Response of the Ionospheric Vertical Total Electron Content (VTEC) over the African Regions during the Period of Geomagnetic Storms

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Abstract

The aim of this study is to investigate the ionospheric VTEC response over the equatorial African region during the three recent intense and severe geomagnetic storms of February, March and April 2023. We have used the ground-based GPS measurements of VTEC in the stations: MBAR (geographic coordinates: 0.60° N, 30.74° E; geomagnetic coordinates: 10.22° S, 102.36° E) and YKRO (geographic coordinates: 6.87° N, 5.24° W; geomagnetic coordinates: 2.84 ° S, 67.41° E). The February 27 has a Dst minimum value of -132 nT and occurred at 12:00 UT; the March 24 has a Dst minimum of -163 nT at 02:00 UT; and the severe geomagnetic storm of April 24 has a Dst minimum value of -212 nT and occurred at 05:00 UT. The TEC perturbation was calculated using the five quietest days' mean TEC values, which allowed us to reduce the quiet-time environment fluctuation. The results showed that on both stations, the three geomagnetic storms that caused positive and negative VTEC disturbances were observed during the initial, main and recovery phases. In most hours of the storm days on both stations, the two intense geomagnetic storms of February 27 and March 24, 2023, had positive effects on the ionospheric enhancement, while the severe geomagnetic storm of April 24, 2023, had negative effects on the ionospheric variability. The post day of the storm day has higher values of VTEC during the intense geomagnetic storms of February 27 and March 24, 2023, but this is not the case for the severe geomagnetic storm of April 24, 2023. This enhancement of the electron density observed during the recovery day is most likely due to proton density, plasma temperature and neutral composition changes. Generally, during different phases of the three geomagnetic storms, there are positive and negative responses to the values of the VTEC deviations from their quiet-time states, ranging from -80 % to 280 %.

1. Introduction

In today's world, measuring Total Electron Content (TEC) with GPS is a crucial tool for understanding the ionosphere. Since the ionosphere is a dispersive medium, it has an impact on radio signal propagation, which contributes to GPS transmission range inaccuracy (Chakraborty et al., 2015). One of the most important events that affects the TEC is geomagnetic storms. The disturbances in the Earth's magnetosphere are responsible for the occurrence of geomagnetic storms (Habyarimana et al., 2023). Despite decades of intensive research, the ionospheric effects resulting from geomagnetic storms remain not completely understood, since the storm has experienced sophisticated worldwide effects on the ionosphere. Unlike the African region, the American and Asian equatorial and low-latitude ionospheres' responses to geomagnetic storms in February, March, and April 2023 have been extensively investigated. For instance, Rajana et al. (2024) studied the ionospheric TEC response during the two geomagnetic storms of March 23–24, 2024, and April 23–24, 2024, over the Indian longitude sector. They observed that there were no fluctuations in daytime TEC recorded during the initial phase of the geomagnetic storm

of March 23–24, 2024. On the other hand, according to Zhou et al. (2016), there were notable longitudinally opposing fluctuations in the TEC perturbations that occurred throughout the St. Patrick's Day storm 2015 recovery phase. Additionally, the studies of Ikubanni et al. (2018), Kuai et al. (2016), and Akala et al. (2020) found significant longitudinal variance in low-latitude ionospheric responses to geomagnetic storms. In this study, we investigated the impact of three geomagnetic storms on the longitudinal ionospheric TEC variability on February 27, 2023, March 24, 2023, and April 24, 2023, during the ascending phase of the 25th solar cycle. We used the two ground-based GPS measurements of VTEC at the stations MBAR and YKRO over the equatorial African sector.

2. Data and Methodology

In this study, we chose and investigated three major geomagnetic storms that occurred during solar cycle 25. Our data sets include some days before the day of the storm's main phase, the day of the storm's main phase, and some days after, allowing us to analyze the solar wind plasma features during different storm phases. A positive or negative ionospheric storm is defined as an increase or decrease in plasma density (Habyarimana et al., 2023). Thus, the following equation was used to analyze the consequences of geomagnetic storms on the ionospheric TEC:

$$\Delta TEC(\%) = \left(\frac{TEC_{disturbed} - TEC_{quiet}}{TEC_{quiet}} \right) x\,100 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where TEC_disturbed is the TEC value in the storm time, while TEC_quiet is the average TEC value in the quiet time. According to equation (1), a positive value indicates an increase in TEC, whereas a negative value suggests a decrease during the period of the geomagnetic storm. In order to level out the quiet day data, the TEC data points were calculated for each GPS station for the first five quietest days before and following the disturbed days of the month. Then TEC perturbation was calculated by applying the quiet days mean TEC values as shown equation (1) (Ikubanni et al. 2018; Amabayo and Cilliers, 2013). The quiet time mean TEC values allow us to eliminate the quiet-time environment fluctuation, and they represent the average of the five quietest days of each month of concern.

