



# Observation of Travelling Ionospheric Disturbances over Morocco during the Godzilla Sand and Dust Storm of 15<sup>th</sup> to 26<sup>th</sup> June 2020 Using GNSS

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## **Authors' contributions**

*This work was carried out in collaboration among all authors. Authors UE and CIU did the conceptualization, data curation, methodology, analysis, software, resources, writing and editing original document and revision of the final manuscript. Authors SOL, ADO, FJB, KN, MW, BN and OG did the data curation, reviewing and editing the original draft, software, methodology and data analysis and revision of the final manuscript. All authors read and approved the final manuscript.*

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## ABSTRACT

Using Vertical Total Electron Content (VTEC) data from four GNSS receiver stations: IFR1 (Ifrane Seismic), MELI (Melilla), TETN (Tetouan) and OUCA (Ouca) in Morocco, we investigate the Godzilla sand and dust storm (SDS) event of June 2020 as a source of energetics for generation of travelling ionospheric disturbances (TIDs). Godzilla SDS event began on 5<sup>th</sup> June 2020 in Algeria following a decrease in pressure and spread to other areas across the Sahara between 6<sup>th</sup> and 28<sup>th</sup> June 2020. It was tracked using the Sentinel-5P Satellite mission. Solar wind parameters: Horizontal component of interplanetary magnetic field (IMF B<sub>z</sub>), Y-component of interplanetary electric field (IE-E<sub>y</sub>), and solar wind speed (V<sub>z</sub>) and geomagnetic indices: disturbance storm time (Dst) and planetary K (kp) indices were examined and showed very minimal geomagnetic influence during the period. The study showed that TEC exhibited wave-like structures having distinct troughs and peaks over IFR1-MELI-TETN and OUCA-IFR1-TETN arrays which were clear indicators of generation of TIDs. The arrays and de-trended TEC plots showed that the TIDs propagated poleward. Neutral winds were seen to play a very important role in the propagation of the atmospheric gravity waves (AGWs) which are manifestations of TIDs.

*Keywords: Vertical total electron content; sand and dust storm; travelling ionospheric disturbances; atmospheric gravity waves.*

## 1. INTRODUCTION

Travelling ionospheric disturbances (TIDs) are known to be signatures of atmospheric gravity waves (AGWs) in the ionosphere [1,2]. These wave-like or TID perturbations in the F-layer depend on ionospheric parameters such as wind, electron density and ion temperature [3]. These fluctuations propagate as waves through the ionosphere with wide range of velocities and frequencies. TIDs play an important role in the exchange of energy and momentum between various regions of the upper atmosphere and ionosphere [4]. TIDs and AGWs are related in such a way that TIDs are manifestations of AGWs in the atmosphere [3]. This relationship has been highlighted by various notable studies by Hines, [1,2], Richmond, [5], Hunsucker, [6], Jing & Hunsucker, [7], Hocke & Schlegel, [3]. TIDs are triggered by the ions being forced along the field lines by the neutral air winds driven by the pressure wave [8]. They can also be triggered by geomagnetic or auroral activity, tropospheric activities associated with earthquakes, tsunamis, volcanic eruptions, underground nuclear explosions, seismic events, and sand and dust storm (SDS) [4].

Based on their intrinsic properties, TIDs can be categorized either as Large Scale Traveling Ionospheric Disturbances (LSTIDs) or Medium Scale Traveling Ionospheric Disturbances (MSTIDs). LSTIDs have propagation period of 30 minutes to an hour while MSTIDs have propagation period of 15 to 60 minutes. LSTIDs

have a wavelength greater than 1000 km and travel with velocities between 300-1000 m/s. MSTIDs have a wavelength of less than 1000 km and travel at a speed of between 100-300 m/s [1,2,5,6,7]. Geomagnetic or aurora activities generate LSTIDs while the lower atmosphere phenomena are a source of MSTIDs [9,10]. When the AGWs propagate vertically upwards from the lower atmosphere carrying energy, they become unstable and start losing energy. However, their amplitude increases due to reduced air density and mechanical friction [11]. MSTIDs have no correlation with geomagnetic activity. They are known to occur during both daytime and nighttime even though the mechanisms of generations causing the daytime and nighttime occurrences vary [12].

Daytime MSTIDs are known to originate from lower or middle atmosphere [13] while nighttime MSTIDs originate from electrodynamic processes which include the Perkins instability, that is associated with the E and F region coupling [14]. The climatology of MSTIDs has a strong dependence on longitude [4]. Tsagouri et al., [4] analyzed LSTIDs based on Digisonde observations over European region over Athens (38°N, 23.5°E), Dourbes (50.1°N, 4.6°N) and Ebre (40.8°N, 0.5°E). They observed a significant uplifting of the F2 layer which corresponded with an oscillation pattern in the foF2 during the LSTID activity. Variations in the height of the peak electron density h<sub>m</sub>F2 and the corresponding scale height H<sub>m</sub> were also observed. However, it was difficult to make conclusion on any sensitivity of the method's

results to the electric-field-related disturbances which are common in mid-latitudes zone during geomagnetic storms. Habarulema et al, [14] investigated the storm time equatorward and poleward LSTIDs on global scale. They used total electron content (TEC) observations from GNSS receivers over South American, African and Asian sectors. The results showed the American and African sectors exhibiting predominantly strong poleward TIDs while the Asian sector exhibiting equatorward TIDs which crossed the geomagnetic equator on 9<sup>th</sup> March 2012. Katamzi & Habarulema, [15] also investigated TIDs over South African latitudes during the 29<sup>th</sup> to 31<sup>st</sup> October 2003 which was a geomagnetically disturbed period, using Global Positioning and System (GPS) observations. The results revealed presence of LSTIDs on the days of the geomagnetic storm using line-of-sight vertical TEC measurements from individual satellites. The wave-like structures were seen to propagate equatorward with velocities between 587.04 and 1635.09 m/s.

Sand and dust storm (SDS) events can be sources of energetics that can lead to generation of AGWs which would induce MSTIDs in the ionosphere. The MSTIDs give rise to plasma density gradients as they propagate through the ionosphere leading to electron density instabilities which manifests as TEC variation [16]. An interesting SDS event known as "Godzilla" SDS which occurred between 1<sup>st</sup> June and 30<sup>th</sup> June 2020 across the Sahara Desert was tracked by the Copernicus Sentinel-5P satellite which stores a variety of satellite images used to detect changes in landscape [17] and the offline Satellite Absorbing Index (SAI), which qualitatively shows elevated aerosol layers in atmosphere [18]. The National Oceanic and Atmospheric Administration (NOAA) approximated the Godzilla SDS to be between 60% to 70% larger than the Sand and dust storms experienced in the past [19]. The greatest impact of the Godzilla SDS was felt between 15<sup>th</sup> and 20<sup>th</sup> June 2020 [20,21,22].

In the present paper, we investigate and present results on the propagation characteristics of AGWs associated with the Godzilla SDS event that occurred between 15<sup>th</sup> and 26<sup>th</sup> June 2020 over Morocco. The study is investigated within geomagnetically quiet period, hence geomagnetic storm-related phenomena is eliminated. We analyze GPS-TEC data from four Global Navigation Satellite System (GNSS) receiver stations situated in Morocco.

## 2. MATERIALS AND METHODS

### 2.1 Geomagnetic Indices Data and Solar Wind Parameters

In this study, the periods between 15<sup>th</sup> and 26<sup>th</sup> June 2020 were considered due to greatest intensity of the Godzilla SDS event over Morocco [20]. The geophysical conditions such as Kp index showing the level of the geomagnetic activity, the hourly values of Z-component of the interplanetary magnetic field (IMF-Bz), Y-component of the interplanetary electric field (IEFy), solar wind speed (Vz), Planetary K (Kp) and disturbance storm time (Dst) indices were considered during these periods. These parameters were obtained from the archive of OmniWeb website via <https://omniweb.gsfc.nasa.gov/form/dx1>.

### 2.2 Godzilla SDS Data

The movement of the Godzilla SDS over Morocco was tracked using the Copernicus Sentinel-5P satellite mission which was launched by the European Space agency on 13<sup>th</sup> October 2017. This satellite uses the Google Earth Engine (GEE), which is a cloud-based platform that stores a variety of satellite images used to detect changes in landscape [23] and the Sentinel-5P Aerosol Index (SAI), which qualitatively shows elevated aerosol layers in atmosphere and the Sentinel-5P Aerosol Index (SAI), which qualitatively shows elevated aerosol layers in atmosphere [18].

### 2.3 GPS/GNSS Data

The GPS-TEC data were obtained from four GNSS receiver stations in Morocco as shown in the map displayed in Fig. 1 with the station's geographical locations. Table 1 shows the station codes, the station names, geographical and geomagnetic coordinates, and their respective local time. The GPS-TEC data were accessed from the University of NAVSTAR Consortium dual frequency website: <http://unavco.org/data/gps-gnssdata/>.

