Breber and Hadi Iraqi Journal of Science, 2024, Vol. 65, No. 10(SI), pp: 5999- 6013
DOI: 10.24996/ijs.2024.65.10(SI).9

ISSN: 0067-2904

The Impact of Geomagnetic Storms on the Ionospheric Critical Frequency in the Northern and Southern Mid-Latitude Hemisphere Regions

Salma H. Breber[2]*, Khalid A. Hadi[1]

[1]*Department of Astronomy and Space, College of Science, University of Baghdad, Baghdad, Iraq*

[2]*Ministry of Science and Technology, Directorate of Space Technology and Communication, Baghdad, Iraq*

Received: 1/10/2023 Accepted: 6/5/2024 Published: 15/11/2024

Abstract

In this work, the impact of different geomagnetic storm events on the plasma-sphere layer (ionosphere layer) over the northern and southern hemisphere regions was investigated during solar cycle 23. To grasp the influence of geomagnetic storms on the behavior and variation of the critical frequency parameter of the F2 ionospheric layer (f_oF2), five geomagnetic storms (classified as great, severe, and strong), with Disturbance storm time (Dst) values <-100 nT were chosen. Four stations located in different mid-latitude regions in northern and southern hemispheres were designated, the northern stations are: Millstone Hill (42.6° N, 288.50° W) and Rome (41.90° N, 12.50° E) and the southern stations are: Port Stanley (-51.60° S, 302.10° W) and Grahamstown (-33.30° S, 26.50° E). The findings of this study showed that during events of 16 July 2000 and 24 August 2005, the negative storms cause a noticeable reduction in the values of the f_oF2 parameter at the northern hemisphere stations compared to those at the southern hemisphere. These outcomes are consistent with the results of the examining the variation of D(f_oF2) and the electron density depletion during the tested event times at all stations except in Rome, where minor enhancements in f_oF2 value were observed during the August 24 2005 storm. During equinox storm events occurring on March 31 and November 6 2001, a noticeable negative impact of storms was observed across all stations. However, at Millstone Hill and Port Stanley stations, the results showed a slight positive storm impact during the October 21, 2001event.

Keywords: Critical Frequency foF2, Geomagnetic storm, Dst- index, Ionospheric Disturbance.

تأثير العواصف الجيومغناطيسية على التردد الحرج للغلاف الأيوني في المناطق الوسطى من نصف الكرة الشمالي والجنوبي

سلمى هادي بريبر[2]*، خالد عبد الكريم هادي[1]

[1]قسم الفلك والفضاء ، كلية العلوم ، جامعة بغداد ، بغداد ، العراق

[2]وزارة العلوم والتكنولوجيا، دائرة الفضاء والاتصالات ، بغداد ، العراق

الخلاصة

في هذا العمل ، تم دراسة تأثيرأحداث العواصف المغناطيسية الأرضية المختلفة على الطبقة البلازمية (طبقة الأيونوسفير) فوق مناطق نصف الكرة الشمالي والجنوبي خلال الدورة الشمسية 23. لفهم تأثير العواصف المغنطيسية الأرضية على سلوك وتباين معلمة التردد الحرجة لطبقة F2 الأيونوسفيرية (f_oF2)، تم اختيار خمسة عواصف مغناطيسية أرضية مصنفة على أنها

*Email: Salmahadibrebr@gmail.com

كبيرة وشديدة وقوية ، مع قيم (Dst <−100 nT). وتم اختيار أربع محطات تقع في مناطق مختلفة من خطوط العرض الوسطى في نصفي الكرة الشمالي والجنوبي، المحطات الشمالية هي: Millstone Hill (42.6° N, 288.50° W) و Rome (41.90° N, 12.50° E) والمحطات الجنوبية هي : Port Stanley (−51.60° S, 302.10° W) و Grahamstown (−33.30° S, 26.50° E). أظهرت نتائج هذه الدراسة أنه خلال احداث 16 يوليو 2000 و 24 أغسطس 2005 ، تسببت للعواصف السلبية في انخفاض ملحوظ في قيم المعامل f_oF2 في محطات نصف الكرة الشمالي مقارنة بتلك الموجودة في نصف الكرة الجنوبي. تتوافق هذه النتائج مع نتائج اختبار تباين (f_oF2) D من خلال ملاحظة استنفاد كثافة الإلكترون خلال أوقات الاحداث التي تم اختبارها في جميع المحطات باستثناء محطة Rome ، حيث لوحظت تحسينات طفيفة في قيم f_oF2 خلال عاصفة 24 أغسطس 2005. خلال أحداث عاصفة الاعتدال التي حدثت في 31 مارس و 6 نوفمبر، 2001، لوحظ تأثير سلبي ملحوظ للعواصف في جميع المحطات. كما أظهرت نتائج هذه الدراسة بأن هناك تأثيرًا إيجابيًا طفيفًا خلال العاصفة 21 أكتوبر 2001 في كل من محطتي Millstone Hill و Port Stanley .

1. Introduction

The ionosphere is the upper layer of Earth's atmosphere that extends approximately from 60 to 1000 kilometers [1]. Although the majority of the ionosphere is electrically neutral, an ionized layer is created when solar radiation interacts with the atmosphere's chemical contents causing electrons to be split from atoms and molecules [2]. Extreme ultraviolet (EUV) and X-ray solar electromagnetic radiations are the primary sources of the ionization process, hence the formation of the ionosphere at mid-latitudes. Each type of solar radiation effects on a different layer of ionosphere, depending on its intensity and wavelength, as well as the composition of the atmosphere [3]. The Photons of extreme ultraviolet (EUV) and shorter X-rays have enough energy to dislodge electrons from gas atoms. This process is known as the ionization process and it takes place in the daytime. The grade of ionization depends on the intensity and the wavelength of the incoming solar radiation, as well as the composition of the atmosphere. The inverse process in which an ion and an electron combine with the emission of a photon is called recombination. Overall electron density is determined by the ratio between number of ionization and recombination processes. The ionosphere is directly affected by these two mechanisms, as they play a significant role in conduction, where a low collision rate causes a reduction in communications [4,5]. In general, according to the electron density parameter, the ionosphere is divided into several different layers starting from the lowest region, the D-Layer, followed by the E-Layer and finally the F-Layer, which may be separated into two distinguishable layers, F1 and F2 [6]. The F2 layer is the principal reflecting region for long and short - distance HF communication due to its highest electron densities [7]. Figure 1 shows the main ionospheric layers during the day and night times.

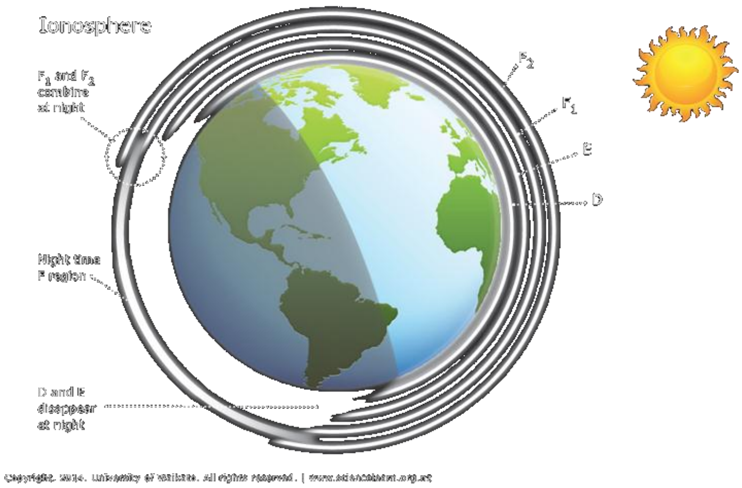

Figure 1: Day and night structure of the ionospheric layer [8].

