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Climatology of Medium-Scale Traveling Ionospheric Disturbances (MSTIDs) Observed with GPS Networks in the North African Region

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Abstract

We present for the first time the climatology of medium-scale traveling ionospheric disturbances (MSTIDs) by using Global Positioning System (GPS) receiver networks on geomagnetically quiet days ($K_p \leq 3$) over the North African region during 2008-2016. The ionospheric Total Electron Content (TEC) were estimated from the dual-frequency GPS measurements, and the TEC perturbations (dTEC) data were derived from the estimated TEC data. We focused on the TEC perturbations (dTEC) associated with medium-scale traveling ionospheric disturbances (MSTIDs) and statistically analyzed the MSTIDs characteristics, occurrence rate, diurnal and seasonal behavior as well as the interannual dependence. The oscillating wave-like pattern of MSTIDs showed a local and seasonal dependence of nighttime and daytime. The results showed that MSTIDs propagation direction is predominantly towards the South (equatorward), MSTIDs event period is ($12 \leq \text{period} \leq 53$ mins), and dominant amplitude ($0.08 \leq \text{amp} \leq \sim 1.5$ TECU), with a propagation velocity higher at daytime than nighttime. The amplitudes of the MSTIDs increase with solar activity. The study reveals that the spatio-temporal variation of MSTIDs depends on local time and solar activity. The study also shows that the disturbance occurrence time is dominant within the hours of (1200–1600 LT), and (1000–1400 LT) in December solstice at daytime for stations located in the Northwest (NW) and Northeast (NE) part of the African region, respectively. While at the nighttime, the MSTIDs exhibits variability in disturbance occurrence time around (NW: 2100–0200 LT) and (NE: 1900–0200 LT) in June solstice, but get extended to March equinox during solar maximum (2014). The mean phase velocity in daytime MSTIDs is higher than the nighttime in every season, except during June solstice. The study revealed that atmospheric gravity waves (AGWs) control the daytime MSTIDs occurrence for a selected day.

Keywords: Medium scale traveling ionospheric disturbances, TEC perturbation, ionospheric irregularities, Atmospheric Gravity Waves, Total Electron Content

1.0 Introduction.

Medium-scale traveling ionospheric disturbance (MSTID) is one of the major and frequent ionospheric irregularity phenomena at the F region Mid-latitude which may degrade positioning systems and it has been studied to have the ability to propagate over long distances (Frissell et al., 2014). MSTIDs could cause a delay in GPS signal transmission between a satellite and the GPS receiver, and produce ionospheric disturbances that can degrade communication and navigation signals where the amplitude of MSTIDs is typical of tenth of a TECU ($1 \text{ TECU} = 10^{16} \text{ electrons/m}^2$) (Wanninger, 2004; Husin et al., 2011; Hernandez-Pajares et al., 2006), and have been thought to be generated by atmospheric gravity waves (AGWs) (Jonah et al., 2016). The AGWs have been proposed to be generated by the sunrise and sunset terminators (MacDougall et al., 2009a), also some studies have reported AGWs to be generated from convection activities (Tsuda et al., 2014) in the troposphere and stratosphere, and through some other meteorological processes (e.g., orography) (Jonah et al., 2016). AGWs are the most impactful waves that contribute to the dynamical nature of the upper atmosphere amongst many waves present in the atmosphere, and it is also an important energy transfer mechanism from troposphere into the stratosphere, mesosphere, and thermosphere (Jia Yue et al., 2019). AGW manifest as a wave-like perturbation of ionospheric plasma in the ionosphere (Hines, 1960), consequently causing fluctuations in Total Electron Content (TEC). The AGW propagation through the neutral atmosphere eventually gets above 50 km into the ionosphere and directly impacts it, causing ionospheric variability and seeds ionospheric irregularities (Azeem and Barlage, 2017) such as MSTIDs. These entire ionospheric frequent phenomena consequently cause fluctuations in Total Electron Content (TEC). The daytime MSTIDs event occurrence is majorly assumed to be caused by atmospheric gravity waves (AGW), (Hines, 1960; Jonah et al., 2016; Oinats et al., 2016; Figueiredo et al., 2018), while the nighttime is assumed to be caused by electrodynamical forces such as Perkins instability respectively (Perkins, 1973; Garcia et al., 2000; Tsugawa et al., 2007). The wavelike structure of MSTIDs is characterized by a wavelength, period and phase speed of 50 - 500 km, 12 - 60 mins and 50–400 m/s, respectively (Ogawa et al., 1987; Hocke and Schlegel, 1996; Grocott et al., 2013). Within the last six decades, a lot of MSTIDs studies have been carried out by various researchers around the globe using different instruments and techniques to understand this irregular ionospheric behavior. To mention a few amongst many are: Ogawa et al. (1987) who investigated MSTIDs occurrence frequency using the U.S. Navy Navigation Satellite System (NNSS) in polar region at a 1000 km altitude during the disturbed geomagnetic condition. The authors concluded that there was no increase in MSTIDs occurrence under disturbed condition. Hernández-Pajares et al. (2006, 2012), Kotake et al. (2007), Valladares and Hei, (2012), Jonah et al. (2016), Figueiredo et al. (2018), and Guanyi Chen et al. (2019) carried out independent research of MSTIDs using GNSS receiver network at difference location and they reported nearly the same results in terms of seasonal occurrences, but with slight differences in the propagation directions characteristics. Many

1 studies have reported the regular and dynamic nature of the ionospheric TEC at different latitudes over the
2 African region (Ouattara and Fleury, 2011; Ngwira et al., 2013; D’ujanga et al., 2016) but these earlier
3 studies have only been confined to short-term time basis observation under limited solar activity. Besides,
4 majority of the investigations reported to date have mostly emphasized the local or regional characteristics
5 of ionospheric irregularities with main focus on scintillation. However, there is yet an important aspect of
6 ionospheric irregularities which is yet to be reported on both local and regional scale over Africa. In recent
7 years, with an improved study of long- term time series of characterization of ionospheric GPS-TEC under
8 different geomagnetic conditions for daytime and nighttime, respectively, during 2009 - 2016 (Oluwadare et
9 al., 2018), certain wave-like structures of ionospheric TEC were observed to be irregularities which vary in
10 time and space. The characteristics of this irregular phenomenon are mostly associated with MSTIDs as
11 described by ionospheric irregularity theories and experimental results from different authors who have
12 reported MSTIDs observations from different regions e.g. North Asia, South America, North America,
13 Europe, and Oceania around the globe except for the African region, and these have created a huge gap in
14 comparison of interregional MSTIDs characteristics. Before now, MSTIDs study over the African region
15 has not been reported, probably due to limitation of ionospheric data availability in the non-African region
16 or none-access to the GPS data and other technical reasons. Hence, this study has considered further
17 observing and investigating the dynamic nature of ionosphere and the occurrence of ionospheric
18 irregularities with main focus on MSTIDs from GPS-TEC estimates. The study investigates the climatology
19 of MSTIDs over the North African region for the first time during the geomagnetic quiet days (i.e. $K_p \leq 3$)
20 for the period of nine years (2008-2016). The primary aim is to present the MSTIDs observations derived
21 from estimated TEC perturbation (dTEC), characteristics and occurrence mechanism. We also made use of
22 temperature profile obtained from low earth orbit (LEO) satellite to observe possible indication of the
23 AGWs passage for a selected day. For the first time, we present the nine years’ climatology of MSTIDs
24 observed by a GPS network over the North African region. The MSTIDs occurrence rate (OR) is estimated,
25 its characteristics as well as the mechanisms are investigated. In addition, the regional distribution of
26 MSTIDs occurrence map is presented and a daytime two-dimensional dTEC map for a case of MSTIDs is
27 also presented.

