Evaluation of the Solar Quiet Reference Field (SQRF) Model for Space Weather Applications in the South America Magnetic Anomaly

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Abstract

In the present work, we evaluate the accuracy of the Solar Quiet Reference Field (SQRF) model for estimating and predicting the geomagnetic solar quiet (Sq) daily field variation in the South America Magnetic Anomaly (SAMA) region. This model is based on the data set of fluxgate magnetometers from 12 magnetic stations of the Embrace Magnetometer Network (Embrace MagNet) from 2010 to 2018. The model predicts the monthly average horizontal field of the geomagnetic quiet (Sq-H) daily variation solving a set of equations for the specified geographic coordinates in terms of the solar cycle activity, the day of the year, and the universal time. We carried out two comparisons between the prediction and observational data of the Sq-H field. The first part attempts to evaluate the accuracy for estimating the Sq-H field over Medianeira (MED, 25.30°S, 54.11°W, dip angle: -33.45°) by using linear interpolation on the SQRF coefficients and compared it with the data collected from April to December in 2018. It worth mentioning that none of the datasets collected at MED is part of the dataset used to build the SQRF model, hence the need to do interpolation. The second part of the analysis attempts to evaluate the accuracy for predicting the quiet daily field variation over Cachoeira Paulista (CXP, 22.70°S, 45.01°W, dip angle: -38.48°). The dataset collected at CXP prior to the period analyzed in the present work is part of the dataset used to build the SQRF model. Thus, the accuracy of the prediction is tested using magnetic data outside the time interval considered in the model. The results of the prediction for both locations show that the outputs from this empirical model present a good agreement with the Sq-H field obtained from the magnetic field data. The accuracy of the SQRF model (high correlation, r>0.9) provides a high potential for estimating and predicting geomagnetic quiet daily field variation for space weather applications, improving the scientific insight and capability of space weather prediction centers to predict the variability of the regular solar quiet field variation as reference conditions, which may include areas with no measurements.

Keywords

Geomagnetic quiet daily field variation; Space weather; Predicting; Empirical model.
1. Introduction

Over the past centuries, the International Polar Years (IPY, 1882-1883 and 1932-1933) and the International Geophysical Year (IGY, 1957-1958) encouraged the studies and monitoring of the Earth’s magnetic field (Jankowski and Sucksdorff, 1996). More recently, the International Heliophysical Year (IHY, 2007-2008) aimed to fulfill fundamental global questions of Earth and space sciences (Davila et al., 2004). These conferences promoted a significant increase in the number of continuous and high-resolution ground-based observations of the geomagnetic field to help in understanding the Earth’s magnetism and space weather conditions (Yumoto et al., 1996; Love, 2008; Thompson, 2014; Love and Finn, 2017).

The increase in ground-based instrumentation is associated with the implementation of several regional warnings and prediction centers for monitoring and predicting the Solar-Terrestrial environment (Schrijver et al., 2015; Denardini et al., 2016). In this context, the Brazilian Study and Monitoring of Space Weather (Embrace) Program lead by the National Institute for Space Research (INPE) joined in part of international collaborations, made an effort to fulfill the gaps of continuous temporal and spatial ground-based magnetometer data in South America (Denardini et al., 2016, 2018a). Some ionospheric indices for the space weather applications using ground-based instrumentation and satellite data developed on the Embrace Program can be found in Resende et al. (2019) and Denardini et al. (2020). Also, several authors use magnetic field measurements to estimate the magnitude of disturbed and storm-time periods driven by solar events (e.g., Klausner et al., 2016; Bolzan et al., 2018; Denardini et al., 2018b). Other studies estimate the magnitude of Geomagnetic Induced Currents (GICs) from those ground-based observations (e.g., Espinosa et al., 2019; Rodger et al., 2020).

A large number of ground-based instrumentation and satellite data is essential to detail the geomagnetic field with a high cadence in time and spatial resolution. The ground-based observations are used to estimate the effects of the changes in the Earth’s system, which may cause damages to technological assets. In the South America Magnetic Anomaly (SAMA) region, magnetometer data from Embrace Magnetometer Network (Embrace MagNet) show that it is important to have a specific index to quantify the
The SAMA is continuously monitored due to its higher levels of radiation that may affect orbiting objects that pass across its region. It is well-known through the past decades that the SAMA region has three main characteristics: (1) its area is increasing, (2) the total field intensity is decreasing, and (3) there is a westward movement of its center (Pinto Jr. et al., 1992; Hartmann and Pacca, 2009; Anderson et al., 2018). Recently, Finlay et al. (2020) observed that the SAMA continues to expand, and single-event electronic upsets recorded onboard the Swarm satellites seen directly related to the magnetic measurements in this region. Consequently, it is fundamental to monitor and study the anomalously weak geomagnetic field to understand how this anomaly can affect the physical parameters and dynamics in terms of space weather besides the technological equipment.

In this context, the development of empirical models has always played an important role. They are mostly used to estimate and predict the space weather during disturbed conditions (e.g., solar flares, coronal mass ejections, solar and galactic energetic particles, and solar wind variations). These models are developed for the practical benefit of human activities affected by the near-Earth space environment (Bala and Reiff, 2018, and references therein). The empirical models of geomagnetic field variations are commonly used to estimate quiet time conditions, e.g., the main field and its secular variation (Thébault et al., 2015; Chulliat et al., 2020). Mandea and Chambodut (2020) have presented some concerns about the range of spatial and temporal variabilities of the geomagnetic field and their implications for space weather. The authors clarify that to understand and predict several aspects and parameters related to the solar-terrestrial relationships needs continuous global observations of these parameters. Also, the Earth’s magnetic field variations play an essential role in space weather and still to be necessary a comprehensive separation and understanding of its internal and external magnetic field sources. In that sense, we have listed some of the empirical models for the external magnetic field developed in time, which are essentially based on Artificial Neural Networks (ANNs) or Spherical Harmonic Analysis (SHA).

