Reply to Reviewer's comments.

I am grateful to the reviewer for very useful and valuable comments and suggestions. They help to improve substantially the quality of manuscript.

The following revisions have been done in according to the comments (colored by blue in the text):

Comment 1

In lines 27 – 28, a brief description of the outer Van Allen radiation belt is provided where this population of charged particles is presented as part of the outer magnetosphere, contrary to what has been widely established and is presented in the following publications:

- Baker (1995), The inner magnetosphere: A review, Surveys in Geophysics, doi: 10.1007/BF01044572

- Ebihara & Miyoshi (2011), Dynamic inner magnetosphere: A tutorial and recent advances, in Liu W., Fujimoto M. (eds) The dynamic magnetosphere, doi: 10.1007/978-94-007-0501-2_9

Reply 1

The sentences were revised accordingly:

"The outer radiation belt (ORB) is populated by energetic and relativistic electrons trapped in the magnetosphere at drift shells above $L \sim 3$ (e.g. Ebihara and Miyoshi, 2011). The ORB is very dynamic and exhibits variations…"

The term "outer magnetosphere" has been removed from whole the text.

Comment 2

Additional references on the long-term variations of the radiation belts' structure that should be considered are the following:

- Fung et al. (2006), Long-term variations of the electron slot region and global radiation belt structure, Geophysical Research Letters, doi: 10.1029/2005GL024891

- Baker & Kanekal (2008), Solar cycle changes, geomagnetic variations, and energetic particle properties in the inner magnetosphere, Journal of Atmospheric and Solar-Terrestrial Physics, doi: 10.1016/j.jastp.2007.08.031

- Glauert et al. (2018), A 30-year simulation of the outer electron radiation belt, Space Weather, doi: 10.1029/2018SW001981

On lines 30 and 35, the semi-annual variation of the outer radiation belt is mentioned. This seasonal and not annual change could be explained by the IMF-effect also known as Russell-McPherron effect which is described in:

- Russell & McPherron (1973), Semiannual variation of geomagnetic activity, Journal of Geophysical Research, doi: 10.1029/JA078i001p00092

- McPherron et al. (2009), Role of the Russell-McPherron effect in the acceleration of relativistic electrons, Journal of Atmospheric and Solar-Terrestrial Physics, doi: 10.1016/j.jastp.2008.11.002

and where origins of the seasonal variability in geomagnetic activity have been traced.

Reply 2

The first paragraph of Introduction section has been revised accordingly:

"The ORB is very dynamic and exhibits variations in a wide temporal range: short-term storm-time and local time variations, 27-day solar rotation, seasonal and solar cycle variations (e.g. Li et al., 2001; Baker and Kanekal, 2008; Miyoshi and Kataoka, 2011). During magnetic storms, the ORB is substantially disturbed and shifted earthward (Baker et al., 2016; Shen et al., 2017). The storm-time variation is the strongest one for both the ORB location and intensity (Baker and Kanekal, 2008). Magnetic storms produced by interplanetary coronal mass ejecta (ICME) and high-speed streams (HSS) of the solar wind from coronal holes. The seasonal variations with maxima at equinoxes can be explained by the effect of interplanetary magnetic field (IMF) orientation relative to the geomagnetic dipole (Li et al., 2001; McPherron et al., 2009). ORB manifests prominent variations with the solar cycle (Fung et al., 2006; Baker and Kanekal, 2008). It was shown that the maximum of ORB is mostly distant from the Earth in solar minimum (Miyoshi et al., 2004) and it is closest to the Earth during solar maxima (Glauert et al., 2018)."

Comment 3

There are minor issues with English language use and several typographical errors. For example, on line 54, the term auroral electrojet is first introduced that should be one word. Since Smith et al. (2017) studied both current in the north and south hemisphere, it should also be plural (auroral electrojets – AEJs).

Reply 3

Corrected

Comment 4

Further down on the same page, on line 72, the work of Kataoka et al. (2015) is listed among the references for the October-November 2003 superstorms although it is focused on the magnetic storm of 17 March 2015 which is mentioned further down, in lines 74-81. It should, therefore, be moved more appropriately further down after the brief description of the 2015 Saint Patrick's Day storm.

Reply 4

Thank you for suggestion. Corrected.

Comment 5

On line 89, it is indicated that the satellite observations used for the study of the outer electron belt location cover the time period from 1998 to 2016. However, the dates listed in Table 2 are within the time period *between 2001 and 2018 which is also the time period on which this study is focused as indicated throughout the manuscript.*

Reply 5

The year 1998 is replaced with 2001

Comment 6

On line 119, it should read "geomagnetic activity was very weak" and not "very week".

Reply 6

Corrected

Comment 7

On line 135, it is indicated that Figure 2 shows POES observations from 3 June 2016, while the figure caption indicated that the observations shown are from 2 June 2016.

Reply 7

Yes, it was misprinting. In Figure 2 caption, 2 June was replaced with 3 June.

Comment 8

In lines 123-126, the close link between increases in solar wind speed and enhancements in electron fluxes in the outer radiation belt is briefly described. Periodic oscillations in the Earth's magnetic field with frequencies in the range of a few millihertz (ultralow frequency waves) may indeed be an intermediary through which solar wind influences radiation belt dynamics due to their potential for resonant interactions with energetic electrons causing the radial migration of resonant electrons. It should, however, be corrected that electrons are accelerated and increase their energy when they are transported earthward to regions of stronger geomagnetic field. Recent, representative publications on this acceleration mechanism are the following:

- Mann et al. (2013), Discovery of the action of a geophysical synchrotron in the Earth's Van Allen radiation belts, Nature Communications, doi: 10.1038/ncomms3795

- Su et al. (2015), Ultra-low frequency wave-driven diffusion of radiation belt relativistic electrons, Nature Communications, doi: 10.1038/ncomms10096

Radial transport acts as a loss mechanism when particle drift outward and are lost to the magnetopause. The work of Horne et al. (2007) and Reeves et al. (2013), provided as reference, is centered on a different acceleration mechanism acting in the heart of the radiation belt (local acceleration) that involves whistler mode chorus waves rather than waves generated through the Kelvin-Helmholtz instability along the magnetopause.

Reply 8

Thank you for very useful papers. Note that storm-time acceleration and transport of energetic electrons in ORB is not the subject of the present study, which is dealing with quiet days. Hence, this part has been revised accordingly:

"Note that the solar wind with the speed of V > 400 km/s is often associated with HSSs from coronal holes. Fast solar wind streams initiate the Kelvin-Helmholtz instability at the magnetopause and also produce recurrent magnetic storms, which are accompanied by intensification of wave activity in the outer magnetosphere that results in effective acceleration and radial transport of the ORB electrons (Engebretsone et al., 1998; Tsurutani et al., 2006; Horne et al., 2007; Su et al., 2015)."

Comment 9

In lines 187-188, the author notes that the inner edge of the outer radiation is defined as the "first high-latitude point of electron flux enhancements". Could the latitude above which the flux enhancement was searched be indicated? In addition, which criterion was applied on flux measurements to determine which fluctuations in electron flux correspond to the enhancement observed at the inner edge of the outer electron belt?

Reply 9

This important issue is described in more details in the revised manuscript:

"Apparently, the electron flux enhancements peak in the maximum of ORB. Hence, the inner edge of ORB corresponds to the beginning of continuous increase of the electron flux from the minimum at low latitudes to the ORB maximum. This criterion allows determining of the inner edge for the electrons with energies >300 keV and in the European sector, where the slot region is not so obvious. Geographic latitude of the inner edge is determined for each year with the accuracy varying from 0.5° to 1°. In the American sector, the inner edge of ORB is situated at lowest latitudes from 43° to 51°, in the European sector – from 55° to 63°, and in the Siberian sector – at highest latitudes from 58° to 65°."

Comment 10

On line 203, the maximum of solar cycle 23 is indicated that it was observed in 2001 and that of solar cycle 24 in 2012-2013. It is not clear to me, and perhaps the reader, how this maximum was defined as both solar cycles were double-peaked according to the number of sunspots observed on the surface of the Sun that has been presented in Figures 4 and 5 with the solid grey line.

Reply 10

Solar maximum, as a physical phenomenon of the solar magnetic field reversal, has the double-peak structure both in the 23rd and 24th solar cycles. Those cycles peaked, respectively, in November 2001 and in April 2014. After the peaks, the declining phases started and the solar activity was quickly decreasing. Dramatic changes in the solar magnetic field (including the reversals) were observed from 2000 to 2001 and from 2012 to the beginning of 2014, respectively. In this sense, the maximal phases of those cycles occurred definitely in 2001 - 2002 and 2012 - 2013. The year of 2014 belongs both to the maximum and to the declining phase of the 24th solar cycle.

In the original paper, the year 2000 was not shown and, hence, it was mentioned.

In the revised manuscript, this issue is described in more details:

"Note that the maximum phases of the 23rd and 24th solar cycles occurred in the years 2000 - 2001 and in 2012 – April 2014, respectively. The years 2008 – 2009 are the solar minimum phase. The declining phases lasted from 2003 to 2007 and from 2014 to 2018. In Figures 4 and 5, one can see that during the declining phase of the current 24th solar cycle (especially in the years 2016 – 2018), the behavior of the ORB maximum and inner edge is different from that during the declining phase of the previous 23rd solar cycle. Namely, their latitudes increased only slightly or even decreased above North America and especially above Siberia."

Comment 11

Further down, in the paragraph starting with line 208, an example of how the IGRF-12 model was used on the geographic coordinates of the outer radiation belt maximum flux to obtain the corresponding geomagnetic coordinates is provided. What height was selected as input to the model to determine the geomagnetic or geographic coordinates?

Reply 11

The height of POES orbit at 850 km was used. Actually for a given magnetic coordinates, the long-term changes in geographic latitudes predicted by the IGRF-12 model do not vary much with the heights for the low-earth orbits and ground (10% of the Earth's radius). The latitudes are different, but their changes with time are almost same.

Comment 12

The choice of a simple linear fit over the set of outer radiation belt latitudes that have been calculated for the selected quiet days in the period 2001-2018 and are presented in Figures 4 and 5 puzzles me as it seems inadequate to support the main conclusion of the study. There is significant variability in the outer radiation belt location that is related to the solar activity variability that has not been accounted for – although it should - during linear regression.

Reply 12

The using of linear fit can be justified in the following way:

"Unfortunately, there is no any model of the ORB location variation with the solar cycle because the driving mechanisms are not well established.