28

29 **2.0 Data and method**

30 MSTIDs have been observed and estimated during 2008-2016 using seven ground-based dual-frequency
31 GPS receiver network stations majorly situated at Northern African, a mid-latitude region. The location of
32 the stations is given in the table (1) below. The entire seven GPS network stations are shown in Fig. 1.

33

34

35

1 Table 1. GPS receiver stations showing geographical coordinate values and geomagnetic latitude values.

Station name	Geog. Lat	Geog. Lon	Geomag. Lat
RABT	33.99°N	6.85°W	37.4°N
TETN	35.56°N	5.36°W	38.6°N
IFR1	33.51°N	5.13°W	36.7°N
NOT1	36.88°N	14.91°E	36.5°N
ALX2	31.20°N	29.91°E	28.5°N
NICO	35.14°N	33.40°E	31.8°N
RAMO	30.60°N	34.76°E	27.1°N

5 **Fig. 1** Location of the GPS receiver stations (red triangles) used in this study with an elevation mask $\geq 35^\circ$. GPS
6 geometric networks were formed by choosing minimum of three stations (enclosed in red box) to form new sub
7 networks (Northwest: RABT-TETN-IFR1, Northeast: ALX2-NICO-RAMO)

8
9 The observation GPS data in Rinex format were obtained from the following FTP sites: <ftp://data-out.unavco.org/pub/rinex/>, <ftp://igs.ign.fr/pub/igs/data/>, <http://www.afrefdata.org/> and <ftp://www.station-gps.cea.com.eg/ALX2/>, respectively. The GPS distribution is presented with red triangle with the
10 corresponding ionospheric pierce point (IPP) trajectory (blue color curve) of the GPS satellites (Fig. 1). To
11 avoid water vapor scattering multipath effects and effect from the mapping function uncertainty from the
12 data, an elevation cut-off angle greater than 35° (Bagiya et al., 2009; Valladares and Hei, 2012) was
13 adopted.
14
15

Fig. 2 (a) An example illustrating one of the sub-networks (RABT-TETN-IFR1) used in studying MSTIDs characteristics. (b) The configured network geometry for obtaining the MSTIDs propagation direction and velocity.

Also, the low geomagnetic activity conditions were considered using K planetary (K_p) index. The magnitude of K_p index ≤ 3 was considered for low geomagnetic quiet conditions during the study period. The K_p index data were obtained from the GFZ German Research Centre for Geosciences, Indices of Global Geomagnetic Activity, Potsdam, Germany (<ftp://ftp.gfz-potsdam.de/pub/home/obs/kp-ap>). Days with $K_p \leq 3$ during 2008-2016 were filtered out and used for this study. Furthermore, we observed and extracted temperature profile data from the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) satellite, and Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument satellite. The disturbed temperature profiles exhibit signatures which have been thought to be majorly due to the vertical propagation of AGW (Grant et al., 1998; Jonah et al., 2018). Both the COSMIC and SABER satellites are low Earth orbit (LEO) satellites which also provides other lower atmospheric products for different altitude observations, aside from temperature data product.

The COSMIC and SABER data are respectively, available at:

<https://cdaac-www.cosmic.ucar.edu/cdaac/tar/rest.html>, and http://saber.gats-inc.com/browse_data.php#.

3.0 Estimation of Ionospheric GPS-TEC derived

The ionospheric Total Electron Content (TEC) was derived from Global Positioning System (GPS) measurements. The GPS-TEC derived was used to capture the Medium-Scale Traveling Ionospheric Disturbances (MSTIDs). TEC was computed using dual frequencies GPS receivers in which the first carrier frequency f_1 is centered at 1575.42 MHz and the second carrier frequency f_2 centered at 1227.60 MHz. Following Gao and Liu (2002), Carrano and Groves (2006), Zhao et al. (2009) and Abe et al. (2017), the code and carrier phase measurements obtained from GPS were used to compute the slant TEC (sTEC) along the signals path from the satellite to the receiver as follows:

$$sTEC_p = \frac{f_1^2 f_2^2}{40.3(f_1^2 - f_2^2)} [(P_2 - P_1) - (B_s + B_r + \varepsilon_p)] \quad (1)$$

$$sTEC_L = \frac{f_1^2 f_2^2}{40.3(f_1^2 - f_2^2)} [(\lambda_2 L_2 - \lambda_1 L_1) - (\lambda_1 A_1 + \lambda_2 A_2 + \varepsilon_L)] \quad (2)$$

where P_1 is the code-delay measurement on frequency f_1 (m), P_2 is the code-delay measurement on frequency f_2 (m), B_s is the satellite differential code biases (m), B_r is the receiver differential code biases (m), L_1 is the carrier phase measurement on frequency f_1 (cycles), L_2 is the carrier phase measurement on frequency f_2 (cycles), A_1 is the ambiguity integer measure on the carrier phase on L_1 frequency (cycles), A_2 is the ambiguity integer measure on the carrier phase on L_2 frequency (cycles), ε_p is the noise within the frequency channel and multipath associated with the code-delay measurements (m), ε_L is the noise and multipath associated with the carrier phase measurements (cycles), λ_1 and λ_2 are the wavelengths (m) corresponding to f_1 and f_2 , respectively. The $sTEC_p$ obtained in equation (1) is much noisy due to the inbuilt noise in the frequency channel while the $sTEC_L$ obtained in equation (2) is much ambiguous due to some cycle slips and many loss of lock (inability of the receiver to track the signals). The noisy but unambiguous $sTEC_p$ was used to level the $sTEC_L$ to arrive at a logical $sTEC$ that is neither noisy nor ambiguous. As TEC is dependent on the ray path geometry through the ionosphere, it is needful to calculate an equivalent vertical TEC ($VTEC$) value which is independent of the elevation of the ray path. Hence, the $VTEC$ is obtained by taking the projection from the slant to vertical using a mapping function $M(\theta)$ as contained in (Klobuchar, (1986); Mannucci et al. (1998); Ciraolo L, et al. (2006)),

$$VTEC = STEC \times M(\theta) \quad (3)$$

$$M(\theta) = \frac{VTEC}{STEC} = \left[1 - \left(\frac{R_e \cos(\theta)}{R_e + h_{\max}} \right)^2 \right]^{\frac{1}{2}} \quad (4)$$

where R_e is the mean earth radius; 6371 km, θ = elevation angle of the satellite in degrees, $h_{\max}$ is the maximum height above the surface of the Earth, (Mannucci et al., 1993; Langley et al., 2002), 350 km, has been taken to be $h_{\max}$ value, this is because at this height the ionosphere is assumed to be spatially uniform and simplified to be a thin layer, hence, this is considered as the height of maximum electron density at the F2 peak (Mannucci et al., 1998; Norsuzila et al., 2009). More details about $VTEC$ estimation can be found in Mannucci et al. (1998) and Ciraolo L. et al (2006). The background trends of the TEC time series were obtained by using singular spectrum analysis (SSA) with sliding window duration of 60 mins and thereafter the output is subtracted from the original TEC time series resulting to TEC perturbation ($dTEC$), see equation (9) in the next section.