The terrestrial ionosphere can be roughly divided into three geographic regions with relatively distinguished properties based upon their geomagnetic latitude. The *low-latitude* zone, which is below 30 degrees' magnetic latitude. The second one is *mid-latitude*, which is between 30 and 59 degrees' magnetic latitude, and the last one is *high-latitude*, which is between 60 and 90 degrees' magnetic latitude and it is also called the *auroral area* [9,10].

2. Ionospheric Critical Frequency Parameter

Various parameters are used to describe the ionosphere, the critical frequency parameter (f_c) or (f_o)is one of the most crucial parameters that can be used to study the ionospheric behavior both in quiet and disturbed conditions. It can be defined as the highest frequency signal, depending on the time of day and the day of the sunspot cycle, below which the waves will reflect directly back to the site from which it was transmitted. It is related to the maximum electron density of F2 layer (N_mF2), according to the following equation [11,12]:

$$(f_oF2)^2 = \frac{N_m F2 \cdot e^2}{4\varepsilon_0 \pi m} \tag{1}$$

where:
f_oF2: critical frequency of the F2 layer.
NmF2: maximum electron density of the F2 layer.
e: electron charge.
ε_o: vacuum permittivity.
m: mass of electron.

When radio waves with frequencies higher than the critical frequency of a certain layer are sent out, they pass through the layer and go into space. Radio waves with frequencies lower than the critical frequency will also reflect to Earth unless the lower layer either absorbs or refracts them [13].

3. Geomagnetic storms

The geomagnetic storms are the most important space weather phenomena; it represents the strongest disturbance in Earth's environment because of the large amount of energy transferred from the sun into the space around Earth. Geomagnetic storms occur when the Earth's magnetic field attracts ionized particles emitted from the sun by coronal mass ejections or coronal holes. The storm is supplied by solar wind energy captured by the magnetosphere, and transformed and dissipated in the high latitude upper atmosphere (ionosphere). Geomagnetic storms affect the complex morphology of the electric currents, winds, temperature and neutral composition, also cause changes in the state of ionospheric ionization [14,15]. Space weather phenomena are associated with geomagnetic storms intense storms can affect the Earth's ionosphere and magnetosphere. Depending on the storm's commencement, latitude, and season, the ionosphere responds by increasing or decreasing electron density. During a storm, an increase in electron density is referred to as a positive ionospheric storm, while a decrease in electron density is referred to as a negative ionospheric storm [16,17].

Geomagnetic indices are fundamental evaluations of magnetic activity, such as the *Disturbance Storm-Time* (Dst) index, which is a measure of geomagnetic activity used to determine the intensity of magnetic storms. Dst is expressed in nanoteslas (nT) and is based on the hourly mean horizontal component of the Earth's magnetic field measured at four geomagnetic observatories near the equator [18]. Based on the minimum value of Dst during the time of storm occurrence, geomagnetic storms were classified by Loewe and Prolss in1997 into weak (−30 ≥ Dst > −50), moderate (−50 ≥ Dst > −100), strong (−100 ≥ Dst > −200), severe (−200 ≥ Dst > −350) and great (Dst ≤ −350) [19]. Typically, a geomagnetic storm is comprised by three phases, namely: the initial phase, the main phase and the recovery phase. The initial phase is referred to as a Sudden Storm Commencement (SSC). The main phase is a defining feature of the geomagnetic storm throughout this phase, an energized plasma injection has increased the equatorial ring's current. The duration of the main phase is typically 2-10 hours. The recovery phase represents the period when the Dst index changes from its minimum value to its quiet time value. The duration of the recovery phase may last 8 hours or it may extend to up to 7 days [20]. Figure 2 illustrates the phases of a geomagnetic storm.

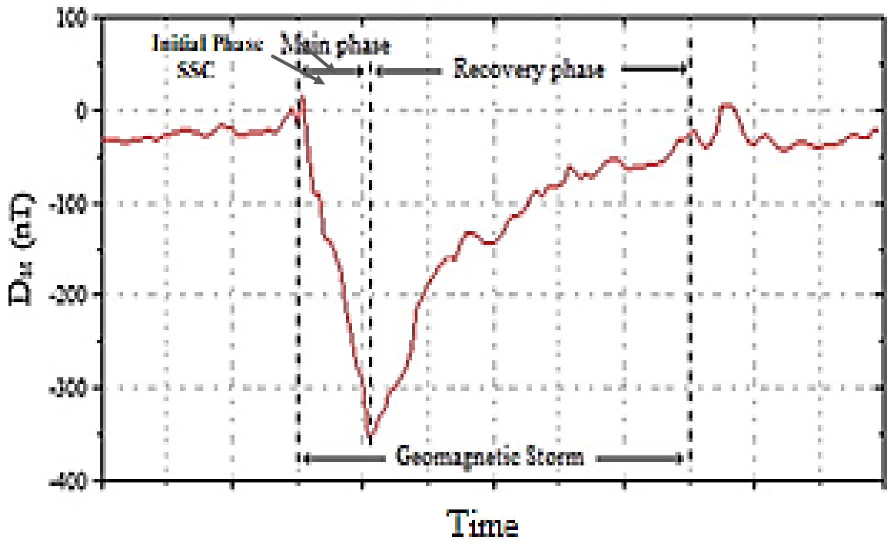

Figure 2: Phases of Geomagnetic Storms [9]

Atulkar, R., et al. (2014) studied the effect of solar and geomagnetic activities on the critical frequency (foF2) at high, mid and low latitude regions. The study's findings revealed that the effect of solar and geomagnetic storm disturbances is stronger at the low latitude than at high latitude during geomagnetic storm times [21]. Kim, V. P., et al. (2015) studied the Response of the Mid-latitude F2 Layer to five strong geomagnetic storms during Solar Minimum years as observed by two pairs of ionosondes in different hemispheres. The results showed similar storm responses in foF2 during the equinox and no noticeable positive disturbances in foF2 during the December solstice magnetic storm at Northern Hemisphere station Wakkanai and Southern Hemisphere station Mundaring. Also showed that no positive ionospheric storms were observed during the events over the European "near the pole", but the "far-from-pole" Southern Hemisphere Station Port Stanley showed prominent enhancements in F2-layer peak electron density [22]. Atıcı, R., et al. (2020) studied the Global investigation of the ionospheric irregularities during the severe geomagnetic storm on September 7-8, 2017 by using the Total Electron Content (TEC) parameter obtained from fifty stations. The results indicated that a greater number of northern hemisphere stations observed ionospheric irregularities in mid-latitude regions than southern hemisphere stations [23]. Saleh, M. H., et al. (2021) studied the correlation of AE-index with solar wind parameters during strong and severe geomagnetic storms during the period (2012-2017) of the solar cycle 24. The correlation results between AE-index and solar indices (Bz, Bt and EF) showed that there was a good correlation between them and the correlation coefficients were within the range (0.63 - 0.74) [24].