The GPS-TEC data in the GPS receivers is usually saved in the zipped Receiver Independent Exchange (RINEX) Format which is converted to GPS observable files using appropriate software [24]. In this study, the Gopi software developed by Prof Gopi Krishna Seemala [25] was used to convert the RINEX to

observation files. GPS measurements are either code pseudoranges ( $P$ ) or carrier phases ( $\phi$ ). The GPS receiver receives the code time delay and carrier phase difference by cross-correlating the  $f_1$  and  $f_2$  modulated carrier signals, which are normally considered to travel along the same path through the ionosphere [26]. Estimates of GPS-derived ionospheric TEC can be obtained using dual frequency GPS measurements [27,28]. GPS receiver data is critical for estimating the electron density along a ray path between a GPS satellite and a ground receiver [29,30]. Dual-frequency GPS receivers may offer integral information on the ionosphere and plasmasphere. This is done by computing the differential of the code and carrier phase measurements, in addition to removing ionospheric inaccuracies in TEC estimates [31,32]. As a result, the GPS-TEC computed by the dual-frequency receivers is offered as an input to an ionosphere assimilation model [33]. For the present study, GPS-TEC data collected in dual-frequency receivers was used. The GPS-TEC data was obtained using the pseudo-range and carrier phase measurements. The TEC

calculated from the pseudo-range measurement (slant TEC) is given by Equation 1:

$$STEC = \frac{1}{40.3} \left[ \frac{f_1^2 f_2^2}{f_1^2 - f_2^2} \right] (P_2 - P_1) \quad (1)$$

Similarly, the TEC from carrier phase measurement may be calculated as follows using Equation 2:

$$STEC = \frac{1}{40.3} \left[ \frac{f_1^2 f_2^2}{f_1^2 - f_2^2} \right] (\phi_2 - \phi_1) \quad (2)$$

where  $f_1$  and  $f_2$  are GPS satellite frequencies determined from the fundamental frequency,  $f_o = 10.23\text{MHz}$  as: ( $f_1=154$ ,  $f_o=1,575.42\text{MHz}$ , ( $f_2=120$ ,  $f_o=1,227.60\text{ MHz}$ ), and the differential code and phase measurements are  $(P_2 - P_1)$  and  $(\phi_1 - \phi_2)$ , respectively [34]. The vertical total electron content (VTEC) is obtained using the relations in Equation 3:

$$VTEC = STEC \times \text{Cos}(\chi') \quad (3)$$

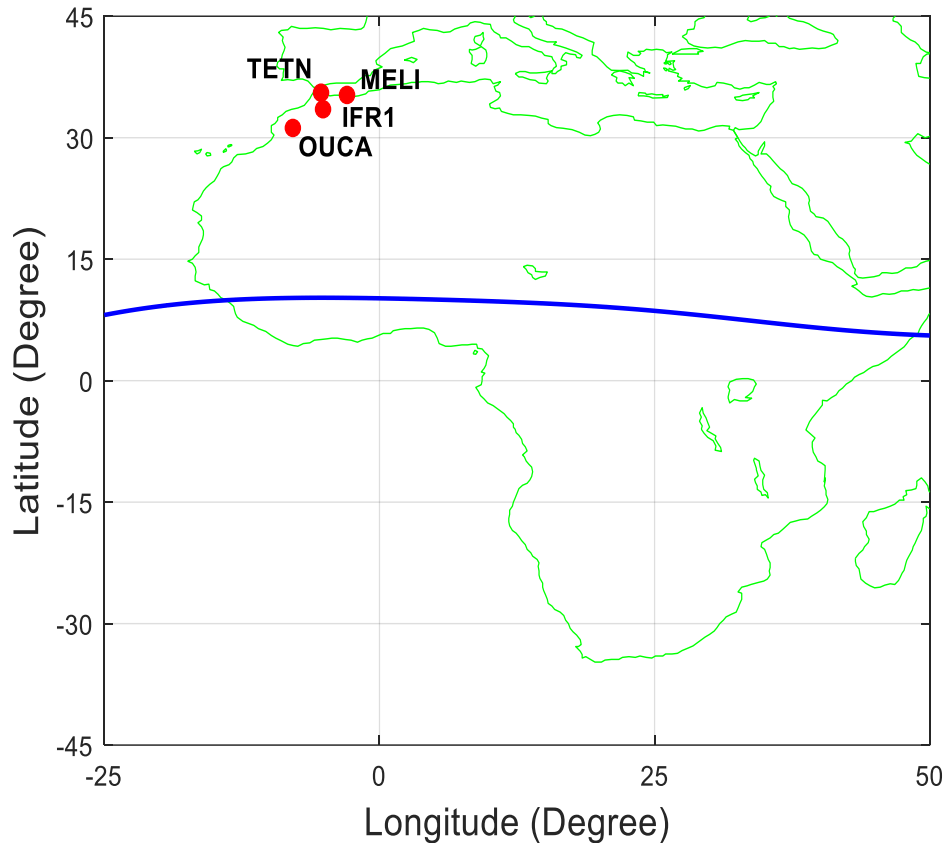


Fig. 1. Geographic locations of the the four GNSS receiver stations over Morocco

where the zenith angle  $\chi'$  is given by Equation 4:

$$\chi' = \arcsin\left[\frac{R_E \cos\alpha}{R_E + h} \sin(\chi)\right] \quad (4)$$

VTEC is therefore given by equation 5:

$$VTEC = STEC \left\{ \cos\left[\arcsin\left(\frac{R_E \cos\alpha}{R_E + h}\right) \sin(\chi)\right] \right\} \quad (5)$$

Where  $\alpha$  is the satellite's elevation angle,  $R_E$  is the Earth's mean radius, and  $h$  is the height of the ionospheric layer, which is considered to be 400 km.

To reduce multipath effects, the data selected was for elevation angles of 30° and above [35]. This was to eliminate multipath errors.

Information for the four GNSS receiver stations: MELI, IFR1, OUCA and TETN is given in Table 1.

The average of VTEC for all PRNs for IFR1, MELI, OUCA and TETN during study period were obtained by averaging the VTEC values for all identical pseudo-random numbers (PRNs) within a 24 hour period [36] and used to plot VTEC against Universal Time (UT) for each day and station. The VTEC against universal time (UT) plots for each day were analyzed.

## 2.4 Methodology

### 2.4.1 Extracting travelling Ionospheric disturbances (TIDs) from GPS-TEC data

Background or unperturbed ionospheric TEC was determined by fitting each satellite's time series of the VTEC data with a fourth polynomial across all the four GNSS receiver stations. This was done using equation 6.

$$VTEC_{fit} = at_{ij}^4 + bt_{ij}^3 + ct_{ij}^2 + dt_{ij} + \varepsilon \quad (6)$$

where  $VTEC_{fit}$  is fitted VTEC at time  $t, i = 1, 2, 3, 4$ . (No of receiver stations),  $j = 1, 2, \dots, 32$  (the number of satellites),  $\varepsilon$  is the residual error of the fitting process and coefficients  $a, b, c$  and  $d$  are obtained using least squares method [14].

High frequency changes in  $\Delta VTEC$  due to irregular ionospheric plasma was detected by finding the difference between actual VTEC data and modeled data using equation 7.

$$\Delta VTEC = VTEC - VTEC_{fit} \quad (7)$$

Where,  $\Delta VTEC$  = deviation of VTEC

VTEC = actual VTEC data at time  $t$

$VTEC_{fit}$  = modeled data

$\Delta VTEC$  gives information about the spectral content of the signal and how it changes with time. Plots of VTEC verses UT were plotted alongside their corresponding  $\Delta VTEC$  verses UT plots. The potential wavelike structures were monitored across the across three stations along close latitudes. In this case, two receiver arrays were considered: OUCA-IFR1-TETN and the IFR1- MELI-TETN receiver arrays. The amplitudes of the wavelike structures (TIDs) that modulate TEC were inferred by monitoring  $\Delta VTEC$  [14,37].

Detrended TEC from GPS-TEC data was created using the Savitzky-Golay filter with a 60-minute sliding window for all the four GNSS receiver stations and visible satellites [38]. The Savitzky-Golay filter uses quadratic polynomial that is fitted over each sliding window. The detrended TEC over all geographic latitudes against Universal time (UT) were directly constructed in a temporal resolution of 10 minutes. The derived detrended TEC plots along geographical latitudes were then used to investigate propagation behavior of the Godzilla SDS induced TIDs [39].

**Table 1. Information of the geographical and geomagnetic locations of the stations over Morocco**

Station code	Station Name	Geographic Latitude	Geographic Longitude	Geomagneti c Latitude	Geomagneti c Longitude	Local Time
MELI	Melilla	35.28°N	2.95°W	25.64°N	77.44°W	UT+1
IFR1	Ifrane Seismic	33.52°N	5.13°W	23.14°N	79.03°W	UT+1
OUCA	Ouca	31.206°N	7.87°W	20.04°N	81.12°W	UT+1
TETN	Tetouan	35.56°N	5.36°W	26.15°N	79.51°W	UT+1