3. Results

For the purpose of studying the consequences of geomagnetic disturbances on the ionosphere, we chose three storms that occurred on February 27, March 24, and April 24, 2023. The next subsections explain the particular geomagnetic parameter variations that occurred during these three storms. Every geomagnetic storm has distinct features that result from differences in interplanetary parameters, disturbances in the magnetosphere, and variations in the solar wind, leading to distinct ionospheric effects with respect to storm-time electron density. The following subsections show the behavior of the three geomagnetic storms on the ionospheric TEC variability.

3.1. The Storm of 27th February 2023 (Dst minimum = -132 nT)

The storm of February 27, 2023, was jointly caused by the baseline coronal hole high-speed streams and two successive coronal mass ejections (CME). In particular, the primary CME was generated on February 24 at roughly 20:30 UT because of an M3.7-class solar flare, and it touched down on Earth on February 24, 2023, at approximately 19:00 UT. In addition to this, the second CME was generated on February 25 at approximately

19:40 UT because of an M6.3-class solar flare, which started at 18:40 UT, attained its maximum at 19:44 UT, and ended at 20:27 UT. Due to this, the storm of 27th February 2023 main phase started on February 26, 2023, at 21:00 UT, reaching a minimum Dst value of -132 nT at 12:00 UT on 27 February, with a gradual recovery on February 28, 2023, as shown in Figure 1.

