I thank both reviewers for helpful comments.

Response to Referee #1

1. Authors mentioned (lines 20-22) that: "The Southern Hemisphere contains at least two large anomalous regions: South Atlantic Magnetic Anomaly and Weddell Sea Anomaly. The latter consists in the modulation of TEC's diurnal oscillations by the solar-modulated seasonal oscillations, which produces a diurnal anomaly in the Discussion paper vicinity of the Weddell Sea during Southern Hemisphere summer (October to March) (Lean et al., 2016)." I recommend author to take the traditional (more clear) definition of WSA phenomenon.

This part of introduction was changed:

"It is known that Southern Hemisphere contains some anomalous regions. South Atlantic Magnetic Anomaly (SAMA) is formed by a configuration of geomagnetic field which has a global minimum of intensity over South Atlantic and South America and makes it easier for energetic particles of inner radiation belt to precipitate, thus increasing ionospheric conductivity over the region (Abdu et al., 2005). South of the SAMA, in the south-eastern Pacific and South Atlantic Antarctic regions, combination of the geomagnetic field features and thermospheric winds produces an inverted diurnal plasma density pattern at equinoxes and in SH summer (October-March): the nighttime maximum is larger than the daytime minimum, and the phenomenon is known as the Weddell Sea Anomaly (WSA) (Horvath, 2006). Jakowski et al. (2015) showed that during periods of low solar activity in Asian longitudinal sector of SH it is possible to observe so called nighttime winter anomaly (NWA), when values of electron concentration are higher in winter that in summer. At the same time Yasyukevich et al. (2018) showed that winter anomaly manifests itself much less intensively in SH that in NH. It is possible to conclude that ionosphere of each hemisphere has some specific features."

2. (Lines 34-35): "During analysis of ionosphere response to a geomagnetic storm of 15 August 2015, a curious structure was detected in global ionospheric maps (GIMs), which we call localized TEC enhancement or LTE (Edemskiy et al., 2018)." The term localized TEC enhancement was mentioned many years before by Foster and Rideout (2007) and Foster and Coster (2007). Note that Foster et al. studies present localized TEC enhancement in Northern hemisphere many times. I recommend author to read John Foster's et al. articles in order to understand the morphology and physical explanation of localized TEC enhancement in NH. I believe that these papers should give you new information.

Thank you for your recommendation. The text was changed and reference to Foster et al. papers was added. At the same time it should be noted that their papers mostly describe ionosphere during geomagnetic storms, investigating manifestation of storm enhanced density (SED), whereas the considered LTEs are observed almost independently on geomagnetic conditions, even during quiet periods (Kp=1).

The introduction was changed and the following was added:

"The most typical irregularities in distribution of electron concentration are produced during geomagnetic storms. Foster and Coster (2007) investigating storm enhanced densities (SED). They showed that during severe and extreme storms it is possible to detect SEDs which in maps of total electron content (TEC) could be observed as localized TEC enhancements (LTE). The authors showed that during a storm recovery phase LTEs could be detected in the night side ionosphere at the middle latitudes of both hemispheres, in magneto-conjugated regions. The authors note that the observed enhancements are approximately corotating in place over the positions in which they were formed earlier in the event. However, the LTE phenomenon studied by Foster and Coster (2007) is different from the LTE phenomenon studied by us.

During analysis of ionospheric response to a geomagnetic storm of 15 August 2015 Edemskiy et al. (2018) detected a curious LTE in global ionospheric maps (GIMs). Unlike the LTEs observed by Foster and Coster (2007) this enhancement was detected and observed in sunlit area of the Southern Hemisphere and lasted for several hours. It was not corotating but changing position following the Sun and propagating along the geomagnetic parallels. Using quite a simple detection algorithm Edemskiy et al. (2018) found about 30 similar events in the Southern Hemisphere during 2010-2016 and some of the detected LTEs were observed during relatively quiet periods. The authors showed direct dependence of number of the detected LTEs on solar activity level and suggested that their generation is connected with the orientation of interplanetary magnetic field (IMF), namely with Bz."

3. (Lines 45-55). Unfortunately there are many remarks about definition of LTE's. According to first sentence here "The localized TEC enhancement is a positive disturbance of ionosphere." But according to two detection criteria the LTE is a spatial-temporal structure in the UT map of TEC and is not a disturbance.

Yes, thank you, you are absolutely right. Now it is noted in the text that LTE should not be considered as a disturbance. The criteria were changed as well:

"In this paper a TEC enhancement is considered as LTE if it is:

- located in middle latitudes of sunlit region. Mainly we investigate LTEs, which are clearly observed in Indian and Southern part of Atlantic Oceans and do not take into account enhancements in Northern Hemisphere. At the same time, LTEs in SH are not accompanied by any LTE in NH and fuch a focusing on SH LTEs is quite reasonable.

- spatially limited by relatively lower TEC values. Normalized difference between squared maximal value in LTE and minimal one at its border (Δ=1 - (I_{edge}/I_{max})^2) should be no less than 20%. Generally that means that there should be a clear trough between an enhancement and the equatorial ionization anomaly (EIA).

- confined and have a border of lower TEC values ($\Delta \geq 20\%$) no farther than in 40° in longitude from the location of maximal TEC value. Mainly that means that we do not consider longitudinally stretched enhancements assuming different mechanism of their generation."

4. (Lines 47-48): "*1. Spatial limitation and clear borders. An enhancement should not be wider than 40 ◦ and 120 ◦ in latitude and longitude, respectively. Gradients at an LTE edges should be high enough to make LTE borders possible to distinguish.* ***" According to such limitation almost all of winter UT map of TEC should reveal LTE due to 1) short duration (therefore limitation in longitude smaller then 90 ◦) and significant gradients of TEC diurnal variation during sunlight hours; 2) clear border at sub-auroral latitudes due to pronounce main ionospheric trough structure (for daytime also). So according to these criteria, I don't understand how LTE can be distinguished from the usual TEC maps in winter and equinox seasons. Figure 3 demonstrate many cases of consistence between LTE and typical TEC diurnal variation (that is presented in view of longitude-latitude map for UT epoch). Another problem is statement: "Gradients at an LTE edges should be high enough". Please provide mathematical formulation for "should be high enough". Or this criteria was checked manually for each maps?***

Thank you for this remark. The criteria definition was changed to describe an LTE more precisely. Key point which was missed previously is a presence of trough between EIA and the observed enhancement. Demands on the minimal depth of this trough is given mathematically. All the enhancements in fig. 3 fulfill the criteria and are considered as LTE.

Several examples of maps showing other types of enhancement or absence of enhancement are available via the link below. Such situations were considered as non-LTE cases and were not considered during the investigation.

https://drive.google.com/drive/folders/1u6GTyRe9bIFb-Kb25gMKkGM5_LIvbQAv?usp=sharing

5. *(Lines 52-54): "We search LTEs only in the Southern Hemisphere, because Edemskiy et al. (2018) detected LTEs only at SH. A disturbance should follow the Sun having the maximal intensity no latter than 1-2 hours after local noon (in a period 12-14 LT as observed by Edemskiy et al., 2017).* ***I disagree with argument for LTE limitation only in the Southern Hemisphere. Edemskiy et al. (2018) study concern to geomagnetic storm response on particular event on Aug***

2017. There are many examples of daytime storm-time localized TEC enhancement (Foster and Rideout, 2007; Zhao et al., 2012) in NH. Why author's algorithm exclude all these situations? I did not found Edemskiy et al., 2017 in the reference list.

Misprint "Edemskiy et al., 2017" is corrected: "Edemskiy et al., 2018"

The statement was badly formulated. The point was that this particular paper is dedicated only to LTEs detected in Southern Hemisphere, particularly in South Indian and South Atlantic regions. The same LTE was described by Edemskiy et al. (2018) and the idea of the current paper is to find other similar enhancements using GIMs. During the investigation it was found that these structures can be detected not only during magnetic storms but during quiet days as well. The author does not claim absence of LTEs in Northern Hemisphere or in other ranges of longitude. However during SH LTE we do not see any corresponding effect in NH. At the same time the aim was not to describe only storm-time LTE, but any such formation which are observed only in Southern Hemisphere**.** This is reflected in new formulation of the criteria.

6. (Lines 89-92): "*An example of a clearly observed LTE was detected at April 5, 2014 (Fig. 1). The disturbance reached the highest intensity in a period 10-12 UT when TEC values in a center of the disturbance exceeded 78 TECU. This value is comparable to equatorial TEC values. The highest values were detected in a latitudinal region 45-70 ◦ S. At the same time, TEC values of the entire region (30-70 ◦ S, 0-90 ◦ E) were enhanced.****" The reason for SLTE is associated to geomagnetic disturbances during 5 April. Please see AE index on Fig. 1. It is evident that geomagnetic disturbances in AE started at 06 UT on 5 April, 2014 (the same as SLTE). The maximal geomagnetic disturbance occur at 10-12 UT. At the same time the highest intensity of SLTE occur when TEC values in a center of the disturbance exceeded 78 TECU. So SLTE in reality can be SED structure or something else that associated with geomagnetic disturbances.***

Thank you very much for this remark. It moved the investigation forward.

SED structures are mentioned both in introduction and discussion sections and briefly described in the latter. The possible connection between SED and LTE is discussed and some statistical analyses are added as well. At the same time it is shown that clear SLTE are observed during relatively quiet conditions with positive Dst and small AE values; and otherwise: not all storms were accompanied by SLTEs.

7. (Lines 94-95): "*As it will be shown later, such a strong SLTE is not typical and in some cases it is not detected at all.****" Why author to select this case if this case is not typical?***

This day was chosen since despite the more intense SLTE both the enhancements are observed quite clearly. This structure fulfills the criteria of LTE and at least partially can be clearly seen in SWARM data. Another map with a LTE confirmed by SWARM is added to the discussion.

