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On the Response of the Mid-latitude Ionosphere to the Severe Geomagnetic Storm of March 17-18, 2015

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Abstract: *The response of the ionosphere to heliophysical, interplanetary and geophysical structures during the severe geomagnetic storm ($D_{st} = -223\ nT$) of March 17-18, 2015 has been investigated. Deviations of ordinary wave critical frequencies from the reference values based on four international geomagnetically quiet days preceding the storm ($\delta f_o F_2$) and F_2 layer maximum electron density ($N_m F_2$) were calculated using manually scaled $f_o F_2$ records from a chain of stations in Japan of the mid-latitude Asian sector. Results show that the pre-storm and main phases of the geomagnetic storm were accompanied by positive ionospheric storm typified by enhancement while the recovery phase was accompanied by a negative storm marked by the depletion of $N_m F_2$. Also, $\delta f_o F_2$ values showed, on the average, greater than 20% positive deviation from $f_o F_2$ during the pre-storm and main phase, and also negative deviations in the recovery phase. Significant enhancement of $N_m F_2$ which occurred at least twenty-four hours ahead of the storm onset was observed in all the stations and tends to lend credence to the veracity of the contentious pre-storm $N_m F_2$ enhancement phenomenon. The study also shows that the F-region virtual height was significantly raised during the main phase of the geomagnetic storm.*

Keywords: *geomagnetic storm, positive storm, negative phase, pre-storm enhancement, ionospheric storm, drift of ionospheric plasma, uplift of F2-region virtual height*

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1.0 Introduction

The ionosphere, an ionized region of the atmosphere with free electrons in proportions sufficient to affect the propagation of radio waves, is highly sensitive to variation of heliophysical, interplanetary and geophysical phenomena on various time scales. The variability of ionospheric electron density is critical to the propagation of radio signals and attracts much research interest. It is now understood that the disturbance of the earth's magnetic field (geomagnetic storm) may be accompanied by ionospheric disturbance (ionospheric storm). Of particular interest to geomagnetic storm studies, due to their predictive properties, are the contentious pre-storm ionospheric phenomena which consist of the appearance of positive phase ionospheric disturbance (enhancement of electron density at F_2 maximum heights) and/or negative phase (depletion of the same) before the commencement of and during the geomagnetic storm (Burešová, and Laštovika, 2008; Astafyeva, 2009a; Danilov, 2013; Liu *et al*., 2014, Jiang *et al*., 2017). It is, in general, recognised that the source of the ionospheric storm is input energy and momentum of solar wind into the high latitude magnetosphere, giving rise to changes in thermospheric properties (composition, temperature and circulation) (Buonsanto, 1999; Kane, 2005; Pirog *et al*., 2006; Liu *et al*., 2008; Yadav *et al*., 2011; David and Chukwuma, 2012; Kuai *et al*., 2016; Zhou *et al*., 2016).

Although scientific literature is replete with research articles on ionospheric response to geomagnetic storms, understanding of the phenomenon appears to be incomplete and pre-storm phenomena reportedly still appear to have unsolved problems (Prölss, 2006; Chukwuma, 2010). Studies on quiet-time F_2-layer variability such as Mikhailov *et al*. (2004) and Depueva *et al*. (2005) seem to reveal positive and negative quiet-time disturbances whose magnitude are comparable to those purportedly induced by geomagnetic storms. In particular, Mikahilov and Perrone (2009) argue that pre-storm enhancement is a delusion rather than reality because in all cases of their observation, F_2-layer maximum electron density (N_mF_2) enhancements were most likely the outcomes of previous geomagnetic storms, moderate auroral activity or a class of positive quiet-time (Q-time) disturbances. Commenting on this observation Chwukwuma (2010) pointed out that there was also the need to ascertain whether or not such a pre-storm auroral activity led to the ensuing geomagnetic storm. In other words, the geoeffectiveness of such moderate auroral activity in triggering a geomagnetic storm needs to be further investigated based on established criteria for heliophysical and interplanetary structures to be considered geoeffective (Zhang *et al*., 2007; Adebisin, 2008; Chukwuma, 2009; Richardson and Cane, 2011., Kilpau *et al*., 2015b., Lugaz *et al*., 2016., Susanta *et al*., 2016; Adekoya and Chukwuma, 2017; Oliveira and Samsonov, 2018). However, a flurry of recent results of research on pre-storm ionospheric disturbances, using different techniques, seem to confirm the reality of the phenomena (Adebiyi *et al*., 2014; Liu *et al*., 2014; Astafyeva, *et al*., 2015, Borries *et al*., 2015; Greer *et al*., 2017; Berényi *et al*., 2018; Danilov and Konstantinova, 2019; Krypiak-Gregorczyk, 2019). The present study re-examines the veracity of the phenomena of pre-storm enhancement and/or depletion of ionospheric electron density concerning an intense geomagnetic storm ($D_{st} = -223$ nT) of March 17-18, 2015, during a very low solar activity cycle. The geomagnetic storm, which was the strongest space weather event of solar cycle 24, was reportedly without any heliosphysical precursors typified by X- or M-type flares (Kamide and Kusano, 2015) although some researchers argue that the event was the result of a C9.1 class flare from active region AR2297 accompanied by a halo coronal mass ejection (CME) on March 15, 2015 (Wu *et al*., 2016; Watari, 2017; Navia *et al*., 2018). However, evidence in support of the interplanetary rather than heliophysical source of the geomagnetic storm under study has also been presented (Ibanga and Agbo, 2020). Solar cycle 24, by all indications, was very weak compared to other cycles in the last 100 years (Ibanga *et al*., 2020).

