19th International Beacon Satellite Symposium
27 June – 1 July, 2016
The Abdus Salam International Centre for Theoretical Physics : Trieste, Italy

# Climatological Response of Equatorial and Low Latitudes Ionosphere to Geomagnetic Storms: First Results

Sunanda Suresh and N. Dashora

National Atmospheric Research Laboratory
Department of Space, Govt. of India
Gadanki – 517 112, India
Correspondence E-mail: ndashora@narl.gov.in
sunanda@narl.gov.in

01 July 2016

## Equatorial Ionization Anomaly (EIA) in Low Latitudes

### Complex Interplay of Neutral winds, Currents and Electric Fields

- ❖ Realistic Representation of the observed features and variability of equatorial and low latitude ionosphere is a complex task (Shim et al., 2012).
- ❖ Variations on several scales during Quiet periods are governed by a complex interplay of Solar Flux, Winds and Electric fields (Dashora and Suresh, JGR, 2015)
- ❖ Effects of Individual Events of CMEs and subsequent Geomagnetic storms have been reported in several studies in literature.

- ✓ **Present work is an effort to characterize the climatology of responses of low latitude TEC during geomagnetic storms**
- ✓ **Main emphasis has been given to**
  - Define Quiet time Day-to-day variability
  - Generic Definition of storm-time departures from Quiet time
  - Define Categories of Storms based upon equatorial sensitivity and responses
  - Provide a statistical forecast model to an extent a typical kind of storm could perturb the low latitudes at a given time of day.
- ✓ **Global Ionospheric Map (GIM) data has been used owing to its continuity & validity required for long term statistical studies.**

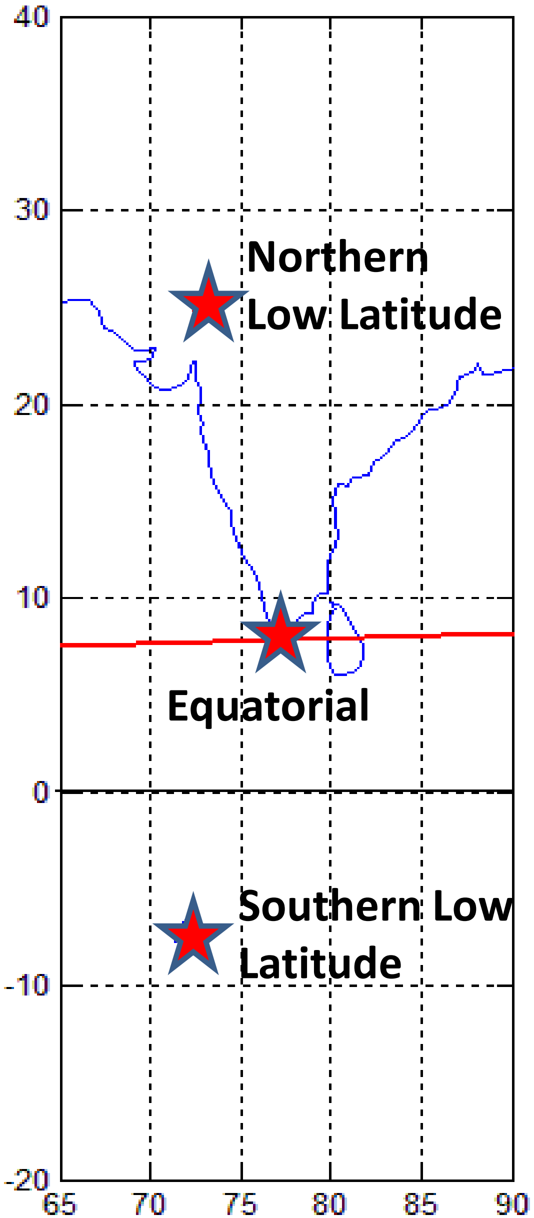
# Aim

**To bring out**

- **Statistical responses of equatorial and low latitude ionosphere to geomagnetic storms that occurred during solar cycles 23 and 24 from 1998 to 2015**

- **Ionospheric deviations due to storms during daytime, further divided into forenoon and afternoon durations**

- **The seasonal deviation pattern of peak positive and negative excursions from monthly mean of quiet durations**




# Data and Method

**Selection of locations from GIM data**

- To represent the characteristics of Equatorial Ionospheric Anomaly (EIA) in Indian sector three locations are selected
  - Northern hemisphere
    (Geomag. Lat. 16.08° N, Geog. Long. 73.7 ° E)
  - Equator
    ( Geomag. Lat. 0.17 ° S, Geog. Long. 76.95° E)
  - Southern hemisphere
    (Geomag. Lat. 15.26 ° S, Geog. Long.72.37 ° E)

- Important to note that –

The southern low latitude location is geomagneticaly conjugate to the northern location.

Also, the locations have been selected based upon past availability of results from these places.

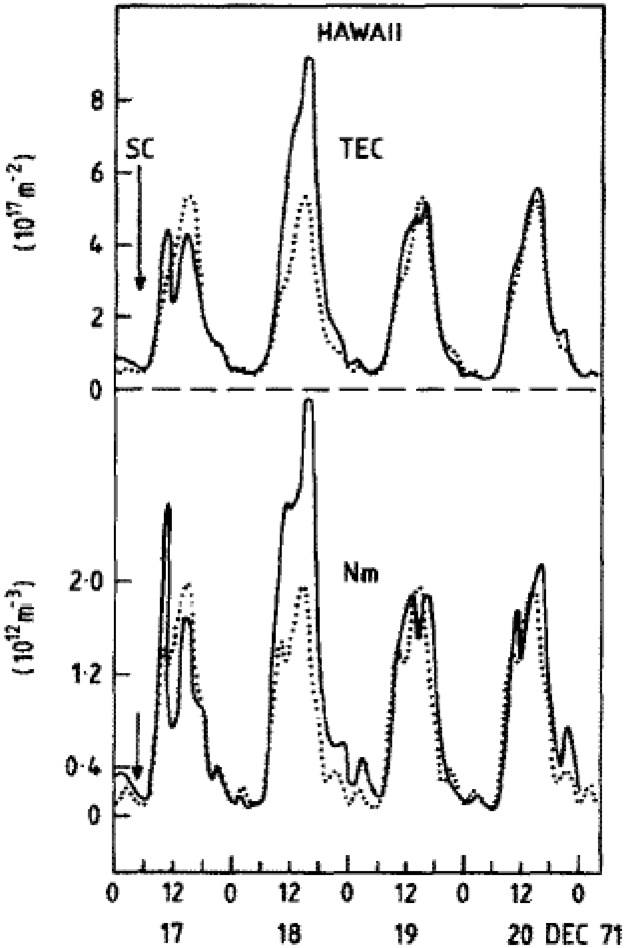
# Previous Statistical Studies and Debatable Definitions

Deviations of ionospheric density from average quiet time level following geomagnetic storms is the widely used definition of an ionospheric storm.

1) **How is average quiet time defined?**
2) **How much deviation can be allowed??**

1. **Several definitions of quiet time**, e.g.,
   - Seven days prior to storm commencement (Balan and Rao, 1990)
   - Four quietest days chosen within a period of 30 days centered on the main phase (Sobral etal.,2001)
   - Quietest day of month(Batista et al., 2012)
   - Monthly median (Danilov, 2013)
2. **Several degrees of deviations (Positive or Negative)**
   - If the observed behavior of foF2 satisfies the following three conditions it is defined as a positive type: (1) foF2 is enhanced above the monthly median value more than 9 h in succession; (2) mean magnitude of enhancements in foF2 is greater than 15%; (3) enhanced period is located in the daytime for more than 6 h. (Tanaka., 1978)
   - Increase or decrease from day before storm (Wang et al., 2010)
   - Storm time deviation of Nmax ($\Delta$Nmax) exceeds ±25% for more than three hours (Vijaya Lekshmi et al., 2011)

# Previous Statistical Studies and Debatable Definitions




1. Example of the stormtime variations of TEC and Nm [H]awaii for a night-time SC. The vertical arrow marks the [onset] time of the SC at 14:18 UT on 17 December 1971. The [dott]ed curve is the control curve, which is the mean of the seven days prior to the SC.

Balan and Rao (1990)

The storm time change of the ionospheric TEC is defined as

$$\mathrm{RTEC} = (\mathrm{TEC} - \mathrm{TECq})/\mathrm{TECq}. \quad (1)$$

We choose a smooth 27-day median value as TECq. That means the 24-hourly median values were obtained in each cell within the 27-day window and assigned to the central 14th day. Then the window was sliding forward one day and again the new hourly medians were assigned to the next central day. Repeating the procedure, median values were obtained for each cell from 16 September 1998 to 31 December 2006. The advantage of employing the 27-day window smooth medians is to remove diurnal variation and the trend with a period longer than 27 days, for example, the annual and semiannual component. It should be mentioned that this method also does not do a good job whenever the magnetic activity is high throughout the 27-day interval considered.

