Reply to the comments by Topical Editor:

Dear Dr. Roussos,

I am submitting herewith the revised manuscript (MS No.: angeo-2020-62): “Seasonal dependence of the Earth’s radiation belt: new insights”. Thank you for valuable comments and suggestions. The manuscript is revised based on comments and suggestions by you and the Referee #1. The modifications are marked in the revised version with “track changes”. I explain below how your suggestions are incorporated in the revision. I also include a response file listing all comments and suggestions by the referee and describing how they are incorporated in the revision.

Dear Dr. Hajra,

Thank you for submitting your manuscript “Seasonal dependence of the Earth’s radiation belt: new insight”. As you may have realised from the referee report, the reviewer considers that your study has some original aspects and its therefore worth considering for publication in our journal. However, I agree with the reviewer that discussion of your methods and results could be further enhanced. (Reply: Thank you. The manuscript is now revised based on all comments and suggestions by the reviewer.) On balance, I see very few references to results by the Van Allen Probes (VAP), which show much more dynamics in the slot region and also the inner boundary of the outer belt. The review paper by Baker et al. 2018 on space weather is included but in a generic way in the first paragraph of the manuscript (Reply: Thank you for the comment. We now add more references to the VAP study related to dynamics of the inner boundary of the outer belt.). Analysis of the inner belt is shown in Figure 2, but with little suspicion about its contamination by protons: VAP has shown that the spectrum there does not extend above 1.5 MeV (while the data shown in the manuscript are between 1.5 – 6 MeV) and part of the signal in older measurements may have been due to contamination (Reply: Thank you for the comment. Contamination of the inner belt by protons is now discussed in the manuscript.). Also, several studies of the outer belt show a strongly energy dependent evolution of the electron distributions in the 1.5 to 6 MeV range – how much can the energy dependence contribute to your variability measurements? (Reply: Thank you for raising this issue of energy dependence. In fact, further study using multi-energy observations by VAP can be useful for this. This is mentioned in the manuscript.)

Your effort to provide answers to the reviewer comments in the interactive discussion is nevertheless appreciated. To the extend these answers can be reviewed at an editorial level by myself, they seem sufficient for your manuscript to go into the next round of the peer review process. (Reply: Thank you)

I therefore encourage you to proceed with a submission of the revision along the lines of what you have already offered in the interactive discussion. You may use the same answers in addition to updating your manuscript accordingly for your formal revision submission, but of course you are free to make further changes if you consider this necessary. Please also consider my editorial comments before proceeding and include also a marked-up version of your revised manuscript where it is indicated which changes were made. (Reply: Thank you. The manuscript is now revised based on comments and suggestions by you and the referee. The modifications in the manuscript are shown in the version with “track changes”.)

I expect that your manuscript will be sent back to the reviewer for a follow-up review.

Kind regards,

Rajkumar Hajra

Reply to the comments by Referee #1:

I would like to thank the Referee #1 for carefully reading the manuscript and giving valuable comments and suggestions. The manuscript is now revised accordingly. I outline below how your comments and suggestions are incorporated in the revision.

This article presents an analysis of the periodicity of electron flux enhancements in the Earth’s radiation belts, and of its main solar wind drivers. Periodgrams are established, showing various periodicities (mainly linked to the solar cycle and the seasonal periodicity), depending on the L-shells and for different solar wind parameters. Focusing on L=3.5, this articles then shows that the seasonal dependency can only be seen on multi-year statistics, and a large variability is shown from one year to another in the presence and position of flux peaks. While not surprising, these observations might not have been published earlier, and a careful analysis of the year-wise variability of the electron outer belt is of interest to the community.

- Reply: Thank you.

The language in this article is clear and concise, and the figures are clear, easily readable and appropriately described.

- Reply: Thank you.

However, I have the following remarks concerning this article:

- Why was the L parameter used for this study? The L* parameter, which is an invariant of the motion of the particles, would certainly provide a clearer picture of the electron radiation belt dynamics, particularly at high L values.
- Reply: I agree with you that the L* parameter (Roederer L parameter) would provide a clearer picture of electron radiation belt dynamics compared to the McIlwain L parameter for large L/L* > 5. However, for smaller L/L* the results will remain the same. I used the readily available L parameter, which was directly provided with the SAMPEX data. It should be noted that the L parameter has been widely used by SAMPEX scientists (references are provided in the manuscript). In addition, because most of the primary results presented in the work pertain to L < 5.0, it is felt that the L parameter is reasonable to use for this effort. I believe that this will not largely impact the results and interpretations.

