Dear Editor,

I would like to sincerely thank you for you valuable comments in an effort to improve my article.

In the revised version I have already addressed your concerns:

1) From my side, I would like to point out that the space weather event you analysed, was very interesting, but complicated. Four days-long period before the storm maximum was under the diminishing influence of a positive polarity coronal hole high speed stream (CH HSS), when solar wind speed ranged from 430 to 680 km/s with total field between 3-9 nT. According to the warning issued by NOAA, the geomagnetic field was already at the active levels on 5-6 September. Total field increased twice, for the first time it increased to 16 nT at 6 of September at 23:24 UTC and solar wind increased to a maximum of 610 km/s at 23:09 UTC, once more the enhancement was observed at 8 of September at 11:21 UTC to a maximum of 18 nT while the Bz component went southward to a maximum of -17 nT. Geomagnetic sudden impulses of 21 nT (Fredericksburg magnetometer) were observed at 6 of September at 23:48 UTC and 70 nT at the end of the next day with the arrival of both CMEs. In addition, the Earth atmosphere experienced an influence of extraordinary flares (e.g., the M5 flare on 4 of September, X9 flare on 6 of September and the X8 flare on 10 September). The complicated situation before and after the 8 of September, influence of two CMEs gave a rise for some doubts of the referees, if the 8-days running mean is an appropriate measure for the comparison. My suggestion is to discuss in more details important aspects/display and consequences of the event taking into account significant dependences of the ionospheric response at different locations.

Thank you very much for the detailed description as to what happened before and after the storm, I really appreciate it. Indeed, this is a complicated one. As I replied to referee #2, I ran my code using as well a 9-days or 10-days running window and the results are indistinguishable (please, see attached figure 1 and 2). Thus I think there is no need to have doubts on the results. Moreover, very recently, a new study (Sotomayor-Beltran, International Journal of Geophysics, vol. 2018, 2018) has used a 8-days runnning window showing good results. Hence, I believe in this case as well the statistical method used should not rise any doubts. In the references citing the statistical method ("Data and methods" section), the work from Sotomayor-Beltran 2018 was added as well.

As for the paper Edemskiy et al. Ann. Geophys. vol 36, pp. 71-79, the authors were discussed particularly the anomalous feature which was observed at higher latitudes of the Southern Hemisphere (please, see the area indicated by the black ellipse in the middle panel of the figure below). If you see in your data some similar phenomenon, then it would support the finding published in the Edemkiys paper.

Figure 1: Differential VTEC map for September 7 using 9-day running window

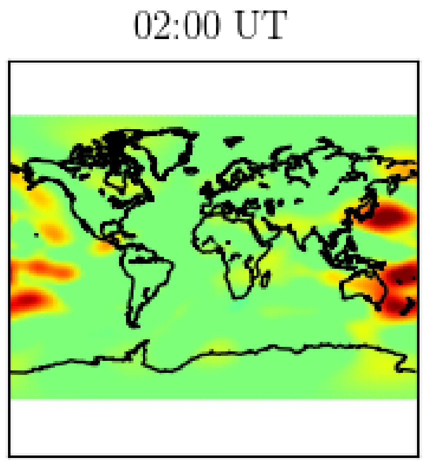
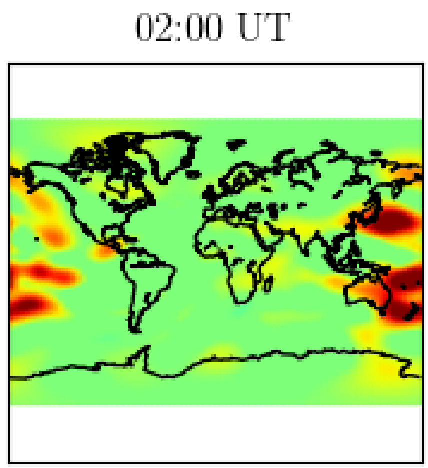


Figure 2: Differential VTEC map for September 7 using 10-day running window



Yes, you are correct, Edemskiy et al. Ann. Geophys. vol 36, pp. 71-79, 2018 paid particular importance to the higher latitutde LTE. However, in view of the new recent study (Sotomayor-Beltran, International Journal of Geophysics, vol. 2018, 2018), that supports also the finding of Edemskiy et al. Ann. Geophys. vol 36, pp. 71-79, 2018 and does not present a high latitude LTE, only one at $\sim 44°$S, I believe the findings for the September 8, 2017 storm will undoubtedly provide further support to the work of Edemskiy et al. Ann. Geophys. vol 36, pp. 71-79, 2018. The LTE that appeared during the April 20, 2018 storm was also mentioned in the "Introduction" and "Results and Discussion" sections

Response to Referee #1

Firstly I would like to sincerely thank the referee for his/her valuable comments in an effort to improve my article.

In the revised version I have already addressed all the concerns of referee #1:

1) Total electron content (TEC) enhancements during ionospheric storms of 2017 and 2015 are analyzed in the paper. The author uses his own method of determining deviations in TEC during a storm from quiet conditions. In the majority of ionospheric storm studies, the deviations in foF2 or TEC are studied comparing observed values of the studied parameter with its values during the preceding quiet days, or with a median. The author presents a brief discussion of the method used in the paper (Section 2), however the description is not clear. As far as I understand, for each spatial sell of the data, the 8-day running window is used to calculate the median (X). However, the median is not mentioned later in the text. The formulae (1) and (2) for the upper and lower bounds (UB and LB, respectively) relate UB and LB to μ and σ (UB = μ+σ and LB = μ σ), ... were μ and are the mean and standard deviation, respectively. One could understand form this determination that μ is a mean deviation. However then formulae (1) and (2) became senseless, because UB and LB would have a dimension of errors, but not of absolute values of TEC. If the author means that μ is a mean value, then it is not clear how it has been obtained. Probably, X should stand in formulae (1) and (2) instead of μ. Then at least, the formulae would be understandable.

The brief description of the statistical method indeed is not that understandable as it appears in the paper. But the method (equations) I am following and which I implemented in my software are the ones used and shown in detail in the paper of Zhu et al., 2010. In view of this, I will change lines 19-21 in page 2 with the following text to keep equations (1) and (2) as they appear in the manuscript: "... Li et al.,2015). Assuming that for each cell or line-of-sight the VTEC follows a Gaussian distribution, the mean (μ) of the 8-day VTEC and its associated standard deviation (σ) are calculated in order to define the upper and lower bounds:". If desired I can add the exact calculation of the mean and the standard deviation. However, this will be basically the same as the ones that appear in the paper of Zhu et al., 2010.

2) The description of the results begins from an error. In the first paragraph of Section 3, Figure 1 is considered. In this paragraph, March 7 and March 8 are mentioned while considering this figure. However, it follows from the caption to Figure 1 that the figure contains data for September, 2017. Obviously, March 7 and March 8 in the text should be September 7 and September 8, respectively.

This is correct. I have already changed in lines 17 and 19 of page 3 the month of March with the month of September (the correct one).

3) Figure 1 does not have dates at the abscissa (only numerals 2), so it is impossible to relate the behavior of geomagnetic and interplanetary indices to UT and dates and to compare this behavior with the TEC data shown in Fig. 2.

This is correct. In the manuscript version ready to download from the ANGEO website these dates are missing. However, I noticed this a couple of days after my manuscript went online. Reason why, I posted the corrected figures as a comment on July 13, 2018 (which is online in the interactive discussion area). I believe this was a problem with the font types. Now, I am using ones that do not disappear. All figures are now complete.