Zhao(2007)

A11328 VIJAYA LEKSHMI ET AL.: GEOMAG

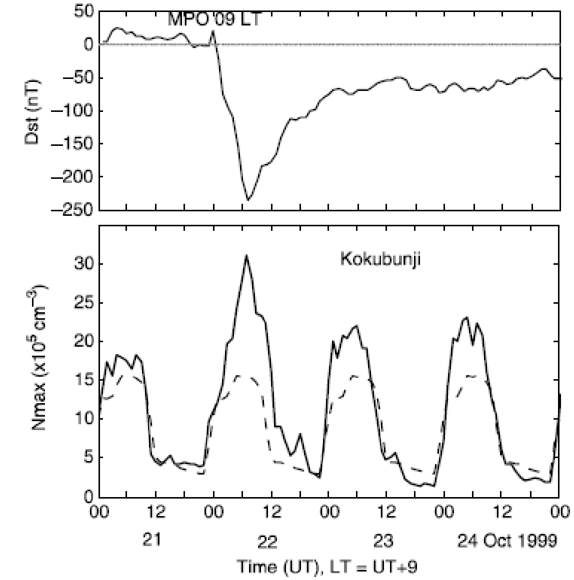



**Figure 2a.** (bottom) Example of a positive ionospheric storm at Kokubunji during (top) the geomagnetic storm of 22–25 October 1999. Following the main phase onset (MPO) at around 09 LT (=UT + 9 hrs) on 22 October the storm-time Nmax (solid curve) remains much greater than the seven quiet-day average prior to the storm (dashed curve).

Vijaya Lekshmi et al., (2011)

The F2-layer reaction to geomagnetic disturbances is usually described in two ways. Either the absolute difference between foF2 (or the F2-layer height, hmF2) during the storm period and on selected quiet days (or monthly median) ΔfoF2 in MHz (ΔhmF2 in km) are considered, or the relative difference in percents between the same parameters is used

$$\delta\mathrm{foF2} = \{\mathrm{foF2(obs)} - \mathrm{foF2(med)}\}/\mathrm{foF2(med)},$$
$$\delta\mathrm{hmF2} = \{\mathrm{hmF2(obs)} - \mathrm{hmF2(med)}\}/\mathrm{hmF2(med)}.$$

Danilov (2013)

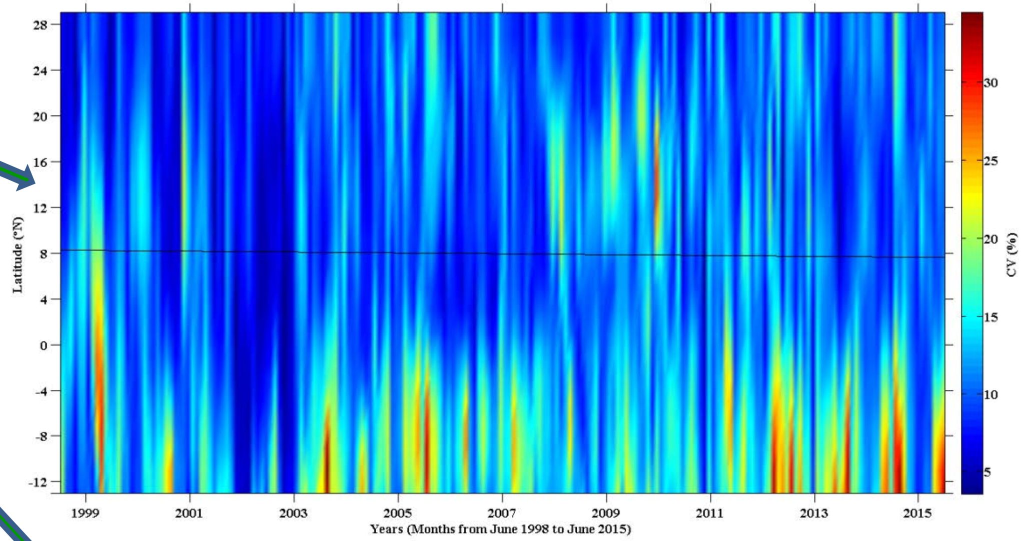
**Results –**

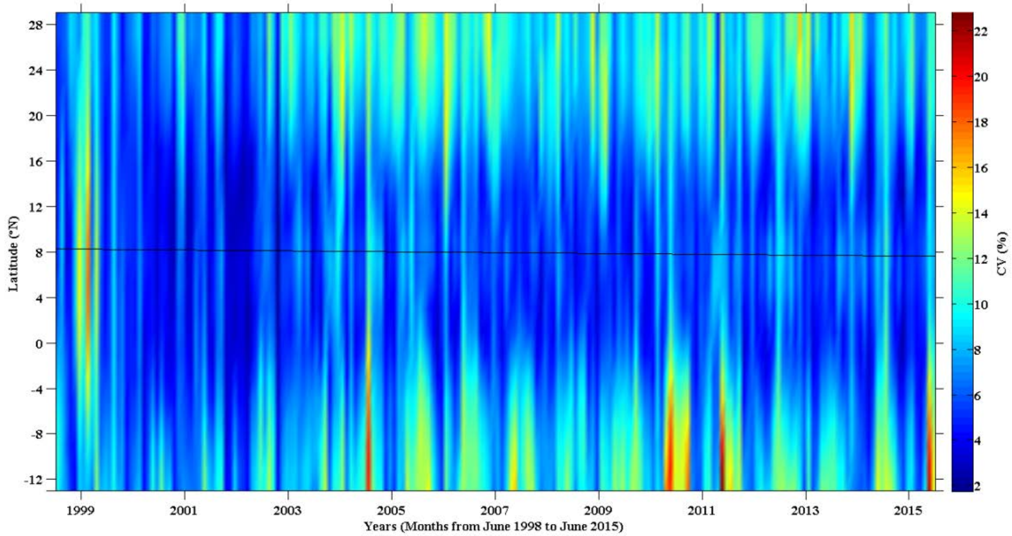
## Examination of Quiet time variability from June 1998 to June 2015
## Geomagnetic Latitudes 19.2$^{o}$N and 20.4$^{o}$S

Forenoon – 06:30-11:30 IST

Afternoon – 12:30-17:30 IST

(IST=UT+05:30 Hrs)




- Dramatic variations of CV=STD/Mean in low latitudes ranging from 2% and 30% with Seasonal Highs and Lows on Solar Cycle basis.

**In this scenario wherein the mean and the STD exhibit several scales of variability, a fixed value of CV or STD cannot fiducially represent the variations**

- Definition of geomagnetic storm and its ionospheric effects are correlated with Ap and Kp indices, But NOT Dst index in most of the previous studies.

- Most studies were performed for mid latitudes where Ap and Kp are geo physically more relevant

- However, for low latitudes, ionospheric response to geomagnetic storms shall be more relevant with Dst. Case studies have used Dst as an established criteria for low latitude (Immel et. al., 2013 and references therein).

- Mid latitude specific statistical studies based on long term data like Balan and Rao (1990), Vijayalekshmi et al. (2011), Zhao (2007), Mendillo and Narvaez, (2009, 2010) etc have used various definitions and results have not been comparable.

- So far there is no study from equatorial/low latitudes that ensures a single and generic definition as most studies are from mid latitudes.

## Resolutions

In this study, for the first time, we have used various generic definitions for

- ✓ Defined quiet days (Dashora and Suresh.,2015)
- ✓ ionospheric storm

exclusively for Daytime response

# Data & Methodology

The **quietest days** from 18 years of data are identified using a cut-off value of

- Dst > -50 nT and
- Solar flares < Class M5.5 on a given day.

All other days are considered as geomagnetic storm days.