This work focuses on the daily variation of the geomagnetic field caused by horizontal...
geomagnetic quiet field variation has been extensively reviewed and described by Richmond (1979), Campbell (1989), and Yamazaki and Maute (2017). This horizontal field daily variation, or Sq field, is related to the solar thermal wind tides generated in the thermosphere and the ionospheric conductivities. There are models developed for the South African (Sutcliffe, 1999), Asian and Oceania (Yamazaki et al., 2011), and Indian sectors (Unnikrishnan, 2014). Besides, other models were developed for high latitude regions, such as those presented by Janzhura and Troshichev (2008) and Stauning (2011). A global-scale empirical model of the geomagnetically quiet daily variation was developed by Campbell et al. (1989). However, this model has not been updated. Soares et al. (2020) described the Sq field at the Brazilian station Tatuoca (1.2°S, 48.5°W) and its long-term changes associated with the secular variation. But, Tatuoca is a few thousand kilometers away from the SAMA, and the behavior of the Sq field in the SAMA region is still to be understood. Recently, satellite and ground-based magnetic field measurements were used to developed global-scale Sq field models by Sabaka et al. (2020) and Chulliat et al. (2016). These recent works provide much greater spatial coverage of the Sq field over the globe by using satellite magnetic field measurements compared to the ground-based magnetic field measurements. Nevertheless, there is still low spatial coverage of ground-based magnetic field measurements around the SAMA region.

In the present study, we attempt to establish an estimating and predicting tool for obtaining the solar quiet daily variation of the geomagnetic field in the SAMA region. The analysis performed is based on the empirical model developed by Chen et al. (2020). This predicting tool estimates the Sq-H field for a region based on a linear interpolation method on the SQRF parameters of two magnetic stations, both close to the same meridian. The predicting tool estimates the daily variation for a given location with high accuracy within 1 to 3 months. The evaluation shows high accuracy for estimating and predicting the geomagnetic quiet daily field variation, with a good agreement to the magnetic field data.
2. The empirical model for Sq-H field and input parameters

We used the Solar Quiet Reference Field (SQRF) model to estimate and predict the Sq-H field in the SAMA region (Chen et al., 2020), an empirical model based on the daily variation of the horizontal field obtained by magnetic field data collected from Embrace MagNet (Denardini et al., 2018a). Such a model reveals the climatology of geomagnetic quiet daily variation across South America. This model expresses the combination of primary (external) and secondary (induced) Sq fields, and which is sufficient for the purpose of this work.

In short words, the SQRF model was obtained by fitting a function that depends on solar radio flux \( (F_{10.7}) \), day of the year (DOY), and universal time (UT). The model was built using magnetic field data collected from 12 stations across the Brazilian sector from 2010 to 2018, as seen in Table 1. A map with the location of such Embrace MagNet stations is shown in Figure 1. In this figure, the red stars indicate the magnetic stations and circles indicate the center of the SAMA region, where the minimum field intensity was 22,567 nT in 2010 and evolved to 22,287 nT in 2018. Solid lines indicate the SAMA region where the total intensity is lower than 23,000 nT. Dashed lines correspond to the magnetic equator. The orange and green colors indicate the year 2010 and 2018, respectively. The total field intensity, the magnetic equator, and quasi-dipole geomagnetic coordinates were obtained using the IGRF-13.

| Station Code | Station Name | Geog. Coord. | Geom. Quasi-Dipole |
|--------------|--------------|--------------|-------------------|
| MAN | Manaus | -2.89 | -59.97 | 4.23 | 13.40 |
| ALF | Alta Floresta | -9.87 | -56.10 | -3.74 | 15.17 |
| SLZ | São Luís | -2.59 | -44.21 | -3.82 | 27.73 |
| ARA | Araguatins | -5.60 | -48.10 | -4.26 | 23.34 |
| EUS | Eusébio | -3.88 | -38.42 | -8.02 | 32.55 |
| CBA | Cuiabá | -15.55 | -56.07 | -8.68 | 13.87 |
| JAT | Jataí | -17.93 | -51.72 | -12.69 | 16.92 |
Figure 1. Map of geographic coordinates of the Embrace MagNet stations (stars) in the Brazilian sector, along with solid lines indicating the SAMA region (23,000 nT) and the magnetic equator. The total field intensity and the magnetic equator were obtained using the IGRF-13 for epochs 2018.0 (green) and 2010.0 (orange).