Ionospheric response to heliosphysical, interplanetary and geomagnetic structures that precede the onset of geomagnetic storms promises to offer reliable precursors to the occurrence of severe space weather events. Given the apparent disagreement as to its existence, especially during very low solar activity cycles, this study aims to isolate storm-time from normal diurnal ionospheric variability to provide additional evidence.

2.0 Materials and Methods

Data used in the present study and their sources are as follows: Data on geomagnetic response to heliophysical and interplanetary phenomena comprising hourly average B_z based on geocentric solar ecliptic system (GSE) coordinates and D_{st} were obtained from Space Physics Data Facility, Goddard Flight Centre website. Data on f_oF_2 records from which N_mF_2 and h_mF were calculated were obtained from World Data Centre, National Institute of Information and Communications Technology (NICT), Tokyo, Japan website. Data on International Geomagnetic Quiet Days (IGQDs) were sourced from the Geoscience Australia website. The geographic and geomagnetic coordinates of the four stations, Wakkanai, Kokubunji, Yamagawa and Okinawa are shown in Table 1.

Table 1: Geographic and Geomagnetic Coordinates of Stations

Station	Geographic Latitude	Geographic Longitude	Geomagnetic Latitude	Geomagnetic Longitude
***Wakkanai/Sarobetsu**	45°10'N	141°45' E	36.4°N	208.9°
Kokubunji	35°43' N	139°29' E	26.8°N	208.2°
Yamagawa	31°12' N	130°37' E	21.7°N	200.5°
Okinawa	26°41' N	128°09' E	17.0°N	198.6°

***The facilities at Wakkanai were relocated to Sarobetsu since February 2009. The new site, which is about 26 km south of the old observatory, commenced its operations on March 6, 2009.**

Four international most quiet days preceding the onset of the geomagnetic storm in the month under consideration were chosen for the fact that they were the closest to the first disturbed day and are shown in Table 2

The average hourly values of the ordinary wave critical frequency for the F_2-layer, $(f_oF_2)_{ave}$, for the four quiet days were calculated. These constitute the reference values.

Table 2: 10 International Quiet and 5 Most Disturbed Days in March, 2015

Event	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	D1	D2	D3	D4	D5
Day	10	30	05	14	09	15	13	27	26	12	17	18	02	19	01

Hourly deviations of the F_2-layer ordinary wave critical frequency (δf_oF_2) for the four stations, were calculated using the equation:

$$\delta(f_oF_2) = \frac{f_oF_2-(f_oF_2)_{ave}}{(f_oF_2)_{ave}} \times 100\% \quad (1)$$

Hourly values of F_2-layer maximum electron density (N_mF_2) for the four stations, were calculated using:

$$N_mF_2 = \frac{(f_oF_2)^2}{80.5} \quad (2)$$

Although the study focuses on the storm days, 17-18 March, 2015, two days, 16 and 19 of March, 2015, were included to seek information concerning pre-storm and post-storm phenomena. Finally, plots of hourly diurnal variations of δf_oF_2 and N_mF_2 were obtained. These were contrasted with plots of quit-day diurnal variation of the relevant parameters (reference values) to isolate possible effects of geomagnetic disturbance.