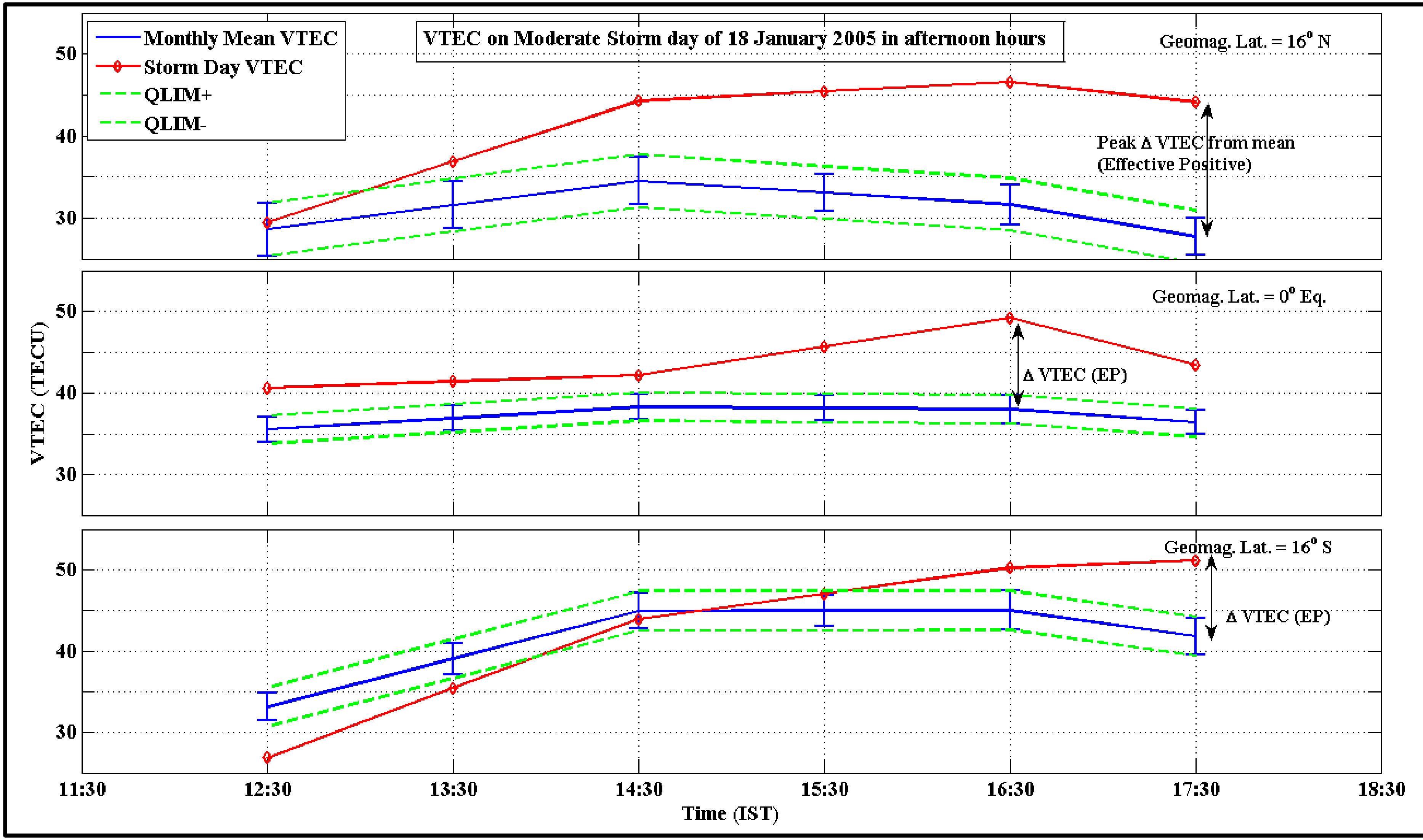
- ✓ Further, only those storm days are considered in which **minimum Dst** occured during **local daytime** between 06:30IST and 17:30IST
- ✓ Further, all storm days are classified into **Forenoon** and **Afternoon** depending upon occurrence time of minimum Dst in either time sector.
- ✓ Forenoon = 06:30 to 11:30 IST = 06 Hours
- ✓ Afternoon =12:30 to 17:30 = 06 hours

Geomagnetic storms categorized as (Gonzalez, 1994 and based on low latitude response)

- **Major** storms: minimum Dst<-200 nT,
- **Moderate** storms : -200nT< minimum Dst <- 100nT and
- **Minor** storms : -100nT< minimum Dst<-50nT

Further the storm days are selected as mutually exclusive sets of days for the three categories of storms to prevent any overlap in analysis.

# Example : Selection of Effective Storm (ES) from Total Storms (TS)



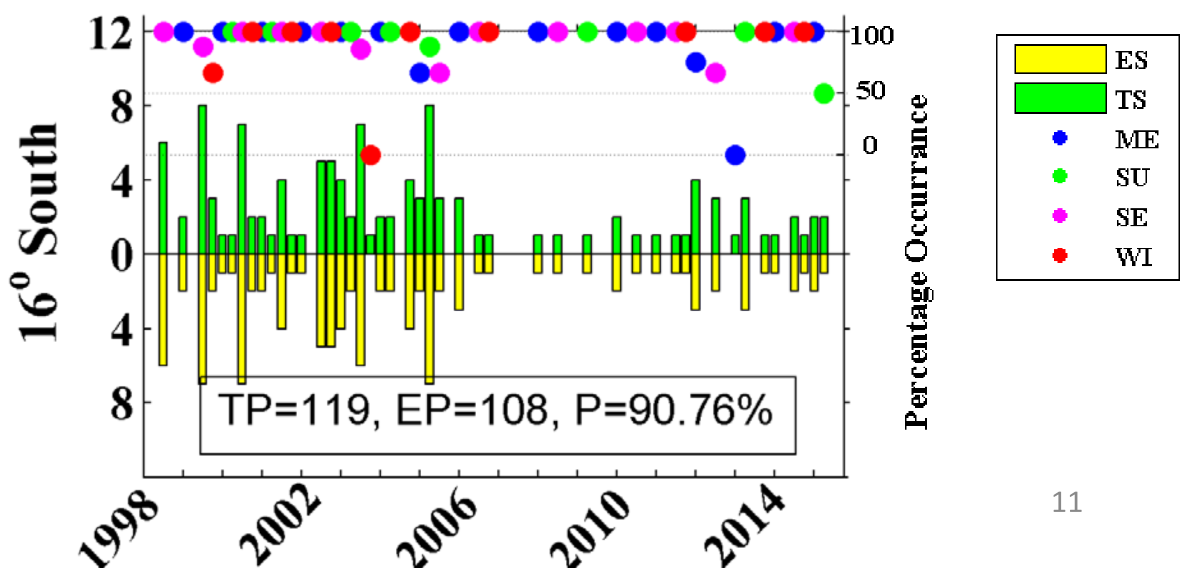

Time is limited to Indian Daytime
Minimum Dst is the criteria for selection of Main Phase

# 1. Occurrence statistics for positive and negative storms

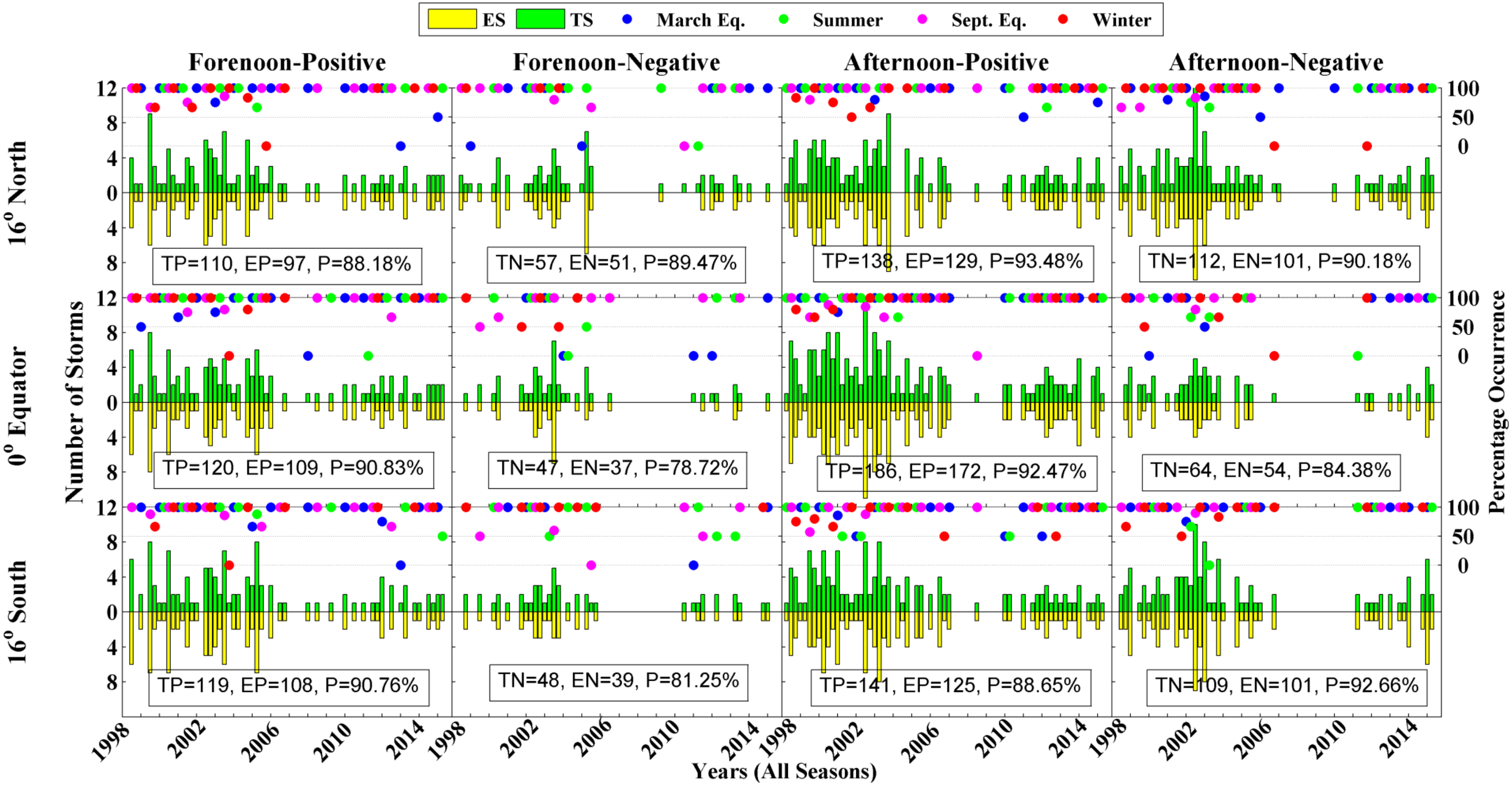
- Storm occurrence statistics for 16$^o$N, 0$^o$ Eq., 16$^o$ S
- Number of total storms (TS) for each one of the 72 seasons obtained from Dst based criteria are green bars
- Effective storms (ES) obtained from VTEC criteria are yellow bars

