Behavior of MeV electrons at geosynchronous orbit during last two solar cycles

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[1] A comparison of MeV electron measurements at geosynchronous orbit, GEO, with solar wind shows that the MeV electron prediction model developed for GEO using data from the declining phase of solar cycle 22 (1995–1996) works well for the declining phase of solar cycle 23 (2006–2008), indicating that the MeV electron flux has a predictable and systematic response to the solar wind. The same comparison for solar maximum (2000–2003) shows that the model works less well partly because it does not match the high flux cutoff seen in the data and partly because it does not reproduce the sudden drops in flux that occur when the magnetopause is close to GEO. The model also reproduces the nonlinear correlation of the solar wind speed with the log of the MeV electron flux seen at GEO. An examination of 15 yr of solar wind and the MeV electron data shows that geomagnetic activity driven by a southward orientation of the interplanetary magnetic field, IMF, is a necessary condition for MeV electron enhancements at GEO and that high-speed solar wind are not necessary. The reason that high-speed solar wind is almost always associated with the enhancement of MeV electrons is mainly because high-speed solar wind almost always has some southward components of the IMF.


1. Introduction

[2] Recently, Reeves et al. [2011] have used newly available, almost-continuous MeV electron data at geosynchronous orbit (GEO) to re-examine the relation between solar wind speed, VSW, and MeV electron fluxes at GEO. Motivated by this study and these data, we have re-examined our electron prediction model [Li et al., 2001]. Our model was developed from data during the declining phase of solar cycle 22 (1995–1996).

[3] The main goals of this report are

[4] 1. To show the results of using the newly available MeV electron data at geosynchronous orbit (GEO) to test our previously developed electron prediction model, Li et al. [2001], against out-of-sample data. We show that the model works well for the declining phase of solar cycle 23 (2006–2009).

[5] 2. To show the results of using the model during solar maximum. We demonstrate that the model works less well during solar maximum and discuss why this may be.

[6] 3. To show that the nonlinear relationship between solar wind speed and the log of the MeV electron fluxes at GEO recently described by Reeves et al. [2011] is a natural feature of the model and thus a natural consequence of the simple physics underlining the model.

[7] 4. To show, by examining the data, that despite the good correlation of MeV electron fluxes at GEO with solar wind speed, the essential feature required for enhancements of MeV electron fluxes at GEO is geomagnetic activity which in turn requires a southward component of the interplanetary magnetic field (IMF).

[8] The Li et al. [2001] model uses only the solar wind to predict MeV electron fluxes at GEO. Knowledge of a correlation between the solar wind and electrons in the outer radiation belt has a long history. A correlation between VSW and relativistic electrons in the magnetosphere was identified soon after the solar wind was first measured. The correlation was demonstrated by a 27 day periodicity (Sun’s synodic spin period near the maximum region of sunspots) in the intensity of trapped electrons in the outer radiation belt for two energy channels: >280 keV and >1.2 MeV [Williams, 1966]. Paulikas and Blake [1979] more firmly established the correlation between VSW and MeV electrons by showing that MeV electrons at GEO enhance two days after the passage of...
high-speed solar wind streams. Concurrently, Baker et al. [1979] showed that low-energy electrons (10 s of keV) at GEO as well as relativistic electrons, respond to large \( V_{SW} \). Based on this correlation, Baker et al. [1990] developed a linear filter model to predict MeV electrons at GEO using \( V_{SW} \). The linear filter was developed from limited intervals of continuous solar wind and MeV electron flux measurements. The method achieved a prediction efficiency (PE) of 0.52 in their 3 month sample period [Baker et al., 1990].

The location of GEO is viewed as the outer edge of the outer radiation belt and the gateway into the inner part of magnetosphere. The peak intensity of outer radiation belt electrons normally resides inside GEO. Figure 1 shows the yearly window-averaged sunspot numbers and the weekly window averaged solar wind speed (km/s) (Figure 1, top) and the monthly window averaged flux of 2–6 MeV electrons (\#/cm\(^2\)-s-sr) from PET instrument on the Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) [Cook et al., 1993] (Figure 1, bottom). The period is from SAMPEX’s launch (3 July 1992, into a low-altitude, highly inclined orbit) to the end of 2009. The superimposed black curve represents every 10 day’s minimum plasmapause location based on an empirical model [O’Brien and Moldwin, 2003]. The yellow vertical bars on the horizontal axis mark the equinoxes. Calibrated daily averaged electron fluxes from SAMPEX are only available up to day 74 of 2004. We also have daily count rate from the same instrument from day 1 of 2003 to the end of 2009. For the period where the flux data and count rate data overlaps, we performed a linear least squares fit independently for each of the 60 L-shell bins. This gave two coefficients for each L-shell bin, which best converted the count rate to pseudo-flux (after day 74 of 2004). Then we applied this set of coefficients to the count rate data to complete the figure.