As a first approach, the variations of ORB location with years are considered as random and can be fitted by a linear function (indicated by dashed strait lines in Figures 4 and 5):

$$\lambda = a * \text{year} + b, (1)$$

where λ is the latitude of maximum or inner edge of ORB. The slope a, parameter b and their standard errors are calculated from a linear regression for various longitudinal regions and various energies of electrons. The results are presented in Tables 3 and 4 for the ORB maximum and the inner edge, respectively."

Further

"As one can see in Figures 4 and 5, the long-term variation in IGRF-12 is almost linear function of the year and, hence, this variation can be easily compared with the linear fits of the ORB location."

Comment 13

The difference in the variability observed in the location of the inner edge of the outer radiation belt or the location of the maximum electron flux has also not been quantified nor considered in the evaluation of the difference estimated between electron observations and magnetic field predictions from the IGRF-12.

Reply 13

An effort of inter comparison between the ORB inner edge and maximum was made in the original paper:

"As can be seen in Figures 4 and 5, the location of ORB manifests the well-known solar cycle variation: the latitudes of ORB maximum and inner edge have a tendency to be highest around solar minimum in 2008 – 2009 and lowest during solar maxima in the years 2001 and 2012 – 2013."

In the revised manuscript, the difference is quantified and discussed for each longitudinal sector. For example:

"Similar pattern can be found for the inner edge of ORB in the Siberian sector (see Figure 5c). Namely, the IGRF model predicts a decrease of ~1°. The inner edge was shifted toward lower latitudes by ~3°, ~2° and ~1°, respectively, for >30 keV, >100 keV and >300 keV electrons. From Table 4, one can see that the slope a is calculated with errors of ~30% and ~20%, respectively, for >30 keV and >100 keV electrons. It means that the decrease in latitude might be ~2° (instead of ~3°) and ~1.5° (instead of ~2°), respectively. These values are again larger than 1° of the model prediction. Hence, there is a tendency that the change in the latitudinal location of ORB maximum is underestimated by the model. This fact indicates that during 17 years from 2001 to 2018, ORB is abnormally displaced toward the lower latitudes in the Siberian sector."

Comment 14

On line 264, among the reference provided for the effect of the tilt angle variation on the location of the outer radiation belt, the study of Newell et al. (2006) is found. The specific study was centred on the cusp location as it is detailed in the next paragraph and should, therefore, be excluded from the reference list provided here.

Reply 14

Corrected, the reference has been replaced.

Comment 15

In lines 269 and 270, the cusp location is suggested as a proxy of the outer radiation boundary. The author must imply the outer edge of the electron radiation belt or more correctly that a displacement of the cusp influences the location of the outer radiation belt but this is not clear from the text. It is also not substantiated by the findings of Newell et al. (2006).

To date, the inner edge of the outer radiation belt has been suggested to be defined by the plasmapause, the outer boundary of the plasmasphere. Specifically, in the following publication:

- Baker et al. (2014), Impenetrable barrier to ultrarelativistic electrons in the Van Allen radiation belts, Nature, doi: 10.1038/nature13956 the authors analysed 20 months of electron flux data from the NASA/Van Allen Probes to identify a barrier in the inward transport of ultrarelativistic electron transport.

Earlier, - Darrouzet et al. (2013), Links between the plasmapause and the radiation belt boundaries as observed by the instruments CIS, RAPID and WHISPER onboard Cluster, Journal of Geophysical Research, doi: 10.1002/jgra.50239

had reached a different conclusion. The radiation belt location was found to be dependent on the energy range of particles examined but also that the plasmapause is more variable that the inner edge of the outer radiation belt. Namely, the inner or outer edge of the outer electron belt does not always coincide with the plasmapause.

Reply 15

Thank you very much for very useful papers.

This paragraph has been revised accordingly:

"The effect of solar wind parameters, including IMF *Bz* and dynamic pressure (*P*d), to the ORB location is not obvious. It is found that the slot region location can be related to the plasmapause but the relation is ambiguous (Darrouzet et al., 2013; Baker et al., 2014). We can make indirect estimation of the effect using a dependence of the cusp location from the solar wind parameters (Kuznetsov et al., 1993; Newell et al., 2006). The equatorward edge of the cusp separates the open and close magnetic filed lines in the dayside magnetosphere. Hence the latitude of the equatorward edge can be considered as a proxy of the ORB outer edge. In the first approach, we assume that the effect of solar wind parameters to the ORB location can be represented by the dynamics of the ORB outer edge or the cusp equatorward edge. It can be shown that *Bz* = -4 nT results in less than 0.5° equatorward shift of the cusp and a change of *P*d from 1 to 2 nPa results in ~0.2° decrease in the latitude of the cusp equatorward edge. Hence, the effects of both *P*d and IMF Bz are several times weaker than the difference of 3°."

Comment 16

In lines 274 and 275, the statement "Variations of the ORB location from cycle to cycle are not investigated *yet" is not entirely correct. There are indeed significant limitations in such studies due to the lack of data covering several years that could be discussed at this point. Reference to studies such as Glauert et al. (2018) could also be provided.*

Reply 16

Thank you very much for very useful paper. This part was revised accordingly:

"Variations of the ORB location from cycle to cycle and during different phases of solar cycles are still poorly investigated. It was well established that during solar minima and maxima, the ORB is located, respectively, at highest and lowest latitudes (Miyoshi et al., 2004; Glauert et al., 2018). From these findings, we can speculate that lower(higher) solar activity results in an increase (a decrease) of the ORB latitudes."

Comment 17

On line 295, the findings of Finlay et al. (2015) suggesting rapid changes in the geomagnetic field in the past 15 years are briefly mentioned. Although the latest change observed in 2012-2013 seems to influence the location of the outer radiation belt, is there a signature of the change observed in 2006 and 2009 in the POES measurements from the same period analysed here?

Reply 17

This important issue is clarified in the following manner:

"We can assume that the abnormal ORB displacement might be related to the geomagnetic jerks. Though, there is no prominent change in the ORB location in 2006, one can indicate very high latitude of ORB in 2009. Note that the jerk in 2009 coincided with the abnormally deep solar minimum and, hence, it could be hard to distinguish between the two effects. On the other hand, we have found significant change in the ORB dynamics after 2012 – 2013."

Comment 18

Individual graphs in Figure 2 are difficult to read because of the dark background colour. The font size selected for the x and y axis labels are so small that, even after blowing them up to 200%, labels are still difficult to read. On the other hand, titles over the two columns (2016 for the right column and 2006 for the left column) seem to be misplaced.

Reply 18

Figure 2 has been revised accordingly.

Comment 19

Fonts on plots in Figure 3 could also be enlarged if these are selected to be the final sizes of the graphs.

Reply 19

The multi-plot Figure 3 is mainly presented in order to demonstrate qualitatively the structure of ORB and its dynamics in various longitudinal sectors. The results of numerical analysis are presented in Figures 4 and 5.

On the radiation belt location in the 23 – 24 solar cycles

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Abstract

Within the last two solar cycles (from 2001 to 2018), the location of the outer radiation belt (ORB) was determined with using NOAA/Polar-orbiting Operational Environmental Satellite observations of energetic electrons with energies above 30 keV. It was found that the ORB was shifted a little (~1 degrees) in the European and North American sectors while in the Siberian sector, ORB was displaced equatorward by more than 3 degrees. The displacements corresponded qualitatively to the change of geomagnetic field predicted by the IGRF-12 model. However in the Siberian sector, the model has a tendency to underestimate the equatorward shift of ORB. The shift became prominent after 2012 that might be related to a geomagnetic jerk occurred in 2012 – 2013. The displacement of ORB to lower latitudes in the Siberian sector can contribute to an increase in the occurrence rate of mid-latitude auroras observed in the Eastern Hemisphere.

Keywords: electron radiation belt, secular geomagnetic variation, mid-latitude aurora

1. Introduction

The outer radiation belt (ORB) is populated by energetic and relativistic electrons trapped in the magnetosphere at drift shells above $L \sim 3$ (e.g. Ebihara and Miyoshi, 2011). The ORB is very dynamic and exhibits variations in a wide temporal range: short-term storm-time and local time variations, 27-day solar rotation, seasonal and solar cycle variations (e.g. Li et al., 2001; Baker and Kanekal, 2008; Miyoshi and Kataoka, 2011). During magnetic storms, the ORB is substantially disturbed and shifted earthward (Baker et al., 2016; Shen et al., 2017). The storm-time variation is the strongest one for both the ORB location and intensity (Baker and Kanekal, 2008). Magnetic storms produced by interplanetary coronal mass ejecta (ICME) and high-speed streams (HSS) of the solar wind from coronal holes. The seasonal variations with maxima at equinoxes can be explained by the effect of interplanetary magnetic field (IMF) orientation relative to the geomagnetic dipole (Li et al., 2001; O'Brien and McPherron, 2002; McPherron et al., 2009). ORB manifests prominent variations with the solar cycle (Fung et al., 2006; Baker and Kanekal, 2008). It was shown that the maximum of ORB is mostly distant from the Earth in solar minimum (Miyoshi et al., 2004) and it is closest to the Earth during solar maxima (Glauert et al., 2018).

Apparently, the intense variations mask relatively weak long-term changes related to a secular variation of the core and crustal magnetic fields. Recently, a number of authors reported significant changes in the Earth's magnetic field. The magnetic axial dipole has decreased over the past 175 years by 9% (e.g. Finlay et al., 2016). It was also shown that the north magnetic dip pole, the point where the magnetic field inclination is vertical, drifted from Canada toward Siberia with the speed rapidly increasing from 10 km/yr in 1990s to more than 50 km/yr at present (Chulliat et al., 2010; Thebault et al. 2015). From 1989 to 2002, most dramatic magnetic field changes of >50 nT/yr have been found in the Canadian Arctic and Eastern Siberia.

The effects of dipole decay and pole drift are predicted by International Geomagnetic Reference Field 12th generation (IGRF-12) model (e.g. Thebault et al. 2015). However in the Siberian sector, significant anomalies of the main geomagnetic field were found at high latitudes within the 80º-130º longitudinal range (Gvishiani et al., 2014). In this sense, independent verification of changes in the geomagnetic field at high and middle latitudes is required. Namely, the decrease of magnetic dipole should result in a global equatorward shifting of the magnetospheric domains such as ORB and auroral region. The drift of the north magnetic pole should cause a decrease(increase) of ORB and auroral latitudes in the Siberian(North American) sectors.