Because data on the F_2-region minimum virtual height of the ordinary wave ($h'F_2$) for these stations were sparse, it was difficult to investigate the uplift or otherwise of $h'F_2$ during the geomagnetic storm. However, the phenomenon was investigated using the whole F-region minimum virtual height of the ordinary wave (h'F). Also, hourly diurnal variations of storm time indices (B_z, E_y, AE and D_{st}) were plotted. Sudden storm commencement (SSC) was set as the reference time for the onset of the geomagnetic storm.

3.0 Results and Discussion

Diurnal variation of the interplanetary and geomagnetic parameters before and during the geomagnetic storm (16-19 March, 2015) is displayed in Fig. 1. The upper fields (a-b) show the diurnal variation of the z-component of the interplanetary magnetic field, B_z and zonal electric field, E_y while the lower fields (c-d) display the diurnal variation of auroral electrojet (AE) and storm distension (D_{st}) indices. It is clear from all the fields in the figure that 16 March, was relatively quiet. Storm sudden commencement (SSC) arising from solar wind ram pressure (i.e. the initial contact of the disturbed solar wind with the magnetosphere) occurred at 05:00 UT of March 17, 2015 (red arrow in the figures). Fig. 1 (a) shows that the rise in solar wind dynamic pressure gave rise to a concomitant sudden rise of B_z, at 02:00 UT of March 17, 2015. It rose to 19 nT signaling storm sudden commencement (SSC). A southward rotation with a value of -1.2 nT at 06:00 UT led to a further decrease to -14 nT, and then it rotated sharply, turning northward with a value of

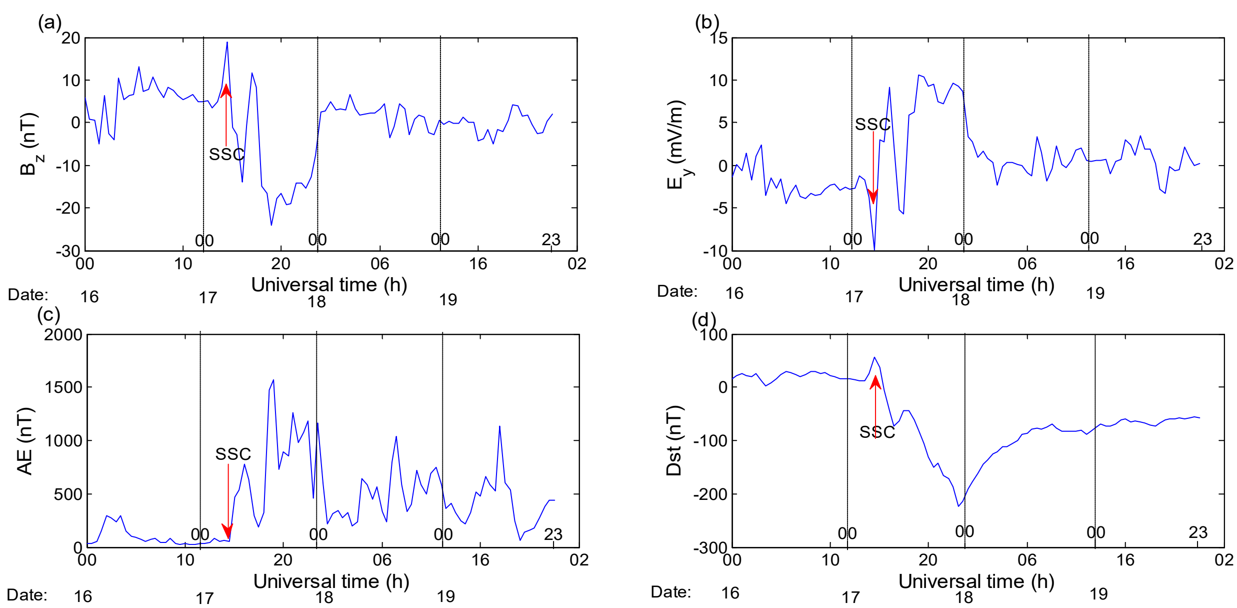

Fig.1: Plots of diurnal variation of interplanetary and geomagnetic parameters 16-19 March, 2015.

