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A Semi-Empirical Model for Forecasting Relativistic Electrons at Geostationary Orbit

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We developed a new prediction model for forecasting relativistic (>2MeV) electrons, which provides a VERY HIGH correlation between predicted and actually measured electron fluxes at geostationary orbit. This model implies the multi-step particle acceleration and is based on numerical integrating two linked continuity equations for primarily accelerated particles and relativistic electrons. The model includes a source and losses, and used solar wind data as only input parameters. We used the coupling function which is a best-fit combination of solar wind/Interplanetary Magnetic Field parameters, responsible for the generation of geomagnetic activity, as a source. The loss function was derived from experimental data. We tested the model for four year period 2004-2007. The correlation coefficient between predicted and actual values of the electron fluxes for whole four year period as well as for each of these years is about 0.9. The high and stable correlation between the computed and actual electron fluxes shows that the reliable forecasting these electrons at geostationary orbit is possible. The correlation coefficient between predicted and actual electron fluxes is stable and incredibly high.

1. Introduction

Relativistic electrons in the Earth's magnetosphere are one of most hazardous phenomena in geospace environment [*Baker*, 2002], and therefore developing a reliable method of their prediction is an important area of research.

The purpose of this paper is to develop a new method for forecasting relativistic electron fluxes at geostationary orbit that is based on numerical integration of particle balance equation for accelerated particles.

2. Data and Method Used for Modeling

As input parameters to our model, we used hourly mean data of the solar wind and Interplanetary Magnetic Field (IMF): the solar wind velocity and density, and the IMF B_y and B_z components that are available at ftp://nssdcftp.gsfc.nasa.gov/spacecraft_data/omni. We used also data of relativistic (>2 MeV) electron fluxes measured with GOES-10 and GOES-12 for four years from 2004 through 2007. The data are available from the NOAA web side at http://spidr.ngdc.noaa.gov.

For forecasting relativistic electron fluxes at geostationary orbit, we developed a method which is based on the idea that the relativistic electrons in the magnetosphere are a result of a multi-step acceleration from primarily acceleration during substorm activity to relativistic energies [e.g., *Baker et al.*, 1990; *Summers et al.*, 2007]. For simplicity, we used only two particle balance equations:

$$\mathrm{d}F_1 / \mathrm{d}t = Q_1 - a_1 F_1 \qquad (1)$$

$$\mathrm{d}F_2 / \mathrm{d}t = Q_2 - a_2 F_2 \qquad (2)$$

where F_1 is the primarily accelerated electron flux, F_2 is the relativistic electron flux, Q_1 and Q_2 are the sources for the generation of the F_1 and F_2 fluxes, and a_1 and a_2 are the coefficients of losses of these fluxes, respectively, due to spreading the accelerated particles on waves and their precipitation into the ionosphere.

The source, Q_1, for the flux F_1 is suggested to be proportional to the electric fields generated during geomagnetic disturbances; therefore, we assumed Q_1 to be proportional to the solar wind coupling function, *CF*, which is a best-fit combination of solar wind parameters, responsible for the generation of geomagnetic activity. We used the coupling function in the form suggested by *Lyatsky et al.* [2007]. The source, Q_2, of the relativistic electrons is assumed to be proportional to the primarily accelerated electron flux, F_1, that is $Q_2 \sim F_1$.

The relativistic electron flux, F_2, was found from solving the two linked equations (1) and (2). For deriving the loss factors a_1 and a_2, we accounted for the recent results by *Onsager et al.* [2007] and *Lyatsky and Khazanov* [2008] that showed that the losses of relativistic electrons are significantly controlled by solar wind density. This effect may be due to the penetration of solar wind plasma into the plasma sheet, which affects the generation of ion- and electron-cyclotron waves responsible for pitch-angle spread of particles and their precipitation into the ionosphere [e.g., *Horne et al.*, 2005; *Summers et al.*, 2007].

We found the coefficients in (1, 2) from the condition of the best-fit correlation of the relativistic electron fluxes, as computed from our model, with the actual electron fluxes at geostationary orbit. Therefore, our prediction model, similarly to the *Li et al.* [2001] model, also may be called a semi-empirical model.

Since the relativistic electron fluxes, F_e, vary by several orders of magnitude, a non-linear scale is commonly used for their analysis. We used the cube root of the electron fluxes, which are more appropriate than the log scale, since it is related to only positive values of the measured fluxes and it is more sensitive than the log F_e for high values of the electron fluxes, which are most dangerous.