The long-term changes in the location of auroral region were reported by Smith et al. (2017). They analyzed the latitudinal location of auroral electro jets (AEJs) and revealed a prominent latitudinal displacement of the AEJs by several degrees in the years 2004 – 2014 relative to the previous solar maxima in 1970 and 1980. Namely, in the Siberian sector, AEJ shifted to lower latitudes and in the American sector, AEJ shifted to higher latitudes. The opposite shifts in different sectors cannot be explained by the solar cycle variation and, thus, it has been attributed to the core and crustal magnetic fields. On the other hand, the technique of auroral precipitations is hard to use for tracing of the long-term geomagnetic variations because of high variability in the intensity, location and extension of aurora (e.g. Cresswell-Moorcock et al., 2013; Smith et al.; 2017).

An additional support of prominent changes in the geomagnetic field can be found from a sudden increase of occurrence of aurora borealis during the years of 2015 to 2017. There were numerous reports about aurora borealis observed at middle latitudes in the North America, Europe and Russia. Table 1 lists the days when discrete aurora was detected in big Russian cities Moscow (geographic location 55°45N 37°37E), St. Petersburg (geographic location 59°57N 30°18E) and Novosibirsk (geographic location 55°01N 82°55E). It is important to note that while in the North American region, the mid-latitude discrete aurora is observed quite often, this phenomenon is rare at lower magnetic latitudes such as in the regions of Central Europe and in particular in Central Russia (MacDonald et al., 2015; Vázquez et al., 2016). The previous low-latitude aurora borealis was observed during extremely strong geomagnetic storms with minimum $Dst < -300$ nT on October - November 2003 (e.g. Shiokawa et al., 2005; Mikhalev et al., 2004).

In contrast, magnetic storms in 2015 – 2017 were not very intense, as one can see in Table 1. The strongest storm on 17 – 18 March 2015, so-called St. Patrick’s Day storm, had minimum *Dst* of -220 nT (e.g. Kataoka et al., 2015). During the St. Patrick’s Day storm, aurora borealis was observed worldwide in North America, Central Europe (e.g. “Strongest geomagnetic storm of SC24 sparks spectacular aurora display” at https://watchers.news/2015/03/18/) and in a number of cities in Central Russia and Siberia (e.g. https://www.rt.com/news/241845-aurora-borealis-central-russia/). Case et al. (2015) found that during the storm, the discrete aurora was observed at unusually low latitudes, which were much lower than those predicted by models of Roble and Ridley (1987) and Newell et al. (2010).

The aurora is produced by charged particles precipitating from the magnetosphere to the high-latitude atmosphere. The charged particles move along the magnetic field lines and, thus, the location of precipitation is controlled both by the location of source and by the geomagnetic field configuration. In the present study, we analyze the configuration of the magnetosphere by using observations of energetic electrons from ORB. At low heights, the ORB electrons are observed at middle to high latitudes adjacent to the region of auroral precipitations (Lam et al., 2010). Here we use experimental data on energetic electrons measured by several low-earth orbit (LEO) polar orbiting satellites during the time period from 2001 to 2016. The method of analysis is described in section 2. The results are presented and discussed in sections 3 and 4, respectively. Section 5 is conclusions.

2. Method

Energetic electrons in energy ranges >30 keV, >100 keV and >300 keV are measured at LEO by the Medium Energy Proton and Electron Detector (MEPED) instruments on board the NOAA/Polar-orbiting Operational Environmental Satellite (POES) satellites (Evans and Greer, 2004; Asikainen and Mursula 2013). Six POES satellites NOAA-16, NOAA-17, NOAA-18, NOAA-19, METOP-01 and METOP-02 (hereafter, P6, P7, P8, P9, P1 and P2, respectively) have Sun-synchronous orbits at altitudes of ~800-850 km in different local time sectors. Different POES satellites were operating during different years as shown in Table 2.

The outer magnetosphere and ORB are very dynamic regions, which are directly controlled by highly variable solar wind plasma streams and interplanetary magnetic field (IMF). As a result, the location of ORB and its high-latitude projection to the heights of LEO vary substantially (e.g. Dmitriev et al., 2010; Rodger et al., 2010). Namely, a strong local time variation is related to the global day-night asymmetry of the magnetosphere such that ORB is observed at higher latitudes during daytime. Variation of geomagnetic tilt angle also causes a change of the ORB latitudinal location. Interplanetary and geomagnetic disturbances result in a prominent equatorward shift of ORB.

In order to eliminate the disturbing factors, we consider so-called quiet days. Figure 1 demonstrates an example of geomagnetic conditions and measurements of the solar wind plasma and IMF acquired from Wind upstream monitor during quiet day on 23 June 2006. At that day, the solar wind velocity was slow (~310 km/s), solar wind dynamic pressure was slightly varying about ~1.6 nPa, IMF had northward orientation that resulted in very quiet geomagnetic activity (*AE* < 100 nT, *Dst* ~ 0 nT).

The list of quiet days selected in the time interval from 2001 to 2018 is presented in Table 2. The solar wind data were acquired from Wind upstream monitor. The selection of quiet days was based on the following criteria:

1. The *Dst* variation was close to 0 and *AE* index was smaller than 200 nT, i.e. the geomagnetic activity was very weak.

2. The solar wind dynamic pressure *P*d varied slightly around its average values falling in the range from ~1 to 2 nPa.

3. The solar wind speed was <400 km/s and the amplitudes of negative IMF Bz were weak (<4 nT).

Note that the solar wind with the speed of V > 400 km/s is often associated with HSSs from coronal holes. Fast solar wind streams initiate the Kelvin-Helmholtz instability at the magnetopause and also produce recurrent magnetic storms, which are accompanied by intensification of wave activity in the outer magnetosphere that results in effective acceleration and radial transport of the ORB electrons (Engebretsone et al., 1998; Tsurutani et al., 2006; Horne et al., 2007; Su et al., 2015).

4. The quiet days were chosen as long as possible after magnetic storms such that storm-time disturbances of ORB had time to relax. Usually, the quiet days occurred after long-lasting recovery phase of recurrent magnetic storms (Suvorova et al., 2013).

The local time variation of ORB latitudinal location was minimized by a choice of narrow LT sector around noon (from 10 to 14 LT). We chose quiet days around June solstice in order to minimize the tilt angle variations. Note that June of 2003 and 2007 was very disturbed and there were no quiet days selected for those years.

Figure 2 shows an example of NOAA/POES measurements of energetic electrons in geographic coordinates during the quiet days on 23 June 2006 and 3 June 2016. The geographic maps are composed from data retrieved over multiple orbits of the NOAA/POES satellites in the noon sector (12±2 LT). For each bin of 3° in longitudes and 0.5° in latitudes, we calculate the average flux of electrons measured by the 90° detector of the MEPED instrument. At high latitudes, the detector observes trapped electrons with pitch angles close to 90°, i.e. near the mirror points.

The limitation of ORB measurements at given local time is originated from fixed local time of POES satellites at sun synchronous orbits. As one can see in Figure 2 and Table 2, large statistics in the Northern hemisphere can be obtained from a number of POES satellites moving in 2-hour vicinity of local noon around the June solstice. ORB can be easily identified as a wide belt of intense electron fluxes at high litutudes. At middle latitudes, in longitudinal ranges from ~90°E to 180°E in the Eastern Hemisphere and from ~80°W to 180°W in the Western Hemisphere, one can also see intense electron fluxes from the inner electron belt and a slot region between the outer and inner belts. The slot region is almost vanished in the maps of subrelativistic electrons with energies >300 keV. Qualitative examination of the ORB location in Figure 2 reveals that in the Eastern Hemisphere, the outer electron belt in 2016 is located few degrees lower in latitudes than that in the year 2006. Most obvious difference can be found for the slot region, which corresponds to the low-latitude boundary of ORB.

For quantitative determination of the ORB latitudinal displacement, we analyze electron fluxes in 4° vicinities of three longitudes: 80°W (American sector), 0°E (European sector) and 100°E (Siberian sector). Figure 3 shows latitudinal profiles of >30 keV; >100 keV and >300 keV electron fluxes with pitch angles of ~90° observed by the NOAA/POES satellites around given longitudes during the quiet days in the years from 2001 to 2018. One can easily identify the maximum of ORB at high latitudes and the slot region at middle latitudes for the American and Siberian sectors. Above the Europe, the slot region is not detected at altitudes of the NOAA/POES orbit.

It should be noted that after the year 2014, the experimental data on electrons detected by POES is presented in a different format such that the energy channels of electrons are different from those presented earlier: >40 keV instead of >30 keV, >130 keV instead of >100 keV, and >290 keV instead of >300 keV. Because of that cross-calibration of the electron detectors is difficult. On the other hand, the difference in energies is not very large and, thus, it should not affect strongly the location of ORB. At least the differences are much smaller than the steps between the channels. Therefore, the complex analysis of all three electron channels allows minimization of this effect.

3. Results

In Figure 3, the ORB maxima in the American, European and Siberian sectors can be found in the ranges of latitudes from 50° to 58°, from 64° to 70° and from 62° to 74°, respectively. We determine geographic latitude of the maxima for each year with the accuracy of 0.5° to 1°. One can see that the location as well as the intensity of the maximum varies from year to year. The intensity is minimal during the solar minimum in 2009. The fluxes of >300 keV electrons (Figure 3c) were very weak such as determination of the ORB was very difficult. In addition, the ORB maximum above Siberia could not be determined in 2011 because of limited statistics.

Qualitatively, the position of ORB maximum above Siberia is more close to 70° and 65°, respectively, in 2001 - 2010 and in 2012 – 2018. Above the Europe and North America, variation of the ORB location is more random. The fluxes of >30 keV electrons in the outer region of ORB are very dynamic because of strong contribution from the auroral population. The latter produced additional maxima at latitudes above 70° and 55°, respectively, in the European-Siberian and American sectors. The additional maxima were very intense in the years 2008, 2010 and 2017 that made difficult to determine the actual location of the ORB. In those cases, we chose the maximum located at lower latitude. This choice gives a good agreement with the ORB maximum location for the >100 keV electrons and especially subrelativistic >300 keV electrons, which are practically free from the auroral contamination.

In Figure 3, one can clearly see the slot region between the outer and inner electron belts in the latitudinal ranges 45° - 50° and 45° - 50° above North America and Siberia, respectively. This structure can be well identified and numerically determined, excepting >300 keV electrons. We determine the first high-latitude point of electron flux enhancements as the low-latitude edge of ORB. Apparently, the electron flux enhancements peak in the maximum of ORB. Hence, the inner edge of ORB corresponds to the beginning of continuous increase of the electron flux from the minimum at low latitudes to the ORB maximum. This criterion allows determining of the inner edge for the electrons with energies >300 keV and in the European sector, where the slot region is not so obvious. Geographic latitude of the inner edge is determined for each year with the accuracy varying from 0.5° to 1°. In the American sector, the inner edge of ORB is situated at lowest latitudes from 43° to 51°, in the European sector – from 55° to 63°, and in the Siberian sector – at highest latitudes from 58° to 65°. In Figure 3, one can find that the latitude of ORB edge above Siberia decreases with years from ~65° to 60° for all energy range of electrons. The change of ORB location above the Europe and North America is not so obvious.