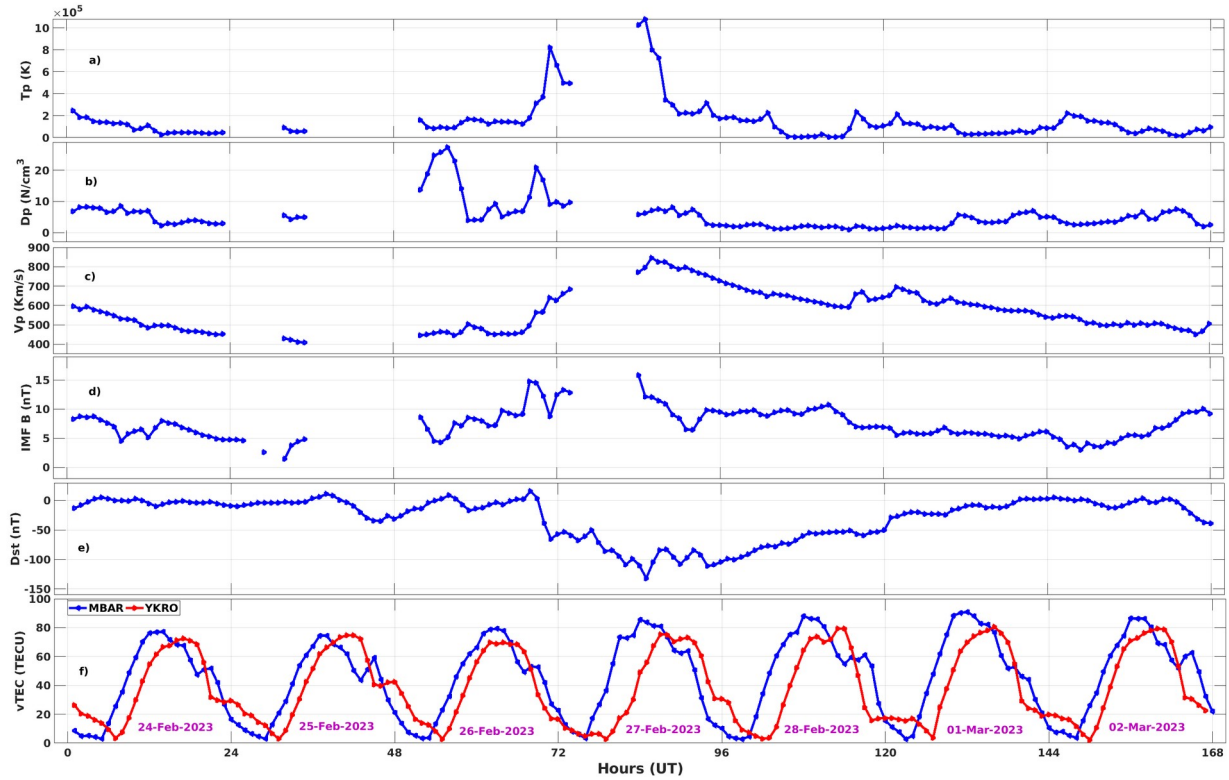


Figure 1. The hourly variability of the SW plasma temperature, Tp (a), SW proton density, Dp (b), SW plasma speed, Vp (c), the scalar interplanetary magnetic filed, IMF B (d), Dst index, Dst (e), and vertical total electron content, vTEC (f) from February 24, 2023 to March 02, 2023, which includes three days before and after the intense geomagnetic storm day of the February 27, 2023

3.2. The Storm of 24th March 2023 (Dst minimum = -163 nT)

Three days prior to (March 21–March 23) and following (March 25–March 27), the intense geomagnetic storm day on March 24, 2023, are represented in Figure 2 as the temporal variations of the SW plasma temperature (a), SW proton density (b), SW plasma speed (c), interplanetary magnetic field (d), Dst index (e), and the vertical total electron content (f). On March 23, just after 05:30 UT, a sharp decline in the Dst index is seen (Figure 2e), suggesting that a magnetic storm is intensifying and the ring current is expanding (Nykiel et al., 2024). According to the world data center (WDC) for geomagnetism in Kyoto, the storm's initial phase began on March 23 at around 12:00 UT, and on March 24, at 03:00 UT, the Dst index dropped to its minimum value of −163 nT, as shown in Figure 2. On March 23, approximately at 14:00 UT, the storm's main phase started with a sharp and then steady rise in the IMF B values. On March 24, at around 7:00 UT, the storm's recovery phase started, characterized by various fluctuations and a decline in IMF B values.