8. (Lines 106-107): "*In-situ measurement of electron concentration Ne from SWARM satellites allow us to check validity of TEC distribution presented by GIM.****" In my own opinion Fig. 2 provide clear evidence of SLTE, but not for MLTE. So according to my points 6-8 Figs. 1 and 2 does not give to reader typical examples of LTE. I recommend to add a typical example of MLTE that does not associated with geomagnetic disturbances.***

Thank you for this remark. Another figure containing MLTE and corresponding SWARM measurements are added to the paper. Some text clarifying this problem was added to the discussion section.

9. Figure 5. IMF intensity is not a good choice of parameter that determine geomagnetic activity because direction of IMF Bz can be more important for ionospheric disturbances. In my opinion AE or AP index can be more effective in this investigation.

Analysis of LTE occurrence rate dependence on geomagnetic indices or IMF components did not reveal any trends that is why these distributions were not shown in figures. The dependence on Bz was the initial hypothesis which was not supported by observations. The fig. 5 is changed now and contains all the basic geomagnetic indices.

10. About discussion part. It is very chaotic. I still did not understand which of the mechanisms, according to the author, is the main one for the formation of LTE. There are a lot of additional questions according to LTE, but I stopped here in order to obtain some clarification about LTE.

The discussion part was almost fully rewritten and now contains more details and suggestions about LTEs.

Response to Referee #2

1. It is not clear from the text what the author regards as a possible mechanism of LTE generation. A possible mechanism of LTE generation should be one of the main conclusions in section 4. The author is obviously not yet able to indicate the exact mechanism. However, he should single out and discuss possible mechanisms.

Discussion section was almost fully rewritten and now contain some suggestions about the mechanism

2. As I believe (see Comment for Line 163), the author uses the intensity of the interplanetary magnetic field (IMF) to analyze LTE dependence on geomagnetic activity level. But for this analysis, it is better to use the magnetic activity indices Dst (or SYM-H) and AE, which make it easy to select disturbance periods in Earth's magnetic field variations. In addition to Figures 4 and 5, it would be useful to add a figure to show the time variations of Dst, AE, F10.7 and "temporal position" of each LTE during all the years (2014, 2015, 2018).

Thank you for the recommendation. The figure 4 is replaced by plots showing temporal position of each LTE and the corresponding values of F10.7 and SYM-H indices. Speaking of IMF intensity usage for the comparison, figure 5 is updated and now presents dependencies on AE, Dst and SYM-H as well.

3. Throughout the text, please check the season names in the Southern Hemisphere: in some places March-July are called "autumn-winter" (Lines 143-144, 187-188), and in other places they are referred to as "spring-summer" (Lines 148-149, 227-228).

Thank you. This confusion in the names was corrected.

Thank you for all the comments. They really helped to improve the paper

Comments

Lines 5-6. In Abstract, it is not clear what the author means by "LTE series". Please keep in mind that a lot of people read Abstract only.

I changed the Abstract in accordance with the comment

Lines 7-8. "It is shown that LTE intensity varies in dependence on solar flux and does not directly depend on interplanetary magnetic field orientation." LTE dependence on interplanetary magnetic field orientation is not discussed in the paper.

Line 231. "No clear dependence between orientation of IMF and LTEs' parameters was observed." LTE dependence on interplanetary magnetic field orientation is not discussed in the text. Therefore, this conclusion is not substantiated.

The distributions similar to ones in fig. 5 were calculated but were not presented since they do not show any trend or dependence of LTE occurrence. The figure was changed to show distributions versus all the main parameters and the corresponding text was added.

Lines 19-25. "The Southern Hemisphere contains at least two large anomalous regions: South Atlantic Magnetic Anomaly and Weddell Sea Anomaly." Since the author mentions two large anomalous regions in the Southern Hemisphere (South Atlantic Magnetic Anomaly and Weddell Sea Anomaly), he should characterize both of them, not one (Weddell Sea Anomaly).

Moreover, I would recommend to pay particular attention to the South Atlantic Magnetic Anomaly (SAMA). The SAMA region is very close to the area where LTEs are detected (Fig. 1A and Fig. 3). Perhaps SAMA (itself or together with some other factors, such as a neutral wind, for example) promotes the LTE formation.

On the other hand, LTE looks like a continuation of the region occupied by the Equatorial Ionization Anomaly (EIA) in Fig. 1A (unfortunately, the boundaries of Fig. 3 cut off the EIA, and nothing can be said here). Maybe sometimes one get conditions that allow a plume from EIA "fountain" to reach higher latitudes.

The description of the SH anomalies is corrected and now contains more details about each anomaly.

Obviously the presented LTEs are connected with configuration of geomagnetic field as well as SAMA anomaly, but it should be noted that the last one is mostly located in Atlantic ocean, when LTE is typically generated and develops in Indian ocean and in geomagnetic latitudes which are usually higher than those of SAMA.

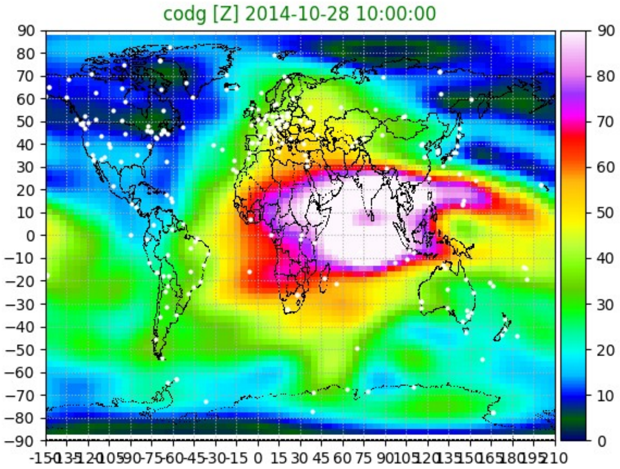
Speaking of continuation of EIA, there are several things to be noted:

- we observe SH LTEs asymmetrically: independent on the season there are no similar structures in NH even during equinox periods, when amount of solar radiation is quite the same in both hemispheres. And it is not clear why we do not have the same continuation in NH.

- being observed in near-noon area LTE should be formed by solar ionization which impact is maximal in sub-equatorial region.

- It is possible to observe enhancements which are continuation of EIA (e.g. a figure below) and we do not consider them as LTE since they are not localized (do not have clear border)

The figure below shows enhanced values in SH, which do not fulfill the criteria and looks like a continuation of EIA.



Lines 32-33. "However, none of these models predict the occurrence of the LTE phenomenon." Neither the abbreviation "LTE" nor the term "LTE" have been used before. Please, explain what "LTE" is before using it. In a scientific article, one should avoid term/abbreviation explanations after their first use. This makes understanding difficult.

The abbreviation was introduced in abstract, but I agree that it should be introduced in the text as well. A short explanation is added.

Line 48. "Gradients at an LTE edges should be high enough to make LTE borders possible to distinguish." Please, specify the numerical value of the gradient threshold you use.

The formulation of the criteria was changed:

"In this paper a TEC enhancement is considered as LTE if it is:

- located in middle latitudes of sunlit region. Mainly we investigate LTEs, which are clearly observed in Indian and Southern part of Atlantic Oceans and do not take into account enhancements in Northern Hemisphere. At the same time, LTEs in SH are not accompanied by any LTE in NH and fuch a focusing on SH LTEs is quite reasonable.

- spatially limited by relatively lower TEC values. Normalized difference between squared maximal value in LTE and minimal one at its border (Δ=1 - (I_{edge}/I_{max})^2) should be no less than 20%. Generally that means that there should be a clear trough between an enhancement and the equatorial ionization anomaly (EIA).

- confined and have a border of lower TEC values (Δ≥20%) no farther than in 40° in longitude from the location of maximal TEC value. Mainly that means that we do not consider longitudinally stretched enhancements assuming different mechanism of their generation.”

Line 54. "Edemskiy et al., 2017" Probably, the author meant "Edemskiy et al., 2018"
Yes, that was a misprint

Lines 125-126. "Blue dashed line (Fig. 2, right) presents a profile measured at 10:12 UT at October 19, 2014 when there was no LTE observed in GIM." Please, explain why October 19, 2014 was chosen as a day without LTE. Though April days with LTE are analyzed. Why did not you use a day without LTE closer to April?

The problem consists of two parts: COSMIC should be at a proper position near the local noon to make it possible to observe the given area in Southern Hemisphere; and we did not observe enhanced TEC at this moment. As it could be seen from fig. 4, there was the only day without LTE (Apr 12) and during this day TEC values were enhanced but not fulfilled the LTE criteria. A corresponding short explanation is added to the text:

“Due to the phenomenon of LTE series which will be described later, TEC values over the given region are enhanced almost during the whole month. To demonstrate ionosphere profile without any enhancement in GIM we have chosen October 19, 2014. The profile measured by COSMIC at 10:12UT is shown by dashed blue line in fig. 2.”

Lines 133-134. "The intensity and the shape of the presented LTEs vary but at the same time of day all of them occupy the same region." should be replaced with "The intensity and shape of the presented LTEs vary from day to day, but at the same time of day all of the LTEs occupy the same region".

Your text is better, thank you. Your formulation is used in the text.

Lines 137-138. "In a similar way LTE series were observed during other investigated years of relatively high (2015) and low (2018) solar activity." It is necessary to clarify what the level of solar activity was in 2014 and what index was used for the solar activity characteristic. The author should also indicate numerical values of the solar activity level for each year. Please, explain what "LTE series" is.