Figures 4 and Figure 5 show long-term variations in the location of ORB and corresponding predictions of the IGRF-12 model during 17 years from 2001 to 2018. As one can see, the ORB maximum and inner edge of >30 keV electrons are usually located at higher latitudes than those of >100 keV electrons, and the ORB of subrelativistic >300 keV electrons is located at lowest latitudes. Note that the location of ORB maximum for >30 keV electrons is scattered significantly and it is different from those for the more energetic electrons because of substantial contamination from the auroral electrons. In contrast, the ORB maxima and inner edge of >100 keV and >300 keV electrons demonstrate very similar dynamics.

As can be seen in Figures 4 and 5, the location of ORB manifests the well-known solar cycle variation: the latitudes of ORB maximum and inner edge have a tendency to be highest around solar minimum in 2008 – 2009 and lowest during solar maxima in the years 2001 and 2012 – 2013. Note that the maximum phases of the 23rd and 24th solar cycles occurred in the years 2000 - 2001 and in 2012 – April 2014, respectively. The years 2008 – 2009 are the solar minimum phase. The declining phases lasted from 2003 to 2007 and from 2014 to 2018. In Figures 4 and 5, one can see that during the declining phase of the current 24th solar cycle (especially in the years 2016 – 2018), the behavior of the ORB maximum and inner edge is different from that during the declining phase of the previous 23rd solar cycle. Namely, their latitudes increased only slightly or even decreased above North America and especially above Siberia. Unfortunately, there is no any model of the ORB location variation with the solar cycle because the driving mechanisms are not well established.

As a first approach, the variations of ORB location with years are considered as random and can be fitted by a linear function (indicated by dashed strait lines in Figures 4 and 5):

$$\lambda = a * \text{year} + b, \quad (1)$$

where λ is the latitude of maximum or inner edge of ORB. The slope a, parameter b and their standard errors are calculated from a linear regression for various longitudinal regions and various energies of electrons. The results are presented in Tables 3 and 4 for the ORB maximum and the inner edge, respectively.

The linear fits are compared with geomagnetic field trends predicted by the IGRF model in different regions. The trends were calculated in the following manner. First, we took a point with given geographic coordinates and calculated its magnetic coordinates for the quiet day on 29 June 2001 using the IGRF model of epoch 2000. Namely, for the ORB maximum, we took points (70°N, 80°W), (66°N, 0°E) and (54°N, 100°E), respectively, for the American, European and Siberian sectors and calculated their geomagnetic coordinates (64.12°N, 11.44°W), (67.05°N, 95.66°E) and (59.5°N, 174.3°E), respectively. For the inner edge of ORB, we took, respectively, (46.5°N, 80°W), (59°N, 0°E) and (63°N, 100°E), with corresponding geomagnetic coordinates (56.62°N, 10.61°W) (60.59°N, 89.34°E) and (52.47°N, 173.7°E). Then we supposed that the geomagnetic coordinates of the points do not change with time and we used them to calculate geographic coordinates from the IGRF-12 model for corresponding quiet days listed in Table 2. The geographic coordinates of a point with given magnetic coordinates should be changed with time because of long-term variation of the geomagnetic field. As one can see in Figures 4 and 5, the long-term variation in IGRF-12 is almost linear function of the year and, hence, this variation can be easily compared with the linear fits of the ORB location.

In the American sector (see Figure 4a), the latitude of ORB maximum demonstrates a little decrease of about 1° while the IGRF-12 model predicts an increase of ~1°. The decrease results from relatively low latitudes, where the ORB maximum is located from 2013 to 2018. The location of inner edge of ORB in the American sector (see Figure 5a) does not practically change within the experimental uncertainty of ~1°. Note that in both cases, the slope *a* has very large error (see Tables 3 and 4). The errors are comparable or even exceed the values of slope. Hence, from the statistical consideration one can conclude that the model prediction does not contradict to the observations.

In the European sector (Figures 4b and 5b), the IGRF-12 model predicts very small change of 0.3° in the ORB location that is in good agreement with the ORB maximum dynamics. The location of ORB inner edge for electrons with energies >30 keV and >100 keV demonstrates an increase of ~3°. However, the slope of increase is determined with a substantial error of up to 50% (see Table 4) that produces an increase by only ~1.5°. In addition, the >300 keV electrons follow the model and do not exhibit any prominent trend. Hence in the European sector, the IGRF model predicts the ORB dynamics with sufficient accuracy.

in the Siberian sector, the IGRF model predicts ~1° decrease in latitude of the ORB maximum and inner edge as shown in Figures 4c and 5c. From the POES observations, we find that the ORB maximum is displaced to lower latitudes by at least ~3° in all electron energy channels: from ~69° to ~66° for >300 keV electrons, from ~70° to 66° for >100 keV electrons and from ~71° to 67° for >30 keV electrons (see Figure 4c). The difference is related to very low latitudes (~67° and less) of the ORB maximum during solar maximum and on the declining phase of the current 24th solar cycle in the years 2012 - 2013 and 2016 - 2018, respectively. In the solar maximum and on the declining phase of the previous 23rd solar cycle (the years 2001 and 2004 - 2006), the ORB maximum was located at higher latitudes (above 67°). Note that the error in determination of the slope *a* is ~50% as shown in Table 3. Hence statistically, the decrease of latitude might be two times smaller, i.e. ~1.5° to 2°. This decrease is slightly larger than 1° of the model prediction, within 0.5° to 1° statistical uncertainty in determination of latitude.

Similar pattern can be found for the inner edge of ORB in the Siberian sector (see Figure 5c). Namely, the IGRF model predicts a decrease of ~1°. The inner edge was shifted toward lower latitudes by ~3°, ~2° and ~1°, respectively, for >30 keV, >100 keV and >300 keV electrons. From Table 4, one can see that the slope *a* is calculated with errors of ~30% and ~20%, respectively, for

>30 keV and >100 keV electrons. It means that the decrease in latitude might be ~2° (instead of ~3°) and ~1.5° (instead of ~2°), respectively. These values are again larger than 1° of the model prediction. Hence, there is a tendency that the change in the latitudinal location of ORB maximum is underestimated by the model. This fact indicates that during 17 years from 2001 to 2018, ORB is abnormally displaced toward the lower latitudes in the Siberian sector.

It is interesting to point out the year 2017, when the maximum and inner edge of ORB shifted to very low latitudes of 62° and ~59° respectively. The shift was observed during two quiet days on 9 and 10 June 2017. Similar pattern of displacement can be found on the declining phase of the previous 23rd solar cycle in the year 2005, when the ORB suddenly shifted equatorward by more than ~2°. Note that if we exclude the year 2017 from the linear fitting then the results are not practically changed because ORB is located at relatively low latitudes during the years 2012 to 2018.

4. Discussion

We have found up to 4° equatorward displacement of the ORB in the Siberian sector. The displacement is larger than that predicted by the IGRF-12 model. The difference is statistically significant. It might result both from a change of the geomagnetic field and from changes of driving parameters such as geomagnetic activity, the tilt angle, IMF *Bz* and solar wind dynamic pressure. It is well known that those parameters affect the latitudinal location of domains in the magnetosphere. The effect of geomagnetic activity was eliminated by the choice of quiet days. The other drivers are considered below.

The tilt angle in the noon region at given longitude (80°W, 0°E and 100°E) varies a little (<2°) during the June month. The change of local time in 2-hour vicinity of noon produces ~5° variation of the tilt angle. The tilt angle variations of a few degrees result in a tiny change of ~0.1° in the ORB latitude (e.g. Dmitriev et al., 2010). Hence, we can neglect the effect of tilt angle.

The effect of solar wind parameters, including IMF *Bz* and dynamic pressure (*P*d), to the ORB location is not obvious. outer magnetosphere domains was comprehensively investigated (Kuznetsov et al., 1993; Newell et al., 2006;). Namely it was shown a dependence of the cusp low-latitude boundary on the IMF Bz such that *B*z = -4 nT results in less than 0.5° equatorward shift. The cusp location can be considered as a proxy of the ORB boundary. Similar situation can be found with the solar wind dynamic pressure: a change of *P*d from 1 to 2 nPa results in ~0.2° decrease in the latitude of the ORB boundary. Hence, the effects of both *P*d and IMF Bz are several times weaker than the difference of 3°.

Another possible effect is the solar cycle variation. Variations of the ORB location from cycle to cycle and during different phases of solar cycles are still poorly investigated. It was well established that during solar minima and maxima, the ORB is located, respectively, at highest and lowest latitudes (Miyoshi et al., 2004; Glauert et al., 2018). From these findings, we can speculate that lower(higher) solar activity results in an increase (a decrease) of the ORB latitudes. In Figure 3, one can see that the intensities of electrons are weaker after the beginning of the 24th solar maximum in 2012 in comparison with the 23rd solar cycle. Note that the 23rd solar cycle was stronger than the 24th one. Following this logic, the ORB should be located at relatively higher latitudes during the weak 24th solar cycle than during the strong 23rd solar cycle. However, we have found totally opposite effect: ORB over Siberia is located at lower latitudes after 2012.

From the above, we can conclude that the difference between the observations and predictions can be rather originated from anomalous dynamics of the geomagnetic field. This idea is supported by the observations of ORB location over the Europe and North America, where the ORB displacement is well predicted by the IGRF-12 model. An additional support can be found from results of long-term magnetic observations in Siberia where significant anomalies of the main geomagnetic field have been revealed in the 80°-130° longitudinal range (Gvishiani et al., 2014). Namely, the IGRF-12 model predicted the magnetic field up to 300 nT stronger than that measured by ground based magnetic stations that was close to 0.5% of the total magnetic filed in this region. For the geodipole, stronger magnetic field corresponds to higher latitudes.