The SQRF model is based on the monthly average of the quiet daily variation of the geomagnetic field horizontal component measured by fluxgate magnetometers. This quiet daily field variation is an average of the magnetic field measured during the 5 quietest days of the month, which is based on the list of International Quiet Days (IQDs) from GeoForschungsZentrum (GFZ) Potsdam. The derived daily variation of observational data is given by:
\[ H_{QDC}(UT) = \frac{1}{N} \sum_{i=1}^{5} H_{QDi}(UT), \]  
\[ \Delta H_{QDC}(UT) = H_{QDC}(UT) - H_{QDC}(00:00LT). \]

\( H_{QDC} \) is the Sq-H field, \( H_{QDi} \) is the daily variation of the \( i \)-th quietest day of the month, \( UT \) is the universal time given with 1-min time resolution (from 00:00 up to 23:59 UT), and \( N \) is the number of days used in the calculation. Eventually, the number of days used for the \( H_{QDC} \) computation can be less than 5, depending on the data availability. \( \Delta H_{QDC} \) is the Sq-H field amplitude obtained from the magnetic data by subtracting the baseline. \( H_{QDC}(00:00 \text{LT}) \) is the baseline subtracted and corresponds to the daily variation during local midnight.

The model development of the Sq-H field consists of parametrization of solar cycle dependence, seasonal variation, and daily variation on the observational data of \( \Delta H_{QDC} \). These three parameters are computed separately for each magnetic station. The solar cycle parameter describes the linear relationship between the monthly average of the \( \Delta H_{QDC} \) during local noon (12 LT) and the monthly average solar radio flux, \( F_{10.7} \) (1 sfu \( = 10^{-22} \text{W.m}^{-2}.\text{Hz}^{-1} \)), given by Equation (3). The seasonal parameter describes the parametrization of the time-series for the monthly average of the \( \Delta H_{QDC} \) during local noon over the days of the year, given by Equation (4). Lastly, the daily parameter describes the time-series for the monthly average of the \( \Delta H_{QDC} \) during the 24 hours of the day, caused by 24-, 12-, 8-, and 6-hours harmonics of the day, given by Equation (5). Thus, these parameters are modeled by the following set of equations:

\[ C(F_{10.7}) = C_0 + C_1 F_{10.7}, \]  
\[ S(\text{DOY}) = S_0 + \sum_{j=1}^{N} S_j \cos(2\pi j \text{DOY} + \phi_j), \]  
\[ D_m(UT) = D_{m,0} + \sum_{n=1}^{N} D_{m,n} \cos(2\pi f_n UT + \phi_{m,n}). \]

\( C \) is the solar cycle parameter given in nT, where \( C_0 \) and \( C_1 \) are the coefficients from linear regression between the \( \Delta H_{QDC} \) (12 LT) and its monthly average of the solar radio flux, \( F_{10.7} \). \( S \) is the seasonality parameter, in which \( S_0 \) up to \( S_N \) (being \( N=6 \)) are coefficients obtained from the Fourier series fitting, \( j \) is the number of the \( j \)-th harmonic, \( \phi_j \) is the phase angle of the \( j \)-th harmonic, and \( \text{DOY} \) is the day of the year. \( D_m \) is the daily...
variation parameter referred to the selected month $m$ (i.e., Jan=1, Feb=2, Mar=3, …, Dec=12 and corresponds to the central date of each month; DOY=15, 46, 74, ..., 349), where $D_0$ up to $D_N$ are the fitted coefficients, $f_n$ is the frequency of the $n$-th harmonic, $\phi_n$ is the phase angle of the $n$-th harmonic (being $N=4$). Notice that $S$ and $D_m$ are dimensionless parameters that account for the seasonality and daily variation, respectively.

Considering the three mentioned modeled parameters in equations above ($C$, $S$, and $D_m$), the Sq-H field is given by:

$$\Delta H^*_QDC(F_{10.7}, DOY, UT) = C(F_{10.7}).S(DOY).D_m(UT). \quad (6)$$

The parameter $S(DOY)$ uses the day of the year to model the $\Delta H^*_QDC$ seasonal variation. On the other hand, the parameter $D_m(UT)$ considers changes overtime during a day. The latter is obtained for each month $m$ separately as this improved the model performance. We normalized the seasonal and daily parameters to obtain their relative geomagnetic field variations. $\Delta H^*_QDC$ is the Sq-H field amplitude obtained from the model. Details about the coefficients, as well as the description of all fitting equations of parameters above are given in Chen et al. (2020).

The SQRF model is based on Yamazaki et al. (2011), in which the geomagnetic field daily variation is calculated through the least-square fitting of multivariable functions to observational data. However, the SQRF model does not consider the lunar tide on the geomagnetic field daily variation since the model only provides a monthly Sq variation based on the 5 quietest days of each month. Additionally, Yamazaki et al. (2011) developed a model for the $210^\circ$ magnetic meridian, which has none of the characteristics of the SAMA region mentioned above. Thus, the SQRF model may successfully describe the SAMA region dynamics since it is based on ground-based magnetic field measurements in this region.

Thus, we present two analyses to evaluate the SQRF model accuracy in estimating and predicting the Sq-H field in the SAMA region. The first one is about an interpolation method that was used to estimate the Sq-H field over MED, a region close to the center of the SAMA. The other is about predicting the Sq-H field for CXP, considering the empirical model coefficients obtained from the magnetic field data from 2010 to 2018.
The observational data used to compare with the empirical model has been derived from Equations (1) and (2).

3. Results and Discussions

3.1 Estimating the Sq-H field

The purpose of this analysis is to present a spatial interpolation method to improve the SQRF model, which allows the user to estimate the Sq-H field over a region where magnetic data is not available. This method consists of using linear interpolation on the parameters of the empirical model based on the geographic latitude of the magnetic stations. To achieve the main purpose of this technique, we presented an example of this interpolation. Initially, we selected a substantial amount of magnetic field data collected by two magnetic stations from the Embrace MagNet from 2010 to 2018. Afterward, we estimate the Sq-H field for a site between those magnetic stations.

