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Abstract We present a reconstruction of the dynamics of the radiation belts from solar cycles 17 to 24 which allows us to study how radiation belt activity has varied between the different solar cycles. The radiation belt simulations are produced using the Versatile Electron Radiation Belt (VERB)-3D code. The VERB-3D code simulations incorporate radial, energy, and pitch angle diffusion to reproduce the radiation belts. Our simulations use the historical measurements of $Kp$ (available since solar cycle 17, i.e., 1933) to model the evolution radiation belt dynamics between $L^* = 1–6.6$. A nonlinear auto regressive network with exogenous inputs (NARX) neural network was trained off GOES 15 measurements (January 2011–March 2014) and used to supply the upper boundary condition ($L^* = 6.6$) over the course of solar cycles 17–24 (i.e., 1933–2017). Comparison of the model with long term observations of the Van Allen Probes and CRRES demonstrates that our model, driven by the NARX boundary, can reconstruct the general evolution of the radiation belt fluxes. Solar cycle 24 (January 2008–2017) has been the least active of the considered solar cycles which resulted in unusually low electron fluxes. Our results show that solar cycle 24 should not be used as a representative solar cycle for developing long term environment models. The developed reconstruction of fluxes can be used to develop or improve empirical models of the radiation belts.

1. Introduction

Discovered in 1958, the Earth’s radiation belts are two torus shaped regions consisting of highly energetic protons and electrons that remain trapped by the Earth’s magnetic field (Van Allen & Frank, 1959). The inner radiation belt is located between the 0.2–2 Earth radii ($R_e$), McIlwain $L$ shells = 1–3 (Roederer, 1970), and is composed of ∼100–700 keV electrons (Fennell et al., 2015) and protons with energies ranging from ∼10 to ∼100 MeV. The outer radiation belt extends from $L = 2.8–8$ ($3–7 R_e$) and consists mostly of high-energy and relativistic (0.5 to ∼10 MeV) electrons. While the inner belt is generally stable, the outer belt is extremely dynamic, with variations of up to several orders of magnitude possible within hours (Craven, 1966; Rothwell & Mcilwain, 1960), especially during periods of enhanced geomagnetic activity (Baker et al., 1986, 1997; Reeves et al., 1998).

The dynamics of the radiation belt electrons are dominated by a balance of acceleration and loss processes (Reeves et al., 2003; Shprits et al., 2008a, 2008b; Turner et al., 2014). Resonant wave-particle interactions influence both the acceleration and loss of radiation belt electrons (Jordanova et al., 2008; Lyons et al., 1972; Subbotin et al., 2011b; Summers & Throne, 2003; Summers et al., 2007a; Thorne, 2010; R. M. Thorne & Kennel, 1971; Zhang et al., 2016), with varying wave parameters dictating the effectiveness of those interactions (Ni et al., 2013). Furthermore, the scattering rates and acceleration of electrons are also dependent upon the particle’s energy, pitch-angle, magnetic latitudes, radial distances, background density, and magnetic field as well as the various properties of waves (e.g., frequency distribution, wave amplitude, wave normal angle distribution, and spatial distributions) (Shprits et al., 2008b). Geomagnetic storms play an important role in the radiation belt dynamics through their ability to enhance or deplete electron populations at certain energies (Bingham et al., 2018; Reeves et al., 2003; Turner et al., 2014, 2019).

Since Earth’s magnetosphere is susceptible to the external solar wind conditions, the dynamics of the radiation belts are influenced by the solar cycle (Reeves et al., 2013). Furthermore, the strength, number, and type (coronal mass ejections (CMEs) or corotating interaction regions (CIRs)) of geomagnetic storms is
dependent upon whether the solar cycle is on its ascending or descending phase (i.e., solar maximum or solar minimum) (Gonzalez et al., 1994, 2002). During the declining phase of the solar cycle, high-speed streams with peak velocities between 600 and 1,000 km/s are more commonly observed. High speed solar wind accompanied by the fluctuating magnetic fields, result in the strong enhancement of the radiation belts. CME storms cause intense geomagnetic storms (Borovsky & Denton, 2006; Gonzalez et al., 1999, 2002) and fast depletions followed by rapid acceleration. CMEs can occur during any phase of the solar cycle, although they are more prevalent during solar maximum. Conversely, CIRs are more dominant during the descending phase of the solar cycle and are not as intense as CMEs. Less active solar cycles will produce fewer and weaker geomagnetic storms, thereby producing less VLF, ELF, and ULF wave activity (Gonzalez et al., 1994; Saikin et al., 2016) that can impact the radiation belts. Therefore, exploring and examining the radiation belts over an entire, or multiple, solar cycles is required for a description of radiation belt dynamics and estimating potential damage on spacecrafts from deep dielectric charging. Furthermore, such investigation allows for an examination how the radiation belt dynamics depend on the solar cycle and level of geomagnetic activity.

However, radiation belt measurements are historically limited with previous studies lamenting how the uneven spatial and time distribution of previous missions has stalled data interpretation (e.g., Abel et al., 1994) while others call for the continuous collection of data to further the understanding of the radiation belts under extreme geomagnetic conditions (Koons, 2001). Continuous, but still sparse observations are available only after 1986 (i.e., the start of solar cycle 22) (Glauert et al., 2018) or later (Baker et al., 2019a; Li et al., 2017). Over the years, missions have observed the radiation belts (i.e., POES, THEMIS, Cluster, and MMS). However, each mission presents its own challenges when observing the radiation belts. For example, POES only provides low earth orbit data and therefore presents difficulties in finding unique mapping to a variety of L shells (which becomes complicated when accounting for the variation in geomagnetic activity levels under the different solar cycles). The MMS, Themis, and Cluster missions only briefly traverse the radiation belts and do not provide consistent data coverage (Saikin et al., 2015). Furthermore, many data products at various electron energy channels may suffer from proton contamination.

Over the last few decades, significant progress has been made in the development of Kp-driven radiation belts modeling (Beutier & Boscher, 1995; Drozdov et al., 2015, 2017b; Glauert et al., 2014; Ma et al., 2016; Reeves et al., 2012; Shprits et al., 2008a, 2009; Subbotin & Shprits, 2009). Models, like DREAM (Reeves et al., 2012) or the Salammbô electron code (Maget et al., 2006), can incorporate geomagnetic data (i.e., Dst or Kp) as well as data assimilation for satellite missions. Improvements have also been made on the specification of radial diffusion coefficients (Ali et al., 2016; Brautigam & Albert, 2000; Lejosne, 2019; Liu et al., 2016; Ozeke et al., 2014), parameterization of wave properties (Albert et al., 2020; Gu et al., 2012; Orlova & Shprits, 2014; Santolik et al., 2003; Zhu et al., 2019), diffusion coefficients (Summers, 2005; Summers et al., 2007a, 2007b), and plasmapause location (Carpenter & Anderson, 1992; Darrouzet et al., 2013; O’Brien & Moldwin, 2003). There is also a significant progress in understanding the loss processes such as loss to the magnetopause driven by outward radial diffusion (Shprits et al., 2006b) and magnetopause shadowing losses (Herrera et al., 2015). These advances in modeling wave-particle interactions, Kp-driven radiation belt modeling, and the plasmapause location provide us the knowledge of how the radiation belts dynamics operate and gives us an opportunity to simulate the radiation pre1986 (solar cycle 22) using only a single geomagnetic index, Kp. Historical measurements of Kp began in 1932 (i.e., end of solar cycle 16), prior to the discovery of the radiation belts. This Kp data set, along with the progress in radiation belt modeling allows us to examine how energetic or relativistic electron populations behaved under varied geomagnetic conditions and several solar cycles.