3.1 Fitting tool: Singular Spectrum Analysis (SSA)

Different order of polynomial fittings as a band-pass technique to filter out diurnal variability and TEC perturbations associated with MSTIDs have been used in previous studies (Ding et al., 2004; Wang Min et al., 2007; Valladares and Hei, 2012; Jonah et al., 2016). However, most of these techniques have some limitations because the direction of the trend of the fitness line and degree of smoothness/resolution cannot be controlled due to imposition of predetermined function. This is the reason we adopted singular spectrum analysis (SSA) algorithm as a detrending tool for dTEC. Our choice of SSA (see equation 5-8) among other things is because it is a nonparametric spectral estimation method for time series which cannot be affected by the limitations described above and most importantly due to its ability to find trends of different degrees of resolutions. We use equations (5) to (8) to map the original one-dimensional TEC time series (i.e. FN) of length N into a multi-dimensional series of lagged vectors of size L, where N is greater than two.

$$\overbrace{f_1, f_2, f_3, \dots, f_L}^{\text{window}}, f_{L+1}, \dots, f_N, \text{ implies } \mathbf{F}_1^T = (f_1, f_2, f_3, \dots, f_L) \quad (5)$$

$$f_1, \overbrace{f_2, f_3, f_4, \dots, f_L}^{\text{window}}, f_{L+1}, \dots, f_N, \text{ implies } \mathbf{F}_2^T = (f_2, f_3, f_4, \dots, f_{L+1}) \quad (6)$$

$$f_1, f_2, \overbrace{f_3, f_4, f_5, \dots, f_L}^{\text{window}}, f_{L+2}, \dots, f_N, \text{ implies } \mathbf{F}_3^T = (f_3, f_4, f_5, \dots, f_{L+2}) \quad (7)$$

$$\mathbf{F} = [\mathbf{F}_1, \mathbf{F}_2, \mathbf{F}_3, \mathbf{F}_4, \dots, \mathbf{F}_K] = \begin{pmatrix} f_1 & f_2 & f_3 & \dots & f_K \\ f_2 & f_3 & f_4 & \dots & f_{K+1} \\ f_3 & f_4 & f_5 & \dots & f_{K+2} \\ \vdots & \vdots & \vdots & & \vdots \\ f_L & f_{L+1} & f_{L+2} & & f_N \end{pmatrix}, \quad \begin{cases} 1 < L < K \\ K = N - L + 1 \end{cases} \quad (8)$$

F implies TEC time series which formed a trajectory matrix ($\mathbf{F}$), f_i implies TEC values at each epoch of each PRN as time increases, and f_i must not be series of zeros, $i = 1, 2, 3, \dots, L$. Golyandina et al. (2001) provides further details about SSA.

3.2 Estimation of TEC perturbation (dTEC) and MSTIDs event threshold

An SSA fit is determined for each TEC time series ($\text{TEC}_{\text{SSA-fit}}$) of the corresponding satellite. The TEC perturbation (dTEC) is obtained by subtracting the $\text{TEC}_{\text{SSA-fit}}$ from the TEC estimate.

$$\text{dTEC} = [\text{TEC}] - [\text{TEC}_{\text{SSA-fit}}] \quad (9)$$

1 The approach to obtain dTEC in equation (11) is known as detrending. We determine that an MSTID event is
 2 detected whenever the TEC perturbation (dTEC) points fall above the event threshold (ETH) value of 0.07
 3 TECU (Husin et al., 2011). The choice of ETH value was based on computing the standard deviation of the
 4 TEC perturbation (dTEC) of all epochs per observed satellite (Warnant, 1998; Warnant and Pottiaux, 2000).
 5 We iterated the entire standard deviation process for several satellites for different days and then found an
 6 approximate value of the most dominant standard deviation value which we set as the ETH point value.

7
 8 **Fig. 3** (a) TEC time series in PRN 13 as observed at RABT GPS station exhibiting wave-like structures depicting to
 9 be MSTIDs. The red line fitted curve ($TEC_{SSA-fit}$) is the background trend while (b) is the corresponding
 10 detrended TEC time series known as dTEC.
 11

12 3.3 Determination of MSTIDs Characteristics

13 In this study, we define MSTIDs as the dTEC that satisfy the following criteria: (1) the dTEC has as
 14 amplitude exceeding 0.07 TECU ($1TECU=10^{16}$ Electron/ m^2) (Fig. 3b); (2) the horizontal wavelength is
 15 described as the distance between peak to peak of each wave event using visual assessment of dTEC signals
 16 and estimated to be less than 500 km; (3) the dTEC series was transformed from the time domain to the
 17 frequency domain in order to determine the event dominant period using a Fast Fourier Transform (FFT)
 18 (Husin et al., 2011; Arikan et al., 2017) and the period is estimated to be less than 60 mins; (4) the
 19 propagation velocity does not exceed 450 m/sec. The geometry of calculating the MSTIDs propagation
 20 parameters is plotted in Fig. (2b) as an illustration in determining the azimuth and velocity. It must be noted
 21 that GPS receiver stations that are relatively close to each other are considered to form a sub-network
 22 (minimum of three stations) following the approach of Afraimovich et al. (1998); Hernández-Pajares et al.
 23 (2012); Valladares and Hei, (2012); and Habarulema et al. (2013a). Hence, we form a sub-network as seen
 24 in Fig.1, where the GPS receiver station RABT, TETN and IFR1 is represented by X, Y and Z, respectively
 25 in Fig 2(a-b). We assume that the TID's wavefront propagates along the Earth's spherical surface and
 26 crosses point positions X, Y and Z with speed v and propagation azimuth (ϕ). The azimuth is measured
 27 from the north (N) towards the east along the horizon. The phase fronts propagation velocity satisfies the
 28 equations below (Ding et al., 2007).

$$V\Delta t_1 = \Delta S_1 \cos(\Phi - \psi_1), V\Delta t_2 = \Delta S_2 \cos(\Phi - \psi_2) \quad (10)$$

Where Δt_1 and Δt_2 are time delays for dTEC to move from point X to Y and Z respectively along the Earth spherical surface and computed using cross-correlation. ΔS_1 is the spherical distances between X and Y, ΔS_2 is the spherical distance between X and Z, while ψ_1 and ψ_2 are the azimuths of spherical paths XY and XZ.

$$\Phi = \arctan\left(\frac{\Delta t_1 \cdot \Delta S_2 \cdot \cos\psi_2 - \Delta t_2 \cdot \Delta S_1 \cdot \cos\psi_1}{\Delta t_2 \cdot \Delta S_1 \cdot \sin\psi_1 - \Delta t_1 \cdot \Delta S_2 \cdot \sin\psi_2}\right) \quad (11)$$

Phase velocity of the TIDs was computed using

$$V = \frac{\Delta S_1}{\Delta t_1} \cos(\Phi - \psi_1) \quad (12)$$

Different observation points of X, Y, and Z were chosen to compute absolute values of V and Φ ; thereafter we take the average value of V and Φ as the MSTIDs propagation velocity and azimuth. One important criterion that must be noted for computation of azimuth using equation (11), is that each of the GPS receiver stations within a sub-network must see the same satellite per observation time. Hence, the same satellite that could be seen by a sub-network is filtered for computation while other satellites are discarded. We also calculated the MSTIDs percentage occurrence rate (POR) of the event using equation (13).

$$POR = \left[\frac{\alpha}{\omega} \right] \times [100] \quad (13)$$

where α is the total count number of dTEC estimation above ETH per epoch, ω is the total count number of dTEC estimation per epoch.