3. Test and Results

The objective of this research is to investigate of the influence of geomagnetic storms on the Earth's upper atmosphere (Ionosphere Layer) at the northern and southern regions of the Earth's mid-latitude regions during solar cycle twenty-three. The datasets of the hourly ionospheric critical frequency (f_oF2), geomagnetic index (Dst-index), and solar wind speed parameter (Vsw) were acquired from the following websites, respectively: GIRO DID Base (Global Ionospheric Radio Observatory) (http://giro.uml.edu/didbase/scaled.php), World Data Center for Geomagnetism, (WDC) Kyoto (http://wdc.kugi.kyoto-u.ac.jp/dst_final/index.html), and the NASA's Space Physical Data Facility (SPDF) (NASA/OMNI) (http://omniweb.gsfc.nasa.gov). The total geomagnetic storms that occurred in solar cycle 23 with (Dst ≤ -100 nT) were about (125) storms. In this work, five different geomagnetic storms (strong, severe, and great) were adopted to study the impact of the geomagnetic storms on the Earth's ionosphere layer. Table 1. presents information about the selected geomagnetic storms, their time, duration and type.

Table 1: Selected magnetic storm events

Event Date / Time (UT)	Period of events	Start of geomagnetic storm	End of geomagnetic storm	Duration	DST (nT)	Type
16/07/2000 00:00	(11-21)/07/2000	15/07/2000 19:00	17/07/2000 17:00	46 h	-300	Severe
31/3/02001 08:00	(26/03-5/04)/2001	31/03/2001 05:00	02/04/2001 18:00	61 h	-387	Great
21/10/2001 21:00	(16-26)/10/2001	21/10/2001 18:00	24/10/2001 11:00	65 h	-187	Strong
06/11/2001 06:00	(1-11)/11/2001	05/11/2001 21:00	08/11/2001 13:00	64 h	-292	Severe
24/08/2005 11:00	(19-30)/08/2005	24/08/2005 10:00	26/08/2005 08:00	46 h	-184	Strong

The Impact of the geomagnetic storms was investigated by studying the variations of f_oF2 parameter values during the storms time events at four different locations (stations), distributed in the northern and southern hemispheres. Two of the four selected stations are located in the northern mid-latitude region, which are: Millstone Hill and Rome, whereas the other two stations located in the southern mid-latitude region are: Port Stanley and Grahamstown. Table 2. presents the geographical coordinates of the chosen stations locations.

Table 2. Geographical location coordinates (latitude and longitude) of the selected stations

Stations	Latitude	Longitude	Location
Millstone Hill	42.6 N	288.50 W	USA
Rome	41.90 N	12.50 E	Italy
Port Stanley	-51.60 S	302.10 W	Falkland Islands
Grahamstown	-33.30 S	26.50 E	Southern Africa

The influence of the selected geomagnetic storm events on the tested ionospheric parameter (f_oF2) for the northern and southern Mid-latitude hemisphere stations was examined. The examination was made for eleven days' period corresponding to each tested event (five days before day of event, day of event, and five days after the event). Figures 3-7, presents samples of the variations of f_oF2 parameter for the five selected storm events. Figures' panels depict the variations of f_oF2 parameter for the four selected stations corresponding to the Dst-index and Vsw for the hourly time variation (Hour of Day (HOD)).

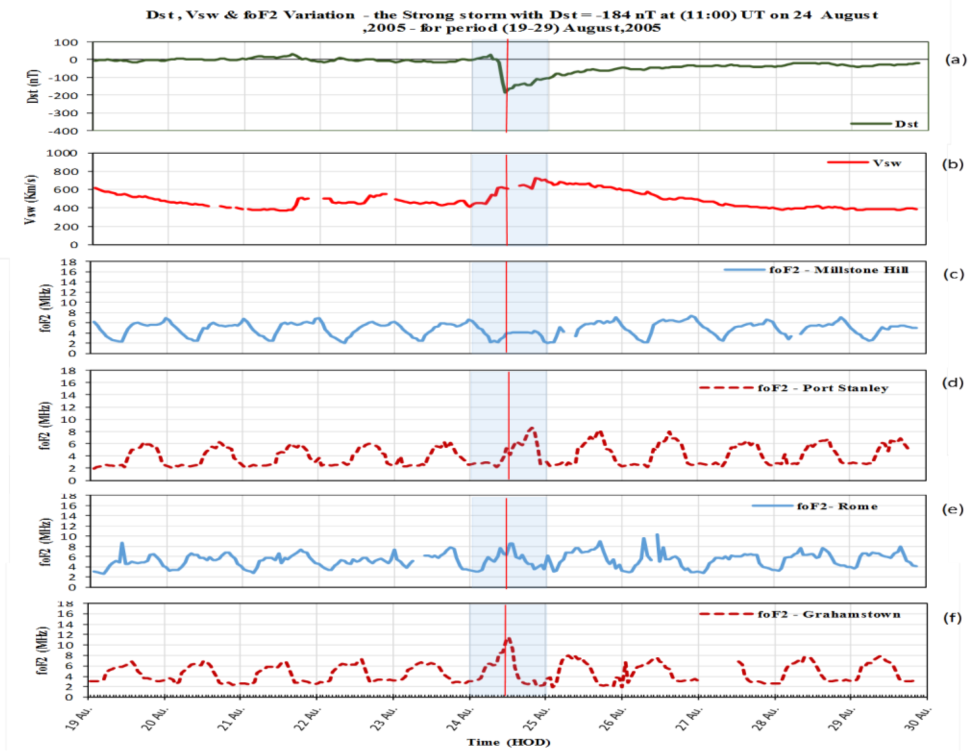

Figure 3: Variation of f_oF2 (c–f) corresponding to Dst index (a) and solar wind speed (b) for Millstone Hill (c), Port Stanley (d), Rome (e) and Grahamstown(f) stations during the geomagnetic storm period 19-29 August 2005. The shaded Blue column indicates the day of storm event and the vertical red line indicates the time of event.

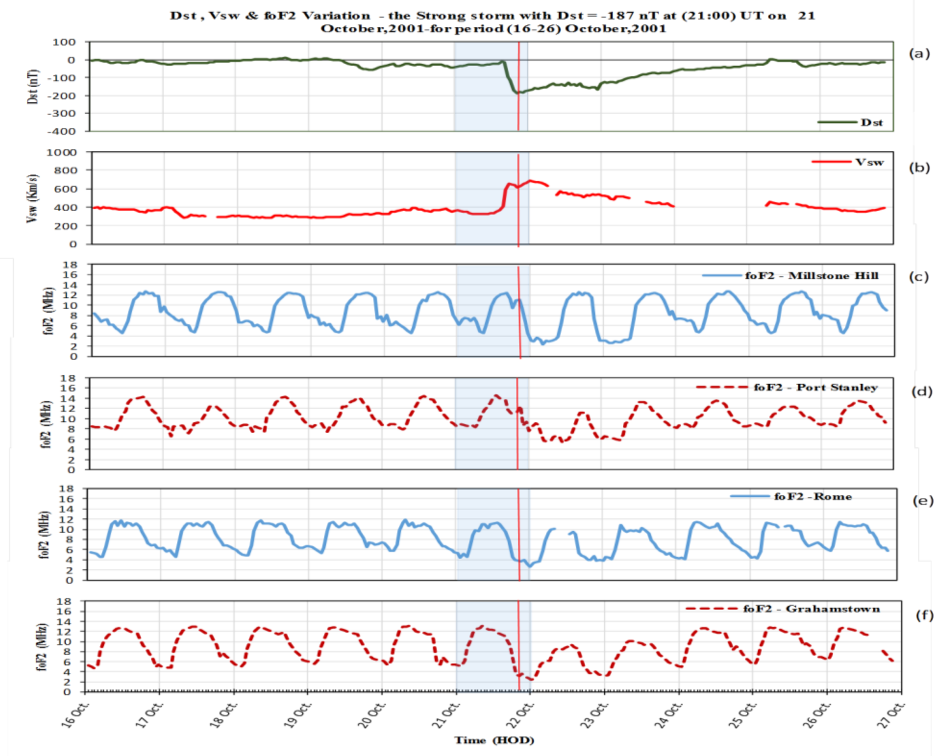

Figure 4: Variation of f_oF2 with Dst index and solar wind speed during the geomagnetic storm period 16-26 October 2001

