Comments on, "**Latitudinal variations of ionospheric-thermospheric responses to Geomagnetic Storms from Multi- Instruments**" by Shahzad et al

General comments:

Using ground and space-based multi-instruments the authors investigated the longitudinal and latitudinal variations of ionospheric total electron content and the plausible reasons during the geomagnetic storm conditions. The strength of this study is the multi-instrument data however the presentation is not clear. For example, the authors used GNSS TEC, SWARM-TEC, and TIMED-O/N2 but they did not talk about the co-incident time of these three different measurements and how these observations agree or disagree with each other. Instead, they only mention the overall changes. There are more figures but the scientific content them are not explored. Moreover, it is very hard to follow the result section because the GNSS data is for a particular location and the SWARM and TIMED-O/N2 are on the global map. First, the authors should compare these parameters where the GNSS data is available which is more important for this study then they can give additional information about other locations. In my opinion, this manuscript needs a major revision. Therefore, I recommend to the editor for a major revision. The detailed comment and suggestions are as follows:

Dear Reviewer thanks for your suggestion and useful comments. We have tried to improve the discussion as per your comments.

In the results section:

There is no clear information about how the authors differentiate the day-to-day variation and storm-induced variations in the TEC. Moreover, the TEC variation at different locations may due to local time variations. This point should be clarified.

Ans:

Asia, and Oceania region effect during the 2 geomagnetic storms (Figure 4). The results show normal behavior before the commencement of storm (i.e., two days before SSC). However, during the storm, several regions at the low-latitude exhibited vTEC enhancements twice larger of the nominal value. During the initial phases of both storms, no clear enhancements occurred at the low

anomalies during the recovery phases of both storms. During both storms, quite days exhibited similar vTEC pattern before the SSC and after the recovery phase, as seen in AUCK, STK2 and YSSK stations in figure 5. However, in South America region, the SANT station exhibited similar trend in 2015 during the quite days, but in 2018 the vTEC values were slightly higher than the pattern before the SSC.

What do the authors mean by anomalies? How does it differ from the daily variation? How the anomalies are defined?

Ans: Anomaly is a term used for something that is different from the normal trend. Anomalies were defined by comparing the vTEC pattern of both quiet and disturbed days with respect to different storm phases by considering the vTEC behavior at that specific time. It was observed at various region the vTEC values exhibited unusual behavior in respond geomagnetic storms through multiple sources.

The authors' wish to convey a message from the GIMs model is not clear. How much does the model agree or disagree with the observation? Clarify it.

Ans: Thank you very much for this suggestion, we have included descriptions about the model performance.

"The TEC variations in GIMs for both storms are shown in Figures 7-8. In general, the model performs very well as a quiet-time background, with deviations up to approximately ±5 TECU previous and afterwards the storms. These results are obvious in Africa and Asia, while in America the deviations are more prominent after the storm. The residuals clearly show the short-term variations due to magnetospheric forcing; i.e., those variations mainly caused due to geomagnetic storms. The deviations during the storms reach up to approximately ±20 TECU, mostly at the low latitude regions. During the storm…"

Discussion:

Lines 369-374: These are vague arguments! First of all the exact time of these three different observations should be mentioned before the comparison! At least, there should be a table that should show the VTEC of these three measurements with coinciding time.

Ans: Thank you very much for your concern, the phases of the storms are indicated in the plots to identify the time of events. We have revised the text with more appropriate descriptions.

"All the 3 sources of VTEC data used in this study, i.e. GNSS, Swarm, and IGS GIM TEC, have reflected similar responses to the storms. Several minor differences are seen, specifically between GNSS and IGS GIM TEC, mostly due to local anomalies not well represented by GIMs of TEC (Lisa et al. 2020). The PPEF and thermospheric O/N2 variations show a clear agreement with TEC variability. Smaller PPEF, O/N2 and TEC variations are detected during the 2018 storm than during the storm of 2015. Positive TEC enhancements…"

Lines 408-413: It is hard to see these results from the figures presented in this study.
Ans: With all the respect, note figure 12 is representing PPEF variation in longitude, so that the variation can be localized.

Line-by-line comments:

Line 57, The Ionospheric irregularities… unknown. These references cited here are not relevant to the above statement. Corrected
Ans:

Moreover, GNSS based TEC and in-situ data from multi-instruments describe the ionosphere abnormalities in different spatial and temporal resolution at different latitudes during solar and geomagnetic conditions (Donat et al. 2018). The ionospheric irregularities have significant effects

Line 187, equation (5), in the original equation from Ley Huy and Amory-Mazaudier, did not include the Ho, and H is **Δ**H in their equation. Since the authors use the equations from other paper better to use the equation and the symbols as it is. Done
Ans:

components of the magnetic field (i.e., $H = \sqrt{X^2 + Y^2}$). The observed ΔH component corresponds to the current flow into the magnetosphere-ionosphere systems (Cole, 1966). The equation is as follows:

$$\Delta H = S_R + D \quad (4)$$

system, respectively (Zaourar et al. 2017). According to Le and Amoray-Mazaudier (2005), the ΔH component can be rewritten as follows:

$$\Delta H = S_R + D_M + D_{iono} \quad (5)$$

$$D_{iono} = \Delta H - D_M - S_q \quad (6a)$$

$$S_q = \langle \Delta H^{quiet} \rangle = \frac{1}{n} \sum_{i=1}^{n} \Delta H_i^{quiet} \quad (8)$$