Previous 3D radiation belt simulation studies generally fall into two time periods: case studies (e.g., such as modeling the radiation belts during a geomagnetic storm) (Glauert et al., 2014; Ma et al., 2016, 2018; Shprits et al., 2016), or long-term (i.e., multiple months or years) (Drozdov et al., 2015, 2017b; Glauert et al., 2018; Maget et al., 2006; Miyoshi et al., 2004; Ozeke et al., 2018; Subbotin et al., 2011b). Current long-term efforts have focused on simulating the radiation belts from relatively recent or contemporary missions (e.g., CRRES, Van Allen Probes, GOES, etc.). Other studies have employed the use of extreme value analysis to predict how energetic the radiation belts may become using primarily geomagnetic indices (Bernoux & Maget, 2020; Koons, 2001) or data observations (Meredith et al., 2015, 2017).
Recent success in simulating electrons within the radiation belt has been found utilizing the Versatile Electron Radiation Belt (VERB) code (Shprits et al., 2016). Through the incorporation of $K_p$-driven models of radial, pitch angle-energy, and mixed-term diffusion coefficients, the VERB-3D code has successfully reproduced the general dynamics of the radiation belts from both CRRES and the Van Allen Probes missions (Drozdov et al., 2015, 2017b; Shprits et al., 2008a, 2008b; Subbotin & Shprits, 2009; Subbotin et al., 2011b). VERB-3D has also been used to model extreme storms, such as the 2003 Halloween storm (Shprits et al., 2011). Most recently, VERB-3D has been extended to the ultra-relativistic energies which is required to account for electromagnetic ion-cyclotron (EMIC) wave scattering (Drozdov et al., 2017b). In this study, we utilize the VERB-3D code with the historical $K_p$ measurements to perform a reconstruction analysis of the radiation belts from solar cycles 17 to 24 (1933–2017). This reconstructive simulation allows us to explore how the radiation belt dynamics vary under different solar cycle activity levels. The reconstruction of the radiation belt fluxes will allow us to compare across the solar cycles and will allow us to understand how recent Van Allen Probes measurement can be compared to previous missions.

The longest long-term simulation of the radiation belts utilized several GOES missions and encompassed 1986 until 2015 (solar cycles 22–24) (Glauert et al., 2018). Glauert et al. (2018) inferred electron phase space density (PSD) from the GOES observations and interpolated it to their upper boundary condition (at $L^* = 6.1$). From there, the data was incorporated into a simplified version of British Antarctic Survey Radiation Belt Model (BAS-RBM) (Glauert et al., 2014) that ignores mixed terms. However, the reliance on data observations from the GOES missions limits the historical time period (i.e., presolar cycle 22) available to examine due to lack of an upper radial boundary condition. In this study, we utilize machine learning (ML) tools to construct an upper boundary condition based on data observations. With its $K_p$-dependency, the VERB-3D code can simulate the radiation belts independently of mission observations (i.e., before solar cycle 22) and thus enables the potential exploration of radiation belts previously unexamined or observed.

This study presents a reconstructive model of the dynamics of the radiation belts for solar cycles 17–24 (1933–2017) as simulated by the VERB-3D code to examine how solar cycle variability produces variation in the radiation belts. This manuscript is structured as followed: in Section 2, we discuss the methodology and the used observations and codes. In chapter 3, we validate the nonlinear auto regressive network with exogenous inputs (NARX) results and the VERB-3D code driven by NARX and VERB-3D simulations with the CRRES and Van Allen Probes data to demonstrate that it can successfully reconstruct the general evolution of the fluxes. In Section 4, we show the results from the VERB-3D code simulations for the 87 years, we discuss the implication of our results, and summarize our findings in Sections 5 and 6, respectively.

2. Methodology

2.1. Observations

For this study, we have used observations from three missions to either compare our simulations to (CRRES and the Van Allen Probes) or to help train a neural network used to determine an upper radial boundary condition (GOES-15). The Combined Release and Radiation Effects Satellite (CRRES) was launched in July 1990 and performed an orbit with a perigee and apogee of 1.05 $R_e$, 6.26 $R_e$, respectively, and with an inclination of 18° and orbital period of 9.4 h. Electron measurements from the CRRES mission were taken by the Medium Electron A (MEA) instrument (Vampola et al., 1992) over a logarithmic distribution of energies from 0.15 to 1.58 MeV with a total of 17 channels.

Launched in 2012, the Van Allen Probes are two identical spacecraft which orbited around the Earth with a perigee and apogee of 1.1 and 5.8 $R_e$, respectively. The probes, denoted as A and B, execute highly elliptical, low inclination ($\sim 10^\circ$) orbit with a $\sim 9$ h orbital period. Onboard both probes are both the Relativistic Electron-Proton Telescope (REPT) (Baker et al., 2013) and the Magnetic Electron Ion Spectrometer (MagEIS) (Blake et al., 2013) instruments, which are part of the Radiation Belt Storm Probes-Energetic Particle Composition and Thermal Plasma Suite (RBSP-ECT) (Spence et al., 2013). Both MagEIS and REPT provide measurements of electrons with energies between 20 keV–5.0 MeV and 1.6–$\sim$19 MeV, respectively.

Finally, to train the neural network used to determine the upper radial boundary condition employed in the VERB-3D code simulations, we used the data observations from the Geostationary Operational Envi-
enronmental Satellite-15 (GOES-15). The Energetic Proton, Electron, and Alpha Detector (EPEAD) provided the 1-min measurements of electrons (>0.8 and >2.0 MeV energy channels) at geostationary orbit (6.6 Re). Both the east and west telescope were averaged. To represent the full energy spectrum range, we assumed an exponential nature of the spectrum and used the GOES measurements of the 0.8 and 2.0 MeV energy channel. Then we converted the integral flux to differential flux at the two energies (0.8 and 2.0 MeV) and between them using a linear interpolation of the logarithm of the flux. For each data point we calculated \( L^* \) (using the T89 magnetic field model (Tsyganenko, 1989)). Using the conservation of the first adiabatic invariant \( (\mu) \), we determined the respective energy for each GOES \( L^* \) that corresponded to 1 MeV at the boundary of our simulation \( (L^* = 6.6) \). PSD was calculated from the derived differential flux, assuming a flat PSD profile, for the 1 MeV electrons at \( L^* = 6.6 \). On the outer boundary, we assume a sine function distribution for the pitch angle measurements, obtained by The MAGnetosopheric Electron Detector (MAGED). Our method of determining differential flux and PSD from the GOES-15 mission has similarly proven to be an effective when comparing simulations to observations (Cervantes et al., 2020).

Given the cross-calibration accuracy between the Van Allen Probes and the GOES-15 mission at the higher \( L^* \) shells \( (L^* > 5) \) (Baker et al., 2019b), the use of the GOES-15 measurements to model the upper boundary condition is an appropriate choice. Though the Van Allen Probes measure higher flux values compared to GOES-15 at the same energy channels, on average by a factor of \( \sim 2−3 \), this may only impact our simulation near the \( L^* = 6.6 \) boundary by underestimating flux values.

### 2.2. The VERB-3D Code

The VERB-3D code models the relativistic electrons within the radiation belts by solving the Fokker-Planck equation numerically (Shprits et al., 2008a; Subbotin & Shprits, 2009; Subbotin et al., 2011b). The Fokker-Planck equation encompasses several processes that impact the dynamics of the relativistic electron population. Through wave-particle interactions (i.e., radial transport, local acceleration, or the loss of electrons to the atmosphere), chorus, plasmaspheric hiss, EMIC waves, lightning whistler waves often impact the electron population through a combination of pitch-angle, energy, mixed diffusion, and radial diffusion (caused by ultralow frequency (ULF) waves).

Following Subbotin and Shprits (2012), we solve the 3-D Fokker-Planck equation assuming a single grid configuration of modified adiabatic invariants, \( K = J / \sqrt{8m_0 \mu} \), where \( \mu \) and \( m_0 \) represent the first adiabatic invariant and the electron mass, respectively and \( V = \mu \ast (K + 0.5)^3 \). Since \( K \) is independent of the particle’s energy and \( V \) is only loosely dependent on the particle’s pitch angle, these parameterizations serve as a convenient method for numerical calculations and defining boundary conditions. This approach allows us to avoid the interpolation between numerical grids as was used in earlier VERB-3D simulation and reduces the numerical errors or unstable code behavior (Subbotin & Shprits, 2009). The modified invariants cause the Fokker-Planck equation to take the form:

\[
\frac{df}{dt} = \frac{1}{G \text{CL}} G (D_{LL}) \frac{\partial f}{\partial L} + \frac{1}{G \text{LV}} G \left( (D_{VV}) \frac{\partial f}{\partial V} + (D_{VK}) \frac{\partial f}{\partial K} \right) + \frac{1}{G \text{VK} K} G \left( (D_{VV}) \frac{\partial f}{\partial V} + (D_{KK}) \frac{\partial f}{\partial K} \right) - \frac{f}{\tau} \tag{1}
\]