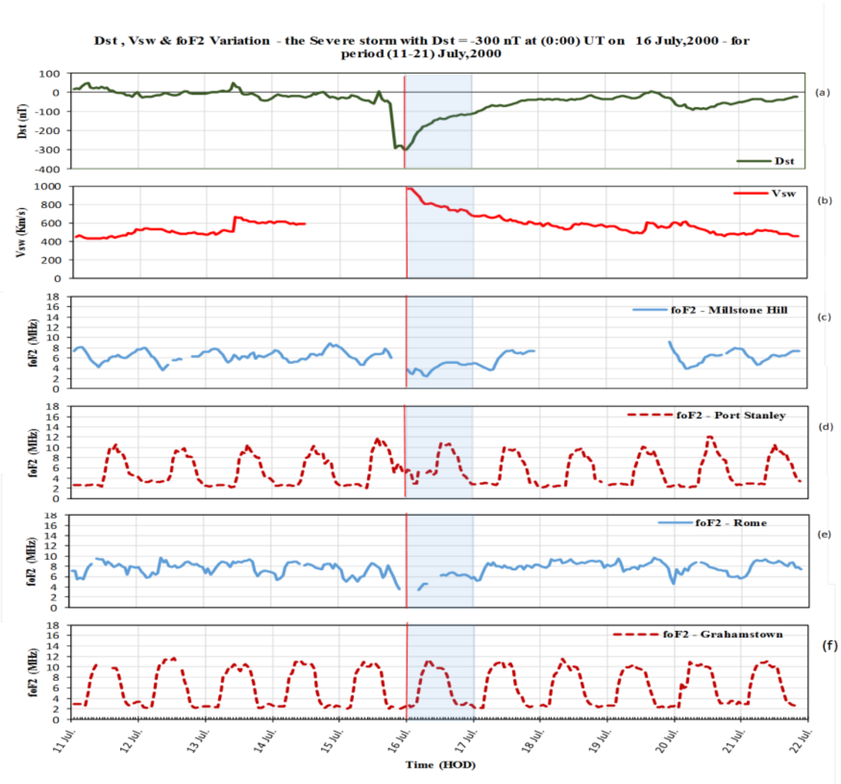

Figure 5: Variation of f_oF2 with Dst index and solar wind speed during the geomagnetic storm period 11-21 July.2000.

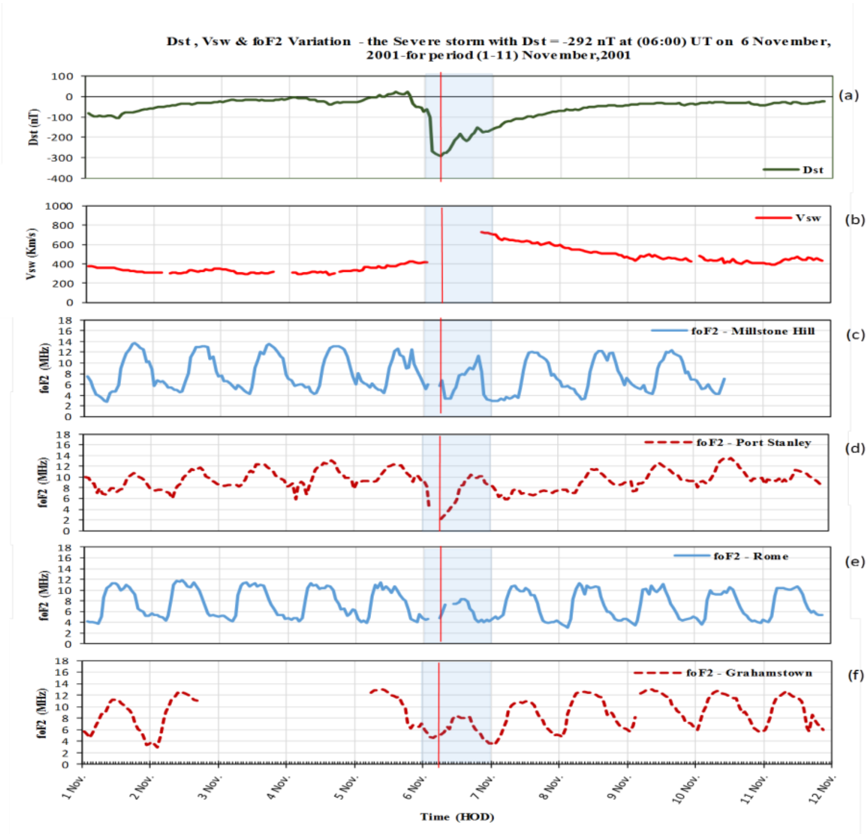

Figure 6: Variation of f_oF2 with Dst index and solar wind speed during the geomagnetic storm period 1-11 November 2001

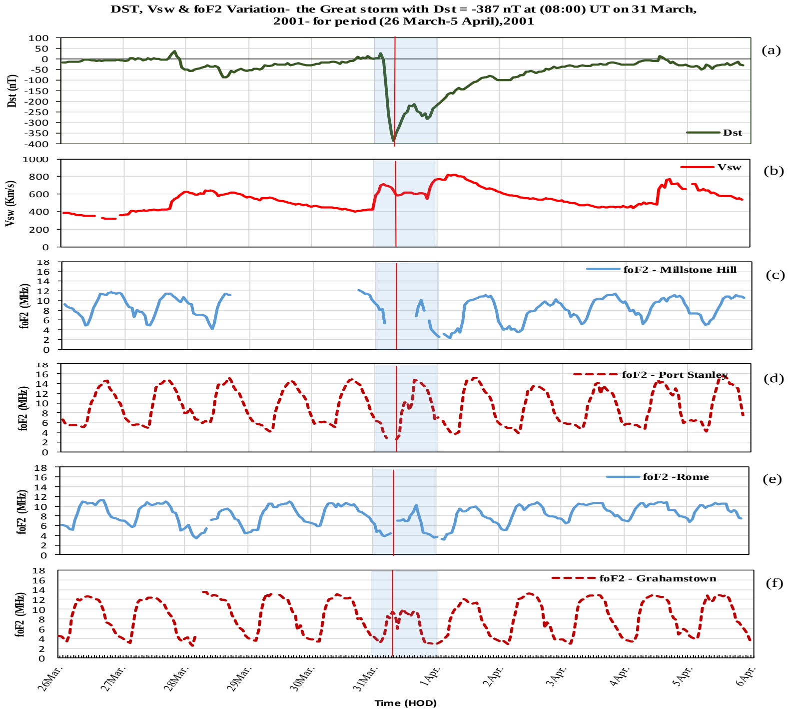

Figure 7: Variation of f_oF2 with Dst index and solar wind speed during the geomagnetic storm period 26 March- 5 April 2001.

