Study of Ionospheric TEC Variations and its synchronization with Solar Activity Indices, using GPS measurements during Solar Maxima and Minima Phases

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***Abstract*— The aperiodic fluctuations in the Solar Activities intensively affect ionospheric TEC (Total Electron Contents). These fluctuations are commonly studied with the help of Solar Activity Indices. For the present study, we have used three Solar Activity Indices [viz. Sunspot Number (Rz), Solar Extreme Ultraviolet Flux (EUV) and Coronal Mass Ejections (CME)]. These indices provide a wonderful opportunity to remotely observe the different Solar Phases. The aim of this study is to observe the relationship between the Solar Activity Indices and the Ionospheric TEC during Solar Maxima year 2012 and Solar Minima year 2017 at low latitude IGS station Pathum Wan, Thailand (Code-CUSV) at 13.74° N & 100.54° E. To perform this study, we have analyzed the diurnal variation of TEC during the solar Maxima and the Minima. We also analyzed the monthly as well as seasonal variation of the ionospheric TEC. We also investigated the relationship between Ionospheric TEC and solar activity indices.**

Keywords*— *Solar Minima, Solar Maxima, CME, EUV, Sunspot Number

I. INTRODUCTION

The Sun is the nearest star of the Earth, situated 149.6 million km away from our planet. Though, it is situated at such a great distance, but it has a deep impact on the organisms sustain at the planet and fulfills most of our energy requirements. Every second more than four million tons of the solar matter is converted into energy and produces neutrinos and radiations. The main component of the solar radiation is Solar Extreme Ultraviolet (EUV). The EUV covers the wavelength range of 10-120nm of the electromagnetic spectrum. It is an extremely energetic radiation. It heats up the upper atmosphere and creates the ionosphere. It is a partially ionized layer of the upper atmosphere of the Earth. It consists of electrically charged particle in sufficient amount that can affect propagation of electromagnetic waves. Apart from photo-ionization the other source of ionization is the collision of the energetic particles from the magnetosphere at the auroral latitude region. The EUV photons are completely absorbed by the upper atmosphere (almost above 80km) therefore; the EUV measurement is performed above the thermosphere by the skyrockets or the satellites. Because of the difficulties in measurement techniques, researchers use f10.7cm as a proxy for Solar EUV flux, as it bears a good correlation with the solar EUV Flux [1]. The solar radiation follows a periodic pattern that reoccurs in 11 years, this cycle is called Solar Cycle or Sunspot Cycle [2], [3].

The sunspots do not affect our lives directly, but they are the indicative of the presence of the Sun's magnetic field. This magnetic field induces Solar Flares, Coronal Mass Ejection and Solar Prominences. The magnetic energy of the Sun explodes that causes Solar Flares. The Solar Flares were first observed in 1859 by Carrington and Hodgson. They are the huge explosions on the surface of the Sun that occur, when energy stored in twisted magnetic field in sunspots, suddenly released. The Coronal Mass Ejection (CME) is an explosion of plasma from the corona of the Sun. It carries a billion of tons of coronal material and embedded magnetic field. CMEs were first observed in 1970 from the Skylab [4] and the spacecrafts observations. It is seen that during the solar maxima period, a higher number of sunspot occur, which produces a higher magnitude of magnetic energy. This high magnetic energy cause more flares and CMEs, consequently, a large number of flare and CMEs are observed during the solar maxima phases and vice versa. It is also seen that solar flare can occur without CMEs, but a CME is always accompanied by the solar flares. The frequency of appearing of CMEs' is correlated with sunspot number [5].