It is evident in Figure 1 that the intensity of outer belt electrons is very well correlated with the solar wind speed. However, the essential feature required for enhancements of the MeV electron fluxes at GEO, as we are going to show later, is geomagnetic activity that in turn requires a southward component of the IMF.

As part of the International Solar Terrestrial Program, the solar wind has been almost continuously measured since December 1994 by the Wind [Acuña et al., 1995] and by the Advanced Composition Explorer (ACE, launched in 1998; ACE home page: http://www.srl.caltech.edu/ACE/) spacecraft [Stone et al., 1998]. Using data from 1995–1996, Li et al. [2001] developed an improved model to predict MeV electrons at GEO based on solar wind velocity and velocity fluctuations and the south component of the IMF. They achieved a PE of 0.81 for this two-year sample period. They found that though \( V_{SW} \) is the most important parameter governing relativistic electron fluxes at GEO, relativistic electrons are enhanced even more when the IMF polarity is predominantly southward (\( B_z < 0 \)).

The physical mechanism for the correlation is under debate. In one mechanism, solar wind variations perturb the magnetosphere, generating ultra low frequency (ULF) waves [Engebretson et al., 1998; Vennerstrom, 1999], which drive radial diffusion [Rostoker et al., 1998; Baker et al., 1998a; Mathie and Mann, 2000, 2001; O’Brien et al., 2003; Barker...
et al., 2005; Ukhorskiy et al., 2006; Li et al., 2009] and thus energize electrons. Magnetohydrodynamic simulations and test-particle tracing have shown that radiation belt electrons respond to such magnetospheric fluctuations [Hudson et al., 1999; Elkin et al., 1999; Kress et al., 2008]. Alternatively, the solar wind drives geomagnetic activity, which produces very low frequency (VLF) waves with frequencies comparable to the electrons’ local gyrofrequency. These waves can both energize and pitch angle scatter electrons [Temerlin et al., 1994; Selesnick and Blake, 2000; Meredith et al., 2001, 2002; Albert, 2002; Horne and Thorne, 2003; Bortnik and Thorne, 2007; Li et al., 2007; Tu et al., 2009], energizing some electrons to relativistic energies while precipitating others into the atmosphere. Though it is generally accepted that both mechanisms work, their relative contribution remains uncertain. It should be noted that a fast interplanetary shock (regardless the orientation of IMF) can cause enhancements of MeV electrons at GEO and much inside GEO [e.g., Blake et al., 1992; Li et al., 1993, 2003].

[12] Reeves et al. [2003] showed that MeV electron enhancements are associated with geomagnetic storms, but that MeV electrons increase above their pre-storm levels for only half of the storms. For the other half, MeV electrons either decrease or only recover to their pre-storm levels. Weigel et al. [2003] noted that a $V_{SW}$ above 600 km/s is not a necessary condition for a large enhancement of MeV electrons and that such large solar wind speeds do not precede many enhancements. Reeves et al. [2011] also concluded that high solar wind speed was not a necessary condition but argued that it was a sufficient condition for high MeV electron flux. Li et al. [2005] analyzed the correlation of electrons from 50 keV to 6 MeV to solar wind variations and found that electron enhancements occur after increased $V_{SW}$ with a time delay that increases with energy but that also depends on the average polarity of the IMF, a shorter delay if the IMF $B_z < 0$ and a longer delay if the IMF $B_z > 0$ during the $V_{SW}$ enhancement. Miyoshi and Kataoka [2008] investigated the variation of MeV electrons after the arrival of solar wind stream interaction regions and found that the greatest MeV electron enhancements occur in the highest-speed streams with a southward IMF, indicating that a large $V_{SW}$ is not a sufficient condition for large flux enhancements. More recently, Kataoka and Miyoshi [2010] focused on the year 2009 and suggested that the extremely weak IMF of the very slow solar wind of 2009 played an essential role in diminishing source processes associated with magnetic storms and substorms which, in turn suppressed the relativistic electron flux at GEO. The MeV electron fluxes were indeed very low during 2009, as well as during 2006, as is evident in Figure 1.