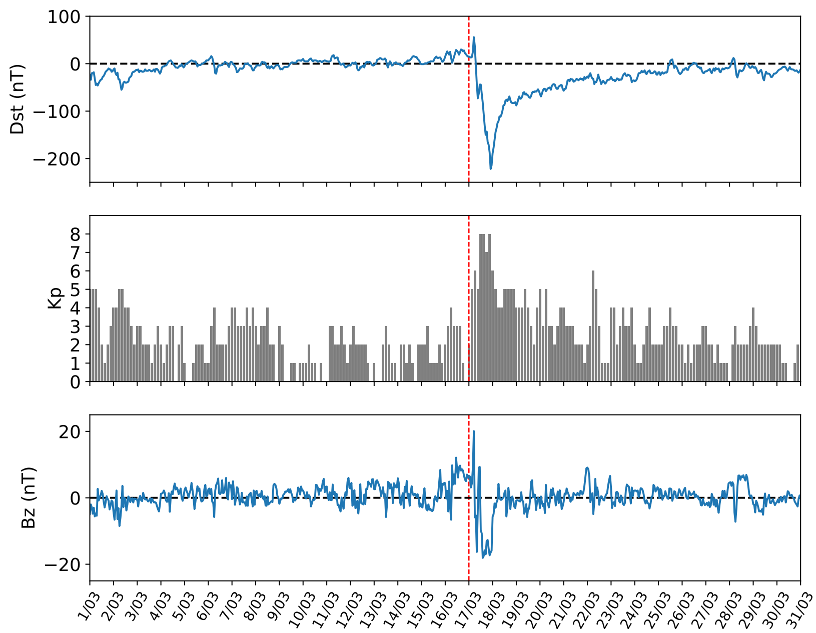
4) Besides the comments made above, I think that a figure similar to Figure 1 should be included for the March 2015 storm in order to make it possible to compare the data in Fig. 4 with the behavior of geomagnetic and interplanetary indices.

A new figure has been produced (attached to this reply) and its description added to the paper.

5) The language of the paper is poor and needs a serious improvement.

It is correct and my sincere apologies because my mother tongue is not English. I have once again thoroughly checked for typos or gramatic mistakes, and all that needed to be changed has been corrected in the revised version.

Figure 3: The Dst and Kp geomagnetic indices and the southward interplanetary magnetic field (B z) for the month of March 2015. The vertical red dashed line in all the plots indicates the day that the 2015 St. Patricks day storm occurred (March 17, 2015).



Response to Referee #2

Firstly I would like to sincerely thank the referee for his/her valuable comments in an effort to improve my article.

In the revised version I have already addressed all the concerns of referee #2:

1) Abstract A common response to geomagnetic storms due to the southern vertical interplanetary magnetic fiel (Bz) is the enhancement of the electron density in the ionosphere. This statement general is incorrect. Not all ionospheric storms start with a positive phase. The storm pattern depends on season, longitudinal sector, the intensity of a geomagnetic storm, LT of a magnetic storm commencement.

Yes the statement as it is, is incorrect. On the other hand, I am well aware that the storm pattern depends on season, longitudinal sector and the intensity of a geomagnetic storm. Thus to properly express the statement, I have changed "A common response to ..." to "One of the responses to ..."

2) Looking at the figure 2 I see that the increase of TEC is more extended versus the mid-latitude in the Southern hemisphere but it is possible to see it also in the northern hemisphere. So for my point of view is not a localized enhancement .Looking at the paper by Lei et al. (2017 - 0.1029/2017JA02516) that analyze the same event with TEC and ionosonde data and in their figures it can be seen an increase of differential TEC for all latitudes in the first hours of 8 September, that corresponds to the storm main phase, in the northern hemisphere and in the southern also(but they arrive at 24 degree in latitude)that correspond to a positive ionospheric storm. In the following days a negative ionospheric storm occurred from higher to lower latitude. So it is a typical ionospheric storm with a positive and negative phase , the physical mechanism for the positive phase occurred at 02UT(daytime) that the author identify as a localized event seeing only the figure at 2UT could be due to an expanded convection electric field dur- ing geomagnetic storms in these cases frequently it is observed dTEC enhancements in the mid latitude dayside ionosphere but more investigations are necessary.

As you are pointing out more investigations are necessary for the "expanded convection electric field dur- ing ...". I am also indiating in the very last sentence of the conclusion section that further observations are necessary because the meachnism I am putting forward (a contribution of the super-fountain effect) is not my definite conclusion. Based on Fig.3 from Edemskiy et al. Ann. Geophys. vol 36, pp. 71-79, 2018, if you could observe at the LTE (plume) located at 35°S, this LTE has an extended shape along the mid-latitude, which is similar to the one I am indicating for the September 8, 2017. Hence, following the published results from Edemskiy et al.2018, it is my point of view that the extension south of the EIA during the September 8, 2017 storm is a LTE.

3) L 6 P1 What is the G4 storm? G4 should be explained

I removed G4 from L6 P1 and the title and explaining what it is in the first paragraph of the ”Results and dicussion” section.

4) L8 P1 what it is was unexpected Grammar

Thank you very much I corrected this to: what it was unexpected

5) L26 P1 Global Navigation Satellite System (GNSS) receivers, due to its global cover- age, are used as one of the main tools for ionospheric studies. This is not so. The whole morphology of ionospheric storms has been obtained and understood using the world-wide ground-based ionosonde network observations. Only vertical ionospheric sounding gives directly electron concentration in the ionospheric layers. VTEC on one hand is obtained from slant TEC observations on the other hand it includes the plasma- spheric part which is not related to the underlying ionosphere. For this reason VTEC may be only considered as a complementary source of information for such type of analysis.

Yes, I am aware that the ionosondes provide directly electron concentration in the ionospheric layers. However I guided myself from the paper of Hernandez-Pajares et al, J Geod vol 83, pp. 263-275, 2009: ”The IGS VTEC maps: a reliable source of ionospheric information since 1998”. I have then changed in L26 P1: ”.. are used as one of the main tools for ionospheric ..” to ” .. are used as one of the tools for ionospheric ..”

6) L 18 P2 . . .we apply a running window of 8 days. . . Why 8 day window? What is the idea for such choice? What to do with such background if these 8 previous days were disturbed?

What I have seen in several works is 10 day window (Liu et al., Ann Geophys., 2004; Hasbi et al., NHESS 2011; Li et al., Geodesy and Geodynamics 2015; Sharma et al., Quaternary International 2017). I have actually ran my software for 8, 9, 10 ,11, and 12 days and the results of the maps were quite indistinguishable. I have chosen a 8 day window due to the quantity of IONEX files I downloaded from CODE, and which allowed me to see the behavior of the ionosphere in DVETC maps 4 days after the storm. If it is a wish I could changed the maps to the result I get from a 10 day window, but as I mentioned there won’t be a noticeable change.

7) L 17 P3 Figure 1 shows that Kp = 8 during the last 3 hours (UT) of March 7 and the first three hours of March 8. March has not been discussed yet in the paper.

Thank you very much for pointing that out. I corrected from ”March” to

"Spetember". It was also one of the concerns from referee #1.

8) A positive storm phase (the first phase) of a two-phase ionospheric storm is a normal reaction of the day-time mid-latitude ionosphere to a strong geomagnetic storm (started in the daytime sector). Some examples and mechanisms may be found in J. Atmos. Solar-Terr. Physics., 81-82, 59-75, 2012. Two types of positive disturbances in the daytime mid-latitude F2-layer: Morphology and formation mechanisms.

L 1 P 5 Looking at the figure 2 I see that the increase of TEC is more extended versus the mid-latitude in the Southern hemisphere but it is possible to see it also in the north- ern hemisphere. So for my point of view is not a localized enhancement .Looking at the paper by Lei et al. (2017 - 0.1029/2017JA02516) that analyze the same event with TEC and ionosonde data and in their figures it can be seen an increase of differential TEC for all latitudes in the first hours of 8 September, that corresponds to the storm main phase, in the northern hemisphere and in the southern also(but they arrive at 24 degree in latitude)that correspond to a positive ionospheric storm. In the following days a negative ionospheric storm occurred from higher to lower latitude. So it is a typical ionospheric storm with a positive and negative phase , the physical mechanism for the positive phase occurred at 02UT(daytime) that the author identify as a localized event seeing only the figure at 2UT could be due to an expanded convection electric field dur- ing geomagnetic storms in these cases frequently it is observed dTEC enhancements in the mid latitude dayside ionosphere but more investigations are necessary.