### 3. RESULTS AND DISCUSSION

#### 3.1 The Movement of the Godzilla SDS between 15<sup>th</sup> and 26<sup>th</sup> June 2020 over Sahara

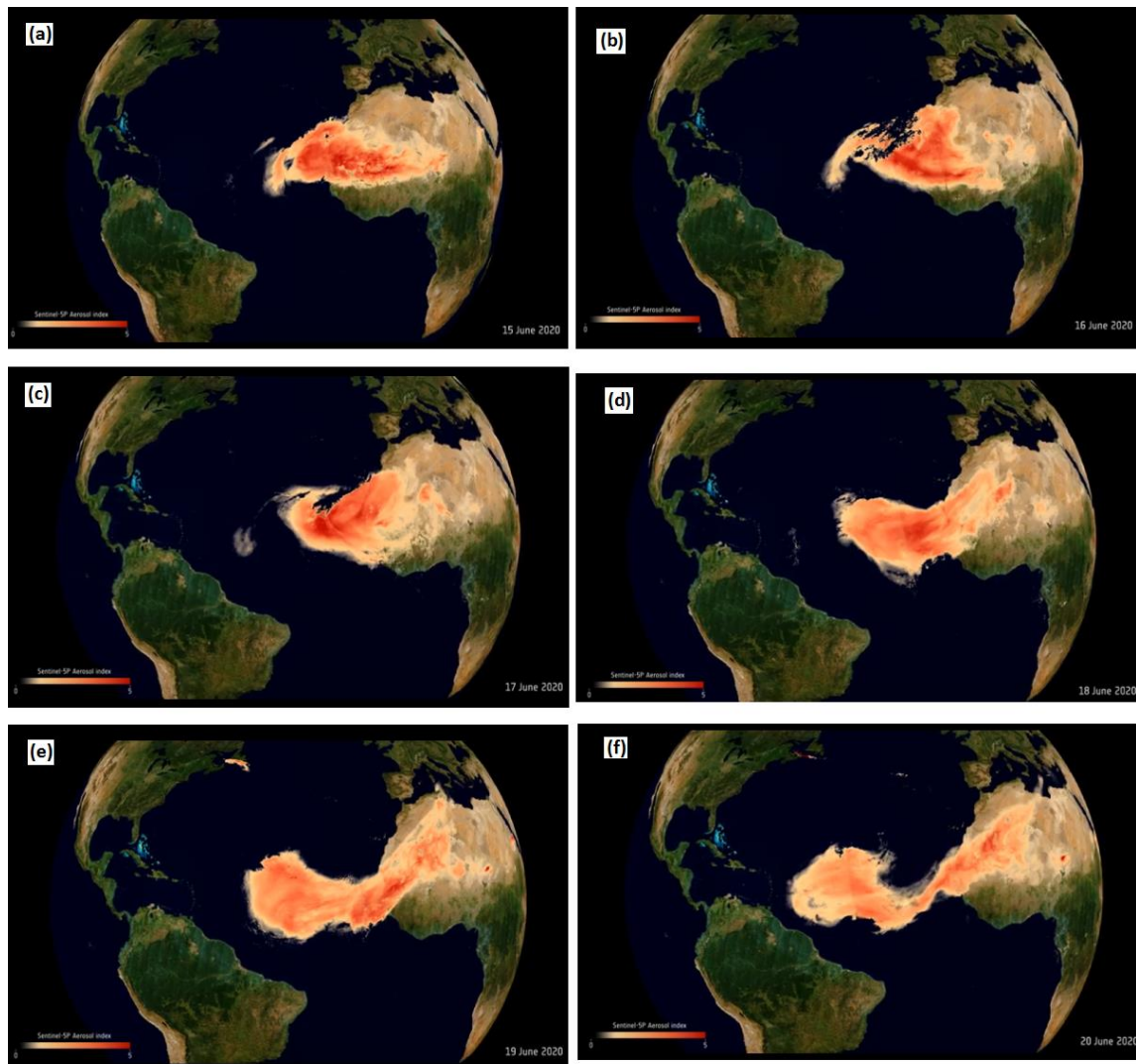
The movement of the Godzilla SDS over Morocco between 15<sup>th</sup> and 26<sup>th</sup> June 2020 was tracked using the Copernicus Sentinel-5P satellite. During the study period, the Western part of Africa such as Mauritania, Mali, Morocco and Western Sahara felt the greatest impact of the Godzilla SDS [2] as in 2 and 3. By 20<sup>th</sup> June 2020, the first traces of dust had reached the Caribbean [40]. Large SDS traces were observed over the upper parts of the Sahara between 21<sup>st</sup>

June and 26<sup>th</sup> June 2020 as shown in Fig. 3.

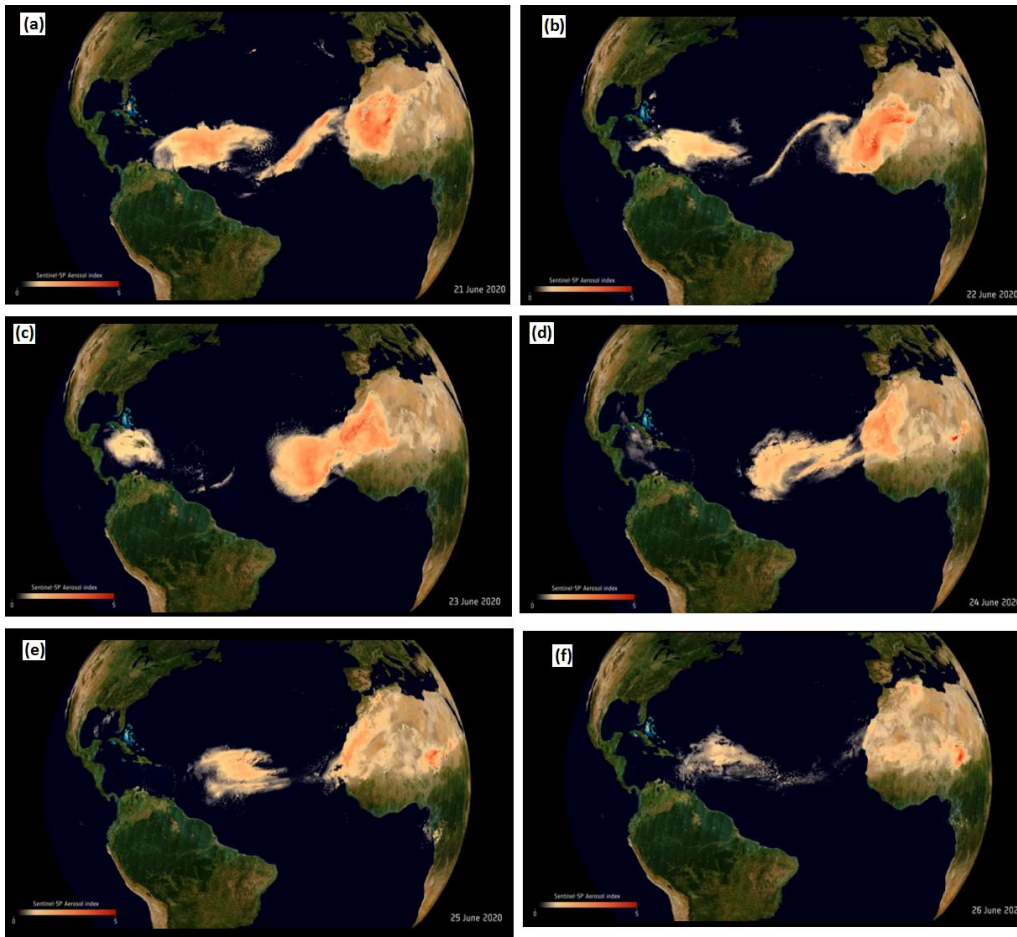
In Figs. 2 and 3, the cream colour on the SAI indicates low aerosol concentrations in the atmosphere while red colour shows presence of high aerosol concentrations in the atmosphere during the Godzilla SDS of June 2020 as tracked by the Copernicus Sentinel-5P satellite.

#### 3.2 The Variation of Solar Wind Parameters between 15<sup>th</sup> and 26<sup>th</sup> June 2020

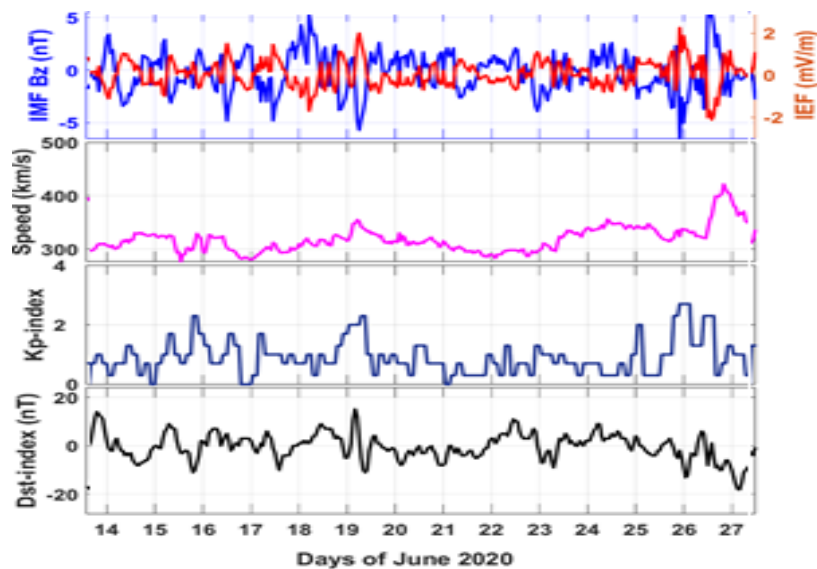
Fig. 4 depicts the changes in IMF Bz, IEF Ey, the solar wind speed,  $k_p$  and Dst indices between 15<sup>th</sup> and 26<sup>th</sup> June 2020.