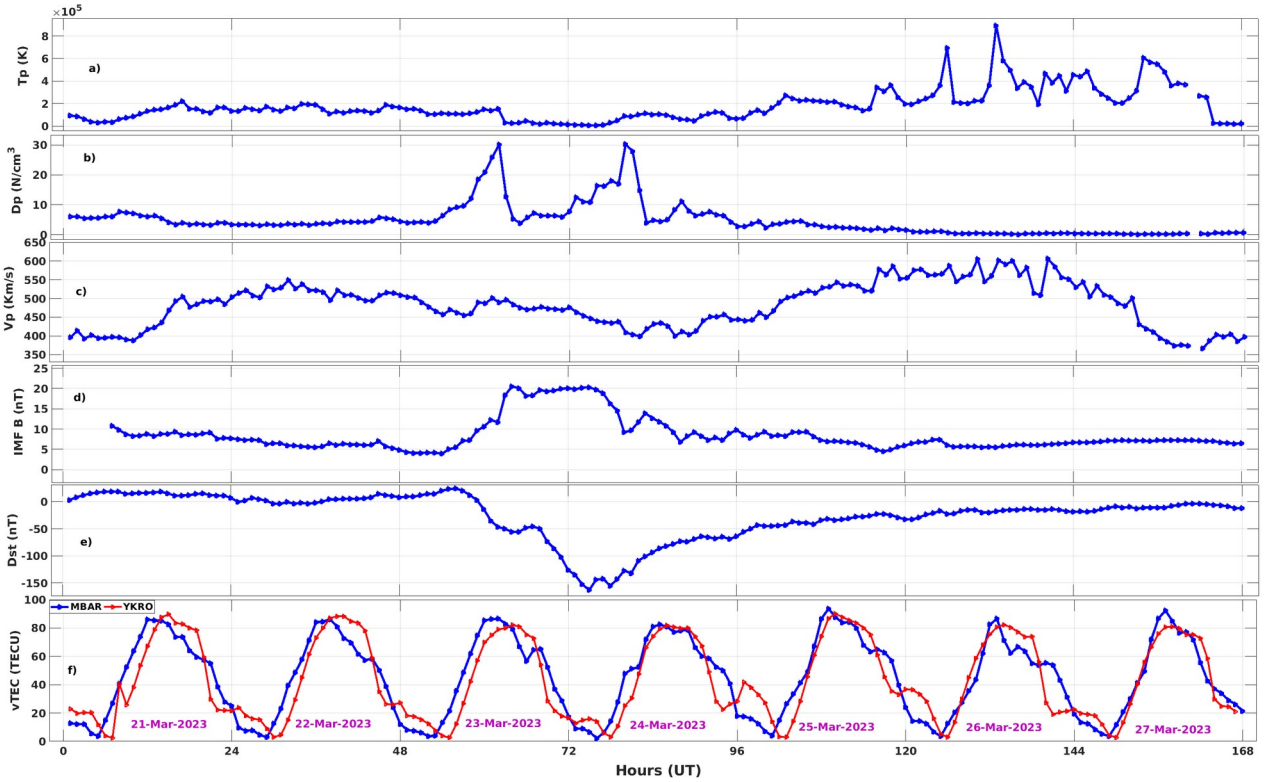


Figure 2. The hourly variability of the SW plasma temperature, Tp (a), SW proton density, Dp (b), SW plasma speed, Vp (c), the scalar interplanetary magnetic filed, IMF B (d), Dst index, Dst (e), and vertical total electron content, vTEC (f) from March 21, 2023 to March 27, 2023, which includes three days before and after the intense geomagnetic storm day of the March 24, 2023.

3.3. The Storm of 24th April 2023 (Dst minimum = -212 nT)

A halo Coronal Mass Ejection (CME) from an extremely active solar region reached Earth's area on April 21, 2023, at around 18:12 UT. This event led to a severe geomagnetic storm on April 24 (Rajana et al., 2024). Figure 3 shows the geomagnetic and interplanetary parameters of the temporal variations from April 21, 2023, to April 27, 2023, of the SW plasma temperature (a), SW proton density (b), SW plasma speed (c), interplanetary magnetic field (d), Dst index (e), and vertical total electron content (f) three days before and after the intense geomagnetic storm on April 24, 2023. The SW proton density (Dp) displays the initial changes at about 05:00 UT on April 23. The IMF B value begins fluctuations at 08:00 UT on April 23 and increases the values, indicating a potential solar wind relationship with the Earth's magnetosphere. The SW plasma speed (Vp) began to increase in value, ranging from 359 km/s to 711 km/s during 16:00 to 21:00 UT. The Dst index was substantially declining (-212 nT), resulting in a severe geomagnetic disturbance throughout the year.