17

18 4.0 Results

We have analyzed the derived dTEC in the North African region during 2008-2016 and the wave-like structures depicted to be MSTIDs were estimated. The MSTIDs percentage occurrence rate (POR) was determined and divided into hourly bins. Variations in local time (LT) are analyzed by sorting the data into one-hour bins. Following Jayawardena et al. (2016) and Wang et al. (2017), we considered the daytime (DT: 0600–1800 LT) as dawn to dusk while the nighttime (NT: 1800–0600 LT) as dusk to dawn. However, for easy analysis and convenience, we converted the LT to universal time (UT) in a case where MSTIDs event are being observed simultaneously at more than one station in different sub-region. MSTIDs are observed and their characteristics are determined. Fig.4 shows an illustration for the case of a single day.

27

4.1 Observation of MSTIDs during 07 March 2010

In this section we determine the MSTIDs characteristics for 7th March 2010 (DOY 066) using equations (10), (11), and (12).

Fig. 4 (a) TEC versus UT measured by the GPS receivers (RABT, TETN and IFR1); color blue, green and black signal traces represent TEC values from the three receivers and the red lines represent the estimated background/unperturbed TEC values. (b) Corresponding detrended TEC time series of fig. (a), (c) Perturbed temperature profile from COSMIC satellite (blue color) and its fit (red color), (d) MSTIDs minimum and maximum dominant periods, (e) polar plot representing MSTIDs velocities and azimuth for daytime during DOY 066 (f) Signature of upward AGW propagation obtained from the detrended temperature profile in fig. (c).

The TEC time series exhibited continuous fluctuations as observed in PRN 13 at different local times (LT) in different stations located within the same sub-region. We used COSMIC temperature profile measurement within the geographic coordinate (lat: 31.4° N - 32° N, long: 1.7° E - 1.8° E) that is most aligned or close in distance to the geographic area of interest during. The DOY 066 daytime phenomenon in Fig. (4a) has majorly been thought to be caused by AGW as stated in the introductory section, and the perturbed temperature profile in Fig. (4c) characterizes a possible passage of AGWs from the troposphere to the ionosphere, and which eventually propagate above 50 km into the ionosphere (Azeem and Barlage, 2017). Following Jonah et al. (2016), the plotted Fig. (4c) indicates how the perturbed temperature profile exhibits the AGWs passage from the troposphere to the ionosphere. The wave on reaching the mesosphere (above 50 km) breaks and release momentum where some waves travel further into the thermosphere (Tsuda et al., 2015), this brief process suggests a possible source of the MSTIDs during the selected day.

1 Unfortunately, the COSMIC satellite could not capture temperature measurements above 60 km altitude,
 2 and this is one of the limitations of the COSMIC satellites for temperature measurement.
 3
 4 In order to validate the possibility that the AGWs propagated beyond 60km as shown in Fig. (4c),
 5 temperature data from SABER satellite is plotted in Fig. 4(g-i). We filtered and obtained three temperature
 6 profile measurement within the geographic coordinate (lat: 28.07° N – 37.07° N, long: 4.00° E - 4.22° E)
 7 that is most aligned or close in distance to the geographic area of interest during 1440 to 1445 UT.
 8

9
 10 **Fig. 4** (g-i) Perturbed temperature profile from SABER satellite (black color) and its fit (red color),
 11

12 We observed a temperature change as the height increases in Fig. 4 (g-i), and the perturbed temperature
 13 profile structure (black line curve) shows an indication of vertical propagation of the AGWs (Jonah et al.,
 14 2018). We also observed a considerable dynamic variation at a height between ~65 and 100 km in each of
 15 the temperature profiles, it is obvious that the AGWs propagation survived to the ionosphere. Hence, it is
 16 possible that the observed AGWs during the selected day is responsible for MSTIDs generation.
 17

18 One of the important atmospheric parameters that shows an evidence of the AGWs passage is the cloud top
 19 brightness temperature as a consequences of convection activities. Hoffmann et al. (2010) reported that
 20 brightness temperature (BT) value that is less than 250° K (i.e. BT < -23.15 °C) corresponds to deep or
 21 strong convection activities. In addition, Figueiredo et al. (2018) also reported that cloud top brightness
 22 temperature which ranges (i.e. threshold) between -65°C and -20°C during convection activities is an
 23 important atmospheric parameter that exhibit the AGWs passage. Therefore, we may deduce from the
 24 reports of Hoffmann et al. (2010) and Figueiredo et al. (2018), that the observed MSTIDs during the
 25 selected day (DOY 066) is possibly generated by AGWs which is as a consequence of convection activities.

1 The minimum and maximum dominant period of MSTIDs is obtained using FFT and it is computed to be an
2 average of 11.7 mins and 18 mins, respectively. Fig.4 (e) shows that MSTIDs propagates towards the
3 equator (southward) but indicated a higher percentage towards the south-east (SE). The temperature profile
4 is detrended, in line with Wang et al. (2009), describing the output structure to be the vertical signature of
5 upward AGW propagation.

6

7 **4.2 Two-dimensional observation of MSTIDs over North Africa**

8 Fig.5 shows the two-dimensional maps of MSTIDs over North Africa region at selected times during 1019
9 to ~1200 UT (daytime) of day 066, 2010, using PRN 20 in all the eight stations. With careful observation,
10 Fig.5 (a-b) shows an example of two-dimensional maps of TEC perturbations during the passage of
11 MSTIDs over North African with maximum amplitude of 0.3 TECU. We splitted Fig.5 (a-b) into two to
12 increase the map resolution.

13

14 **Fig. 5** Two-dimensional maps of MSTIDs over North Africa at 1019 to ~1200 UT on 7th March, 2010 (DOY 066).

15 The GPS receiver stations situated at the northwest have a close intra-distance than stations at the northeast,
16 and this is the reason why Fig. (5a) produce a better MSTIDs formation and resolution than Fig. (5b).

