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Impact of geomagnetic variation over sub-auroral ionospheric region during high solar activity year 2014

Arun Kumar Singh [a,b,*], Shailendra Saini [c], Rupesh M. Das [a,b]

[a] CSIR-National Physical Laboratory, Dr. K. S. Krishnan Marg, New Delhi 110012, India
[b] Academy of Scientific and Innovative Research (AcSIR), CSIR-HRDC Campus, Postal Staff College Area, Sector 19, Kamla Nehru Nagar, Ghaziabad, Uttar Pradesh 201002, India
[c] National Centre for Polar and Ocean Research, HeadlandSada, Vasco-da-Gama, Goa 403804, India

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Abstract

The present work is an attempt to evaluate the impact of changing space weather condition over sub-auroral ionosphere during high solar activity year 2014. In view of this, the GPS based TEC along with Ionosonde data over Indian permanent scientific base "Maitri", Antarctica (70°46′00″S, 11°43′56″E) has been utilized. The results suggested that the nature of ionospheric responses to the geomagnetic disturbances not only depended upon the status of high latitudinal electro-dynamic processes but also influenced by the seasonal variations. The results revel both negative and positive type of ionospheric response in a single year but during different seasons. The study suggested that the combination of equator-ward plasma transportation along with ionospheric compositional changes causes a negative ionospheric impact especially during summer and equinox seasons. However, the combination of pole-ward contraction of the oval region along with particle precipitation may lead to exhibit positive ionospheric response during the winter season. The plasma transportation direction has been validated with the help of convection boundary (HM boundary) deduced with the help of SuperDARN observations. The ground based ionosonde observations clearly provided the evidence of deep penetration of high energetic particles up to the E-layer heights which results a sudden and strong appearance of E-layer. The strengthening of E-layer is responsible for modification of auroral electrojet and field-aligned current system. Also, the sudden appearance of E-layer along with a decrease in F-layer electron density suggested the dominance of NO^+ over O^+ in a considered region under geomagnetic disturbed condition.

Keywords: Sub-auroral ionosphere; Space weather; Geomagnetic storms; Sub-storm

1. Introduction

The geographic locations designated as sub-auroral, auroral and polar cap regions are highly sensitive to the changing near space environmental conditions. However, the boundaries of above three regions are not fixed and changes according to the nature of events and electro-dynamic processes. The auroral region ionosphere is very well known for continuous and intense precipitation of energetic particles emanating from the Earth's plasma-sheet whereas the energetic particles can be stored and accelerated to very high energies (up toMeV) before eventual precipitation into the middle atmosphere of the sub-auroral ionosphere (Brum et al., 2006). However, due to open geomagnetic field lines, the polar cap region is directly connected to the interplanetary medium. The interaction of solar-wind and sun blown high energetic particles with high latitude ionosphere increases the ionospheric conductivities (Behera et al., 2015). The electric field mapping from the

* Corresponding author.
E-mail addresses: arsurya123@gmail.com (A.K. Singh), shailendra@ncaor.gov.in (S. Saini), rupesh@nplindia.org (R.M. Das).

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magnetosphere into the ionosphere along with magnetic field lines establishes the dawn-to-dusk field in the polar cap; the field-aligned currents connect the currents flowing in the magnetosphere and ionosphere, forming a three-dimensional current system (Olsen et al., 2016). When vertical component of interplanetary magnetic field (IMF) Bz is strongly negative (southward), magnetic reconnection between the IMF and the geomagnetic field produces open field lines which allow mass, energy, and momentum to be transferred from the solar wind to the Earth's magnetosphere, (as first suggested by Dungey, 1961) which results a decrease in H-component of Earth's geomagnetic field. This is responsible for the equator-ward expansion of auroral oval. The boundary of auroral oval can be estimated with of the quantitative change in Auroral Electrojet (AE-index) values. The AE provides a global, quantitative measure of auroral zone magnetic activity produced by enhanced Ionospheric currents flowing below and within the auroral oval. The AE is mainly driven by particle precipitation and field-aligned current system, therefore, any changes in near-earth space environment system will cause expansion of auroral oval both equator or poleward directions. Such expansion of auroral oval changes the regional characteristics of sub-auroral and polar cap dynamics and directly perturb the ionization distribution over the high latitude region. The high-mid latitude positive storm effect arises due to intensification and equator-ward expansion of sub-auroral electric fields (Foster, 1993; Heelis et al., 2009). However, (Prölss et al., 1991) proposed that the sudden and simultaneous enhancement in ITEC over the low and mid-latitude region is due to traveling atmospheric disturbances (TAD). These TADs (Prölss,1993) are originated from higher latitudes due to change in thermospheric compositions mainly because of upwelling of molecular rich air to the higher altitudes driven by enhanced joule heating (Mayr et al., 1978; Burns et al., 1991; Fuller-Rowell et al., 1994) resulted in the equator-ward neutral wind. The consequences are observed in terms of negative ionospheric responses at higher latitudes. On the other hand, (Shagimuratov et al., 2002) reported positive ionospheric responses at high latitudes caused due to the lifting of ionospheric plasma along with geomagnetic field lines to areas with lower ion-loss rates.

Inline of this, the present study is an attempt to describe the behavior of ITEC over the sub-auroral ionospheric region under quiet and disturbed conditions during high solar activity period and to define the correlation of temporal and diurnal variation of TEC with the H component of the magnetic field and the auroral electrojet index (AE).

2. Data analysis

To study the sub-auroral ionospheric behavior to the changing space weather condition, the ITEC data acquired with the help of Novatel make GPS receiver installed at Indian Research Base "Maitri", Antarctica (70°46′00″S, 11°43′56″E) has been utilized. The said receiver is an automated system which is capable to estimate Slant Total Electron Content (STEC) at the resolution of 1 sec. along with other parameters like amplitude and phase scintillation. The STEC is then converted into Vertical TEC (VTEC) with help of indigenously developed algorithm in C++ programming language. The algorithm is capable to estimate the Ø-angle (angle between satellite ray-path and normal) at Ionospheric Pierce Point (IPP). This provided the obliquity factor which is utilized in Eq. (1) to convert STEC into VTEC.

$$VTEC = STEC \times OF \tag{1}$$

where OF is obliquity factor.