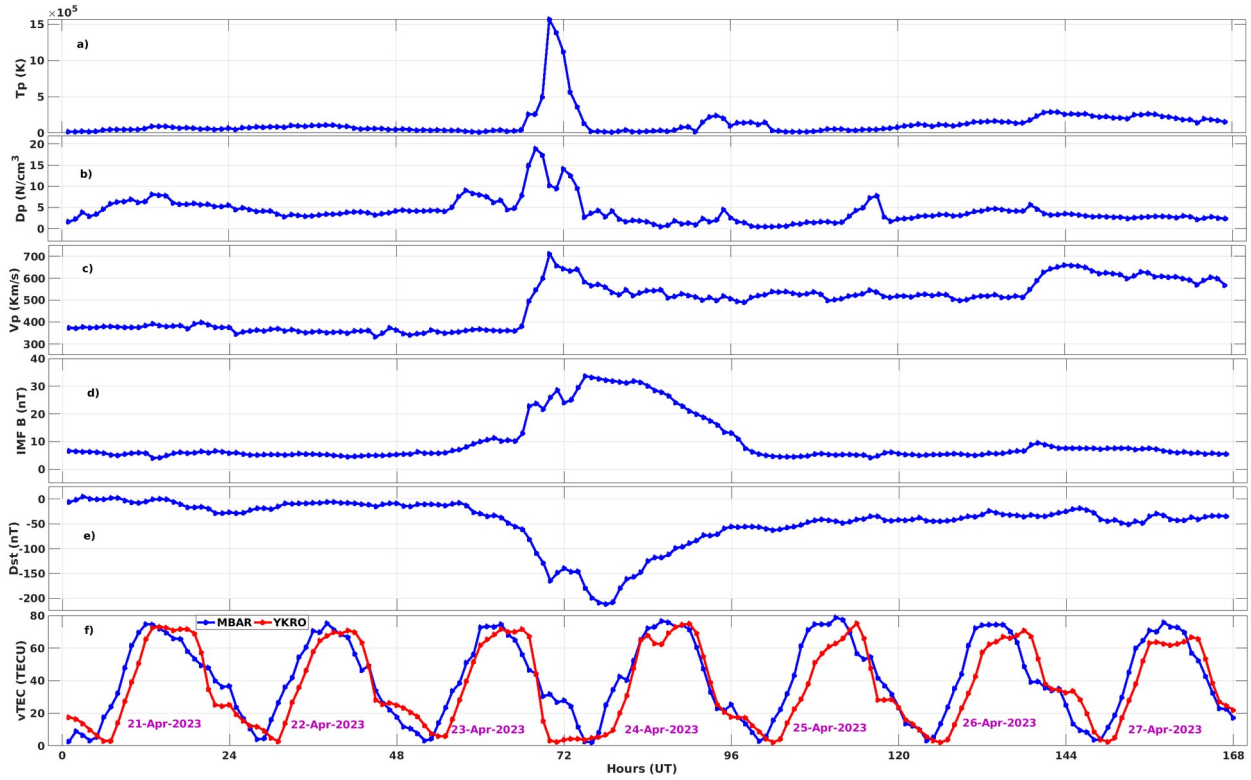


Figure 3. The hourly variability of the SW plasma temperature, Tp (a), SW proton density, Dp (b), SW plasma speed, Vp (c), the scalar interplanetary magnetic filed, IMF B (d), Dst index, Dst (e), and vertical total electron content, vTEC (f) from April 21, 2023 to April 27, 2023, which includes three days before and after the intense geomagnetic storm day of the April 24, 2023.