In this study, variations of the f_oF2 ionospheric parameter during the periods of chosen geomagnetic storms events were described in terms of $D(f_oF2)$, the normalized deviations of the critical frequency f_oF2 from the reference (quiescent' days) [25]

$$D(f_oF2) = \frac{f_oF2 - (f_oF2)_{ave}}{(f_oF2)_{ave}} \times 100\ \% \qquad (2)$$

The variations in $D(f_oF2)$ are expressed as a percentage of the critical frequency (f_oF2) from the reference. Positive and negative storms take place when the absolute maximum value of $D(f_oF2)$ exceeds 20% [26]. The $D(f_oF2)$ values was derived from the respective hourly f_oF2 values during the five selected geomagnetic storms events for the selected stations, while the reference for each hour was determined by calculating the average value of f_oF2 during that hour from the data collected from three consecutive quiescent days for each event. The $D(f_oF2)$ was investigated for five days' period (two days before and after the day of event). Figures 8-12, show the variations of the $D(f_oF2)$ values during five geomagnetic storm for the selected stations.

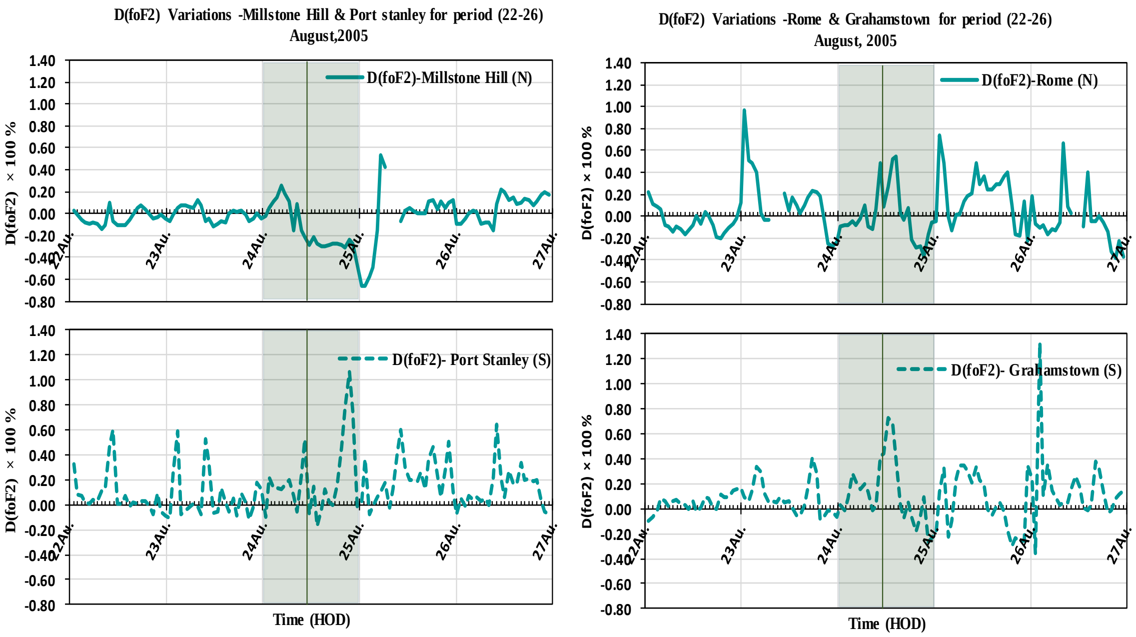

Figure 8*:* Variations of D(foF2) for northern stations (Millstone Hill and Rome) and southern stations (Port Stanly and Grahamstown) during the storm period (22-26) August, 2005.

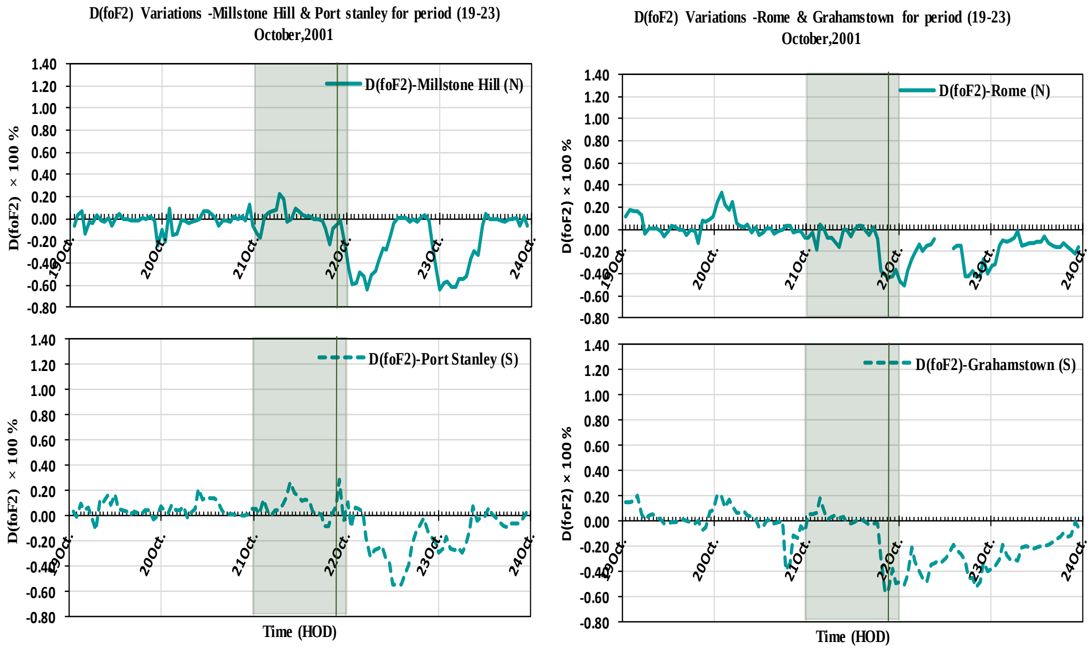

Figure 9: Variations of D(foF2) for northern stations (Millstone Hill and Rome) and southern stations (Port Stanly and Grahamstown) during the storm period (19-23) October, 2001.