17 **4.3 Local observation of MSTIDs over selected GPS receiver stations in North Africa**

18 Figure 6(a-b) exhibits local diurnal and seasonal variations of MSTIDs occurrence at the different GPS
19 receiver's stations located at mid-latitude stations. Data gap are indicated by the white portions on figure.
20 Each station in each panel exhibited a similar contour structure but clearly shows different occurrence rate
21 in terms of season and local time. In Fig. 6(a), the MSTIDs occurrence shows a strong dependence on the
22 season (June solstice) and local times but with a major peak around the (nighttime) 2100-0200 LT (~27 % to

1 ~45 %). Also, the daytime MSTIDs exhibited some minor peaks in December solstice around 1200–1600
2 LT. In Fig. 6(b), the nighttime MSTIDs occurrence exhibited similar seasonal (June solstice) and local times
3 features as Fig. 6(a) but during 1900-0200 LT (~25 % to ~40 %). In addition, the daytime (09000–1600 LT)
4 MSTIDs exhibited some peaks but not as pronounced as Fig. 6(a) during 2011 – 2015. Nighttime MSTIDs
5 seems to decrease with an increasing solar activity. All stations exhibited an increasing MSTIDs POR
6 consistently with the solar cycle. The highest MSTIDs POR at the Mid-latitude is consistently observed in
7 June solstice during 2008-2016. The POR density shows that the occurrence rate varies with time of the day
8 and season. This result seems to reveal occurrence variation and a level of inconsistency during day and
9 night time from year to year. Hence, in subsequent section, we analyze day and nighttime amplitudes
10

11 **Fig. 6a:** Local diurnal and seasonal variations of MSTIDs occurrence at different stations. White portions indicate
12 data gap. Top panel is TETN station, Middle panel is RABT station, and bottom panel is IFR1 station

Fig. 6b: Local diurnal and seasonal variations of MSTIDs occurrence at different stations. White portions indicate data gap. Top panel is ALX2 station, Middle panel is NICO station, and bottom panel is RAMO station

4.4 Interannual and seasonal dependence of MSTIDs amplitudes

MSTIDs daily maximum amplitudes obtained from all stations were at mid-latitude were analyzed in this section. Figure (7) shows MSTIDs daily maximum amplitudes for daytime and nighttime. For better visual analysis and to observe slightest changes in the multiple scatter plots, we introduced a mathematical function (simple moving average) which estimates the average value to determine the trend line-curve for both day and night (red and blue line) which we use for analysis. Both nighttime and daytime exhibited similar pattern of trend curve but different amplitude variability. For instance, the nighttime amplitude consistently and dominantly higher than daytime during the solar minimum year (2008-2010), having a high peak around (0.22 - 0.37 TECU) in June solstice.

Fig. 7: MSTIDs amplitude time series for both nighttime and daytime

The high peak amplitudes switched from nighttime to daytime, exhibiting major peaks around (0.45 - 0.94 TECU) in September equinox during 2011 - 2015, and March equinox of 2014. The nighttime amplitude consistently exhibits higher peak during the June solstice, while the daytime consistently exhibits higher peak during the equinox months during 2008-2016. The dominant major higher peaks are observed in solar maximum year of 2014. By considering the solar minimum and maximum years, the nighttime amplitude seems to be slightly decreasing with increase in solar activity during June solstice. The daytime amplitude values increase with solar activity. However, it must be noted that the high background TEC experienced during high solar activities in equinox season also could influence the high MSTIDs amplitude, in that whenever the TEC background is large, the amplitude of TEC perturbation is also large. Hence, this has in a way shown a correlation between background TEC and MSTIDs (Jonah et al., 2020).

4.5 MSTIDs characteristics

In estimating the MSTIDs azimuth, we followed equation (11) in section 3.3, and we choose to focus only on stations with the closest intra-distance between one another. Hence, we selected GPS receiver stations (RABT-TETN-IFR1) which have an estimated intra-distance of 206 km, while other stations have their intra-distance more than 600 km. Fig. 8 (top panel) shows polar plots representing MSTID velocities (in m/s) and azimuths during 2008 - 2016 for March equinox, June solstice, September equinox, and December solstice. In order to estimate a discrete propagation direction as a function of percentage since the polar measurements look clustered, and for clearer analysis, we further divided the azimuth measurements into daytime (DT) and nighttime (NT) and get it plotted on a bar-chart (Fig. 8 (bottom panel)). The bar-chart shows discrete cardinal directions; North (N), North-East (NE), East (E), South-East (SE), South (S), South-West (SW), West (W), and North-West (NW) following Otsuka et al. (2013) approach, the bar chart also shows the daytime and nighttime mean velocity for each of the seasons. The MSTIDs propagation velocity

1 is within 50 - 450 m/s, with velocity dominance of 200 - 300 m/s for every season except September
 2 equinox which has a dominance velocity value between 100 - 200 m/s.
 3

4
 5 **Fig. 8:** (top panel) shows polar plots representing MSTID velocities (in m/s) and azimuths for different seasons.
 6 (bottom panel) Bar chart showing cardinal directions of MSTIDs propagation having the percentage azimuth
 7 occurrence rate on the vertical axis, while the corresponding cardinal directions are on the horizontal axis.

8 Generally, the entire MSTIDs dominantly propagates southward (equatorward) as seen in Fig. 8 (top panel),
 9 dominantly between 120° - 230°. However, there are slight variations in propagation direction during
 10 daytime and nighttime as seen in Fig. 8 (bottom panel) which reveals the preferred propagation direction.
 11 Some few MSTIDs are observed to propagate northward, but most observation are seen to be dominantly
 12 southeastward and southwestward for both daytime and nighttime MSTIDs in all the seasons but with slight
 13 exceptional cases in March equinox, June solstice and December solstice, where the nighttime MSTIDs
 14 propagation towards the southwest is slightly higher than the daytime by ~1.80 %, 4.01 %, and 2.01 %,
 15 respectively. Furthermore, both daytime and nighttime discretely propagated southward within 17% - 19%
 16 (azimuth occurrence rate) in all seasons, with the daytime slightly higher than the nighttime during the
 17 March equinox, and June solstice, respectively. On the other hand, the nighttime is slightly higher than the
 18 daytime during the September and December solstice, respectively. In addition, the daytime MSTIDs
 19 propagates towards the southeast, and slightly higher than the nighttime which also propagates in the same
 20 direction by ~ 4.0 %, and ~ 3.0 % during the March equinox, and December solstice, respectively. The

1 nighttime MSTIDs percentage of propagation direction is higher in both southeast and southwest direction
2 during June solstice, and during the September equinox the daytime MSTIDs percentage of propagation
3 direction is higher southwest direction while the nighttime is slightly higher than the daytime in southeast
4 direction. There are certain exceptions where the percentage of the southeastward propagation of daytime
5 MSTIDs is comparable with that of the southwestward propagation during March equinox, the same thing
6 also applies to nighttime MSTIDs but during December solstice. The detrended TEC time series were used
7 to obtain the MSTIDs period by using fast Fourier transform (FFT) following (Husin et al., 2011; Arikan et
8 al., 2017). The MSTIDs occurrence periods estimated with less than 6 minutes were regarded as noise
9 fluctuations and therefore eliminated (Valladares and Hei, (2012)). The velocities were computed using
10 equation (12) and the wavelengths were estimated from the distance the TEC wave-like structure traveled in
11 space (latitude or longitude) following (Jonah et al., 2016). The daytime MSTIDs mean velocity is larger
12 than the nighttime in all season, except in June solstice where the MSTIDs velocity experiences a reverse
13 case. All seasons exhibited similar mean MSTIDs occurrence period (DT: 14 - 38 mins, NT: 13 - 35 mins)
14 and wavelength (DT: 118 - 391 km, 96 - 382 km). The estimated values for velocity, period, and
15 wavelength, respectively are within the ranges typically associated with MSTIDs discussed in section (1.0).
16 The regional distribution of MSTIDs on a spatio-temporal map over the mid-latitude of North Africa region
17 is shown in Fig. (9). MSTIDs maps from different sectors at mid-latitude were superimposed. The local time
18 (LT) was converted to UT for time uniformity, easy analysis and most importantly to observe the dominant
19 event time of occurrence for each year covering geographic latitudes (GL) 30°N to 42°N and longitude
20 18°W to 42°E (Otsuka et al., 2013).