The Solar cycle is characterized by the increase and the decrease of sunspot numbers, also termed as Solar Maxima and Minima. They are two extremes of a solar cycle. The Solar Maxima is a period of high solar magnetic activities and Solar Minima is a period of low solar magnetic activities. It is seen that during solar maxima, large amount of sunspot exist all the time. They last for several weeks, whereas during the solar minima period, hardly any sunspot is found, if any appears it is short-lived. The Solar Maxima is the period of strong solar wind, high magnetic field strength and dark sunspot, which are indicative of increased emission of Solar Flares and Coronal Mass Ejections (CMEs). It is seen that most of the cosmic rays are blocked from entering the heliosphere, during solar maxima period. The strong solar magnetic field also blocks radiations such as Gamma and X-rays from space. Whereas Solar Minima is the period of weaker solar magnetic field, during this period more galactic cosmic rays penetrates the atmosphere & reach the surface of the Earth. These cosmic rays adversely affect the planet and causes erratic rainfall, snowstorms, global cooling, etc. On the contrary Solar Maxima is generally considered as the period of favorable climate. It was also investigated that ionosphric TEC shows higher numeric values during solar maximum & seems to be greater and more violent than that in solar minimum [6].

Apart from regular solar cycles, some notable extreme periods in solar phases were also observed over the centuries. One such extreme period was 70 years grand minima in the seventeenth century, continued from 1645 to 1715. This period is known as Mauner Minimum. It is also known as prolonged sunspot minima [7], [8]. During this period almost no sunspot was observed. Delton minimum was the similar event which was shorter and less severe, occurred in the beginning of the 19th century. In total twenty seven such grand minima had been noticed during the Holocene [9]. On the contrary of these minima, it is the age of Modern Grand Maximum that extends from the beginning of the 20th century to present time. It was the period of high solar activities and warmer temperatures, which helped the planet to emerge from successive solar minima events and the little ice age. It was also seen that every peak (of solar activities) between two Grand Minima is not classified as a Grand Solar Maximum [10].

The present sunspot cycle termed as the 24th solar cycle, with the expected span from 2008 to 2019. It had a short memory. It has started with minimal solar activities and this phase continued until early 2010 [11]. It is expected to be the solar cycle with the lowest sunspot activities. It is anticipated that the next cycle could be even more quiescent. The 24th solar cycle had twin peaks occurred in 2012 and 2014, with higher peak in 2014. This was the weakest maxima in the last 100years [12]. It is also found that the solar minima occurred between 23rd and 24th solar cycle, i.e. from 2007 to 2009 was the longest and deepest minima in the last 100years [13].

In our present work, we studied solar activity indices; these indices provide an opportunity to remotely observe the different solar phases. This study aims to observe the relationship between the solar activity indices and the ionospheric TEC during Solar Maxima 2012 and Solar Minima 2017 at the low latitude station.

II. Data Sets and Methodology

To accomplish this study we have used three types of data sets: Ionospheric data (TEC derived from GPS), Solar Activity Indices (viz. Sunspot Number (Rz), Solar EUV Flux and CME occurrences) and geomagnetic index (Dst. index). The Total Electron Content (TEC) is defined as the total number of electron present along the path between the satellite and the receiver. The VTEC is defined as the total number of electron present in a vertical column of unit meter square cross section area along the path of the ray [14]. The higher number of electrons present in the path of the signal, the greater impacts the signal sustains. For the precision in navigation and ranging, it is imperative to predict the ionospheric variations. For our study, we have selected low latitude IGS stations Pathum Wan, Thailand (Code-CUSV). The data were collected using universal time (UT) zone, the local time (LT) is hr 7 ahead of UTC. We collected the data from SOPAC URL http://sopac.ucsd.edu/dataArchive/. The raw data taken is in RINEX format, which is then processed to get the required Total Electron Content (TEC). The temporal resolution of the data is usually 30s. The data retrieved from IGS network is obtained as RINEX (Receiver Independent Exchange) observation files. It is a standard ASCII format (in a readable text) [15].