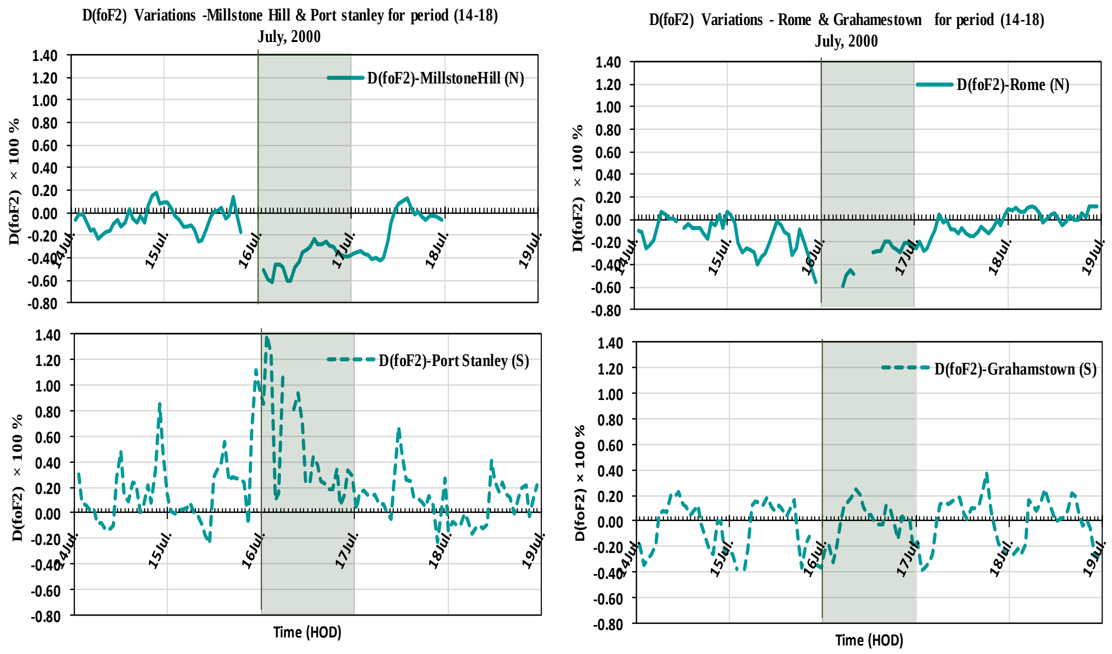

Figure 10: Variations of D(foF2) for northern stations (Millstone Hill and Rome) and southern stations (Port Stanly and Grahamstown) during the storm period (14-18) July, 2000

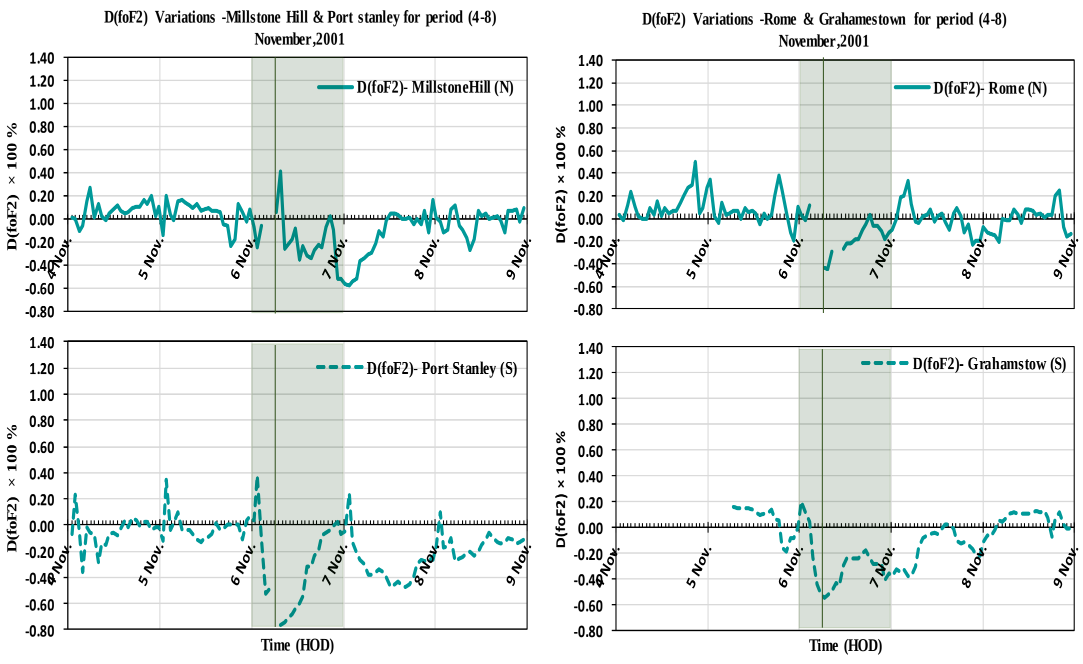

Figure 11: Variations of D(foF2) for northern stations (Millstone Hill and Rome) and southern stations (Port Stanly and Grahamstown) during the storm period (4-8) November, 2001

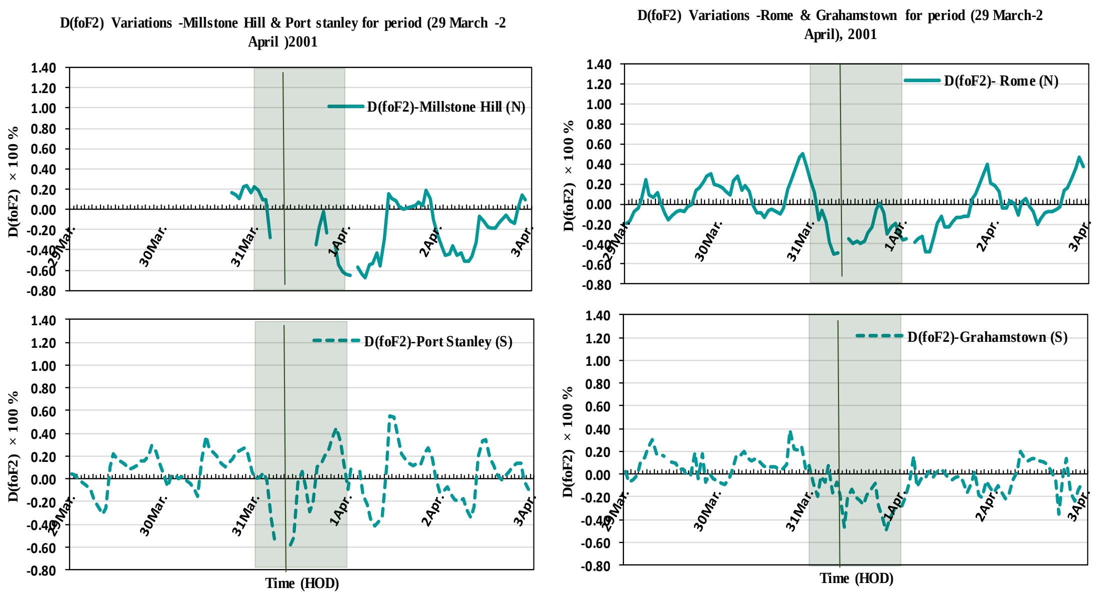

Figure 12: Variations of D(foF2) for northern stations (Millstone Hill and Rome) and southern stations (Port Stanly and Grahamstown) during the storm period (29 March - 2 April), 2001.