where \( f \) represents the three-dimensional PSD and \( \tau \) is the electron’s lifetime. Here, \( (D_{LL}) \), denotes the radial diffusion coefficients while \( (D_{VV}) \), \( (D_{KK}) \), and \( (D_{VK}) \) represent the drift and bounce-averaged diffusion coefficients. The required Jacobian transformation from an adiabatic invariant system \( (\mu, J, \Phi) \) is denoted by \( G \left( G = -2\pi B_0 R_E^2 L^2 \sqrt{8\mu m_0} \left( K + 0.5 \right)^3 \right) \). \( R_E \) represents the Earth radius and \( B_0 = 0.3 \) G (the magnetic field on the equator of the Earth’s surface). Finally, \( f/\tau \) is a loss term accounting for losses to the atmosphere and those caused by magnetopause shadowing. Inside the loss cone the lifetime is equal to a quarter of the bounce period and is dependent upon \( L^* \) (see Section 2.3 for more details on the relationship between equatorial pitch angle and bounce period). The location of the magnetopause is calculated from determining the last closed drift shell (LCDS). Using the T89 magnetic field model (Tsyganenko, 1989), the LCDS was calculated for 90° pitch angle particles as a function of \( Kp \). From these data points, we used a linear relationship to describe the position of the LCDS with respect to \( Kp \).
The $Kp$-dependent electromagnetic (DLL$_m$) radial diffusion coefficients derived from Brautigam and Albert (2000) were used in keeping with previous VERB-3D simulation studies (Kim et al., 2011; Subbotin et al., 2011b). Utilizing the $Kp$-dependent radial diffusion coefficients from Ozeke et al. (2014) produces basically identical behavior to the simulations with the Brautigam and Albert (2000) radial diffusion coefficients were derived was limited to $\sim 250$ keV–$\sim 1$ MeV. As will be discussed in Section 2.4, this is a subset of the full energy range (10 keV–10 MeV) used in our simulation. For this reason, results shared in this paper will be limited to energies between (0.5–2 MeV).

This simulation also accounts for the gyro-resonant wave-particle interactions by incorporating parameterizations of waves occurring both inside and outside the plasmasphere. Inside the plasmasphere the simulations include wave-particle interactions from lightning, very low frequency (VLF) transmitter generated whistler waves, and plasmaspheric hiss waves. The diffusion coefficients for hiss waves were based on the recent parameterization by Zhu et al. (2019), while the lightning and VLF generated whistlers were based on Subbotin et al. (2011a). Outside the plasmasphere, chorus waves are used for wave-particle interactions and were parametrized from observations on the dayside or nightside magnetosphere. The wave amplitude and frequency corresponding to chorus waves were based on statistical models from Van Allen Probes measurements (Drozdov et al., 2017a; K. Orlova et al., 2016). Diffusion coefficients obtained from these previous studies were then converted into the modified adiabatic invariants ($V$ and $K$) grid by determining the derivative between the corresponding parameterizations (e.g., $\delta V / \delta \alpha \alpha$, $\delta K / \delta pp$, etc., see below) (Subbotin & Shprits, 2012).

\[
\frac{\delta V}{\delta p} = \frac{\sin \alpha_0 \cos \alpha_0 p^2}{m_i B} \tag{3}
\]

\[
\frac{\delta V}{\delta \alpha_0} = \frac{\sin \alpha_0 \cos \alpha_0 p^2}{m_i B} \left( \frac{Y(\alpha_0)}{\sin \alpha_0} \cdot L\sqrt{B} + C_{grid} \right) + \left[ \frac{Y(\alpha_0)}{\sin \alpha_0} \frac{L\sqrt{B} + C_{grid}}{\sin \alpha_0} - L\sqrt{B} \frac{2T(\alpha_0)}{\sin \alpha_0} \right] \tag{4}
\]

\[
\frac{\delta K}{\delta p} = 0 \tag{5}
\]

\[
\frac{\delta K}{\delta \alpha_0} = \frac{2 \cos \alpha_0}{\sin \alpha_0^2} \cdot L\sqrt{B} \cdot T(\alpha_0) \tag{6}
\]

Here, $p$ is the particle’s momentum, $\alpha$ is the particle’s pitch angle, $\alpha_0$ is the particle’s equatorial pitch angle, is the, $C_{grid}$ is a constant coefficient ($\approx L'T\sqrt{B}$), $Y(\alpha_0)$, and $T(\alpha_0)$ are functions related to the bounce motion (Schulz & Lanzerotti, 1974; Subbotin & Shprits, 2012). Given the spatial distribution and prevalence of EMIC waves (Saikin et al., 2015), their incorporation into electron radiation belt modeling is essential for ultra-relativistic electrons. Efforts on incorporating and parameterizing EMIC waves via solar wind conditions have been performed and were found to increase the accuracy of the VERB-3D code simulations (Drozdov et al., 2017b). Since continuous solar wind observations are available only starting from the 1960s
for certain solar wind or geomagnetic activity parameters, we used the Kp-driven EMIC wave parameterization presented in Drozdov et al. (2017b). In that study, the best agreement with the observations was obtained when EMIC wave amplitude was fixed at 0.1 nT and EMIC driven diffusion was assumed to operate when the Kp index exceeded 2. The inclusion of EMIC waves is considered necessary, especially for multiMeV electrons. Without EMIC waves, our test simulations (not shown) showed dramatic overestimation at multiMeV energies. EMIC waves are assumed to be efficient on the edge of the plasmasphere and in the regions of plasmaspheric plumes. The assumed plasmapause boundary is modeled according to Carpenter and Anderson (1992). Finally, the Full Diffusion Code (FDC) (K. G. Orlova & Shprits, 2011; Shprits & Ni, 2009) was used to calculate average gyroresonant diffusion coefficients for all VLF and ELF waves.

2.4. Initial Conditions and Parameters

We performed a single continuous simulation beginning on January 1, 1933 (i.e., solar cycle 16), several months before the formal start of solar cycle 17 (September 1933), and ending in December 2017 (end of solar cycle 24). The total simulation period covers solar cycles 17–24 (i.e., 86 years). The January 1, 1933 simulation start date was chosen to avoid the simulation being affected by and to allow the code to spin up and “forget” the initial conditions (e.g., Shprits et al., 2013). An hour was used as the timestep in the simulation, with the results at the end of a 24-h period being saved.

All simulations were performed on an orthogonal grid of size $29 \times 62 \times 61$ points for $L$, $V$, and $K$, respectively. The range in $L$ was confined from 1.0 to 6.6. Note, that Equation 1 is written in terms of $L$ which represents the third adiabatic invariant. However, to define the boundary condition we use $L^*$ (Roederer, 1970) as a more accurate representation of the third adiabatic invariant in a nondipole field. Also, the LCDS parameterization uses $L^*$. The initial conditions are calculated assuming a steady state solution for the radial diffusion equation. The boundary conditions are set at $L^* = 6.6$ for energies from 10 keV to 10 MeV and pitch angles from 0.7°–89.3°, respectively. $K$ is defined as $K = 0$ MeV/G at the equator. The $L^*$ and pitch angle ($K$) grid points are distributed linearly, while the $V$ grid points are distributed on a logarithmic scale.

The lower $K$ boundary condition denotes the losses within the loss cone and does not represent the loss cone proper. Effective loss in the loss cone is simulated through the $\dot{f}/r$ term. PSD is set to zero while the upper $K$ boundary condition is set to a zero-gradient PSD (which represents a flat distribution at 90°). PSD at the upper $V$ boundary is set to zero while PSD at the lower $V$ boundary is set to an initial value and remains constant representing the steady state balance between sources and losses of the low energy population. While the VERB code simulation does not incorporate convection, previous studies have shown that a lower energy boundary condition set at ~tens of keV has little effect on radiation belt electrons (Castillo et al., 2019; Subbotin et al., 2011a). The lower boundary condition in $L^*$ is set to zero to represent losses to the atmosphere.