**Fig. 2.** The Copernicus Sentinel-5P satellite images of Godzilla SDS over the Sahara for (a) 15.06.2020 (b) 16.06.2020 (c) 17.06.2020 (d) 18.06.2020 (e) 19.06.2020 (f) 20.06.2020 (European space Agency, 2020)



**Fig. 3.** The Copernicus Sentinel-5P satellite images of Godzilla SDS over the Sahara for (a) 21.06.2020 (b) 22.06.2020 (c) 23.06.2020 (d) 24.06.2020 (e) 25.06.2020 (f) 26.06.2020 (European space Agency, 2020)



**Fig. 4.** Variations of Solar wind parameters; IMF-Bz, IEF-Ey and the solar wind speed and the geomagnetic indices;  $k_p$  and Dst index, between 15<sup>th</sup> and 26<sup>th</sup> June 2020

Noted that from Fig. 4, on 15<sup>th</sup> June 2020, there was a southward turning of the IMF-Bz of -3 nT with a corresponding rise of IEF-Ey of 1. The solar wind speed rose to maximum, of 330 km/s. The highest Kp index value of 1.5 and lowest Dst value of -8 nT were attained. On 16<sup>th</sup> June 2020, the southward turning of -2.5 nT was attained with a corresponding rise in IEF-Ey of 1.5. The lowest solar wind speed of 280 km/s was attained. The maximum Kp index value attained was 2.2 with minimum Dst value of -11 nT. On 17<sup>th</sup> and 18<sup>th</sup> June 2020 there was a southward turning of -5 nT with a corresponding IEF-Ey of 1. The solar wind speed dropped from 320 km/s to 280 km/s on 17<sup>th</sup> June and rose to a maximum of 320 km/s on 18<sup>th</sup> June 2020. The maximum Dst value of 1.8 nT was attained on 17<sup>th</sup> and 18<sup>th</sup> June with a corresponding Dst value of -10 nT. On 20<sup>th</sup> June 2020, the IMF-Bz southern turning reached -6 nT with a corresponding IEF-Ey value of 2. This corresponded well with a solar wind speed of 350 km/s. Between 15<sup>th</sup> and 26<sup>th</sup> June 2020, the highest Kp value of 2.2 was attained with a corresponding Dst index value of -11 nT on 19<sup>th</sup> June 2020. The solar wind parameter shows a minimum solar wind speed of 270 km/s on 16<sup>th</sup> June 2020 and maximum solar wind of 360 km/s on 20<sup>th</sup> June 2020. During solar minimum, solar wind of speeds between 250 km/s and 400 km/s originates from regions close to the heliospheric current sheet at the heliomagnetic equator while the fast solar wind having speeds of between 400 km/s and 800 km/s which originates from coronal holes when the magnetic field is open [41]. The solar wind parameters and geomagnetic indices in Fig. 4 indicate a very minimal geomagnetic field influence on the ionosphere between 15<sup>th</sup> and 26<sup>th</sup> June 2020.

### 3.3 Variations of TEC and VTEC<sub>fit</sub> against UT

Figs. 5 and 6 show the VTEC and VTEC<sub>fit</sub> against UT for OUCA-IFR1-TETN receiver array while Figs. 7 and 8 shows the VTEC and VTEC<sub>fit</sub> against UT for IFR1- MELI-TETN receiver array between 15<sup>th</sup> and 26<sup>th</sup> June 2020 respectively.

#### 3.3.1 OUCA-IFR1-TETN receiver array

Based on Figs. 5 and 6, on 15<sup>th</sup>, 23<sup>rd</sup> and 24<sup>th</sup> June 2020 triple peak structures (indicated by black arrows) were observed between 7:00 and 21:00 UT with the first peak appearing approximately at 08:00 UT, the second peak appearing approximately at 16:00 UT, while the

third peak appearing approximately at 20:00 UT. From 16<sup>th</sup> to 20<sup>th</sup> June 2020, double peak structures were observed between 07:00 and 12:00 UT with the first peak appearing approximately at 08:00 UT and the second peak appearing approximately at 20:00 UT. On 16<sup>th</sup>, 17<sup>th</sup>, 18<sup>th</sup>, 19<sup>th</sup>, 21<sup>st</sup>, 22<sup>nd</sup>, 25<sup>th</sup> and 26<sup>th</sup> June 2020, double peak structures however were observed between 7:00 and 12:00 UT with the first peak appearing approximately at 08:00 UT and the second peak appearing approximately at 20:00 UT.

#### 3.3.2 IFR1-MELI-TETN receiver array

Based on Figs. 7 and 8, it was also noted that on 15<sup>th</sup>, 23<sup>rd</sup> and 24<sup>th</sup> June 2020, triple peak structures were observed between 7:00 and 21:00 UT with the first peak appearing approximately at 08:00 UT, the second peak appearing approximately at 16:00 UT while the third peak appearing approximately at 20:00 UT. Double peaks were observed on 16<sup>th</sup>, 17<sup>th</sup>, 18<sup>th</sup>, 19<sup>th</sup>, 20<sup>th</sup>, 21<sup>st</sup>, 22<sup>nd</sup>, 25<sup>th</sup> and 26<sup>th</sup> June 2020 with the first peak appearing approximately at 10:00 UT, the third peak appearing approximately at 18:00 UT. A close analysis of Figs. 5, 6, 7 and 8 showed that the two receiver arrays exhibited similar wave-like structures. The peaks were observed to all appear between 7:00 and 12:00 UT after sunrise and between 18:00 and 21:00 UT after sunset.

It was also noted that the two receiver arrays show peak structures for the lower latitude stations (OUCA and IFR1) being observed first as compared to the other receiver stations. This indicates that there was a pole-ward propagation of the TIDs.

### 3.4 Changes in Detrended TEC ( $\Delta$ TEC)

Figs. 9 to 14 show plots of detrended TEC along geographic latitude against UT for the four GNSS receiver stations between 15<sup>th</sup> and 26<sup>th</sup> June 2020.

In these Figures, band structures were observed over the 24-hour period for all the days between 15<sup>th</sup> and 26<sup>th</sup> June 2020. In Figs. 9(a), 9(b), 11(b), 12(a) and 12(b) the band structures for DTEC ranged between 0.5 and 1.0 TECU. In Figs. 10(a), 10(b), 11(a), 13(a), 13(b) the band structures for DTEC ranged between 0.6 and 1.5 TECU. In Figs. 14(a) and 14(b), the band structures for DTEC ranged between 0.5 and 1.2 TECU.



