional winds add and modify the quiet-time background wind circulation. The results of Malki et al. (2018) [25], for example, revealed that there was conspicuous westward motion of the wind in Morocco during the geomagnetic storm of 27–28 February 2014, reaching a peak magnitude of ~75 m/s (when averaging the east and west look measurements) around 01:00 LT of the night. The impact was clearly distinct because the westward peak was reached at a time around the middle of the night, and the magnitudes returned thereafter to expected values towards sunrise. This westward motion was also recorded in a month close to winter (when westward winds are usually not recorded) in the station.

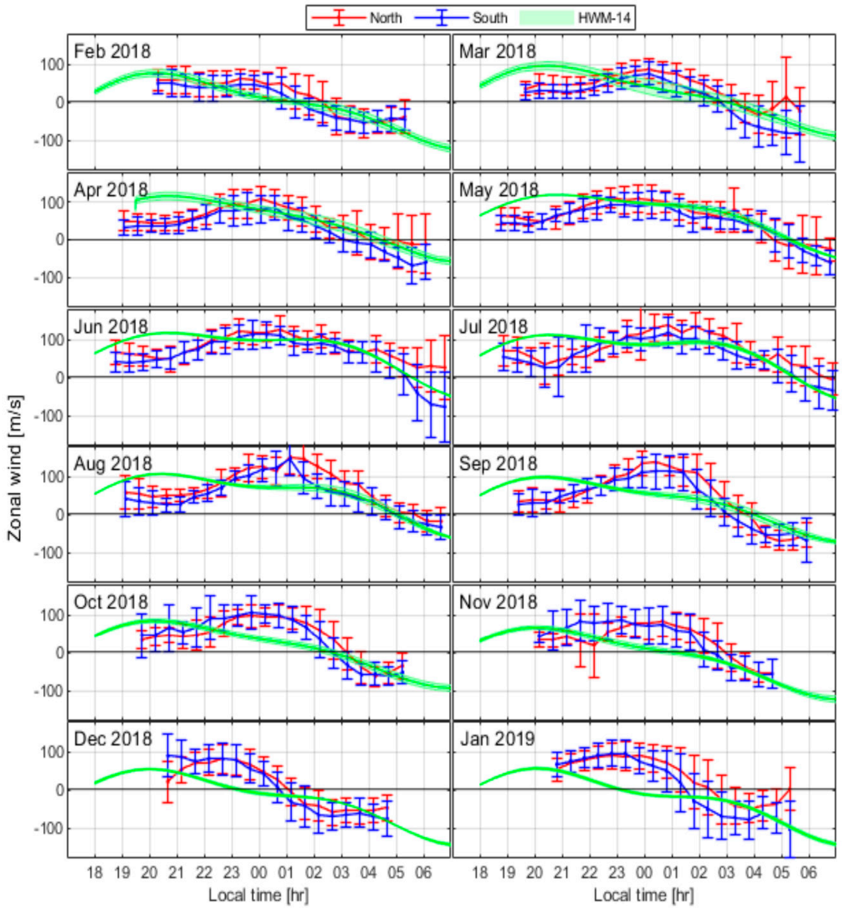

Figure 6. Zonal winds in South Africa for February 2018 to January 2019. The red and blue plots represent the FPI measurements looking in the North and South directions, respectively, while the green plots represent corresponding HWM-14 predictions. The vertical error bars indicate the standard deviations of the observations. Adapted with permission from Ref. [13]. 2022, Ojo et al.

In mid-latitude South Africa, Ojo et al. (2022) [13] observed that there were westward winds during the early morning hours in all of the months investigated. The wind directions typically start with eastward; the magnitudes increase in that direction and peak often around midnight, then decrease thereafter until they become westward in the hours before sunrise. This is the only station in the region where westward directed winds were consistently recorded throughout the months investigated. This is because the South African station is nearer to the geomagnetic pole, which can be more influenced by the high-latitude forcing. Morocco, which has a lower magnetic latitude, is less affected by the sub-auroral process.

In Morocco, the winds rarely turn westward during winter (the eastward speeds keep decreasing towards zero magnitude), but during summer (May–July), they turn westward between the hours of 01:00 and 03:00 LT. In South Africa, the winds also turn westward between the hours of 01:00 and 03:00 LT during summer (November–January). However, during the South African winter (May–July), the time of the eastward-to-westward switch is delayed till around 06:00 LT, portraying a weakened effect of the westward wind during this season. In Morocco, the overall peak magnitude of the eastward wind is ~100 m/s, while in South Africa, the value is ~150 m/s. In both stations, the peak eastward magnitudes are observed during the winter months; the peaks of the eastward winds are greater during winter than during summer. Conversely, in the two stations, the peak westward wind magnitudes are observed during the summer months; the peaks of the westward winds are greater during summer than during winter. In Morocco, the value is ~50 m/s [17], while in

South Africa, the value is ~100 m/s [13]. Both values are recorded towards local daybreak. The results suggest that the peaks of the wind amplitudes are consistently greater in South Africa than in Morocco. This is perhaps due to increased ion-neutral drag caused by the equatorial ionization anomaly, as Morocco is closer to the geomagnetic equator [31]. It was observed that the winds grew stronger with increasing geomagnetic latitude [16].