3. Simulations of the Kp Dependent Boundary Condition

To perform long-term simulations, we need to set up an upper boundary condition in $L^*$. Usually such a boundary is set up based on the observations by GEO spacecraft, radiation belt fluxes, and ring current. However, continuous observations of the radiation belts are not available before the 1980s. To determine an upper boundary condition that could be used over the course of the 86-year simulation period, we developed and validated an empirical model based on Kp, NARX. NARX is a ML algorithm designed for time series using both the current and past time step inputs to determine the current and future outputs (Ayala Solares et al., 2016). The time history is automatically incorporated into NARX and therefore does not require the additional construction of time series for historical values as additional inputs. An alternative neural network, a feed forward network, was considered for the purpose of developing an upper boundary condition. However, the feed forward network has not performed as well as NARX for the purposes of this study. Another method, the nonlinear autoregressive moving average modeling (NARMAX) has been used to perform similar studies (Balikhin et al., 2011). However, we have elected to use NARX. Following Brautigam and Albert (2000) we assume that the shape of the spectrum at GEO does not change in time and is constant. Therefore we use and train NARX to obtain a scaling factor that can be multiplied by an average spectrum at GEO $J(E, L = 7)$ (Shprits et al., 2006a; Subbotin & Shprits, 2009; Subbotin et al., 2011b)
to obtain a variable outer boundary condition normalized scaling factor (Bf). It is assumed that the flux at \( L^* = 6.6 \) is given by \( J_{\text{model}} \text{(GEO)} = J_{\text{averaged (at GEO)}} \times Bf \).

To train NARX and determine the normalized scaling factor (bf), we used 1 MeV electrons flux obtained from the GOES-15 measurements, as described in Section 2.1, over the period from January 2011 to March 2014. The normalized scaling factor is calculated using Equation 7 in Subbotin et al. (2011b) using the local 90° pitch angle particles. These scaled flux values were used as a training data set for NARX. The corresponding \( Kp \) measurements during this period were provided as a driver for the empirical model. In keeping with the VERB code's timestep (1 h), the 1-min resolution NARX derived bf was averaged into 1-h steps.

The NARX network parameters consists of feedback delay (how many previous time steps are used to determine the new target data, i.e., the upper boundary condition), and the input delay (how many previous time steps are used for the input data i.e., \( Kp \)). A total of 20 networks were trained based on varying the feedback and input delay. The training input was separated into three groups with 60%, 20%, and 20% of the input used for training the NARX network, validation, and testing, respectively. On the training step we train various models with various hyper parameters. The testing step is used to select the best performing model while the validation set is used to determine the accuracy of the trained model. After six iterations where the network performance decreases when compared to the validation set, the network stops training and reverts to the weights and biases associated with the set before the six iterations. The best performing network by correlation coefficient (0.53) was used for our simulations. The feedback and input delay used for the best performing network were 80- and 24-time steps (with each step consisting of 1 h), respectively.

The training, validation, and testing data sets spanned from January 1, 2011 to March 12, 2014, March 13, 2014 to November 17, 2014, and November 18, 2014 to July 25, 2015, respectively.

Figure 1 shows the \( Kp \) index and the comparison between the normalized Bf (upper boundary condition) index modeled by NARX (blue) and the Bf derived from the CRRES (orange) observations (b).

Figure 1. The \( Kp \) index (a) and the comparison between the normalized Bf (upper boundary condition) index modeled by NARX (blue) and the Bf derived from the CRRES (orange) observations (b).
Furthermore, between December 24, 1990 and July 13, 1991 there is a data observation gap in the CRRES data set, hence there is no corresponding CRRES Bf value during that time. This period also coincided with an interplanetary shock induced superstorm on March 24, 1991 (Kellerman et al., 2014), which is represented by the extremely high Bf values (>5). Note, the period shown in Figure 1 does not overlap with the training, testing, and/or validation data set and is being used to demonstrate how well the NARX derived Bf can be used to simulate previous time periods independent of available observations.

3.1. Comparisons With Observations: CRRES and Van Allen Probes

To instill confidence in our simulations, we have compared their results to observations taken by these two missions (CRRES and the Van Allen Probes) during two different solar cycle periods (solar cycles 22 and 24). Figures 2 and 3 show the results and comparisons of the 1 MeV electrons for the CRRES and Van Allen Probes missions. For completeness, the difference comparisons between the 0.5, 1.0, and 2.0 MeV electrons can be found in the supplementary materials (Figures S2–S7).

Figure 2 shows CRRES measurements (panel a) of the 1.0 MeV, 85° pitch angle electrons and compares them to the VERB-3D simulation outputs for the same particle population (panel b) during the same 1-year long period (August 1, 1990–July 31, 1991). Figures 2c and 2d shows the measured Kp and Dst values observed during the same time period. Here, CRRES data has been averaged into daily bins for easy comparison with the VERB simulations. This period coincided with when solar cycle 22 was at its peak strength (see Figure 4f). With respect to the times and \( L^* \) range \((L^* = 3.6–5.8)\), the VERB 3D simulations can reproduce...
when the radiation belts should become enhanced. During these enhancement periods, the VERB 3D simulations fall within an order of magnitude ($<10^7$ #/sr/keV) when compared to the CRRES observations (Figure S3). The VERB-3D NARX simulation performs well when having to account for enhancements (e.g., July 31–August 7, August 24–August 28, October 12–October 22, 1990, each starting time denoted by a black dashed line) and dropouts (e.g., February 20, 1991 at $L^* = 6.6$, denoted by the white dashed line). However, decreases in the electron flux produced by the simulation, generally, are not as sharp as compared to the CRRES observations (e.g., December 20–30, 1990, February 1991, see Figures S8–S10 for a flux comparison between CRRES and the VERB simulation at given $L^*$). The aforementioned interplanetary shock-induced superstorm on March 24, 1991 caused electrons and protons to be accelerated into the inner radiation belt, forming a new radiation belt in the time frame of a few minutes (Blake et al., 1992; Kellerman et al., 2014; Li et al., 1993). During this same period, the VERB-3D simulation replicates the deep enhancement signature ($L^* = \sim 3.0–\sim 5.5$) as well as the low $L^*$ ($L^* = 2.5$) enhancement observed in the CRRES measurements (granted high energy particle contamination contributed to the prolonged low $L^*$ signature observed in the CRRES data set). There is some overestimation of fluxes during February–March 1991 (see also Figures S8, S9, and S10) when $Kp \leq 6$. (possibly caused by lower $Kp$ values not triggering our LCDS condition). During the periods of peak enhancements, the VERB-3D simulation is usually within one order of magnitude of the observations. Furthermore, the $L^* = \sim 2.5$ belt signature caused by the March 24, 1991 geomagnetic storm (Figure 2a) is due to contamination and was not included in the calculation of the normalized difference.

Unlike the active solar cycle 22, the Van Allen Probes missions coincided with the much less active solar cycle 24 (i.e., 2012–2019) (Saikin et al., 2016). A comparison of the peak sunspot values shows that solar cycle 24 was nearly half as strong as solar cycle 22 (~140 vs. 250, respectively). Despite these weaker sunspot

**Figure 3.** Same format as Figure 3, except showing the comparisons between the 1 MeV 85° pitch angle electrons measured by Van Allen Probe-A (panel a) and the VERB-3D simulation during the same period (panel b).
numbers, enhancements in the 1.0 MeV electron fluxes are still observed both by Van Allen Probe-A (Figure 3a) and the VERB-3D simulations (Figure 3b) during the 2013–2017 period. The Van Allen Probes data in Figure 3 has also been averaged into daily bins. Van Allen Probe-A observations of the radiation belts show significant ($\sim 10^4$) flux enhancements between $L^* = 3.5\sim6$. The VERB-3D simulations does produce flux signatures ($\sim 10^1\sim10^2$) below $L^* = 3$. However, flux values observed by Van Allen Probe-A below $L^* = 3$ are comparatively low (<$10^1$ #/sr/s/cm$^2$/keV). Here the VERB-3D simulation appears to underestimate fluxes when compared to the Van Allen Probes observations but are still within an order of magnitude ($\sim 10^1$ #/sr/s/cm$^2$/keV) during the peak enhancement periods. As described above, both the CRRES and Van Allen Probes data observations have been daily averaged. This averaging may lead to a general variation reduction over the course of the daily average. However, this does not affect the overall comparison between the VERB simulation and the CRRES and Van Allen Probes observations.