This concern is basically the same as concern 2) in page C2 of you interactive comment. Hence I give the same reply that I give to comment 2):
As you are pointing out more investigations are necessary for the "expanded convection electric field dur- ing ...". I am also indiating in the very last sentence of the conclusion section that further observations are necessary because the meachnism I am putting forward (a contribution of the super-fountain effect) is not my definite conclusion. Based on Fig.3 from Edemskiy et al. Ann. Geophys. vol 36, pp. 71-79, 2018, if you could observe at the LTE (plume) located at 35°S, this LTE has an extended shape along the mid-latitude, which is similar to the one I am indicating for the September 8, 2017. Hence, following the published results from Edemskiy et al.2018, it is my point of view that the extension south of the EIA during the September 8, 2017 storm is a LTE.

In general the paper does not present either any new morphological effect or physical interpretation. I cannot recommend this paper publication.

As in the paper of Edemskiy et al. Ann. Geophys. vol 36, pp. 71-79, 2018, my work presents a new result in the area of LTEs, so I am convinced that it can provide further insights to the community working in this field. I believe as well there is some physical interpretation to my results. One of them, is that looking into Fig. 3 for the day of the storm (Spetember 9, 2018) the EIA increases, as a consequence of the super-fountain effect, and the crests expand towards the poles. I guess it would have been a breakthrough if for instance the crests would have moved towards the magnetic equator, but still I believe there is a physical interpretation in my work.

Emergence of a localized total electron content enhancement during the ~~G4~~ severe geomagnetic storm of September 8, 2017

Carlos Sotomayor-Beltran[1]

[1]Image Processing Research Laboratory (INTI-Lab), Universidad de Ciencias y Humanidades, Lima 39, Peru

Correspondence: Carlos Sotomayor-Beltran (csotomayor@uch.edu.pe)

Abstract.

In this work, the first results of the analysis on total electron content (TEC) data before, during and after the geomagnetic storm of September 8, 2017 are reported. ~~A common response~~ One of the responses to geomagnetic storms due to the southern vertical interplanetary magnetic field (B_z) is the enhancement of the electron density in the ionosphere. Vertical TEC (VTEC) from the Center for Orbit determination in Europe (CODE) along with a statistical method were used to identify positive and/or negative ionospheric storms in response to the geomagnetic storm of September 8, 2017. When analysing the response to the ~~G4~~ storm of September 8, 2017 it was indeed possible to ~~observed~~ observe an enhancement of the equatorial ionization anomaly (EIA); however what it ~~is~~ was unexpected, was the identification of a local TEC enhancement (LTE) to the south of the EIA (∼40° S, right over New Zealand and extending towards the south-eastern coast of Australia and also eastward towards the Pacific). This was a very transitory LTE that lasted approximately 2 hours, starting at ∼02:00 UT on September 8 where its maximum VTEC increase was of 241,2%. Using the same statistical method we looked for LTEs in a similar category geomagnetic storm, the ~~G4 storm of~~ 2015 St. Patrick's day ~~of 2015~~storm; however for this storm, no LTEs were identified. As also indicated in a past recent study for the August 15, 2015 geomagnetic storm, an association between the LTE and the excursion of B_z observed during the September 8, 2017 storm is observed. Nevertheless, it is more likely that a direct impact of the super-fountain effect along with another ionospheric physical mechanism may be playing an important role in the production of this LTE. Finally, it is indicated that this LTE is the second one to be detected during the current solar cycle minimum (24-25).

1 Introduction

Anomalies in the ionosphere can be product of different natural phenomena (Afraimovich et al., 2013). For instance earthquakes can produce positive or negative ionospheric anomalies (e.g., Zakharenkova et al., 2008; Yao et al., 2012; Guo et al., 2015; Li et al., 2015), although such variations are expected to be localized within the earthquake's preparation region (Dobrovolsky et al., 1979). On the other hand, major changes in the ionosphere are caused by geomagnetic storms (e.g., Buonsanto, 1999; Danilov, 2013). The response of the Earth's ionosphere to the geomagnetic storms are known as ionospheric storms. These ionospheric storms can disrupt technologies relying on transmission of radio frequencies (e.g., Buonsanto, 1999; Borries et al., 2015), and thus they can have an impact in the modern society in general.

In order to understand better ionospheric variability in time and space produced by geomagentic storms, Global Navigation Satellite System (GNSS) receivers, due to its global coverage, are used as one of the ~~main~~ tools for ionospheric studies. According to several studies (e.g., Huang et al., 2005; Mannucci et al., 2005; Astafyeva, 2009), one common response to a geomagnetic storm due to the excursion of the southward interplanetary magnetic field is the significant increment in the equatorial and mid-latitude total electron content (TEC), which manifests as an enhancement of the equatorial ionization anomaly (EIA; Appleton, 1946; McDonald et al., 2011). Such increase of TEC in the EIA is possible to visualize in global ionospheric maps (GIMs). Besides changes in the EIA, it was recently observed by Edemskiy et al. (2018) and Sotomayor-Beltran (2018) that localized TEC enhancements (LTEs) can also emerge as a response to ~~a geomagentic storm~~geomagnetic storms.

In this paper vertical TEC maps, also known as global ionospheric maps (GIMs), due to its reliability on ionospheric information (Hernández-Pajares et al., 2009), were used to analyse the response to the geomagnetic storm of September 8, 2017. Section 2 introduces the ionospheric data and the technique for the corresponding analysis. In Sect. 3 the results and the discussion are presented. Section 4 presents the final remarks or conclusions.

2 Data and methods

VTEC maps were downloaded via ftp[1] from the Center for Orbit Determination in Europe (CODE) between August 21, 2017 and September 20, 2017. VTEC maps, which have a resolution of 2.5° x 5° (latitude and longitude, respectively), come in daily IONnosphere Map EXchange files (Schaer et al., 1998) and they are produced every hour. Due to the format of the IONEX files, which consists of headers and the actual VTEC data, a code entirely written in Python was implemented for this work. Using the NumPy[2] library, which handles relatively easily N-dimensional arrays, the VTEC data was stored in a 3D cube for further analysis. The x, y and z axes in the 3D cube are longitude, latitude and number of maps, respectively.

In order to indentify ionospheric anomalies ~~we apply~~ a running window of 8 days to every cell in the 3D VTEC cube ~~(e.g., Liu et al., 2004; Zhu et al., 2010; Zou and Zhao, 2010; Li et al., 2015). Within this window the median ($\bar{X}$) and the interquartile range (IQR~~is applied (e.g., Liu et al., 2004; Zhu et al., 2010; Zou and Zhao, 2010; Li et al., 2015; Sotomayor-Beltran, 2018). Assuming that for each cell or line-of-sight, the VTEC follows a Gaussian distribution, the mean (μ) VTEC and its associated standard deviation (σ) are calculated in order to define the upper and lower bounds~~. However, assuming that the VTEC data follows a normal distribution within the window, the upper and lower bounds can be defined as~~:

$$UB = \mu + 2\sigma, \tag{1}$$

$$LB = \mu - 2\sigma. \tag{2}$$

[1] ftp://ftp.aiub.unibe.ch/CODE/

[2] http://www.numpy.org/

were μ and σ are the mean and standard deviation, respectively. If a VTEC value for a certain day at a particular time falls above the UB, then a positive ionospheric anomaly is detected with a confidence level of 95%. The difference between the VTEC and UB or LB is defined as differential VTEC (ΔVTEC). On the other hand, if the VTEC falls bellow the LB, then a negative anomaly is detected. In this way, a cube of ΔVTEC is created, with a total of 744 maps. If $UB >$ VTEC $> LB$, then ΔVTEC = 0

Some important geomagnetic parameters are also needed to be taken into account for the analysis. The Dst index (Sugiura, 1964) provides information about the strength of the ring current around the Earth. According to Loewe and Prölss (1997) a magnetic storm can be considered as weak when -50 nT $<$ Dst $\leq$ -30 nT. A moderate and strong storm occurrs when -100 nT $<$ Dst $\leq$ -50 nT and -200 nT $<$ Dst $\leq$ -100 nT, respectively. Finally, a severe storm happens when Dst $\leq$ -200 nT. For this study Dst data for the month of September 2017 was downloaded from World Data Center for Geomagnetism in Kyoto[3]. Another very important index which measures the fluctuations caused in the Earth's magnetic field by a geomagnetic storm is the Kp index. According to Gosling et al. (1991) when Kp $\geq$ 8- and Kp $\geq$ 6- for at least three 3-h intervals, the storm can be considered a major one. A large storm occurs when 7- $\leq$ Kp $\leq$ 7 and Kp $\geq$ 6 for at least three 3-h intervals. For other cases when Kp $\geq$ 6- for at least three 3-h intervals the storm can be considered of medium strength. Finally, a small storm happens when -5 $\leq$ Kp $\leq$ 5. Kp data for September 2017 was retrieved from the German Research Centre for Geosciences (GFZ[4]). The vertical interplanetary magnetic field (B_z; Tsurutani et al., 1988) also is a good indicator of a geomagnetic storm. When there is a strong southward B_z for more than 3 hours a geomagnetic storm is in development (Gonzalez et al., 1994; Liu and Li, 2002). Hourly averages from for B_z where dowloaded from the OMNI datasabe[5]. In Fig. 1 the Dst and Kp indices and also the southward interplanetary B_z (in geocentric solar magnetospheric coordinate system) can be observed for the month of September 2017.