The estimated VTEC is then segregated as per the background geomagnetic conditions as depicted in world data center, Kyoto for the representative months of summer (January), winter (June) and Equinox (October). Further, the observation of bottom side ionospheric parameters with the help of Canadian Made Digital Ionosonde (CADI) has been utilized to investigate the lower altitudinal ionospheric responses to the considered events. The said Ionosonde has been operated at the same location and set to acquire ionospheric values at the interval of every 10 min. The direction of plasma transportation over the considered location has been validated with the help of status of convection boundary which is also known to be as HM (Heppner-Maynard) boundary. The said HM boundary has been estimated from the SuperDARN (Super Dual Auroral Radar Network) database (http://vt.superdarn.org/tiki-index.php?page=Conv+map+overview). However, to estimate the background geophysical conditions, the proxies like AE index and IMF-BZ have been obtained from Kyoto world Data Centre and OmniWeb (https://omniweb.gsfc.nasa.gov/form/dx1.html) website, respectively, while the local H component of Earth's geomagnetic field has been obtained from the Indian Institute of Geomagnetic, Mumbai, India. Apart from this the O/N_2 figures have been obtained from the website of Community Coordinated Modeling Center (CCMC) (https://ccmc.gsfc.nasa.gov/models/modelinfo.php?model=CTIPe).

3. Results

The 1 min ITEC data derived from GPS receiver along with the bottom side ionospheric parameters derived with the help of Ionosonde have been utilized to study the behavior of sub-auroral (i.e. over Maitri) ionosphere during different seasons under the adverse geomagnetic conditions for the high solar activity period. The considered region is unique and highly unstable in nature due to various types of electro-dynamic processes. The region is unique because of 24 h sunlight exposure during the month of December and January (Called as summer) and 24 h of darkness during the month of May and June (winter). However, the months of February, March, September, and October provided a variable day light and dark night hours. Hence, a long time series ionospheric data during day-light, dark-night and the normal diurnal pattern has been available to study the seasonal response of sub-auroral ionosphere under different disturbed geophysical conditions.

3.1. Sub-auroral ionospheric response to the perturbed geomagnetic field during summer season

A geomagnetic perturbation has been observed during January 2, 2014, with a maximum negative excursion of ~ -349.2 nT in H-component of earth geomagnetic field recorded at sub-auroral station Maitri, Antarctica at around 0400 UT (shown in the 2nd panel from the top of Fig. 1). The other three panels of Fig. 1 show IMF Bz, AE-index and TEC values of considered event day along with the monthly median values. It can be seen from Fig. 1 that the H-component of earth magnetic field (H-field) is well responded to the southward turning of IMF Bz. The H-field starts decreasing along with the IMZ Bz and takes four hours to reach at its minimum level followed by quick recovery to attend its normal value within an hour. The depression in H-field and high energetic particle precipitation modifies the different electrodynamic processes over the high latitude region. The modification of electro-dynamic processes has been reflected in observed AE index, which shows enhancement and the time are coinciding with H-field depression hours. Also, the time of AE maxima (708 nT) has been well coinciding with the time of H-field minima. The depression of H-field along with enhancement of auroral electrojet has been manifested due to injection of high energy particle up to the lower ionospheric altitudes i.e at E-region heights. The sudden and strong appearance of E-layer (Fig. 2 shows the observed ionograms) provided evidence of particle precipitation up to lower ionospheric heights. The sudden increase in E-layer electron density is further responsible for strengthening of auroral electrojet hence consequences appeared as an increase in $E \times B$ drift. The enhancement of E-layer layer electron density accompanied by the upwelling and decrease in F-layer electron density is evident of such effect. The uplifting of ions along with the equator-ward expansion of auroral oval causes overall depletion in electron density at higher latitudes as it can be seen in the bottom panel of Fig. 1. The bottom panel of the figure shows negative ionospheric effect with a significant decrease in TEC with respect to the reference monthly median values. The direction of auroral oval movement can be explained with the help of HM boundary derived from SuperDARN observations. It can be seen from Fig. 3 that the observed TEC has been well responded to IMF-Bz. The result shows that the increase in TEC values coincides with the northward turning of IMF-Bz. However, decrease in TEC values has been associated with the southward turning IMF-Bz. The increase and decrease of TEC values are well correlated respectively with contraction and expansion of auroral oval region. This can be with the HM boundary derived from SuperDARN observations. The effect is well explained by Milan et al. (2009)

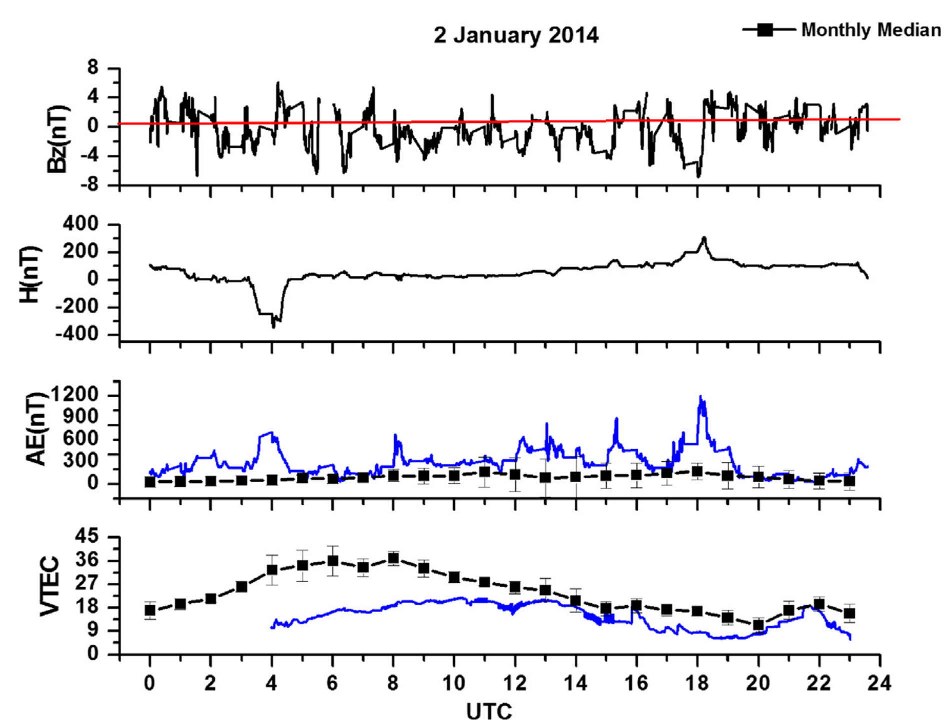

Fig. 1. The top panel shows the variation of IMF Bz on January 02, 2014. The bottom three panels show the variation of AE-index, H-component of earth magnetic field and ionospheric TEC during January 02, 2014 along with monthly median value as a reference.