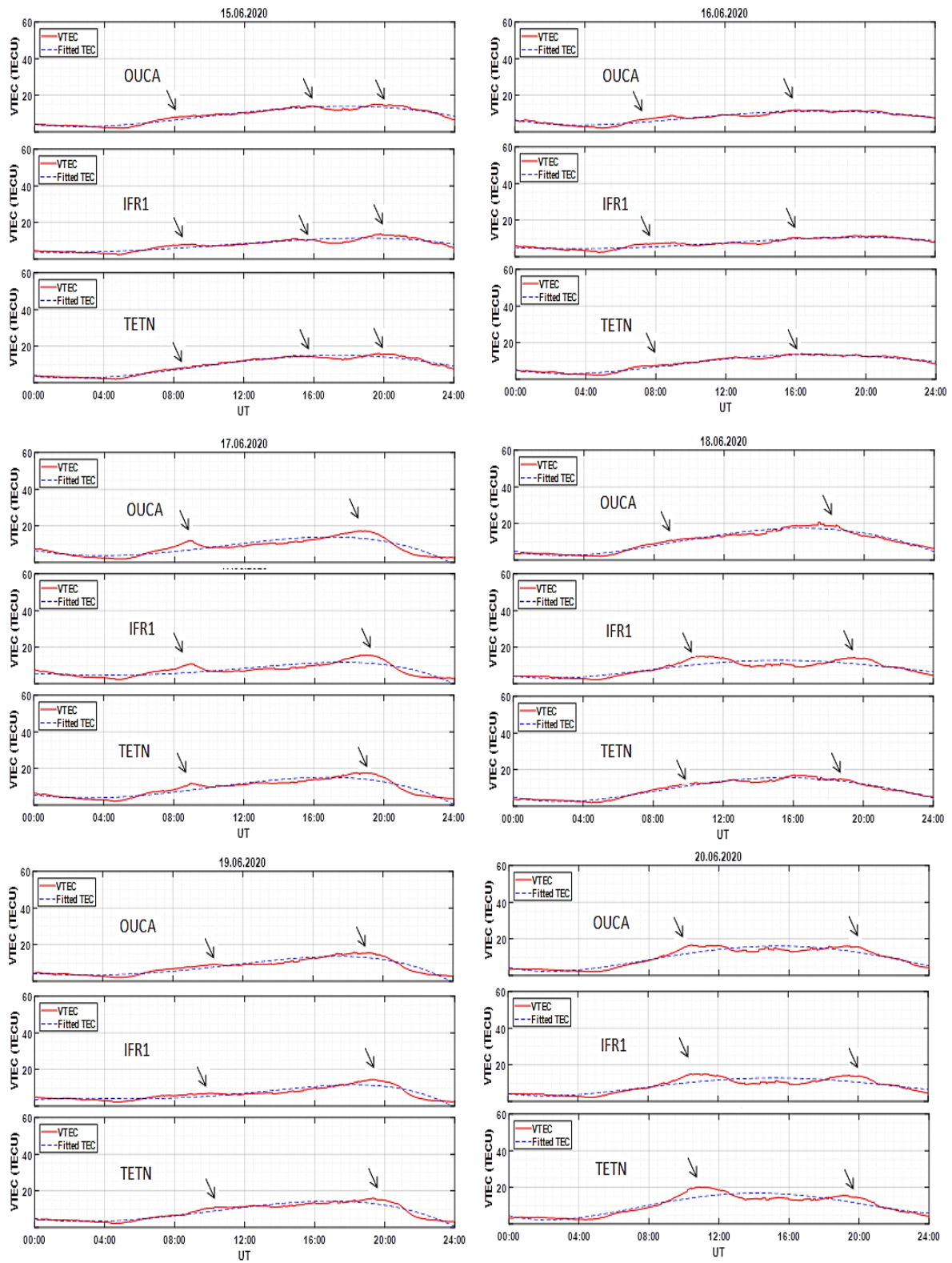
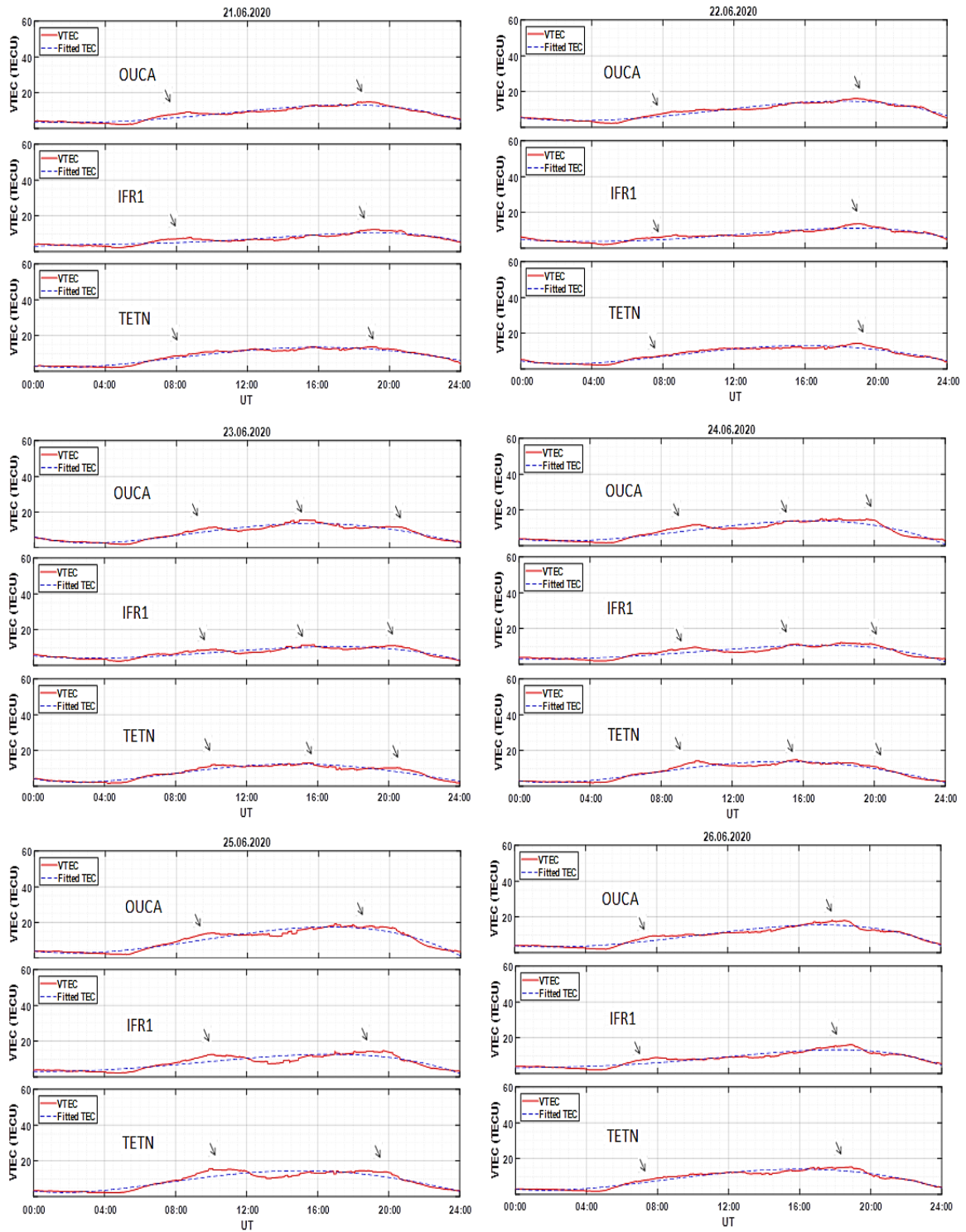
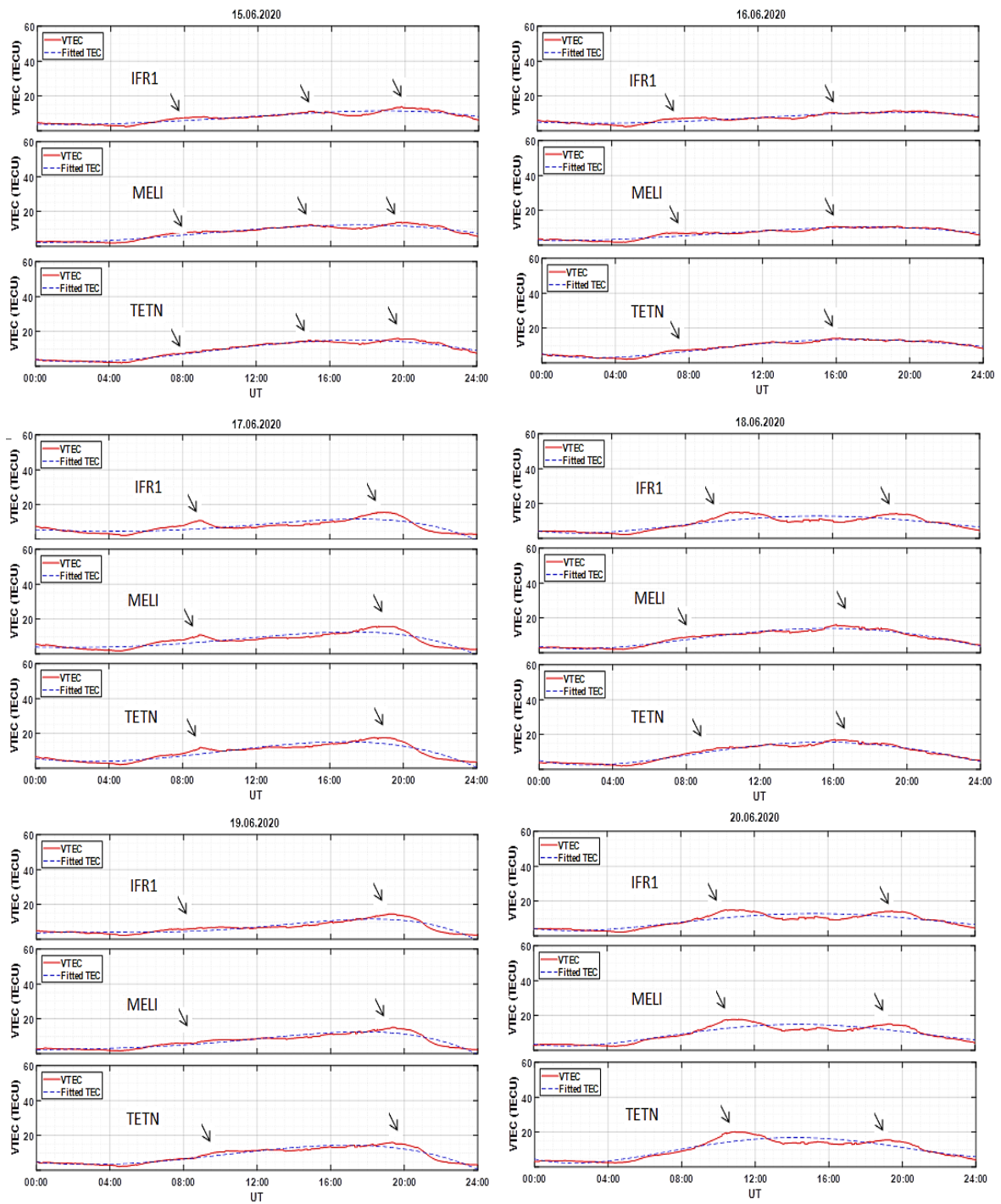


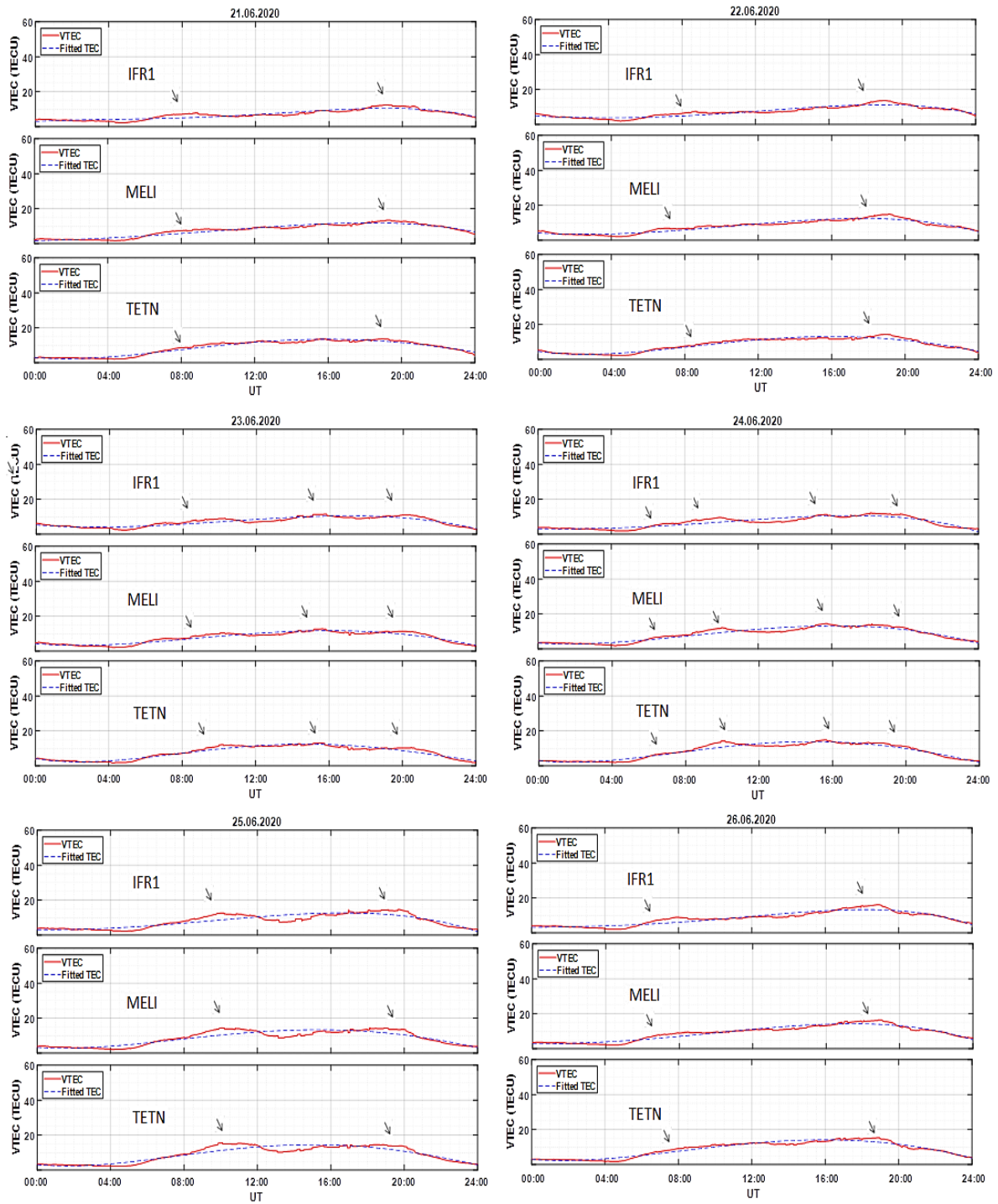
Fig. 5. VTEC and VTEC<sub>fit</sub> against UT for OUCA-IFR1-TETN receiver array between 15<sup>th</sup>- 20<sup>th</sup> June 2020