The same as the majority of other researchers, we used daily mean values of measured electron fluxes, which reduce the diurnal variation. We examined our model for the period of 2001-2007; however, in this study we are presenting the results for 2004-2007 only. For the analysis, we used the average values of electron fluxes measured with GOES-10 and GOES-12 spacecraft.

3. Main Results

In order to show how our model is operating, first we will show the result of real-time computing the electron fluxes from solar wind data (we remind that for predicting, not real-time data, but data taken for previous time should be used).

Figure 1 shows the correlation between the cube root of computed and actual daily mean relativistic (>2 MeV) electron fluxes at geostationary orbit for 2004-2007. The left panel shows the running daily averages of the electron fluxes, computed beginning from each UT hour. The right panel shows the electron fluxes, computed for four UT = 0, 6, 12, and 18 hrs (as the results for different UT are slightly different). This figure is based on 33,576 hourly mean values. The linear correlation coefficients, R, shown on both panels in Figure 1, are very high ($R \approx 0.90$). The similar high correlation coefficients took place for each of the four years considered. This shows the high reliability of our model.

Figures 2 and 3 show the results of modeling in a prediction regime, when for computing the expected electron fluxes we used solar wind data from previous day.

Figure 2 shows the correlation between the actual and predicted (for one day ahead) electron fluxes for 2004-2007 combined for four UT = 0, 6, 12, and 18 hrs. The left panel shows the correlation between actual and computed electron fluxes without any accounting for the actual electron fluxes. The right panel shows the correlation between actual and computed electron fluxes with accounting for the value of the fluxes from previous day. Each of the panels in this figure includes 5,596 values of the electron fluxes. The correlation between predicted and actual electron fluxes is very high; the correlation coefficient is ~0.89 for the prediction without any accounting for real data and ~0.92 for prediction with accounting for the actual data, taken from a previous day.

Figures 3a and 3b show the time variations of the predicted (for one day ahead) and actual relativistic electron fluxes for 2004-2007 without any accounting for the real data. Shown are the running daily averages of the cube root of computed and actual values of the electron fluxes. The correlation coefficients for the correlation between these quantities are shown for each year. One can see that the correlation coefficient remain very high (~0.88-0.9) for each of these four years. The values of electron fluxes for 2007 are presented for part of the year when the data were available.

4. Discussion and Conclusion

Thus, for predicting relativistic electron fluxes at geostationary orbit, we used numerical integration of the continuity (particle balance) equation for electron fluxes that includes a source and losses. We used solar wind data as only input parameters for the model. We used as a source a combination of solar wind parameters, so-called coupling function, responsible for the generation of geomagnetic disturbances. The loss function in our model was chosen with accounting for recent results by *Onsager et al.* [2007] and *Lyatsky and Khazanov* [2008] that showed an important role played by solar wind density in the decay of relativistic electrons.

The relativistic electron fluxes, predicted from our model, show the high correlation with actual electron fluxes at geostationary orbit. We tested the model for four year period from 2004 through 2007. The correlation coefficients for each of these years and for whole 4-year period are about 0.88-0.90 that is higher than results obtain from other predicted models.

An important feature of our model is that it does not specify which of two possible mechanisms (the electron acceleration in large-scale electric fields, leading to the radial diffusion of accelerated particles [*Li et al.*, 2001], or the local gyro-resonance acceleration by whistler mode waves [*Horne et al.*, 2005; *Summers et al.*, 2007]) is responsible for particle acceleration to relativistic energies, though the latter mechanism seems potentially more prospective.

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Figure Caption

Figure 1. Correlation between the cube root of computed and actual relativistic electron fluxes at geostationary orbit for 2004-2007. The left panel shows the running daily averages of computed electron fluxes; the right panel shows the computed fluxes combined for four UT = 0, 6, 12, and 18 hrs. The correlation coefficients are shown.

Figure 2. Correlation between the cube root of predicted (for one day ahead) and actual relativistic electron fluxes at geostationary orbit for 2004-2007 combined for four UT = 0, 6, 12, and 18 hrs. The left panel shows the correlation between actual and computed electron fluxes without accounting for real data for previous day; the right panel shows the correlation between actual and computed electron fluxes with accounting for the actual fluxes for previous days. The correlation coefficients are shown.

Figure 3a. Time variations of the predicted (for one day ahead) and actual relativistic electron fluxes for 2004-2005. Shown are the running daily averages of the cube root of computed and actual (shown by blue and red lines, respectively) values of the electron fluxes without accounting for real data for previous day. Correlation coefficients between these quantities are shown for each year.