The EEJ at each station is computed by differences of the ΔH component inside and outside the EEJ region at similar longitudes. These differences are related to the contribution of the EEJ current (Anderson et al. 2004):

$$EEJ = \Delta H_1 - \Delta H_2 \quad (9)$$

In equation 9, ΔH_1 and ΔH_2 are the average of ΔH components inside and outside the EEJ region,

Lines 203-210, Provide more detail about which are the stations used inside EEJ and which stations are considered as outside EEJ in this study. Done
Ans:

In equation 9, ΔH_1 and ΔH_2 are the average of ΔH components inside and outside the EEJ region, respectively. Furthermore, during the geomagnetic storm of 2015, ΔH component from the EEJ zone, including HUA (America), GUA (Pacific Ocean), and MBO (Africa), were compared with the stations outside the EEJ zone but within or near the longitude of aforementioned stations. For the 2018 storm, EEJ were computed by comparing HUA and OTT for America region; GUA and CTA for Pacific Ocean region; DLT and LZH for Asia region.

From Figures 2 & 3, How does the SSC are identified? I feel from the Dst of figure 2 the SSC1 should be around 18 UT but the authors marked it at 05:46 UT why?
Ans: As it is well known SSC is the sudden increase in the magnetic field on the dayside of the Earth and magnetopause compression due to its interaction with solar winds. In figure 2, at 22/05:45 a small hock is observable. During this shock, not much change was exhibited but the wind speed increases from 350-430 km/s along with IMF Bz fluctuation from northward to southward i.e., ~6nT to ~-10nT.

Line 228, Does the solar wind speed have any role in the IMF Bz variations? If not then no need the emphasis the solar wind speed in that sentence.

Ans: IMF Bz variation is not affected by the solar wind speed. Speed is mentioned in this sentence to give more detail about the solar wind parameters.

Line 251, similar intensity in which parameter?

Ans: Both storms were of comparable intensity in terms of Dst. Both storms exhibited -210<Dst<-170nT along with Kp max 8. It has been corrected as:

variations during the main phase. For the South American stations, only the KOUR showed significant variability. Although both storms are of comparable intensity, vTEC enhancements of

Line 254 remove the space between 18 and < Done

Line 280, Do the authors think 2TECu variation is an enhancement? Remember that the error is the TEC estimation itself few TECu. Comment on it.

Ans: In that specific station vTEC values vary between 1-8TECu. 2TECu was considered as an enhancement because according to previous day (i.e., quiet day) pattern vTEC was decreasing but in relation to geomagnetic storm a variable increase was observed.

Line 281, depletion: How much reduction in the TEC is considered depletion?

Ans: According to line written there, vTEC was rising after the initial phase. But afterward a sudden 3 TECu drop was observed.

Lines 305-309, Does the time of vTEC and O/N2 observations are similar? If not then the argument is not valid.

Ans: Dear reviewers: 'Using GUVI, we showed the longitudinal behavior profile to confirm the thermospheric contribution to ionosphere variations. Furthermore, GUVI provide diurnal profile. Which we compare with ionosphere variation in different regions.'

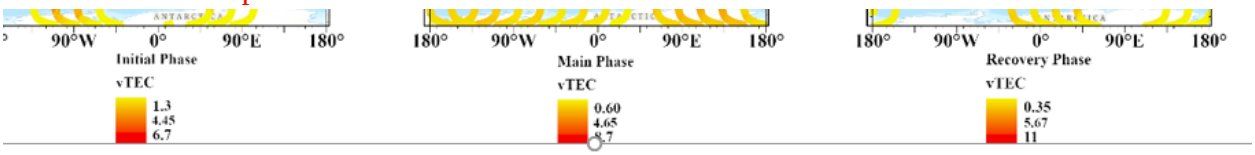
From figures 10 and 11 it is very hard to interpret the TEC variations, the TEC range from the color bar looks like a daily and latitudinal variation rather than the storm-induced variation. Comment on it. Better to make the color bar clear with more tick labels.

Ans: These variations are positively correlated with vTEC derived from various GNSS stations with respect to various geomagnetic storm phases over the globe.

More ticks have been added in both figures.

In figure 11, VTEC is negative! How is it possible?

Ans: There was a problem with ArcGIS Pro. It has been corrected.



Lines 416-417: The ionosphere…satellite data. It is well known. What is the new message here, emphasis on it?

Ans: Dear reviewers: As mentioned in the text. 'In this work, PPEF variability has demonstrated strong influences to TEC variability. High PPEF was detected in East and West regions during both storms, depicting clear variations in Oceania and not in the American sector. As the storm commenced, Asia, Oceania, and Russia exhibited VTEC enhancements at the low- and mid-

latitudes due to PPEF. Storm time variations at the low- and mid-latitudes were generated by a large fountain effect, creating a stronger EIA. In fact, many researchers (Manucci et al. 2005; Abdu et al. 2007; Sharma et al. 2011; Lu et al. 2013) have reported these effects. The ionosphere exhibited a variable response along different longitudes. This has also been confirmed by different magnitudes of PPEF and satellite data (Figure. 4-8 & 10-12).' Using multiple satellite data, we demonstrated these variations in multiple regions and linked them to various storm phases.