To characterize solar activity we have used three Solar Activity Indices viz. Sunspot Number, Solar EUV Flux and CME Occurrence. We had downloaded Sunspot Numbers data (hourly interval) were taken from from: Space Physics Data Facility OMNI website. (http://omniweb.gsfc.nasa.gov/). CME data catalog is made available by Solar & the Helliospheric Observatory (SOHO). The data is recorded with the help of the coronagraph namely LASCO (Large Angle & spectrometric coronagraph). Presently, it is the primary tool to analyze and categorize CMEs. The CMEs occurrences were calculated from CME catalog provided by SOHO at the URL http://cdaw.gsfc.nasa.gov/cme.list/. The Solar EUV Flux data were downloaded from https://dornsifecms.usc.edu/space-sciences-center/download-sem-data/. The data is recorded and online provided by the Solar EUV Monitor (SEM), aboard the SOHO satellite. The data include two channels, Broadband (0.1 to 50nm) and Narrowband (26 to 34 nm). For our study, we have considered narrowband data.

The characterize geomagnetic activity (storm intensity) is characterized by the Dst index. The data of Dst index is obtained from Space Physics Data Facility OMNI website (http://omniweb.gsfc.nasa.gov/) with one hour resolution.

III. Results and discussion

A. Diurnal TEC variation

The diurnal variations of ionospheric TEC for the solar maxima 2012 and minima 2017 are shown the Fig. 1 and Fig. 2. The yellow bold lines represent an average of the diurnal TEC variations and the multicolored lines show diurnal variation of TEC for the days of the month. It was observed from the figures, that solar maxima 2012 shows wider spread than that of solar minima 2017. It was also seen that the yellow bold lines show an increasing trend for the first half of the days and the trend reverses during the second half. This pattern found to be more prominent during the solar maxima period. It was also seen, that the curves achieved diurnal peak normally between 1200UT to 1600UT, it is also seen that the peaks are higher during the solar maxima period and shallow during the solar minima. It was also noticed that the least diurnal variations occurred, mostly between 2000UT to 2400UT [16].

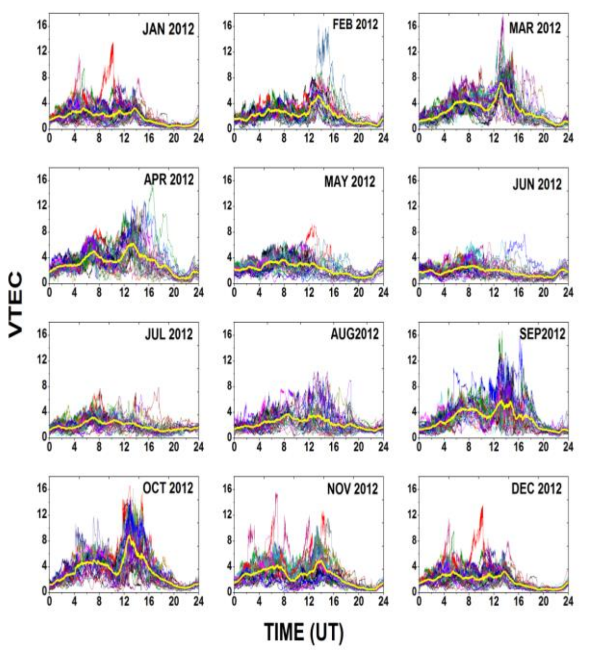

Fig. 1. Diurnal variation of VTEC during Solar Maxima (2012)

It was also observed that the yellow lines obtained comparatively highest peaks in March, September and October months (i.e. Equinox) and the shallow peaks in Jun and July (i.e. Solstice) during the solar maxima and the minima years. It was also noticed that the peaks are relatively higher during solar maxima than that of the solar minima. The study confirms earlier presumption, that the solar activities and ionospheric TEC show a fair linear relationship. As during the higher solar activity period greater number of sunspots appear, that increases the quantum of charged particle triggered into the ionosphere. Thus, a solar maxima period is the period of higher ionization process and vice versa [17].