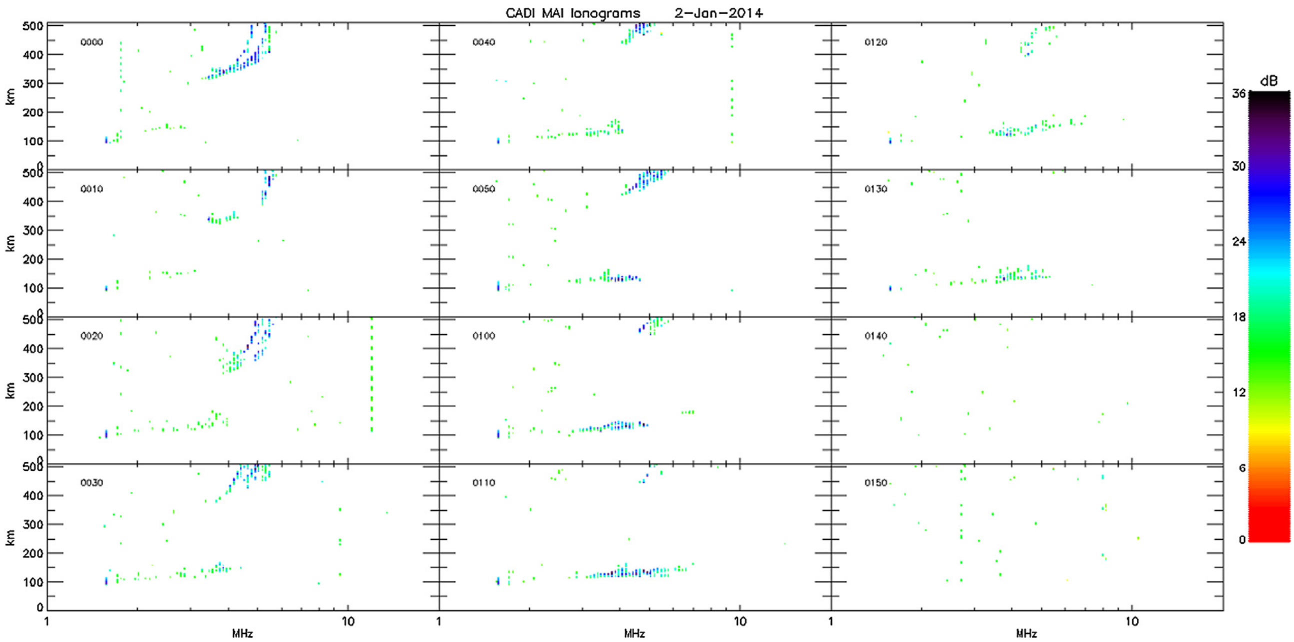

Fig. 2. The 10-min interval ionograms of January 02, 2014 observed between 0:00 and 1:50 UT. The ionograms clearly show the strong appearance of E-layer with the uplifting of F-layer base height.

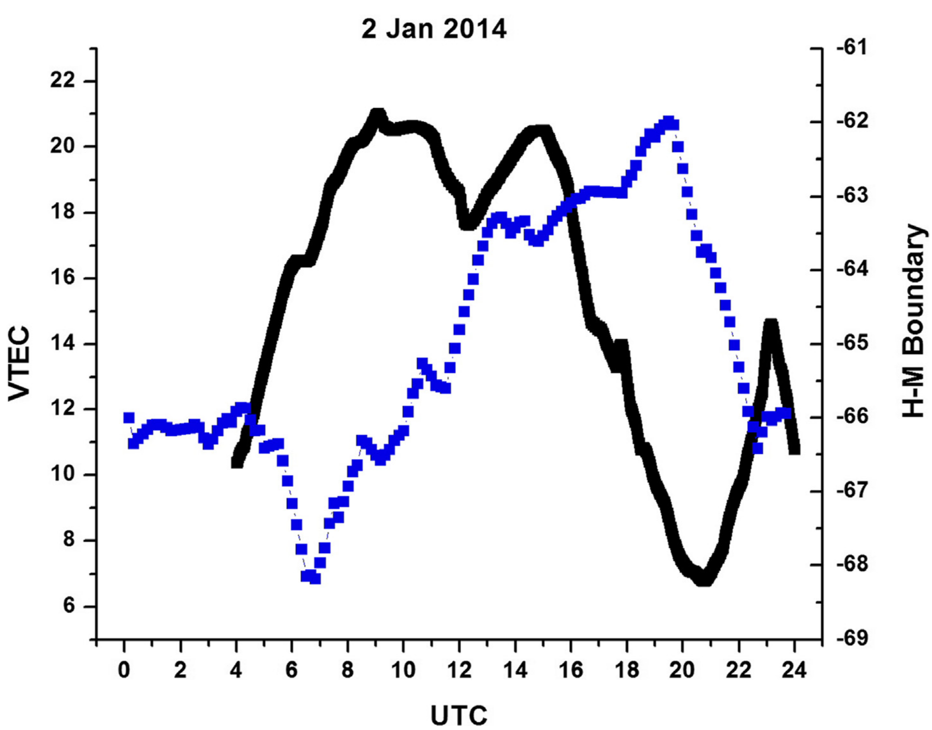

Fig. 3. The line + symbol plot of hourly VTEC variation (Black) and HM boundary variation (Blue) on January 02, 2014. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and suggested that the association of IMF-Bz with size of polar cap region is very complex. He also reported that the strong southward IMF condition is necessary for the polar cap to expand, hence simultaneously the auroral oval moves to lower latitudes.

3.2. Sub-auroral ionospheric response to the perturbed geomagnetic field during equinox season

Similar to the case 1, a case study for sub-auroral ionospheric response to the geomagnetic perturbation during equinox season (October 2014) of high solar activity period has been investigated by using GPS derived TEC and ionosonde based bottom side ionospheric parameters. The analysis shows depression of −409.54 nT in H component of Earth's magnetic field on October 18, 2014, at around 0400 UT. The said depression well coincides with the south-ward turning of IMF Bz (as shown in 1st Panel of Fig. 4). The AE-index also responded to the southward turning of IMF-Bz and shows significant enhancement during the depression period of H-field (as shown in 3rd panel of Fig. 4). Hence attribute to similar ionospheric response as explained for case 1. The Ionosonde observation (shown in ionograms in Fig. 5) confirms the deep penetration of energetic particle which results in enhanced E-layer electron density along with lifted F-layer. Further, the F-layer ionization starts drifting equator-ward due to the expansion of auroral oval and shows a negative ionospheric response to the geomagnetic perturbation. The depleted TEC with reference to monthly median (as shown in bottom panel of Fig. 4) confirms such ionization transportation from higher latitude to low-mid latitude regions. These transportation phenomena could be well explained by the HM boundary expansion and contraction of the oval. Fig. 6 shows that during October 18, 2014, the TEC follow the trend of IMF-Bz northward and southward alignment. As IMF-Bz turns northward (shown in the first panel from the top of Fig. 4), the boundary of auroral oval started moving towards pole from 600UT to 1200UT. After 1300UT when IMF-Bz turns into southward direction, the boundary of auroral oval shifts towards the equator and Total electron content started decreasing from 1400UT to 2000UT.

