Predicting the maximum aa/Ap index through its relationship with the preceding minimum

Zhanle Du

Key Laboratory of Solar Activity, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China.

Correspondence to: Z. L. Du
(zldu@nao.cas.cn)

Abstract

Predicting the strength and peak time of geomagnetic activity for the ensuing cycle 25 is important in space weather service for planning future space missions. The minimum aa geomagnetic index around the solar minimum has been often used to predict the maximum amplitude of sunspot cycle, but seldom used to directly predict the maximum aa index. This study analyzed the relationships between the maxima and minima of both the geomagnetic aa and Ap indices for the 11-year cycle. The maximum aa index is found to be well correlated to the preceding minimum with a correlation coefficient of $r = 0.860$. As a result, the maximum aa index for the ensuing cycle 25 is predicted to be $aa_{\mathsf{max}}(25) = 26.9 \pm 2.6$. This value is equivalent to $Ap_{\mathsf{max}}(25) = 17.3 \pm 1.8 \pm 1.2$ if employing the high correlation between aa and Ap ($r = 0.939$).

The maximum Ap index is also found to be well correlated to the preceding minimum with a correlation coefficient of $r = 0.862$. Based on this correlation, the maximum Ap index is predicted to be a slightly higher value of $Ap_{\mathsf{max}}(25) = 19.0 \pm 1.6$. The rise time of the $aa(Ap)$ index for the 11-year cycle is found to be nearly uncorrelated to the following maximum, $r = -0.16(-0.17)$. If the data point for cycle 24 (which is far from others) were not considered, the rise time of the Ap index for the 11-year cycle would be weakly correlated to the following maximum, $r = -0.404$ at a confidence level of 62%. The rise time for cycle 25 would be roughly estimated to be 89.9 ± 31.6 (months), implying that the geomagnetic activity for the ensuing cycle 25 would peak around April 2025 ± 32 months.

1   Introduction

Studying and predicting geomagnetic activities are important in both geophysics and space weather. Severe geomagnetic activities may cause intense geomagnetic storms (Gonzalez et al., 1989, 1994; Chen et al., 2019), leading to disruptions in communication and deviations of spacecrafts. With the current solar cycle 24 approaching its end,

satellite and spacecraft-related departments want to know the strengths of both solar and geomagnetic activities in the ensuing cycle 25 for planning future space missions.

Among the various indices to quantitatively describe the geomagnetic activity, the aa index (Mayaud, 1972), derived from the 3-hourly K indices at two near-antipodal
5   midlatitude stations in England and Australia, is the longest time series (since 1868) and has been widely used for analyzing long-term trends in the global geomagnetic activity (Russell and Mulligan, 1995; Marat et al., 2017; Du, 2011a; El-Borie et al., 2019) and for analyzing its correlation with both climate change (Cliver et al., 1998; Dobrica et al., 2009; Gavrilyeva et al., 2017) and solar activity (Echer et al., 2004; Prestes et
10   al., 2006; Lukianova et al., 2009; Du, 2011b,c; Du and Wang, 2012; Singh and et al., 2019). The minimum aa index (aa_{min}), at or near the solar minimum of the solar cycle, has been widely used in predicting the maximum amplitude of the sunspot cycle (R_m), the so-called Ohl's precursor method (Ohl, 1979; Brown and Williams, 1969; Du et al., 2009). But it is seldom used to directly predict the maximum aa index (aa_{max}) of an
15   ensuing cycle.

The planetary geomagnetic index Ap (Bartels, 1963) available since 1932, derived from the average of the measurements at 13 observatories around the globe, is a daily measure of the response of geomagnetic field to variations in the interplanetary magnetic field (IMF) and the solar wind (Li, 1997; McPherron, 1999; Tsurutani et al., 2006).
20   It is the main global magnetic index forecasted by government agencies (McPherron, 1999). Most works on forecasting geomagnetic activity have been over short intervals, on the order of hours or days (McPherron, 1999; Abunina et al., 2013). At earlier years, Kane (1988) pointed out that it is impossible to forecast the long-term geomagnetic activity through analyzing the daily, monthly and annual values of the Ap and aa indices.
25   Gordon (2015) demonstrated that long-term geomagnetic activity can only be predicted to within a limited threshold of accuracy due to the irregular trends and cycles in the annual data and nonlinear variability in the monthly series, through analyzing the aa index.