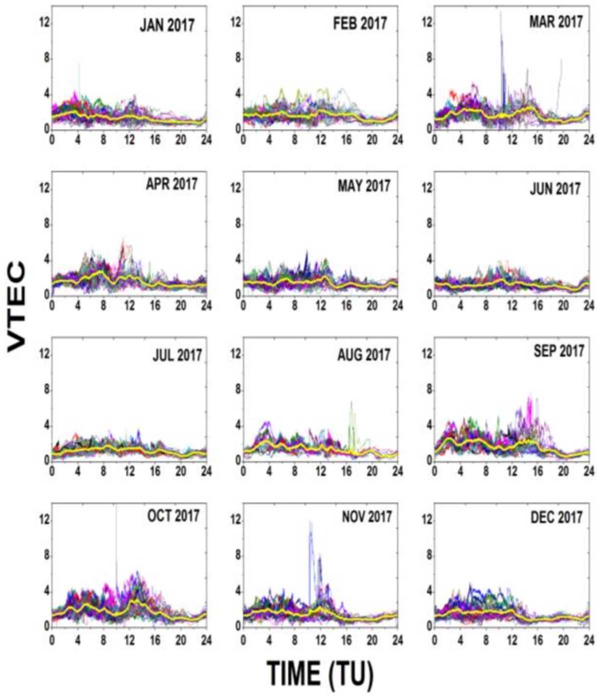

Fig. 2. Diurnal variation of VTEC during Solar Maxima (2017)

B. Seasonal variation of TEC

The seasonal TEC variability takes places because of the rotation and the tilt in the rotation axis of the Earth. This tilt makes the Earth inclined towards the sun (that causes summer) and inclined away from the sun (that causes winter), in between both the positions, equinox occurs. The relative position of the sub-solar points changes from one hemisphere to the other, this annual cycle causes seasons. We compared the average seasonal value of the ionospheric TEC during Solar Maxima 2012 and Solar Minima 2017 over the chosen GPS station, during Equinox (March, April, September and October), Summer (May, June, July and August) and Winter seasons (January, February, November and December). It was seen that both the extreme years follow a similar seasonal pattern, showing maximum seasonal VTEC during equinox and minimum seasonal VTEC during summer. The higher values are recorded during equinox, as it is the period, when subsolar points pass through equator. The lowest values of VTEC were observed in summer, it may be due to asymmetric heating of the northern and the southern hemispheres. This asymmetry moves the neutral constituents from summer to winter hemisphere, thereby reduces the recombination rates in winter hemisphere. This fall in the recombination rate causes the rise in VTEC during winter than summer solstice. [18], [19].

We also quantitatively compared seasonal peaks for both the solar extreme periods. It was found that the mean VTEC peak of the equinox season for the Solar Maxima 2012 was 83% higher than that of the Solar Minima 2017. It was also noticed that the VTEC peak of the summer season for the Solar Maxima was 57% higher than that of the Solar Minima. The results go with the assumption that, solar activities and ionospheric TEC show a linear correlation.

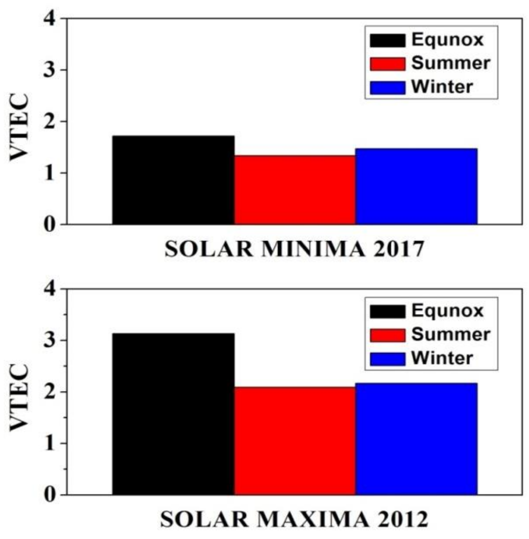

Fig. 3. Seasonal variation of VTEC during Solar Maxima (2012) and Solar Minima (2017)