- On line 20, the explained mechanism mostly applies to the outer radiation belt, and obviously not in or below the slot. This is confirmed by the provided periodgrams, but should be noted.
- Reply: Thank you for the comment. That the described mechanism applies for outer zone radiation belt is now made clear in the manuscript.

- On line 94, the fact that the VB parameter has a 6-month component that is not shared by Vsw is not surprising, since the seasonal periodicity is due to the magnetic configuration. The absence of periodic component in Vsw below a period of a few years is of interest, and shows that the solar wind activity is intrinsically aperiodic on these time scales, so that the observed seasonal dependency can only be proper to the geospheric system (which is compatible with the usual explanation of the seasonal effect).
- Reply: Thank you for the comment. That the 6-month periodicity in VBs originated from magnetic configuration and that solar wind does not have any intrinsic seasonal variation are now discussed in greater detail in the revised manuscript.

- On line 105, the article seems to imply that the current understanding of the seasonal effects (namely the equinoctial configuration of the magnetic field being linked to increased geoeffectiveness of the storms) does not explain the observations presented here, due to the variability of the observed peaks from one year to another. I think, the community is aware that the seasonal effects are statistical in nature, since they act on the geoeffectiveness of the storms, and not on the occurrences of the storms (which are aperiodic on short time scales, and have a solar-cycle period component, as shown in the plots of Vsw). The observed year-wise variability is expected with the classical model, which is not clear at all in this article. A more detailed and rigorous analysis of this variability would be of interest to the community, but the mere existence of this variability seems obvious.
- Reply: Thank you for the comment. The discussion is now revised. The current understanding of the seasonal effects in terms of equinoctial configuration of the magnetic fields leading to increased geoeffectiveness are mainly based on studies of magnetic storms. And this is mostly statistical in nature. However, in order to discuss the L-shell distribution of radiation belt electrons, we need to consider the important role of the solar wind speed which is aperiodic on short time scales; the geomagnetic configuration cannot entirely explain the observations. This is because relativistic electrons are mainly associated with substorms and convection events during HILDCAAs, the latter exhibit strong associations with solar wind high-speed streams. In addition, HILDCAAs do not exhibit any semi-annual variation. These are now made clearer in the revised manuscript.

Seasonal dependence of the Earth's radiation belt: new ~~insight~~insights

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Abstract. Long-term variations of the relativistic ($\sim$MeV) electrons in the Earth's radiation belt are explored to study seasonal features of the electrons. An L-shell dependence of the seasonal variations of the electrons is ~~revealed~~reported for the first time. A clear ∼6-month periodicity, representing one/two peaks per year, is identified for 1.5-6.0 MeV electron fluxes in the L-shells between ∼3.0 and ∼5.0~~, representing two peaks per year~~. The ~~two-peak~~relativistic electron flux variation is ~~strong~~strongest during solar cycle descending to minimum phases, with weaker/no variations during solar maximum. ~~The peaks~~If two peaks per a year occur, they are largely asymmetric in amplitude. ~~These are not essentially equinoctial: sometimes~~The peaks generally do not have an equinoctial dependence. Sometimes the peaks are shifted to solstices and sometimes one annual peak is only observed. No such seasonal features are prominent for $\mathrm{L} < 3.0$ and $\mathrm{L} > 5.0$. The results imply varying solar/interplanetary drivers of the radiation belt electrons at different L-shells. This has a potential impact on the modeling of space environment. Plausible solar drivers are discussed.