Such a definition of LTE series is given in text:

“We define such a continuous sequence of LTEs observed day by day as a series of LTE. At least two consequently observed LTEs are considered as a series.”

The following text was added to the section Data and methods.

“The estimation of solar activity level is based on $F_{10.7}$ index from OMNI database. During the investigated years monthly averaged $F_{10.7}$ values were varying in ranges 130-160 (2014), 95-135 (2015), 65-75 (2018) sfu corresponding to high, relatively high and low level of solar activity. ”

Line 163. "distribution of this ratio vs IMF intensity." Please, explain: - what "IMF" is; -what "IMF intensity" is: whether it is B intensity or Bz intensity;

IMF intensity was standing for B intensity. All the mentioned terms “IMF intensity” are replaced by “IMF intensity B”.

Line 178. Article [Cherniak et al., 2012] is not included in References.
The missed reference was added

Line 225. "5 Discussion" Probably, the author meant "5 Summary".
The misprint is corrected to “5 Conclusions”

Lines 240-305, References. Articles [Afonin et al., 1995], [Chen et al., 2011], [He et al., 2011], [Krankowski, et al., 2009], [Matyjasiak, et al., 2005], [Sun, et al., 2017] are not mentioned in the text.

Unused references were removed

Localized TEC enhancements in the Southern Hemisphere

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Abstract

The paper is dedicated to investigation of localized TEC (total electron content) enhancements (LTEs)~~, particularly of LTE series~~, detected in the Southern Hemisphere via analysis of ~~using~~ global ionospheric maps. Using data for different ~~solar activity~~ years (2014, 2015, 2018) we show presence of LTE almost independently on solar activity. It is shown as well that LTE is a phenomenon which can be observed~~–~~ in a series: at the same universal time (UT) similar enhancement can manifest itself during several days. ~~i~~Intensity of LTEs varies in dependence on solar flux and does not directly depend on interplanetary magnetic field orientation; they occur under both geomagnetically disturbed and quiet conditions. ~~The enhancements occur in a subsolar region and could be observed during a continuous series of days.~~ The highest LTE occurrence rate is observed during period of local winter (April-September) for all analyzed years. The longest observed LTE series was detected during 2014 and lasted 80 days or 120 days if we exclude 2 daily gaps.

Keywords: Ionosphere, LTE, TEC enhancements, GIM, Southern Hemisphere, GNSS, SWARM, COSMIC.

1. Introduction

The Southern Hemisphere (SH) ionosphere has not been investigated so broadly as one of the Northern Hemisphere (NH). Historically, most of the geophysical observations and measurements have been made to the north of the equator. Even now, having lots of observatories all around the globe, we have a lack of ground-based observations for a larger part of the Southern Hemisphere since it is mostly occupied by ocean. Satellite measurements allow us to investigate ionosphere over oceans but due to its high variability and the movement of satellites it is very difficult to observe the same region in the same conditions.

~~The Southern Hemisphere contains at least two large anomalous regions: South Atlantic Magnetic Anomaly and Weddell Sea Anomaly.~~

It is known that Southern Hemisphere contains some anomalous regions. South Atlantic Magnetic Anomaly (SAMA) is formed by a configuration of geomagnetic field which has a global minimum of intensity over South Atlantic and South America and makes it easier for energetic particles of inner radiation belt to precipitate, thus increasing ionospheric conductivity over the region (Abdu et al., 2005). South of the SAMA, in the south-eastern Pacific and South Atlantic Antarctic regions, combination of the geomagnetic field features and thermospheric winds produces an inverted diurnal plasma density pattern at equinoxes and in SH summer (October-March): the nighttime maximum is larger than the daytime minimum, and the phenomenon is known as the Weddell Sea Anomaly (WSA) (Horvath, 2006). Jakowski et al. (2015) showed that during periods of low solar activity in Asian longitudinal sector of SH it is possible to observe so called nighttime winter anomaly (NWA), when values of electron concentration are higher in winter than in summer. At the same time Yasyukevich et al. (2018) showed that winter anomaly manifests itself much less intensively in SH that in NH. It is quite clear that due to these anomalies the structure and dynamics of ionosphere in both hemispheres should be different and should be investigated separately.~~The latter consists in the modulation of TEC's diurnal oscillations by the solar-modulated seasonal oscillations, which produces a diurnal anomaly in the vicinity of the Weddell Sea during Southern Hemisphere summer (October to March) (Lean et al., 2016).~~

~~So called nighttime winter anomaly (NWA) was shown to occur during low solar activity period in Asian longitudinal sector of SH (Jakowski et al., 2015). In general the winter anomaly in~~

~~SH does not manifest itself with the same intensity as that in NH (Yasyukevich et al., 2018). Globally ionosphere dynamics in the both hemispheres is different.~~

The most widely used and generally accepted the International Reference Ionosphere (IRI) empirical model (e.g., Bilitza, 2018) does not predict some features of the SH ionosphere sufficiently. Karia et al. (2019) analyzing predictions of IRI-2016 showed that the model does reproduce the observed NWA effect, though at a different longitude and could be improved for better predictions. Comparing TEC measurements and results of IRI-PLAS, Alcay and Oztan (2019) found that in SH the model generally overestimates the GPS-TEC measured at stand-alone stations with the maximal~~um~~ difference about 15 TECU. Karpachev and Klimenko (2018) proposed a new model reproducing the structure of the high-latitude ionosphere more accurately than IRI-2016 and noted that inaccuracies of IRI in that region are connected with inaccuracy of ground-based sounding data, which varies during a day. However, none of these models predict the occurrence of localized enhancements of electron concentration especially in Southern Hemisphere.~~the LTE phenomenon.~~

The most typical irregularities in distribution of electron concentration are produced during geomagnetic storms. Foster and Coster (2007) investigating storm enhanced densities (SED). They showed that during severe and extreme storms it is possible to detect SEDs which in maps of total electron content (TEC) could be observed as localized TEC enhancements (LTE). The authors showed that during a storm recovery phase LTEs can be detected in the night side ionosphere at the middle latitudes of both hemispheres, in magneto-conjugated regions. The authors note that the observed enhancements are approximately corotating in place over the positions in which they were formed earlier in the event. However, the LTE phenomenon studied by Foster and Coster (2007) is different from the LTE phenomenon studied by us.

~~During analysis of ionosphere response to a geomagnetic storm of 15 August 2015, a curious structure was detected in global ionospheric maps (GIMs), which we call localized TEC enhancement or LTE (Edemskiy et al., 2018).~~

~~The~~ During analysis of ionospheric response to geomagnetic storm of 15 August 2015 Edemskiy et al. (2018) detected a curious LTE in global ionospheric maps (GIMs). Unlike the LTEs observed by Foster and Coster (2007) this enhancement was ~~detected in~~ observed in sunlit (near-noon) area of the Southern Hemisphere and lasted for several hours. It was not corotating but changing position following the Sun and propagating along the geomagnetic parallels. Using quite a simple detection algorithm Edemskiy et al. (2018) found about 30 similar events in the Southern Hemisphere during 2010-2016 and the most of the detected LTEs were observed during relatively disturbed periods. The authors showed direct dependence of number of the detected LTEs on solar activity level and suggested that the generation of the enhancements is connected with the orientation of interplanetary magnetic field (IMF), namely with Bz. ~~Assuming the phenomenon to be rare, we developed a detection algorithm, which allowed us to find about 30 similar events in the Southern Hemisphere during 2010-2016 and to suggest direct connection of their occurrence rate with solar activity. Unfortunately the algorithm had disadvantages: fixed detection threshold and comparison with a weekly median TEC value. The first assumption did not allow us to detect relatively weak but existing LTEs, the second one excluded from the consideration possible series of such disturbances.~~

The present article is an attempt to detect more LTEs developing in Southern Hemisphere during different solar activity periods and to investigate them more carefully trying to understand mechanisms of their generation. Section 2 describes data and methods, section 3 presents results, section 4 deals with discussion and possible mechanism, and section ~~five~~5 summarizes main results.

2. Data and methods

The algorithm used by Edemskiy et al. (2018) had some disadvantages. The used fixed detection threshold did not allowed them to detect relatively weak LTEs. The applied comparison with a weekly TEC median excluded from the consideration possible series of such formations.

Trying to improve the effectiveness of LTE detection we introduced following criteria for the TEC formation. In this paper a TEC enhancement is considered as LTE if it is:

- located in middle latitudes of sunlit region. Mainly we investigate LTEs, which are clearly observed in Indian and Southern part of Atlantic Oceans and do not take into account enhancements in Northern Hemisphere. At the same time, LTEs in SH are not accompanied by any LTE in NH and such a focusing on SH LTEs is quite reasonable.

- spatially limited by relatively lower TEC values. Normalized difference between squared maximal value in LTE and minimal one at its border ($\Delta=1 - (I_{edge}/I_{max})$^2) should be no less than 20%. Generally that means that there should be a clear trough between an enhancement and the equatorial ionization anomaly (EIA).

- confined and have a border of lower TEC values (Δ≥20%) no farther than in 40° in longitude from the location of maximal TEC value. Mainly that means that we do not consider longitudinally stretched enhancements assuming different mechanism of their generation.