- Seasons are March equinox (February, March and April), September equinox (August, September and October), Summer (May, June and July) and Winter (November, December and January).
- Equinoxes are taken common for both geographical hemispheres whereas solstices are taken local for each hemisphere.
- Percentage occurrence of ES with regard to TS is seasonally segregated shown as colored dots scaled on the right ordinate axes

Data Duration:
June 1998 to June 2015

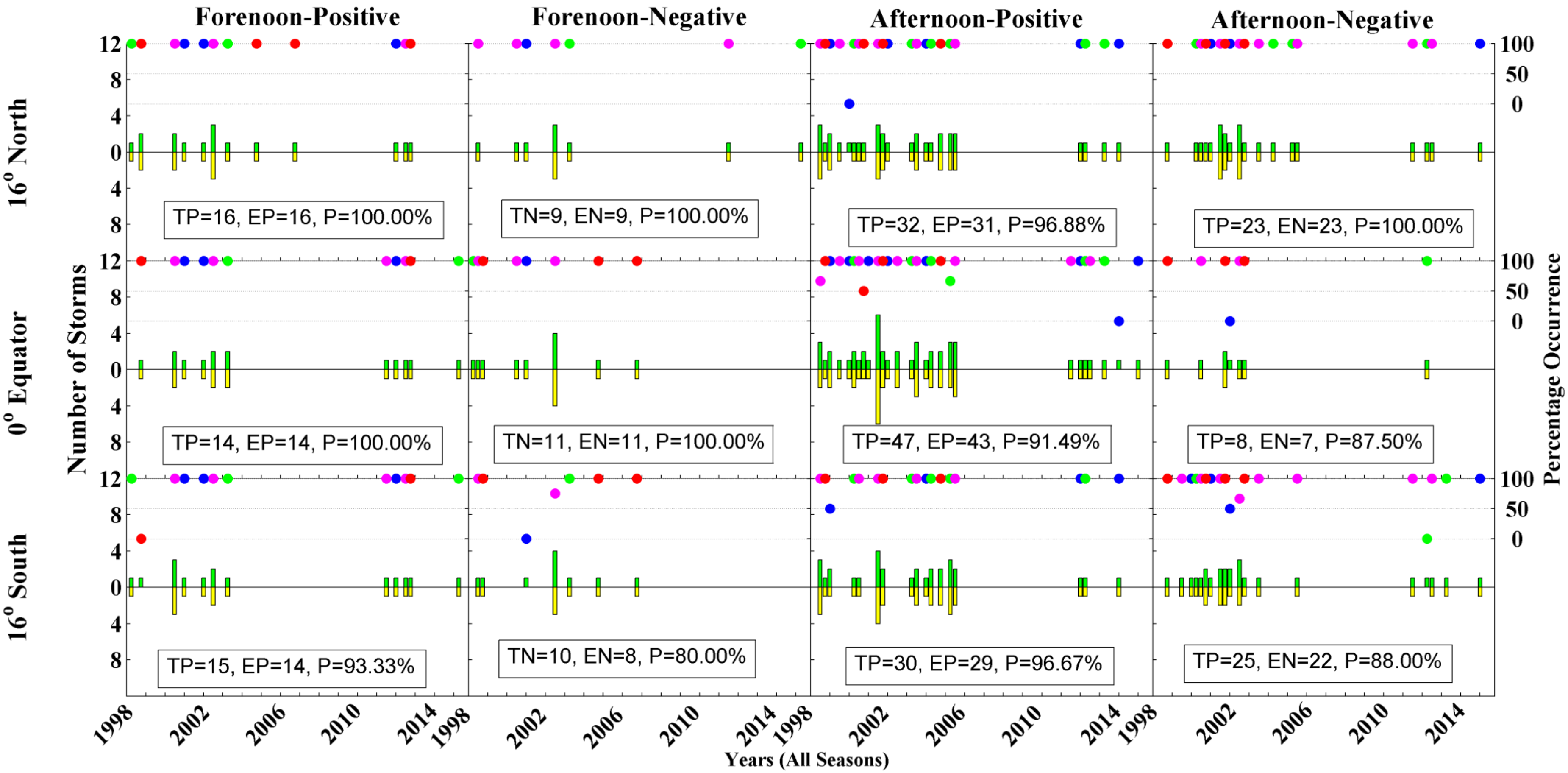


# Occurrence Statistics: Minor Storms



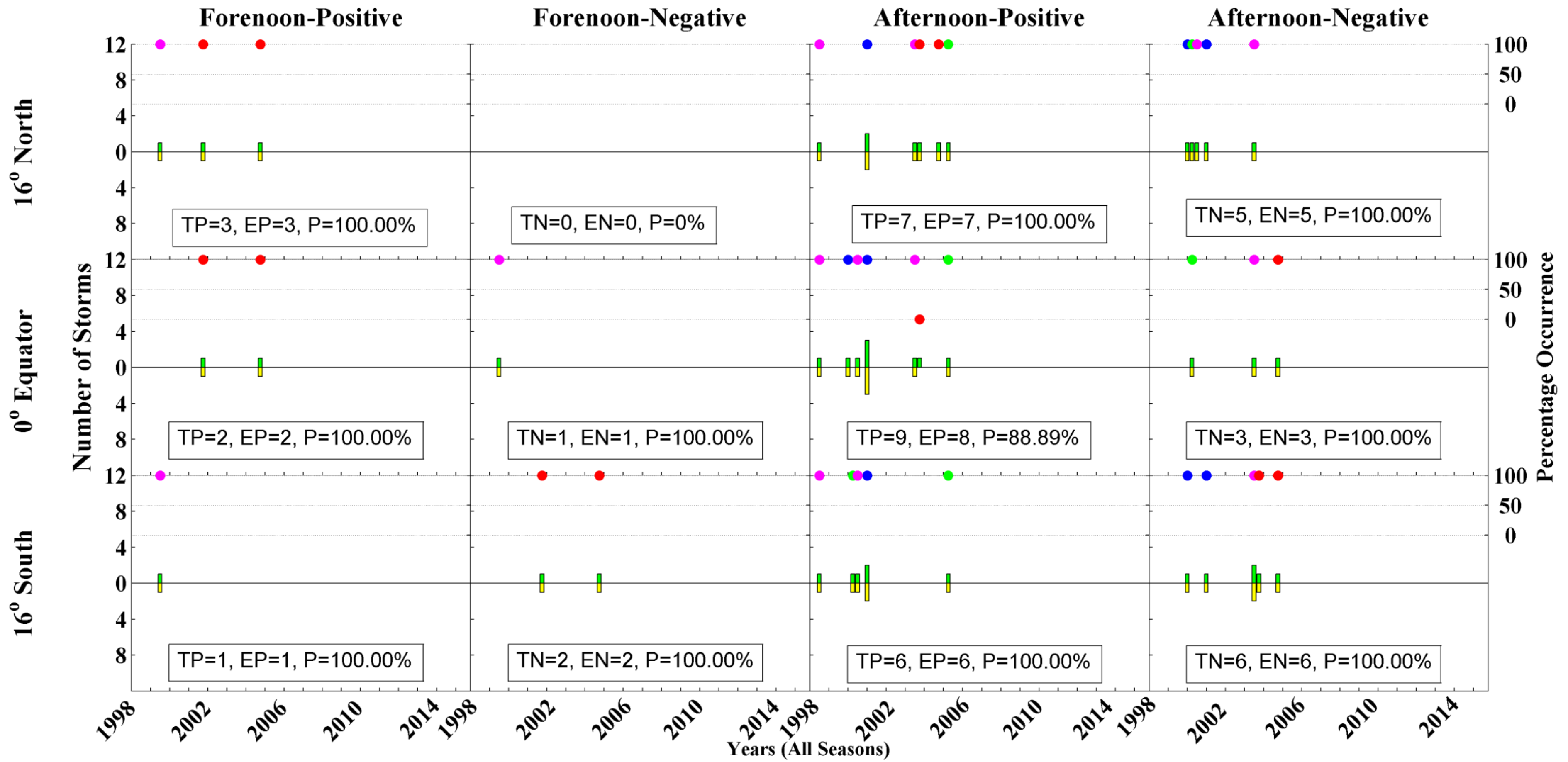

- ✓Highest occurrence of positive and negative TS and ES found in **Afternoon** category
- ✓ High number of Effective **positive storms** during minor geomagnetic conditions
- ✓ Drastic difference in TS, ES and percentage ES for a **given season**
- ✓ **Latitudinal difference** within low latitude ionospheric response to a global storm
- ✓**Difference in response during HSA of cycle 23** and LSA and HSA of cycle 24

## Occurrence Statistics: Moderate Storms




- ✓ Highest occurrence of TS and ES remains limited to **afternoon positive** category
- ✓ No significant difference between positive and negative storms in occurrence of ES and TS
- ✓ Percentage occurrence of **ES is significantly higher than 90%** in most of the panels
- ✓ Indicates that the impact of moderate storms on low latitude ionosphere is such that probability of a geomagnetic storm to result into an effective ionospheric storm (EP or EN) is **very high irrespective of solar activity, season or latitude**.