3.3. Sub-auroral ionospheric responses to the perturbed geomagnetic field during winter season

To study the seasonal ionospheric effects in response to the geomagnetic variations, the GPS derived TEC and Ionosonde derived bottom side ionospheric data for the month of June have been analyzed. The analyses reveal a major geomagnetic disturbance on June 08, 2014 with diminution of −972.57 nT in H-component of Earth's magnetic field at around 0400 UT (shown in 2nd panel of Fig. 7). As explained in the earlier two cases, the process shows similar trend i.e. the H-field diminution started with the time of southward turning of IMF Bz and continue till orientation reached to the maximum positive value. The impact has also been seen in terms of modification in auroral electrojet system with the maximum positive departure of 1780 nT. The duration and time of enhanced AE-index exactly matched with H-field diminution period. The ionograms show the strong occurrence of E-layer with no trace of F-layer up to 500 km which means that the F-layer is lifted to the higher altitude and shows enhanced ionization in term of increased TEC at sub-auroral region (as shown in Figs. 8a and 8b). The positive response of sub-auroral ionosphere is something different as compared to the other two cases. This anomalous behavior reveals that the ionization over the considered region has not been transported towards the low-mid latitude region but restricted at high-mid latitude region due to poleward movement of the oval region along with the change in neutral ion composition. Fig. 9 shows that during June 8, 2014, the TEC value is low for southward orientation of IMF-Bz between 0000UT and 0500UT (shown in the first panel from the top

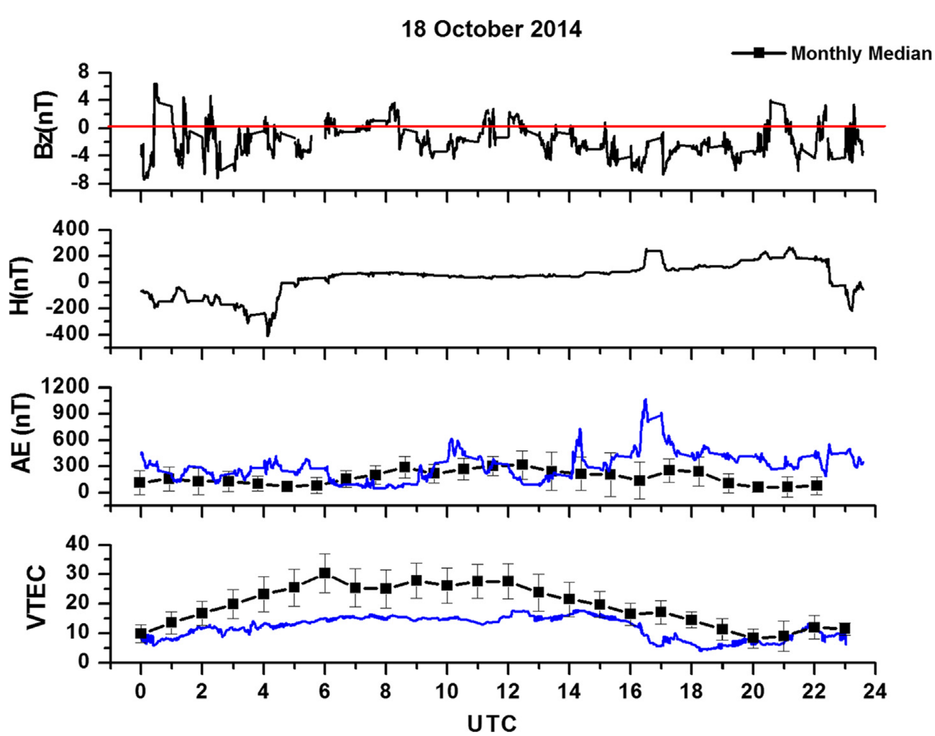

Fig. 4. Same as Fig. 1 but for October 18, 2014.

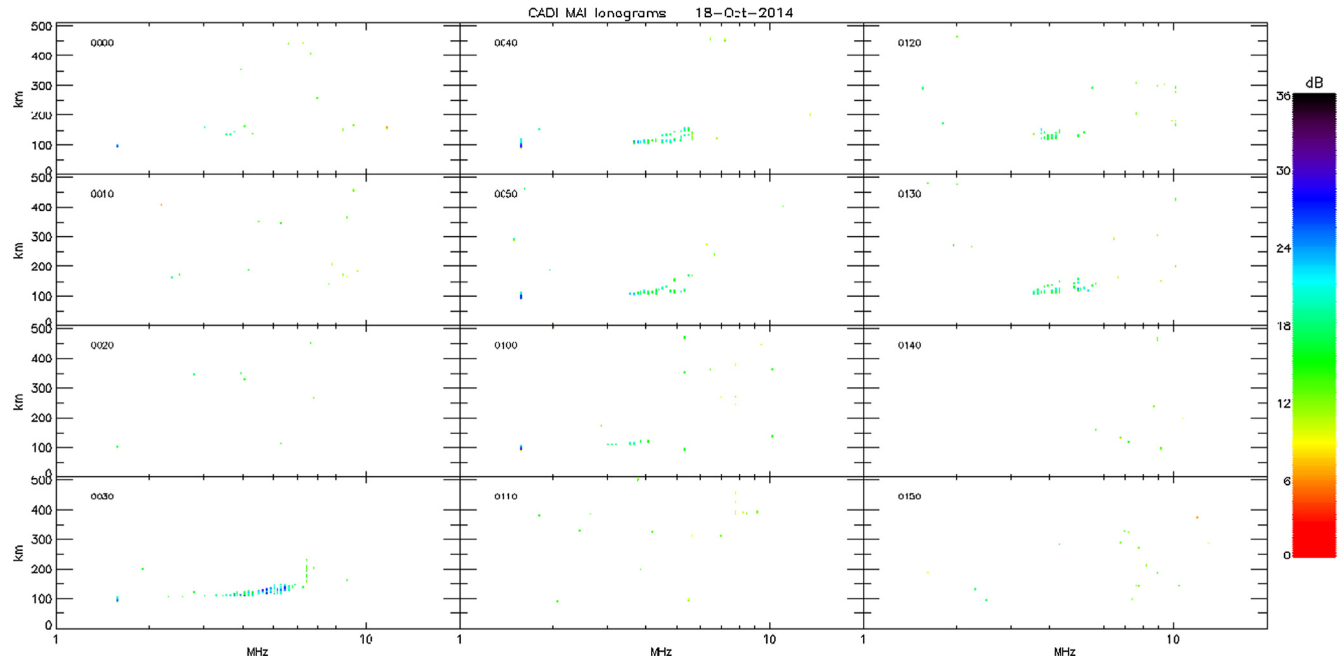

Fig. 5. Same as Fig. 2 but for October 18, 2014.