1 Introduction

Earth-orbiting satellites ~~around~~traversing through the radiation ~~belt~~belts (Van Allen et al., 1958) are ~~known to be~~ vulnerable to ~~the~~ relativistic ($\sim$MeV) electrons that can cause internal charging leading to satellite component damage or even satellite loss in extreme cases (e.g., Wrenn, 1995; Iucci et al., 2005; Horne et al., 2013; Baker et al., 2018, and references therein). The MeV electrons in the outer radiation belt ($\mathrm{L} > 2.5$) are known to be accelerated from the ∼10-100 keV (energetic) electrons which are injected into the nightside magnetosphere by ~~magnetic storms and~~ substorms (e.g., DeForest and McIlwain, 1971; Horne and Thorne, 1998) and convection events in high-intensity long-duration continuous AE activities (HILDCAAs; Tsurutani et al., 2004). The temperature anisotropy of the electrons leads to plasma instability generating whistler-mode chorus waves (Kennel and Petschek, 1966; Tsurutani and Smith, 1974). Resonant interaction of the ∼100 keV electrons with chorus waves ~~is considered to be the main mechanism for~~leads to MeV electron acceleration (Inan et al., 1978; Horne and Thorne, 2003; Summers et al., 2007; Tsurutani et al., 2013; Xiao et al., 2014; Foster et al., 2017; Matsui et al., 2017; Omura et al., 2019; Zhang et al., 2020).

From the above scenario, it implies that the injections of seed (∼10-100 keV) electrons through ~~magnetic storms/~~substorms/HILDCAAs along with electron loss processes control the variability of magnetospheric MeV electrons in the outer radiation belt.

In other words, the solar wind-magnetosphere coupling processes that cause ~~magnetic storms and~~ substorms and HILDCAAs, play an important role in MeV electron variability. The electrons are reported to vary in the time scales of a ~~few minutes~~fraction of a second (e.g., microbursts; Tsurutani et al., 2013) to several years. While short-scale variations are attributed to ~~geomagnetic activity~~wave-particle interactions and associated solar wind and interplanetary variations, long-term variations are associated with solar activity cycle (e.g., Baker et al., 1986; Tsurutani et al., 2006, 2016; Miyoshi and Kataoka, 2011; Hajra et al., 2013, 2014a, b, 2015a, b, 2020; Li et al., 2015; Hajra and Tsurutani, 2018). Several studies of MeV electrons (e.g., Baker et al., 1999; Li et al., 2001; Kanekal et al., 2010) reported strong semi-annual modulations of the electrons, and discussed this in the context of the Earth's position in the heliosphere (Cortie, 1912), relative angle of solar wind incidence with respect to Earth's rotation axis (Boller and Stolov, 1970), and geometrical controls of interplanetary magnetic fields (Russell and McPherron, 1973). The aim of this present work is a critical exploration of the seasonal features of the MeV electrons, and to identify their solar activity and L-shell dependencies, if any.

2 Data analysis and Results

Figure 1 (top panel) shows the variation of the monthly mean differential fluxes of the electrons in the energy range between 1.5 and 6.0 MeV in different L-shells from 0.5 to 8.5 from ~~1992 July~~July 1992 ~~to~~through ~~2004 June~~June 2004. The L parameter is the radial distance in Earth radii at the equator for a dipole approximation of the Earth's magnetic field (McIlwain, 1961). A L* parameter (Roederer, 1970) could have been used, but because most of the primary results pertain to L < 5.0, it is felt that the L parameter is reasonable to use for this effort. The electron observations are made by the Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX; Baker et al., 1993) that monitored the radiation belts from a low-altitude (∼520-670 km), highly (82°) inclined orbit. Figure 1 shows a classical picture of the Van Allen radiation belts: an inner belt with lower fluxes of 1.5-6.0 MeV electrons at L < 2.0, separated by a slot region devoid of any electrons up to L ∼2.5, followed by an outer belt extending up to L ∼7.0. Peak fluxes occur around L ∼3.0-4.5, shown by superposed black lines.

The MeV electron flux variations are compared with monthly mean solar wind speed Vsw (Figure 1 (second panel), red curve, legend on the right), percentage occurrences of days with daily peak Vsw $\geq 500\ \mathrm{km\,s^{-1}}$ (marked as D500, Figure 1 (second panel), histograms, legend on the left), monthly mean solar wind electric field VBs (Figure 1 (third panel)) where V represents Vsw, and Bs is the southward component of interplanetary magnetic field (IMF) or is zero in absence of southward component. ~~The~~ VBs has been shown to be the main driver of geomagnetic activity (e.g., Burton et al., 1975; Tsurutani et al., 1992, 1995; Finch et al., 2008). The bottom panel (Figure 1) shows the monthly mean F10.7 solar flux that depicts the ∼11-year solar activity cycle. The period under study extends from the descending phase of solar cycle 22 to the descending phase of solar cycle 23. The solar wind and IMFs are obtained from the OMNI website (https://omniweb.gsfc.nasa.gov/). The OMNI database is formed by time-shifting the ~~data collected from~~observations made by the NASA's ACE, Wind and IMP 8 spacecraft to the Earth's bow shock nose. The IMFs in geocentric solar magnetospheric (GSM) coordinates are used in this work.