C. Monthly variation of TEC

We compared the monthly variation of the ionospheric TEC during the Maxima and the Minima years. We observed weak ionospheric activities (low values of TEC) during the Solar Minima year and strong ionospheric activity (higher values of TEC) during the Solar Maxima year. It was also observed from Fig. 4 that both the Maxima and the Minima years showed a similar Sinusoidal Pattern. The crest of the monthly TEC graph was obtained during March (Vernal equinox) and October (Autumnal equinox) and the trough during June and December (i.e. Solstice). It was concluded that the maxima occur during equinox and minima occurs during the solstice. Equinox is the period, when solar declination is 0^0 (The solar declination is the measure of the latitude of the earth, at which the sun is directly overhead at noon.) In other words, equinox is the only time during the year, when sub-solar points are just on the equator (i.e. 0^o latitude), during the period the plane of the Earth's equator passes through the centre of the Sun's disk or the sun is directly over the equator, hence more solar energy is received by the earth, which leads to higher ionization during the period.

After the equinox the sub-solar points moves northern or southern hemisphere. After the March equinox the sub-solar points moves towards northern hemisphere. The sub-solar points hit 'Tropic of Cancer' on 21 June that is called June solstice, i.e. the day from which the sub-solar points start moving towards south. After September equinox, the sub-solar points move into southern hemisphere. The sub-solar points hits the 'Tropic of Capricorn' on 21 December, this is the beginning of December solstice. Thus, the sub-solar points move between the Tropic of Cancer and Tropic of Capricorn.

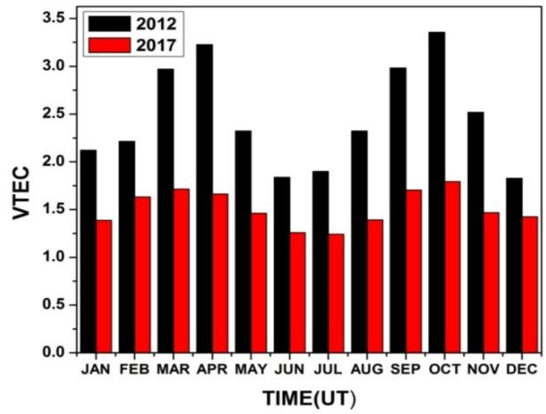

Fig. 4. shows the monthly variation of VTEC during Solar Maxima (2012) and Solar Minima (2017).

D. Relation between TEC and Solar Activity Indices

We analyzed monthly average values of ionospheric TEC and Solar Activity Indices (viz. EUV flare, CME occurrence and Sunspot Numbers) for the maxima and the minima years. From Fig. 5, it was observed that VTEC along with the solar activity indices showed higher numeric values during Solar Maxima 2012 year and lower values during the Solar Minima 2017. The result is quite obvious, since the primary source of ionospheric ionization is solar radiation flux. Thus, the higher (lower) magnitude of solar radiation is the causative agent of the greater ionization (lower ionization) during solar maxima (solar minima) period.

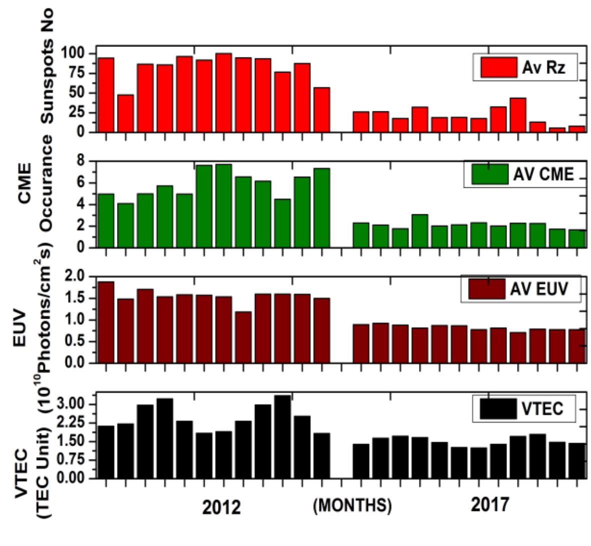

Fig. 5. Monthly average variation of VTEC alongwith Sunspot Number, CME Occurrences and EUV flux.