3 Results and discussion

Figure 1 shows that Kp = 8 during the last 3 hours (UT) of March September 7 and the first three hours of March September 8. According to the National Oceanic and Atmospheric Administration (NOAA) space weather service[6], this geomagnetic storm can be classified as a G4 severe storm (Kp = 8). Additionally, for March September 8, 2017 between 00:00 and 04:00 UT the Dst index had values lower than -100 nT (Fig. 1).

The origin of this geomagnetic storm lies in the coronal mass ejection (CME) that occurred on September 6, 2017 at ~12:40 UT. This CME was observed with the Camera 2 of the Large Angle and Spectrometric Coronograph on board of the Solar and Heliospheric Observatory (SOHO[7]). Figure 1 also shows that on September 8 at ~00:00 UT the vertical interplanetary magnetic field decreased significantly to a minimum of -24 nT. One hour before (September 7 at 23:00 UT), B_z already

[3] http://wdc.kugi.kyoto-u.ac.jp/wdc/Sec3.html
[4] https://www.gfz-potsdam.de/en/kp-index/
[5] https://omniweb.gsfc.nasa.gov/form/dx1.html
[6] https://www.swpc.noaa.gov/noaa-scales-explanation
[7] https://sohowww.nascom.nasa.gov/

decreased considerably to -20.6 nT, time of the storm sudden commencement (Fig. 1). In addition, it can be noticed that almost simultaneously with the drastic change of B_z, the Dst index reached its peak at 01:00 UT on September 8, 2017. This relationship between B_z and the Dst index hints to a physical response of the ring current in the magnetosphere to the interplanetary field B_z (Patel and Desai, 1973; Gonzalez and Echer, 2005).

In the right column of Fig. 2, GIMs for September 7, 8 and 9, 2017 at 02:00 UT are presented. It is clearly seen in the GIM of September 8 at 02:00 UT (just three hours after the storm sudden commencement) that the VTEC was enhanced in the EIA region with respect to the day before (September 7) and the day after (September 9) at the same hour. This increment of VTEC was already observed in previous studies about ionospheric responses to geomagnetic storms (e.g., Zhao et al., 2005; Pedatella et al., 2009; Astafyeva et al., 2015; Chakraborty et al., 2015). Moreover, a ionospheric localized anomaly (∼40° S), or as named by Edemskiy et al. (2018) a localized TEC enhancement (LTE), to the south of the southern conjugate geomagnetic region of the EIA was identified in the GIM map of September 8, 2017 at ∼02:00 UT. This LTE was very transitory, in the ΔVTEC maps it appeared at ∼02:00 UT on September 8 and at ∼04:00 UT it was already gone. In the left column of Fig. 2, ΔVTEC maps for September 7, 8 and 9, 2017 at 02:00 UT are also presented. It can be seen from these ΔVTEC maps that a day before and after that the LTE appeared, no anomalies were visible. However as already indicated, the day that the ionospheric storm occurred (September 8), the dramatic enhancement of the VTEC to the south of the EIA, manifested as a LTE, is observed. This unforseen positive ionospheric storm covers most of New Zealand and extends westward towards the south-eastern part of Australia and eastward towards the Pacific. The maximum peak of this LTE happened as well on September 8 at 02:00 UT with ΔVTEC = 6.47 TECU (where 1 TECU = 10^{16} electrons/m^2). To better visualize this LTE to the south of the EIA, the shape of the VTEC along the meridional line of 170°E is shown in Fig. 3 between September 7 and 9, 2017 at 02:00 UT. From the ΔVTEC maps, it can be confirmed that the EIA follows its normal variability one day after (September 9 at 02:00 UT) and before (September 7 at 02:00 UT) that the storm occurred (no anomalous VTEC enhancements are visible). However, on September 8 at 02:00 UT the EIA is significantly enhanced and hence this translates in a much sharper definition of the double-crest with a trough shape observed in Fig. 3. This shape is expected because when the LTE is above New Zealand, it is still day time, the local time is 14:00 (02:00 UT). In addition to the two crests from the EIA, a third one in the southern hemisphere is visible (Fig. 3). This third crest is simply the LTE observed in the ΔVTEC and GIM maps for September 8 at 02:00 UT. The peak increment for this day and this time in the southern crest of the EIA is of 172% and in the LTE of 241,2%. Edemskiy et al. (2018) ~~has~~ have also reported for the August 15, 2015 G2 geomagnetic storm that the two LTEs they observed were located to the south of the EIA (between Africa and Antarctica)~~.~~, whereas Sotomayor-Beltran (2018) has also identified to the south of the EIA a LTE over the Indian ocean during the G2 moderate storm of April 20, 2018.

In order to look for such LTEs in a similar geomagnetic storm category, the author turned to the G4 geomagnetic storm that happened during the St. Patrick's day of 2015, which has been thoroughly studied (Astafyeva et al., 2015; Cherniak et al., 2015; Nava et al., 2016; Yao et al., 2016; Jin et al., 2017; Zhang et al., 2018). This storm was also product of a CME ~~an~~ and it was reported that the storm sudden commencement was at ∼04:45 UT on March 17, 2015 (Yao et al., 2016). In Fig. 4, the variability of the geomagnetic indices Dst and Kp during the month of March 2015 can be observed. The Kp index reached a value of 8 at 12:00 UT on March 17, 2015, whereas the Dst index started to decrease drastically starting at ∼08:00 UT until

22:00 UT of that same day; at this time it reached its minimum of -222 nT. On the other hand it can also be seen in Fig. 4, that B_z decreases significantly to -16 nT at 08:00 UT. The interplanetary magnetic field remained afterwards with values lower than -10 nT between ∼13:00 and 23:00 UT on March 17, 2015. The statistical method applied to the G4 storm of September 8, 2017 in this paper was also applied to GIMs during the St. Patrick1000Patrick's storm. IONEX files from CODE were downloaded and processed with the Python software written for this work for the range of days between February 27, 2015 and April 3, 2015. Part of the resultant ΔVTEC maps are shown in Fig. 5. Going through the ΔVTEC maps created for the aforementioned range of days, it was possible to observe a positive ionospheric storm starting on March 17, 2015 at ∼18:00 UT right over the southern Atlantic, right north off the Antarctic coast. This positive storm started to move westward and it reached its maximum strength on March 18, 2015 at ∼02:00 UT with a peak of ΔVTEC = 12.88 TECU (Fig. 5). .In this case however, the enhancement of VTEC observed in the southern hemisphere is not a LTE, it is only the sourthern crest of the EIA which underwent an increment of VTEC and shifted some degrees southward. On the other hand in the ΔVTEC maps of March 17, 2015 starting at ∼22:00 UT, negative ionospheric storms were also observed and they lasted until the end of the day of March 18, 2015. These both results agree well with the ones from previous studies, using different methods, for the St. Patrick's day 2015 storm (Astafyeva et al., 2015; Yao et al., 2016). It can also be finally noticed in Fig. 4 in the ΔVTEC maps that at 02:00 UT the day before and the day after the maximum peak of the positive ionospheric storm, the increment or decrement of VTEC are minimal.