In this study, we analyze the relationships between the maxima and minima of

smoothed monthly values for the 11-year cycle of both the aa and Ap indices. It is found that the minima of both the aa and Ap indices are well correlated to the following maxima, and thus, the latter can be predicted by the former.

This study is arranged as follows. The data used in the current work are shown in
5   Sect. 2. Section 3 is devoted for the results. First, in Sect. 3.1, we simply analyze the relationship between the smoothed monthly mean Ap and aa indices. Then, in Sect. 3.2, we predict the maximum aa index (aa_{max}) for cycle 25, through analyzing the relationship between aa_{max} and the preceding minimum aa index (aa_{min}). Similar analysis is performed in Sect. 3.3 for predicting the maximum Ap index (Ap_{max}) for cycle
10   25, through analyzing the relationship between Ap_{max} and the preceding minimum Ap index (Ap_{min}). In Sect. 3.4, we analyze the relationships between the rise times of the aa and Ap indices for the 11-year cycle and the following maxima, followed by estimating the peak time of geomagnetic activity for the ensuing cycle. Some conclusions are discussed and summarized in Sect. 4.

15 **2 Data**

In this study, we use the (13-month) smoothed monthly mean aa index since 1868 from the International Service of Geomagnetic Indices (ISGI)[1]. We also employ the "equivalent" aa index, based on the declination data from Helsinki[2] (Nevanlinna and Kataja, 1993; Lukianova et al., 2009), during the period from 1844 to 1867 for expanding the
20   data back to 1844. This index is assimilated by multiplying the mean scale factor (1.14) of this index to that by ISGI for the overlapping period from July 1868 through December 1879. The smoothed monthly mean Ap index[3] is also used in this study for comparison.

---

[1]http://isgi.unistra.fr/
[2]http://www.ava.fmi.fi/MAGN/magn/Helsinki/D/Helsinki.act
[3]http://www.gfz-potsdam.de/en/kp-index
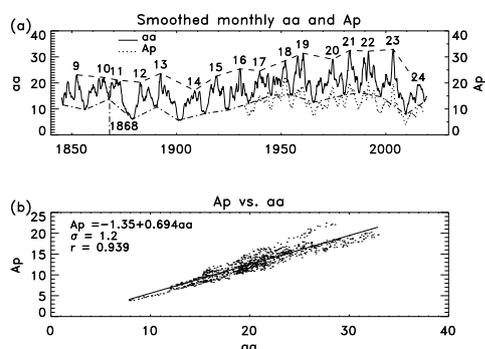
Fig. 1. (a) The smoothed monthly mean time series of aa (solid) since 1844 and Ap (dotted) since 1932. The numbers in the figure indicate those of the solar cycle. The upper dashed and lower dash-dotted lines represent the maxima (aa_{max}) and minima (aa_{min}) of aa, respectively, for the 11-year cycle. (b) Scatter plot of the smoothed monthly mean Ap against aa since 1932 (dots) and the linear fit (solid).

3 Result

Figure 1(a) shows the time series of the smoothed monthly mean aa index (solid) since 1844 and Ap index (dotted) since 1932. The numbers in the figure indicate those of the solar cycle. The upper dashed and lower dash-dotted lines represent the maxima (aa_{max}) and minima (aa_{min}) of the aa index, respectively, for the 11-year solar cycle. The parameters used in the current work are listed in Table 1, in which, T_a is the rise time of the aa index for the 11-year cycle; Ap_{max} and Ap_{min} are the maxima and minima of the Ap index for the 11-year cycle, respectively; T_r is the rise time of the Ap index for

Table 1. The minima, maxima and rise times of aa and A_p for the 11-year cycle.