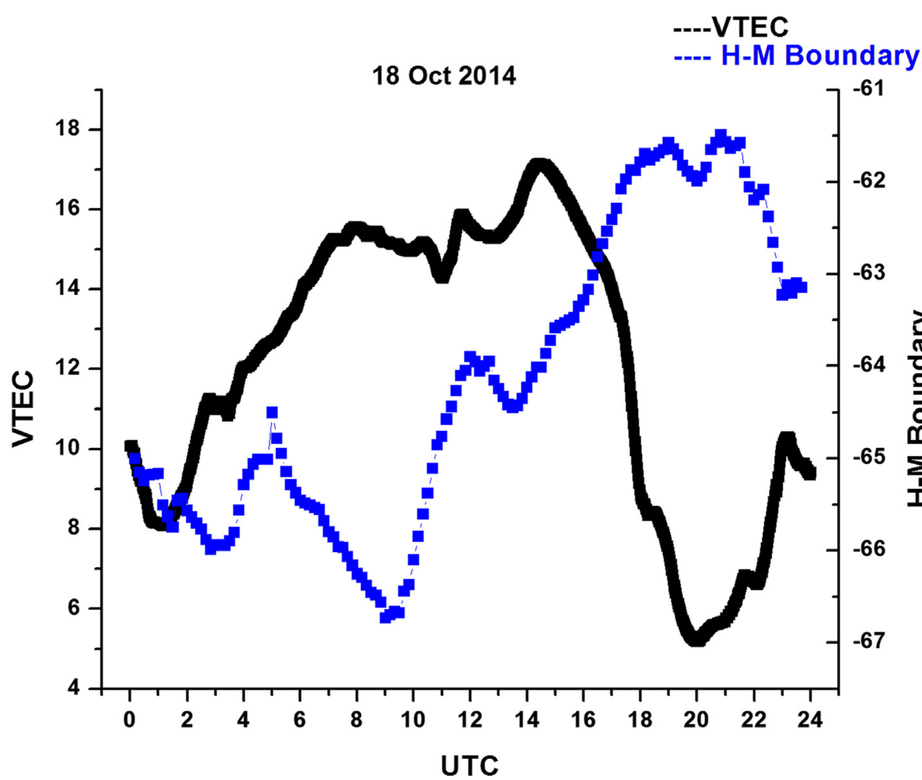

Fig. 6. Same as Fig. 3 but for October 18, 2014.

of Fig. 7) and boundary movement is towards the equator. But at 0600UT there was a rapid change in the direction of IMF-Bz from southward to northward. The sudden change of IMF-Bz orientation from southward to northward is responsible for the pole-ward movement of the convection boundary (HM boundary) along with increase of TEC value at 600UT. The results very much agreed with the work reported by Lee et al. (2010) in which they explained that strong northward orientation IMF Bz has been responsible for reduction of polar cap size due to pole-ward movement of pole-ward boundary of the night-side oval.

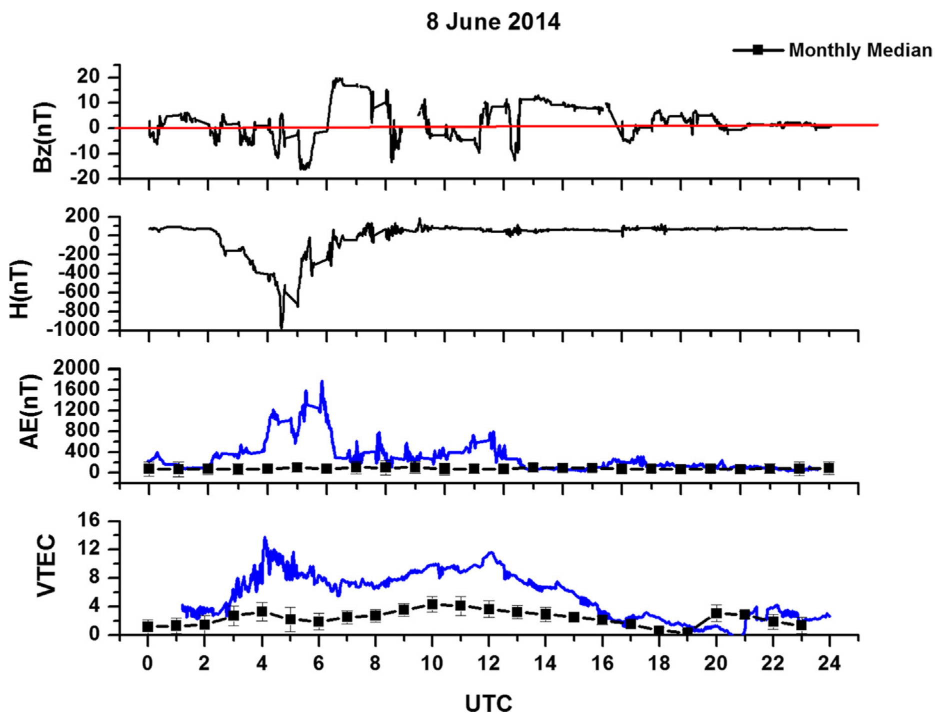

Fig. 7. Same as Fig. 1 but for June 08, 2014.