In Figures 4c and 5c, one can see that the decrease of ORB latitude in the Siberian sector is most prominent after 2012. On the other hand in the years 2012 –2013, a sudden change was found in the acceleration of secular variation in the geomagnetic field (Finlay et al., 2015). Analyzing time interval from 1999 to 2015, Finlay et al. (2015) revealed 3 pulses in time evolution of the mean square secular acceleration power: in 2006, in 2009 and in 2012 – 2013. Chulliat et al. (2015) attribute these pulses, or so-called sharp geomagnetic "jerks", to magnetic field variations originating in the Earth's core. We can assume that the abnormal ORB displacement might be related to the geomagnetic jerks. We can assume that the abnormal ORB displacement might be related to the geomagnetic jerks. Though, there is no prominent change in the ORB location in 2006, one can indicate very high latitude of ORB in 2009. Note that the jerk in 2009 coincided with the abnormally deep solar minimum and, hence, it could be hard to distinguish between the two effects. On the other hand, we have found significant change in the ORB dynamics after 2012 – 2013.

The several degrees equatorward displacement of ORB in the Siberian sector indicates an equatorward shifting of all domains in the magnetosphere, including the region of auroral precipitations. Apparently, the shifting contributes to the increase in occurrence rate of the mid-latitude auroras in Siberia and, perhaps, in entire Russia. In addition, Finlay et al. (2015) expect that the next jerk might occur around 2016. We do not have any reports about the recent jerks yet. But very strong decrease of the ORB latitude observed in 2017 might indicate the sudden change in the geomagnetic field.

5. Conclusions

NOAA/POES observations of electrons with energies of few tens and hundreds of keV allowed revealing and measure a latitudinal displacement of the outer radiation belt during last 18 years. The displacement corresponds qualitatively to the change of geomagnetic field predicted by the IGRF-12 model. However in the Siberian sector, the model has a tendency to underestimate the equatorward shift of ORB. ~~However, numerically the equatorward shift in the Siberian sector was found more than ~2° larger than that predicted by the model.~~ The shift became prominent after 2012 that might be related to the geomagnetic jerk occurred in 2012 – 2013. The increase in the occurrence rate of mid-latitude auroras in the Eastern Hemisphere can be explained, at least partially, by the equatorward displacement of the high-latitude projection of the magnetosphere domains.

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Table 1. Observations of discrete aurora in Russia in the years 2015 to 2016

Date	min Dst, nT	City	Geomagnetic location	Reference
2015 March 17-18	-220	Moscow	51°16N 122°06E	Ref1
2015 June 22-23	-200	Moscow	51°16N 122°06E	Ref2
2015 August 16-17	-84	St. Petersburg	56°23N 117°36E	Ref3
2015 October 7-8	-120	St. Petersburg	56°23N 117°36E	Ref4
2016 February 17-18	-50	St. Petersburg	56°24N 117°37E	Ref5
2016 April 3-4	-50	St. Petersburg	56°24N 117°37E	Ref6
2016 August 24-25	-80	St. Petersburg	56°24N 117°37E	Ref7
2017 September 7-8	-124	Novosibirsk	45°56N 160°07E	Ref8
2017 November 7-8	-74	St. Petersburg	56°25N 117°38E	Ref9

Ref1 - www.dp.ru/a/2015/03/18/Severnoe_sijanie_uvideli_zh/

Ref2 - www.dp.ru/a/2015/06/23/Severnoe_sijanie_uvideli_v/

Ref3 - http://47news.ru/articles/92419/

Ref4 - www.dp.ru/a/2015/10/08/Severnoe_sijanie_v_Peterbu/

Ref5 - www.fontanka.ru/2016/02/17/058/

Ref6 - www.dp.ru/a/2016/04/03/ZHiteli_Peterburga_deljatsja/

Ref7 - www.fontanka.ru/2016/08/24/035/ and www.topnews.ru/news_id_92986.html

Ref8 - http://www.ntv.ru/video/1515160/

Ref9 - https://www.fontanka.ru/2017/11/07/134/

Table 2. List of quiet days in June selected for POES observations of the outer radiation belt.

Year	Day in June	Start UT	Duration, hours	V* km/s	Pd** nPa	$Bz_{min}^{\$}$ nT	POES Satellites#
2001	29	0	24	350	1.6 (1.0 – 3.2)	0.6 (-4)	P6
2002	28	0	24	340	1.2 (0.8 – 1.8)	2.2 (-3)	P6
2004	24	12	24	330	1.1 (0.5 – 2.5)	1.2 (-2)	P6, P7
2005	21	0	18	350	0.9 (0.5 – 2.0)	3.1 (-4)	P6, P7, P8
2006	23	0	24	310	1.6 (1.1 – 2.3)	3.4 (-1)	P6, P7, P8
2008	13	0	24	310	1.5 (0.8 – 1.9)	1.8 (-0.8)	P2, P7, P8
2009	17	0	24	300	1.1 (0.5 – 1.7)	1.9 (-3)	P2, P7, P8, P9
2010	12	0	24	350	1.1 (0.6 – 2.4)	0.2 (-2)	P2, P7, P8, P9
2011	28	6	24	390	0.8 (0.5 – 1.7)	1.8 (-2)	P2, P6, P8, P9
2012	15	0	24	320	0.8 (0.5 – 1.3)	0.0 (-3)	P2, P6, P8, P9
2013	16	0	24	330	0.9 (0.6 - 1.5)	1.0 (-3)	P2, P6, P8, P9
2014	1	0	36	300	1.7 (1.1 – 4.0)	1.5 (-4)	P1, P2, P9
2015	4	0	24	280	1.0 (0.7 – 1.7)	0.9 (-3)	P1, P2, P9
2016	3	0	24	300	1.0 (0.7 – 1.4)	-0.3 (-3)	P1, P2, P9
2017	9	6	24	310	1.9 (1.0 – 2.6)	-1.3 (-4)	P1, P2, P9
2018	12	8	24	300	1.3 (0.9 – 2.0)	0.0 (-4)	P1, P2, P9

*Daily average of the solar wind velocity

**Daily average of the solar wind dynamic pressure and its minimum and maximum in brackets

$Daily average Bz component of the interplanetary magnetic field and Bz minimum in brackets

#POES satellites observed the outer radiation belt

Table 3. Coefficients of the best linear fit of the latitudinal change of the ORB maximum location with years for various longitudes and energy of electrons

Longitude, deg	Energy, keV	a, deg/year	b, deg
-80	>30	-0.153 ± 0.112	362
-80	>100	-0.069 ± 0.097	192
-80	>300	-0.057 ± 0.084	167
0	>30	0.021 ± 0.089	24
0	>100	-0.032 ± 0.063	129
0	>300	-0.027 ± 0.042	119
100	>30	-0.265 ± 0.119	602
100	>100	-0.208 ± 0.106	486
100	>300	-0.167 ± 0.084	403

Table 4. Coefficients of the best linear fit of the latitudinal change of the ORB inner edge location with years for various longitudes and energy of electrons.

Longitude, deg	Energy, keV	*a*, deg/year	*b*, deg
-80	>30	-0.029 ± 0.065	106
-80	>100	-0.021 ± 0.059	89
-80	>300	-0.014 ± 0.063	73
0	>30	0.195 ± 0.107	-332
0	>100	0.241 ± 0.078	-424
0	>300	0.032 ± 0.069	-4
100	>30	-0.183 ± 0.058	432
100	>100	-0.211 ± 0.037	487
100	>300	-0.097 ± 0.069	257

Figure captions

Figure 1. Solar wind and geomagnetic conditions on 22 to 24 June 2006 (from top to bottom): solar wind bulk velocity V; solar wind dynamic pressure Pd; interplanetary magnetic field magnitude B (blue dotted curve) and Bz component (black solid curve); auroral electrojet index AE; storm-time *Dst* index. The day on 23 June (indicated by vertical red dashed lines) is very quite in the solar wind and geomagnetic parameters.

Figure 2. Geographic maps of energetic electron fluxes with energies >300 keV (a,b), >100 keV (c,d), >30 keV (e,f) and pitch angles of ~90° observed by POES satellites at height of ~850 km in 2 hour vicinity of local noon (left column) on 23 June 2006 and (right column) on 2 June 2016. The solid wide curve indicates the geomagnetic equator. The outer and inner electron belts and a slot region between them are clearly seen (excepting of >300 keV electrons), respectively, at high and middle latitudes in the longitudinal range from ~90° E to ~80°W.

Figure 3. Latitudinal profiles of electron fluxes with pitch angles of ~90° observed by POES satellites during quiet days in different years at height of ~850 km in vicinity of local noon at longitudes around 100°E (red circles), 0°E (blue crosses), and 80°W (black diamonds) for various energy channels: (a) >30 keV, (b) >100 keV, and (c) >300 keV. Vertical dashed and solid lines indicate latitudes of the maximum and inner edge of the outer radiation belt, respectively.

Figure 4. Geographic latitude of the maximum of the outer radiation belt measured at height of ~850 km during geomagnetic quiet days around 80°W (a), 0°E (b), and 100°E (c) for electrons with energies of >30 keV (red circles), >100 keV (blue crosses), and >300 keV (green triangles). Dashed curves of corresponding colors show the best linear fit of the latitudinal change of the maximum location with years (see Table 3). Solid black curves show the latitudinal change predicted by the IGRF model of corresponding epochs (see details in the text). The grey curve shows sunspot number (right axis).

Figure 5. The same as Figure 4 but for the inner edge of the outer radiation belt. Coefficients of the best linear fit are presented in Table 4.