n	$aa_{\min}$	$aa_{\max}$	T_a	$Ap_{\min}$	$Ap_{\max}$	T_r
9	11.55	23.10	81			
10	9.72	22.08	108			
11	13.78	21.10	48			
12	6.07	20.25	44			
13	10.77	23.66	23			
14	5.64	17.12	93			
15	8.26	22.60	63			
16	9.57	25.39	68			
17	12.06	24.66	64	7.29	16.82	112
18	15.26	28.56	79	9.78	22.45	82
19	15.34	31.42	62	10.55	18.64	56
20	12.56	29.07	109	7.37	18.81	111
21	15.33	32.51	31	10.37	20.08	29
22	16.18	32.20	51	9.62	20.24	57
23	14.69	32.90	72	8.11	19.65	72
24	7.85	18.81	73	3.84	11.72	71
25	12.78	?26.9		8.77	?17.3	?90
Av.	11.61	25.34	66.8	8.41	18.55	73.8

the 11-year cycle. The last row denotes the averages of the observations.

3.1 Relationship between Ap and aa

First, we simply analyze the relationship between the Ap and aa indices. Figure 1(b)
illustrates the scatter plot of the smoothed monthly mean Ap against aa indices since
5 1932 (dots). The solid line represents the linear fit of Ap to aa with the least-squares-fit

regression equation given by

$$Ap = -1.35 \pm 0.17 + (0.694 \pm 0.008)aa, \tag{1}$$

where $\pm$ represents the 1σ deviation. The standard deviation of fitting is $\sigma = 1.2$, and the correlation coefficient between the fitted and observed values is $r = 0.939$ at a confidence level greater than 99%. It is obvious that Ap is highly correlated with aa.

3.2 Relationship between aa_{max} and aa_{min}

Now, we analyze the relationship between aa_{max} and aa_{min}. Figure. 2(a) depicts the scatter plot of aa_{max} against aa_{min} for cycles 9-24 (triangles). The solid line represents the linear fit of aa_{max} to aa_{min} with the least-squares-fit regression equation given by

$$aa_{\mathrm{max}} = 10.5 \pm 2.4 + (1.29 \pm 0.20)aa_{\mathrm{min}}, \tag{2}$$

The standard deviation of fitting is $\sigma = 2.6$, and the correlation coefficient between aa_{max} and aa_{min} is $r = 0.860$ at a confidence level greater than 99%.

Therefore, aa_{max} is well correlated with the preceding aa_{min}, and one can use the latter to predict the former. Substituting the value of aa_{min} (12.78) for cycle $n = 25$ into this equation, one obtains $aa_{\mathrm{max}}(25) = 26.9 \pm 2.6$ (labelled by asterisk). It implies that the maximum aa index for the ensuing cycle 25 would be similar to or slightly higher than the average (25.34) over the past cycles, but would be much higher than that (18.81) of cycle 24 by about 35%.

If using the relationship between the smoothed Ap and aa in Eq. (1), the above prediction is equivalent to $Ap_{\mathrm{max}}(25) = 17.3 \pm 1.8 \pm 1.2$, here ± 1.8 is the uncertainty derived by the uncertainty (± 2.6) of $aa_{\mathrm{min}}(25)$ and ± 1.2 is the standard deviation of the regression.

3.3 Relationship between Ap_{max} and Ap_{min}

Then, we analyze the relationship between Ap_{max} against Ap_{min}. Figure 2(b) illustrates the scatter plot of Ap_{max} against Ap_{min} for cycles 17-24 (triangles). It is seen in the
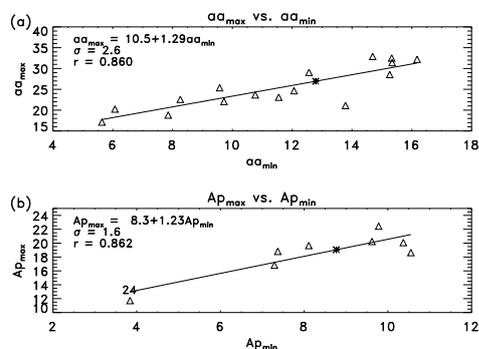
Fig. 2. (a) Scatter plot of aa_{max} against aa_{min} (triangles) and the linear fit (solid). (b) Scatter plot of Ap_{max} against Ap_{min} (triangles) and the linear fit (solid).