[13] Recently, using solar wind data and a considerably longer data set (1989–2010) from the LANL energetic particle instruments at GEO, Reeves et al. [2011] re-examined the relationship between relativistic electron fluxes and $V_{SW}$. They found a triangle shaped distribution in which fluxes have a velocity dependent lower limit but a velocity-independent upper limit rather than a roughly linear relation between $V_{SW}$ and the log of the MeV electron flux. They also found that the highest electron fluxes can occur for any value of $V_{SW}$ with no indication of a $V_{SW}$ threshold and concluded that the relationship between the log of the radiation belt electron fluxes and $V_{SW}$ is more complex than a simple linear correlation. Such similar findings were reported earlier by Baker et al. [2004], who showed the triangle-shaped distribution between total radiation belt electron fluxes (with energy greater than 2 MeV and over the range of magnetic L shells: $2.5 < L < 6.5$) versus solar wind speed and noted the same complexity and nonlinearity.

[14] These recent studies (Reeves et al. [2011], in particular) plus the many more years of continuous measurements of the solar wind and of energetic electrons at GEO, motivated us to re-examine the correlation between the solar wind and MeV electrons at GEO, using our electron prediction model [Li et al., 2001], which was developed from data during the declining phase of solar cycle 22 (1995–1996). The declining phase and minimum of solar cycle 23 thus provide an independent test of the model. This model has also been revised to make real-time forecasts one and two days ahead of >2 MeV electron fluxes at GEO using real-time solar wind data from ACE, normalized with real-time GOES measurements at GEO [e.g., Li, 2004; Turner and Li, 2008; Turner et al., 2011].

2. Data

[15] The solar wind data used in this study are from the OMNI database. Solar wind measurements were made at various locations, mostly near the L1 point, and have been propagated to the sub-solar point of the magnetopause (see http://omniweb.gsfc.nasa.gov/). All solar wind parameters used in this study have a time resolution of 10 min. The energetic electron data are from the LANL energetic particle measurements at GEO, combining daily averages from LANL–GEO ESP instruments on all available satellites (up to seven). The data were inter-calibrated and processed for a long-term study of GEO electron fluxes [Reeves et al., 2011]. In this report, we use the 0.7–1.8 MeV ESP channel.

3. Model

[16] The GEO electron prediction model in this study is the same as in Li et al. [2001]. The model uses a diffusion equation, modeled after radial diffusion, to predict the electron fluxes at GEO, using solar wind parameters as input. The inner and outer boundary are set at $L = 4.5$ and $L = 11$, respectively. The radial diffusion equation is solved by setting the phase space density $10^4$ times greater at the outer boundary than at the inner boundary with a constant decay rate. The diffusion coefficient in the model is a function mainly of the solar wind velocity and the southward component of the IMF (The functional form of the diffusion coefficient also includes a velocity fluctuation term but the effect of that term is small). The result of the diffusion equation is then adjusted by a solar wind pressure term and by a Dst term, calculated from a Dst model [Temerlin and Li, 2002, 2006], which is also based on solar wind parameters. Thus the model is completely driven by the solar wind.

[17] The diffusion term in the model smoothes, averages, and delays the effect of solar wind changes on the predicted electron flux at GEO. While the diffusion term in the model is based on radial diffusion theory, any agreement between the model and the data should not be taken as definitive proof that radial diffusion is operating since other processes that smooth, average, and delay the effects of the solar wind...
on the GEO electron flux may be modeled with such an equation. In particular, heating of electrons by VLF hiss, as mentioned above, can also have such an effect.

[18] All the parameters in the model are also the same as in Li et al. [2001] except that an overall multiplicative factor is applied to the model results to normalize the model to the data. For application of the model to different periods, the normalization factor is likely different. Even for the period 1995–1996, which was used to determine the parameters by Li et al. [2001], the normalization is now different because the electron data have been recalibrated and some data gaps have been filled.