We also analyzed daily average values of ionospheric TEC and Solar Activity Indices (viz. EUV flare, CME occurrence and Sunspot Numbers) for the maxima and the minima years. From Fig. 6 Fig. 7, we observed a weak synchronization between ionospheric TEC and solar activity indices. It was also observed that the ionospheric TEC shows semiannual oscillation during both the years, with the maxima in spring and autumn and the minima at summer and winter. This semi-annual variation can be satisfactorily explained by Russell-McPherron effect. The effect explains that the Bz component of the Geomagnetism increases in the spring (March) and autumn (September), under the influence of southern interplanetary magnetic field (IMF) conditions, which causes more variation in the ionospheric TEC during equinoctial period than that of the solstice period.

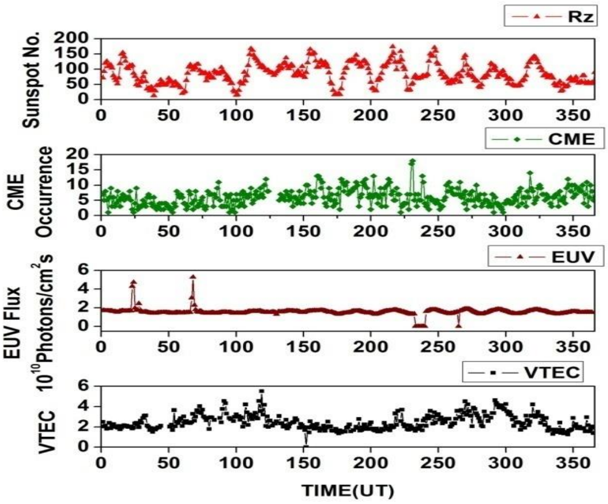

Fig. 6. Shows Annual TEC variation along with Solar Actively Indices for the year 2012.

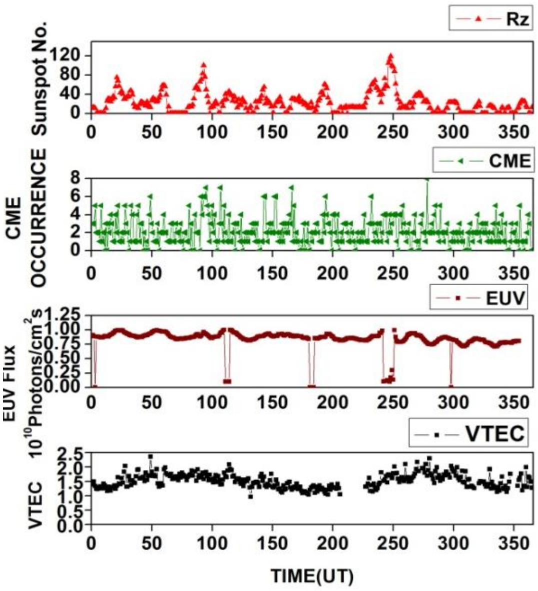

Fig. 7. Shows Annual TEC variation along with Solar Actively Indices for the year 2017.