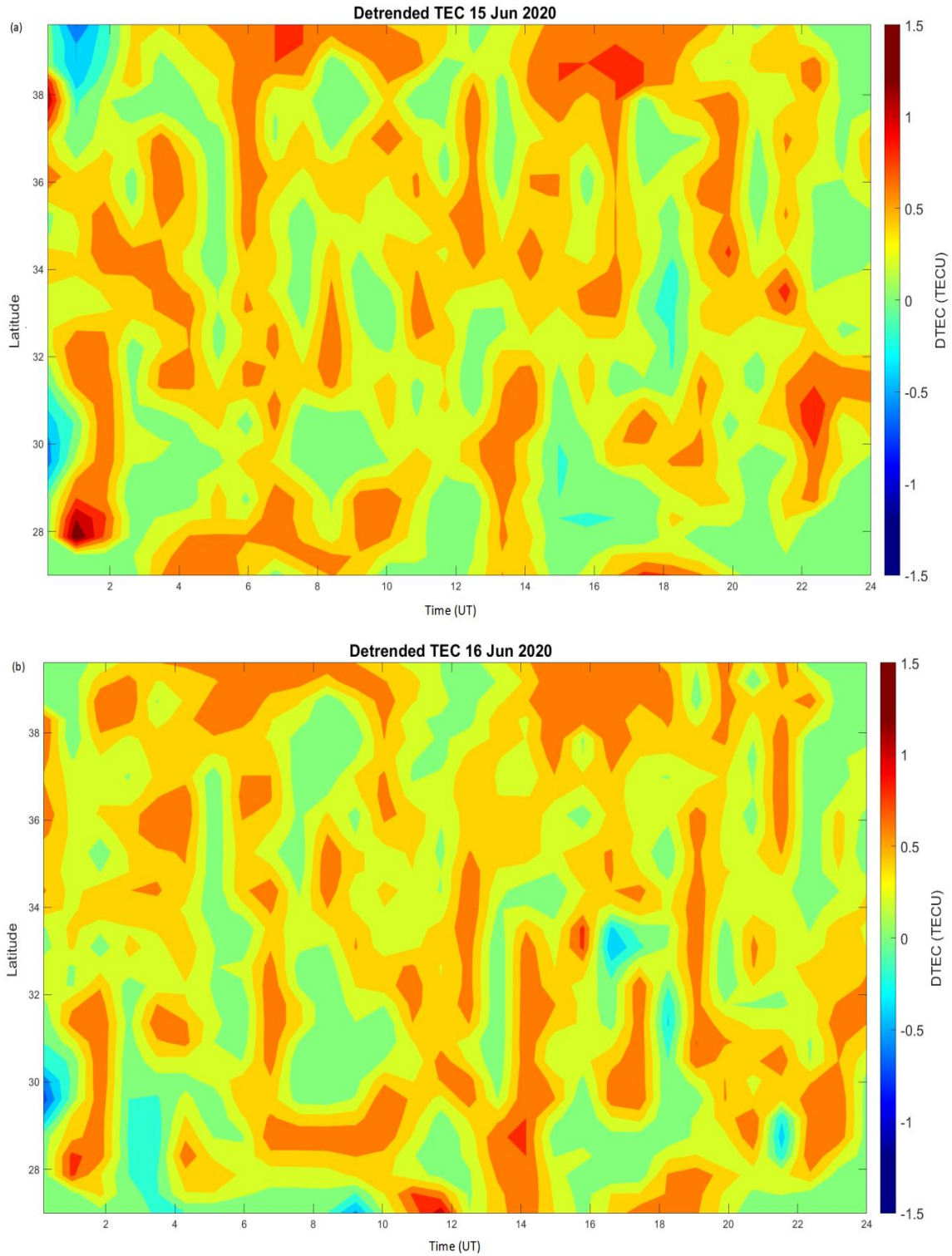
**Fig. 6.** VTEC and VTEC<sub>fit</sub> against UT for OUCA-IFR1-TETN receiver array between 21<sup>st</sup>-26<sup>th</sup> June 2020



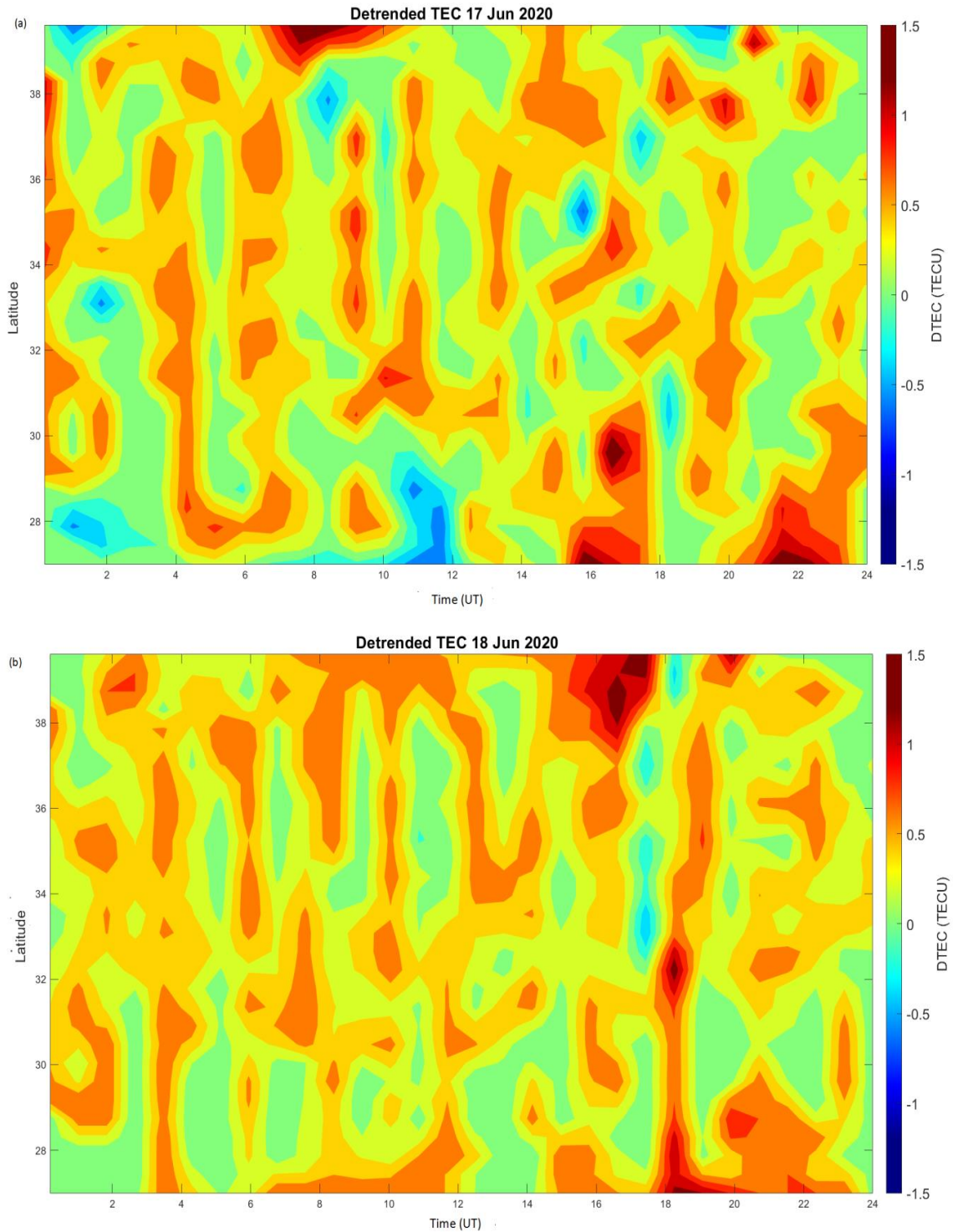
**Fig. 7.** VTEC and VTEC<sub>fit</sub> against UT for IFR1-MELI-TETN receiver array between 15<sup>th</sup>- 20<sup>th</sup> June 2020