4. Results

[19] All of the model parameters (except the normalization) were determined by comparing the predicted results with LANL–GEO electron measurements in 1995–1996 by maximizing the prediction efficiency, PE, defined as the fraction of the variance that is 'explained' by the prediction or as \([1-(\text{mean squared residual})/(\text{variance of data})]\) where the residual is the difference between the data and the prediction [Li et al., 2001]. We also calculated the linear correlation between the model prediction and the electron data, LC, as another index. We re-ran the same model for the year of 1995–1996 using the OMNI solar wind data and the newly calibrated LANL–GEO ESP 0.7–1.8 MeV electron data and achieved a PE of 0.78 and a LC of 0.88. Data gaps are excluded in the calculation of PE and LC and all PE’s and LC’s in this report use the logs of the fluxes.

[20] Figure 2 shows the application of the model to out-of-sample data. The figure shows a comparison of the 2006–2008 daily averages of the MeV electron flux measured at GEO with the model prediction. The overall variations of the MeV electrons are well reproduced, with a PE of 0.72 and a LC of 0.85. Solar wind conditions during 2006–2008 were similar to those during 1995–1996. Both periods were in the declining phase of the solar cycle approaching solar minimum. It is worth noting that during electron data gaps at GEO; e.g., early in 2008, the model likely provides a good estimate of the actual electron flux.

[21] For the 15 yr period (1995–2009), the model achieved a PE of 0.62 and a LC of 0.79. The model does not work as well overall mainly because it works less well during solar maximum. For the solar maximum period, 2000–2003, the PE equals 0.56 and LC equals 0.76. In particular, the model sometimes over-predicts the electron flux at levels higher than the maximum levels seen in the data. Figure 3 shows the comparison between the measured electron flux and the predicted flux (the model results are from a 15 yr run and thus the normalization is based on the whole data set). The over-prediction during solar maximum is obvious (Using the normalization for 1995–1996 would make the over-prediction during 2000–2003 13% larger).

[22] Another reason the model may not work as well for solar maximum is that the dayside magnetopause is often pushed close to or inside GEO during solar maximum, leading to a rapid loss of MeV electrons through the magnetopause. Figure 4 shows a comparison of MeV electrons at GEO during solar maximum (2001), top four panels, with MeV electrons during the solar declining phase (2007), bottom four panels. During 2001 high-speed solar wind occurs irregularly and the IMF Bz component is often larger than in 2007. These solar wind properties produced much larger magnetic storms (red line in panel 3) and also pushed the dayside magnetopause close to or inside GEO more frequently. The vertical red bars on the top of panel 4 and panel 8 show the sub-solar location of the magnetopause in Earth radii, based on the magnetopause model by Shue et al. [1998].

[23] The model results are from the same 15 yr run for both 2001 and 2007. MeV electrons at GEO during 2007 are well reproduced, except that the modeled electrons decay a little faster than the measured electrons. Rapid variations, especially rapid decreases of MeV electrons during 2001 are not well reproduced by the model, which doesn’t properly handle the effects of magnetopause crossings.

[24] During solar maximum solar wind speed, density, pressure, and magnetic field enhancements occur in an irregular fashion, disrupting the radiation belt. In contrast, during the declining phase of the solar cycle, solar wind speed, pressure, and density enhancements occur in a regular
Figure 3. The same as Figure 2 except for 2000–2003.

Figure 4. Daily averages of measured and predicted 1.7–1.8 MeV electron fluxes at geosynchronous orbit, selected solar wind parameters, Dst index, and calculated location of magnetopause for the second half-year of 2001 (top four panels) and 2007 (bottom four panels).
fashion at the leading edge of recurring high-speed streams emanating from coronal holes. Since the model is based on data from the declining phase, it is not too surprising that it performed well during the declining phase of another solar cycle, and didn’t do as well during solar maximum.