~~The localized TEC enhancement is a positive disturbance of ionosphere. To distinguish it from other large-scale disturbances of electron concentration we introduce detection criteria:~~

~~1. Spatial limitation and clear borders. An enhancement should not be wider than 40° and 120° in latitude and longitude, respectively. Gradients at an LTE edges should be high enough to make LTE borders possible to distinguish. If an enhancement occupies relatively wide area, stretched in any direction (usually along a geomagnetic parallel) for more than 120° or has no significant variations of intensity we do not take such disturbance into consideration.~~

~~2. Location in the mid- or subpolar-latitude dayside ionosphere of Southern Hemisphere (30-70°S of geomagnetic latitude).We search LTEs only in the Southern Hemisphere, because Edemskiy et al. (2018) detected LTEs only at SH. A disturbance should follow the Sun having the maximal intensity no latter than 1-2 hours after local noon (in a period 12-14 LT as observed by Edemskiy et al., 2017). All the others localized enhancements, observed at local night, morning or evening are not considered.~~

~~According to these criteria we detect LTEs in global ionospheric maps.~~

These criteria were applied to analysis of global ionospheric maps (GIMs). Currently, ~~global ionospheric maps~~these maps are provided by several scientific groups: CODE (codg), ESA (esag), JPL (jplg), UPC (upcg), Whuan university (whug), Chinese Academy of Sciences (CAS - casg). IGS service also provides maps (igsg) created as a combination of maps from CODE, UPS, ESA and JPL. The spatial resolution is 2.5°x5° in latitude and longitude, respectively, and temporal one is 2 h (1 h for CODE maps since 2015). Maps are calculated from slant (sTEC) values measured at 200-350 GNSS receivers (in dependence~~ing~~ on the data availability and the used method) ~~GNSS receivers~~ all around the world with application of some interpolation method. Global ionospheric maps from all the above mentioned groups are freely available at CDDIS server (ftp://cddis.gsfc.nasa.gov/gps/products/ionex). According to Roma-Dollase et al. (2018) CODE and CAS maps have the lowest relative errors in the South Atlantic and Indian Ocean regions. Taking into account the high temporal resolution of CODE maps and more clear information about the used data in the headers of these maps, we use CODE GIMs in the present paper.

To confirm an LTE presence we use measurements from SWARM and COSMIC satellite missions. The SWARM mission was launched by ESA at the end of 2013. It is mainly aimed to investigation of Earth's magnetic field. The mission includes three satellites at polar orbits of about 500 km (460 km for Alpha and Charlie, and 530 km for Bravo). The data are available via browser-based application (https://vires.services/) or via API tool (https://github.com/ESA-VirES/VirES-Python-Client). In the present paper SWARM in-situ measurements of electron density are used.

The project COSMIC (Constellation Observing System for Meteorology Ionosphere & Climate) provide measurements of upper atmosphere and ionosphere parameters. In the present paper we use TEC profiles obtained via radio occultation (RO) receiving of GPS signals. To distinguish this data from the standard ground-based TEC measurements, we use abbreviation SS TEC (satellite-to-satellite TEC). COSMIC data is freely provided as NetCDF files (https://cdaac-www.cosmic.ucar.edu/).

We analyze mainly the occurrence rate of LTE and its dependence on space weather. Quantitative analysis of LTEs generally consists of definition of maximal TEC value over the investigation region and calculation of its relation to mean TEC value over the region. Analysis of the dependence of these parameters on near space conditions was made during the investigation. LTE shapes vary widely and are quite difficult for formalization.

To analyze connection of the observed features of ionospheric dynamics with geomagnetic field we use SuperDARN altitude adjusted corrected geomagnetic coordinates (AACGM) [(Shepherd, 2014)] as a Python module developed by Angeline Burrell (https://github.com/aburrell/aacgmv2). To create maps in geomagnetic coordinates we place each TEC cell from GIM map at the corresponding magnetic latitude and longitude calculated with AACGM for an altitude of 100 km.

Files of GIMs in IONEX format were treated with the python package GNSS-LAB created by Ilya Zhivetiev (https://github.com/gnss-labhttps://pypi.org/project/gnss-tec/). Processing and presentation of data were made with Python libraries Numpy (https://numpy.org) and Pandas (https://pandas.pydata.org/). Geomagnetic indices (Kp, Dst, AE, etc.) and other parameters of near space (including $F_{10.7}$ index for estimation of solar activity) were taken from OMNI database (https://omniweb.gsfc.nasa.gov). During the investigated years monthly averaged $F_{10.7}$ values were varying in ranges 130-160 (2014), 95-135 (2015), 65-75 (2018) sfu corresponding to high, relatively high and low level of solar activity. It should be noted that AE index values during 2018 are available only for January and February both in OMNI and Kyoto WDC (http://wdc.kugi.kyoto-u.ac.jp/dstae/index.html) databases.

3. Results

An example of a clearly observed LTE was detected at April 5, 2014 (fig. 1). The disturbance reached the highest intensity in a period 10-12 UT when TEC values in a center the most intense part of the disturbance exceeded 78 TECU. This value is comparable to equatorial TEC values. The highest values were detected in a latitudinal region 45-70°S. At the same time, TEC values of the entire region (30-70°S, 0-90°E) were enhanced.

It is possible to distinguish two parts in presented LTE: midlatitudinal (M_{LTE}MLTE) and subpolar (S_{LTE}SLTE). The LTE of April 5 has strong subpolar part and weaker but still pronounced midlatitudinal one. As it will be shown later, such a strong S_{LTE} SLTE is not typical and in some cases it is not detected at all. However, both MLTE and SLTE were presented during this even quite clearly for several hours and that was the main reason to describe this particular case in more details.

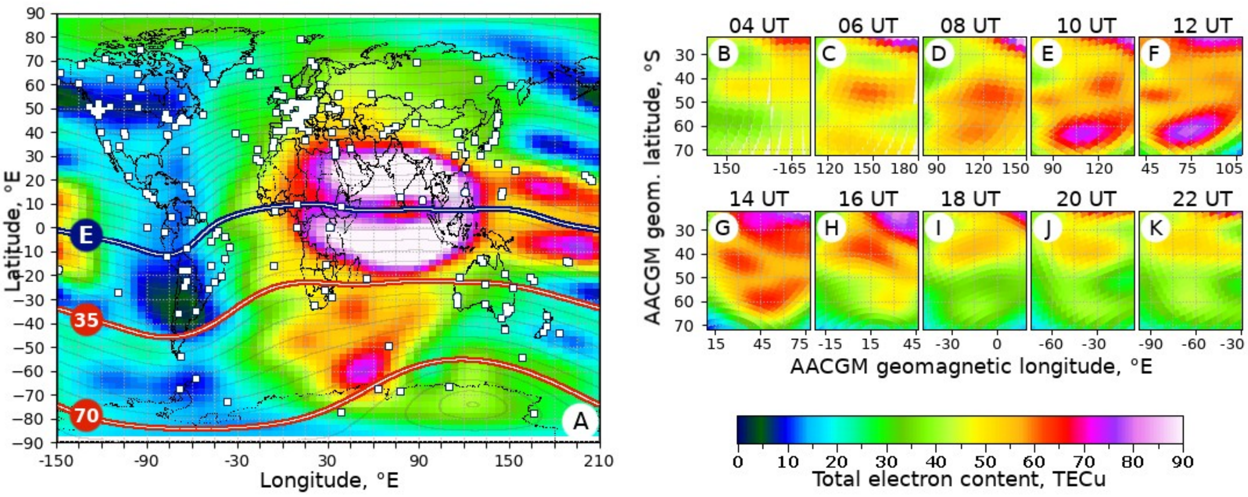


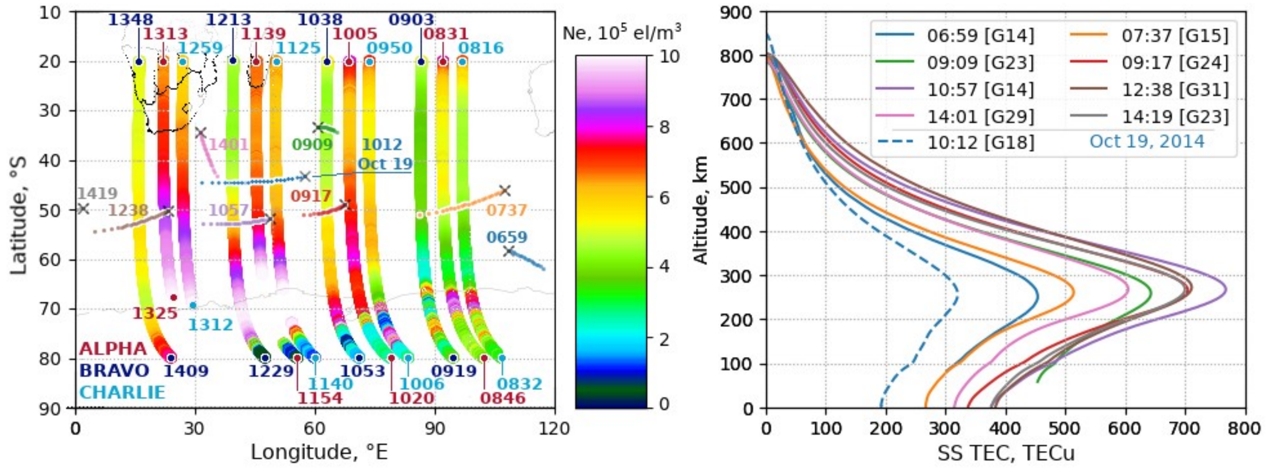
Fig. 1. Intense LTE observed at 10:00 UT of 05.04.2014 near Antarctica (A) and its development during a day in geomagnetic coordinates (B-K). LTE develops along geomagnetic parallels in a region 35-70°S (A, red lines).