For the case of the St. Patrick storm of 2015, when the observed positive storm in the southern hemisphere and negative storm in the northern hemisphere are co-existing (what is also known as hemispheric asymmetry), it could be assumed that the mechanism at work producing this asymmetry was the storm-time thermospheric circulation (Fuller-Rowell et al., 1994; Fang et al., 2012). However according to this theory, the positive ionsopheric storms are expected in the winter hemisphere and the negative ionospheric storms in the summer hemisphere; hence, Astafyeva et al. (2015) and Yao et al. (2016) ruled out this theory as a possibility for the origin of the detected ionospheric storms. They, nevertheless, indicated three more suitable candidates: the strength of the geomagnetic field, the B_y component of the interplanetary magnetic field and composition changes in the thermosphere. On the other hand, for the moderate G2 storm of August 15, 2015 (Edemskiy et al., 2018) there was not a clear mechanism put forward to account for the observed LTEs. Only a dependance of the emergence of these LTEs to the interplanetary B_z was hinted at, but still as indicated by the authors of that study it was not their definite conclusion. For the LTE observed during the September 8, 2017 severe storm in this work, an excursion the interplanetary B_z, along with a consequent decrease of the Dst index, was also observed (Fig. 1). Thus, it can be suggested that there is as well an association between the interplanetary B_z and the emergence of the LTE. As per to the overall enhancement of the EIA (Fig. 2 and 3) and shifting of the crests in the direction of the poles observed in Fig. 3, it is suggested by many studies (e.g., Tsurutani et al., 2004; Mannucci et al., 2005; Astafyeva, 2009; Astafyeva et al., 2014; Chakraborty et al., 2015) that the mechanism at work for this change of shape of the EIA is the ionospheric super-fountain effect. How this effect is connected or contributes to the appeareance of the LTE observed on September 8, 2017 at ∼02:00 UT is still not clear, but that the super-fountain effect is playing an important role in its origin can not be ruled out. A partial contribution of this effect to the production of the LTE observed during the April 20, 2018 storm was suggested by Sotomayor-Beltran (2018). Furthermore, this would be the second time a LTE is detected during the solar cycle 24-25 minimum (Hathaway and Upton, 2016), as the first one was the one observed during the April 20, 2018 geomagnetic storm (Sotomayor-Beltran, 2018).

4 Conclusions

Ionospheric response to the G4 severe geomagnetic storm of September 8, 2017 was analysed by using VTEC maps from CODE along with a statistical method to identify ionospheric anomalies. By producing differential VTEC maps it was possible to identify not only an enhancement of the EIA but also a localized TEC enhancement. The maximum intensity of this LTE was on September 8, 2017 at 02:00 UT and it was localized right over New Zealand and extending towards the south-eastern coast of Australia and eastward towards the Pacific. The LTE was quite transitory, it lasted only about two hours, on September 8 at 04:00 UT it faded away. This LTE is the second one to be observed during the solar cycle 24-25 minimum. By analyzing the latitudinal profiles, it could be determined that the increment in intensity for this LTE was of 241.2%.

Due to its category, the G4 storm from March 17, 2015 was also investigated in order to look for LTEs; however, there was no LTE detections. What is was discovered was a hemispheric asymmetry of ionospheric storms in the northern and southern hemisphere. The origin of this asymmetry was explained in past studies by the strength of the geomagnetic field, the B_y component of the interplanetary magnetic field and composition changes in the thermosphere.

One geomagnetic storm which presented the same traits (LTEs) as in the one of September 8, 2017 was the G2 August 15, 2015 moderate storm. During this storm also LTEs were identified south of the geomagnetic conjugate region of the EIA. These LTEs, was indicated, seem to be associated with the negative excursion of B_z. Because for the September 8, 2017 storm also such negative excursion was observed, it can be suggested then that the vertical interplanetary magnetic field component has an effect on the origin of the LTE. However, due to the fact that the EIA undergoes a dramatic enhancement, the contribution of the super-fountain effect in the generation of the LTE would have to be taken into account as well. To shed more light into how these LTEs are created, further observations of these events along with physical modeling of the effects of the B_z on the super-fountain effect and possibly other contributing ionospheric mechansims would be needed.

Competing interests. The author declares that he does not have conflict of interest.

Acknowledgements. The author is very thankful to CODE for making publicly available IONEX files. The author would like also to acknowledge the World Data Center for Geomagentism in Kyoto, the German Research Center for Geosciences and the OMNI database for providing data for the Dst index, the Kp index and the vertical interplanetary B_z, respectively.

References

Afraimovich, E. L., Astafyeva, E. I., Demyanov, V. V., Edemskiy, I. K., Gavrilyuk, N. S., Ishin, A. B., Kosogorov, E. A., Leonovich, L. A., Lesyuta, O. S., Palamartchouk, K. S., Perevalova, N. P., Polyakova, A. S., Smolkov, G. Y., Voeykov, S. V., Yasyukevich, Y. V., and Zhivetiev, I. V.: A review of GPS/GLONASS studies of the ionospheric response to natural and anthropogenic processes and phenomena, Journal of Space Weather and Space Climate, 3, A27, 2013.

Appleton, E. V.: Two anomalies in the Ionosphere, Nature, 157, 691, 1946.

Astafyeva, E.: Effects of strong IMF B_z southward events on the equatorial and mid-latitude ionosphere, Annales Geophysicae, 27, 1175–1187, 2009.

Astafyeva, E., Yasyukevich, Y., Maksikov, A., and Zhivetiev, I.: Geomagnetic storms, super-storms, and their impacts on GPS-based navigation systems, Space Weather, 12, 508–525, 2014.

Astafyeva, E., Zakharenkova, I., and Förster, M.: Ionospheric response to the 2015 St. Patrick's Day storm: A global multi-instrumental overview, Journal of Geophysical Research: Space Physics, 120, 9023–9037, 2015.

Borries, C., Berdermann, J., Jakowski, N., and Wilken, V.: Ionospheric storms—A challenge for empirical forecast of the total electron content, Journal of Geophysical Research: Space Physics, 120, 3175–3186, 2015.

Buonsanto, M.: Ionospheric Storms - A Review, Space Science Reviews, 88, 563–601, 1999.

Chakraborty, M., Kumar, S., De, B. K., and Guha, A.: Effects of geomagnetic storm on low latitude ionospheric total electron content: A case study from Indian sector, Journal of Earth System Science, 124, 1115–1126, 2015.

Cherniak, I., Zakharenkova, I., and Redmon, . J.: Dynamics of the high-latitude ionospheric irregularities during the 17 March 2015 St. Patrick's day storm: Ground-based GPS measurements, Space Weather, 13, 585–597, 2015.

Danilov, A. D.: Ionospheric F-region response to geomagnetic disturbances, Advances in Space Research, 52, 343–366, 2013.

Dobrovolsky, I. P., Zubkov, S. I., and Miachkin, V. I.: Estimation of the size of earthquake preparation zones, Pure and Applied Geophysics, 117, 1025–1044, 1979.

Edemskiy, I., Lastovicka, J., Buresova, D., Habarulema, J. B., and Nepomnyashchikh, I.: Unexpected Southern Hemisphere ionospheric response to geomagnetic storm of 15 August 2015, Annales Geophysicae, 36, 71–79, 2018.

Fang, H., Weng, L., and Sheng, Z.: Variations in the thermosphere and ionosphere response to the 17–20 April 2002 geomagnetic storms, Advances in Space Research, 49, 1529 – 1536, 2012.

Fuller-Rowell, T. J., Codrescu, M. V., Moffett, R. J., and Quegan, S.: Response of the thermosphere and ionosphere to geomagnetic storms, Journal of Geophysical Research: Space Physics, 99, 3893–3914, 1994.

Gonzalez, W. D. and Echer, E.: A study on the peak Dst and peak negative Bz relationship during intense geomagnetic storms, Geophysical Research Letters, 32, 2005.

Gonzalez, W. D., Joselyn, J. A., Kamide, Y., Kroehl, H. W., Rostoker, G., Tsurutani, B. T., and Vasyliunas, V. M.: What is a geomagnetic storm?, Journal of Geophysical Research: Space Physics, 99, 5771–5792, 1994.