11.7 nT at 08:00 UT. It sharply turned southward again at 10:00 UT and reached a maximum value of 11.7 nT at 08:00 UT before sharply turning southward again at 10:00 UT, reaching a maximum value of -24.1 nT at 14:00 UT of the same day Fig.1(b) shows that the zonal electric field, E_y responded with a sudden increase indicating an efficient exchange of solar wind energy with the magnetosphere and coupling of IMF with magnetospheric electric circuits according to the requirement: $\mathbf{E} = -\mathbf{V} \times \mathbf{B}$ or or $E_y \approx VB_z$. The response of the geomagnetic field to the variation of the interplanetary structures is seen in the variation of AE and D_{st}. As Fig.1c shows, AE promptly increased with SSC, reaching a maximum of 1570 nT simultaneously with the southward IMF maximum B_z at 14:00 UT of March 17, 2015. With the northward rotation and decrease in the magnitude of B_z, AE also decreased in magnitude, although not to the pre-storm values. During SSC, the value of D_{st}, suddenly rose to 56 nT and then decreased rapidly, in two successive steps of -73 nT at 09:00 and -150 nT at 17:00 UT (moderate storm) to a minimum of -223 nT (severe storm) at 23:00 UT on March 17, 2015. The main phase lasted for 17 hours (05:00 to 22:00 UT on March 17, 2015). Then, it recovered slowly, not to pre-storm but moderate storm values (-58 nT at 23:00 UT of March 19, 2015).

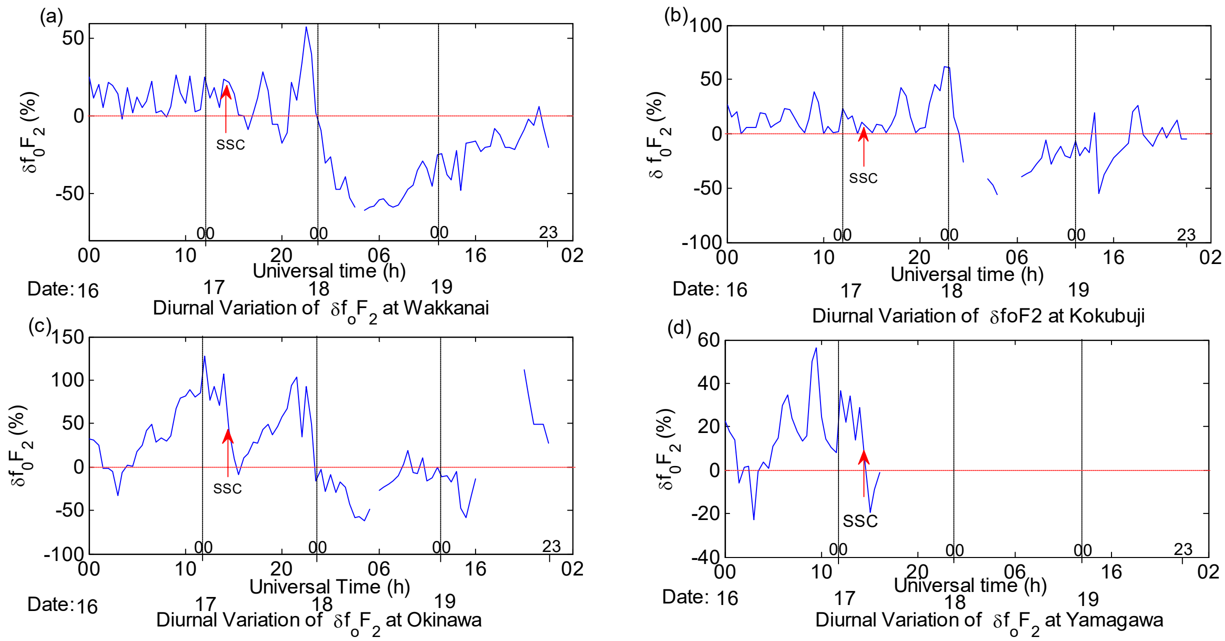

Fig. 2: Computed deviations of the ordinary wave critical frequency of F_2 layer (δf_oF_2) from the average quiet-day values for Wakkanai (a), Kokubunji (b) Okinawa (c) and Yamagawa (d).