Provided in the supplementary materials are a series of line plots which compare the VERB simulated fluxes at $L^* = 4, 5,$ and 6 for electron energies 0.5, 1.0, and 2.0 MeV 85° pitch angle particles compared to their respective CRRES and Van Allen Probes observations (Figures S8–S13). With each line plot comparison in Table S1 are their corresponding correlation coefficients (both the Spearman rank correlation coefficient (RCC) and the correlation metric used by Balikhin et al. [2016]). Over the time scales for both missions, the VERB code simulation (as shown in Table S1) does correlate well with the Van Allen Probes and CRRES observations with values generally falling between 0.14 and 0.86 (Spearman RCC) and 0.00–0.81 (Balikhin et al., 2016), with the highest correlations being found at $L^* = 4$ and $L^* = 5$ while the lowest correlations are found at $L^* = 6$ for all energies. Though the correlations at $L^* = 4$ are the highest among all energies for both missions, the simulation does not accurately reproduce the extended decay observed during the CRRES mission (1 and 2 MeV). Given the need to scatter electrons, improvements in wave-modeling are required for future study. Conversely, the correlation at $L^* = 6$ for both missions comprise the lowest values. These correlations at the higher $L^*$ may be more directly influenced by the NARX derived upper boundary condition than compared to the correlations at $L^* = 4$ and $L^* = 5$. The same is true when comparing to the Van Allen Probes era with a notable exception. The Van Allen Probes do not consistently observe $L^* = 6$ which may further cause the lower correlation values. The Van Allen Probes only have 55.97% of data observation which overlap with the reconstruction at $L^* = 6$. 

Figure 4. Monthly median $Kp$ (blue) and sunspot number (orange) observed over solar cycles 17–24 (panels a–h, respectively). The monthly median $Kp$ range (light blue) and the maximum $Kp$ value (gray) per month are also overplotted.
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The assumed spectrum shape at the outer boundary may also induce more errors for the 2 MeV simulations. The over or underestimation of electron fluxes may be attributed to the simplified description of the plasmasphere. Wave excitation and wave-particle interactions are strongly affected by the cold plasma density. Plasma density changes the resonance condition for the interactions and controls the efficiency of the pitch angle and energy scattering. Furthermore, the assumed spectrum shape at the outer boundary may also induce more errors for the 2 MeV simulations. Incorporating future work on the role of EMIC waves as a source mechanisms of multiMeV electrons may alleviate this simulated flux discrepancy.

4. VERB-3D Simulations

4.1. Overview: Solar Cycles 17–24

Figure 4 shows the combination of the monthly observed sunspot number (orange), the monthly median Kp (blue), and the median Kp range (i.e., the monthly median of the monthly maximum and monthly minimum Kp values) (light blue) over the course of solar cycles 17–24 (panels a–h, respectively). Also included, for comparison, are the maximum observed monthly Kp values in gray. Table 1 lists the start and end times for each solar cycle covered in this study. Each solar cycle lasts between 120 (i.e., solar cycle 22) and 150 (i.e., solar cycle 23) months.

Solar cycle activity varies in strength from cycle to cycle. Table 2 shows the total number of sunspots observed over the entire solar cycle. Solar cycle 19 had the highest total number of sunspots (~1.6 × 10^8) while solar cycle 24 has the lowest number of sunspots (~6.5 × 10^7). Of the eight solar cycles examined in this reconstruction simulation, solar cycle 24 is the only cycle observed with less than 10^8 sunspots, roughly a ~50% decrease in solar cycle activity compared to the other cycles. Furthermore, solar cycle 24 had the lowest median Kp value (1.3) of all the cycles indicating that solar cycle 24 was also the least geomagnetically active solar cycle. This weaker geomagnetically active solar cycle has been considered the cause of a less enhanced radiation belts (Li et al., 2017; Morley et al., 2017; Rodger et al., 2016).

4.2. Simulation Results

Figures 5–7 show the results from these VERB-3D simulations with the Kp derived NARX boundary condition for the 0.5, 1, and 2 MeV 85° pitch angle electrons for solar cycles 17–24 (panels a–h, respectively) as a function of L* and time. Each panel covers the range L* = 1–6.6. Despite variable solar cycle time durations, each cycle produces numerous enhancements in the electron fluxes (up to 10^5 #/sr/s/cm²/keV for the 0.5 and up to 10^8 #/sr/s/cm²/keV for 1.0/2.0 MeV electron energies, respectively). Notably, during the end of solar cycle 23 (i.e., April 2008–December 2008) and the beginning of solar cycle 24 (i.e., January 2009–March 2010) the simulation does not produce any electron flux enhancements on the order of 10^7 for the 1.0 and 2.0 MeV electron energy simulations. This “electron desert” has been attributed to weak geomagnetically active period (Kataoka & Miyoshi, 2010) coinciding with a very weak solar minimum between solar cycles 23 and 24 (Ryden et al., 2015).

The enhanced flux signatures below L* = 3 (particularly for the 0.5 and 1 MeV electron fluxes) are caused by the radial diffusion parameterization at high Kp values. At high Kp, the radial diffusion coefficients increase significantly (Brautigam & Albert, 2000; Miyoshi et al., 2004) causing particles to become transported into the lower L shells. These low L* belts subsequently decay due to plasmaspheric hiss and the lightning generated whistlers waves as the plasmasphere replenishes and expands after the high geomagnetic activity subsides. However, our parameterization of hiss and lighting generated whistlers waves may be too weak to

### Table 1
**Solar Cycle Start and End Dates**

<table>
<thead>
<tr>
<th>Solar cycle</th>
<th>Start date</th>
<th>End date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar cycle 17</td>
<td>September 1933</td>
<td>February 1944</td>
</tr>
<tr>
<td>Solar cycle 18</td>
<td>March 1944</td>
<td>April 1954</td>
</tr>
<tr>
<td>Solar cycle 19</td>
<td>May 1954</td>
<td>October 1964</td>
</tr>
<tr>
<td>Solar cycle 20</td>
<td>November 1964</td>
<td>March 1976</td>
</tr>
<tr>
<td>Solar cycle 21</td>
<td>April 1976</td>
<td>September 1986</td>
</tr>
<tr>
<td>Solar cycle 22</td>
<td>October 1986</td>
<td>August 1996</td>
</tr>
<tr>
<td>Solar cycle 24</td>
<td>January 2009</td>
<td>August 2019</td>
</tr>
</tbody>
</table>

### Table 2
**Total Sunspots per Solar Cycle Organized in Descending Order**

<table>
<thead>
<tr>
<th>Sunspot number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar cycle 19</td>
</tr>
<tr>
<td>Solar cycle 21</td>
</tr>
<tr>
<td>Solar cycle 18</td>
</tr>
<tr>
<td>Solar cycle 22</td>
</tr>
<tr>
<td>Solar cycle 23</td>
</tr>
<tr>
<td>Solar cycle 17</td>
</tr>
<tr>
<td>Solar cycle 20</td>
</tr>
<tr>
<td>Solar cycle 24</td>
</tr>
</tbody>
</table>
completely scatter these low $L^*$ ($<3$) electrons. Low $L^*$ electrons have also been observed in other simulation studies (Maget et al., 2006; Miyoshi et al., 2004). As these injections are not the focus of this study, it remains unclear if all of these low $L^*$ belts are realistic, but it shows that conditions may often occur for the creation of such belts and that they are not frequently observed during the Van Allen Probes era. At higher

**Figure 5.** The VERB-3D simulation results for the evolution of electron dynamics over the course of solar cycles 17–24 (panels a–h, respectively) for the 0.5 MeV 85° pitch angle particles as a function of time (a daily cadence) and $L^*$.

**Figure 6.** Same format as Figure 3, except showing the VERB-3D simulation results for the 1.0 MeV 85° pitch angle particles.
energies (i.e., 2.0 MeV), EMIC waves play a more prominent role in the scattering of electrons (Drozdov et al., 2017b; Shprits et al., 2013; Zhang et al., 2016) and hence are not as effective at scattering the lower energy (0.5 and 1.0 MeV) electrons at the lower $L^*$. To showcase how the variation of the sunspot number and hence, the variation of $Kp$ impacted the simulations shown in Figures 5–7, Figure 8 present histograms of the total integrated, over the entire simulated radiation belt ($L^* = 2–6.6$), 85° pitch angle electron flux (Figure 8) for each of the three energies (0.5, 1, and 2 MeV) and each solar cycle. Figure 9 is another histogram that shows the peak simulated electron flux values (across all $L^*$) in the same format. Most of the histograms presented take the form of a single peak distribution, specifically solar cycles 17–22 for all three energies, also the 0.5 and 1.0 MeV energy electrons for solar cycle 23. Concerning the total integrated flux and starting with the 2.0 MeV solar cycle 23 electrons, there is a long tail distribution for the high fluxes. For solar cycle 24, at all energies, there is a double peak distribution that is, shifted toward the lower values while also covering a wider range of flux values. During these last two solar cycles, the median fluxes observed also is lower than for other cycles (Table 3). Furthermore, the 95th and 98th percentile flux (Tables 4 and 5, respectively) observed in solar cycle 24 is also the lowest among the considered solar cycles. This is reflected in the peak electron flux value histograms (Figure 9). Solar cycles 23 and 24 have the lowest median, 95th, and 98th percentile peak flux values (Tables 6–8, respectively).