In this example, the SQRF computed the values for Cuiabá (CBA, 15.55°S, 56.07°W, dip angle: -18.58°) and São Martinho da Serra (SMS, 29.44°S, 53.82°W, dip angle: -37.69°) to obtain the modeled results for Medianeira (MED, 25.30°S, 54.11°W, dip angle: -33.45°). Embrace MagNet installed a magnetometer in Medianeira, a new site close to the center of the SAMA region at the beginning of April 2018. Thus, none of the datasets collected at MED was considered to obtain all the parameters in the SQRF model. Instead, the parameters for MED were obtained from interpolation between parameters from other magnetic stations. Therefore, we can state that we were able to compare the estimated Sq-H field for the MED station and the magnetic data collected over it for 2018, with no bias. Additionally, these three locations almost at the same meridian.

Figure 2 shows the parameters used as input in the model for MED (red), based on CBA (blue) and SMS (green) stations. The fitted parameters were based on (a) the solar cycle dependence, (b) the seasonal variation, and (c) the daily variation. Notice that the daily variation in Figure 2c corresponds to December ($m=12$). However, $D_m$ was obtained for all 12 months, individually (i.e., from $m=1$ up to $m=12$).
Figure 2. Interpolated parameters obtained for MED (red), based on CBA (blue) and SMS (green) parameters. (a) Solar cycle parameter. (b) Seasonal variation parameter. (c) Daily variation parameter for December ($m=12$).

The solar cycle dependence ($C$ parameter) is represented by a linear relationship between the Sq amplitudes at 12 LT (LT=UT-3) and the $F_{10.7}$ index (Figure 2a). This behavior agrees with previous works such as Rastogi et al. (1994) and Shinbori et al. (2017) over the Indian and Asian sectors, respectively. This parameter is essential in the model since the $F_{10.7}$ index estimates the solar cycle dependence in the heights of our interest.

Figure 2b shows that the Sq-H field at local noon (12 LT) has a cyclic component during the year, which is the seasonal variation ($S$). This parameter agreed with the tidal behavior of the atmospheric oscillations described by Forbes et al. (2008). The results show that the highest amplitude values were observed during March (DOY 75) and September equinoxes (DOY 255). In contrast, the lowest amplitude values were seen during the winter solstice period (between DOY 135 and 195) in the Southern Hemisphere.

Kane (1976) shows that the Sq field at local noon has a semiannual variation with maximum values at the equinoxes. Recently, Yamazaki et al. (2014) showed that the region close to the magnetic equator has a well-defined semiannual variation, due to the high conductivity. At low latitudes, which is the focus of this study, previous works have shown that these phenomena are more expressive in the equinoxes. It is well-known that the tidal winds in the ionospheric E-region play an important role in the ionospheric dynamo (Campbell, 1989), contributing to the seasonal variation in this
region’s heights. Batista et al. (2004) showed that the diurnal and semidiurnal tides have a well-defined variability characterized by maximum amplitudes at the equinoxes over the Brazilian sector. Resende et al. (2017) analyzed the influence of the tidal components in the denser layer formation in the ionospheric E-region, widely known as Sporadic (Es) layers, at low latitude regions. The authors showed that these layers occurred with more intensity during the equinoxes since the tidal winds are stronger in these periods. Therefore, there is a good agreement of the seasonal behavior obtained using the magnetometer data with the previous studies, corroborating the model effectiveness.

The daily parameter, or $D_m$ in the SQRF model, refers to the daytime variation considering the harmonics of atmospheric tides. $D_m$ determines the daily variation amplitude of the geomagnetic field horizontal component concerning the diurnal, semidiurnal, terdiurnal, and quarterdiurnal tides (whose periods are 24-, 12-, 8-, and 6-hours, respectively). Figure 2c shows the Sq-H amplitude considering those oscillations for December ($m=12$).

One of the characteristics of the horizontal field daily variation behavior is its relationship with the ionospheric conductivities (Moro, 2015; Moro et al., 2016). During the summer solstice, in geomagnetically quiet periods, the solar incidence is higher, increasing the ionospheric conductivity in the E-region (Van de Kamp, 2013). Thus, the Sq field varies proportional to the conductivity and the ionospheric electric field, being the amplitude in CBA reached almost 60 nT in December. Additionally, the CBA station is characterized by higher values than those observed in SMS. It occurs because the former station is closer to the magnetic dip equator than the second station. Thus, the configuration of the Sq current system makes the horizontal currents stronger.

The interpolated parameters over MED have intermediate values between CBA and SMS. The values of the coefficients for each parameter of the SQRF model from CBA and SMS stations are presented in the Appendix. A grid of values from these two stations’ parameters is estimated according to its geographic latitude and being used linear interpolation for MED. Thus, we evaluated the interpolation method applied to $C$, $S$, and $D_m$ parameters in the SQRF model and checked if it was adequate to study regions with
a low quantity of data such as MED. The empirical model results were compared with
the magnetic field data collected by the MED station, as shown in Figure 3. The Sq field
variation estimated from the magnetic field data is obtained by the average of the 5
quietest days of the month, using Equations (1) and (2). We presented September
(m=9), November (m=11), and December (m=12) of 2018 as an example of this
comparison (top panels in Figure 3). Hereafter, we performed a comparison between the
estimated and the magnetic field data based on the linear fitting correlation of the
monthly quiet daily field variation (bottom panels in Figure 3).