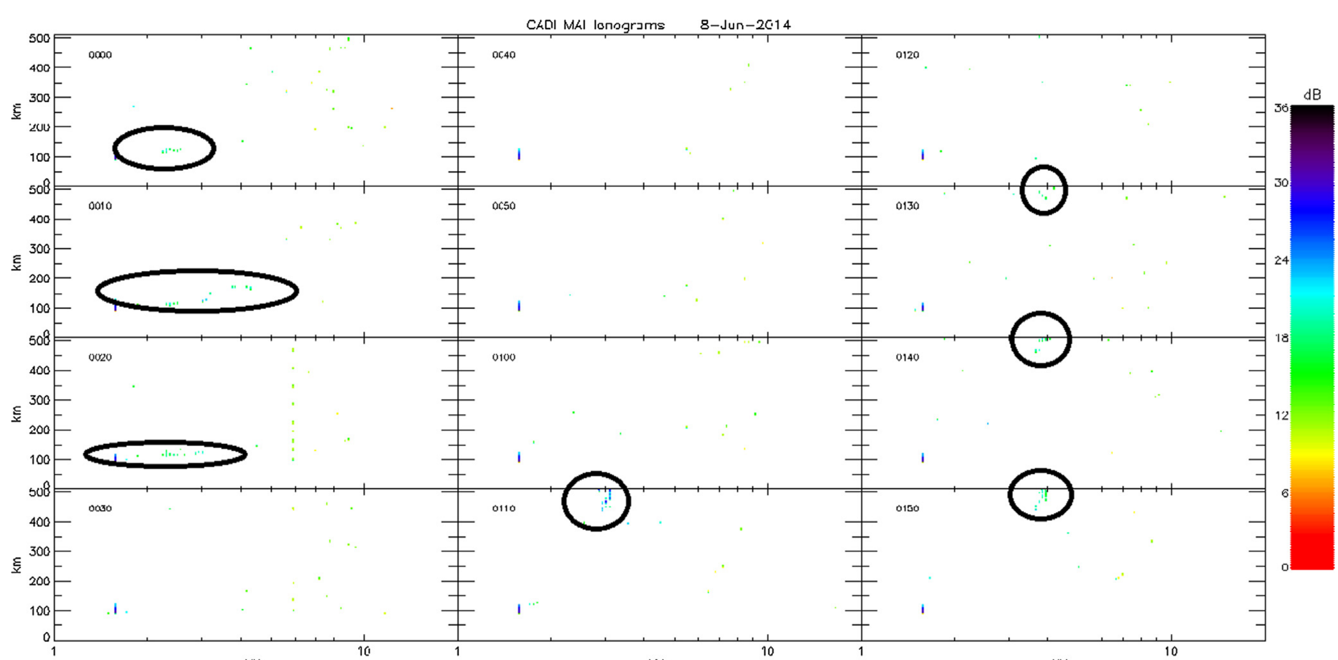

Fig. 8a. Same as Fig. 2 but for June 08, 2014.

4. Discussion

The study reveals various features of high-latitudinal ionospheric responses to the geomagnetic disturbances. It is noted from the results that the nature of ionospheric responses changes with the season. The summer and equinoctial negative ionospheric response to the geomagnetic disturbances are mainly due to the combined effect of compositional changes and equator-ward displacement of the trough region. On the other hand, winter positive ionospheric response is caused by the combined effect of composition changes and pole-ward contraction of auroral oval region. Basically, the present work also deals with the different types of geomagnetic disturbances and its impact on sub-auroral ionospheric region but the categorization of geomagnetic storms is still very controversial. Baker

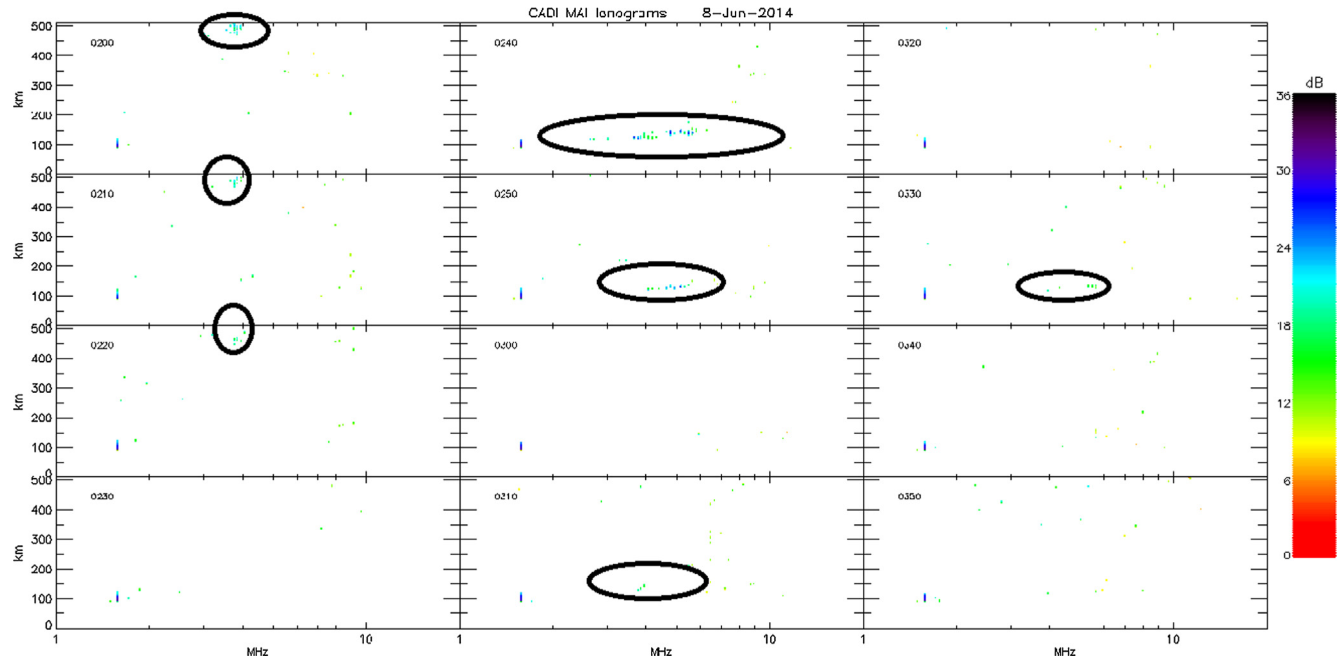

Fig. 8b. Same as Fig. 2 but for June 08, 2014 and observed between 2:00 and 3:50 UT.

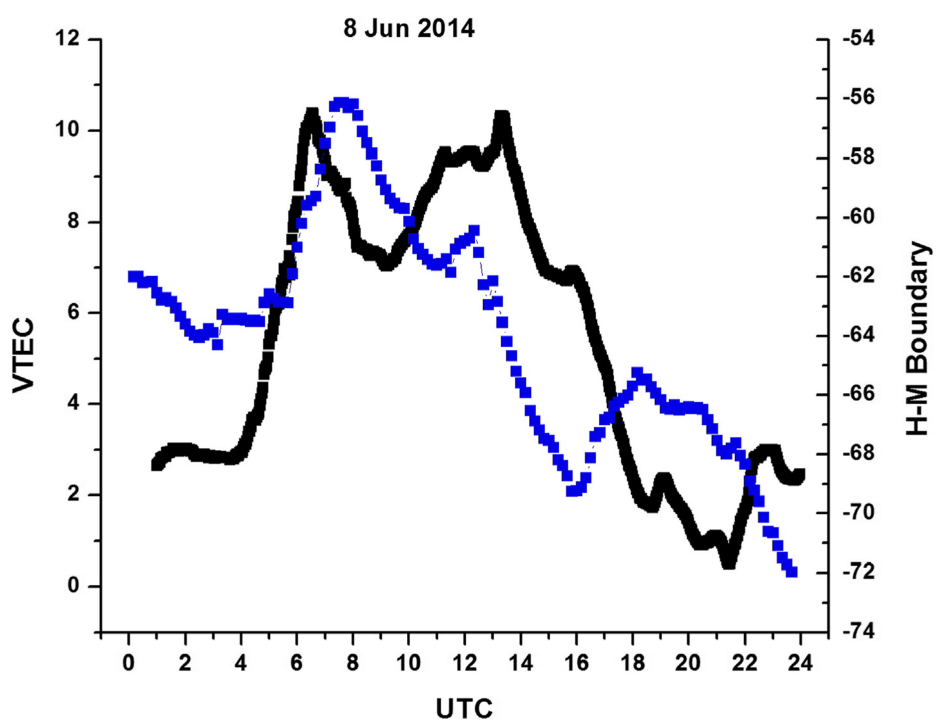

Fig. 9. Same as Fig. 3 but for June 08, 2014.