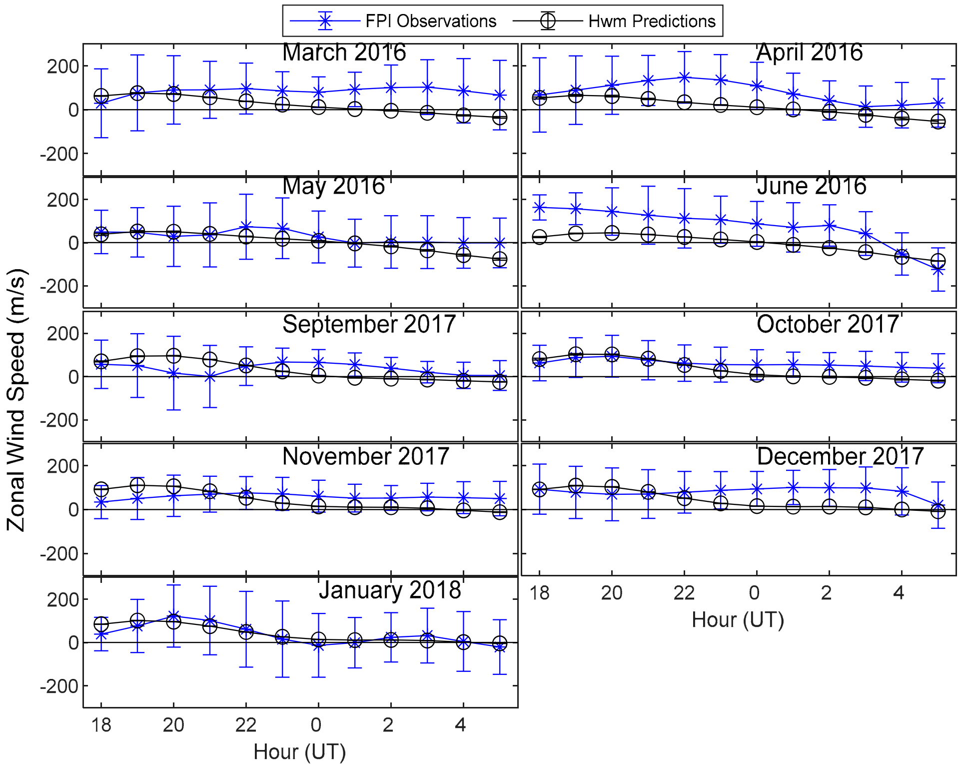

Figure 7. Zonal winds in Nigeria for March 2016 to January 2018. The blue plots represent the FPI measurements, while the black plots represent corresponding HWM-14 predictions. The vertical error bars indicate the standard deviations of the observations. Adapted with permission from Ref. [4]. 2021, Rabiu et al.

Table 1 contains a summary of the information on the maximum meridional and zonal wind speeds reported at each of the stations. It is important to emphasize that the values reported in Table 1 are indicative of the mean values, typically averaged monthly, and do not represent the maximum of instantaneous values. The maximum of instantaneous wind measurements is expected to be greater than the maximum of monthly averaged values. For example, Okoh et al. (2021) [7] indicated that the zonal wind speeds in Nigeria could reach ~300 m/s, which exceeds the 160 m/s monthly averaged maximum given in Table 1.

5. Comparisons with HWM-14 Predictions

The HWM is a standard climatologic empirical model of the horizontal thermospheric neutral wind, in both meridional and zonal directions, across the globe. Hedin et al. (1988) [20] developed the initial version using data limited to satellite observations from Dynamic Explorer 2 and Atmospheric Explorer. Thereafter, the model was greatly improved by including measurements from other instruments, e.g., FPIs, incoherent scatter radars, and additional satellite measurements [22,32,33]. The most recent version of the model is the HWM-14 (updated in 2014, and detailed by Drob et al., 2015 [22]). It is this version of the model that was primarily used for comparisons and validations in the studies from the African region on which the present paper reports. These studies indicate that the HWM-14 is fairly accurate in predicting the meridional and zonal wind patterns at the locations of the FPI stations on the continent, but with some notable differences between the model predictions and the FPI observations.

At the mid-latitude station of Morocco, the model accurately predicts the poleward motion of the winds in the early evening hours of the winter season. It also accurately predicts the decrease in the poleward magnitude, and eventual switch to equatorward direction, during the early evenings of the summer season [23,26]. A notable disparity is that the model underestimates the equatorward wind magnitude by as much as 30 m/s, especially during the months of April and May. On the other hand, the model overestimates the equatorward wind magnitude by as much as 40 m/s during the months of September to November. During the months of July to September, the times of the peaks for the equatorward winds are observed to be earlier for the model than for the FPI measurements [23].