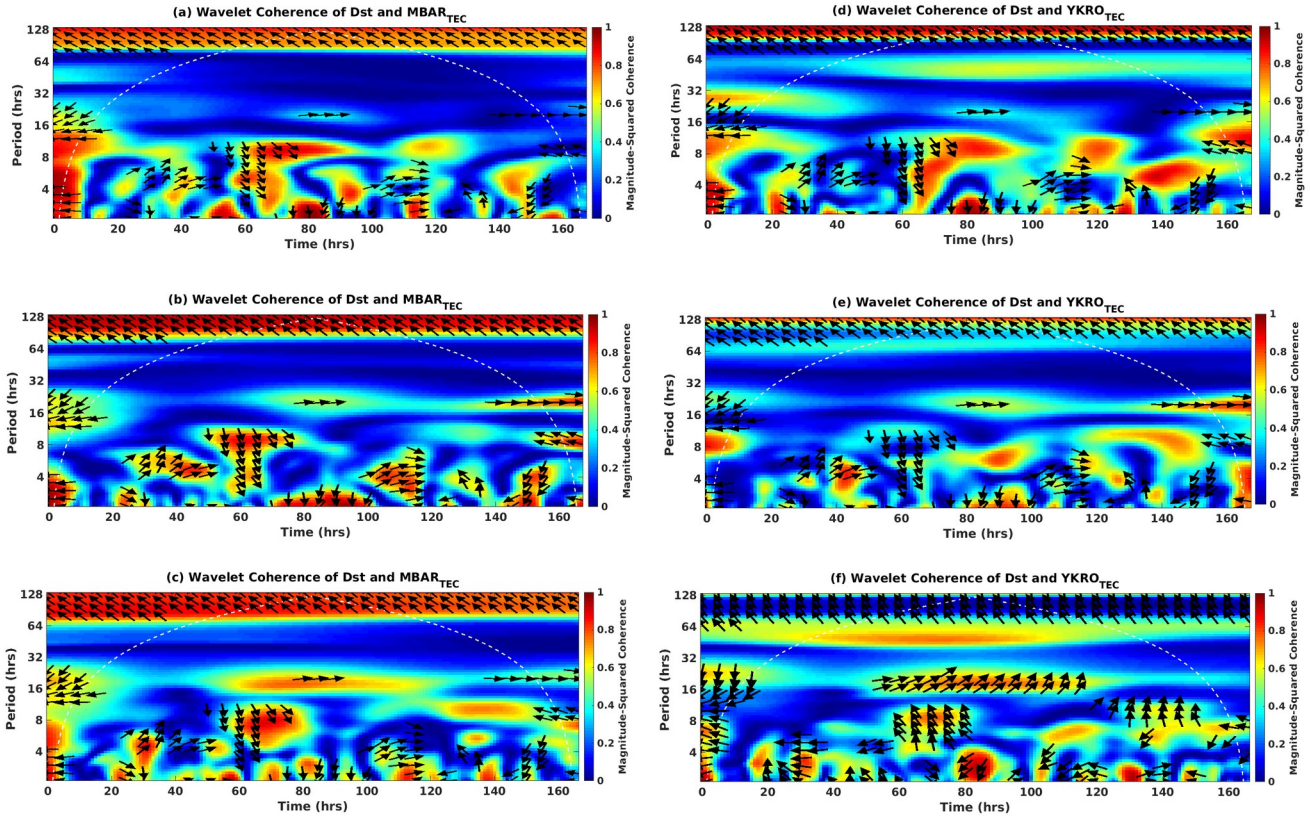


Figure 4. The hourly TEC wavelet coherence spectra between MBAR and Dst (left side) and YKRO and Dst (right side) for the geomagnetic storm day of February 27, 2023 (a and d); for the intense geomagnetic storm day of March 24, 2023 (b and e); for the intense geomagnetic storm day of April 24, 2023 (c and f).

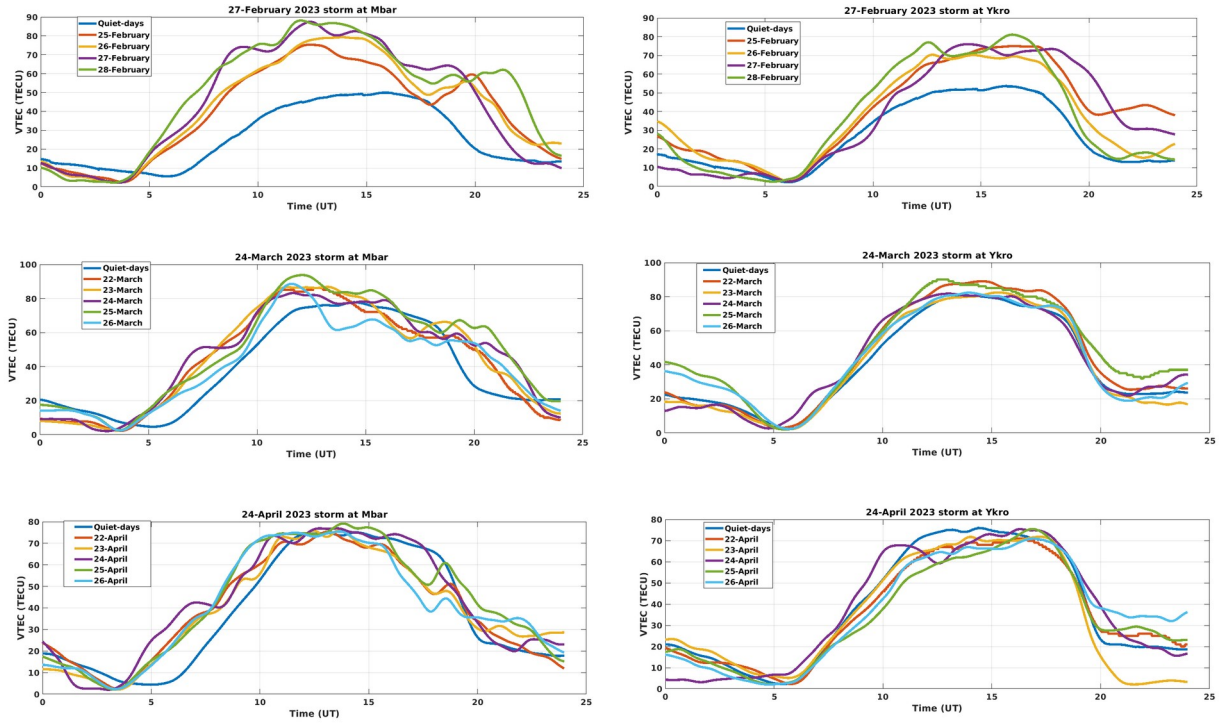


Figure 5. The hourly values of TEC at the stations MBAR (left side) and YKRO (right side) for the geomagnetic storm days of February 27, 2023 (upper panels), March 24, 2023 (middle panels), and April 24, 2023 (lower panels), including some days before and after the geomagnetic storm days, along with the mean values of the first five quietest days of each month.