E. Study of high energy CMEs during Solar Maxima 2012 & Solar Minima 2017

Fig. 8 shows the annual distribution of the special CMEs events and its impact on geomagnetic storm (Dst) and ionospheric TEC during the solar maxima and the minima year. We have considered some special high energy CMEs events (viz. Hallo CMEs, Fast & Wide CMEs and Fast & Halo CMEs), that are capable of affecting ionosphere variability, producing geomagnetic storms. The CMEs with the linear speed more than 900km/s are defined as Fast CME, those with angular width more than 60˚ is defined as Wide CME and the CMEs with an angular width 360˚ are defined as Halo CME. The 900km/s is an average speed of the CME that produces interplanetary type II radio bursts. Halo CMEs are capable to produce geomagnetic storms, (when frontsided). It was observed that eleven geomagnetic storms occurred during solar maxima 2012. All of them are in the category of moderate storms. The strongest of them occurred on 10 March (69th day of the year) with Dst -98 nT. And during solar minima 2017, total four geomagnetic storms (three moderate and one intense storm) occurred. The intense storm occurred on 8 September (251th day of the year) with Dst -107 nT. All the storms are represented by a trough in the Dst graph. From the CME data analysis, it was observed that only a fraction of CMEs, out of Total number of CMEs events; belong to high energy CMEs during the maxima and the minima period. It was also observed that during the Solar Maxima (i.e. the period of stronger ionospheric activities), there were a higher number of the total number of CMEs, Hallo CMEs, Fast & Wide CMEs and Fast & Halo CMEs events occurred than that of the Solar Minima (i.e. the period of weaker ionospheric activities). It was also observed that the greater number (lesser number) of CME events, triggered a higher number (a lower number) of geomagnetic storms during solar maxima (solar minima) period. It is evident that the geomagnetic storms lead to ionospheric variation. Hence, it seems that ionospheric activity is connected to the occurrences of high energy CMEs events (especially during geomagnetic storms).

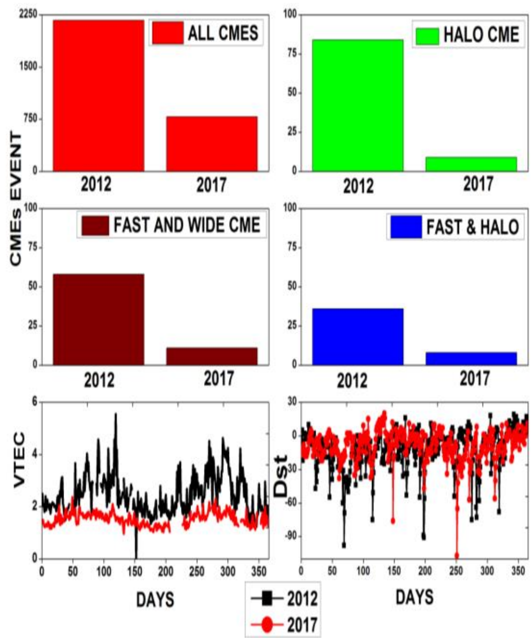

Fig. 8. Shows annual variation of inospheric TEC & Dst along with the distribution of special CMEs during 2012 and 2017.

IV. CONCLUSION

It was seen that the average diurnal variations of TEC showed an increasing trend for the first half of the day and the trend reversed during the second half. The pattern found to be more prominent for the solar maxima period than that of solar minima. It was also seen, that the curves achieved diurnal peak normally between 1200UT to 1600UT, also the peaks were higher during the solar maxima period. It was seen that during both Solar Maxima 2012 and Solar Minima 2017 periods, VTEC follows a similar seasonal pattern, with the highest values during equinox and the lowest during summer season. We also quantitatively compared seasonal peaks (mean VTEC) for both the solar extreme periods. It was found that the mean seasonal (Equinox, summer & Winter) VTEC peaks for the Solar Maxima 2012 were higher than that of the Solar Minima 2017. From monthly variations, we observed weak ionospheric activities during the Solar Minima year and strong ionospheric activity during the Solar Maxima year. It was also observed that both the Maxima and the Minima years showed a similar Sinusoidal Pattern. The crest of TEC curves were obtained during the equinox and trough during the Solstice. We observed a weak synchronization between ionospheric TEC and solar activity indices. It was also observed that the ionospheric TEC shows semiannual oscillation during both the years, with the maxima in spring and autumn and the minima at summer and winter. It was observed that during the Solar Maxima there were a higher number of CMEs, Hallo CMEs, Fast & Wide CMEs and Fast & Halo CMEs events occurred than that of the Solar Minima. It was observed that this greater number of CME events during solar maxima period triggered a higher number of geomagnetic storms. It is evident that the geomagnetic storms lead to ionospheric variation. Hence, it seems that ionospheric activity is connected to the occurrences of high energy CMEs events, especially during geomagnetic storms.

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