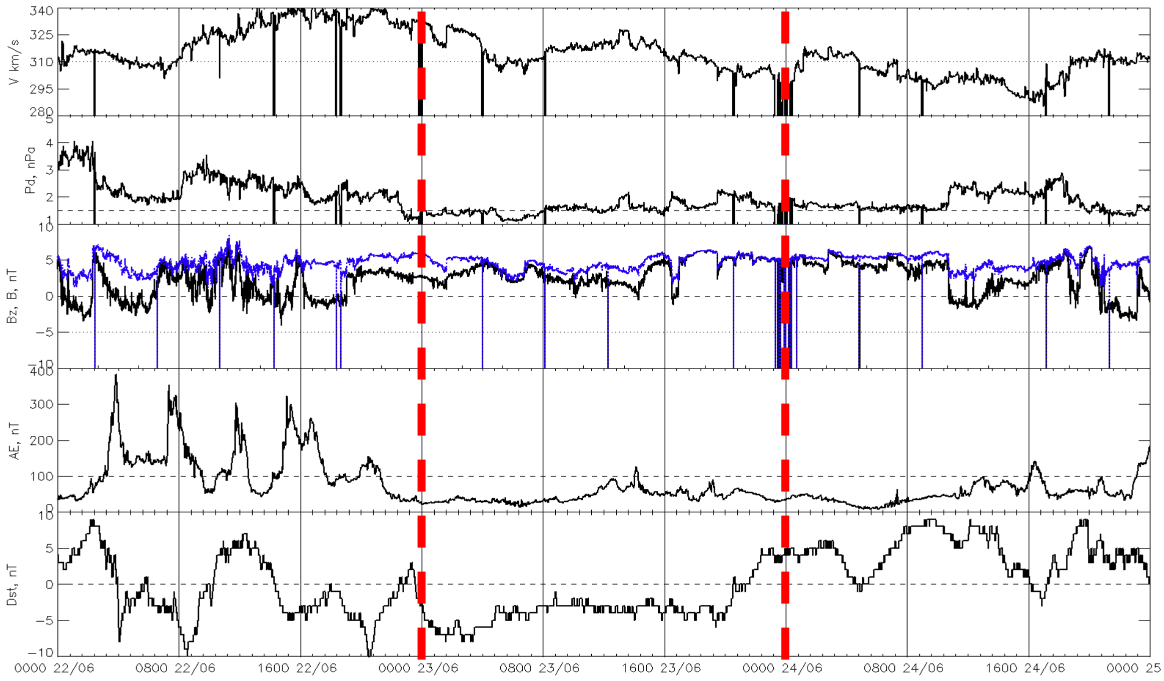


Figure 1. Solar wind and geomagnetic conditions on 22 to 24 June 2006 (from top to bottom): solar wind bulk velocity V; solar wind dynamic pressure Pd; interplanetary magnetic field magnitude B (blue dotted curve) and Bz component (black solid curve); auroral electrojet index AE; storm-time *Dst* index. The day on 23 June (indicated by vertical red dashed lines) is very quite in the solar wind and geomagnetic parameters.

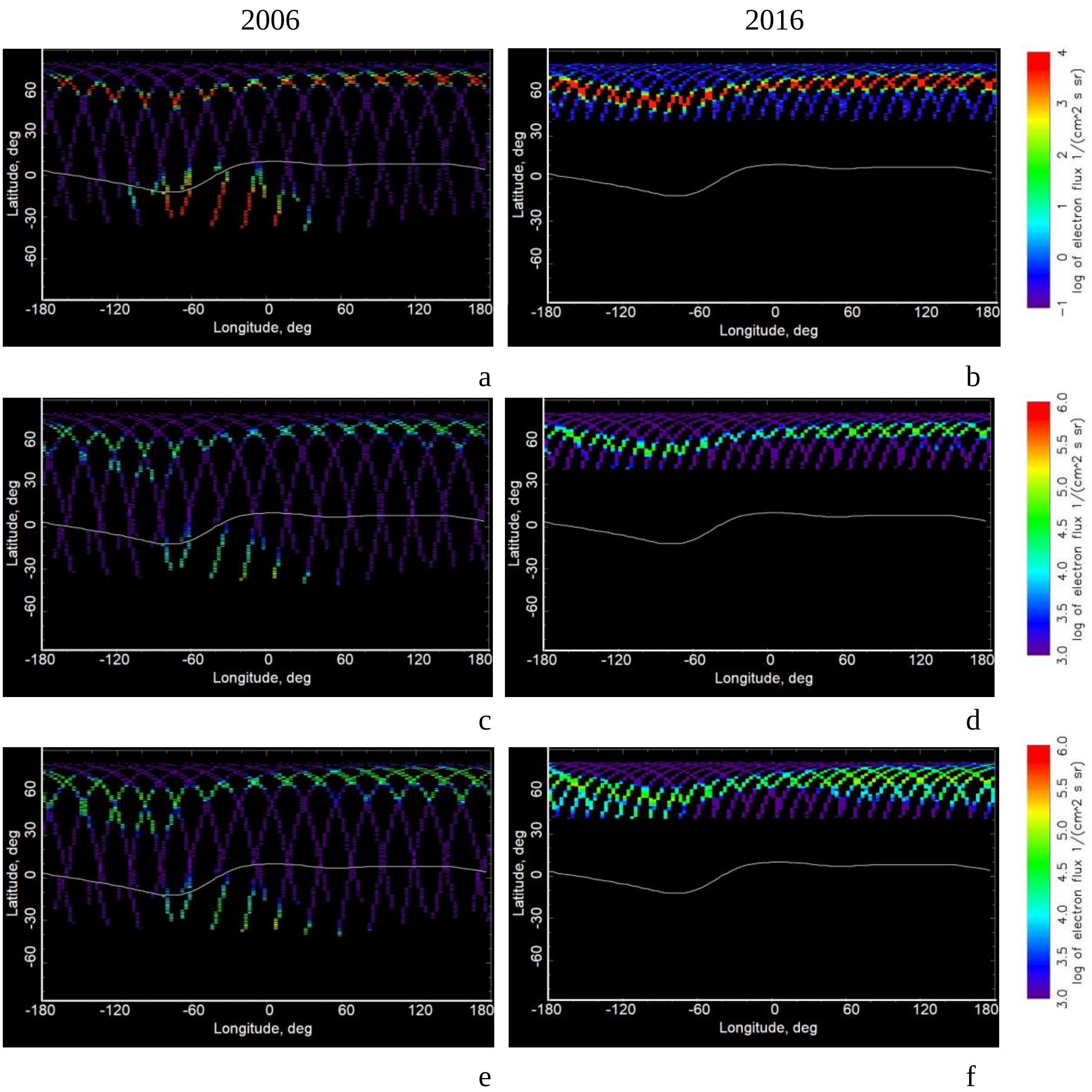
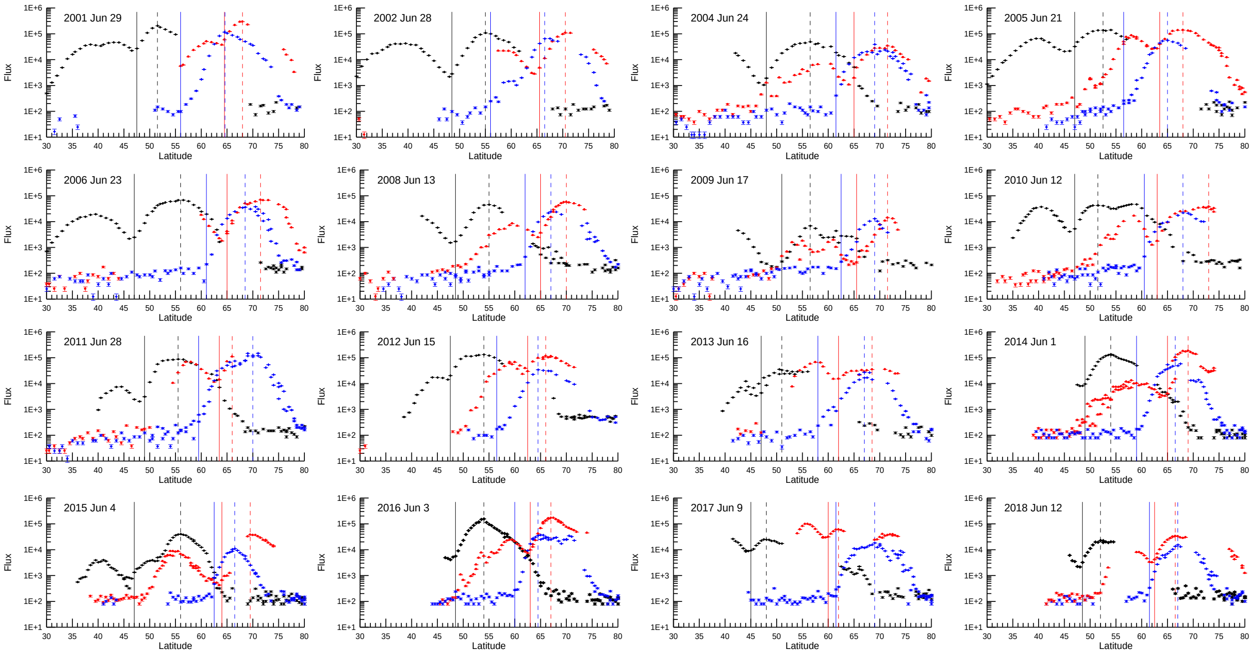
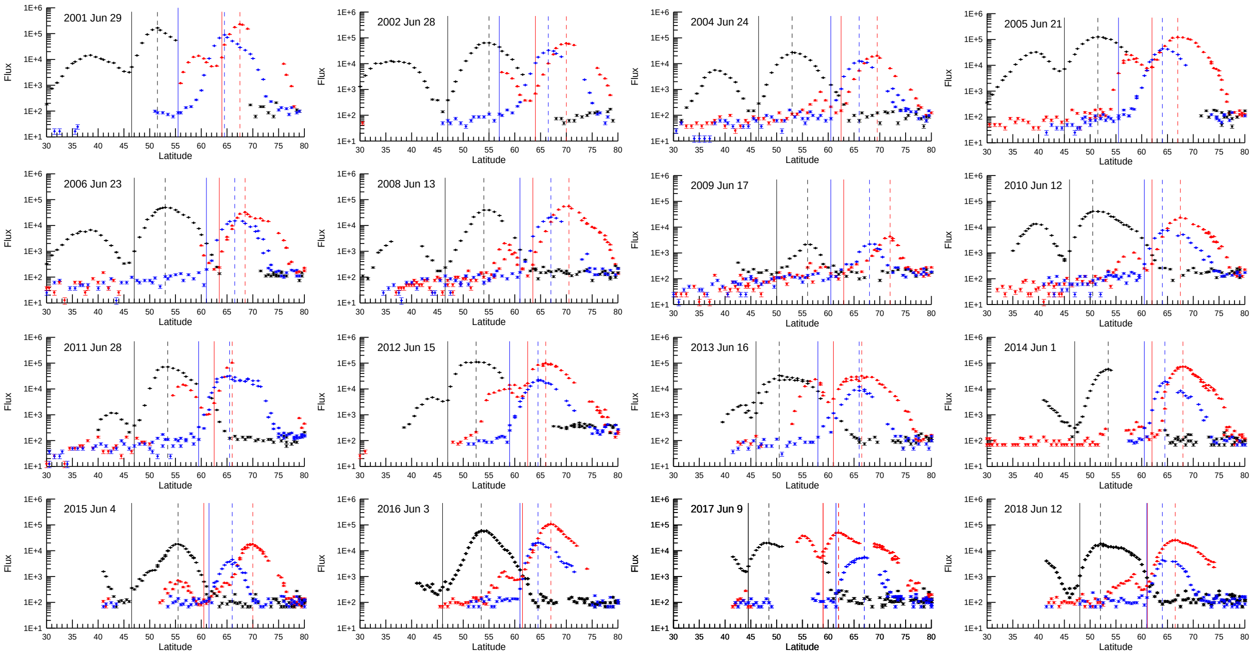