figure that Ap_{max} is also well correlated to Ap_{min}, with a correlation coefficient of $r = 0.862$ at a confidence level greater than 99%. The linear fit of Ap_{max} to Ap_{min} (solid) is

$$Ap_{max} = 8.3 \pm 2.5 + (1.23 \pm 0.29)Ap_{min}, \tag{3}$$

with a standard deviation of $\sigma = 1.6$. From this relationship, one can roughly estimate
5   the maximum Ap index for cycle 25, $Ap_{max}(25) = 19.0 \pm 1.6$, by substituting the value of Ap_{min} (8.77) for cycle $n = 25$ into this equation. This value is slightly higher than the average (18.55) over the past cycles, but much higher than that (11.72) of cycle 24, similar to the case for $aa_{max}(25)$.
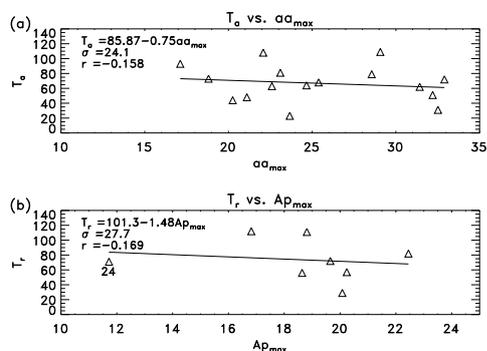
Fig. 3. (a) Scatter plot of T_a against aa_{max} (triangles) and the linear fit (solid). (b) Scatter plot of T_r against Ap_{max} (triangles) and the linear fit (solid).

3.4 Estimating roughly the peak time of geomagnetic activity for the ensuing cycle 25

At last, in this section, we try to analyze whether or not the rise time of the geomagnetic index for the 11-year cycle could be estimated through its relationship with the following
5   maximum, as the case often used in sunspot cycle (Waldmeier, 1939).

Figure 3(a) shows the scatter plot of the rise time of aa index (T_a) for the 11-year cycle against the maximum (aa_{max}). It is seen in this figure that the data points are much scattered, and so T_a is nearly uncorrelated to the following aa_{max}, $r = -0.158$. One can not use this correlation to estimate the rise and peak times of aa_{max}.

10   Similarly, the rise time of the Ap index for the 11-year cycle (T_r) is also nearly uncorrelated to the following maximum (Ap_{max}), $r = -0.169$, as shown in Fig. 3(b) for the
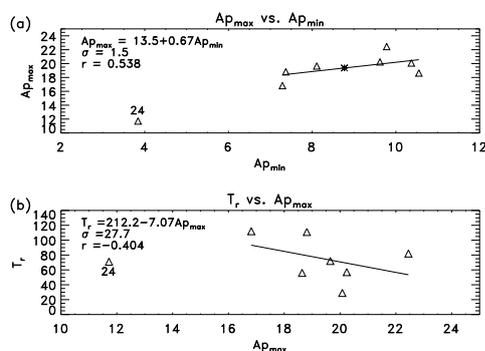
Fig. 4. (a) Linear fit of Ap_{max} to Ap_{min} (solid) if not considering the data point of cycle 24. (b) Linear fit of T_r to Ap_{max} (solid) if not considering the data point of cycle 24.

scatter plot of T_r against Ap_{max}. Thus, this correlation is also unable to be used to estimate the peak time of Ap_{max}.

One may note in Figs. 2(b) and 3(b) that the data point of cycle 24 is far from others. The related relationships depend largely on the data point of cycle 24. If this point were not considered, there would be only seven data points left (Fig. 4(a)), and the correlation coefficient between Ap_{max} against Ap_{min} would be only $r' = 0.538$ at a confidence level of about 78%. Under this condition, the regression equation would become

$$Ap_{max} = 13.5 \pm 4.3 + (0.67 \pm 0.47)Ap_{min}, \tag{4}$$

with a standard deviation of $\sigma = 1.5$. The maximum Ap index would be predicted to be $Ap_{max}(25) = 19.4 \pm 1.5$, slightly higher than the original one (19.0 ± 1.6).