4. Discussion

In this research, the impact of five selected geomagnetic storms (strong, severe and great) on the ionospheric critical frequency (f_oF2) during solar cycle 23 was investigated. The investigation was conducted for different stations that lay over the northern and southern Mid-latitude hemisphere regions, (Millstone Hill, Rome) and (Port Stanly, Grahamstown), respectively. The impact of the chosen geomagnetic storms on the ionospheric f_oF2 parameter depicted in Figures 3-7, will be discussed based on the storm type sequence (strong, severe, and great), as follow:

- In figure 3, the storm event that occurred on August 24, 2005 at 11:00 UTC (strong storm type), the minimum recorded Dst value was (-184 nT) and the utmost recorded solar wind speed was about (721.64 km / s). As observed from the figure, there is a clear impact of the geomagnetic storm on the f_oF2 values during the day of the event at Millstone Hill station through the noticeable decrement in the values of the ionosphere parameter, also observed, there is a slight improvement of f_oF2 at Rome station. while the inversely impact was observed in the southern stations through the increase in the parameter values. Noting that the variation at the northern hemisphere stations was in summer time while the southern was in the wintertime.
- For the storm event on October 21, 2001, at 21:00 UTC, (strong storm type), is shown in figure 4, the lowest Dst value recorded during that day was (-187 nT) and the solar wind speed increased reaching its highest value of (690.40 Km/s) on the 22nd October. As figure showed, there was a noticeable impact of this storm on the southern stations, compared to northern stations, during the hour of event (21:00 UT). It causes a reduction of about 15% of foF2 value, which last for about two days of the storm, starting late of 21Oct. till (mid- 23Oct. in Port Stanley and to 24 Oct in Grahamstown)
- In a storm event (main phase) on July 16, 2001 at 00:00 UTC, (severe storm type), is shown in figure 5, the lowest recorded Dst value was (-300 nT) while the highest recorded Vsw value was (975 Km/s). It has observed, due to the impact of the geomagnetic storm, there

was a fluctuation, abnormal behavior, and a reduction in the values of the ionospheric parameter foF2 at the northern stations compared to those at the southern stations that showed almost normal behavior. Except for Port Stanley station, where there was a slight increase in the parameter value during the daylight hours before the day of the storm

- For the storm event that take placed on November 6, 2001 at 06:00 UTC, (severe storm type),

as shown in figure 6, the lowest recorded Dst value was (-292 nT), while the highest recoded solar wind speed was (729.97 Km/s) on that day. Form the figure, the impact of the geomagnetic storm during the day of event was obvious on the ionospheric parameter values at both northern and southern hemisphere stations, by noting the decrease in the values of the ionospheric parameter f_oF2 especially during the hour of the event. This may be due to the fact that the event occurred during the autumn and spring season times at the northern and southern hemisphere stations, respectively. This means that the storms that occurred in the equinoctial seasons did not have a different impact on the values of the f_oF2 parameter between the northern and southern stations.

- For the storm event on March 31, 2001, at 08:00 UTC, (great storm type), as shown in figure 7, the lowest recorded Dst value was (-387 nT), whereas the speed of solar wind increased and recorded to its highest value as (822.47 Km/s) on 1^{st} April, the day after the storm event. During the day of the event, a decrease in f_oF2 values were observed over all selected stations except Port Stanly station, After the day of storm, a slight decrease in the parameter values were observed at the northern stations and (Grahamstown) south station. A noticeable decline in the value of the f_oF2 parameter was also observed (during 2-3 Apr.) at Millstone Hill and Port Stanly stations.

The variations in D(f_oF2) values during the period from 22 to 26 August 2005, were illustrated in figure 8. The resulted D(foF2) reveled the existence of a negative storm with (-47%) and (-38%) f_oF2 peak depletion during the storm event on 24 August 2005 over northern stations Millstone Hill and Rome, respectively. The opposite storm impact (positive) was observed at southern hemisphere stations, with increasing the D(foF2) values. At Grahamstown station during the 26August, there was a lack of data at hour 2, which caused this peak to appear in the data and thus was reflected in the special value calculations in the value of D(f_oF2) ratio. Figure 9, presents the variations in D(f_oF2) values of the selected stations for the period 19 to 23 October 2001. The figure showed the variations of D(f_oF2) values recorded a negative storm, through observing a deplete in f_oF2 values with (-44%) and (-57%) at Rome and Grahamstown stations during the day of event, especially during the hour of the storm. Figure 9 also showed that variations in D(f_oF2) at Millstone Hill and Port Stanley stations showed that the ionosphere recorded positive storm with (49%) and (29%) f_oF2 peak enhancement. respectively. Figure 10. the calculated D(f_oF2) values showed that the ionosphere recorded a negative storm through observing a depletion in f_oF2 values during the day of event (16 July,2000), where D(f_oF2) recorded a value of (- 61%) and (- 59%) at the northern stations (Millstone Hill and Rome, respectively). The variations of D(foF2) at the Port Stanley, revealed of a positive storm that was recorded on the day of the event, with an increment of f_oF2 parameter values for more than 99%. At Grahamstown station, a slight negative storm was recorded on the storm day with a decrease in D(f_oF2) value to about (-33%) before it back to increase to (25 %) which revealed a slight positive storm. During the storm period from 1 to 11 November, 2001, the decrease in D(foF2) values was observed on the day of the storm event (main phase) (6 November,2001) at both southern and northern mid-latitude stations, as shown in figure 11. A decrement of about (-52%, -45%, -77%, and -55%) in D(f_oF2) values was recorded at Millstone Hill, Rome, Port Stanley, and Grahamstown stations, respectively. Also, it was observed that the D(f_oF2) data variations recorded a positive storm with (41%) and (38 %) peak f_oF2 enhancement at the firstly hours of the event day at Millstone Hill and Port Stanley respectively. Figure 12, illustrates the variations in D(foF2) values during the period from 29 March to 2 April 2001 at the northern and southern hemisphere stations. The figure showed a decrement in the D(foF2) values to about (-61%), (- 50%), and (-50%) at Millstone Hill, Rome, and Grahamstown, respectively, which indicate the existence of a negative storm during the day of event (31March,2001). At Port Stanley station, the ionosphere recorded a negative storm with a decrement of D(f_oF2) to about (-58%) after that increased to about (45%), indicating a positive storm occurred.

5. Conclusions

Based on the foregoing discussion of the five selected geomagnetic storm events, at northern and southern hemisphere stations, a set of conclusions can be summarized as follows: -

1- The variations of the tested parameter (f_oF2) for two storm events (16 July,2000) and (24 August,2005) showed that the impact of the negative storms was more obvious over the northern hemisphere stations (summer season time) than the southern hemisphere stations (winter season time), which witnessed improvement in f_oF2 values, it was more obvious at Port Stanley station.
2- During the storm events on (31 March,2001) and (6 November 2001), the impact on the f_oF2 parameter values was observed at all northern and southern stations by noting a decrement in the critical frequency values during the day of the storm, this may be due to the fact that the storms occurred during the equinox seasons for both the northern and southern hemisphere stations.
3- Throughout the storm event on October 21, 2001, Millstone Hill and Port Stanley stations experienced a very slight positive effect of the storm on the parameter value, but the occurrence of negative storms was more frequent, especially in the northern stations.

4- The calculated percentage results of the ionospheric critical frequency (variations in D(foF2)) were in consistent with the behavior of the variation results of foF2 that illustrated in figures 3-7.

5- The results showed that the impact of geomagnetic storms on the variations in foF2 ionospheric parameter were stronger and clearer during the storms of severe and great type than in the strong storm.

6- The variation results in foF2 parameter indicated that the time and type of storm occurrence had an important role in determining the extent of the influence of the geomagnetic storm on the ionospheric parameter in all tested stations.