Table 9 shows the first and second moments for each of the integrated flux distributions. Except for solar cycle 24, the first moment values for all the solar cycles are very similar. The first moment values for solar cycle 24 tend to decrease by 10$^{0.2–0.4}$ (depending which energy flux) compared to the next highest value. Similarly, the second moments associated with these distributions also show a decrease from solar cycles 22 to 24.

Figure 10 shows the respective percentiles (5th, 10th, 25th, 50th, 75th, 90th, 95th) for the total integrated fluxes for each of the solar cycles and over the three energy spectrums. As observed in Figures 8 and 9 and Tables 3–8, there is a distinct drop in flux over each percentile for solar cycle 23 and 24 compared to the previous cycles. Furthermore, the VERB-3D simulations show that the weaker flux values for solar cycles 23 and 24 also appears over the three different energies (0.5, 1.0, and 2.0 MeV).
Throughout our entire 85-year reconstruction, peak flux enhancement occurs at different times for different energy values. The highest values of total integrated flux occurred during the geomagnetically intense period of March 29, 1946 for the 0.5 and 1.0 MeV electrons and on September 6, 1957 for the 2.0 MeV electrons. The highest singular peak enhancement also occurred during these periods: 0.5 and 2.0 MeV electrons (September 6, 1957) and 1.0 MeV electrons (March 29, 1946). The radiation belt reconstruction for these time periods can be found in the supplementary materials as Figures S14 (March 29, 1946) and S15 (September 6, 1957).

5. Discussion and Conclusion

In this study, we have presented a reconstructive simulation of the radiation belts from solar cycles 17 to 24 (1933–2017) using the VERB-3D code and the historical Kp measurements. Our simulations relied on
the construction of an upper boundary condition produced by a NARX algorithm and $K_p$-driven statistical diffusion coefficients. The 1 MeV electrons obtained from the GOES-15 measurements were used to train the neural network along with the observed $K_p$ values. Simulations of VERB-3D with the NARX boundary condition were validated for 5 years of the Van Allen Probes and 1 year of CRRES observations. Using this NARX upper boundary condition (the Bf scaling), we conducted simulations for solar cycles 17–24 (Figures 5–7) and presented the selected energies 0.5, 1.0, and 2.0 MeV electrons using the historical measurements of $K_p$.

The comparisons of modeled and observed fluxes showed that the VERB-3D simulations were able to reproduce the amplitudes of flux intensifications, dropouts, the general evolution of fluxes and spatial distributions of radiation belt fluxes within an order of magnitude.

However, while the timing of dropouts is reproduced, the simulation does not scatter enough electrons to accurately match the observed electron flux of both CRRES and the Van Allen Probes during dropouts. This

**Figure 9.** Histograms for the distribution of peak simulated flux values for the 0.5 (blue), 1.0 (green), 2.0 (red) MeV energies over all solar cycles.
may be attributed to our LCDS criteria requiring a $Kp$ value $\geq 5.7$. A lower $Kp$ threshold would produce more losses and could potentially better reflect the Van Allen Probes and CRRES observations. Conversely, since the VERB code is $Kp$-driven, lower $Kp$ values would not produce the higher flux values observed during solar cycles 17–23.

Using the Van Allen Probes during a case period of February 24–March 31, 2013 Fennell et al. (2015) found that MeV electrons were not observed in the inner radiation belt despite coinciding with the two geomagnetic storms within that time frame. Our VERB simulation results during the Van Allen Probes era show some low $L^*$ electron signatures ($\sim < 10^2 \#/$ sr/s/cm$^2$/keV).

These simulations revealed the evolution of the radiation belts over an 85-year period and, for the first time, allow a consistent comparison between the solar cycles. Solar cycles 17–22 were simulated to be consistently active and boasted the higher average values of median fluxes per energy and the observed sunspot number. However, solar cycle 24 was found to coincide with a significantly less active solar cycle ($\sim$45–60% decrease in sunspots than the next weakest and strongest solar cycles, respectively) and estimated the lowest average median flux values for all three energies examined among all considered solar cycles.

### 5.1. The Importance of Solar Cycle Activity

We also examined the activity levels of the solar cycles themselves by exploring both the $Kp$ values and the observed sunspot number (Figure 4) from cycle to cycle. Each cycle lasts at least 120 months, with the longest cycle (solar cycle 23) lasting around $\sim$150 months. Despite lasting the longest, solar cycle 23 does not feature the highest overall number of sunspots over the course of the cycle. Conversely the most active cycle, solar cycle 19, is also one of the shorter cycles at $\sim$128 months.

For solar cycles 23 and 24, median flux values are substantially lower for all three electron energies examined. Solar cycle 24 coincides with the lowest median flux values and the lowest number of sunspots for all solar cycles by a significant margin (Table 2). This is also reflected in the median $Kp$ values observed during each solar cycle (Table 10). Solar cycles 23 and 24 are the only cycles to have a $Kp$ median value less 2.0. Since the VERB code is primarily $Kp$-driven, this would produce lower flux values compared to the Van Allen Probes measurements. Conversely, the median $Kp$ value during solar cycle 22 was 2.3 (one of the highest among all solar cycles) which may cause the VERB code to overestimate fluxes compared to the CRRES measurements.

Unlike the previous solar cycles, solar cycle 24 has been characterized both by the lowest sunspot numbers and the least enhanced radiation belts. This further coincides with the observations that solar cycle 24 has had not only fewer geomagnetic storms than previous solar cycles, but also fewer intense geomagnetic storms (Dst $< -100$ nT) (Watari, 2017). Despite the double peak distribution of storm intensity and frequency (Gonzalez et al., 1994; Le et al., 2012), a less active solar cycle would produce fewer and weaker geomagnetic storms throughout the entire cycle (Saikin et al., 2016). With fewer and weaker storms, there are less events that could cause enhancements in the radiation belts. This may explain the significant drop in median flux for the 0.5, 1.0, and 2.0 MeV electrons produced in our simulations. Similar conclusion have been made after examining 2 MeV electrons observed by SAMPEX (1992–2012) and the Van Allen Probes (2012–2016) (Li et al., 2017).

Another study, Glauert et al. (2018), performed a 30-year simulation (solar cycle 22–24) and examined the radiation belts for the 0.8 and 2.0 MeV electrons using data observations from the GOES missions and the BAS-
Table 5
Logged 98th Percentile Flux (#/sr/s/cm²/keV) per Solar Cycle and Energy

<table>
<thead>
<tr>
<th>Solar Cycle</th>
<th>0.5 MeV</th>
<th>1.0 MeV</th>
<th>2.0 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar cycle 17</td>
<td>4.776</td>
<td>4.354</td>
<td>3.925</td>
</tr>
<tr>
<td>Solar cycle 18</td>
<td>4.849</td>
<td>4.433</td>
<td>3.970</td>
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<td>Solar cycle 19</td>
<td>4.846</td>
<td>4.470</td>
<td>4.030</td>
</tr>
<tr>
<td>Solar cycle 20</td>
<td>4.743</td>
<td>4.317</td>
<td>3.833</td>
</tr>
<tr>
<td>Solar cycle 21</td>
<td>4.800</td>
<td>4.369</td>
<td>3.888</td>
</tr>
<tr>
<td>Solar cycle 22</td>
<td>4.828</td>
<td>4.422</td>
<td>3.964</td>
</tr>
<tr>
<td>Solar cycle 23</td>
<td>4.749</td>
<td>4.332</td>
<td>3.885</td>
</tr>
<tr>
<td>Solar cycle 24</td>
<td>4.577</td>
<td>4.088</td>
<td>3.472</td>
</tr>
</tbody>
</table>