However, if the data point of cycle 24 in Fig. 3(b) were not considered as shown in Fig. 4(b), the correlation coefficient between T_r and Ap_{max} would increase to $r = -0.404$ at a confidence level of about 62%. The linear regression equation of T_r to Ap_{max} would become

$$T_r = 212.2 \pm 140.4 - (7.07 \pm 7.16)Ap_{max}, \tag{5}$$

with a standard deviation of $\sigma = 27.7$. From this relationship, one could roughly estimate the rise time, $T_r(25) = 89.9 \pm 12.7 \pm 8.5 \pm 27.7 \sim 89.9 \pm 31.6$ (months), by substituting $Ap_{max}(25) = 17.3 \pm 1.8 \pm 1.2$ into this relationship, in which $\sqrt{12.7^2 + 8.5^2 + 27.7^2} = 31.6$. According the time of $Ap_{min}(25)$ (October 2017), the peak time of $Ap_{max}(25)$ would be predicted to be around October 2017 $+ T_r(25) =$ April 2025 ± 32 (months).

4 Discussions and Conclusions

There are many methods that can be used to predict the maximum amplitude of sunspot cycle (R_m), such as 1) statistical methods, employing the relationship between the inter-cycle parameters (Thompson, 1988; Hathaway et al., 1994) or the early rising rate (Thompson, 1988; Cameron and Schüssler, 2008; Du and Wang, 2012); 2) the functional methods, using mathematical functions containing a few parameters (Hathaway et al., 1994; Du, 2011d) for extrapolating the following monthly values; 3) the geomagnetic precursor methods (Ohl, 1979; Brown and Williams, 1969; Du et al., 2009), using the geomagnetic activity near the solar minimum; and 4) the solar precursor ones (Schatten et al., 1978; Pesnell and Schatten, 2018), using the previous cycle's polar field.

In contrast, there are less methods found to predict the maximum amplitude of geomagnetic index. Geomagnetic activity forecast has been over the order of hours or days (McPherron, 1999; Abunina et al., 2013). The annual or monthly prediction on the geomagnetic activity is within a limited accuracy (over 20%) due to the irregular variation in the time series (McPherron, 1999; Gordon, 2015). At earlier years, Kane

(1988) even pointed out that it is impossible to forecast the long-term geomagnetic activity through analyzing the time series of the Ap and aa indices. The geomagnetic activity near the solar minimum or at the decreasing phase of the solar cycle has been widely used to predict the maximum amplitude of sunspot cycle, but were seldom used
5 to predict the maximum amplitude of the geomagnetic activity itself.

In the current work, we analyzed the relationships between the maxima (aa_max) and minima (aa_min) of the aa index for the 11-year solar cycle, and between the maxima (Ap_max) and minima (Ap_min) of the Ap index. It is found that aa_max (Ap_max) is well correlated to the preceding minimum, aa_min (Ap_min), with a correlation coeffi-
10 cient of about $r = 0.86$. So, these relationships can be used to predict the strength of geomagnetic activity for the ensuing cycle, $aa_\mathrm{max}(25) = 26.9 \pm 2.6$, or equivalently $Ap_\mathrm{max}(25) = 17.3 \pm 0.5 \pm 1.2$. It implies that the strength of the ensuing cycle 25 would be similar to the average over the past cycles, but higher than that of cycle 24.

The well known 'Waldmeier effect' (Waldmeier, 1939) that the rise time of a solar
15 cycle is well anti-correlated to the amplitude has been widely used to estimate the rise and peak times of a solar cycle if the amplitude has been predicted. However, such a correlation disappears in the aa geomagnetic index. If not considering the data of cycle 24, the rise time of Ap index for the 11-year cycle would be found to be weakly ($r = -0.404$) correlated to the following maximum (Ap_max). Using this correlation, one
20 could roughly estimate the rise time, $T_\mathrm{r}(25) \sim 89.9 \pm 31.6$ (months), and the peak time, April 2025 ± 32 months, of geomagnetic activity for the ensuing cycle 25. Certainly, this estimate is much less reliable than the predictions on the peak size.

According the analysis above, the main conclusions of this study may be summarized as follows,

25 1. The maximum aa index for the 11-year cycle (aa_max) is found to be well correlated to the preceding minimum (aa_min), with a correlation coefficient of $r = 0.860$. As a result, the maximum for the ensuing cycle 25 is predicted to be $aa_\mathrm{max}(25) = 26.9 \pm 2.6$. This value is equivalent to $Ap_\mathrm{max}(25) = 17.3 \pm 1.8 \pm 1.2$ if employing the high correlation between aa and Ap ($r = 0.939$).