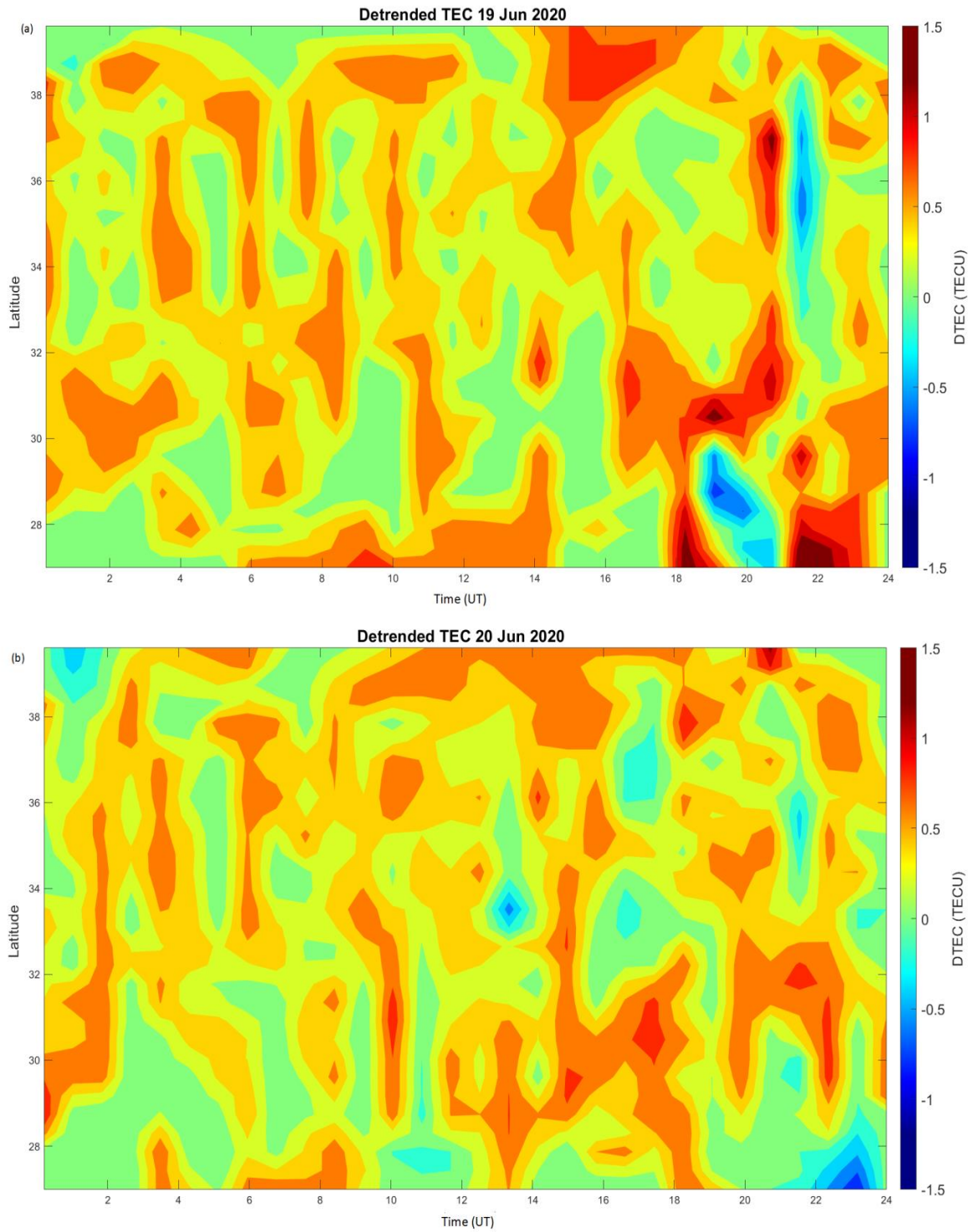
**Fig. 8.** VTEC and VTEC<sub>fit</sub> against UT for IFR1-MELI-TETN receiver array between 21<sup>st</sup>- 26<sup>th</sup> June 2020



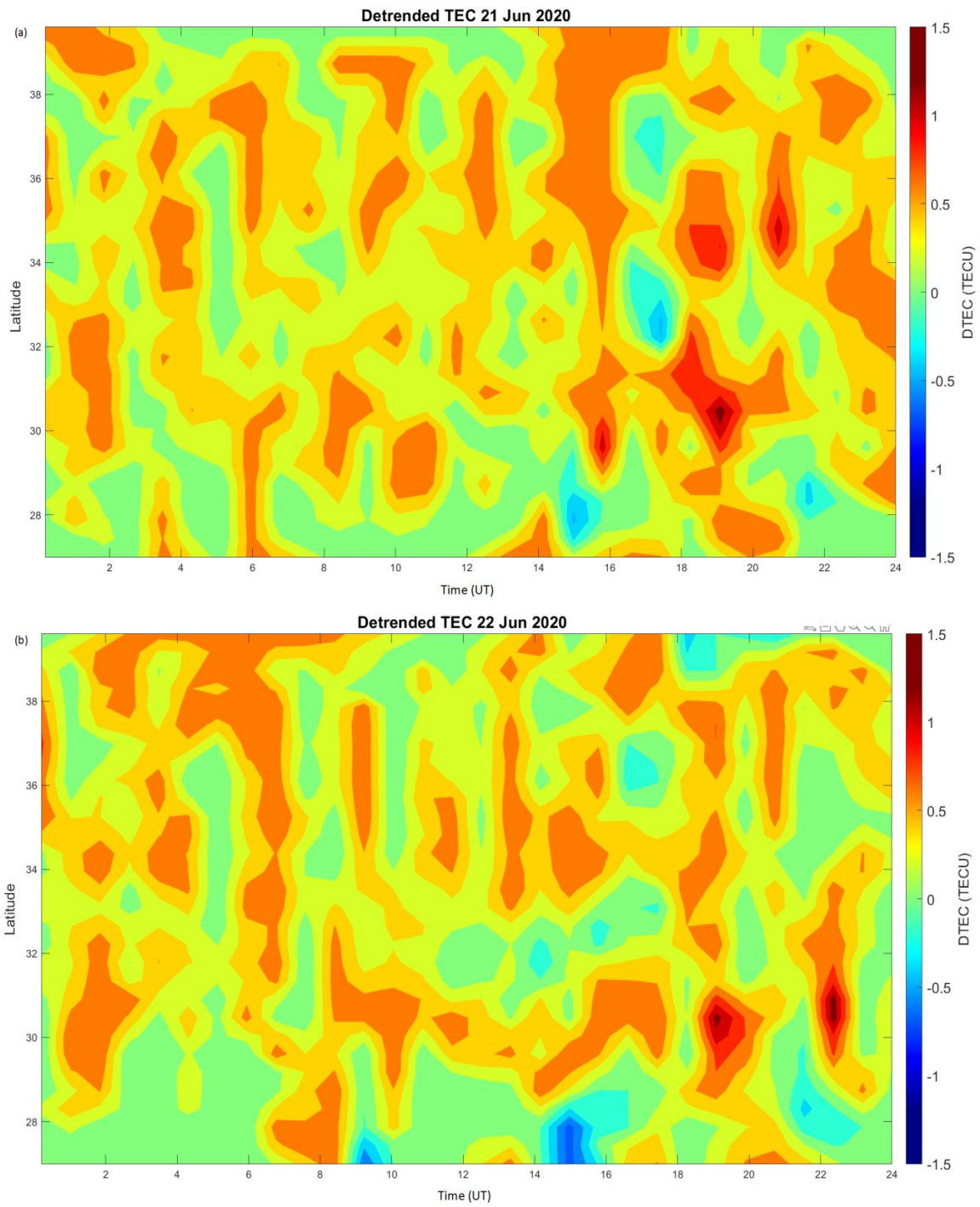
**Fig. 9.** Plot of detrended TEC along geographic latitudes against UT for: (a) 15.06.2020, (b) 16.06.2020