Gosling, J. T., McComas, D. J., Phillips, J. L., and Bame, S. J.: Geomagnetic activity associated with earth passage of interplanetary shock disturbances and coronal mass ejections, Journal of Geophysical Research: Space Physics, 96, 7831–7839, 1991.

Guo, J., Li, W., Yu, H., Liu, Z., Zhao, C., and Kong, Q.: Impending ionospheric anomaly preceding the Iquique M_w 8.2 earthquake in Chile on 2014 April 1, Geophysical Journal International, 203, 1461–1470, 2015.

Hathaway, D. H. and Upton, L. A.: Predicting the amplitude and hemispheric asymmetry of solar cycle 25 with surface flux transport, Journal of Geophysical Research: Space Physics, 121, 744–753, 2016.

Hernández-Pajares, M., Juan, J. M., Sanz, J., Orus, R., Garcia-Rigo, A., Feltens, J., Komjathy, A., Schaer, S. C., and Krankowski, A.: The IGS VTEC maps: a reliable source of ionospheric information since 1998, Journal of Geodesy, 83, 263–275, 2009.

Huang, C.-S., Foster, J. C., and Kelley, M. C.: Long-duration penetration of the interplanetary electric field to the low-latitude ionosphere during the main phase of magnetic storms, Journal of Geophysical Research: Space Physics, 110, 2005.

Jin, S., Jin, R., and Kutoglu, H. J.: Positive and negative ionospheric response to the March 2015 geomagnetic storm from BDS observations, Journal of Geodesy, 91, 613–626, 2017.

Li, J., You, X., Zhang, R., Meng, G., Shi, H., and Han, Y.: Ionospheric total electron content disturbance associated with May 12, 2008, Wenchuan earthquake, Geodesy and Geodynamics, 70, 2015.

Li, J., You, X., Zhang, R., Meng, G., Shi, H., and Han, Y.: Ionospheric total electron content disturbance associated with May 12, 2008, Wenchuan earthquake, Geodesy and Geodynamics, 70, 2015.

Liu, J. Y., Chuo, Y. J., Shan, S. J., Tsai, Y. B., Chen, Y. I., Pulinets, S. A., and Yu, S. B.: Pre-earthquake ionospheric anomalies registered by continuous GPS TEC measurements, Annales Geophysicae, 22, 1585–1593, 2004.

Liu, S.-L. and Li, L.-W.: Study on Relationship between Southward IMF Events and Geomagnetic Storms, Chinese Journal of Geophysics, 45, 301–310, 2002.

Loewe, C. A. and Prölss, G. W.: Classification and mean behavior of magnetic storms, Journal of Geophysical Research: Space Physics, 102, 14 209–14 213, 1997.

Mannucci, A. J., Tsurutani, B. T., Iijima, B. A., Komjathy, A., Saito, A., Gonzalez, W. D., Guarnieri, F. L., Kozyra, J. U., and Skoug, R.: Dayside global ionospheric response to the major interplanetary events of October 29–30, 2003 “Halloween Storms”, Geophysical Research Letters, 32, 2005.

McDonald, S. E., Coker, C., Dymond, K. F., Anderson, D. N., and Araujo-Pradere, E. A.: A study of the strong linear relationship between the equatorial ionization anomaly and the prereversal E X B drift velocity at solar minimum, Radio Science, 46, 1–9, 2011.

Nava, B., Rodríguez-Zuluaga, J., Alazo-Cuartas, K., Kashcheyev, A., Migoya-Orué, Y., Radicella, S. M., Amory-Mazaudier, C., and Fleury, R.: Middle- and low-latitude ionosphere response to 2015 St. Patrick’s Day geomagnetic storm, Journal of Geophysical Research: Space Physics, 121, 3421–3438, 2016.

Patel, V. L. and Desai, U. D.: Interplanetary magnetic field and geomagnetic Dst variations, Astrophysics and Space Science, 20, 431–437, 1973.

Pedatella, N. M., Lei, J., Larson, K. M., and Forbes, J. M.: Observations of the ionospheric response to the 15 December 2006 geomagnetic storm: Long-duration positive storm effect, Journal of Geophysical Research: Space Physics, 114, 2009.

Schaer, S., Gurtner, W., and Feltens, J.: IONEX: The ionosphere map exchange format version 1, pp. 233–247, 1998.

Sotomayor-Beltran, C.: Localized Increment and Decrement in the Total Electron Content of the Ionosphere as a Response to the April 20, 2018, Geomagnetic Storm, International Journal of Geophysics, 2018, 2018.

Sugiura, M.: Hourly value of equatorial Dst for the IGY, Annals of the International Geophysical Year, 35, 1964.

Tsurutani, B., Mannucci, A., Iijima, B., Abdu, M. A., Sobral, J. H. A., Gonzalez, W., Guarnieri, F., Tsuda, T., Saito, A., Yumoto, K., Fejer, B., Fuller-Rowell, T. J., Kozyra, J., Foster, J. C., Coster, A., and Vasyliunas, V. M.: Global dayside ionospheric uplift and enhancement associated with interplanetary electric fields, Journal of Geophysical Research: Space Physics, 109, 2004.

Tsurutani, B. T., Gonzalez, W. D., Tang, F., Akasofu, S. I., and Smith, E. J.: Origin of interplanetary southward magnetic fields responsible for major magnetic storms near solar maximum (1978–1979), Journal of Geophysical Research: Space Physics, 93, 8519–8531, 1988.

Yao, Y., Liu, L., Kong, J., and Zhai, C.: Analysis of the global ionospheric disturbances of the March 2015 great storm, Journal of Geophysical Research: Space Physics, 121, 157–170, 2016.

Yao, Y. B., Chen, P., Wu, H., Zhang, S., and Peng, W. F.: Analysis of ionospheric anomalies before the 2011 M_w 9.0 Japan earthquake, Chinese Science Bulletin, 57, 500–510, 2012.

Zakharenkova, I. E., Shagimuratov, I. I., Tepenitzina, N. Y., and Krankowski, A.: Anomalous modification of the ionospheric total electron content prior to the 26 September 2005 Peru earthquake, Journal of Atmospheric and Solar-Terrestrial Physics, 70, 1919–1928, 2008.

Zhang, W., Zhao, X., Jin, S., and Li, J.: Ionospheric disturbances following the March 2015 geomagnetic storm from GPS observations in China, Geodesy and Geodynamics, 2018.

Zhao, B., Wan, W., and Liu, L.: Response of equatorial anomaly to the October-November 2003 superstorm, Annales Geophysicae, 23, 2005.

Zhu, F., Wu, Y., Lin, J., and Zhou, Y.: Temporal and spatial characteristics of VTEC anomalies before Wenchuan M_s8.0 earthquake, Geodesy and Geodynamics, 1, 23–28, 2010.

Zou, Y. and Zhao, T.: Ionospheric anomalies detected by GPS TEC measurements during the 15 August 2007 Peru earthquake, in: 2010 International Conference on Microwave and Millimeter Wave Technology, pp. 1216–1219, 2010.