2. The maximum Ap index for the 11-year cycle (Ap_{max}) is also found to be well correlated to the preceding minimum (Ap_{min}), with a correlation coefficient of $r = 0.862$. As a result, the maximum for the ensuing cycle 25 is predicted to be $Ap_{\text{max}}(25) = 19.0 \pm 1.6$.

3. The rise time of the $aa(Ap)$ index for the 11-year cycle is found to be nearly uncorrelated to the following maximum, $r = -0.16(-0.17)$.

4. If the data for cycle 24 were not considered, the rise time of the Ap index for the 11-year cycle would be weakly correlated to the following maximum, $r = -0.404$ at a confidence level of 62%. The rise time would be roughly estimated to be $T_r(25) \sim 89.9 \pm 31.6$ (months), and the peak time of the geomagnetic activity for the ensuing cycle 25 would be estimated to be around April 2025 ± 32 months.

Acknowledgements.

References

Abunina, M., Papaioannou, A., Gerontidou, M., Paschalis, P., Abunin, A., and more: Forecasting Geomagnetic Conditions in near-Earth space, Journal of Physics: Conference Series, 409, id. 012197, 2013.

Bartels, J.: Discussion of time variations of geomagnetic activity indices Kp and Ap 1932-1961, Ann. Geophys., 19, 1–20, 1963.

Brown, G.M., Williams, W.R.: Some properties of the day-to-day variability of Sq(H), Planet. Space Sci., 17, 455, 1969.

Cameron, R., Sch*ü*ssler, M.: A robust correlation between growth rate and amplitude of solar cycles: consequences for prediction methods, Astrophys. J., 685, 1291–1296, 2008.

Chen, S., Chai, L., Xu, K., Wei, Y., Rong, Z., and Wan, W.: Estimation of the Occurrence Probability of Extreme Geomagnetic Storms by Applying Extreme Value Theory to Aa Index, J. Geophys. Res.: Space Physics, 124, 9943–9952, 2019.

Cliver, E. W., Boriakoff, V., and Feynman, J.: Solar variability and climate change: Geomagnetic aa index and global surface temperature, Geophys. Res. Lett., 25, 1035–1038, 1998.

Dobrica, V., Demetrescu, C., Boroneant, C., and Maris, G.: Solar and geomagnetic activity effects on climate at regional and global scales: Case study-Romania, J. Atmos. Sol. Terr. Phys., 71, 1727–1735, 2009.

Du, Z. L.: The correlation between solar and geomagnetic activity – Part 1: Two-term decomposition of geomagnetic activity, Ann. Geophys., 29, 1331–1340, 2011a.

Du, Z. L.: The correlation between solar and geomagnetic activity – Part 2: Long-term trends, Ann. Geophys., Ann. Geophys., 29, 1341–1348, 2011b.

Du, Z. L.: The correlation between solar and geomagnetic activity – Part 3: An integral response model, Ann. Geophys., 29, 1005–1018, 2011c.

Du, Z. L.: The Shape of Solar Cycle Described by a Modified Gaussian Function, Solar. Phys., 273, 231–253, 2011d.

Du, Z. L., and Wang, H. N.: The relationships of solar flares with both sunspot and geomagnetic activity, Research in Astron. Astrophys., 12, 400–410, 2012.

Du, Z. L., Li, R., and Wang, H. N.: The Predictive Power of Ohl's Precursor Method, Astron. J., 138, 1998–2001, 2009.

Du, Z. L., and Wang, H. N.: Predicting the solar maximum with the rising rate, Science China (Physics, Mechanics & Astronomy), 55, 365–370, 2012.

Echer, E., Gonzalez, W. D., Gonzalez, A.L.C. et al.: Long-term correlation between solar and geomagnetic activity, J. Atmos. Sol. Terr. Phys., 66, 1019–1025, 2004.