Figure 3b. The same as in Figure 3a but for years 2006-2007. Shown are the running daily averages of the cube root of computed and actual values of the electron fluxes. Correlation coefficients between these quantities are shown. The values of electron fluxes for 2007 are presented for part of the year when the data were available.

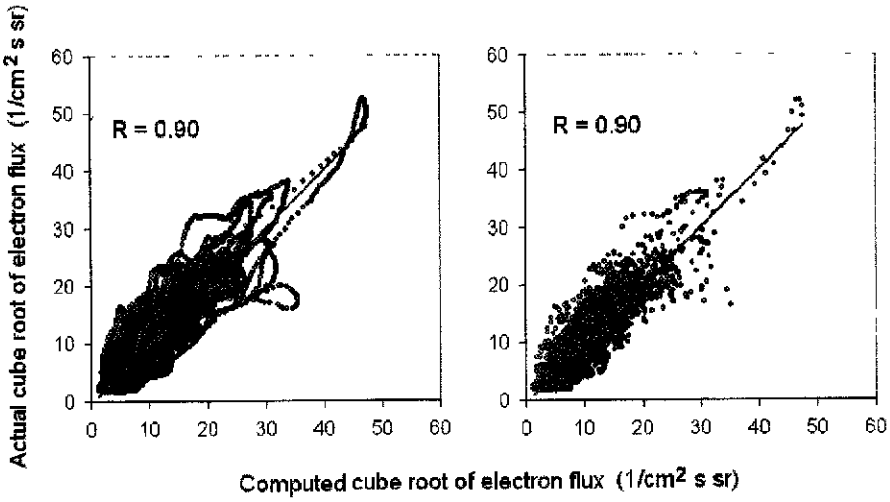


Figure 1.