The normalized deviation of the ordinary wave critical frequency of F_2-layer (δf_oF_2) from the mean quiet-day variation for all four stations is displayed in Fig 2. Due to difficulties of ionospheric origin - the presence of sporadic E (E_s) layer, complex echoes (spread F phenomenon) and non-ionospheric origin – problems occurring in the automatic data processing system and sundry other technical difficulties, some of the observational data were either sparse or not available. In particular, it was difficult to observe some of the ionospheric characteristics that had to do with the minimum virtual height of the ordinary wave for the F_2-layer ($h'F_2$) throughout the interval under study. The phenomenon was investigated using the whole F-region minimum virtual height of the ordinary wave (h'F) instead. Also, the discontinuation of observations for storm days at Yamagawa station was purely due to technical difficulty (non-ionospheric origin). It was observed that the variations at all stations showed some similarities, although they exhibited distinct local time disparities. The similarity of variation at Wakkanai and Kokubunji stations was observed to be very close. This may have to do with the observation that Wakkanai and Kokubunji stations are contiguous in terms of geographic and geomagnetic coordinates (Table 2). The same is the case for Okinawa and Yamagawa stations. The deviations were mostly positive (though of varying magnitudes) prior to storm commencement at all stations, except in very few instances at Wakkanai, Okinawa and Yamagawa stations where occasional negative deviations were recorded. Maximum positive deviation occurred at about 21:00 UT at Wakkanai and Kokubunji stations. At Okinawa station, a dual peak was observed (one at 24:00 UT of 16 and the other at 21:00 UT of 17 March). At Yamagawa station, the maximum positive deviation occurred at 19:00 UT on 16 March. Prominent features of the variation of δf_oF_2 observed at all stations are: (i) positive deviations (positive phase) at 24:00 of 16 March were generally of the same pattern consisting of positive deviation greater than 20%, five hours ahead of SSC. (ii) Large, positive deviation (positive phase) greater than 71% on the average, at 21:00 UT on 17 March during the main phase of the geomagnetic storm (iii) sudden decrease (negative phase) from a large positive deviation to negative, with a minimum at 09:00 UT of 18 March during the recovery phase of the magnetic storm (iv) gradual increase or recovery of δf_oF_2 after 09:00 UT of 18 March which, on the average, remained below pre-storm levels.

Fig.3 reveals that (i) quiet-day and storm-time diurnal variation of F_2-layer maximum electron density (N_mF_2), in general, followed the same pattern, with the disturbed-day variation superposed on the quiet-day variation. Enhancement was observed in the morning to afternoon hours and depletion in the afternoon to night hours. (ii) enhancement of F_2-layer maximum electron density (N_mF_2) occurred at all stations beginning at 05:00 UT of 16 March (24 h to SSC) and reaching the maximum at 13:00 UT of the same day. The quiet-day afternoon bite-out coincided with the disturbed-day maxima at all stations.