[25] It was pointed in Baker et al. [2004], as well as emphasized by Reeves et al. [2011], that the relationship between \(V_{SW}\) and the log of the MeV electron flux at GEO is neither linear nor simple. Here we demonstrate that the complicated relation can be a natural feature of the model and thus a natural consequence of the simple physics underlying the model. The top two panels of Figure 5 show the correlation between \(V_{SW}\) and MeV electrons at GEO, essentially reproducing the results shown in Reeves et al. [2011] (though for a lower energy channel). In particular, the two important features emphasized in Reeves et al. [2011]: (1) the nonlinear nature of the correlation and (2) the distinct velocity-dependent lower limit to the fluxes are reproduced. With no delay between \(V_{SW}\) and the electron flux, the electron fluxes can be at any level for low values of \(V_{SW}\). With a 1.9-day delay (right upper panel - \(V_{SW}\) versus electrons 1.9 days later), the correlation becomes more organized. The model shows a similar correlation between the \(V_{SW}\) and the predicted MeV electrons at GEO, as displayed in the left bottom panel of Figure 5 (for the 15 yr model run) and that, with a 1.9 day delay, the correlation is also greatly improved, right bottom panel. The delay in the electron flux (either measured or modeled) with respect to \(V_{SW}\) was calculated by interpolating daily averaged values of \(V_{SW}\) to optimize the correlation as a function of the delay.

[26] The main difference between the model and the data is the greater scatter in the data but the model displays a similar nonlinear relation between the solar wind speed and the log of the electron flux. However, the model with a 1.9 day delay still displays substantial scatter. This is because the model also does not have a simple relationship between the \(V_{SW}\) and its output: the model depends also on the southward component of the IMF and through the diffusion equation effectively averages the solar wind input over time. In addition, the model has corrections for solar wind pressure and the modeled Dst. Also the model diffusion term has a nonlinear dependence on \(V_{SW}\).

[27] Another difference shown in Figure 5 is in the saturation of the measured electron flux. The data have few points above a flux level of about \(10^6 \text{/(cm}^2\text{-s-sr-keV)}\). Reeves et al. [2011] concluded, with some uncertainty, that the saturation is more likely physical than instrumental. The model doesn’t have an explicit saturation mechanism and the model results occasionally show higher flux levels mostly during solar maximum. Whatever the saturation mechanism may be [e.g., Mauk and Fox, 2010], the model implies it need not be very large, since even in the model, the flux only exceeds the \(10^6 \text{/(cm}^2\text{-s-sr-keV)}\) level by a small amount and only rarely. In the model the flux is limited by the boundary conditions and a decay term with a constant decay rate.

Figure 5. Scatterplots of daily averages of 0.7–1.8 MeV electron fluxes at geosynchronous orbit, both measured and predicted for 15 yr (1995–2009) of data and model run, versus solar wind speed with and without delay.
Figure 6 shows measured electron fluxes versus the model-predicted fluxes. It is clear that the highest values of the predicted fluxes are greater than the measured fluxes as discussed before. The measured fluxes also have more very low values, some of which are from the magnetopause having been pushed near or inside GEO, causing precipitous electron loss.

There exists substantial confusion as to the essential solar wind cause of MeV electron enhancements in the outer radiation belt. On one hand, much of the literature has emphasized the correlation between the high-speed solar wind and outer radiation belt electrons [e.g., Paulikas and Blake, 1979; Baker et al., 1979; Reeves et al., 2011]. On the other hand, such electron enhancements have been discussed as the product of magnetospheric storms [e.g., Baker et al., 1998a; Reeves et al., 2003], which are known to be crucially dependent on a large and southward oriented IMF. Of course, much of this confusion arises because most magnetic storms are associated with high-speed solar wind and the high-speed solar wind compresses the IMF at its leading edge producing the large southward IMF fields required for a magnetic storm.

However, there are cases when the compressed IMF at the leading edge of high-speed stream is almost wholly...
northward. As pointed out by Blake et al. [1997], for one example, a high-speed stream with a predominately northward IMF needs not cause a MeV electron enhancement. Another example occurred early in January of 1996 and is shown as the second highlighted period in Figure 7, where $V_{SW}$ was greater than 500 km/s but no significant enhancement of the relativistic electrons occurred with respect to the previous electron fluxes. In terms of the relative enhancement of the electron fluxes, we found several additional examples of high-speed solar wind with $V_{SW}$ over 500 km/s with no appreciable effect (less than a factor of two enhancement) on relativistic electrons. In nearly all these cases (more than 10), Bz was predominately northward and there was no magnetic storm ($Dst > -30$ nT). Table 1 lists the dates and the minimum Dst values for these events.