21

22

23 **Fig. 9** Universal time and seasonal variations in MSTIDs POR at mid-latitudes ($42^{\circ}\text{N} \leq \text{GL} \leq 30^{\circ}\text{N}$); 2008 – 2016

24 The distribution of dominance occurrence of MSTIDs in Fig. (9) shows a semiannual variation with the
25 major primary peak at June solstice (i.e. summer) during the NT (2100 - 0300 UT) and secondary peak at
26 December solstice (i.e. winter) during the DT (1000 - 1500 UT). The maximum MSTIDs POR is observed
27 to be ~45% in 2014 and 2015.

28

1 **5.0 Discussion**

2

3 We have investigated statistically dTEC variations observed by GPS receivers located in Northern African
4 region at mid-latitudes to reveal MSTIDs occurrence rate at local time, seasonal, latitudinal variations and
5 propagation direction at daytime and nighttime, respectively, during 2008-2016.

6

7 Our statistical results show a distinct difference between the observed MSTIDs activities. Fig. (3a) and (4a)
8 shows daytime TEC measurement exhibiting wave-like structures depicting to be MSTIDs due to the
9 passage of AGW (Hines, 1960; Hooke, 1968; Jonah et al., 2016; Oinats et al., 2016; Valladares et al., 2012).
10 The AGWs passage involves vertical displacement of air parcels originating in the troposphere (Hines
11 (1960)) and which causes perturbation in the ionospheric electron density. Temperature and wind
12 perturbations are the two parameters that oscillate for a freely propagating wave which transport energy and
13 momentum from their source into certain height in the ionosphere. The neutral air wind perturbation collides
14 with the plasma at F region, and then the charged ions are set in motion but are constrained to move along
15 the magnetic field lines. The transportation of the charged molecules/ions along the magnetic field lines
16 leads to electron density enhancement in certain places along the wave-front and also depletions in some
17 other places. The continuous and regular enhancement and depletion of the plasma density consequently
18 leads to TIDs occurrence (Hooke, 1968). Our result in Fig 4(g-i) is similar with the results obtained by
19 Jonah et al. (2018) where they reported MSTIDs occurrence as a result of AGWs due to convection
20 activities over North America. The MSTIDs 2-D map in Fig. 5 (a-b) seems to stretch from the Northwest
21 (NW) towards the Northeast (NE) with a maximum amplitude peak value of 0.30 dTECU, this elongation
22 from NW to NE confirms the MSTIDs feature of long-distance propagation or travel hypothesis of MSTIDs
23 (Frissell et al., 2014).

24

25 Fig. 6 (a) and Fig. (b) consist of GPS receiver stations located at NW and NE, respectively, and they show
26 different characteristics between daytime and nighttime MSTIDs occurrence, such as local time, seasonal,
27 and solar activity dependence. These facts indicate that different mechanisms initiate MSTIDs occurrence
28 during daytime and nighttime period, and at different seasons. A high occurrence rate of MSTIDs was
29 observed in the daytime during 1100–1600 LT, and 0900–1400 LT at NW and NE, respectively during the
30 March equinox and December solstice, respectively. However, the nighttime MSTIDs exhibited highest
31 occurrence rate observed in June solstice during ~2100 - 0200 LT and ~1900 - 0200 LT at NW and NE,
32 respectively. Both daytime and nighttime MSTIDs occurrence at NW is more pronounced during 2011-
33 2015, than SE stations. The daytime MSTIDs POR increases with increase with solar activity. The nighttime
34 during 0001- 0200 LT seems to increase with increase in solar activity, while the nighttime during 1900 -
35 2300 LT seems to decrease with increases in solar activity. Our MSTIDs seasonal occurrence results show a

1 good agreement with the MSTIDs investigation conducted by Tsugawa et al. (2006a) who reported MSTIDs
2 occurrence over South-East Asian sector (Japan). In their investigation, they reported nighttime (2100 -
3 0300 LT) MSTIDs to be the highest activities in every year during summer (May–August), they added that
4 the summer nighttime activities become weaker as the solar cycle approaches its maximum. They also
5 observed on the contrary that the daytime (0900 - 1500 LT) MSTIDs occurrence is high during the winter,
6 but there is no clear indication of solar activity dependence of the daytime activities. The slight difference
7 between this current study and Tsugawa et al. (2006a) is that the current study shows a clear increase in
8 daytime MSTIDs occurrence as solar activity increases, and the nighttime MSTIDs seems to be decreasing
9 specifically during 1900 - 2300 LT as solar activity increases. Furthermore, the seasonal results in this
10 current study is similar to the result obtained from with MSTIDs study over the North American sector
11 (California) conducted by Hernández-Pajares et al. (2012), they reported daytime MSTIDs occurrence
12 during winter (November–January) and fall (August–October), and nighttime during summer (May–July)
13 and spring (February–April), whereas this current study report daytime and nighttime occurrence during
14 December solstice and June solstice, respectively. However, the nighttime (0001 – 0200 LT) slightly
15 extends to March equinox season during the solar maximum of 2014.

16
17 In Fig. (7), each year of the MSTIDs amplitude time series exhibited an asymmetric structure, and most
18 especially during the daytime period. The MSTIDs occurrence exhibited a significant increase in the year
19 2011 relative to 2009 - 2010, and 2012 - 2013, during September equinox, possibly due to the increase in
20 solar activity as expressed by an increase in sunspot numbers. The mean sunspot numbers in September
21 equinox in 2009, 2010, 2011, 2012, and 2013 are 4.9, 33.2, 104, 88, and 87, respectively (see.
22 <http://www.sidc.be/sunspot-data/>) (Tariku (2015)). Generally, the MSTIDs amplitude increase with an
23 increase in solar activity, most especially the daytime period, this result agrees with Oinats et al. (2016) who
24 investigated MSTIDs observation over Hokkaido East during 2007 - 2014, and over European-Asian sector
25 during the 2013-2014 using radar data. They reported an increase in amplitude with an increase in solar
26 activity, and that the amplitude tends to increase with increasing auroral electrojet (AE) index, and also
27 found that MSTIDs amplitude is dominantly high at daytime.

28
29
30 In estimating the MSTIDs propagation direction, we grouped the azimuth of the MSTIDs propagation
31 direction into daytime, nighttime and seasons. The propagation direction of MSTIDs for both daytime (DT)
32 and nighttime (NT) are dominantly Southward (equatorward) as observed from the Northern hemisphere in
33 Fig (4e), and Fig. (8-top panel), while Fig. (8-bottom panel) show the azimuth occurrence rate expressed in
34 percentage following Otsuka et al. (2013) approach. Some previous studies have shown agreement or
35 similar result with the current result of propagation direction of MSTIDs. For instance, Jacobson et al.