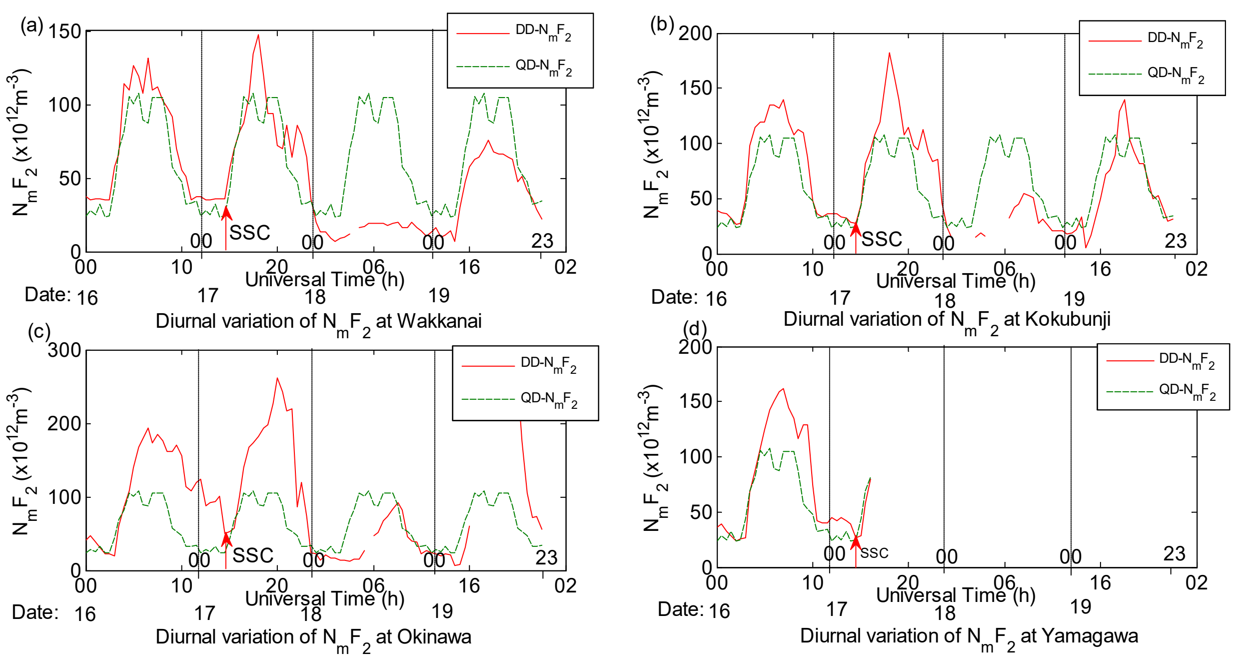

Fig. 3: Plots of computed values of F_2 layer maximum electron density (N_mF_2) for Wakkanai (a), Kokubunji (b), Okinawa (c) and Yamagawa (d). The green broken line represents the reference or quiet-day (QD) values while the red solid line represents disturbed day (DD) variation.

However, the disturbed-day (16 March) maxima were found to be above quiet-day maxima by 50.4 % at Wakkani and Kokubunji stations, 121.4% at Okinawa and 80.4% at Yamagawa stations respectively. (iii) the main phase of the geomagnetic storm was accompanied by the enhancement of F_2-layer maximum electron density above quiet-day maximum by 68.4% at Wakkanai, 107.5% at Kokubunji and 49.7% at Okinanwa stations. (iv) the recovery phase of the geomagnetic storm was observed to be accompanied by depletion of F_2-layer maximum electron density below quiet-day maximum during afternoon bite-out at 13:00 UT of March 18 by 78.4% at Wakkanai, 63.1% at Kokubunji and 50.0% at Okinawa stations respectively. (v) post-storm variation of F_2-layer maximum electron density comprised of enhancement by varying degrees at different stations above quiet-day variation at Kokubunji and Okinawa stations but below quiet-day variation at Wakkanai station.