Table 1. Examples of High-Speed Solar Wind With $V_{SW}$ Over 500 km/s Without Appreciable Effect on Relativistic Electrons at GEO (Less Than a Factor of Two Enhancement)

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<thead>
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<tr>
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<td>-25</td>
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<tr>
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<td>04/04/28</td>
<td>-15</td>
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<tr>
<td>06/03/16</td>
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<tr>
<td>09/01/31</td>
<td>-10</td>
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[31] On the other hand, in some rare cases magnetic storms can occur with slow solar wind speeds, such as the first highlighted period in Figure 7, where $V_{SW}$ was below 450 km/s and there was a significant enhancement of MeV electrons (Bz is mostly negative). Furthermore, the highlighted period in Figure 8 shows a magnetic storm and an electron enhancement (that our model failed to predict) without a high-speed stream—$V_{SW}$ never exceeded 360 km/s. We also found 10 examples where the MeV electron flux enhanced by a least factor of five without a high-speed solar wind ($V_{SW}$ was less than 450 km/s). In all these cases (total 10), Bz was predominately southward and there was enhanced magnetic activity ($Dst < -30$ nT). Table 2 lists the dates and the minimum Dst values for these events.

Table 2. Examples of Significant Enhancement of MeV Electrons at GEO (Greater Than a Factor of Five) Without a High-Speed Solar Wind ($V_{SW} < 450$ km/s)

<table>
<thead>
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<tr>
<td>09/02/04</td>
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Figure 8. Daily averages of measured and predicted 1.7–1.8 MeV electron fluxes at geosynchronous orbit, selected solar wind parameters, and Dst index for a three-month period, starting on 1 April 1997.
Some geomagnetic activity and thus some negative Bz is required to produce a relativistic electron enhancement at GEO; e.g., late December of 1995 as shown in the first highlighted period in Figure 7. Not all electron enhancements are preceded by magnetic storms but there always needs to be some geomagnetic activity, preferably associated with a high-speed stream, to produce a substantial enhancement of the electron flux at GEO. After all, the threshold for a magnetic storm is arbitrary. As an example, based on our survey of 15 yr of data, for $V_{SW}$ less than 450 km/s, a minimum Dst of $\sim$30 nT is required for an enhancement of a factor of five for the 0.7–1.8 MeV electron flux over previous flux level at GEO (see Table 2 for some examples). At the leading edge of high-speed streams, the IMF is usually enhanced and fluctuates. If predominately northward, it may not cause a magnetic storm but if its fluctuations produce at some least southward IMF, there will be some geomagnetic activity and the electron flux may be enhanced. In this manner some high-speed streams produce electron enhancements at GEO without producing magnetic storms.

In summary: high-speed solar winds that produce little geomagnetic activity because of associated small or northward IMF’s do not affect MeV electrons at GEO. On the other hand, slow-speed solar winds with large southward IMF’s can produce magnetic storms and can substantially enhance the MeV electron flux at GEO. Thus we conclude that the essential cause of MeV electron enhancements at GEO is enhanced geomagnetic activity, such as negative Dst, driven by southward oriented IMF, not the high-speed solar wind. Another way to interpret this would be the following: Substorms require southward IMF (high-speed solar wind certainly helps) to produce 100’s keV electrons. Only with source population do we get the subsequent MeV electrons enhancement [e.g., Baker et al., 1998b and Li et al., 2009]. However, a combination of a long lasting high-speed solar wind and a southward oriented IMF produce highest fluxes of MeV electrons at GEO.

The model contains both solar wind speed and the southward component of the IMF. However, the model will produce some electron enhancement even for purely northward IMF. This is probably because the model parameters reflect average conditions rather than rare events.

5. Discussion

Our understanding of the relation between the solar wind and MeV electron fluxes is imperfect. Particularly confusing is the relation of magnetic storms and high-speed streams to MeV electron flux enhancements. Reeves et al. [2003] have shown that only about half of storms lead to electron flux enhancements from the pre-storm level and that there is little correlation between the pre-storm and post-storm electron flux levels. This should not be taken as an indication that no enhancement of the electron flux occurs during the storm. Rather, storms usually deplete the pre-existing electrons before enhancing them. If the pre-existing electron flux is small, chances are the storm will enhance the flux and vice versa.