Figure 3. Top panels correspond to the monthly Sq-H field obtained for MED using the
interpolated parameters of the SQRF model (red) and the magnetic field data (blue) in
September (m=9), November (m=11), and December (m=12) in 2018. The bottom
panels correspond to the dispersion plots of the Sq-H field for each of the presented
months.

We noticed that the estimating results are very similar to the observational data (shape
of the curve), with few discrepancies depending on the month analyzed. In September,
we observed overestimated values during pre-dusk hours (18-21 UT) and
underestimated values during post-dusk hours (21-24 UT) in the estimated Sq-H field.
In November and December, the overestimate values occur mostly between 18 UT and
24 UT. Despite this, the SQRF model estimates almost the same behavior observed in
MED. The best correlation was observed in November 2018 (r=0.99).
Table 2 summarizes the results for the above analysis extended for the whole period of 2018. The averaged of Pearson correlation coefficient $r$ between the observational data and the SQRF model for MED was higher than 0.97, indicating that the regression has a high confidence level. The linear regression obtained from this correlation shows that the Sq-H field estimated ranges about 4% on average (coefficient $b$) than the observational data, which means that the SQRF model provides an accurate estimation for the Sq-H field. Also, the Sq-H field is in good agreement with the magnetic field data collected over the magnetic station, with an offset of about 1.4 nT in the linear coefficient $a$.

**Table 2.** Linear fit coefficients and correlation between the estimated daily field variation and the magnetic field data. The spatial interpolation was performed to modeled parameters for MED in 2018.

| Year | Month | $a$ (nT) | $b$  | $r$   | RMSE (nT) |
|------|-------|----------|------|-------|-----------|
| 2018 | 4     | 1.41     | 0.82 | 0.959 | 3.83      |
|      | 5     | -1.25    | 1.00 | 0.986 | 2.03      |
|      | 6     | 0.99     | 1.12 | 0.976 | 2.94      |
|      | 7     | 1.78     | 1.17 | 0.979 | 3.79      |
|      | 8     | 3.97     | 1.19 | 0.940 | 7.10      |
|      | 9     | 0.80     | 1.04 | 0.983 | 2.81      |
|      | 11    | 1.82     | 0.91 | 0.990 | 2.23      |
|      | 12    | 1.86     | 1.09 | 0.968 | 3.92      |
|      | Average | 1.42 | 1.04 | 0.973 | 3.58      |

The Root Mean Square Error (RMSE) was calculated to evaluate the accuracy of the SQRF model. We attempted to check if it was possible to estimate the Sq-H field behavior for regions with no available data. The averaged RMSE was about 3.6 nT, indicating an error of about 11.4% of the Sq-H field if the amplitude during local noon is 31.5 nT. The results show that the SQRF model achieved an accurate estimation in 2018, being more precise in May (lowest RMSE). However, some discrepancies were noticed in the correlation between the estimated Sq-H field and its magnetic field data in June solstice (June, July, and August). The angular coefficient $b$ observed in June solstice indicates that the SQRF model is predominantly overestimating the Sq-H field.
by about 16%, given that the coefficient \( a \) is small. This result is pointed out that MED station may have almost the same amplitude as observed in SMS during June solstice. This similar magnitude during this period for MED and SMS can be associated with the SAMA region since these stations are close to the anomaly center. Moreover, the highest RMSE was observed in August 2018. In this case, some of the quiet days listed may not be entirely associated with geomagnetically quiet periods, which means that a double check must be done to the magnetic field data in the SAMA region to obtain the Sq-H field. Abdu and Batista (1977) reported the presence of enhanced ionization at E-layer heights under magnetically quiet conditions from ionosonde data in the SAMA region. This, in turn, can explain why the SQRF model underestimates the observational data on some occasions.

We estimated the behavior of the Sq-H field for all months for nine years (from January 2010 to December 2018). Figure 4 shows the contour graphs of the Sq-H field from the SQRF model for (a) CBA, (b) MED, and (c) SMS. The typical Sq-H field behavior in observational data is characterized by a peak on the Sq-H field around the local noon (12 LT), which is cyclical for each year (Chen et al., 2020). We see that the daytime variations are related to seasonality and occur due to the similar solar incidence in the atmosphere over the magnetic stations.

In general, the Sq-H field in the MED station seems to be the average of the stations used for this analysis, as expected. Some discrepancies were noticed, but the behavior is well correlated with that expected in low latitudes. We observed that the contour graph of MED presents the Sq-H field similar to that found in the SMS contour graph. However, the maximum value of the Sq-H field in MED is higher than that observed in SMS. This difference is due to the CBA region influence, in which the Sq magnitude is more enhanced than that observed in SMS, as mentioned before. The interpolation method applied to the SQRF coefficients present a very accurate estimation and can be used to estimate the Sq-H field for previous periods. Therefore, these results indicate that the SQRF model can be used for regions without sufficient data. For the interpolation method to work, one needs sufficient data in adjacent regions.
3.2 Predicting the Sq-H field

In this analysis, the solar cycle, seasonal, and daily parameters of the SQRF model are used to predict the Sq-H field beyond 2018. We have evaluated the accuracy of the model for predicting the Sq-H field over Cachoeira Paulista (CXP, 22.70°S, 45.01°W, dip angle: -38.48°), a station that has the most significant amount of data. We selected three months in 2019 (January, February, and March) to evaluate the performance of the model. The Sq-H field was calculated based on Equations (1) and
(2), using the magnetic field data collected during the five quietest days (IQDs) of each month, as shown in Table 3. GFZ Potsdam provides the list of International Quiet Days. Thus, it is possible to compare the Sq-H field observed for the months of 2019 with the predictions.