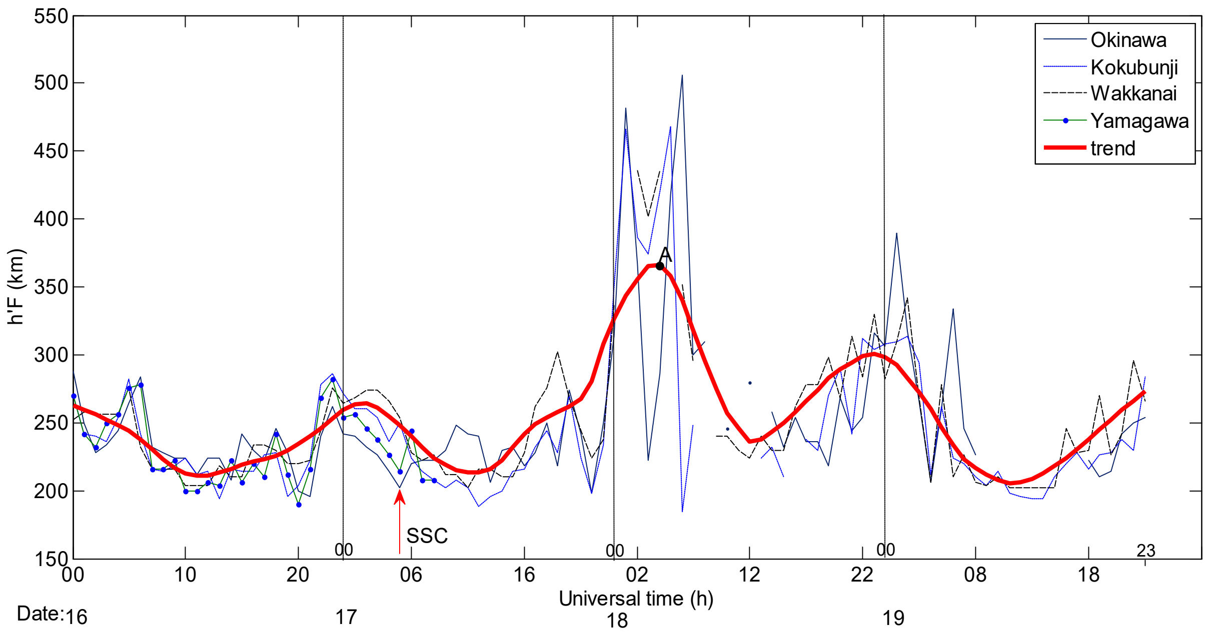

Fig.4: Plots of diurnal variation of the F-region virtual height. The red solid line shows the trend.

Diurnal variation of F-region virtual height (Fig.4) revealed an apparent periodic structure in which the height is raised during nighttime and lowered during daytime. It was observed that variability ranged between F_1 and F_2 regions only. The least height observed was 184 km at Kokubunji station at 06:00 UT of 18 March 2015. There appears to be no significant response to the variation of F-region heights in terms of uplift before the commencement of the geomagnetic disturbance. However, the main phase witnessed a significant uplift. The twelve-hour smooth data demonstrates the trend. Maximum virtual height ranged between 482 to 506 km in the night of 17 and morning of 18 March and 330 to 390 km in the night of 18 and morning 19 March, with an average maximum virtual height of 366.4 km at 04:00 UT on the 18 of March (marked A in Fig.4).

Ionospheric storms are observed to manifest complicated spatio-temporal behavior. The contentious aspects of ionospheric storm are those that have to do with its onset time which is often less distinct than that of the geomagnetic storm usually and clearly signaled by the storm's sudden commencement (SSC). There is also the need to separate quiet-time from storm-time variation. The phenomenon of pre-storm enhancement preceding SSC is even more contentious. From the analyses carried out in this study, it was found that, for the geomagnetic storm of March 17-18, 2015, the positive normalized deviation of f_oF_2 (δf_oF_2) from the reference values did not display a distinctive and consistent pattern sufficient to identify sudden ionospheric storm commencement. But, it could be adduced that the main phase of the geomagnetic storm was accompanied by a positive ionospheric storm typified by more than 70% positive normalized deviation of f_oF_2 from the quiet-time reference values with the time of maximum absolute deviation showing some degree of spatio-temporal variability. The recovery phase was associated with a negative ionospheric storm typified by more than 56% negative normalized deviation of f_oF_2 from the reference values.

In respect of ionospheric electron density, the main phase of the geomagnetic storm was accompanied by a positive phase of ionospheric storm represented by more than 70% enhancement of N_mF_2 above quiet-time variation. The recovery phase was accompanied by a negative ionospheric storm typified by depletion of N_mF_2 by more than 63% below the quiet-time variation. The significance of these observations could be seen in their very close agreement with those obtained at different locations for the same event but using different techniques and parameters. For instance, Zhang *et al.* (2018) obtained similar results using a dual frequency global positioning system (GPS) to estimate the vertical total electron content (VTEC), although with different local and universal time dependence. Also, results of multi-instrumental and multi-sectorial analysis of the same event performed by Astafyeva *et al*. (2015) revealed a global perspective of these observations. Jiang *et al*. (2017), using a combination of direct satellite and ground-based ionosonde observation also reported similar results but, in addition, their results revealed the occurrence of daytime spread F phenomenon, which was, most likely, part of the reason for the scanty data in respect of some ionospheric parameters such as $h'F_2$ at the stations under study. However, none of the corroborative results mentioned above and many other papers that reported on the geomagnetic storm as in this study focused on pre-storm phenomena to investigate their predictive features. Concerning the classification of pre-storm phenomenon (Mikahilov and Perrone 2009), Chukwuma (2010) observed that any pre-storm auroral activity should relate to the following geomagnetic storm. Our investigation shows significant pre-storm enhancement of at least 24 hours to SSC, as the commencement of the enhancement was at 05:00 UT on 16 March, 2015 ahead of SSC at 05:00 UT on 17 March 2015. Also, to isolate quiet-time from disturbed-time variation, it could be seen that the enhancement of F_2-layer maximum electron density on the pre-storm day (16 March 2015) was above quiet-day maximum by 50.4 % at Wakkani and Kokubunji stations, 121.4% at Okinawa and 80.4% at Yamagawa stations respectively. The main phase of the geomagnetic storm's disturbed-time maximum enhancement of F_2-layer maximum electron density above quiet-day maximum was 68.4% at Wakkanai, 107.5% at Kokubunji and 49.7% at Okinanwa stations respectively. The depletion of F_2-layer maximum electron density below quiet-day maximum during afternoon bite-out at 13:00 UT of March 18 in the recovery phase of the geomagnetic storm were 78.4% at Wakkanai, 63.1% at Kokubunji and 50.0% at Okinawa stations respectively.