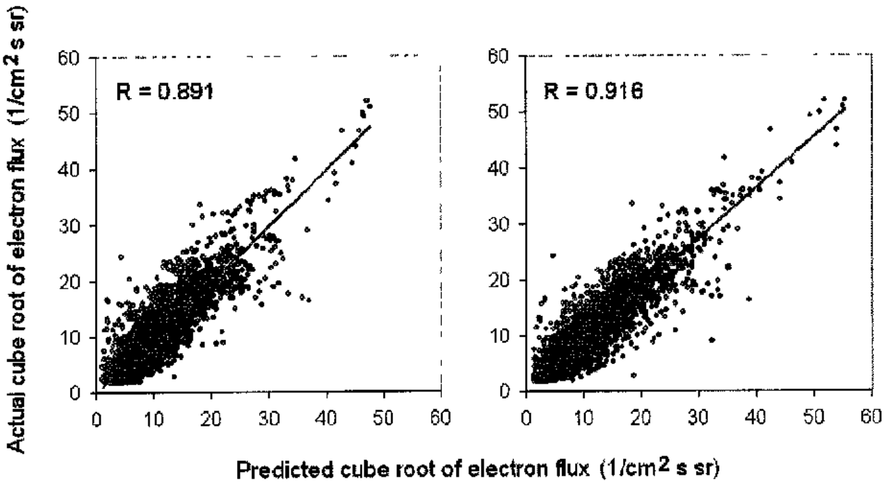
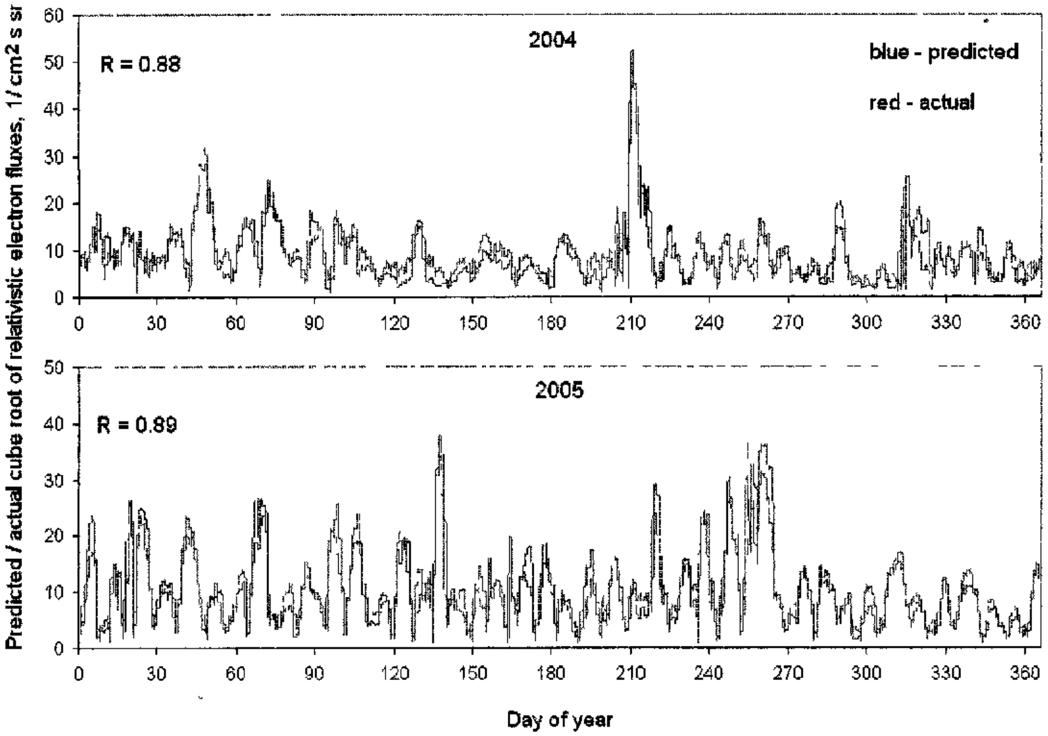
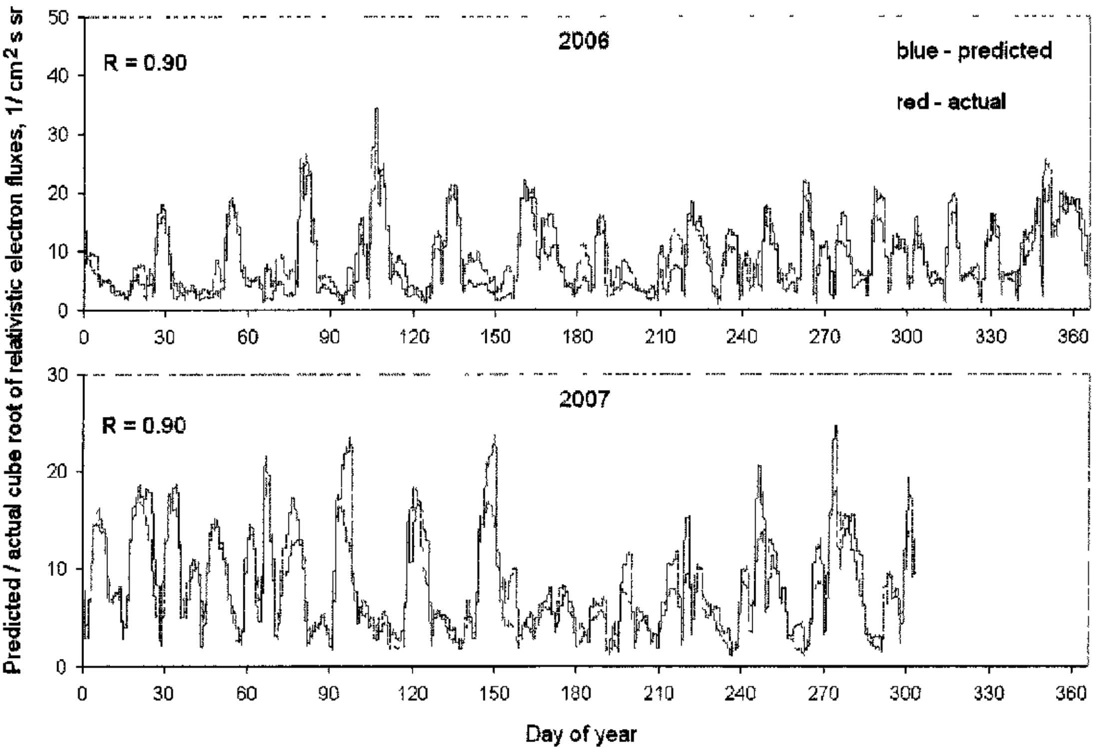


Figure 2.


Predicted / actual cube root of relativistic electron fluxes, 1 / cm^2 s sr
2004
R = 0.88
blue - predicted
red - actual
2005
R = 0.89
0
10
20
30
40
50
60
0
30
60
90
120
150
180
210
240
270
300
330
360
Day of year


Predicted / actual cube root of relativistic electron fluxes, 1 / cm^2 s sr
2006
R = 0.90
blue - predicted
red - actual
2007
R = 0.90
0
10
20
30
40
50
0
30
60
90
120
150
180
210
240
270
300
330
360
Day of year

Figures 3a, b