During its development the LTE changes latitudinal position in a range 30-80°S corresponding to range of ~~and varies along~~ geomagnetic parallels within 35-70°S ~~range of geomagnetic latitudes~~ (red lines in fig. 1A). Phases of the development during April 5 are shown in geomagnetic coordinates (AACGM) in panels B-K in fig. 1. As it could be seen from the figure, the LTE exists during the entire day and changes its intensity unevenly. The less intensive ~~M~~$_{LTE}$MLTE part persists for a longer time and has lower magnitude than the brighter ~~S~~$_{LTE}$SLTE. Both parts are confined in their own ranges of geomagnetic latitudes: 30-50°S (MLTE) and 50-65°S (SLTE)~~, respectively~~. During the whole period shown their positions keep approximately the subsolar point (local noon).

It is necessary to say that the LTEs are detected most clearly over Atlantic and Indian oceans, where amount of GNSS stations is insufficient. White squares in fig. 1 mark location of the receivers providing CODE with data for TEC maps. Only a few are located in ocean (on islands) and the only is in 30-60°S latitudes of Indian Ocean (Kerguelen Islands, KERG). Therefore LTE detection has to be confirmed by other observations.

In-situ measurements of electron concentration Ne from SWARM satellites allow us to validate ~~check validity of~~ TEC distribution presented by GIM. Left panel of figure 2 presents Ne values, observed during 8-14 UT at April 5, 2014. Each track is marked by a colored dot corresponding to satellite: Alpha (red), Bravo (blue) and Charlie (cyan); digits of the corresponding color marks the satellite position at the the beginning and the end of the track in a format HHMM (hours and minutes). All the satellites were moving from equator to pole.

The area of extremely high concentration of electrons is clearly observed in data from all the three satellites. Blank areas in measurements from Alpha and Charlie during 11:30-13:30 mark the zone of concentrations exceeding color axis limitation. Temporal differences between passages of the satellites allow us to observe the dynamics of the LTE. The most intensive part is shown by Alpha's measurements. Charlie is ahead of Alpha by about 15 minutes and 2.5° of longitude and its measurements in general show lower concentration especially for a period 8-12 UT. Most probably such a difference is caused by movement of the enhancement: according to the GIM LTE is located in subsolar region and follows the Sun. Bravo is about 30 min and 12° behind Alpha and its measurements shows significantly lower concentration than the other satellites. It could point not only to the disturbance displacement but also to its distribution with altitude, since the orbit of Bravo is 70 km higher than those of Alpha and Charlie.



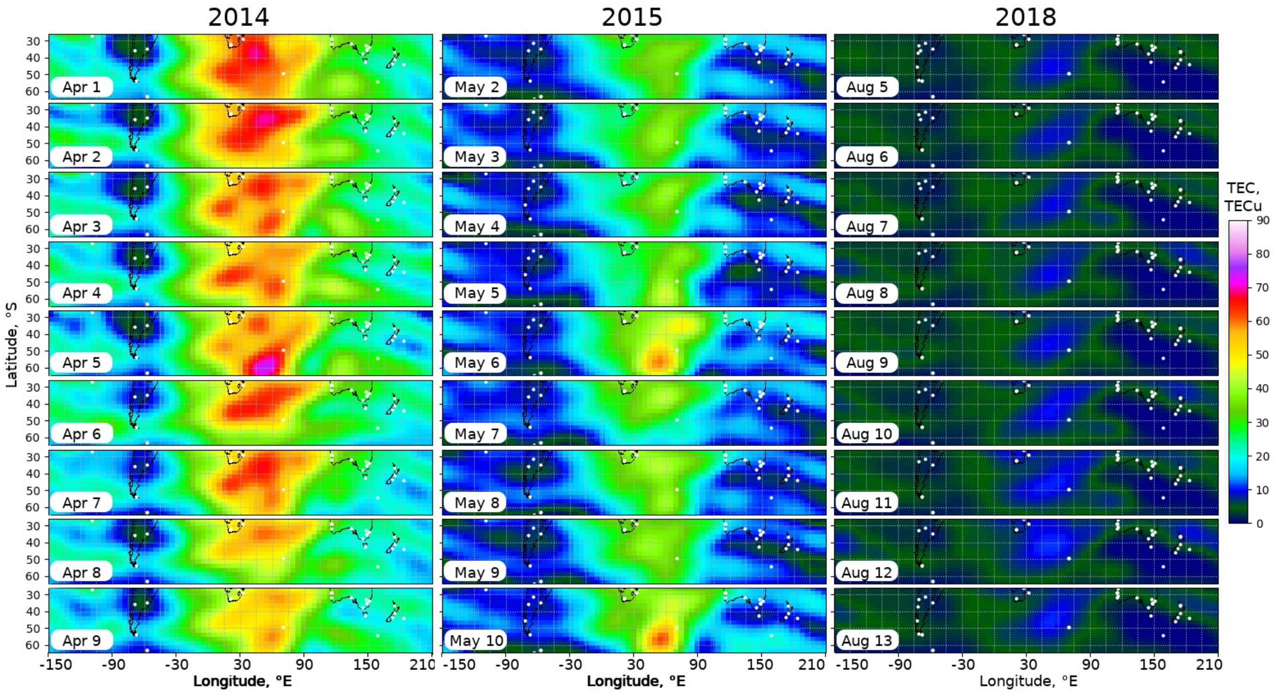


Fig. 3. Series of LTEs observed in Southern Hemisphere at 10 UT during years of different solar activity.

The area of extremely high concentration of electrons is clearly observed in data from all the three satellites. Blank areas in measurements from Alpha and Charlie during 11:30-13:30 mark the zone of concentrations exceeding color axis limitation. Temporal differences between passages of the satellites allow us to observe the dynamics of the LTE. The most intensive part is shown by Alpha's measurements. Charlie is ahead of Alpha by about 15 minutes and 2.5° of longitude and its measurements in general show lower concentration especially for a period 8-12 UT. Most probably such a difference is caused by movement of the enhancement: according to the GIM LTE is located in subsolar region and follows the Sun. Bravo is about 30 min and 12° behind Alpha and its measurements shows significantly lower concentration than the other satellites. It could point not only to the disturbance displacement but also to its distribution with altitude, since the orbit of Bravo is 70 km higher than those of Alpha and Charlie.

The distribution of electron concentration with altitude can be analyzed using radio occultation measurements by COSMIC satellites. Profiles of SS TEC during April 5 are presented in the right panel of fig. 2. Each SS TEC value in a profile is obtained ~~from~~on a bent satellite-to-satellite ~~signal~~ ray and is attributed to a tangent point of the ~~signal~~ ray (Rocken et al., 2000). Projections of the tangent points during each profile measurement are shown in left panel of fig. 2 with the same color as the profile. Cross marks on the trajectories and nearby digits indicate location and time of the lowest altitude measurement (last measured value before GPS satellite occultation). ~~Blue dashed line (fig. 2, right) presents a profile measured at 10:12 UT at October 19, 2014 when there was no LTE observed in GIM.~~ Due to the phenomenon of LTE series which will be described later, TEC values over the given region are enhanced almost during the whole month. To demonstrate ionosphere profile without any enhancement in GIM we have chosen October 19, 2014. The profile measured by COSMIC at 10:12UT is shown by dashed blue line in fig. 2.

It is quite clear that the detected disturbance was propagating according to solar motion and had the highest electron concentration in F region at about 11 UT. Profiles also show that electron concentration at an altitude 460 km could be 1.5-2 times higher that at 530 km, which is in a correspondence with SWARM measurements.

LTEs similar to the one detected on April 5 could be observed during several days in a row. In the particular case of April 2014, LTEs southward of Africa were detected since March 18 till April

11. TEC maps at 10:00 UT for April 1-9, 2014 are presented at the left side of fig. 3. The geomagnetic conditions during this period were slightly disturbed: maximal value of Kp was 4 (April 7), and minimal Dst value was about -25 nT (April 7-8). The intensity and the shape of the presented LTEs vary but at the same time of day all of them occupy the same regionThe intensity and shape of the presented LTEs vary from day to day, but at the same UT all of the LTEs occupy the same region. Intensities of M_{LTE}MLTE and S_{LTE}SLTE vary independently. S_{LTE}SLTE is more intense only on April 5. Mostly its intensity is either close to that of M_{LTE}MLTE (April 1, 3, 4, 7, 9) or weakerlower (April 2, 6 and 8). We define such a continuous sequence of LTEs observed day by day as a series of LTE. At least two consistently observed LTEs are considered as a series.

The other panels of fig. 3 demonstrate LTE series In a similar way LTE series were observed during other investigated years of relatively high (2015, in a middle) and low (2018, at the right) solar activity. The activity level was was estimated $F_{10.7}$ index values (figure 3, middle and right). Intensity of the observed LTEs varies according to global electron content, which depends on solar activity (e.g., Afraimovich et al., 2008). Disturbances of 2015 still have two different zones of LTEs, while all the presented LTEs of 2018 apparently are of M_{LTE}MLTE type (see April 6 in fig. 3, left). Geomagnetic activity during the presented days was from moderate to low and there was no clear correlation between indices (Kp, Dst, etc.) and a form shapes or intensitiesy of the disturbances.