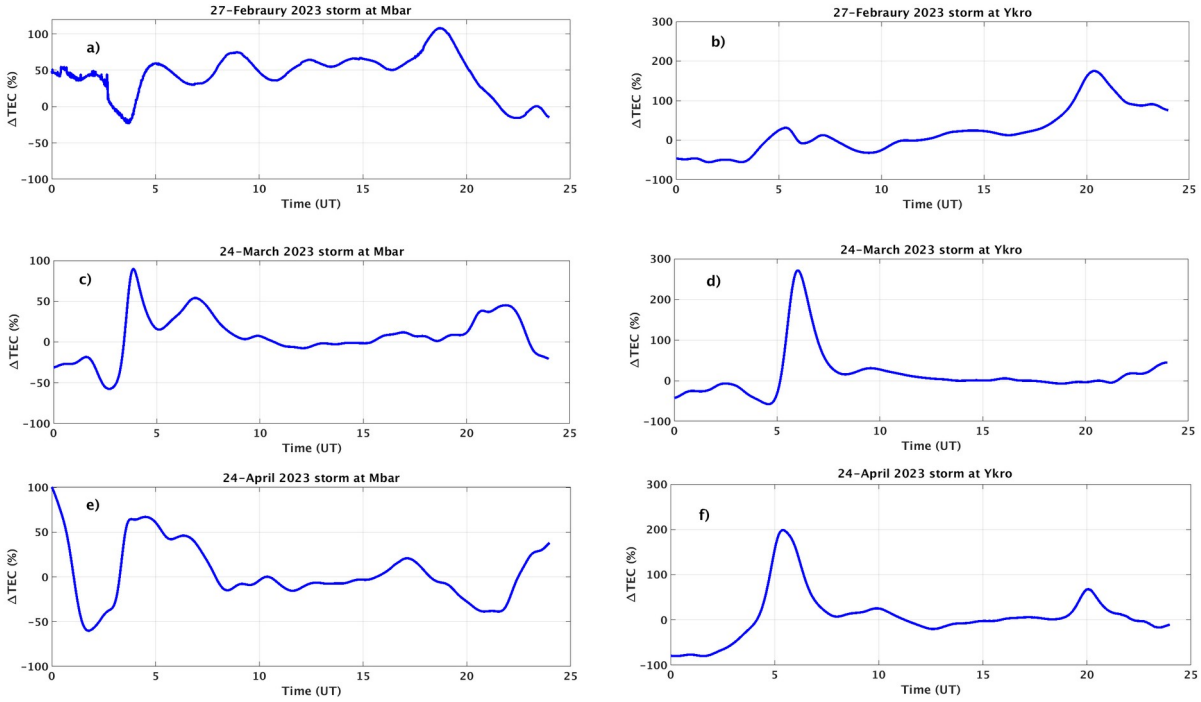


Figure 6. The ionospheric TEC deviation values over the geomagnetic storm days and the mean TEC values of the first five quietest days of each month for the February 24, 2023 storm (a and b), March 24, 2023 (c and d), and April 24, 2023 (e and f).

4. Conclusions

The ionospheric reaction to geomagnetic storms manifests itself as an increase or decrease in electron density from quiet periods of time, defined as a positive or negative ionospheric storm through extend geographical regions. During the initial, main, and recovery periods, both stations experienced three geomagnetic storms that generated positive and negative VTEC disturbances. The two major geomagnetic storms of February 27 and March 24, 2023, had a positive effect on the ionospheric enhancement in most hours of the storm days on both stations, however the severe geomagnetic storm of April 24, 2023, had negative effects on the ionospheric variation. The post-storm day VTEC values are greater during the powerful geomagnetic storms of February 27 and March 24, 2023, but not during the severe geomagnetic storm of April 24, 2023. During various phases of the three geomagnetic storms, there are both positive and negative responses to VTEC deviations from their quiet-time states, which range from -80% to 280%.

5. References

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