**Table 3.** List of five most quiet days from January to March in 2019.

| Year | Month | Quiet days |
|------|-------|------------|
|      |       | Qd1 | Qd2 | Qd3 | Qd4 | Qd5 |
| 2019 | 1     | 2   | 28  | 3   | 30  | 12  |
|      | 2     | 25  | 24  | 23  | 26  | 19  |
|      | 3     | 22  | 23  | 21  | 18  | 11  |

Figure 5 shows the Sq-H field graphs of the observational data (in blue) and the predicting field (in red), for CXP in 2019. The vertical and horizontal axes correspond to the daily variation amplitudes and the hours of the day (UT), respectively. We also present a linear correlation between the observational data and the modeled magnetic field. It is observed that there is a good agreement between the predicted Sq-H field and the observational data for the analyzed period. Nevertheless, during the daytime in March, the model overestimates the observational data from 9 UT to 17 UT, being more expressive around local noon. We were expecting higher values for the Sq-H field amplitude during the March equinox, similar to that observed in Figure 2b. This difference may be associated with the atmospheric tidal winds since the solar radio flux remains almost constant from month-to-month with lower values during solar minimum. Thus, the ionospheric current system variability is more affected by the atmospheric tidal winds than the ionospheric conductivities and electron density (Batista et al., 2004). This was demonstrated by Yamazaki et al. (2016). Therefore, the modeled parameters of the previous data are not susceptible to this variability, causing this difference. The results show that there is a challenge for predicting the Sq-H field more accurately when variabilities occur during quiet periods.
Figure 5. Top panels correspond to the Sq-H field obtained for CXP using the magnetic field data (blue) and the SQRF model (red) for January to March 2019. The bottom panels correspond to the dispersion plots of the Sq-H field for each of the presented months, respectively.

Table 4 shows the linear fitting coefficients $a$ and $b$ obtained from January to March in 2019, with the correlation coefficient ($r$) and the RMSE. It can be seen that the Sq-H field obtained from the SQRF model has a very high correlation ($r > 0.98$) with the observational data. Also, the predictions for the Sq-H field overestimates the magnitude of the quiet daily field variation, which is described by the linear fitting slope ($b$), given that the coefficient $a$ is small. On average, the Sq-H field modeled here output values approximately 12% higher than that of the observational data for this magnetic station. However, this difference in the magnitude of the geomagnetic field quiet daily variation does not appear significant for space weather applications, wherein 10% in 40 nT is about 4 nT. As an example, when deriving geomagnetic indices such as the Dst, this difference in magnitude in the Sq field may correspond to less than 1% for a severe magnetic storm (where the Dst index reaches ~400 nT). We have calculated the RMSE to evaluate the accuracy for predicting the Sq-H field. In this case, the Sq-H field predicted present averaged RMSE (3.8 nT) similar to that obtained in the previous analysis in Section 3.1. We noticed in Table 4 that the RMSE was relatively lower than the local noon amplitude, which indicates a low error when predicting the Sq-H field. These results show that the SQRF model achieved an accurate prediction in all these
months, being more precise in the first and second months (lowest RMSE). However, the SQRF model overestimated the Sq-H field from 9 UT to 24 UT in March 2019. Despite this, its Pearson correlation coefficient ($r=0.987$) shows that the Sq-H field presents almost the same behavior as observational data.

Table 4. Linear fitting coefficients and correlation between the prediction of the daily variation and the magnetic field data. The predicting Sq-H field was based on the modeled CXP station parameters based on the data from 2010 to 2018.

| Year | Month | $a$ (nT) | $b$ | $r$ | RMSE (nT) |
|------|-------|---------|-----|-----|-----------|
| 2019 | 1     | 0.22    | 1.08| 0.986| 2.83      |
|      | 2     | 1.83    | 1.07| 0.990| 3.44      |
|      | 3     | 1.65    | 1.21| 0.987| 5.27      |
|      | Average | 1.23    | 1.12| 0.988| 3.85      |

In general, comparing these results, it is observed that the typical behavior of the Sq-H field was predicted with high accuracy. The daytime variations, including the noon peak on Sq amplitude, appear at the same time and magnitude. Also, the seasonality output by the model seems to match that of the observational data. Concerning the solar cycle dependence, the $F_{10.7}$ index was lower than usual during the solar minimum of solar cycle 24. In that case, the $F_{10.7}$ index used as input for predicting the Sq-H field had the same value for all three months. However, the SQRF model overestimated, on average, 12% of the observational data. Also, we noticed that local noon amplitude could be a threshold of the dawn and the dusk amplitudes in the Sq-H field, in which lower value during local noon may delay dawn hours and being advance in time the dusk hours.