References

[1] K. A. Hadi and M. D. Abdulkareem, "The Suggested Reciprocal Relationship between Maximum, Minimum and Optimum Usable Frequency Parameters Over Iraqi Zone", *Baghdad Science Journal*, vol. 17, no. 3, pp. 1058-1070, 2020. http://dx.doi.org/10.21123 /bsj.2020. 17.3 (Suppl.).1058
[2] M. Atiq, "Historical Review of Ionosphere in Perspective of Sources of Ionization and Radio Waves Propagation", *Journal of Space Science and Technology,* vol. 7, no. 2, pp. 28-39, 2018. http://www.researchgate.net/publcation/338710842
[3] D. A. Al-Shakarchi and M. I. Abd-Almajied, "Response of The Ionospheric E-Region Critical Frequency and Virtual Height to the Solar Cycle 22 over Baghdad", *Iraqi Journal of Science*, vol. 63, no. 10, pp. 4576-4586,2022. https://doi.org/10.24996/ijs.2022.63.10.39%20

[4] M. O. Shulha, "Investigation of the Ion Composition in the Topside Ionosphere at Solar Maximum Using Incoherent Scatter Technique", Master thesis, Faculty of Science and Technology, UiT The Arctic University of Norway, May, 2016.

[5] F. A., Mohammed, "The Relationship Between Solar Indices and Electron Density of D-Region over Baghdad City During the Ascending and the Descending Phases of Solar Cycle 23", *Iraqi Journal of Science*, vol. 57, no. 2A, pp.1031-1040, 2016.

[6] J. H. Mohammed, "Studying the Relationship between the Maximum Electron Density with the Critical Frequency in the Ionospheric E –layer over Kirkuk City During the Solar Cycle 24", *Kirkuk Journal of Science*, vol. 17, no. 4, pp. 8- 25, 2022. http://dx.doi.org/1032894/kujss. 2022. 135136.1069

[7] E. F. Bakr, W. H. Zaki and J. H. Mohammed, "The Effect of Sunspots Number on Critical Frequencies f_oF2 for the Ionospheric Layer-F2 Over Kirkuk City During the Ascending Phase of Solar Cycle 24", *Kirkuk University Journal-Scientific Studies*, vol. 16, no. 3, pp. 19-27,2021. http://dx.doi.org/10.32894/kujss.2021.170001.

[8] Science Learning Hub – Pokapū Akoranga Pūtaiao, University of Waikato, 2014. https://www.sciencelearn.org.nz/images/248-layers-of-the-ionosphere

[9] Ashneel A. Sharan, "Tropical Cyclone, Geomagnetic Storm and Climate Change Effect on the Upper Atmosphere in the South Pacific Region", MSC Thesis, School of Engineering and Physics, Faculty of Science, Technology and Environment, The University of the South Pacific, October, 2019.

[10] R. D. Hunsucker, J. K. Hargreaves, "The high- Latitude Ionosphere and Its Effects on Radio Propagation", Book, New York: Cambridge University Press, 2003.

[11] M. J. Jafar and K. A. Hadi, "Investigating the Compatibility of IRI and ASAPS Models in Predicting the foF2 Ionospheric Parameter over the Mid Latitude Region", *Iraqi Journal of Science*, vol. 62, no. 10, pp. 3759-3771, 2021. https://doi.org/10.24996/ijs.2021.62.10.34

[12] Z. Mošna, P. Šauli, and O. Santolık," Analysis of critical frequencies in the ionosphere", *WDS'08 of Contributed Papers*, Part II, ISBN 978-80-7378-066-1, pp. 172– 177, 2008.

[13] D. A. Mohamed, M. I. Abdalmajied, and O. T. Ali, "A study of the Effect of Solar Cycle 22, on the Critical Frequencies of F1 Layer over Baghdad", *Dirasat, Pure Sciences*, vol. 37, no. 2, pp. 96-104,2010. https://www.researchgate.net/publication/3272086881.

[14] J. A. Lazzus, I. Salfate, and P. Vega-Jorquera, "Intense Geomagnetic Storms in The Maximum Phase of Solar Cycle 24 Observed from a Low-Latitude Ground Station", *Geophysical international*, vol. 61, no. 4, pp. 267-286, 2022. https://doi.org/10.22201/igeof. 00167169p. 2022. 61.4.2028

[15] Bhanupriya, M. Singh, A.S. Sharma, K. Maski, and S. K. Vijay, "Study of the Effect of Geomagnetic Storm on Low Latitude Station in the Low Solar Activity Period during 24th Solar Cycle", *International Journal of Innovation Reserch in Technology*, vol. 8, no. 7, pp. 2349-6002, 2021.

[16] E. A. Kumar, and S. Kumar, "Geomagnetic storm effect on F2-region ionosphere during 2012 at Low-and Mid-Latitude-Latitude Stations in the Southern Hemisphere", *Atmosphere*, vol. 13, no. 3, pp.480, 2022. https://doi.org/10.3390/atmos13030480

[17] S. Kundu, and S. Sasmal, "Study of ionospheric total electron content and its numerical estimation during several geomagnetic storms in the 24 solar cycle", *Research Square*,2022. https://doi.org/10.21203/rs.3.rs-1652015/v1

[18] K. Koklu, "Mathematical Analysis of the 08 May, 2014 Weak Storm", *Mathematical Problems in Engineering*, vol. 2021, pp. 1-12, 2021. http://doi.org/10.1155/2021/9948745

[19] C. A. Loewe, and G. W. Prölss, "Classification and mean behavior of magnetic storms", *Journal Geophysical Research*, vol.102, no. 7, pp. 14209-14213, 1997.

[20] K. A. Berenyi, V. Barta, and A. Kis "Mid Latitude Ionospheric F2-Layer Response to Eruptive Solar Events-Caused Geomagnetic Disturbances over Hungary During the Maximum of the Solar Cycle 24: A Case Study", *Advance in Space Research*, vol. 61, no. 5, pp. 1230-1243, 2018.

[21] R. Atulkar, S. Bhardwaj, P. Khatarkar, P. Bhawre and P. K. Purohit, "Geomagnetic disturbances and its impact on ionospheric critical frequency (foF2) at high, mid and low latitude region", *American Journal of Astronomy and Astrophysics*, vol. 2, no. 6, pp. 61-65, 2014. http://dx.doi.org/10.11648/j.ajaa.20140206.11

[22] V. P. Kim and V. V. Hegai, "Response of the midlatitude F2 layer to some strong geomagnetic storms during solar minimum as observed at four sites of the globe", *Journal of Astronomy and Space Sciences*, vol. 32, no. 4, pp. 297-304, 2015. http://dx.doi.org/10.5140/JASS.2015.32.4.297

[23] R. Atıcı and S. Sağır, "Global investigation of the ionospheric irregularities during the severe geomagnetic storm on September 7–8, 2017", *Geodesy and geodynamics*, vol. 11, no. 3, pp. 211-221,2019. http://dx.doi.org/10.1016/j.geog.2019.05.004

[24] M. H. Saleh, D. M. AL-Feadh, and K. A. Hadi, "Investigating the correlation of AE-index with different solar wind parameters during strong and severe geomagnetic storms", *AIP Conference Proceedings*, vol. 2372, no. 1, 2021. https://doi.org/10.1063/5.0066520

[25] V. U.Chukwuma, "On ionospheric phenomena during pre-storm and main phase of a very intense geomagnetic storm", *Acta Geophysica*, vol. 58, no. 6, pp. 1164-1192,2010. http://dx.doi.org/10. 2478 /s11600-010-0008-7

[26] L. Liu, W. Wan, M. L. Zhang, B. Zhao, and B. Ning, "Prestorm enhancements in NmF2 and total electron content at low latitudes", *Journal of Geophysical Research: Space Physics*, vol. 113, no. A2, 2008. http://dx.doi.org/10.1029/2007JA012832