# Occurrence Statistics: Major Storms



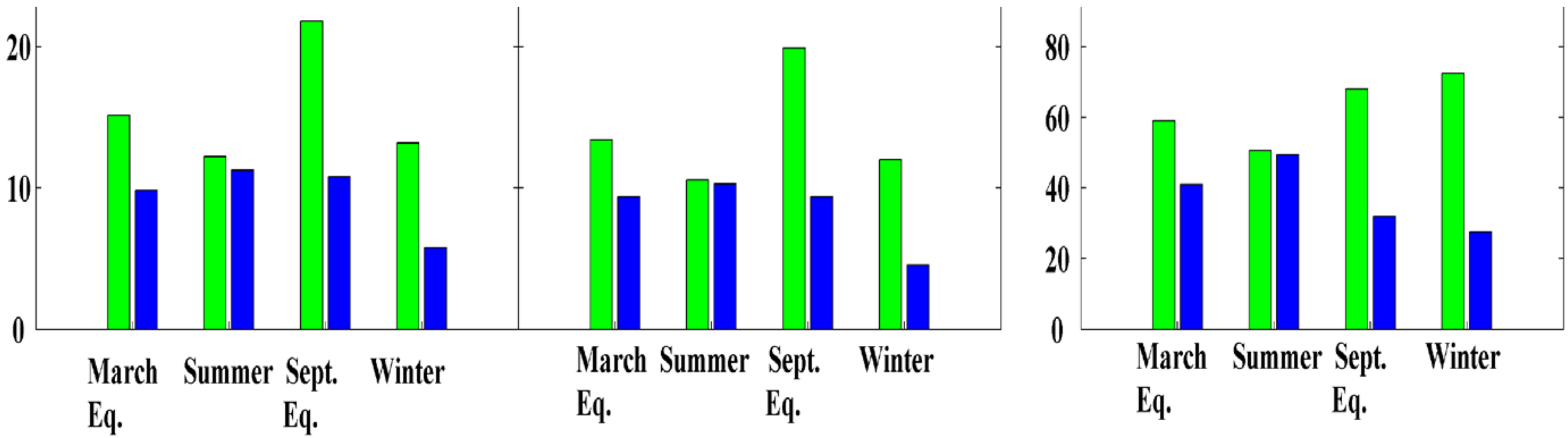

From the impact of all three types of storms on low latitude ionosphere it is found that

- ❑ there is a large probability of an ionospheric storm to be positive at most of the latitudes and seasons
- ❑ when the Dst reaches its minimum in afternoon hours, the ionospheric storms would more favourably be positive
- ❑ percentage of ES occurrence increases with intensity of storms
- ❑ same storm can produce both the positive and negative effects at different latitudes.

# 2. Seasonal distribution of positive and negative storms

• Occurrence statistics indicates seasonal character in positive and negative responses

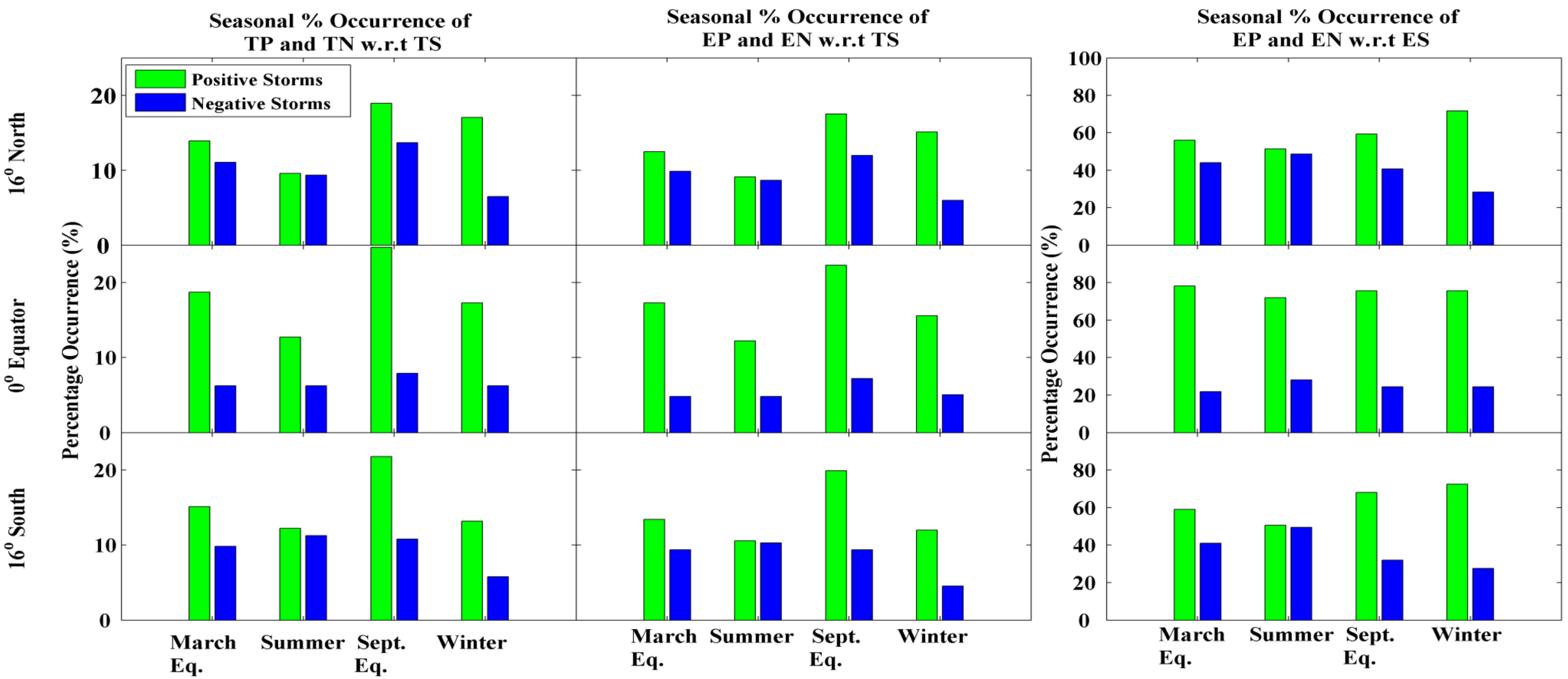
• Respective numbers of forenoon and afternoon storms are combined to obtain the total number of positive and negative storms