An overall association of solar wind high-speed (Vsw $\geq 500\ \mathrm{km\,s^{-1}}$) streams (HSSs) and MeV electron fluxes can be observed from the figure. Both Vsw and D500 exhibit two prominent peaks, one around 1994-1995 and another around 2003-

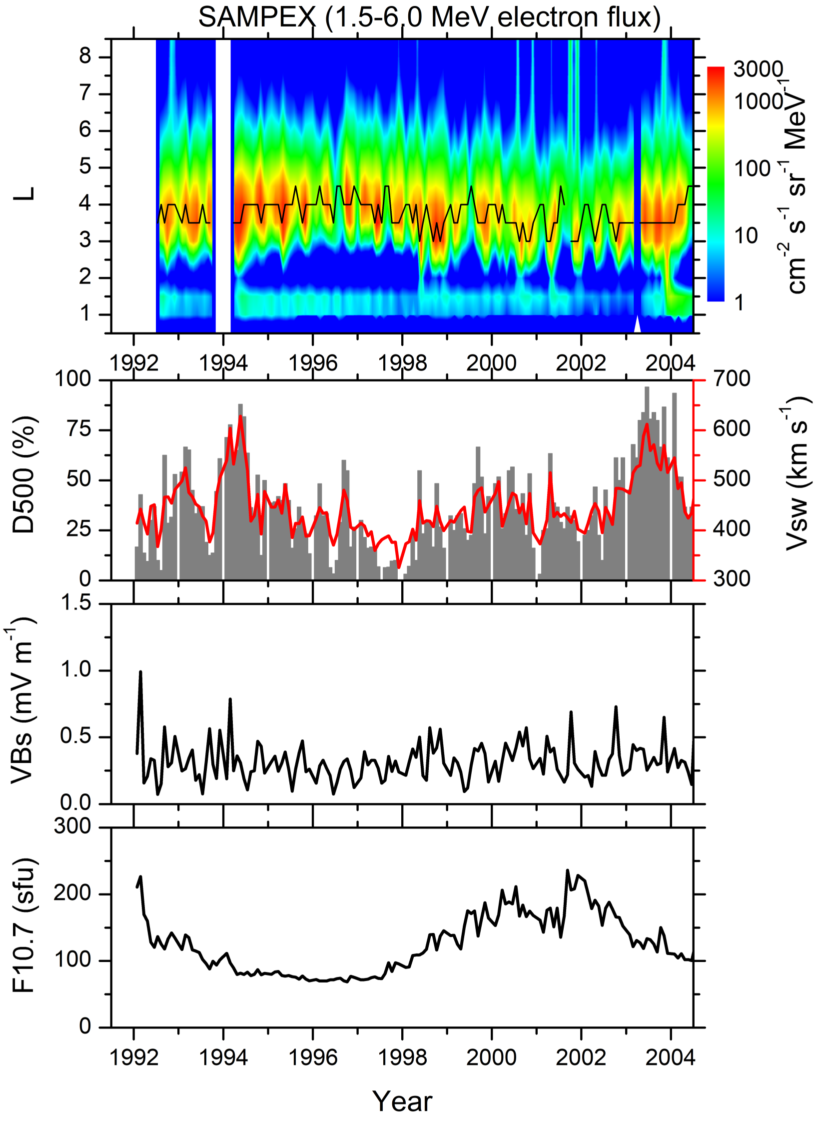

Figure 1. From top to bottom, the panels show the L-shell variation of monthly mean differential 1.5-6.0 MeV electron fluxes (legend on the right showing flux values corresponding to different colours) and L-shells corresponding to peak fluxes (black curve), monthly percentage of days with peak solar wind speed Vsw $\geq$ 500 $\mathrm{km\,s^{-1}}$ (legend on the left) and monthly mean Vsw (red curve, legend on the right), monthly mean VBs, and F10.7 solar flux for the years 1992 through 2004. F10.7 is expressed in solar flux unit (sfu), where a sfu is $10^{-22}\,\mathrm{W\,m^{-2}\,Hz^{-1}}$.