In the declining phase of the solar cycle, most high-speed streams lead to electron flux enhancements from the pre-high-speed stream level because the relatively regular temporal spacing of the high-speed streams allows time for the electron flux enhancement from the previous high-speed stream to decay. Many of these electron flux enhancements during the declining phase are not preceded by storms but are rather the products of an enhanced and prolonged level of geomagnetic activity, which creates and sustains a high level of electron flux. During solar minimum, when weak IMF’s and slow solar wind speeds persist, a prolonged and enhanced level of geomagnetic activity cannot be produced, leading to low MeV electron fluxes; e.g., 1996 and 2009, particularly for 2009, as shown in Figure 1 and also as discussed by Kataoka and Miyoshi [2010], who suggested that the extremely weak IMF of the very slow solar wind during 2009 led to the very low MeV electron fluxes at GEO.

The electron flux is relatively well correlated with the solar wind speed and poorly correlated with the IMF and yet the enhancement of the electron flux requires geomagnetic activity that in turn requires a southward component of the IMF. How can this be? A partial answer is that the high-speed solar wind typically has enhanced levels of IMF fluctuations with both southward and northward components that average to zero. So correlating with the average IMF is not very useful. Only using the southward component of the IMF is more useful but too large a southward component will lead to storms that can also deplete the electron flux degrading the correlation with southward component of the IMF. The southward component is far more effective in driving geomagnetic activity when combined with a $V_{SW}$ (The electric field, often considered the main driver of reconnection at the magnetopause, is a cross product of the velocity and magnetic field). Our model can help clarify the relative importance of high solar wind speeds and southward IMF’s. The model contains both solar wind speed and the southward component of the IMF. In the model the southward component is a significant term and yet removing the southward component from the model and relying only on the solar wind speed (with a readjustment of the parameters) only slightly degrades the performance of the model. One can see why this is by imagining that each high-speed solar wind has an equal amount of both southward and northward IMF’s whose magnitudes are functions of the speed, as, in fact, is approximately the case. Under such conditions the solar wind speed would serve as perfect proxy for the combined effects of the solar wind speed and of the IMF and so adding an explicit IMF term would not help the model. It is only because some high-speed solar wind streams have more northward IMF and some more southward IMF that including the IMF enhances the performance of the model. Figure 9 shows a comparison between predicted results (identical to the prediction results in Figure 2) and a controlled run where Bz is set northward (positive) for the entire interval, which is equivalently in our model to leaving the Bz term out, since the Bz term in the model is given by

$$Bz-term = 1 + (−VxBz + abs(VxBz))^2.$$  

The second term goes zero when Bz is positive (Vx is always negative). The diffusion coefficient is significantly reduced and so is the final result. The normalization factor is kept the same, thus we can see the difference of the modeled results with and without the Bz term. From a casual glance, the difference may appear constant throughout. But actually the difference between the black and red lines on Figure 9 vary with time, because some high-speed solar wind...
Figure 9. A comparison of 3 years of daily averages of 0.7–1.8 MeV electron flux predicted results based solely on measurements of the solar wind (black line, the same as in Figure 2) and a controlled model run (red line) where the IMF Bz term in the model is removed.

6. Summary

[38] In this report we have shown that the MeV electron prediction model developed for geosynchronous orbit using data from the declining phase of solar cycle 22 (1995–1996) works well for the declining phase of solar cycle 23 (2006–2008), indicating that the MeV electron flux at geosynchronous orbit has a predictable and systematic response to the solar wind. For solar maximum (2002–2003) the model works less well partly because it does not match the high flux cutoff seen in the data and partly because it does not reproduce the sudden drops in flux that occur from interactions of the magnetopause with locations close to geosynchronous orbit. We have also shown that the model reproduces the nonlinear correlation of $V_{SW}$ with the log of the MeV electron flux seen at geosynchronous orbit [Reeves et al., 2011]. We have emphasized that the geosynchronous MeV electron flux depends not only on the $V_{SW}$ but also on the orientation of the IMF, the Dst index, which in turn is complex function of the solar wind [Temerin and Li, 2002, 2006], and the solar wind pressure and that these additional dependencies explain some of the scatter in the correlation of the MeV electron flux with the $V_{SW}$. In addition, we have shown that geomagnetic activity driven by a southward orientation of the IMF is a necessary condition for MeV electron enhancements at geosynchronous orbit and, in agreement with Weigel et al. [2003] and Reeves et al. [2011], that high-speed solar wind is not necessary. High-speed solar wind is almost always associated with the enhancement of MeV electrons mainly because high-speed solar wind almost always has some southward components of the IMF.

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