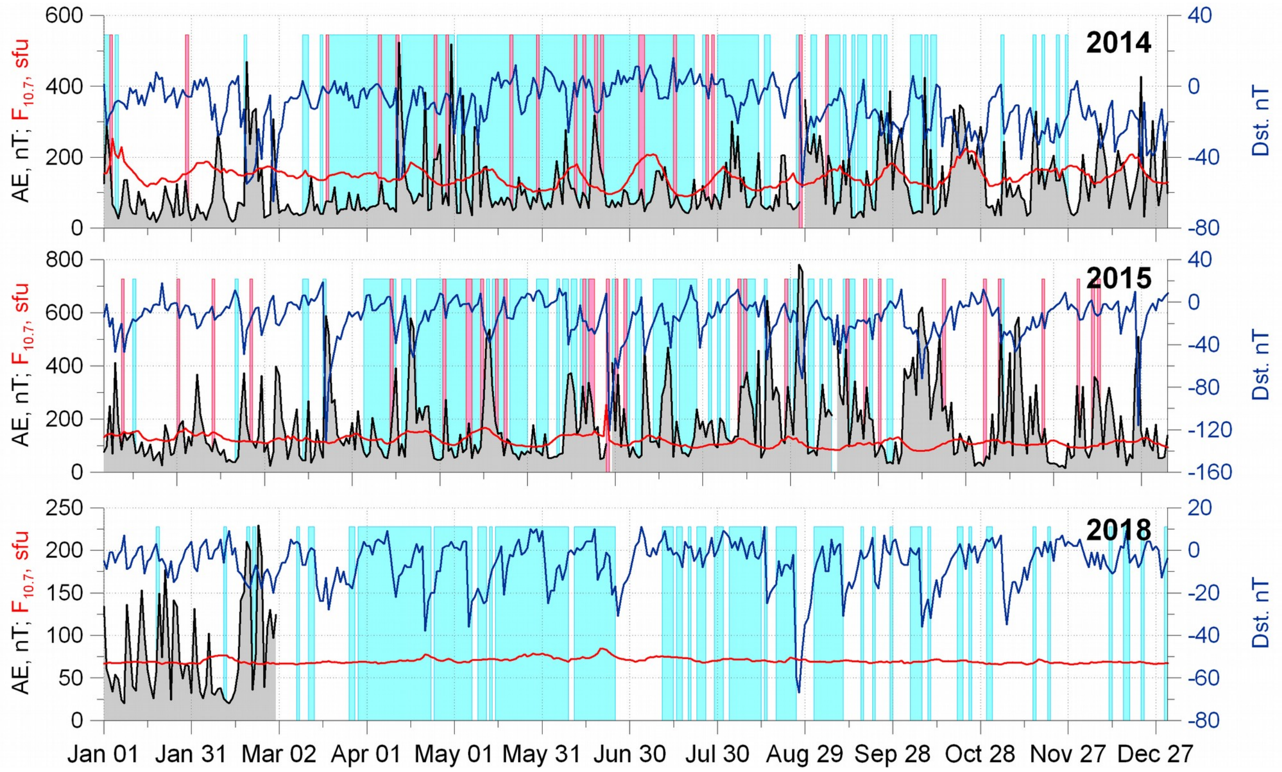


Fig. 4. Days with the LTE observed in SH (blue bars) during 2014 (top), 2015 (middle) and 2018 (bottom). Plots show annual variations of daily average values of F10.7 (red), AE (black, filled with gray) and Dst (navy blue) indices. Cases of bright SLTE observations are highlighted by red bars. In 2018 AE index is available only for Jan and Feb.

Fig. 4. Percentage of days with series of LTEs observed during each year (inner sectors) and temporal position of each LTE (solid color) alternating with days without LTE (light color) (outer sector).

The series of LTE were detected during all the three years. Figure 4 shows variations of solar ($F_{10.7}$) and geomagnetic (AE and Dst) indices during each year indicating days with LTE detected (blue and red bars). All the indices are taken daily averaged. According to the figure the most often LTEs are detected in autumn and at the beginning of winter (since March till June-July). Speaking of the series, the absolute maximum of their occurrence is observed in autumn-winter period as well with the longest ones during April-June. In late spring and in summer no LTE series were usually observed. The most interesting series here lasted 80 days of 2014 from May to July (fig. 4, top). It is possible to see that only several short gaps separate this series from two others in autumn and probably the entire period of late March-July should be considered to include one long series. Such a long sequence occupying the third part of a year definitely points to some regular process. For the other years the same season contains majority of the LTE series, but separated with more frequent and wider gaps. It is interesting to see that during a year of low solar activity (2018) we detect more series than during a moderately active one (2015).

Red bars in fig. 4 mark the days when the intensity of SLTE was higher than the intensity of the accompanying MLTE (as in fig. 1). Such bright SLTEs were detected only during years of relatively high solar activity (2014, 2015). Comparing their occurrence with the averaged indices we can hardly observe clear dependence between the detection of them and conditions of the near space.

~~are most often observed in autumn and at the beginning of winter (since March till June-July), as fig. 4 shows. Each inner sector in fig. 4 represents a months and its color depicts the season: summer (orange), autumn (red), winter (blue) and spring (green). Percentage shows the part of the month occupied by series of LTEs. For example, all the cases from fig. 3 give 9-day series. If such a series was the only series during the month (30 days) the percentage will be 9/30 = 30%. Zero percentage does not mean absence of an LTE during a given period but only the absence of a LTE series.~~

~~As it is seen from fig. 4, the absolute maximum of LTE series occurrence is observed in spring-summer period with the highest values during April-June. In late autumn and in winter no LTE series were usually observed. The most interesting series here is one, which lasted 80 days since May to July of 2014 (fig. 4, left). It is quite clear that only short gaps (one day in both cases) separate this series from two others in spring and probably the entire period late March-July should be considered to include one long series. Such a long series occupying one third of a year definitely points to some regular process.~~

~~For the other years the same season contains majority of the LTE series, but divided with more frequent and wider gaps. It is interesting to see that during a year of low solar activity (2018) we detect more series than during a moderately active one (2015).~~

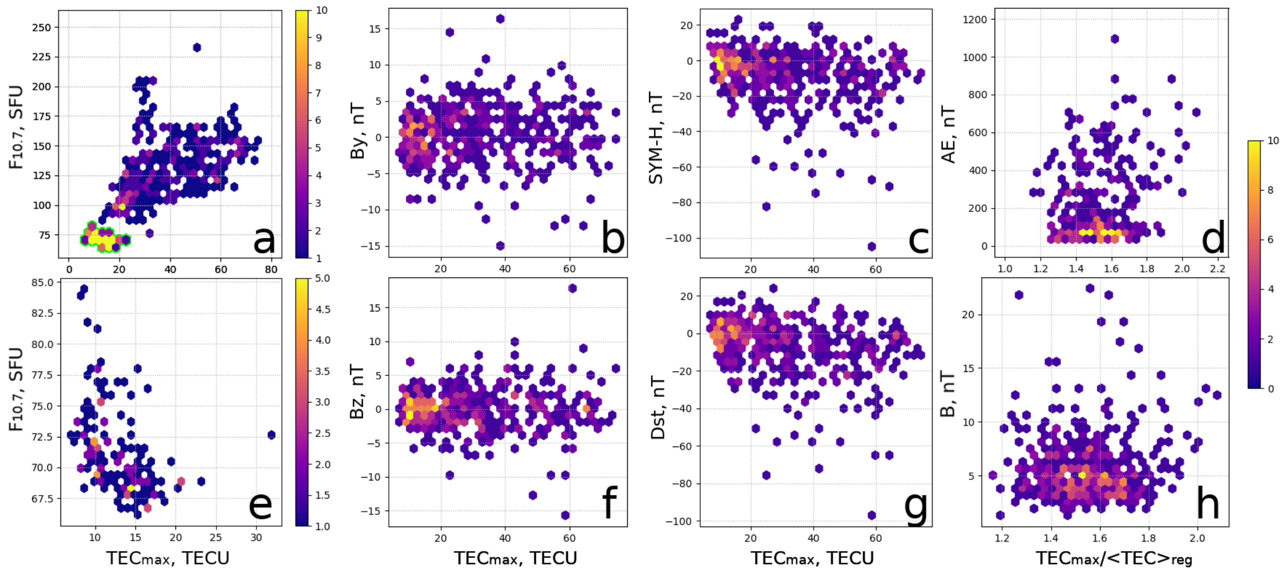


Fig. 5. Distributions of maximal TEC values in a region 30°W-60°E, 30-60°S versus 10.7 nm solar radiation (a, e), components of IMF By (b) and Bz (f), geomagnetic indices SYM-H (c) and Dst (g); and distributions of maximal to regional mean TEC ratio versus Auroral electrojet index AE (d) and IMF intensity B (h). All the TEC values are taken for 10 UT during years 2014, 2015 and 2018. Distribution in (e) is made with data only for 2018; this data is highlighted with green in

panel (a). Distribution of maximal TEC values in a region 30°W-60°E, 30-60°S versus 10.7 nm solar radiation (left) and distribution of maximal to regional mean TEC ratio versus intensity of IMF (right). All the TEC values are taken for 10 UT separately during 2014-2015 (top) and 2018 (bottom). Green-colored part (top, left) shows distribution for 2018.

Due to large variety of spatial forms and intensity distributions of LTEs (fig. 2) it is not easy to select a key parameter for an analysis over three years. We simplified the task by analyzing variations of maximal TEC (TEC_{max}) value observed at 10 UT in a region 30°W-60°E, 30-60°S. Panels of figure 5 present distributions of TEC_{max} during the entire three years versus main parameters of the near space: solar flux at 10.7 nm (F10.7, (a, e)), By(b) and Bz(f) components of IMF, geomagnetic indices SYM-H(c) and Dst(g). Relative intensity of an LTE could be analyzed by a ratio of TEC_{max} to average TEC over the region (TEC_{ratio}). Distributions of TEC_{ratio} versus the main parameters (not presented) are quite chaotic and do not demonstrate any pronounced dependence, except of AE (fig 5d) and IMF intensity B (fig 5h). The last ones do not show a clear dependence as well, but it is possible to see that TEC_{ratio} values tend to be higher with increased AE and B values.