et al. (1996) and Sergeev et al. (1996) suggested that the unstable nature of IMF-Bz i.e. continuous north-south orientation of the IMF-Bz causes episodic energy loading–dissipation cycles termed as magnetospheric sub-storms. In the present study, such unstable nature of IMF-Bz has been observed for two cases i.e. during summer (January 2, 2014) and Equinox (October 18, 2014) as it can be seen in the top panel of the Figs. 1 and 4. Actually, the initial southward turning of IMF-Bz causing injection of solar wind energy into Earth's magnetosphere through dayside magnetic reconnection and it led to the storage of a large amount of energy in the magnetotail (Hones and Schindler, 1979). This followed by expansion phase of the sub-storm leads to sudden conversion of the magnetic energy into particle acceleration in the central plasma sheet due to the formation of so-called X-type neutral point forms within the plasma-sheet by the thinning of near earth tail plasma-sheet. The flows are toward the earth and on the earthward side and are responsible for the rapid release of stored energy. This further is responsible for the enhancement in particle precipitation at higher latitudes and deep at ionospheric lower altitudes i.e. up to E-layer. In the present work, the deep particle precipitation impact is clearly visible in terms of abrupt enhancement in E-layer electron density. Figs. 2 and 5 show the enhanced and sudden appearance of E-layer for the duration of 40 to 45 min. in the observed ionogram over Maitri, Antarctica. This is further responsible for the enhancement in auroral electrojet strength and field-aligned current system along with electron/ion temperature. The ionograms showed in Figs. 2 and 5 also evident of increased ionization at around E-layer with a simultaneous decrease at higher altitudes (F-region) with upward lifting. This might be due to change in O^+ and NO^+ composition by conversion of O^+ into NO^+ due to the elevated ion temperature and the lowering of O^+ peak height. The ratio of atomic oxygen concentration [O] and molecular nitrogen concentration [N2] decreases, when geomagnetic activity enhanced. The reason of O/N_2 decrement (shown in Fig. 10) is [O] recombination becoming faster with height than production rate. At the peak height, the electron density decreases and a negative ionosphereic storm occurs at the region. The whole process is driven by storm induced modifications to thermospheric circulation, thermodynamic modulation, collision coupling, and dynamic drag that make the thermosphere higher in molecular concentration [N2] and lower in atomic concentration [O]. On 2 January 2014 after the trigger of storm at 0200UT, O/N_2 ratio starts decreasing at the sub-auroral region and it starts increasing towards mid latitude region, same behavior is shown by the VTEC at the observatory station, which is shown in Fig. 10 and Fig. 1, respectively. This directly indicated the negative ionospheric effect of geomagnetic storm at the observatory station is due to the decrease in O/N_2 ratio. The negative storms are primarily explained by the decrease of the neutral density ratio O/N_2 leading to an ion loss rate enhancement (Prölss, 1995). On the other hand, enhancement in auroral electrojet is responsible for the equator-ward expansion of the oval hence the lifted F-layer ionization drifted towards low-mid latitude region along with magnetic field lines. Therefore, the combination of equator-ward plasma transportation along with ionospheric compositional changes causes a negative ionospheric impact during summer and equinox over the sub-auroral latitudes as it can be seen in Figs. 1 and 4.

However, the third case observed during winter season shows positive ionospheric effect. The considered event has been observed on June 08, 2017 with a short duration initial negative IMF-Bz followed by an abrupt change in the orientation from southward to northward (see Fig. 7). The sudden orientation change in IMF-Bz from southward to northward leads to the modulation convection pattern from anti-sunward to sunward (Ruohoniemi and Greenwald, 1998). Hence responsible for pole-ward contraction of the oval region as described by Kamide et al. (1974) that the auroral oval contracted in association with the north-ward direction of IMZ–Bz on June 08, 2014. On the other hand, enhancement in E-layer electron density with the uplifting of F-layer observed from ionograms suggested the significant particle precipitation deep of the ionospheric lower altitude as explained for other two cases. During the winter time there is very less EUV available to ionize O so maximum production of O^+ is because of high energetic particle precipitation. On 8 June 2014 after the trigger of storm at 0200UT, the O^+ concentration starts increasing coinciding with decrease in N_2 concentration which results enhancement of O/N_2 ratio. This may cause enhancement in VTEC over the considered region, but

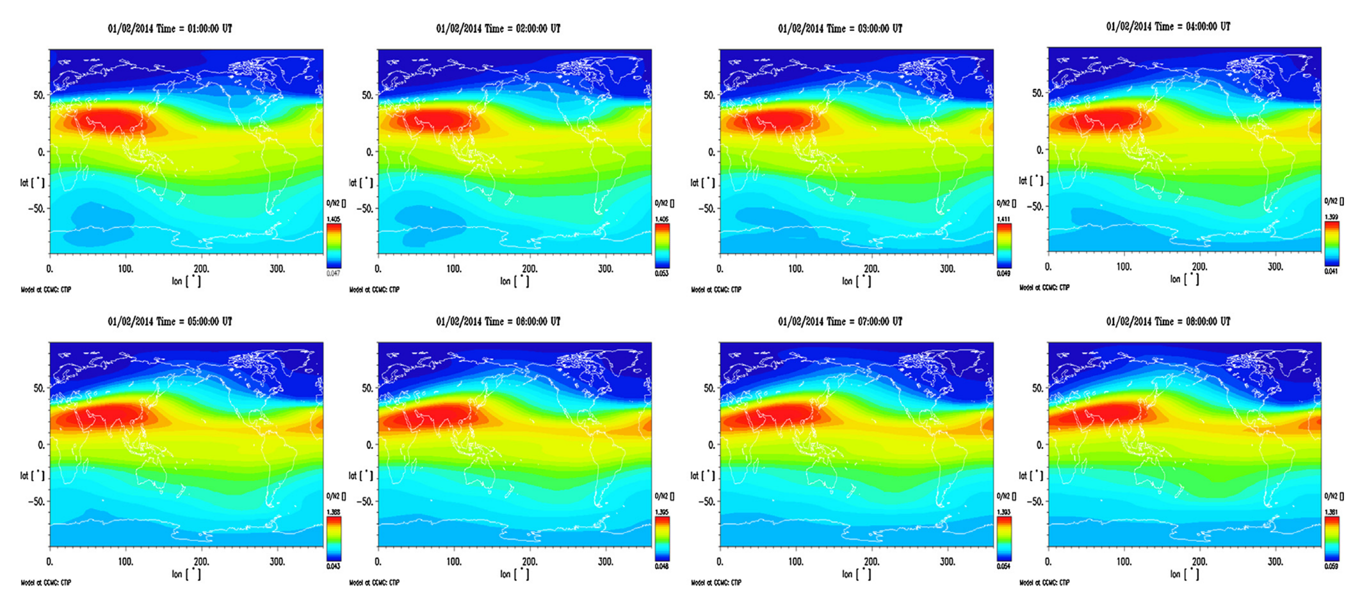

Fig. 10. The graphs show hourly global O/N_2 variation from 0100UT to 0800UT on January 02, 2014.