•These numbers are segregated according to seasons

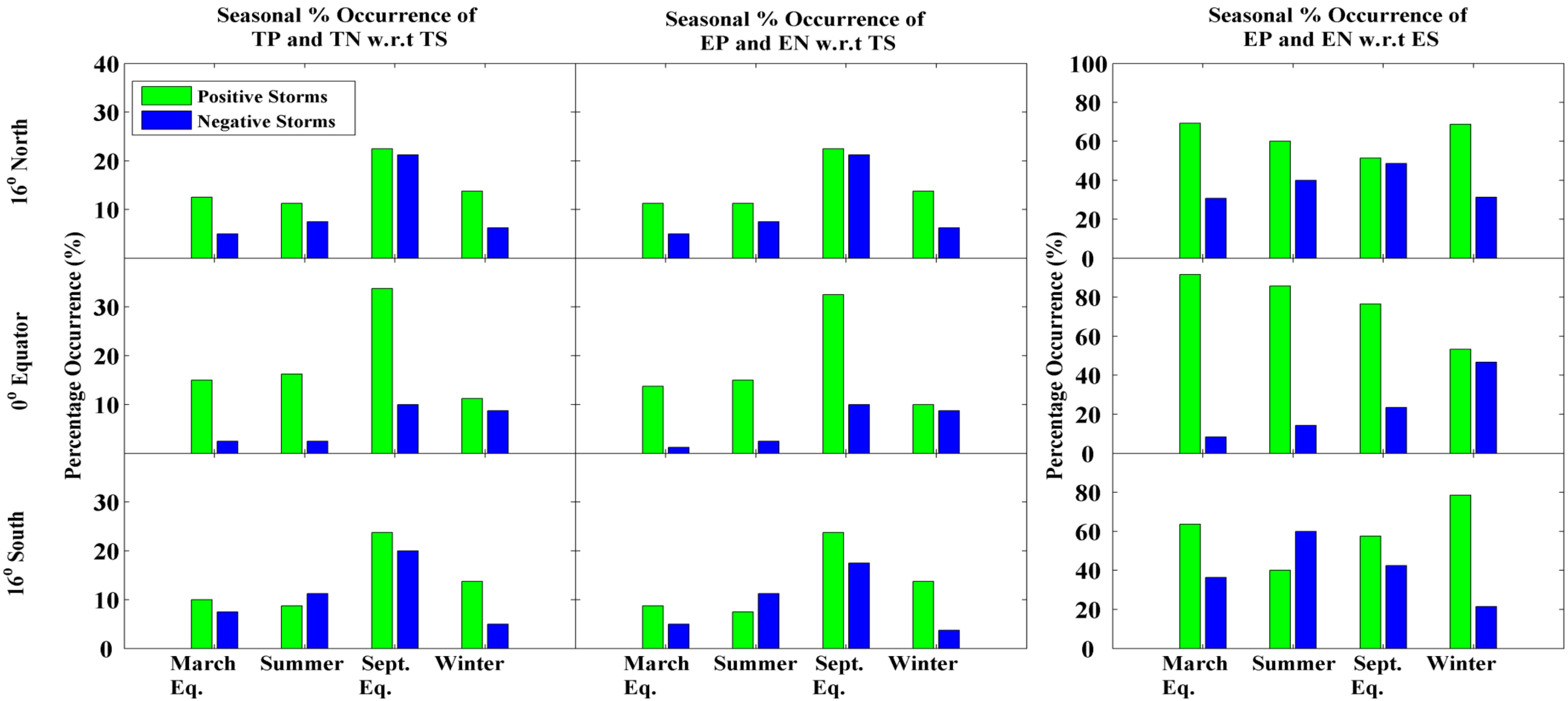
- First column : total number of positive and negative storms
- Second column : total effective positive and negative storms
- Third column : seasonal distribution of total effective positive and negative effective storms out of the total positive and negative storms

# Minor Storms



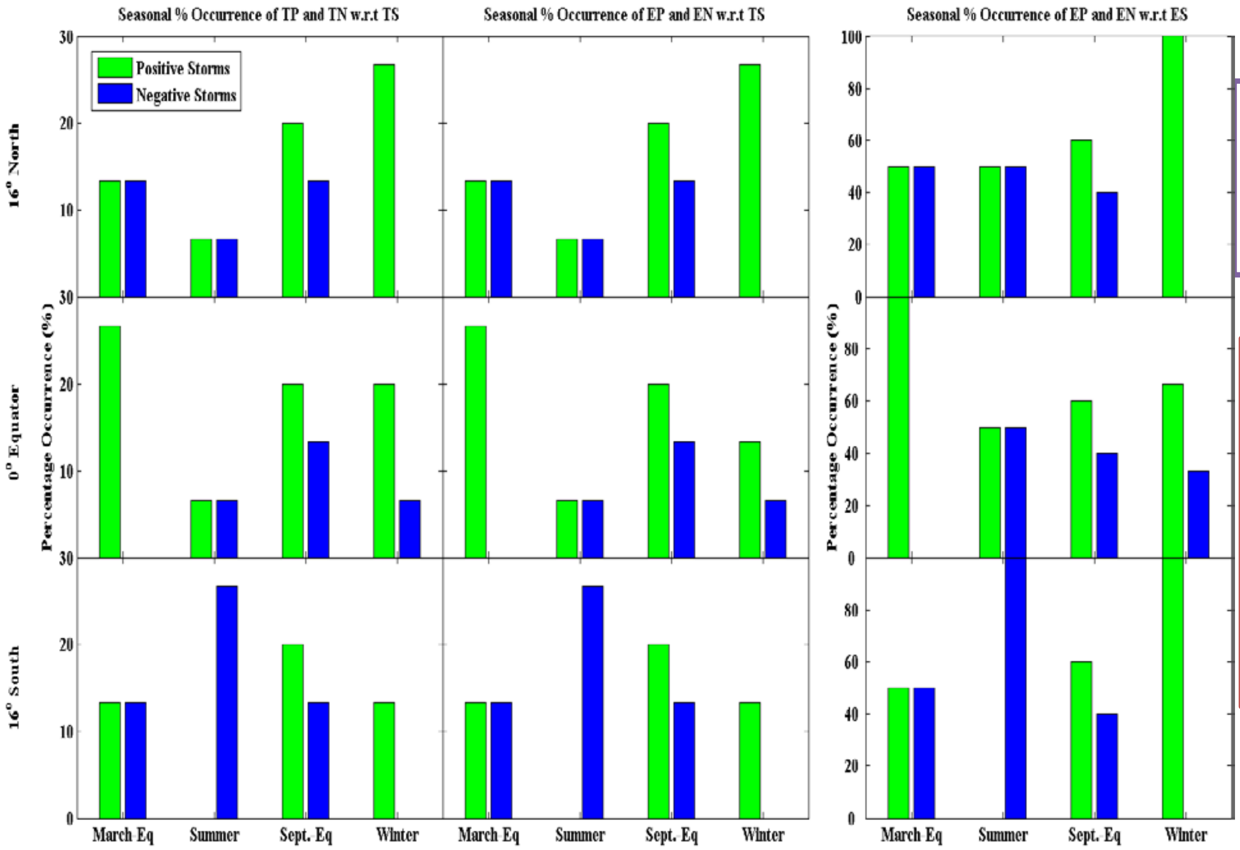

- ✓ Maximum occurrence is found during September equinoxes (~20–25%)
- ✓ Summers showed the minimum occurrence (~10–12%) for positive storms
- ✓ Negative storms maximize in September equinoxes (~15%) and Minimum occurrences in winters (~5–8%)
- ✓ Occurrence of negative storms is minimum over dip equator not higher than ~7% in any season compared to both the low latitudes
- ✓ very high probability (~60–80%) of a storm to be EP in condition given that it is an effective storm, especially at the equator

# Moderate Storms




- ✓ September equinox is found to have the highest percentage occurrence for positive storms (~22–34%) and remained less than 20% for other seasons
- ✓ The highest (lowest) probability of EP (EN) is found over equator in all seasons except winters.
- ✓ The statistics of an effective storm to be EP or EN in low latitudes is equally distributed over seasons and show no specific pattern

## Major Storms

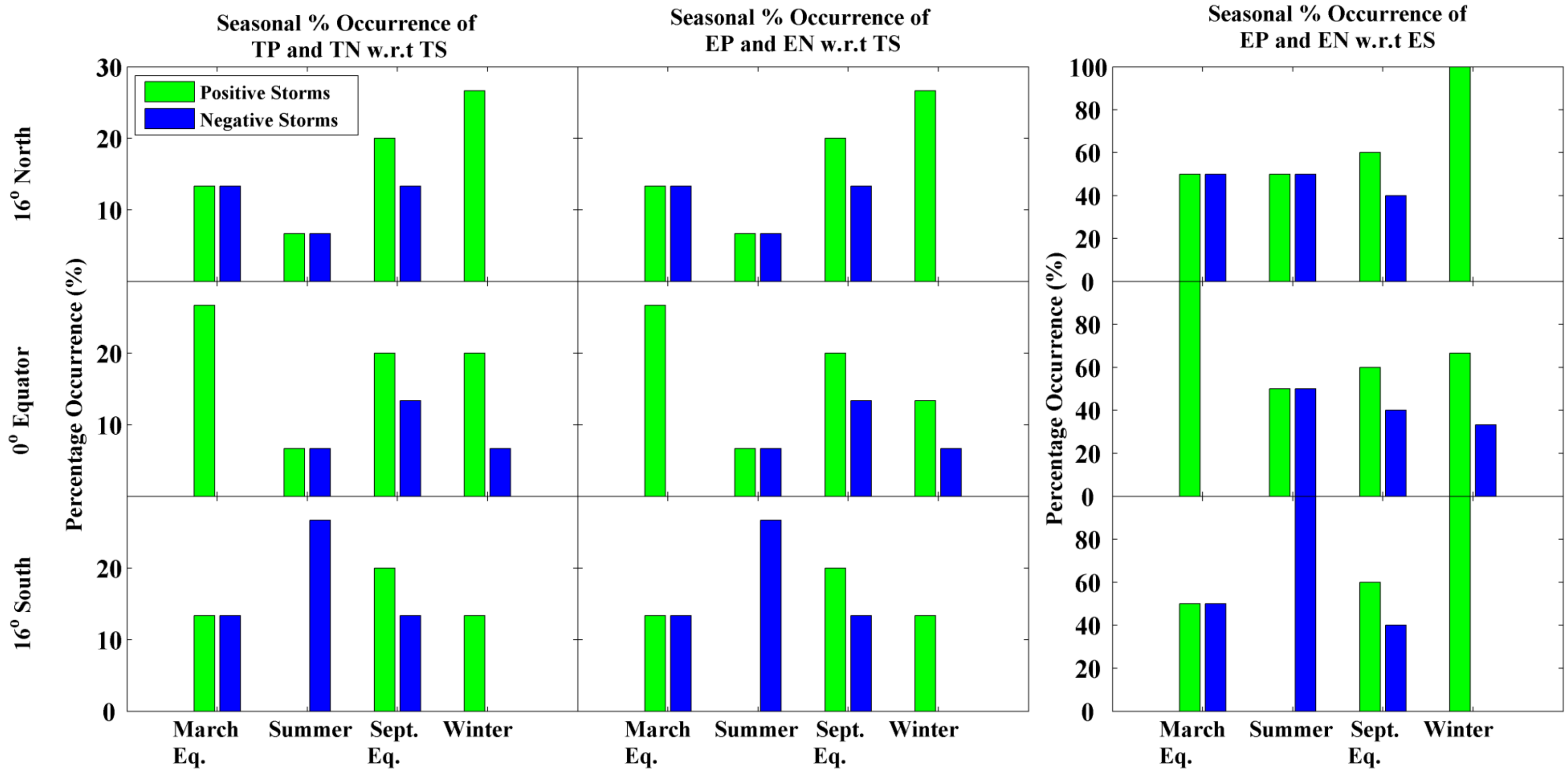



Due to smaller total occurrences, a vital statistics not obtained

Equinoxes and summers: Positive storms
Maximum Positive storms in winters at 16°N
Maximum negative storms in winters at 16°S