Table 6
Logged Median Peak Flux (#/sr/s/cm²/keV) per Solar Cycle and Energy

<table>
<thead>
<tr>
<th>Solar Cycle</th>
<th>0.5 MeV</th>
<th>1.0 MeV</th>
<th>2.0 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar cycle 17</td>
<td>3.231</td>
<td>2.856</td>
<td>2.340</td>
</tr>
<tr>
<td>Solar cycle 18</td>
<td>3.363</td>
<td>2.978</td>
<td>2.534</td>
</tr>
<tr>
<td>Solar cycle 19</td>
<td>3.332</td>
<td>2.960</td>
<td>2.467</td>
</tr>
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<td>Solar cycle 20</td>
<td>3.236</td>
<td>2.839</td>
<td>2.312</td>
</tr>
<tr>
<td>Solar cycle 21</td>
<td>3.346</td>
<td>2.973</td>
<td>2.474</td>
</tr>
<tr>
<td>Solar cycle 22</td>
<td>3.335</td>
<td>2.947</td>
<td>2.461</td>
</tr>
<tr>
<td>Solar cycle 23</td>
<td>3.149</td>
<td>2.732</td>
<td>2.168</td>
</tr>
<tr>
<td>Solar cycle 24</td>
<td>2.930</td>
<td>2.536</td>
<td>1.979</td>
</tr>
</tbody>
</table>

RBM. Instead of using a neural network, Glauert et al. (2018) derived their upper radial boundary condition \((L^* = 6.1)\) from the GOES observations. Also, Glauert et al. (2018) does not include mixed diffusion terms in their simulations, which would yield more scattering of electron.

Despite using different methods to produce our simulations (especially the upper radial boundary condition), both our simulations and the work by Glauert et al. (2018) are consistent during the overlapping period (1986–2015). For example, similar to Glauert et al. (2018), during (1986–2015) we observe that peak flux values for the 2.0 MeV electrons are on the order of \(10^8 \text{#/sr/s/cm²/keV}\). Furthermore, the timing of these enhancements is consistent, and the general evolution looks very similar. For example, one peak intensification event occurring during February–May 1994 is recreated both with our VERB-3D simulations and Glauert et al. (2018). Our peak value for the 2.0 MeV electrons during this peak Glauert et al. (2018) period was \(1.55 \times 10^8 \text{#/sr/s/cm²/keV}\) on April 18, 1994. For comparison, over the course of the 85 year reconstruction, the highest peak value of the 2.0 MeV electrons was \(3.77 \times 10^7 \text{#/sr/s/cm²/keV}\) (6 September 1957). Likewise, the radiation belts are unusually low during the year 2009 (i.e., the beginning of solar cycle 24).

One difference in our results compared to the Glauert et al. (2018) study is that in their 30-year simulation, they do not observe any low \(L^*\) belts. The low \(L^*\) injections of electrons are observed during periods of high \(Kp\) values, but they are relatively quickly scattered away afterward. This may be attributed to the initial condition set by Glauert et al. (2018) setting the PSD equal to \(L^* = 2\) as a boundary condition. This condition ensures that no flux intensifications are observed below \(L^* = 2\) and that strong losses would occur near \(L^* = 2\). Furthermore, differences in the derivation of the diffusion coefficients for plasmaspheric hiss waves used by Glauert et al. (2018) and this study would also yield different results. As previously discussed, it is unclear whether the low \(L^*\) belts we simulate are realistic and therefore requires further study.

Using NOAA satellites, Miyoshi et al. (2004) also examined how variations in the solar cycle affected the enhancement of the radiation belts for the period of 1979–2003 (i.e., solar cycles 21–23). While the focus of their study was to model and simulate 300 keV electron fluxes during those two solar cycles, they found a dependence with respect to ascending and descending solar cycle phase and that the location of maximum electron flux shifted to lower \(L^*\) values during active geomagnetic periods. The decrease in electron flux at the lower \(L^*\) shells was attributed to weaker radial diffusion as well as the expanding plasmapause during the geomagnetic quiet periods. Our results are consistent with their assessment as during periods of high \(Kp\) and minimum Dst, the VERB code simulation produces electron flux at lower \(L^*\) shells. The low \(Kp\) values, but they are relatively quickly scattered away afterward. This may be attributed to the initial condition set by Glauert et al. (2018) setting the PSD equal to \(L^* = 2\) as a boundary condition. This condition ensures that no flux intensifications are observed below \(L^* = 2\) and that strong losses would occur near \(L^* = 2\). Furthermore, differences in the derivation of the diffusion coefficients for plasmaspheric hiss waves used by Glauert et al. (2018) and this study would also yield different results. As previously discussed, it is unclear whether the low \(L^*\) belts we simulate are realistic and therefore requires further study.

Throughout all solar cycles, numerous enhancements in electron flux are observed with peak flux values on the order of \(10^8 \text{#/sr/s/cm²}\) (depending which energy level and solar cycle you examine). The prediction and existence of these possible “extreme” enhancement events has been discussed previously in Koons (2001). In that study, Koons (2001) used GOES data from January 1986 to August 1999 to examine the probability distribution of >2 MeV electrons at geosynchronous orbit. While we do not focus explicitly on the “>2 MeV” GOES electron channel nor geosynchronous orbit in this study, Koons (2001) found that an electron flux \(6.78 \times 10^4 \text{#/sr/s/cm²}\) corresponded to a once in a 10 year event. Our 95th percentile total integrated flux plots for the 0.5 and 1.0 MeV energies channels (Figure 10) nearly overlaps with the Koons >2 MeV extreme value analysis for certain solar cycles. Similarly, another study examining several GOES missions (8, 9, 10, 11, 12, 13, and 15) observations of ex-
between our peak flux events and those determined as the most geomagnetically active by Bernoux and Maget (2020). Some events are featured on both our lists (e.g., October 31, 2003, March 14, 1989, September 20, 1941, March 3, 1946, March 3, 1940, and November 10, 2004) with each of them being considered a once in a 75, 37.5, 30, 25, and 11.5 year event, respectively. However, the events where we observe the highest 0.5 and 2.0 MeV electron flux (e.g., September 6, 1957, March 29, 1946, and June 20, 1941) are not featured on the list compiled Bernoux and Maget (2020). Using the POES15 satellite, Bernoux and Maget (2020) found that the correlation between Ca and convoluted flux, as a function of L shell, for energies >30 keV hovered around ~0.8 while >900 keV energies was consistently <0.4. Bernoux and Maget (2020) conclude that for their parameterization, Ca may not be perfectly correlated with the dynamics of electrons at any energy. This may explain why certain peak flux periods that the VERB code simulated at 0.5 or 2.0 MeV do not appear on Bernoux and Maget’s most intense list.

### 5.2. Summary and Future Work

Using the Van Allen Probes during a case period of February 24–March 31, 2013, MeV electrons were not observed in the inner radiation belt despite coinciding with the two geomagnetic storms within that time frame (Fennell et al., 2015). Our VERB simulation results during the Van Allen Probes era show some low L* electron signatures (~<10^2 #/sr/s/cm²/keV). Conversely, our results for the 0.5 MeV electrons under produces compared to both the Van Allen Probes and CRRES observations. Given that the simulation results tend to over/underestimate electron fluxes at the lower boundary of the radiation belts for a given energy, a more accurate parameterization of plasmaspheric hiss may be required to produce a more efficient scattering of electrons, especially for the subMeV electrons (Malaspina et al., 2019). There may be potentially missing physical processes. It may also be possible that such underestimations are produced by an inaccurate background density specification or other processes that are not included in the code. The importance of EMIC waves in scattering multiMeV energies can also not be understated (Drozdov et al., 2017b). While our parameterization of EMIC waves is exclusively Kp based, incorporating other parameters (e.g., solar wind dynamic pressure, AE index, EMIC wave power, EMIC wave spectrum, etc.) may yield more accurate results in future simulations. The scattering caused by EMIC waves at multiMeV energies may increase, allowing us to better match observations. Thus, a stronger understanding of the loss processes occurring within the radiation belts remains a vital topic of research in order to increase our reconstructive modeling accuracy.