The HWM-14 prediction of the meridional wind pattern in South Africa is also fairly accurate. For example, the magnitudes of the HWM-14 meridional winds during the winter months are smaller than during the summer months, which is in agreement with the FPI measurements [13]. There are, however, substantial differences in the peak times and peak magnitudes predicted by the model, in comparison to the FPI measurements. For example, the HWM-14 overestimates the meridional winds by about 20 m/s during summer, especially at the beginning of the nights. The model predicts the peaks of the equatorward winds to occur later than those of the FPI measurements during winter. During the summer and September equinox, the model predictions of the peak equatorward winds occur much earlier than those of the FPI measurements. These time differences between the peaks of the HWM-14 and FPI equatorward winds are in the range of 2–5 h. It is important to highlight here that this same earlier prediction of the equatorward peak was noted in Morocco for similar months (July to September) [23]. The HWM-14 does accurately predict the eastward zonal winds during the evening hours prior to midnight, before turning westward in the later part of the night. The times for the eastward-to-westward turning of the zonal wind are also correctly predicted by the HWM-14 for most of the months (February–October). However, for the months of November to January, the model's predictions of the times for the eastward-to-westward turning were significantly earlier (~2 h). Other discrepancies in the zonal wind were noted in the hours before local midnight between the months of March and November, when the HWM-14 overestimated the eastward FPI winds by about 30 m/s. The HWM-14 also predicted the peak of the eastward wind to occur ~3 h earlier than observed in the FPI data. In general, the HWM-14 is observed to perform slightly more accurately in Morocco than in South Africa. This could be because the northern hemisphere is more represented empirically in the data used to construct the HWM [13].

In Ethiopia, the HWM-14's predictions of the meridional winds were in good agreement between the months of January and April. However, in November and December, there were discrepancies of about 30 to 50 m/s which were most noticeable before midnight [27]. There were conspicuous differences between the model's zonal wind predictions and FPI measurements during the hours between 23:30 and 01:30 LT for the months of January and February. These differences can be attributed to a temporal apparent phase shift as, for example, noted in Ojo et al. (2022) [13]. In November and December, the discrepancies were seen between the hours of 19:30 and 21:30 LT.

For the Nigerian station, good agreements were noted between the HWM-14 predictions and the FPI measurements of the meridional winds usually after 23:00 LT. During pre-midnight hours in most months of March to June 2016, the HWM-14 meridional predictions were observed to be in an opposite direction to the FPI wind measurements, with discrepancies reaching the order of ~60 m/s. The HWM-14 therefore did not accurately reproduce the FPI wind measurements, as there was a negative correlation in the early evenings. The meridional predictions from September 2017 to January 2018 were fairly accurate. The model's predictions of the zonal winds were largely correct in terms of capturing the general slowing of the eastward wind as the nights progress, and the occasional westward turning of the winds before the next sunrise. However, the model mostly underestimated the FPI eastward wind magnitudes, except for few hours in the early evenings, when it did overestimate them. These sort of discrepancies in the African region are perhaps not terribly surprising, considering that the general construction of HWM-14 lacked data from the Africa region [13]. Another possibility could be that these differences are due to the magnetic and geographic latitude offsets, which are different in the African and American sectors; in the American sector, the magnetic equator is south of the geographic one, while the reverse is the case in the African sector. The actual lower atmospheric forcing and geomagnetic forcing are also different from the parameterization of them in the model.

6. Conclusions

This paper presented a brief review of thermospheric wind studies over the African region focusing on FPI measurements and comparisons with the HWM-14. Currently, FPI instruments are installed in South Africa, Ethiopia, Nigeria, and Morocco. The studies reviewed covered observations during 2018–2019, 2016–2017, 2015–2016, 2013–2016, and 1994–1995 over South Africa, Nigeria, Ethiopia, Morocco, and the Ivory Coast, respectively. We found that the HWM is more accurate in the northern hemispheric part of the African region, a result attributed to the presence of data informing the development of this empirical model. Overall, the HWM reproduces the climatological behavior of meridional and zonal winds. However, varying levels and different types of discrepancies were reported for each of the studied regions.

The comparisons between the HWM-14 and FPI observations showed noticeable differences, particularly in the meridional wind. The discrepancy is attributed to the historical lack of observations over the continent in the construction of the empirical model. As space weather is becoming a more pressing issue all over the world, space weather-related observations and research are becoming more common. We are seeing more FPI observations in Africa. Given that the HWM-14 is a most-used model for space weather research, the need to improve the model with data more evenly distributed around the world is more urgent. It will be very significant to use the African data to validate various first principle models as well. Additionally, coverage of different longitudes is critically important for the study of non-migrating tides with short time scales as ground-based data sample more local times than satellite observations.

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