- ✓ Peak of TS and ES occurrences for both the EP storms found at peak in Winter in North, March Eq. at Equator and Summer/September Eq. in South.
- ✓ No Clear equinoctial and solsticial asymmetries in the seasonal statistics for percentage occurrence and storms to be effective.
- ✓ Seasonal preference of ionospheric response to a geomagnetic storm in low latitudes for major storms is not found.

# Major Storms




- ✓ More number of positive storms in equinoxes and winters
- ✓ Maximum negative storms in summers over low latitudes
- ✓ EP maximum in winters and March equinoxes and maximum in summers for EN

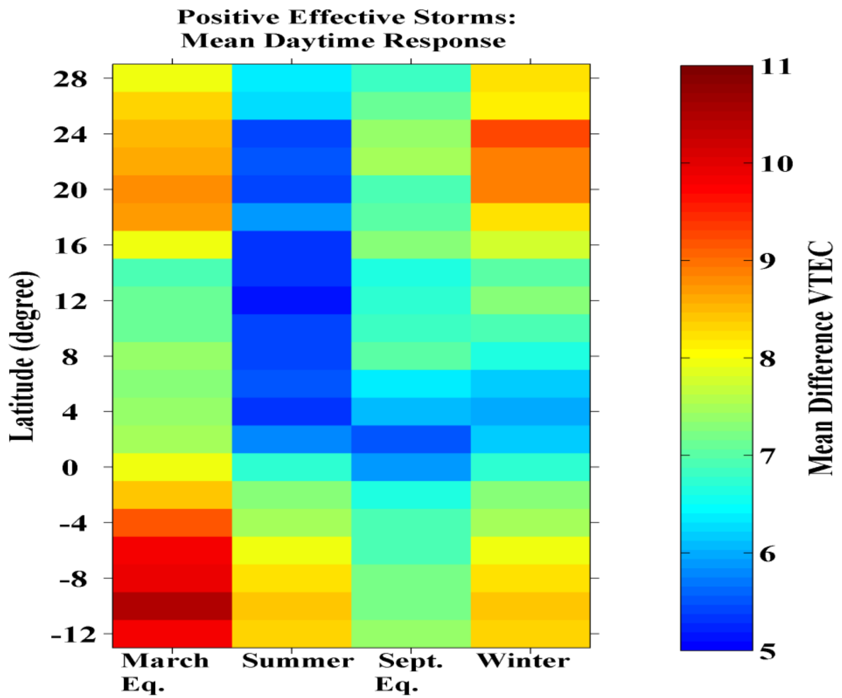
- ✓ Clear equinoctial and solsticial differences appear in the seasonal statistics
- ✓ Seasonal preference with semiannual variation in ionospheric response to a geomagnetic storm in low latitudes

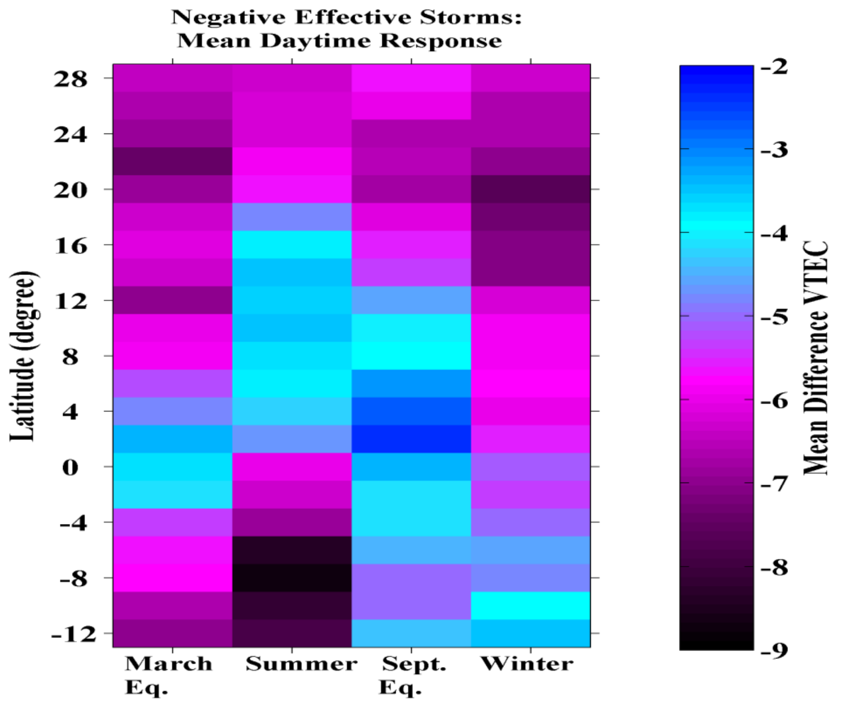
# 3. Amplitude of Perturbation - Latitudinal Response

- Latitudinal response in terms of mean perturbation amplitude for each 2$^o$ latitude from -12$^o$S to 28$^o$N geographic latitudes under the three storm categories
- Geomagnetic equator passes close to 8$^o$N latitude at 80$^o$E longitude and geomagnetically covers both the crests of EIA between 20.5$^o$ geomagnetic south to 19.2$^o$ geomagnetic north

- Storm time mean is computed selecting the peak value of VTEC on a storm day and taking the mean of all such values for a given season and latitude.
- i.e. $\Delta$VTEC is the difference of mean value of the highest VTECs in forenoon and afternoon for 18 years and mean seasonal quiet time VTEC
- $\Delta$VTEC represents the **mean maximum departure from the quiet time** values.
- Forenoon and afternoon storms are combined to examine the mean day time response in latitudinal distribution of ionospheric storms