Furthermore, our plasmapause model is based on a singular index, Kp, and a linear relationship (Carpenter & Anderson, 1992). The

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**Table 7**

Logged 95th Percentile Peak Flux (#/sr/s/cm²/keV) per Solar Cycle and Energy

<table>
<thead>
<tr>
<th>Solar cycle</th>
<th>0.5 MeV</th>
<th>1.0 MeV</th>
<th>2.0 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar cycle 17</td>
<td>3.701</td>
<td>3.332</td>
<td>2.945</td>
</tr>
<tr>
<td>Solar cycle 18</td>
<td>3.782</td>
<td>3.435</td>
<td>3.035</td>
</tr>
<tr>
<td>Solar cycle 19</td>
<td>3.769</td>
<td>3.417</td>
<td>3.069</td>
</tr>
<tr>
<td>Solar cycle 20</td>
<td>3.730</td>
<td>3.306</td>
<td>2.870</td>
</tr>
<tr>
<td>Solar cycle 21</td>
<td>3.768</td>
<td>3.378</td>
<td>2.985</td>
</tr>
<tr>
<td>Solar cycle 22</td>
<td>3.748</td>
<td>3.404</td>
<td>3.057</td>
</tr>
<tr>
<td>Solar cycle 23</td>
<td>3.679</td>
<td>3.299</td>
<td>2.919</td>
</tr>
<tr>
<td>Solar cycle 24</td>
<td>3.503</td>
<td>3.088</td>
<td>2.548</td>
</tr>
</tbody>
</table>

**Table 8**

Logged 98th Percentile Peak Flux (#/sr/s/cm²/keV) per Solar Cycle and Energy

<table>
<thead>
<tr>
<th>Solar cycle</th>
<th>0.5 MeV</th>
<th>1.0 MeV</th>
<th>2.0 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar cycle 17</td>
<td>3.794</td>
<td>3.439</td>
<td>3.123</td>
</tr>
<tr>
<td>Solar cycle 18</td>
<td>3.877</td>
<td>3.532</td>
<td>3.193</td>
</tr>
<tr>
<td>Solar cycle 19</td>
<td>3.867</td>
<td>3.532</td>
<td>3.193</td>
</tr>
<tr>
<td>Solar cycle 20</td>
<td>3.826</td>
<td>3.398</td>
<td>3.036</td>
</tr>
<tr>
<td>Solar cycle 21</td>
<td>3.893</td>
<td>3.472</td>
<td>3.085</td>
</tr>
<tr>
<td>Solar cycle 22</td>
<td>3.858</td>
<td>3.513</td>
<td>3.175</td>
</tr>
<tr>
<td>Solar cycle 23</td>
<td>3.850</td>
<td>3.427</td>
<td>3.092</td>
</tr>
<tr>
<td>Solar cycle 24</td>
<td>3.610</td>
<td>3.196</td>
<td>2.699</td>
</tr>
</tbody>
</table>
plasma density does not evolve with time and the plasma model inside and outside of the plasmasphere is constant. This will impact wave-particle interactions as to which energies and pitch angles may get scattered and may account for the underestimation of particle fluxes throughout the entire simulation. Future endeavors into radiation belt modeling may want to consider using a metric for the plasmasphere location which incorporates a more complicated and in-depth description such as O’Brien and Moldwin (2003). The simulation by Wang et al. (2019) used the more comprehensive plas-

<table>
<thead>
<tr>
<th>Solar cycle</th>
<th>1st moment</th>
<th>2nd moment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar cycle 17</td>
<td>0.5 MeV: 4.372, 1.0 MeV: 3.83, 2.0 MeV: 3.278</td>
<td>0.5 MeV: 8.322, 1.0 MeV: 7.478, 2.0 MeV: 6.610</td>
</tr>
<tr>
<td>Solar cycle 18</td>
<td>0.5 MeV: 4.393, 1.0 MeV: 3.955, 2.0 MeV: 3.418</td>
<td>0.5 MeV: 8.444, 1.0 MeV: 7.612, 2.0 MeV: 6.704</td>
</tr>
<tr>
<td>Solar cycle 19</td>
<td>0.5 MeV: 4.362, 1.0 MeV: 3.93, 2.0 MeV: 3.404</td>
<td>0.5 MeV: 8.432, 1.0 MeV: 7.627, 2.0 MeV: 6.816</td>
</tr>
<tr>
<td>Solar cycle 20</td>
<td>0.5 MeV: 4.268, 1.0 MeV: 3.806, 2.0 MeV: 3.229</td>
<td>0.5 MeV: 8.239, 1.0 MeV: 7.354, 2.0 MeV: 6.391</td>
</tr>
<tr>
<td>Solar cycle 21</td>
<td>0.5 MeV: 4.364, 1.0 MeV: 3.917, 2.0 MeV: 3.358</td>
<td>0.5 MeV: 8.327, 1.0 MeV: 7.462, 2.0 MeV: 6.536</td>
</tr>
<tr>
<td>Solar cycle 22</td>
<td>0.5 MeV: 4.357, 1.0 MeV: 3.915, 2.0 MeV: 3.366</td>
<td>0.5 MeV: 8.426, 1.0 MeV: 7.592, 2.0 MeV: 6.709</td>
</tr>
<tr>
<td>Solar cycle 23</td>
<td>0.5 MeV: 4.228, 1.0 MeV: 3.763, 2.0 MeV: 3.210</td>
<td>0.5 MeV: 8.266, 1.0 MeV: 7.454, 2.0 MeV: 6.626</td>
</tr>
<tr>
<td>Solar cycle 24</td>
<td>0.5 MeV: 4.006, 1.0 MeV: 3.532, 2.0 MeV: 2.864</td>
<td>0.5 MeV: 7.879, 1.0 MeV: 6.913, 2.0 MeV: 5.739</td>
</tr>
</tbody>
</table>

Figure 10. Total integrated flux by percentile (5th, 10th, 25th, 50th, 75th, 90th, 95th) over each solar cycle for the 0.5, 1.0, and 2.0 MeV 85° pitch angle electrons (panels a, b, and c, respectively).
The results can be summarized as follows:

1. Our NARX algorithm was trained off GOES 15 observations (January 2011–March 2014) of 1.0 MeV electrons and the historical Kp measurements. This produced an upper boundary condition (at $L^* = 6.6$) which was used to simulate the radiation belts. This derived upper boundary condition, along with the historical Kp measurements, yielded good agreement when compared to observations from both CRRES (August 1990–July 1991) and the Van Allen Probes (2013–2017), which coincide with solar cycles 22 and 24, respectively.

2. The radiation belts over solar cycles 17–22 are similar and comparable with respect to number of sunspots, the median electron flux values, and their flux distribution. Each of these cycles has at least ~12,000 observed sunspots.

3. Solar cycle 24 was the weakest solar cycle by sunspot activity level, ~6,500 (~45–60% decrease compared to the next weakest and strongest solar cycle, respectively). This coincides with the least enhanced radiation belt activity for all three energies (0.5, 1.0, and 2.0 MeV) over all considered solar cycles. This supports the concept that a less active solar cycle would produce fewer geomagnetic storms which in turn would lead to fewer enhancements in the radiation belts.

4. The reconstructed fluxes will help put into perspective observations from the Van Allen Probes and will allow us to estimate average conditions and variability the fluxes for different solar cycles.

5. The ability to reconstruct fluxes during the 85 years of simulations allows us to experience the potential observation of a satellite mission and estimate the potential radiation belt variability over the last several solar cycles.
Data Availability Statement

Van Allen Probes data used in this study was obtained from the MagEIS and REPT data directories found at https://www.ribm.epss.ucla.edu/. Measurements from the CRRES mission were found at https://cdaweb.gsfc.nasa.gov/pub/data/crres/particle_data/. GOES measurements were obtained from https://satdat.ngdc.noaa.gov/sim/goes/data/avg/. Sunspot numbers were obtained from the Royal Observatory of Belgium at http://www.sidc.be/silso/datafiles. Historical $K_p$ measurements were found at ftp://ftp.gfz-potsdam.de/pub/home/obs/kp-ap/. Use diffusion coefficients and the codes are available at (ftp://rbsp-ect.lanl.gov/). The data produced and shown (PSD for the electron flux data for solar cycles 17–24, the NARX derived bf, and our file used to derive our LCDS condition) in this manuscript can be found at this location: https://doi.org/10.25346/S6/HY1DNT. This work used computational and storage services associated with the Homer2 Shared Cluster provided by UCLA Institute for Digital Research and Education’s Research Technology Group. The authors would like to thank Dominika Boneberg for proofreading this manuscript.

References