(1995) investigated daytime and nighttime MSTIDs occurrence using a very long baseline interferometer (VLBI) array illuminated by 136/137-MHz radio beacons of two geostationary satellites at New Mexico (35.9° N, 106.3° W), and they reported different seasonal variations in terms of occurrence rate and their propagation direction. They further showed that the preferred daytime MSTIDs propagation direction is southward during winter and equinox seasons, respectively, while the nighttime MSTIDs often occur during summer solstice during, autumn equinox and propagate toward the west/northwest. In addition, Kotake et al. (2007) reported the azimuth of the MSTID propagation direction during the daytime to be southeastward (90° to 240°) in equinox and in winter (120° to 240°) season, respectively, and also reported the nighttime MSTIDs to be southwestward and westward propagation (between 210° and 300° in azimuth) in equinox and summer seasons. While Ding et al. (2011) reported a dominant propagation of daytime MSTIDs towards the equator, adding that nighttime and daytime MSTIDs are similar in period and propagation azimuth. However, they stated that the nighttime MSTIDs dominantly propagated southwestward in the Northern hemisphere at all seasons, irrespective of the latitude, and also the nighttime MSTIDs highest propagation occurrence in June, around the summer solstice. In this current study, both the daytime and nighttime MSTIDs are dominantly propagating southward (rotating clockwise from 90° to 240°), but spread into different cardinal directions. Figure (8-bottom panel) exhibited a discrete propagation direction for daytime and nighttime, and it shows the dominant daytime MSTIDs exceeded the nighttime by ~ 4 % in the southeastward propagation during March equinox and December solstice. This result shows similarity with the seasonal propagation dominance obtained by both Jacobson et al. (1995) and Kotake et al. (2007) discussed earlier, but differs in terms of propagation direction with Jacobson et al. (1995). The southwestward dominant propagation direction occurrence for nighttime MSTIDs during March equinox, June solstice, and December solstice which is also similar to Kotake et al. (2007), and Ding et al. (2011), except for December solstice. Furthermore, this study shows June solstice to have the highest percentage of azimuth of the nighttime MSTID propagation direction which agrees with Ding et al. (2011), but the preferred propagation direction is southeastward. Figure (8- bottom panel) also shows certain MSTIDs preferably propagating towards the N, NE, E, W, and NW, having the percentage of azimuth of the propagation direction below ~6.2% which may be as a result of local background geophysical conditions during the propagation period. However, we considered them as insignificant, and hence we focused on the azimuth occurrence rate higher than 17%. Our result shows that not all daytime and nighttime MSTIDs propagates southeast and southwest, respectively, as it has been hypothesized by some previous studies, and based on the comparison of the MSTIDs propagation direction in the current study with previous propagation direction reports by different authors we may then infer that mechanisms causing the azimuth of the MSTID propagation direction could depend on the location, local time, season, background geophysical conditions and prevailing ionospheric conditions over the geographical location of interest.

1 The mean propagation velocity of MSTIDs varies from 205 - 241 m/s, with the daytime propagation
2 velocity mostly higher than nighttime, which is similar with previous study (Husin et al., 2011; Hernandez-
3 Pajares et al., 2012) except during June solstice where the nighttime is higher than the daytime which agrees
4 with Oinats et al. (2016). The major contrast between present study and Oinats et al. (2016) is that, the
5 nighttime MSTIDs propagation velocity is higher than the daytime only in June solstice, on the contrary
6 Oinats et al. (2016) reported higher daytime velocity values over in the nighttime during 2007- 2014, using
7 HF radar data.

8
9 However, several studies have been done to investigate the mechanisms responsible for the daytime and
10 nighttime propagation direction of MSTIDs. Heisler, (1963) stated that propagation direction of TIDs is
11 towards the ionospheric part where it is mostly illuminated by the Sun (from the Northern hemisphere),
12 whereas Thome, (1964) stated that the most supported theory for propagation direction is that TIDs
13 propagates in the direction of the geomagnetic field lines. Hooke, (1968, 1970) in his investigation on
14 ionospheric response to internal gravity waves stated that at F-region heights, the ions move and travel
15 along the geomagnetic field lines through neutral-ion collision, with a velocity the same as the velocity of
16 the neutral motion along the geomagnetic field caused by the gravity waves, during this process some
17 azimuthal directions of wave propagation are preferred as a function of the ionospheric response that are
18 evoked. However, the motion of the ions across the magnetic field line hypothesized by Thome, (1964) is
19 constrained to move along the magnetic field lines because the gyro-frequency of the ions is much higher
20 than the frequency of the ion-neutral collisions. The direction of the motion of the ions consequentially
21 leads to directivity in the response of the electron density variations to the gravity waves. This kind of
22 directivity phenomena could be responsible for daytime MSTIDs southward propagation direction (Kotake
23 et al., 2007). Besides, an anisotropic frictional ion drag force has been thought to also responsible for the
24 Southward propagation of the daytime MSTID direction (Liu and Yeh, 1969; Kelley and Miller, 1997).

25
26 To discuss the observed nighttime MSTIDs occurrence in the current study, it is noteworthy to state that
27 nighttime MSTIDs were previously found to be associated with increases in the F-region peak electron
28 density altitude by Behnke (1979), and its source was conventionally assumed to be generated by
29 electrodynamical forces such as Perkins instability (Perkins, 1973). The main concept of the Perkins
30 instability (PI) is that when a current flow along the Northwest-Southeast wave fronts at the nighttime in the
31 Northern hemisphere, the MSTIDs which are plasma density perturbations produce spatial non-homogeneity
32 of the Pedersen conductivity (Σ). However, when a perturbation of Pedersen conductivity develops a
33 structure that is extended from Northwest to Southeast, electric current $\mathbf{J}$ traverses Pedersen conductivity.
34 During this condition, the polarization electric field ($\mathbf{E}$) which is Northeastward (Southwestward) in the
35 regions of low (enhanced) Pedersen conductivity is generated to maintain a divergence-free current. The

1 generated polarization electric field (∂E) moves the plasma upward (downward) via the $E \times B$ drift, which
2 consequently causes perturbation in the plasma density (Otsuka et al., 2013), and the mechanism for
3 generating polarization electric field (∂E) is mostly consistent with an ionospheric instability mechanism
4 introduced by Perkins (1973). This process is a possible mechanism for generating the nighttime MSTIDs
5 with phase fronts elongated from NW to SE in the Northern hemisphere. In the condition where the wave
6 vector of Σ perturbations is between the $\mathbf{J}$ direction and the zonal direction, the perturbations in both plasma
7 density, and electric field grow with time through the Perkins instability (Perkins, 1973). Therefore, the
8 nighttime MSTIDs observed over North Africa region at nighttime could be caused by the electrodynamical
9 forces processes discussed above. However, it is noteworthy to add that the growth rate of the generative
10 mechanism of Perkins instability at mid-latitudes is very low, and therefore would require additional
11 seeding mechanism such as gravity waves (Huang et al., 1994) as well as electrodynamic coupling
12 processes between F- and E- regions to boost the low Perkins growth rate to allow for the nighttime
13 MSTIDs development (Cosgrove, 2004; Otsuka et al., 2007).