Thus, the SQRF model seems to have good potential to investigate future data. This fact is of great scientific interest since the prediction analyses would help understand the space climate and the near-Earth environment. Here, we show that the SQRF model algorithm provided predictions with a high confidence level. Finally, the SQRF model successfully describes the Sq-H field in the SAMA region, having the potential to be used for space weather applications since the SAMA region is continuously changing through the years.
4. Conclusions

The SQRF is an empirical model based on the daily variation of the horizontal field obtained by magnetic field data collected from Embrace MagNet. We used this model to obtain the quiet daily variation of the geomagnetic field over the South American sector. This model uses data from 12 magnetic stations between 2010 and 2018, of the monthly average horizontal field of functional fitting equations for the specific geographic coordinates. Therefore, in this work, we evaluated the SQRF model accuracy that estimates and predicts the Sq-H field over the SAMA region. We conducted a careful analysis of the Sq-H field data and also compared the results with predictions obtained from this model. In general, the analysis shows that the model results are in good agreement with the observations in the SAMA region using the ground-based measurements. The major contributions are listed as follows:

- We proposed a spatial interpolation of the modeled parameters to improve the capability of estimating the Sq-H field using a linear approximation when there is no available data. The SQRF computed for CBA and SMS to obtain the modeled results for MED station, a site close to the SAMA center. MED is not part of the dataset used to build the SQRF model, hence the need to do interpolation. These three locations were selected since they are almost at the same meridian. Also, for the interpolation method to work, one needs sufficient data in adjacent regions. We compared the Sq-H field for MED station with the observational data collected for 2018. In general, the results show a very similar behavior between predictions and observational data. The best correlation between the estimated field and observational data were observed in November ($r=0.99$) and the poorest correlation was noticed in August ($r=0.94$). The linear regression obtained from this correlation shows that the Sq-H field estimation ranges about 4% on average than the observational data, which means that the SQRF model provides an accurate estimation for the Sq-H field. Also, the averaged RMSE was about 3.6 nT, indicating an error of about 11.4% of the Sq-H field of the mean average of the amplitude during local noon is 31.5 nT over 2018. The results show that the SQRF model achieved an accurate estimation in 2018, being more precise in May (lowest RMSE), and the most discrepancies
occurred in June solstice (June, July, and August). We believe that these
discrepancies were due to the enhanced ionization at E-layer heights from
ionosonde data in the SAMA region. This fact could designate increase
conductivity in this region, which should lead to an enhancement in the Sq-H
field. It may also explain why the SQRF model underestimates the observational
data. Furthermore, we have predicted the behavior of the Sq-H field for all
months for nine years (from January 2010 to December 2018). It is worth
mentioning that this estimation for past dates is useful to understand the SAMA
evolution through the years.

- We also analyzed the accuracy for predicting the Sq-H field over CXP compared
with the quiet daily variation field data in 2019. CXP is part of the dataset used
to build the SQRF model, and the accuracy of the prediction was tested using
data outside the time interval used to build the model. This analysis showed that
the SQRF model could predict the daily variation field with high accuracy and a
correlation coefficient around 0.98. The predictions also presented lower RMSE
when predicting 1- to 2-months ahead. Some improvements would be necessary
to reduce the discrepancies in the predictions that may be associated with the
variability of atmospheric tidal winds. The daytime variations, including the
noon peak on Sq amplitude, appear at the same time and magnitude. Also, the
seasonality output by the model seems to match that of the observational data.
Concerning the solar cycle dependence, the $F_{10.7}$ index was at a lower level
during the solar minimum of solar cycle 24. The SQRF model overestimated
averaged 12% of the observational data, which is considered a low discrepancy.

Thereby, we presented examples of using this empirical model to estimate and predict
the variability of the regular solar quiet field variation as a reference quiet conditions,
being useful when analysis needed quiet time reference conditions and magnetic field
data is absent. From this point of view, the scientific insight into the regular Sq field's
variability is evaluated earlier than the collected magnetic field measurements.

Considering these remarks, we see potential applications for space weather using the
SQRF model to estimate and predict the geomagnetically quiet daily variation field.
Especially over the SAMA region, fast changes are observed in the ionospheric E region in the low latitude region of Brazilian longitude in comparison to other low-latitude regions of the globe during quiet periods by the secular variation. In this context, the SQRF model can improve the scientific insight and capability of space weather prediction centers to the prediction of the variability of the regular solar quiet field variation as a reference to geomagnetically quiet conditions.

Declarations

Availability of data and materials

The empirical model of the Sq-H field is not available online and the run of predictions will be provided under request to the author. The magnetic field data are provided by Embrace/INPE and is available online (http://www.inpe.br/spaceweather/). The list of International Quiet Days is provided by GeoForschungsZentrum (GFZ) Potsdam and the data is available online (ftp://ftp.gfz-potsdam.de/pub/home/obs/kp-ap/quietdst/). The monthly average of solar radio flux data is provided by Natural Resources Canada (NRC) and is available online (https://www.spaceweather.gc.ca/solarflux/sx-5-en.php).
Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

S. S. Chen conceived the empirical model, developed the computational codes of the model, designed the data analysis and leaded writing this manuscript.

C. M. Denardini assisted to conceive the empirical model and design the data analysis.

L. C. A. Resende assisted to conceive the empirical model and design the data analysis.

R. A. J. Chagas assisted to conceive the empirical model and design the data analysis.

J. Moro assisted to review the manuscript and discuss the results in the study.

R. P. Silva assisted to review the manuscript and discuss the results in the study.

C. S. Carmo assisted computational codes for designing the figures.

G. A. S. Picanço assisted to review the manuscript and discuss the results in the study.

All the authors helped to write and revise the manuscript.
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Appendix

All of the coefficients and phase angles defined in Equations (3), (4), and (5) for CBA and SMS are given in Tables 5 to 7, respectively.