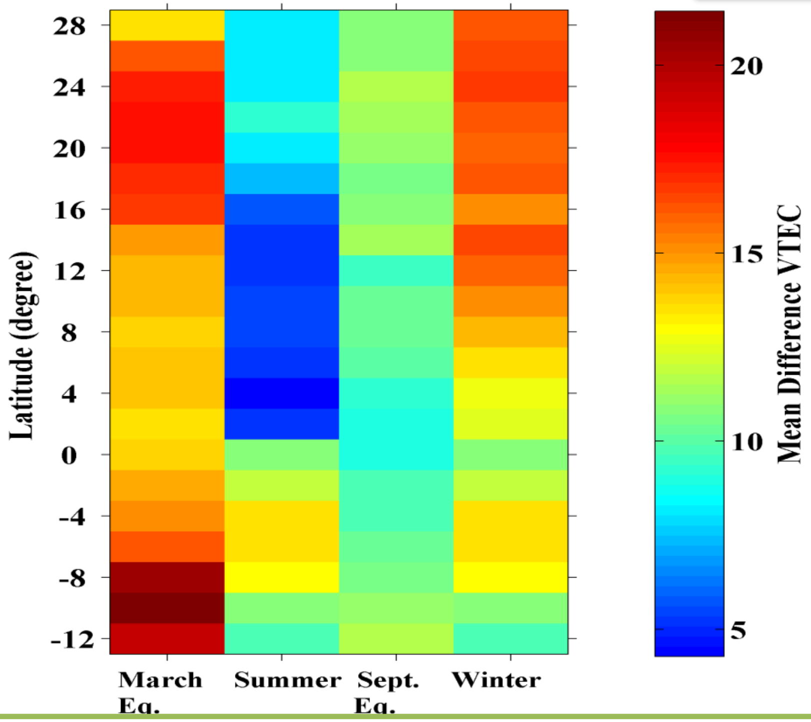
# Minor storms

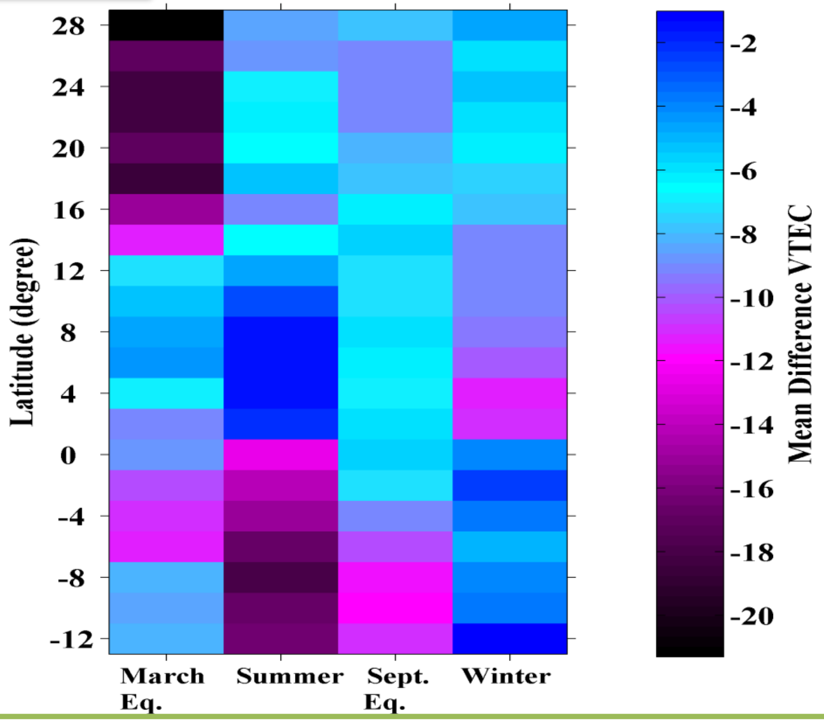



- ✓ storm time VTEC is detrended with monthly mean VTEC essentially removing background seasonal variations
- ✓ color bars for EP and EN are chosen such that the full range of mean ΔVTEC for positive and negative values is covered.
- ✓ ΔVTEC varies from 11 TECU to 9 TECU for EP and EN
- ✓ the magnitude of severity remains same in case of minor EP and EN ionospheric storms, although occurrence of EP is higher than EN
- ✓ Enhanced perturbation magnitudes around the EIA crest locations irrespective of season; dominant effect of equatorial electrodynamics on distribution of electron densities during storms.

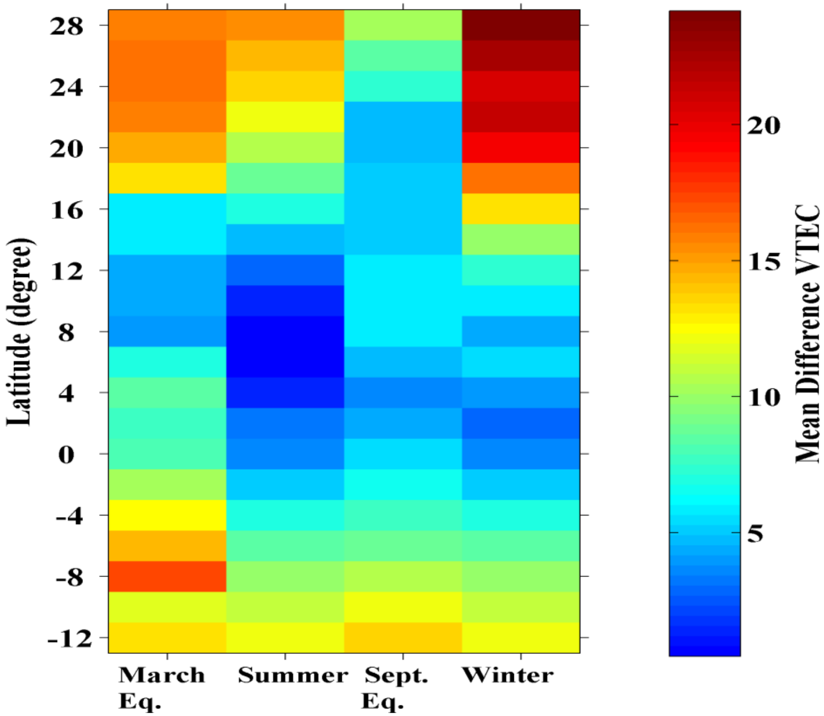
# Moderate storms

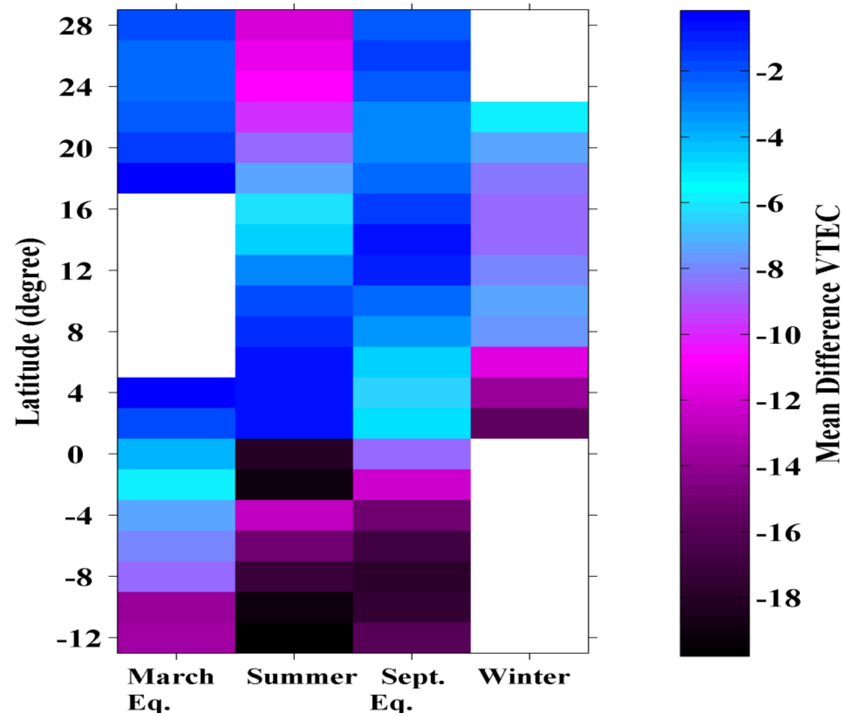



- ✓ March equinoxes show the highest ΔVTEC for EP with a latitudinal distribution similar to a well-developed EIA
- ✓ September equinoxes show a flat latitudinal difference at about 9–12 TECU. The summers show a low at ~6 TECU
- ✓ winters show a decrement with latitude from northern to southern hemispheres in case of EP storms
- ✓ March equinoxes show highest but in northern hemisphere and summer show high in
- ✓ southern hemisphere.
- ✓ ΔVTEC remains mostly in the range of 10 to 15 TECU under EP and 2 to 8 TECU under EN cases, wherein lower values are mostly found in equatorial regions

# Major storms




- ✓ For positive effective storms, ΔVTEC is noted as high as ~25 TECU in northern winters
- ✓ For negative effective storms, it is as low as 20 TECU in southern summers
- ✓ Extreme latitudinal difference in such cases is reported for the first time from Indian region
- ✓ A pronounced EIA kind of ΔVTEC distribution is quite obvious under EP storms in all seasons and for EN storms except in March equinoxes.

- ❑ The lowest ΔVTEC is found during summers over equator in both EP and EN storms.
- ❑ As a general feature, the magnitude of ΔVTEC is found lower around equator and peaking around crest locations in low latitudes akin to EIA.

# Summary

- For the first time a rigorous analysis specific to response of low latitude ionosphere for three storm categories bifurcated into two daytime sectors namely forenoon and afternoon hours covering solar cycles 23 and 24
- Effective positive and negative seasonal statistics are obtained with latitudinal mean seasonal VTEC perturbations.
- The result would be useful for a statistical forecast of ionospheric response to a given storm which can be obtained from Dst index criteria to perform an empirical forecast

- A new criterion to declare the effectiveness of an ionospheric storm in low latitudes is generically defined by standard deviation of quiet time monthly mean diurnal VTEC
- This definition can be further used for comparative studies of ionospheric response at different longitudes and time periods and hence is an important outcome of this study.

- ✓ Latitudinal pattern similar of EIA is obvious in effect of storms in low latitudes. When compared to March equinox, the peak occurrences of total and effective number of storms are found to be more in September but reverse is true for perturbations in VTEC.

# Acknowledgements


- We thank Prof. Patricia Doherty, Prof Sandro Radicella and Organizing committee for full financial support to attend this meeting.

- We thank S. Schaer, H.A. Marques, and S. Hilla for providing the Fortran and C++ codes to process IONEX data

Data Sources Thankfully acknowledged -

- ftp://cddis.gsfc.nasa.gov/pub/gps/products/ionex/
- http://www.spaceweather.gc.ca/solarflux/sx-5-eng.php
- http://wdc.kugi.kyoto-u.ac.jp/dstae/index.html


## Thank You Very Much

Thank you