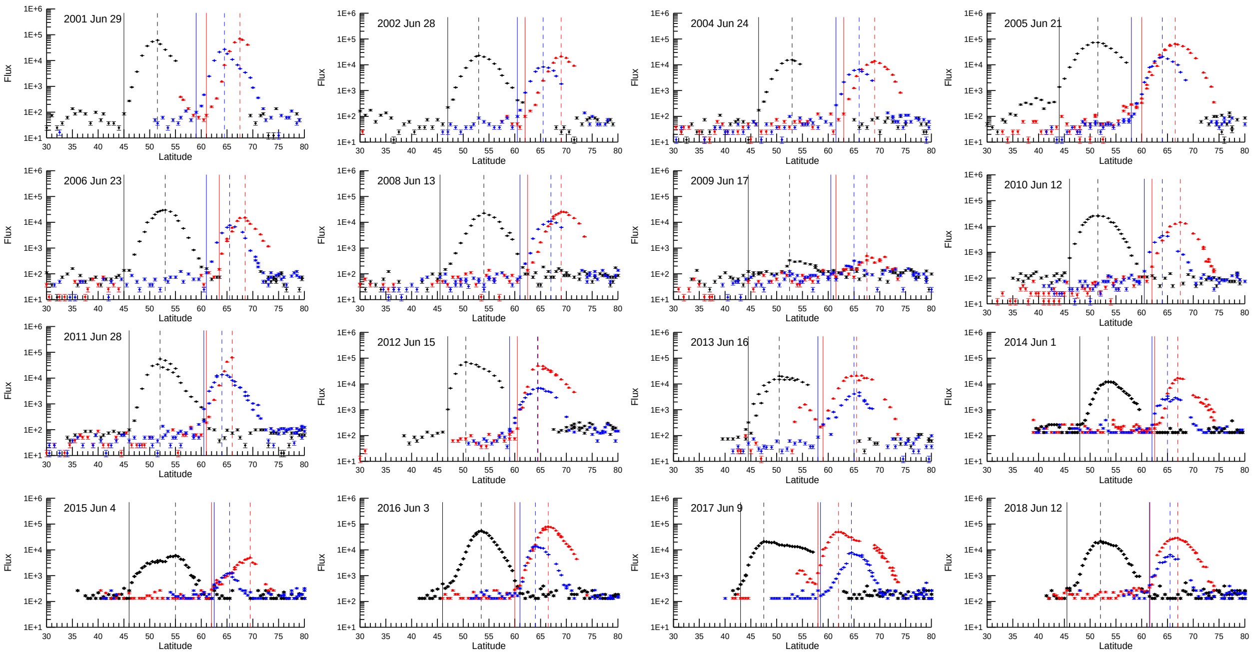
Figure 2. Geographic maps of energetic electron fluxes with energies >300 keV (a,b), >100 keV (c,d), >30 keV (e,f) and pitch angles of ~90° observed by POES satellites at height of ~850 km in 2 hour vicinity of local noon (left column) on 23 June 2006 and (right column) on 3 June 2016. The solid wide curve indicates the geomagnetic equator. The outer and inner electron belts and a slot region between them are clearly seen (excepting of >100 keV electrons), respectively, at high and middle latitudes in the longitudinal range from ~90° E to ~80°W.


2001 Jun 29
2002 Jun 28
2004 Jun 24
2005 Jun 21
2006 Jun 23
2008 Jun 13
2009 Jun 17
2010 Jun 12
2011 Jun 28
2012 Jun 15
2013 Jun 16
2014 Jun 1
2015 Jun 4
2016 Jun 3
2017 Jun 9
2018 Jun 12
Flux
Latitude

a

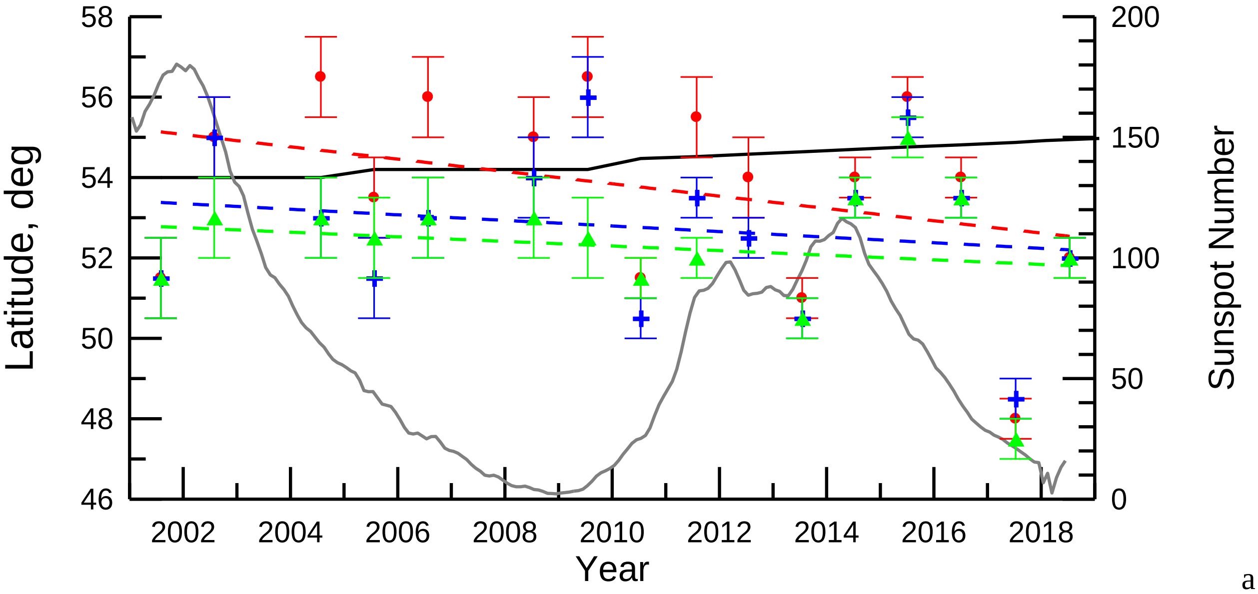

2001 Jun 29
2002 Jun 28
2004 Jun 24
2005 Jun 21
2006 Jun 23
2008 Jun 13
2009 Jun 17
2010 Jun 12
2011 Jun 28
2012 Jun 15
2013 Jun 16
2014 Jun 1
2015 Jun 4
2016 Jun 3
2017 Jun 9
2018 Jun 12
Flux
Latitude

b

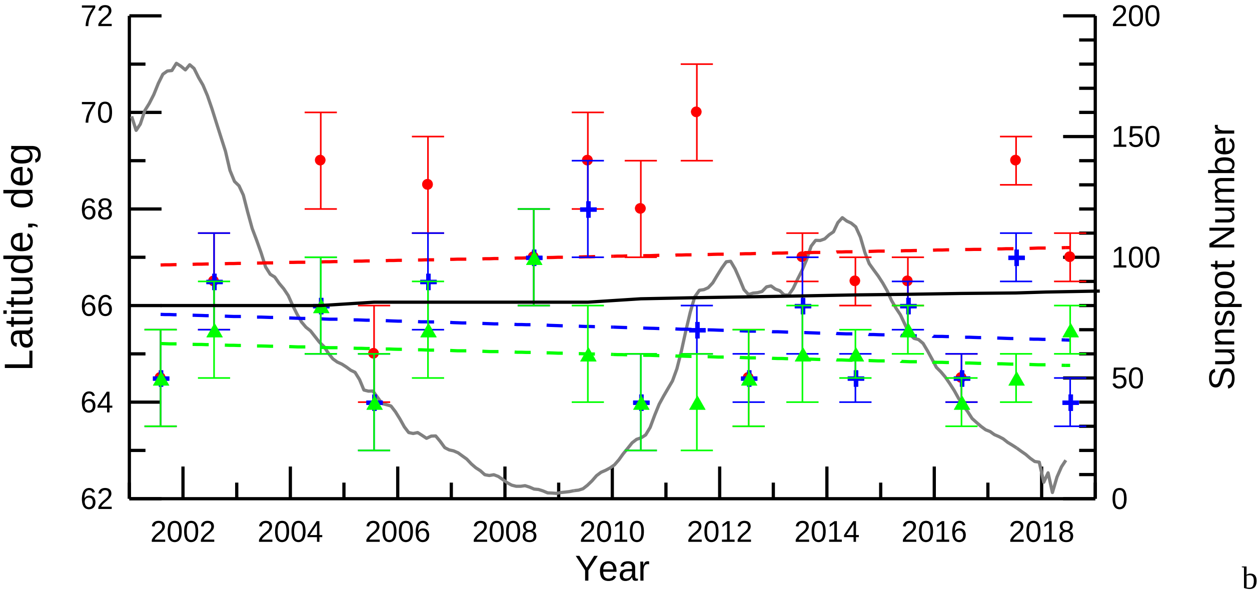


c

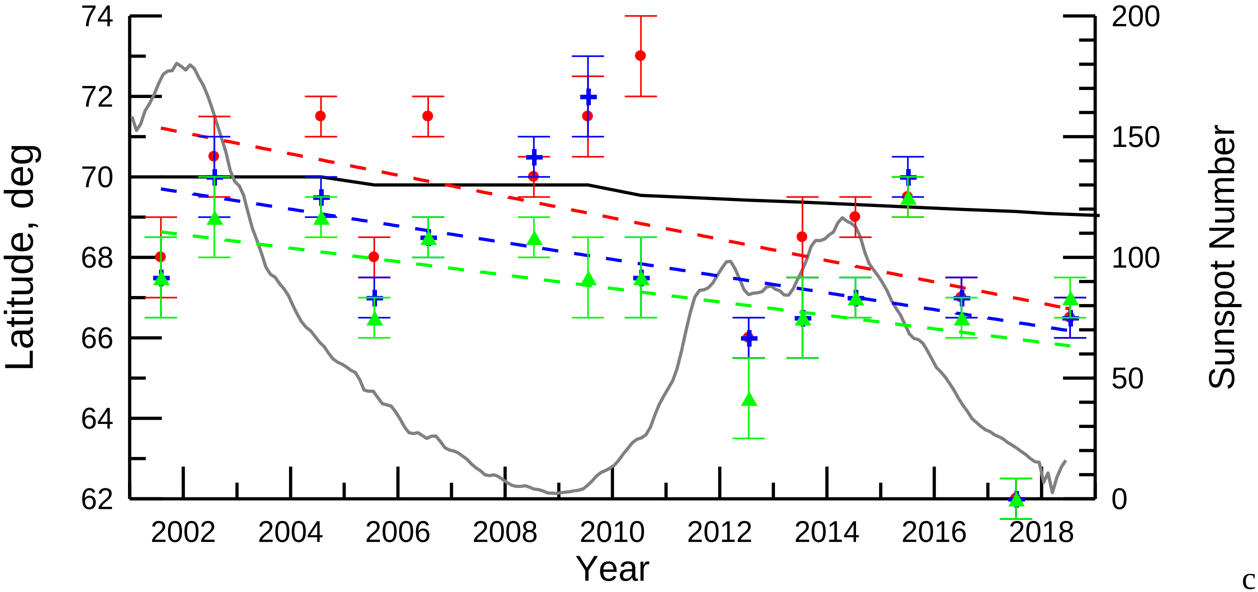
Figure 3. Latitudinal profiles of electron fluxes with pitch angles of ~90° observed by POES satellites during quiet days in different years at height of ~850 km in vicinity of local noon at longitudes around 100°E (red circles), 0°E (blue crosses), and 80°W (black diamonds) for various energy channels: (a) >30 keV, (b) >100 keV, and (c) >300 keV. Vertical dashed and solid lines indicate latitudes of the maximum and inner edge of the outer radiation belt, respectively.