**Fig. 10. Plot of detrended TEC along geographic latitudes against UT for: (a) 17.06.2020 (b) 18.06.2020**

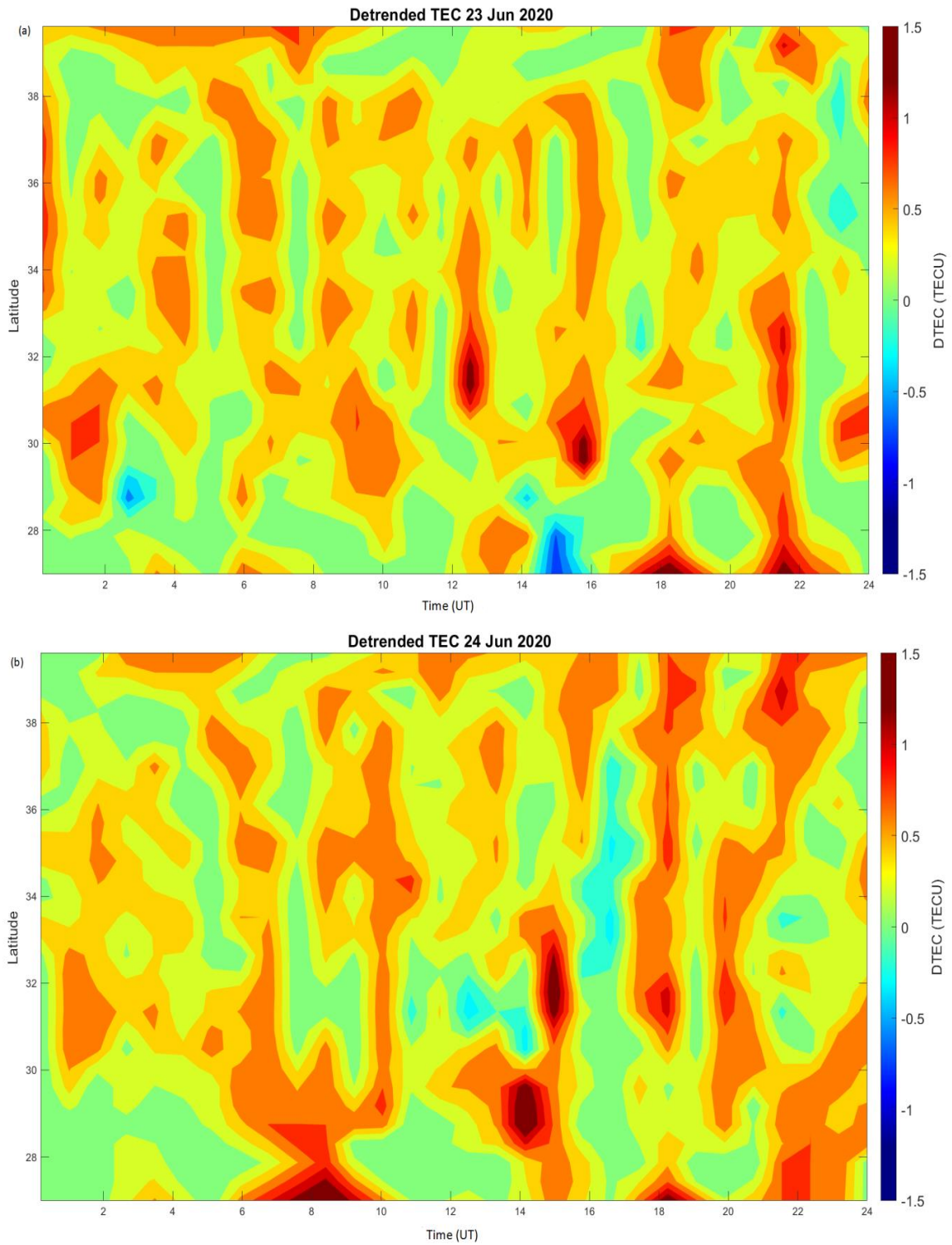


**Fig. 11.** Plot of detrended TEC along geographic latitudes against UT for: (a) 19.06.2020 (b) 20.06.2020

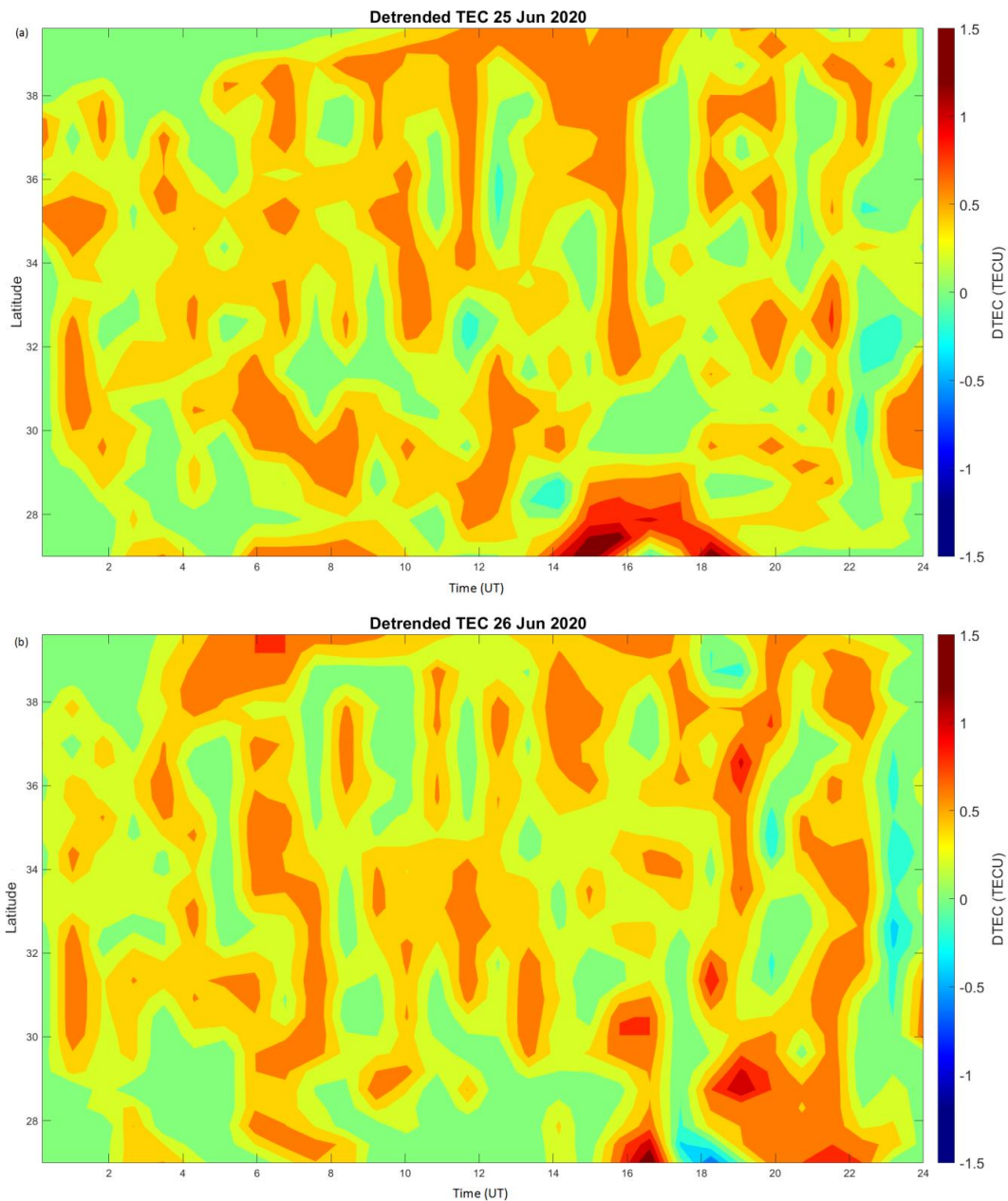


**Fig. 12.** Plot of detrended TEC along geographic latitudes against UT for: (a) 21.06.2020 (b) 22.06.2020





**Fig. 13. Plot of detrended TEC along geographic latitudes against UT for: (a) 23.06.2020 (b) 24.06.2020**



**Fig. 14. Plot of detrended TEC along geographic latitudes against UT for: (a) 25.06.2020 (b) 26.06.2020**

In Figs. 9 - 14, we can observe evident poleward propagating band structures during the 24-hour period for all the days between 15<sup>th</sup> and 26<sup>th</sup> June 2020. The band structures depicts presence of TIDs. We also observe important values of detrended DTEC at the time of VTEC peaks. For example, Figs. 10(a) and 11(a) show DTEC values of above 1 when VTEC has the large peaks around 18:00 UT. The band structures depict presence of TIDs that is important when VTEC is maximum.

The present study successfully demonstrates that SDS events are a source of energetics for generation of TIDs which are signatures of AGWs. The Dst and kp indices in Fig. 4 rule out the influence of geomagnetic activity in the generation of TIDs. Therefore, the TEC results from this study exclude the effect of geomagnetic disturbances but are fully attributed to the effect of the SDS. During SDS events, internal waves are continuously generated and breaking throughout the atmosphere [11]. Wave breaking

effectively mixes sand and dust aerosols through the atmosphere and contributes to driving some larger-scale flows. The gravity waves (GWs) generated are affected by the changing stratification as they propagate. Each of these interactions, in addition to gravity wave dissipation, may contribute to the vertical flux of horizontal momentum and the universal frequency spectrum in the middle atmosphere [42,43,44,45]. The possible cause of these types of disturbances is the neutral winds [46]. Neutral winds play an important role in the wave breaking/dissipation in the mesosphere and lower thermosphere to global redistribution of energy and momentum deposited at high latitudes by the magnetosphere [47]. They are usually slower than the actual wind in stable conditions and faster in unstable conditions i.e. land surface or sea stress. When GWs propagate into the ionosphere, the measured TEC exhibits clear wavelike-structures, as shown in Figs. 5, 6, 7 and 8. Their peaks and troughs are imaged on the ionospheric pierce points (IPP) trajectory at different moments and different propagation distances. This makes observation of GWs propagation possible.

#### 4. CONCLUSION

We have investigated the generation of TIDs during the Godzilla SDS event of June 2020 over Morocco using GPS-TEC data. The obtained results showed TEC exhibited wave-like structures having distinct troughs and peaks over IFR1-MELI-TETN and OUCA-IFR1-TETN arrays which were clear indicators of generation of TIDs. The arrays showed that the TIDs propagated poleward (along latitude). This was supported by the evident poleward propagating band structures on the detrended TEC plots during the 24-hour period for all the days between 15<sup>th</sup> and 26<sup>th</sup> June 2020. The band structures on the plots also depicted the presence of TIDs. Neutral winds were seen to play a very important role in the propagation of the AGWs which are manifestations of TIDs. In conclusion, the study confirms that SDS events can be a source of energetics for the generation of MSTIDs.

#### DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image

generators have been used during writing or editing of manuscripts.

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#### COMPETING INTERESTS

Authors have declared that no competing interests exist.

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