2004, ~~both of~~ which are in the descending ~~phase~~phases of ~~F10.7~~ solar activity cycles 22 and 23, respectively. These intervals are characterized by flux enhancements and broadening of the 1.5-6.0 MeV electron belt in L-shell space ~~(L-shells)~~. On the other hand, a clear narrowing of the belt ~~in~~at higher L-shells and flux decreases can be noted in the ascending and maximum phases of ~~the~~ solar cycle 23. A close-look in the fluxes reveals ~~two-peak~~smaller-scale flux variations in each year around the heart of the outer belt. A similar ~~short~~smaller-scale variation is recorded in VBs.

Figure 2 shows Lomb-Scargle periodograms (Lomb, 1976; Scargle, 1982) of F10.7 solar flux, Vsw, D500, VBs and MeV electron fluxes at different L-shells, shown in Figure 1. As expected, F10.7 exhibits a single periodicity of $\sim$11 years depicting solar activity cycle. Interestingly, Vsw has a broad peak around ~~$\sim$~~9.5-year period with additional significant peaks at $\sim$4.6 and $\sim$3.2 year periods. The D500 exhibited a similar (to Vsw) periodogram. The coupling function VBs is independent of solar activity and has a significant period of $\sim$0.5 years or $\sim$6 months only.

The electron fluxes at different L-shells exhibit large variations in periodicity. At L = 1.0 (inner belt) electrons exhibit significant periods of $\sim$8.9 and $\sim$4.3 years. These seem to be associated with variations in Vsw (D500) with similar periods. However, it should be noted that electron measurement in the inner belt is largely contaminated by very energetic ($\geq$ 10-100 MeV) protons (see, e.g., Singer, 1958; Fennell et al., 2015; Selesnick et al., 2016, and referenes therein). For obvious reason, slot region electrons have no significant variation. At the inner edge of the outer belt (L = 3.0 and 3.5), electrons exhibit a significant periodicity of $\sim$6 months, but no periodicity related to the $\sim$11-year solar activity cycle. In the shells between L = 4.0 to L = 5.0, an $\sim$11-year periodicity is accompanied by a prominent periodicity of $\sim$6 months. The $\sim$6-month periodicity in the electrons (for L = 3.0 to 5.0) can be attributed to the variations in the coupling function VBs. Electrons at L = 5.5 and 6.0 exhibit only a significant periodicity of $\sim$11 years. At L $>$ 6.0, there is no clear periodic variations in MeV electron fluxes.

Figure 2 clearly indicates varying solar activity and seasonal variations of the 1.5-6.0 MeV electrons ~~in~~at different L-shells, which can be attributed to different solar and magnetospheric drivers. This will be discussed later in the paper.

Figure 3 shows the year-month contour plots of monthly mean MeV electron fluxes at L = 3.5 and monthly mean VBs. ~~Top~~The top panel shows the ratio of electron flux seasonal peaks in two halves of each year. This may give an estimate of the seasonal asymmetry of the electron fluxes. It should be noted that months of the peaks varied from year to year, which will be discussed below. Monthly mean F10.7 solar flux is repeated from Figure 1 for a reference of solar activity cycle. Similar analysis is performed for electrons at other L-shells, however they are not shown here to avoid repetition and save space.

While Figure 2 showed ~~an~~a $\sim$6-month (semi-annual) component both in electron flux variation at L = 3.5 and in VBs variation, a clear year-to-year variation can be ~~seen~~observed in Figure 3. In the year 1993, electron fluxes peak around May and August, while two peaks are observed during the months of May and November in 1994. In both cases, the first peaks are $\sim$1.5-1.7 times ~~of~~higher than the second peaks. ~~Two~~In April and October 1995, the two electron flux peaks ~~in April and October~~ are much more distinct and comparable in amplitude ~~in 1995~~. The semi-annual variation is much ~~more~~ weaker in 1996 with a peak in April $\sim$0.5 times of that in October. In 1997, a large peak in fluxes can be noted in May with no prominent equinoctial peaks. In 1998, which is in the ascending phase of ~~the F10.7~~ solar cycle 23, two distinct and comparable peaks are recorded during May and September. In 1999, while electron fluxes are much lower, two peaks can be ~~seen~~noted in February and October ~~months~~. No clear seasonal feature can be ~~conferred~~inferred from 2000, while a solstice peak (May) is observed in 2001, and an October peak in 2002. A two-peak seasonal feature, with two distinct and comparable peaks in May ~~in~~and September, is again observed in 2003, in the descending phase of ~~the~~ solar cycle 23. A consistent variation is observed in VBs with respect to month and year.