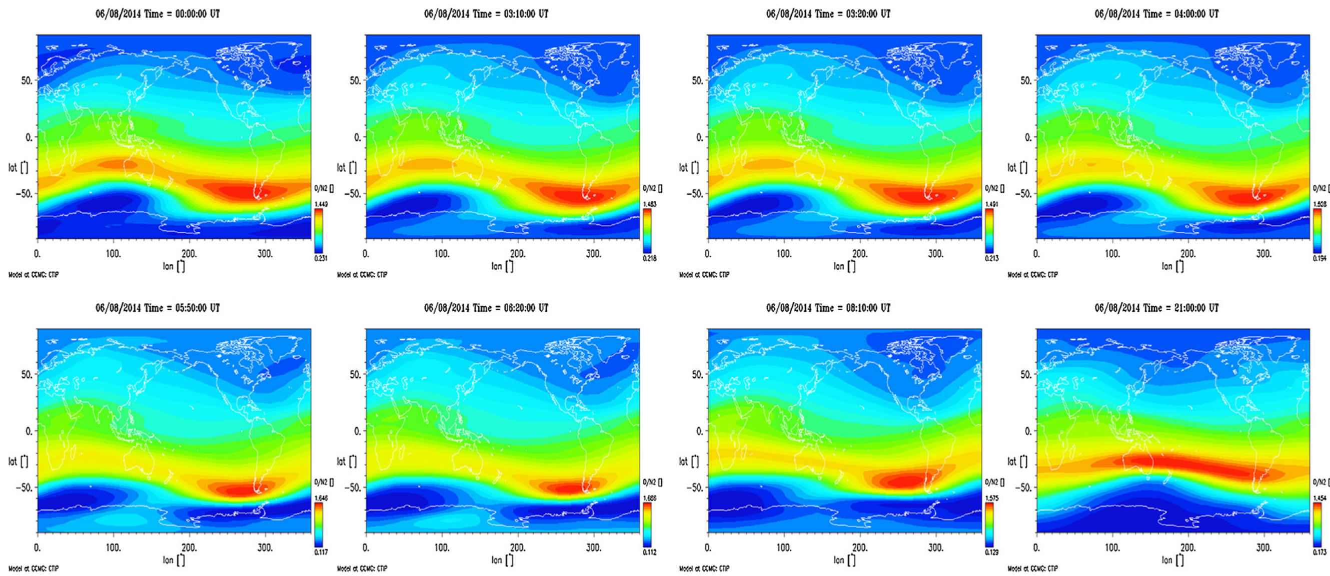

Fig. 11. The graph shows global O/N_2 variation from 00UT to 2100UT at different time intervals on June 08, 2014.

after the 1600UT, O/N_2 ratio is being decreased at the sub-auroral region (at 2100UT shown in Fig. 11) and the same pattern is observed for VTEC, as shown in Fig. 11 and Fig. 3, respectively. It shows that ITEC value is very much dependent on the O/N_2 ratio for any region. The phenomenon is well explained by Burns et al. (1995). The reported work explained that the changes in the O/N_2 ratio occur both because the O densities are enhanced by as much as 50–60% and because N_2 densities are depleted by as much as 30 to 35% on constant height surfaces. The depletion of the N_2 densities causes reduced electron loss rates and can contribute to the enhanced electron densities that have been observed in the part of the winter hemisphere. Also Cader (2018) has reported a positive phase, expressed as a sudden increase in F region electron density beyond climatologically forecast levels for the season and time of day in question, is thought to be caused by a rapid increase in ionization density, particularly pronounced in the local noon and/or afternoon period, a rapid deceleration of both the recombination and downward diffusion of plasma processes, a decrease in N_2/O. Therefore, in the 3rd case, the combination of pole-ward contraction of the oval region along with particle precipitation may lead to exhibition of positive ionospheric response to geomagnetic disturbance observed during winter month of 2014.

The latitudinal expansion and contraction of auroral oval affect the total electron content value over the observation station as discussed above. In the present work, HM boundary data were used in line with the work of Imber et al (2013) reported that during intervals where there are no auroral images available, the HM Boundary latitude and motion could be used as a proxy for that of the auroral oval, and therefore provides information about motions of the open/closed field line boundary. As discussed above that the direction of auroral oval movement changes with the IMF-Bz alignment, the same was also reported by Frey et al. (2004) with the help of HM boundary data. They studied the 276 sub-storms by the superposed epoch analysis using the IMAGE auroral data and showed that the HM boundary moves equatorward in the growth phase of the sub-storm while pole-ward in the recovery phase, as does the auroral oval latitude. So in the results of this paper also the auroral oval latitudinal movement is explained by the HM boundary movement. During the equatorward movement (Negative Bz) of HM boundary, total electron content decreased at the observatory station during summer and equinox seasons. While during the winter season it increased with the pole-ward movement (positive Bz) of HM boundary, same has been reported by the Horvath and Lovell (2015).They have reported that when IMF Bz is northward (from 0530UT to 0532 UT) HM boundary is 65° (pole-ward) the GPS TEC enhances at the polar cap region and when IMF turns to southward (from 0730UT to 0732UT) HM boundary is 50° (equator-ward) the GPS TEC decreases at polar cap and increases towards mid latitude region.

The above three considered cases show that the high latitudinal ionospheric responses are different for different seasonal and background geophysical conditions especially the orientation of IMF-Bz.

5. Conclusion

The space weather effect in the sub-auroral ionospheric region has been studied during three disturbed geomagnetic conditions, by using digital ionosonde and GPS TEC data observed from sub-auroral location namely Maitri, Antarctica. The observational location provides a unique opportunity to study the ionospheric response due to the equator and poleward movement of the auroral oval region and the auroral oval movement are validated with the help of proxy of auroral oval boundary (HM Boundary). The following conclusion has been made from the observed results.

(1) A negative ionospheric response to the geomagnetic disturbances during summer and equinox season might be caused by perturbations of the neutral gas composition and by the equator-ward displacement of the trough region.
(2) A positive ionospheric response during winter season might be caused by the auroral oval contracted in association with the north-ward direction of IMZ–Bz and E-layer electron density enhancement with the uplifting of F-layer.
(3) HM boundary could be used as a proxy for the auroral oval latitude because its movement very well explained the positive and negative effects on polar region ionosphere.
(4) The investigation reveals that O/N $_2$ ratio plays important role over the sub-auroral ionospheric region to decide the nature of effect i.e. negative or positive impact.

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