It was found that during active years (2014-2015) maximal value quite clearly depends on F10.7 index (fig 5a, top left). It was not a surprise since maximal value directly depends on the entire amount of electrons in ionosphere, which is driven by solar radiation. Speaking of all the other parameters, we can hardly see any specific dependence on them. Taking this into account and supposing that not the whole region is usually occupied by the disturbance we analyzed, the ratio between maximal value and mean TEC over the given region. The distribution of this ratio vs IMF intensity is shown in right panels of fig. 5. The most probable value of the ratio is about 1.4-1.6 for 2014-2015 and 1.4-1.7 for 2018. We found that the ratio does not depend directly on space weather parameters, but its upper limit increases with intensity of interplanetary magnetic field (IMF) (fig. 5, right).

5. Discussion

Being observed separately SH LTEs were previously supposed to be a relatively rare phenomenon produced by some specific condition of near space and the detection algorithm was based on this concept (Edemskiy et al., 2018). However the data presented above showed that LTEs occur quite often and can be observed in a sequence during a relatively long period when geomagnetic conditions and solar parameters vary significantly. The presented distributions did not reveal any pronounced dependence except the one between maximal TEC value in the region and solar flux intensity (fig. 5a). Obviously TEC_{max} linearly depends on total amount of electrons in ionosphere or global electron content and the last one is known to be dependent on $F_{10.7}$ index (e.g., Astafyeva et al., 2008). At the same time it is surprising that the other distributions in fig. 5 do not show clear dependence on near space parameters. The previous suggestion (Edemskiy et al., 2018) of SH LTE occurrence only during disturbed conditions and especially with the observed negative Bz appears not to be entirely correct.

Being detected at 10 UT and occupying the same region of Southern Hemisphere all the observed LTEs show wide variety of shapes making it difficult to classify them. At the same time MLTE and SLTE intensities apparently independent and that can aim to different mechanisms of formation and that could be used as a classification. We selected cases of bright SLTE (fig. 4, red bars) and calculated separately distributions of TEC_{max} and TEC_{ratio} versus AE, Bz and SYM-H for these days (fig 6, top) and for all the other LTEs (fig 6, bottom) detected in SH over the investigated years.

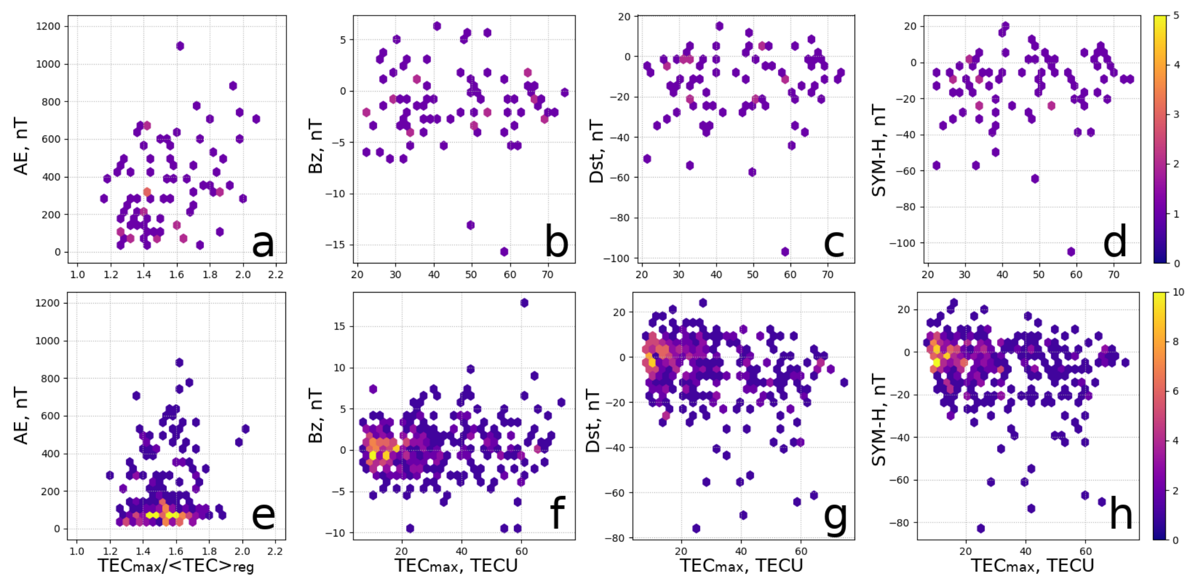


Figure 6. Distributions of TEC_{ratio} and TEC_{max} versus main geomagnetic indices for days with high intensity SLTE (top) and for all the others LTE detected over 2014, 2015, 2018.

The figure shows that most of the bright SLTEs were detected at the moments of negative Dst and SYM-H, and high values of AE index. In total that means that bright SLTEs are often observed during disturbed geomagnetic conditions. It is known that SEDs generated in high latitudes during geomagnetic storms could be observed in TEC maps as localized enhancements (e.g. Foster and and Rideout, 2007) and the detected SLTE could be a manifestation of some SED.

According to Foster (2008) SEDs are typically observed during severe geomagnetic storms and generally are formed by a F-region plasma driven upward and poleward (ExB direction) by eastward electric field penetrated into the inner magnetosphere at the early phase of a geomagnetic storm. Being formed by the fountain effect the enhanced plasma of EIA peaks can be redistributed during extreme events when uplifting plasma reaches higher-latitude flux tubes, resulting in enhanced electron density near the plasmapause. Most often such uplifts are observed in the dusk sector (Foster, 2008). Further development of the event can lead to generation of sub-auroral polarization stream creating SED as a connection between dusk sector and a region of dayside cusp. So partially the detected SLTEs could be generated via the described mechanism.

At the same time several features of SLTE should be highlighted. First, intense SLTEs were detected during a relatively quiet period as well. At least a quarter of them were detected with AE index values lower that 200 nT (fig. 6a). Second, mostly SEDs are believed to be plume-shaped, clearly connected to EIA region, and have high intensities along the entire plume. The used criteria excluded from consideration both the stretched formations and the ones having connection to EIA. So not all of the SLTEs are produced by some kind of SEDs and even if they are, the mechanism of their generation should differs from the one in NH.

Measurements of electron concentration by SWARM clearly confirm presence of SLTE, when in middle latitudes only generally enhanced Ne values are presented (fig. 2) without clear maximum of MLTE. This apparent absence of MLTE should be explained by orbit position: all the flights of the satellites at Apr 5 were crossing MLTE at the east edge (at 10UT it was about 70°E) where TEC falls and do not show significant peak. Due to the orbital motion SWARM satellites appears over the same region at different time and at some moments it is possible to see an exact intersection of a LTE. During Apr 18, 2014 a pronounced LTE was observed both in GIM and in Ne measurements (figure 7). That is quite clear from the figure that enhanced concentration is observed at both altitudes of A/C (460 km) and B (530 km) satellites orbits. Together with the data shown in fig. 2 it makes a good point to believe that LTEs of both types (MLTE and SLTE) are predominantly located in the F2 region.

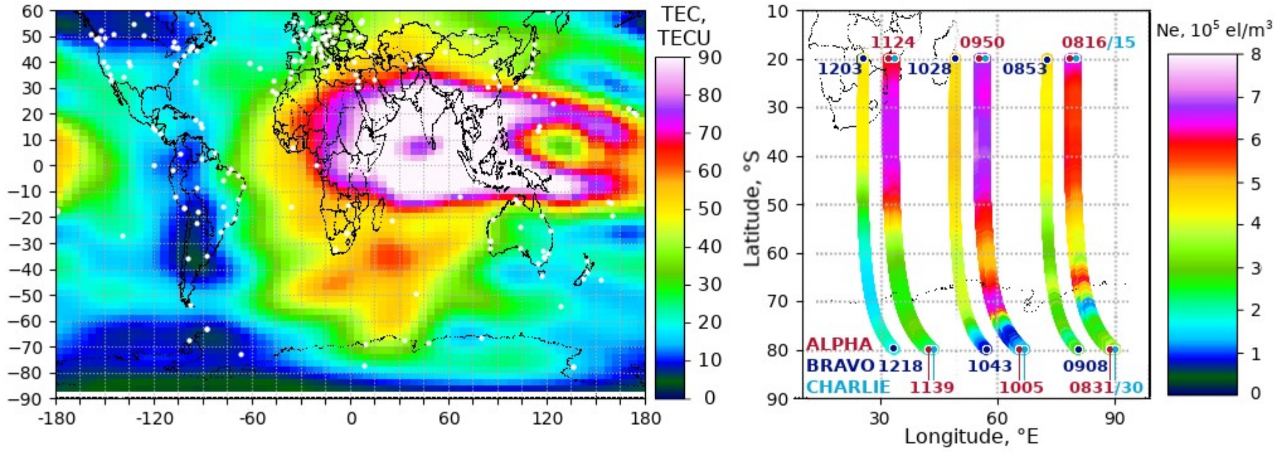


Figure 7. LTE of Apr 18, 2014 observed in GIM (left) and in-situ measurements of Ne by SWARM satellites (right)

Midlatitudinal LTEs are mostly detected in the same region of SH (at 10 UT), but demonstrate wide variety of shapes. It is difficult to say that their generation is driven by space weather since no clear dependence on its main parameters were found for both the occurrence rate and the intensities of LTEs. Most probable the mechanism of their formation is connected to some kind of plasma redistribution since the most often the enhancements are observed during autumn-winter period (April-August, fig 4) when intensity of solar ionization in middle latitudes should be less effective than during summer. Apparently the mechanism is not connected with or not organized like the fountain effect since last one typically gives a quasi-symmetrical (with respect to equator) pattern and similar LTEs were not detected in magneto-conjugated region of NH. Moreover the intensities of TEC in corresponding part on NH during LTE detection are typically lower than ones in SH. Together with seasonal asymmetry that reminds winter anomaly (WA) phenomenon: F2-layer density values are greater in the winter hemisphere than in the summer hemisphere. It should be noted that, using COSMIC RO data Gowtam and Tulasi Ram (2017) showed that at altitudes within 300-700 km WA effect is confined only to morning-noon hours and only to low-latitudes, claiming absence of WA in middle latitudes. Yasyukevich et. al. (2018) analysing GIM and satellites' data confirmed that SH WA is much less pronounced than NH WA and the region of its observation is mostly located in the southern part of Indian Ocean. The authors also showed dependence of the anomaly intensity on solar activity and claimed that it could be observed only during high solar activity years. Moreover, they concluded that in TEC the anomaly could be observed only in periods with $F_{10.7}$ > 170 SFU. As it was shown above only intensity of LTE depends on $F_{10.7}$, but not the occurrence rate and only few of them were detected during periods of such a high values of $F_{10.7}$. Higher TEC values in SH are observed during really low $F_{10.7}$ (entire 2018) as well. So the mechanism of LTE generation probably is not connected with winter anomaly.