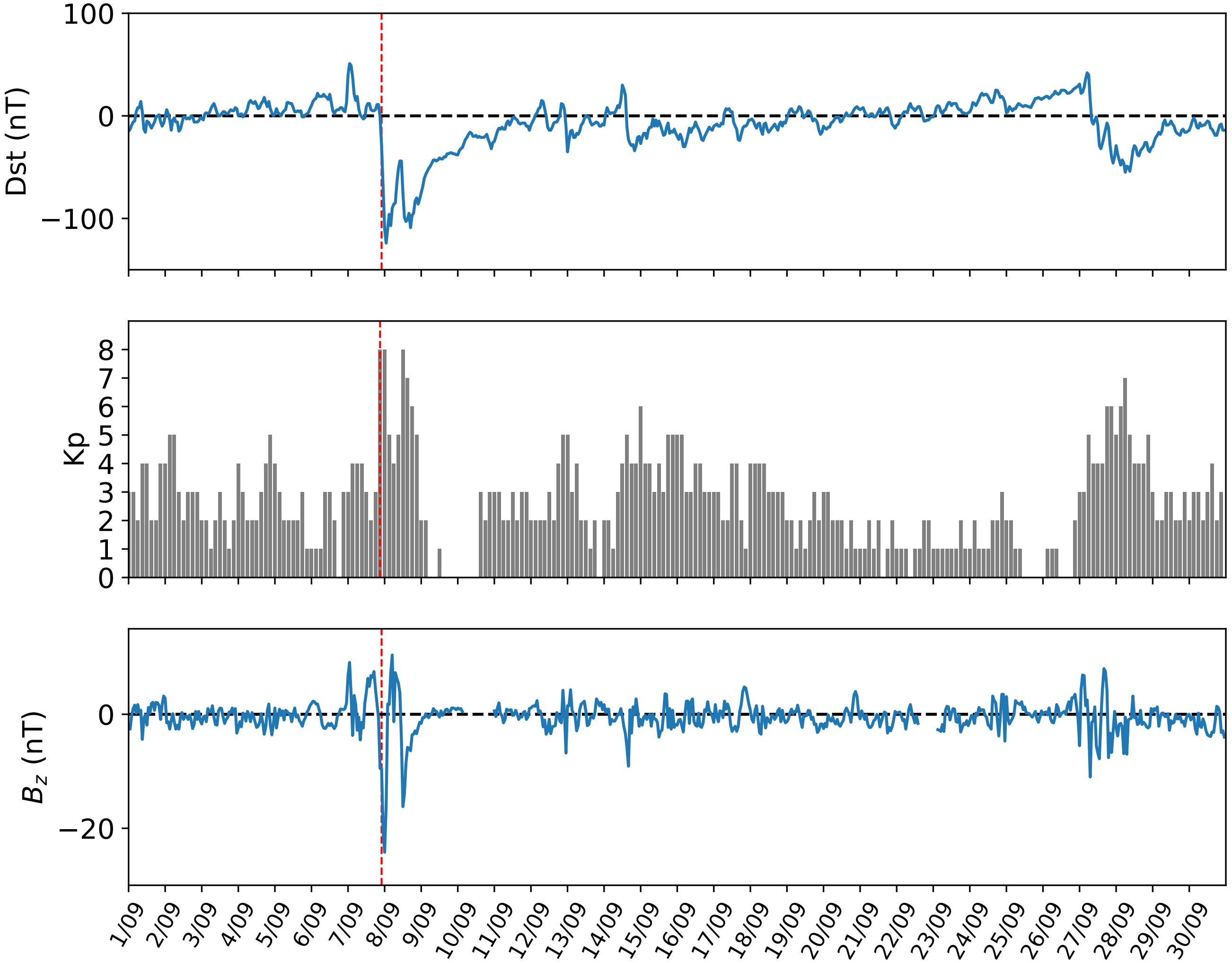


Figure 1. The Dst and Kp indices and the southward interplanetary magnetic field (B_z) for the month of September 2017. The vertical red dashed line in all the plots points to the storm sudden commencement.

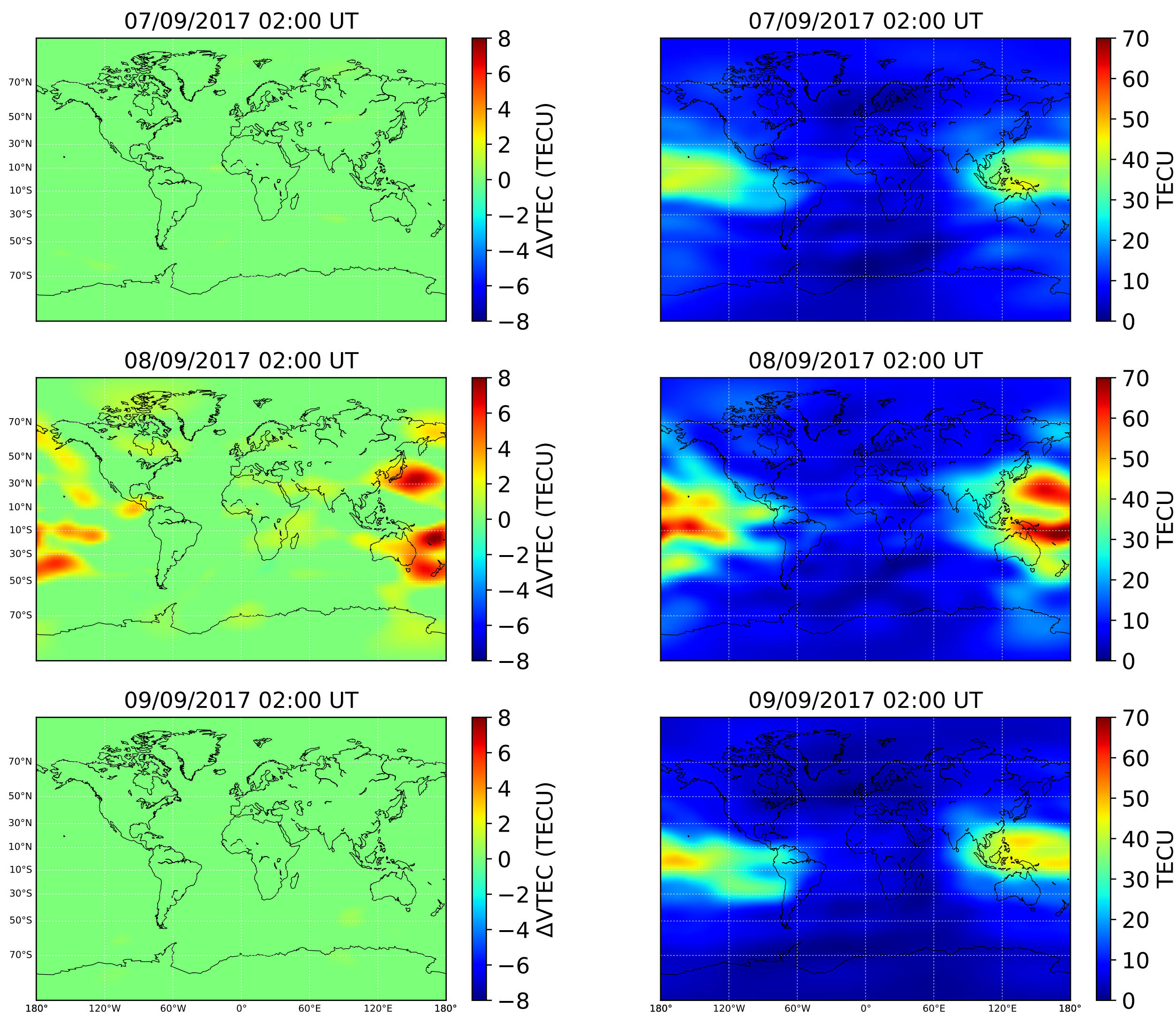


Figure 2. Left column: Differential VTEC maps for September 7, 8 and 9, 2017 at 02:00 UT. Right column: Global ionospheric maps for September 7, 8 and 9, 2017 at 02:00 UT.

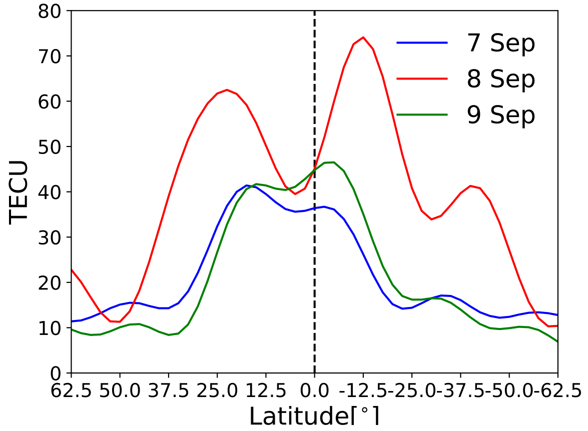


Figure 3. Structure of the VTEC for the 170°E meridian at 02:00 UT between September 7 and 9, 2017. A relevant range of latitudes is shown, 62.5°N–62.5°S. The vertical dashed black line indicates the Equator (latitude = 0°).