58
56
54
52
50
48
46
200
150
100
50
0
2002
2004
2006
2008
2010
2012
2014
2016
2018
Latitude, deg
Year
Sunspot Number

a

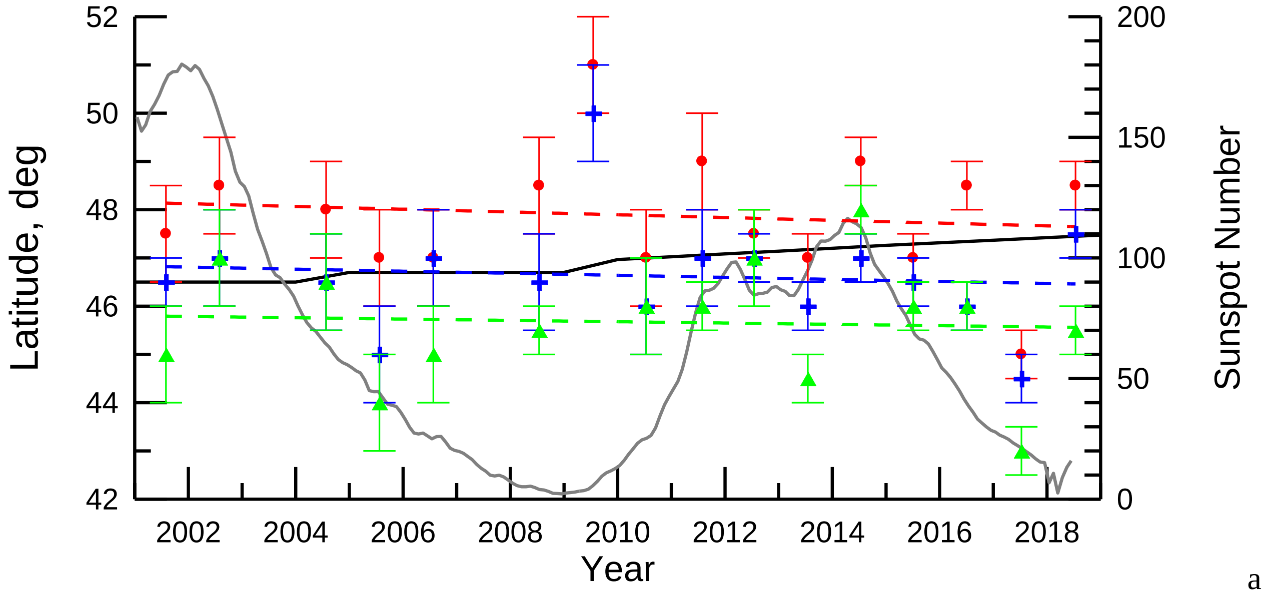

72
70
68
66
64
62
200
150
100
50
0
2002
2004
2006
2008
2010
2012
2014
2016
2018
Latitude, deg
Year
Sunspot Number

b


74
72
70
68
66
64
62
200
150
100
50
0
2002
2004
2006
2008
2010
2012
2014
2016
2018
Latitude, deg
Year
Sunspot Number

c

Figure 4. Geographic latitude of the maximum of the outer radiation belt measured at height of ~850 km during geomagnetic quiet days around 80°W (a), 0°E (b), and 100°E (c) for electrons with energies of >30 keV (red circles), >100 keV (blue crosses), and >300 keV (green triangles). Dashed curves of corresponding colors show the best linear fit of the latitudinal change of the maximum location with years (see Table 3). Solid black curves show the latitudinal change predicted by the IGRF model of corresponding epochs (see details in the text). The grey curve shows sunspot number (right axis).


Latitude, deg
Sunspot Number
Year
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50
48
46
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42
200
150
100
50
0
2002
2004
2006
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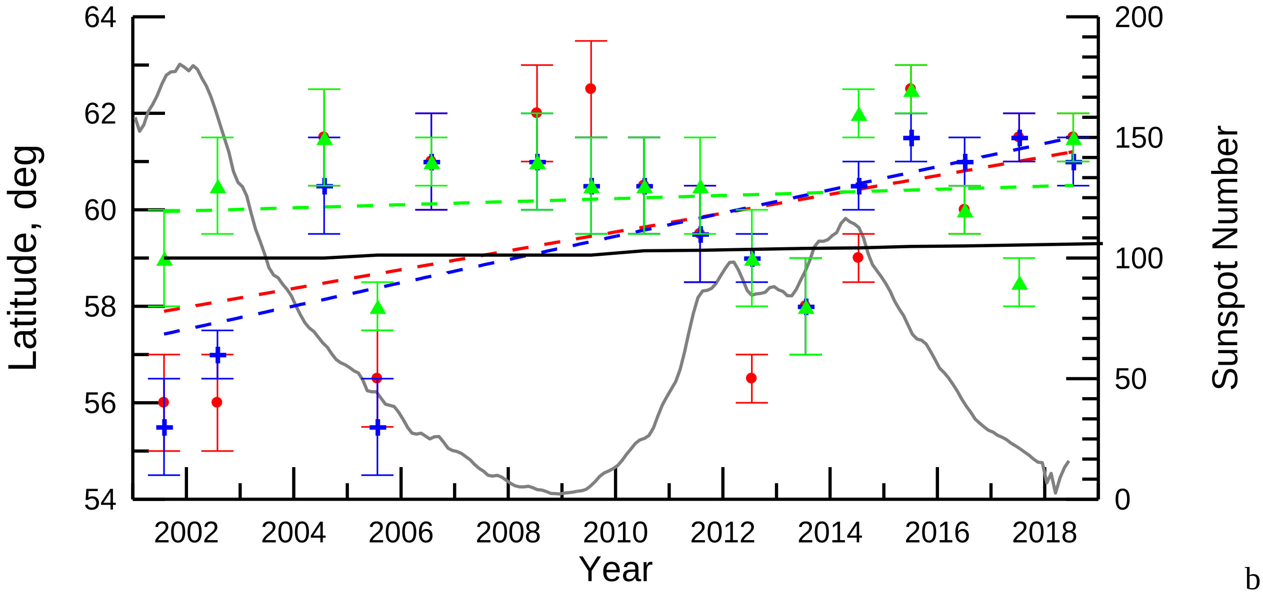
2012
2014
2016
2018

a


Latitude, deg
Sunspot Number
Year
64
62
60
58
56
54
200
150
100
50
0
2002
2004
2006
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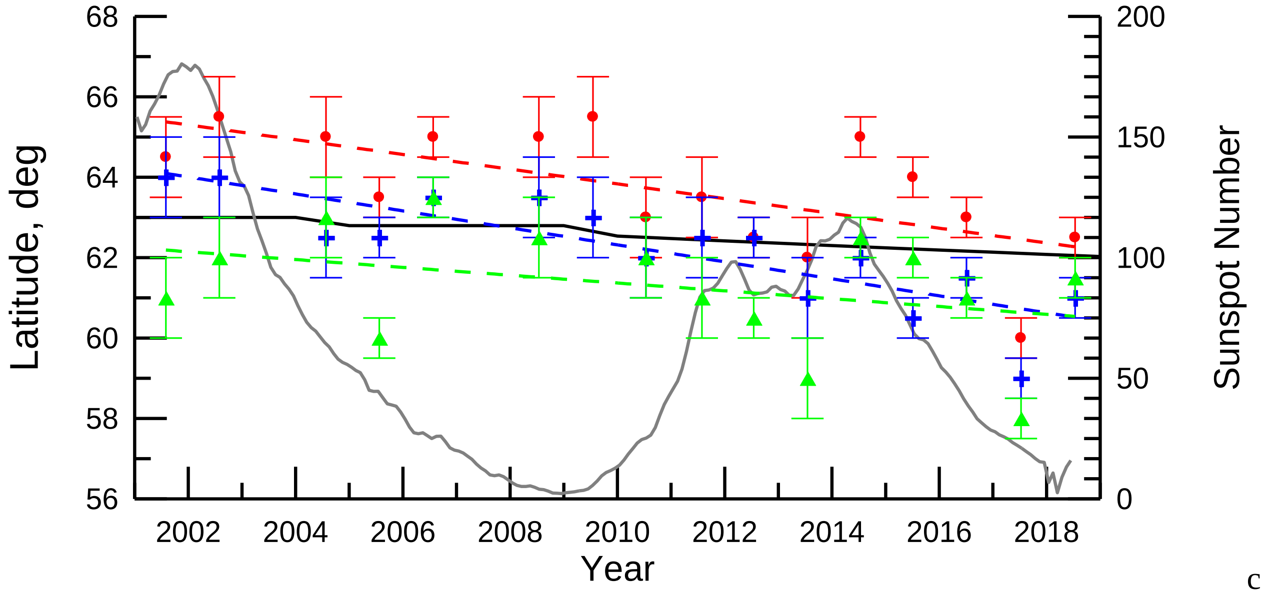
2010
2012
2014
2016
2018

b


Latitude, deg
Sunspot Number
Year
68
66
64
62
60
58
56
200
150
100
50
0
2002
2004
2006
2008
2010
2012
2014
2016
2018

c

Figure 5. The same as Figure 4 but for the inner edge of the outer radiation belt. Coefficients of the best linear fit are presented in Table 4.