Mainly the detection was based on a comparison of near-days maps which does not allow detection of a disturbance during a series of them. Here we showed that LTEs occur more often and it is possible to observe a sequence of such disturbances during a relatively long period when geomagnetic and solar conditions could vary significantly. Analysis of LTE occurrence connection with parameters of near space did not reveal any pronounced dependence except the one between maximal TEC value in the region and solar flux intensity (fig. 5, left). It shows a rise of disturbance intensity with global (or background) electron concentration, which dependence on $F_{10.7}$ index is known (e.g., Astafyeva et al., 2008). Figure 5 (right panels) demonstrates essentially no dependence of occurrence frequency of LTE and of ratio of maximal to mean regional TEC on IMF. The previous suggestion (Edemskiy et al., 2018) of LTE occurrence only during disturbed conditions and especially with the observed negative Bz appears not to be entirely correct. The height structure of the observed enhancements is not really clear. Cherniak et al. (2012) showed that daytime TEC in middle latitudes of Southern Hemisphere is by 30-40% formed in the plasmasphere. According to

~~the maps of ionospheric (h < 700 km) and plasmaspheric (700 km < h < 20000 km) content they presented, the plasmasphere contained more large-scale long-term disturbances than the ionosphere during all the four seasons of 2009.~~

~~SWARM data confirmed presence of an LTE with in-situ measurements at the both altitudes of the satellites orbits and COSMIC measurements do not show any specific changes in shape of ionospheric profiles: SS TEC changes at different heights are similar. This is a good argument to believe that LTEs are predominantly located in the F2 region. At the same time, there were no SS TEC profiles available for the areas of the disturbances highest intensity (neither S_{LTE} nor M_{LTE}). It also should be noted that M_{LTE} was not observed in SWARM data as clearly as S_{LTE} and that could mean that effective altitudes of M_{LTE} and S_{LTE} might be different.~~

~~The presented seasonal distribution of LTEs shows the highest probability of their detection in the period of local autumn-winter independently of solar activity. Due to the solar zenith angle the Sun affects the ionosphere more intensively at local summer (December) producing more electrons than at local winter (July). For example, Gowtam and Tulasi Ram (2017) using COSMIC RO data showed the presence of this seasonal difference for altitudes within 300-700 km. The data presented above (fig. 4) reveal higher occurrence rate of LTE during a period of higher solar zenith angles (local winter and autumn).~~

~~Similar seasonal asymmetry is known for the phenomenon of Winter Anomaly. It has been investigated mostly with N_mF2 measurements in the Northern Hemisphere (e.g., Rishbeth et al., 2005). Some papers are dedicated to its global manifestation (e.g., Mendillo et al., 2005). In the Southern Hemisphere the anomaly is much less pronounced and the region of its observation is mostly located in the southern part of Indian Ocean (Yasyukevich et. al., 2018). Using GIM data (JPL, 1998-2015) and satellite measurements (2001-2015) those authors showed dependence of the anomaly intensity on solar activity and claimed its absence during low activity periods. Their results revealed that winter anomaly in the Southern Hemisphere could be observed only during periods of high solar activity: in N_mF2 it is observed with $F_{10.7}$ > 90 SFU and in TEC with $F_{10.7}$ > 170 SFU. Our results show LTE presence during all three years, even during 2018 when $F_{10.7}$ annual mean was about 70 SFU and the highest $F_{10.7}$ with an LTE detected was 85 SFU (fig. 5). Therefore the mechanism of an LTE generation probably differs from that of Winter Anomaly.~~

Being observed dynamically LTEs show development along geomagnetic parallels within 30-70°S of geomagnetic latitude, approximately in boundaries of magnetic shells L = 2-4 (fig. 1 B-K), and could be observed permanently for several days with slight changes of their form and intensity. Anderson et al. (2014) detected hotspot of energetic electron precipitation E > 300 keV at SH at geomagnetic latitudes 55–72°~~o~~S (much less pronounced at NH) and geographic longitudes 150~~o~~°W–60°~~o~~E. However, this result is based on nighttime observations, i.e. predominantly autumn-winter observations, when almost no LTEs have been detected. Using POES data for analysis of South Atlantic Anomaly, Domingos et al. (~~[~~2017~~]~~) found a plume of particle flux located within L=2.5-3 in South Atlantic. The position of the plume was in a good correlation with a typical LTE position. However, the plume was observed in December when occurrence rate is minimal (fig. 4). Moreover, for the LTE analyzed in detail by Edemskiy et al. (2018) it was shown that particle precipitations ~~is~~are not responsible for that LTE. So most probably LTEs are not directly connected with the increased fluxes.

Statistically electron concentration~~the ionosphere~~ over the western part of Indian Ocean ~~has~~is enhanced ~~electron concentration~~ during equinox periods. Jee et al. (2009) investigating TOPEX data over 1992-2005 showed that during March-April noontime TEC values are significantly increased over the southern part of Africa and its Indian Ocean shore. Similar increment with lower intensity is shown ~~could be seen~~ during September-October. At summertime it is still possible to observe this enhancement with much less intensity. In winter the region of enhanced TEC depends on solar activity: during high activity period no enhancement is observed. They showed that ~~D~~during low activity the Equatorial Anomaly area ~~is shown to wider~~grows, reaching 30ºS over Africa and TEC values at south of Africa are increased as well. Our results show higher probability of wintertime

LTE detection during lower activity years. Analyzing GIMs for 1998-2015 Lean et al. (2016) found typically enhanced TEC over the region during 10-16UT and according to data for 2000-2002 the highest values during March-May.

Investigating GRACE and CHAMP electron density measurements over a period 2003-2007, Lee et al. (2011) also showed presence of enhanced electron concentration formation over western part of Indian Ocean. This formation is clearer in a presented difference between IRI (2001 and 2007) data and satellite measurements. Such a clear difference shows that the enhancement phenomenon in the region is not taken into account in the models.

As a conclusion we should say that at the present moment the generation mechanism is still unclear for us. The phenomenon of SH LTE is observed quite regularly in periods of different solar activity and under different conditions of near space manifesting itself even during geomagnetically quiet periods. Since we did not detect symmetrical phenomena in Northern Hemisphere we could conclude that the enhancements are a feature of Southern Hemisphere ionosphere and therefore they should be driven by combination of its specific conditions: geomagnetic field, oceanic ionosphere and system of winds. Such a regular phenomenon should be taken into account by models as well. Currently it is difficult to say if it is reproduced by models, since it is not well described in the literature. We could mention a paper by Lee et al. (2011) who showed presence of enhanced electron concentration formation over western part of Indian Ocean using measurements from GRACE and CHAMP satellites. The authors concluded that 2001 and 2007 IRI models did not predict the observed enhancement at all. So the phenomenon should be investigated more precisely since it will surely give us more clear understanding of global distribution of ionospheric plasma.

5. Conclusions

The paper shows that localized TEC enhancements in Southern Hemisphere are observed quite regularly and can be detected serially. Having clear seasonal asymmetry of occurrence they do not show any pronounced dependence on space weather parameters. Enhancements can be detected during both disturbed and relatively quiet geomagnetic period with different level of solar activity. Midlatitudinal and subpolar LTEs seem to have different mechanism of generation and should be investigated separately in more details. At least half of the observed SLTEs were detected during disturbed conditions and could be connected with SED structures. At the same time, part of them occurred during relatively quiet conditions and that means that even generation of SLTEs can be driven by several different mechanisms. Midlatitudinal LTEs are observed more regularly and show a big variety of shapes and intensities. TEC values during MLTE detection are typically higher than ones in conjugated region of HN. Absence of clear dependence of MLTEs occurrence rate on space weather makes it difficult to propose any certain mechanism of their generation.

The presented data lead us to the opinion that despite the observed LTEs were supposed to be an ionospheric disturbance they most probable are a feature of the Southern Hemisphere ionosphere. The phenomenon should be investigated in more details with some additional methods including comparison with different models of ionosphere.

Localized TEC enhancement is a relatively frequent phenomenon in the Southern Hemisphere, which could be observed during several months under different ionospheric conditions. The highest probability to observe an LTE series is in spring-summer period (April-June), whereas it is almost zero in November-February (summer). An LTE develops in latitudinal region corresponding to L = 2-4 geomagnetic shells and its intensity clearly depends on solar activity. The most probable LTE intensity is essentially independent of IMF intensity and it is 1.4-1.6 times higher than the mean TEC in the region between Africa and Antarctica. No clear dependence between orientation of IMF and LTEs' parameters was observed. Formation of LTE varies with solar activity and usually do not contain pronounced southern plume during low solar activity. The phenomenon is not predicted by the IRI model.

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Code/data availability

All the used data are available in accordance to links in Data and methods section.

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