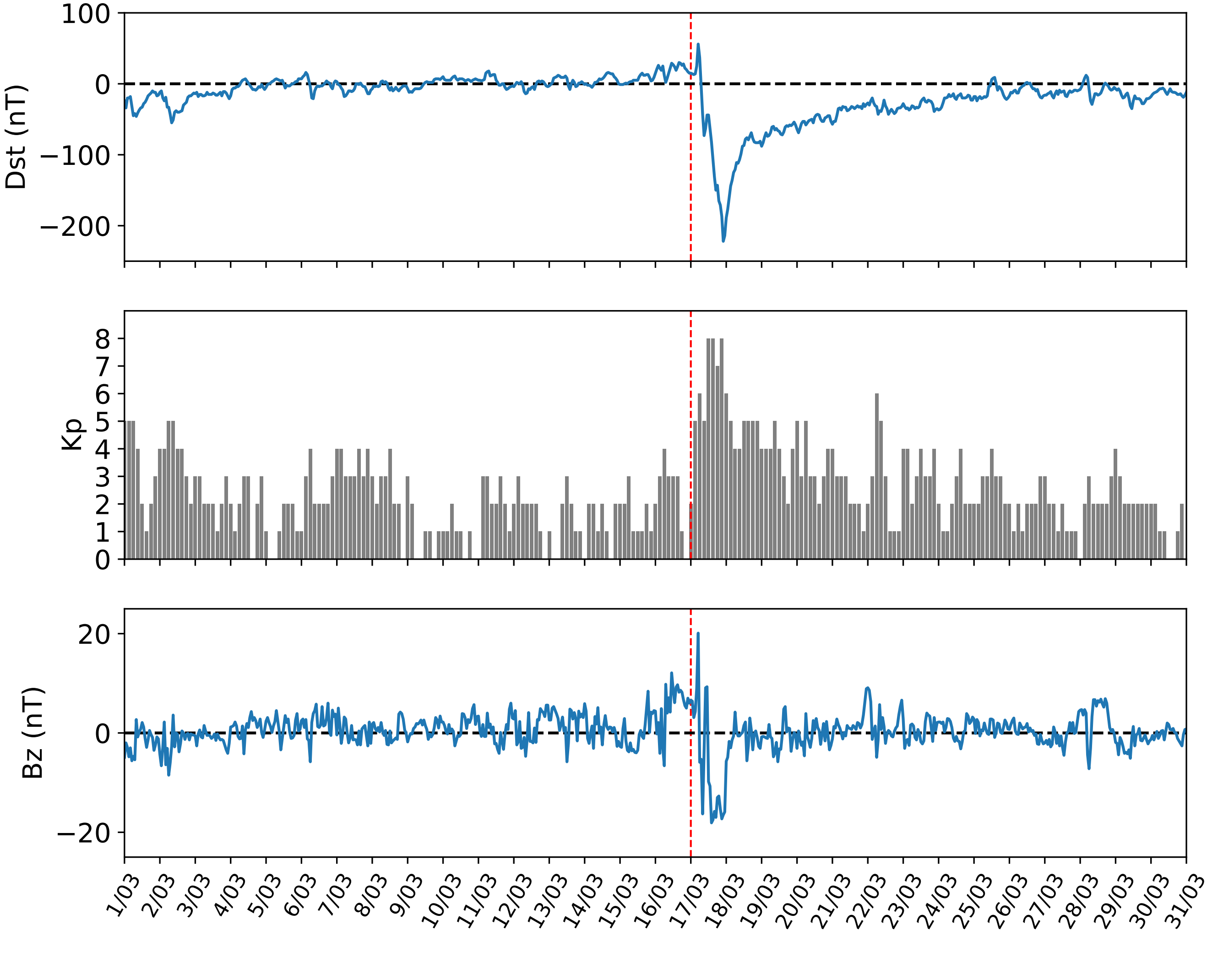


Figure 4. The Dst and Kp geomagnetic indices and the southward interplanetary magnetic field (B_z) for the month of March 2015. The vertical red dashed line in all the plots indicates the day that the 2015 St. Patrick's day storm occurred (March 17, 2015).

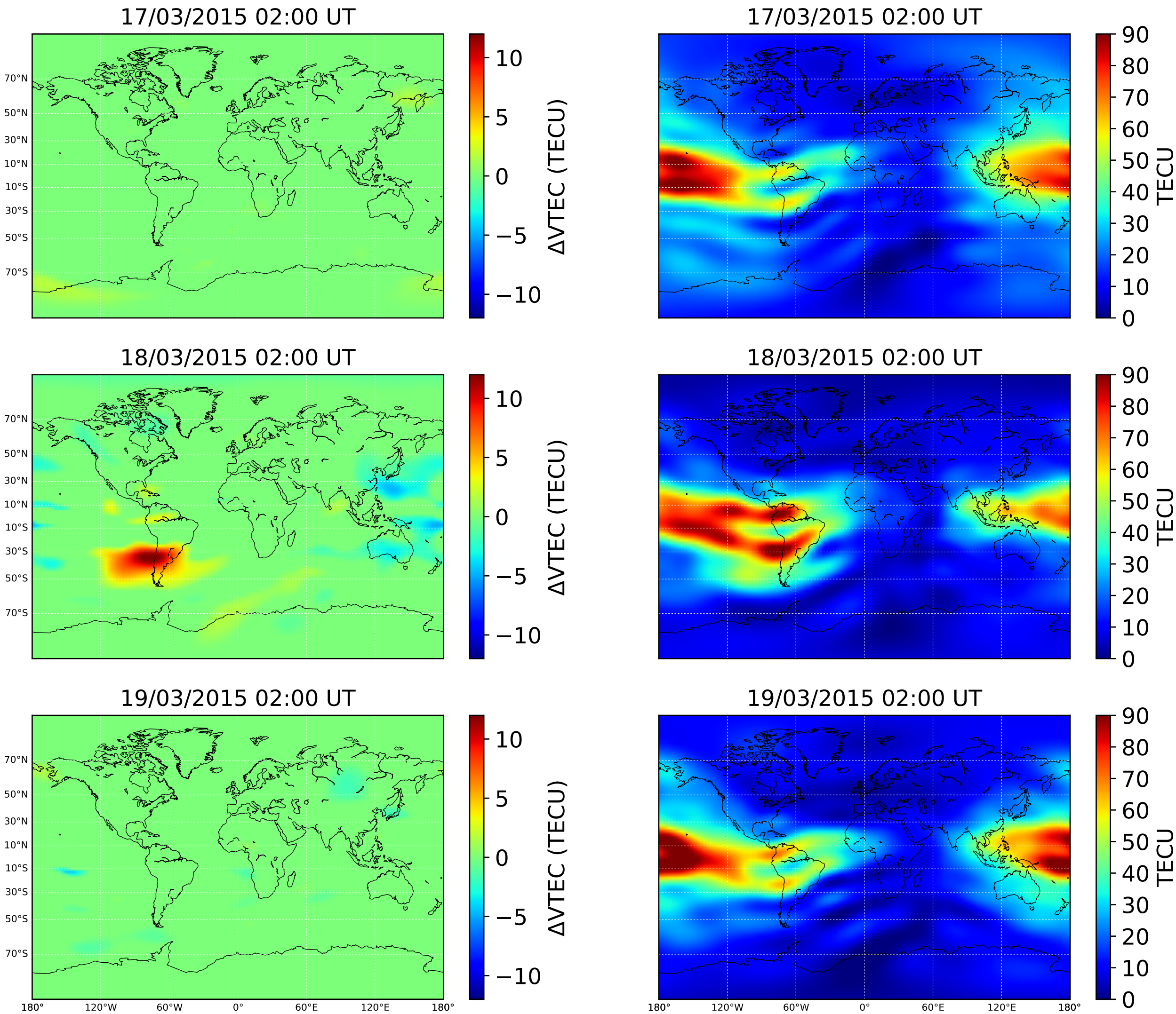


Figure 5. Left column: Differential VTEC maps for March 17, 18 and 19, 2015 at 02:00 UT. Right column: Global ionospheric maps for March 17, 18 and 19, 2015 at 02:00 UT.