El-Borie, M. A., El-Taher, A. M., Thabet, A. A., and Bishara, A. A.: The impact of asymmetrical distribution of solar activity on geomagnetic indices throughout five solar activity cycles, Adv. Spa. Res., 64, 278–286, 2019.

Gavrilyeva, G. A., Ammosov, P. P., Ammosova, A. M., Koltovskoi, I. I., and Sivtseva, V. I.: Geomagnetic activity signature in seasonal variations of mesopause temperature over Yakutia, Proceedings of the SPIE, 10466, id. 1046670, 2017.

Gonzalez, W. D., Gonzalez, A. L. C., Tsurutani, B. T. et al.: Solar wind-magnetosphere coupling during intense magnetic storms (1978-1979), J. Geophys. Res., 94, 8835–8851, 1989.

Gonzalez, W. D., Joselyn, J. A., Kamide, Y. et al: What is a geomagnetic storm?, J. Geophys. Res., 99, 5771–5792, 1994.

Gordon, R.: Forecasting geomagnetic activity at monthly and annual horizons: Time series models, J. Atmos. Sol. Terr. Phys., 133, 111–120, 2015.

Hathaway, D. H., Wilson, R. M., and Reichmann, E. J.: The shape of the sunspot cycle, Solar. Phys., 151, 177–190, 1994.

Kane, R. P.: Forecasting geomagnetic activity, PAGEOPH., 126, 85–101, 1988.

Li, Y.: Predictions of the features for sunspot cycle 23, Sol. Phys., 170, 437–445, 1997.

Lukianova, R., Alekseev, G., and Mursula, K.: Effects of station relocation in the aa index, J. Geophys. Res., 114, A02105, 2009.

Marat, D., Galina, D., Viktor, D., and Anna, D.: Dependence of the F2-layer critical frequency median at midlatitudes on geomagnetic activity, Sol. Terr. Phys., 64, 278–286, 2017.

Mayaud, P. N.: The aa indices: A 100-year series characterizing the magnetic activity, J. Geophys. Res., 77, 6870–6874, 1972.

McPherron, R.L.: Predicting the Ap index from past behavior and solar wind velocity, Physics and Chemistry of the Earth, Part C: Solar, Terrestrial & Planetary Science, 24, 45–56, 1999.

Nevanlinna, H., and Kataja, E.: An extension of the geomagnetic activity index series aa for two solar cycles (1844-1868), Geophys. Res. Lett., 20, 2703–2706, 1993.

Ohl, A. I.: A new method of very long-term prediction of solar activity, In NASA. Marshall Space Flight Center Solar-Terrest. Predictions Proc., 2, 258–263, 1979.

Pesnell, W. D., Schatten, K. H.: An early prediction of the amplitude of Solar Cycle 25, Solar. Phys., 293, 112, 1994.

Prestes, A., Rigozo, N. R., Echer, E., and Vieira, L. E. A.: Spectral analysis of sunspot number and geomagnetic indices (1868-2001), J. Atmos. Sol. Terr. Phys., 68, 182–190, 2006.

Russell, C. T., and Mulligan, T.: The 22-year variation of geomagnetic activity: Implications for the polar magnetic field of the Sun, Geophys. Res. Lett., 22, 3287–3288, 1995.

Schatten, K. H., Scherrer, P. H., Svalgaard, L., and Wilcox, J. M.: Using dynamo theory to predict the sunspot number during solar cycle 21, Geophys. Res. Lett., 5, 411–414, 1978.

Singh, P. R., Tiwari, C. M., Saxena, A. K., Agrawal, S. L.: Quasi-biennial periodicities and heliospheric modulation of geomagnetic activity during solar cycles 22C24, Mon. Not. Roy. Astron. Soc., 94, 105005, 2019.

Thompson, R. J.: The rise of solar cycle number 22, Solar. Phys., 117, 279–289, 1988.

Tsurutani, B. T., Gonzalez, W. D., Gonzalez, A. L. C. et al.: Corotating solar wind streams and recurrent geomagnetic activity: A review, J. Geophys. Res., 111, A07S01, 2006.

Waldmeier, M.: Über die Struktur der Sonnenflecken, Astron. Mitt. Zrich, 14, 439–450, 1939.