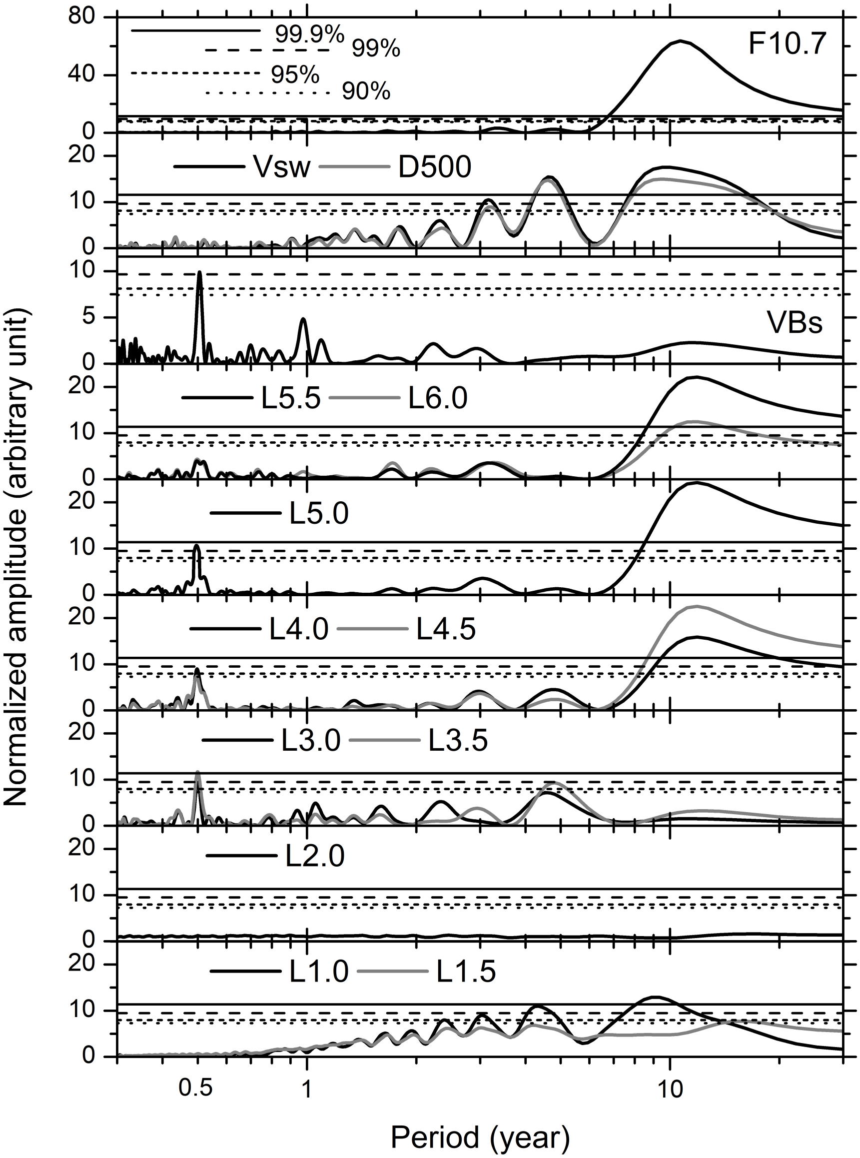

Figure 2. From top to bottom, the panels show Lomb-Scargle periodgrams of F10.7, Vsw and D500, VBs, and 1.5-6.0 MeV electron fluxes at different L-shells. The x-axis shows periods in year and the y-axis shows the normalized amplitudes in arbitrary unit. Confidence levels of the periodograms are shown in each panel by horizontal lines.