14 The nighttime MSTIDs results statistically show propagation direction is dominantly towards the south in
15 the current study, and most nighttime MSTIDs percentage azimuth occurrence rate is higher than the
16 daytime in the southwest direction in all seasons, except during September equinox where the daytime
17 MSTIDs is slightly higher than nighttime MSTIDs, these results are similar with previous studies regarding
18 nighttime propagation direction to a certain extent. Often times, the nighttime MSTIDs have propagation
19 direction to southwestward (northwestward) in Northern (Southern) Hemisphere (Garcia et al. 2000; Kotake
20 et al. 2007), and for this reason Perkins instability (Perkins, 1973) is assumed to be responsible for the
21 generation of nighttime MSTIDs (Figueiredo et al., 2018). Moreover, the dominant nighttime MSTIDs
22 propagation direction during June solstice in the current study is observed to exhibit the highest peak of
23 percentage azimuth occurrence rate but propagated southeastward, while the dominant daytime MSTIDs
24 propagation direction during September equinox is observed to be southwestward. The propagation
25 directions during these seasons are different from the results previously observed by (Kotake et al. 2007)
26 who studied MSTIDs over Southern California using GPS network, and Fukushima et al. (2012) who
27 investigated nighttime MSTIDs over Kototabang, in Indonesia using 630-nm airglow images, both studies
28 done in Northern hemisphere. The former reported nighttime MSTIDs to be propagating southwestward,
29 while the latter reported that most nighttime MSTIDs propagated towards the south and southwest. On the
30 contrary, Figueiredo et al. (2018b) investigated the nighttime MSTIDS morphology over Cachoeira Paulista
31 at Brazil in Southern hemisphere using Optical Thermosphere Imagers, and they reported certain class of
32 nighttime MSTIDs to have propagated towards the northwestward direction in which they explained its
33 mechanism as a consequences of Perkins instability theory, and another class of nighttime MSTIDs to have
34 mainly propagated towards the north-northeastward direction. Also, in the same vein, Paulino et al. (2016)

observed that nighttime MSTIDs over “São João do Cariri” in the Southern hemisphere exhibited propagation direction towards the north, northeast, northwest, and southeast. Comparison of the nighttime MSTIDs propagation direction results from Kotake et al. (2007), Figueiredo et al. (2018b), Paulino et al. (2016), and the current study shows an indication that location of the different MSTIDs source could possibly influence propagation direction, and that Perkin instability theory does not always play out in nighttime MSTIDs propagation direction. In addition, we may also possibly say that these propagation direction differences may be as a consequences of wind filtering (Figueiredo et al., 2018b).

The MSTIDs distribution map is developed in Fig. (9), the map gives a general view of MSTIDs in the North Africa region, and most importantly the MSTIDs occurrence dominance. The regional distribution has similar features such as season and time (Hrs) of occurrence as Fig. (6a-b) but with little difference in occurrence time range, and solar activity dependence. The high MSTIDs occurrence level observed during daytime and nighttime are 0900–1600 UT (December solstice (winter)) and 2000–0400 UT (June solstice (summer)) respectively, in each year but the seasonal peak got extended to March equinox during in 2011, 2014, and 2015, but more pronounced in 2014. The same occurrence mechanism discussed above for local sector is also responsible for the regional distribution. The figure shows a consistent increase in MSTIDs occurrence with increase solar activity.

Conclusions

For the first time, the climatology of MSTIDs has been studied during solar cycle #24 (2008-2016) using the GPS network within the North African sector at the Northern Hemisphere. Quiet days with $K_p \leq 3$ were considered in this study. We examined the MSTIDs occurrence rate, statistical characteristics for daytime and nighttime, the excitation mechanism and spatial-temporal distribution. The study concluded that:

1. From the estimated TEC data, we derive the TEC perturbations (dTEC) by subtracting the TEC time series from corresponding best fitted ($TEC_{SSA-fit}$) obtained from non-parametric models such as SSA as a band-pass technique to filter out TEC perturbations associated with MSTIDs.
2. We deduced from the analysis of TEC wave-like structures and perturbed temperature profile of the selected day (7th March 2010), that AGWs may be responsible for the MSTIDs occurrence. Also, MSTIDs exhibited the ability to propagate over long distances. Hence, MSTIDs have been observed by both short and long baseline measurements as in the case of NW and NE in Fig. 5(a-b) for the selected day.

3. MSTIDs occurrence is a local phenomenon and its occurrence rate is majorly dependent on local time, season and latitude. However, we found that MSTIDs occurrence rate during study period can be categorized into different groups based on location. There is diurnal variability in MSTIDs occurrence at Mid-latitude, but the daytime MSTIDs dominantly occur around (NW: 1200–1600 LT) and (NE: 1000–1400 LT) in December solstice, while nighttime dominantly occurs around (NW: 2100–0200 LT) and (NE: 1900–0200 LT) in June solstice, but get extended to March equinox during solar maximum (2014).
4. MSTIDs occurrence rate were observed to increase during daytime and seems to decrease during nighttime with increase in solar activity, respectively.
5. In the current study, not all daytime and nighttime MSTIDs observations dominantly propagated southeastward and southwestward, respectively, and this may be as a consequence of wind filtering.
6. Both daytime and nighttime MSTIDs over North African propagate southward (equator). However, there are indications that the daytime MSTIDs dominantly propagates towards the southeast, and slightly higher than the nighttime by $\sim 4.0\%$, and $\sim 3.0\%$ during the March equinox, and December solstice, respectively. The nighttime MSTIDs exhibited a high propagation towards the southwest during March equinox, June solstice, and December solstice, but during June solstice both the daytime and nighttime MSTIDs exhibited the largest dominant propagation in southeast direction.
7. The mean phase velocity in daytime MSTIDs is higher than the nighttime in every season, except during June solstice.
8. There is a consistent asymmetrical effect of MSTIDs amplitude at both nighttime and daytime in equinox months. There is dominant annual asymmetry effect of MSTIDs in June solstice during solar minimum with nighttime amplitude higher than daytime, but the amplitude peak switched from June (nighttime) solstice to equinox seasons (daytime). The regional distribution of the MSTIDs activity shows a primary peak during June solstice and secondary peak during December solstice.

Abbreviations

MSTIDs: medium-scale traveling ionospheric disturbances; GPS: Global Positioning System; AGW: Atmospheric Gravity Waves; TEC: Total Electron Content; dTEC: TEC perturbations; NNSS: Navy Navigation Satellite System; SuperDARN: Super Dual Auroral Radar Network; HF: High frequency; COSMIC: Constellation Observing System for Meteorology, Ionosphere, and Climate; RO: radio occultation; OR: occurrence rate; LEO: low Earth orbit; CDAAC: COSMIC Data Analysis and Archive Center; DCB: differential code biases; VTEC: vertical TEC; SSA: singular spectrum analysis; FFT: fast Fourier transform; POR: percentage occurrence rate; LT: local times; UT: universal time; DT: daytime; NT: nighttime; AMEC: annual MSTIDs event count

Availability of data and materials

The datasets generated and/or analysed in support of the findings of this study are available upon request from the corresponding author.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

Oluwadare T Seun performed data processing, MSTIDs estimation, MSTIDs statistical analysis, discussed the MSTIDs mechanisms and drafted the manuscript. Norbert Jakowski and Cesar E. Valladares elaborated on MSTIDs mechanism and propagation direction respectively. Andrew O. Akala, Oladipo E. Abe, Mahdi M. Alizadeh, Harald Schuh participated in the interpretation of the MSTIDs results, proper use of technical language and sequential arrangement of manuscript text structure. All authors have contributed to the work of Oluwadare T Seun.

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