Table 5. Coefficients of solar cycle parameter.

| Station | $C_0$ (nT) | $C_1$ (nT/sfu) |
|---------|------------|----------------|
| CBA     | 27.04      | 0.32           |
| SMS     | 6.96       | 0.26           |

Table 6. Coefficients and phase angles of the seasonality parameter.

| Station | $j$ | $S_j$ (nT) | $\phi_j$ (rad) |
|---------|----|------------|----------------|
| CBA     | 0  | 84.91      |                |
|         | 1  | 3.39       | 2.1933         |
|         | 2  | 9.96       | -2.5773        |
|         | 3  | 0.29       | 2.8454         |
|         | 4  | 2.24       | 1.3937         |
|         | 5  | 1.25       | 0.3308         |
|         | 6  | 1.06       | 0.0000         |

| SMS     | 0  | 46.52      |                |
|         | 1  | 5.13       | 0.7984         |
|         | 2  | 6.36       | -2.1737        |
|         | 3  | 1.98       | 1.3867         |
|         | 4  | 1.10       | 2.0528         |
|         | 5  | 2.72       | 1.1899         |
|         | 6  | 0.24       | 0.0000         |
Table 7. Coefficients and phase angles of the daily parameter.

| Station | \( D_{m,n} \) (nT) | \( m \) | \( n=0 \) | \( n=1 \) | \( n=2 \) | \( n=3 \) | \( n=4 \) | \( \phi_{m,n} \) (rad) | \( n=1 \) | \( n=2 \) | \( n=3 \) | \( n=4 \) |
|---------|---------------------|--------|--------|--------|--------|--------|--------|---------------------|--------|--------|--------|--------|
| CBA     |                    |        |        |        |        |        |        |                    |        |        |        |        |
| 1       | 25.32              | 23.86  | 8.37   | 2.54   | 0.72   | 2.1063 | -2.1558 | 0.5725             | 2.5363 |
| 2       | 24.12              | 23.97  | 9.57   | 3.88   | 1.33   | 2.1068 | -2.0846 | 0.5210             | -3.1238|
| 3       | 29.20              | 27.61  | 12.64  | 7.38   | 1.98   | 2.1415 | -1.8238 | 0.6565             | 3.1343 |
| 4       | 25.62              | 24.45  | 11.91  | 7.54   | 2.30   | 2.2540 | -1.6331 | 0.7865             | 2.8667 |
| 5       | 21.42              | 21.01  | 11.15  | 7.16   | 1.95   | 2.3530 | -1.4675 | 0.8492             | 2.6827 |
| 6       | 19.96              | 20.96  | 11.15  | 6.05   | 1.60   | 2.3695 | -1.5300 | 0.8460             | 2.6151 |
| 7       | 20.76              | 20.55  | 10.53  | 6.48   | 1.95   | 2.2910 | -1.6025 | 0.7483             | 2.3997 |
| 8       | 23.52              | 23.73  | 12.69  | 7.45   | 1.80   | 2.2454 | -1.6966 | 0.6220             | 2.5694 |
| 9       | 27.80              | 28.13  | 14.71  | 9.15   | 2.67   | 2.2764 | -1.6627 | 0.7546             | 2.7935 |
| 10      | 30.05              | 29.82  | 12.78  | 7.19   | 2.58   | 2.1312 | -1.7936 | 1.0084             | -2.6353|
| 11      | 26.44              | 26.76  | 10.87  | 4.42   | 0.87   | 2.2210 | -1.6910 | 1.0463             | -2.5885|
| 12      | 23.82              | 23.20  | 8.59   | 2.88   | 0.27   | 2.1603 | -1.9505 | 0.9166             | 2.7963 |
| SMS     |                    |        |        |        |        |        |        |                    |        |        |        |        |
| 1       | 19.10              | 17.10  | 4.58   | 0.79   | 0.94   | 2.3583 | -2.1424 | -1.0001            | 0.9992 |
| 2       | 15.03              | 16.09  | 6.94   | 2.02   | 0.92   | 2.4085 | -2.0921 | -0.0845            | 2.3666 |
| 3       | 17.21              | 16.27  | 7.12   | 3.03   | 1.30   | 2.3232 | -1.9994 | 0.1858             | 1.6815 |
| 4       | 15.02              | 14.97  | 6.64   | 3.49   | 1.71   | 2.6553 | -1.4531 | 0.6102             | 1.9698 |
| 5       | 9.30               | 9.46   | 5.06   | 3.39   | 1.48   | 2.8168 | -0.7028 | 1.3859             | 2.4201 |
| 6       | 9.29               | 9.75   | 4.54   | 2.86   | 1.30   | 2.8266 | -0.8110 | 1.4376             | 2.5925 |
| 7       | 11.25              | 9.89   | 3.94   | 2.91   | 1.19   | 2.6283 | -0.9581 | 1.3203             | 2.1527 |
| 8       | 14.35              | 14.13  | 6.67   | 3.85   | 1.77   | 2.6597 | -1.2616 | 0.8058             | 2.1330 |
| 9       | 17.48              | 18.62  | 8.45   | 3.96   | 1.83   | 2.6074 | -1.4914 | 0.7222             | 2.0236 |
| 10      | 16.93              | 16.67  | 5.75   | 1.78   | 1.16   | 2.4223 | -1.7852 | 0.6922             | 2.2022 |
| 11      | 17.05              | 17.86  | 6.42   | 1.51   | 1.17   | 2.4628 | -1.7402 | 0.3131             | 1.9680 |
| 12      | 15.88              | 16.11  | 5.67   | 1.37   | 1.27   | 2.4747 | -1.9115 | -0.5914            | 1.3125 |