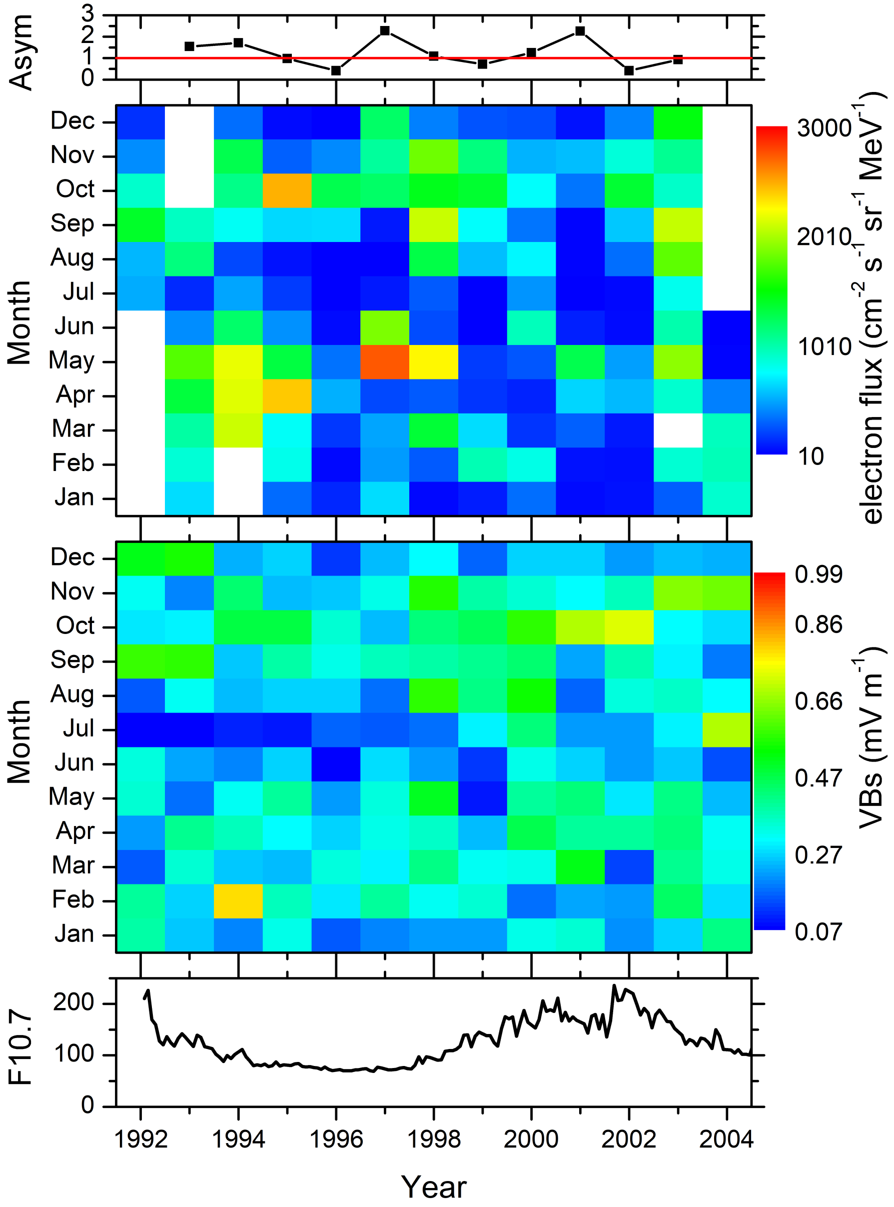

Figure 3. Contour plots in second and third panels show monthly mean 1.5-6.0 MeV electron fluxes at L = 3.5 and monthly mean VBs, respectively during each month of the years 1992 through 2004. Top panel shows seasonal asymmetry (defined in text) and bottom panel shows the F10.7 solar flux during the same interval.

It can be concluded from the above analysis that while the 1.5-6.0 MeV electron fluxes at L = 3.5 exhibit mostly two peaks in a year, they are largely asymmetric in ~~amplitudes~~amplitude and they are not essentially equinoctial. ~~Same~~The same conclusions were drawn for electrons ~~in~~at other L-shells.