Furthermore, the observation that post-storm variation of F_2-layer maximum electron density comprised of enhancement by varying degrees at different stations above quiet-day variation at the respective stations (on 19 March) appears to lend credence to Mikahilov and Perrone (2009)'s description of moderate auroral activity arising from a previous geomagnetic storm as our investigation also reveals that the storm indicators such as D_{st} and AE did not recover to pre-storm values. This is certainly different from the scenario on 16 March, which by all measures, was relatively geomagnetically quiet. It must be noted that 16 March 2015 was not listed as an international geomagnetically disturbed day of the month compared to 19 March (refer to Table 2). The point of emphasis here is that 16 March 2015 was not a day of any degree of auroral activity and as such the observed enhancement of N_mF_2 or any other convenient indicator such as VTEC on this day is predictive of the ensuing geomagnetic storm of March 2015. Similar observations on the same geomagnetic storm made at different latitudes using N_mF_2, VTEC or both reviewed by Danilov and Konstantinova (2019) tend to agree with our results.

On the variation of the virtual height of the F-region (h'F) during the period under study, the apparent increase in height observed during nighttime is probably due to the disappearance of the F_1-region and persistence of the F_2-region. This can be explained by the fact that when F_2-region moves downward during the night, recombination is enhanced in the lower part of the F-region thereby exposing a more strongly ionized upper part of it. However, the observation of elevation to the range between 400 km and 500 km or more during the main phase of the storm is evident of the response of the ionosphere to the magnetic storm. The coincidence of this uplift with the impulsive rise in the values of $\delta(f_oF_2)$, which implies a positive phase of the ionospheric storm, is consistent with the widely accepted view that a positive ionospheric storm arises from upward transport of ionization (Prölss, 2006). The basic theory is that the loss rate is proportional to the densities of molecular nitrogen and oxygen. When the F-region moves upward, the loss rate due to recombination decreases much faster than the production rate which is proportional to the density of atomic oxygen. Thus, the uplift of the F-region leads to an overall increase in ionization density (Prölss, 2004). A comparison of the diurnal variation of the F-region virtual height with the zonal electric field appears to reveal a causal link between them as both exhibit the same pattern of variability after SSC, but with virtual height variation lagging by about six to eight hours. It is proposed that the $\mathbf{E} \times \mathbf{B}$ drift of ionospheric plasma may be responsible for the observed elevation of the F-region virtual height during the magnetic storm.

5. 0 Conclusion

This study focused on the response of the ionosphere to the magnetic storm of March 17-18, 2015. Results reveal a cyclic diurnal variability of maximum electron density of the F_2-region whereby pre-enhancement occurred about a day ahead of the storm's sudden commencement. It also reveals that the main phase was accompanied by a positive ionospheric storm while the recovery phase was accompanied by a negative ionospheric storm. A sudden elevation of the F-region virtual height was observed during the main phase and is possibly attributable to the upward drift of ionospheric plasma. It could be inferred that though quiet-time and disturbed time F_2-region maximum electron density followed a cyclic pattern, disturbed-time variation exhibited significant pre-storm enhancement.

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Conflict of Interest

The authors declared no conflict of interest