3 Discussion and Conclusions

~~Present work~~The results of this paper ~~reveals~~reveal that the MeV electrons in the Earth's outer zone radiation belt exhibit varying solar and seasonal features depending on the L-shells. No $\sim$11-year solar cycle trend was observed in the inner edge (L = 3.0-3.5) of the outer belt, where a dominating $\sim$6-month period was prominent. From L = 4.0 to 5.0, the $\sim$11-year solar cycle variation is accompanied by a secondary $\sim$6-month period. Electrons at L = 5.5 and 6.0 exhibit only a significant periodicity of $\sim$11 years, above which there is no clear periodic variations in MeV electron fluxes. These L-shell dependent seasonal and solar cycle features are reported for the first time. ~~It may be mentioned that~~These are in contrast to previous studies (e.g., Baker et al., 1999; Li et al., 2001; Kanekal et al., 2010) that reported strong and "coherent" seasonal modulations of MeV electrons "throughout the entire outer zone" radiation belt.

Interestingly, no $\sim$6-month component was observed in solar wind speed Vsw, while it was most prominent in the solar wind-magnetospheric coupling function VBs which represents the interplanetary electric field under the condition of southward ~~IMF~~IMFs. This implies that the seasonal feature is due to magnetic configuration (Bs). In addition, the absence of a periodic component in Vsw below a period of a few years is of interest, and shows that the solar wind activity is intrinsically aperiodic on these time scales, so that the observed seasonal dependency can only be proper to the geospheric system (which is compatible with the usual explanation of the seasonal effect). ~~This~~The above result is ~~well~~ consistent with previous results (e.g., Li et al., 2011) suggesting that HSS alone can not predict relativistic electron flux enhancements, but that fast solar wind and southward IMFs are the main requirements for electron enhancements. This makes VBs, involving both solar wind speed and southward IMF, an important factor controlling MeV electron variation.

However, present study involving ~~year-wise~~multi-year analysis of seasonal features in MeV electrons and solar/magnetospheric ~~driver~~drivers reveals that care should be taken in interpreting the $\sim$6-month periodicity obtained through periodogram analysis (present work) or superposed analysis of electrons in the radiation belt (previous reports). Yearly two peaks in the electron fluxes (between L = 3.0 and 5.0) are only sometimes observed around descending phase of the solar cycle. The peaks are largely asymmetric in nature. In addition, the peaks are ~~not~~ essentially not equinoctial: sometimes the peaks are shifted to solstices and sometimes one annual peak is only observed. Clearly the $\sim$6-month periodicity in periodogram (and semi-annual variation) of the magnetospheric MeV electrons is an artifact arising from long-term data superposition in years. That the seasonal effects are of statistical in nature and they apply to the geoeffetiveness of the solar/interplanetary drivers are now well understood (see, Cliver et al., 2000, 2004; Nowada et al., 2009; Mursula et al., 2011; Cnossen and Richmond, 2012; Lockwood et al., 2020; Tsurutani et al., 2020, and references therein). ~~Thus~~However, for applying axial, equinoctial or ~~some~~ geometrical hypothesis to discuss Earth's radiation belt ~~might be premature at this stage~~importance of solar cycle period component and impact of Vsw should be considered. In addition, radiation belt dynamics is strongly dependent on the energy of the electrons. Thus the energy dependence on the seasonal variations should also be investigated for a more complete understanding.

In summary, the L-shell dependent solar and seasonal features and so-called semi-annual variations of magnetospheric relativistic electrons require further attention. Dual satellite Van Allen ~~Probe~~Probes ~~observations~~ (Mauk et al., 2013) involving multi-energy observations of the radiation belts can be useful for further confirmation of the results obtained in the present work.

Data availability. Relativistic (MeV) electrons analyzed in this work is observed by the SAMPEX. These can be obtained from the Coordinated Data Analysis Web (CDAWeb) (https://cdaweb.gsfc.nasa.gov/cgi-bin/eval1.cgi). The solar wind and IMFs are obtained from the OMNI website (https://omniweb.gsfc.nasa.gov/)

Author contributions. RH developed the paper with original idea, data analysis and conclusion of the paper.

Competing interests. The author declares no competing interests.

Acknowledgements. The work is funded by the Science & Engineering Research Board (SERB), a statutory body of the Department of Science & Technology (DST), Government of India through Ramanujan Fellowship. I would like to thank Prof. Bruce T. Tsurutani for helpful scientific discussions.

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