On the Evolution of Geomagnetic Activity in the Last 300 Years. Implications Regarding Solar Wind Dynamic Pressure and Magnetopause Standoff Distance

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Abstract. The geomagnetic activity has long been known as being the result of the interaction of the solar wind and the heliospheric magnetic field with the magnetosphere and ionosphere. It has been used to infer information on various solar and heliospheric parameters prior to instrumental space era. The paper is an attempt to reconstruct back to 1700 the evolution of the interdecadal geomagnetic activity as measured by the aa geomagnetic index, of the solar wind dynamic pressure on the magnetosphere, and of the magnetopause standoff distance, based on correlations between geomagnetic indices and solar parameters, established for instrumental space era. Solar-cycle-free data time series have been used.

Keywords: Geomagnetic activity, Solar wind dynamic pressure, Magnetopause standoff distance, Reconstructions

Introduction

The oldest quantitative information on solar activity concerns the photosphere, by means of the well known number of sunspots that evolve on Sun's surface. It dates back to the Maunder Minimum times (1645-1715). Quantitative information regarding the solar outputs in the space volume affected by the solar activity, the heliosphere, that includes the periterrestrial space, has not been possible until the advent of space era. First in situ measurements on solar, heliospheric and magnetospheric parameters were acquired in 1964 only, making the need to infer information on longer time scales obvious. It has long been recognized that there is a close connection between the geomagnetic activity as recorded on the Earth's surface in the geomagnetic observatories and solar processes and phenomena on Sun's surface or in the solar corona and heliosphere. Some of the noticed correlations enabled extrapolating the instrumental information back to 1868-1870, when the oldest quantitative information on the geomagnetic activity is recorded (Feynman and Crooker, 1978; Svalgaard, 1978; Andreasen, 1997; Lockwood et al., 1999; Svalgaard and Cliver, 2005; Svalgaard and Cliver, 2007; Rouillard and Lockwood, 2007; Lockwood et al., 2009; Demetrescu et al., 2010). The reconstruction of solar and heliospheric parameters using geomagnetic activity explicitly assumes that correlations seen between solar wind and heliospheric magnetic field parameters, on one hand, and geomagnetic indices, on the other, could be extrapolated before 1964 – the beginning of space age. The same applies for the other outcomes of spacecraft measurements, such as the validity of the Parker spiral theory, the heliolatitudinal independence of the heliospheric magnetic flux from the Sun, and the coupling function between the solar wind and the magnetosphere.

In a previous work, Dobrica et al. (2012) reconstructed the solar wind dynamic pressure on magnetosphere, P, and the magnetopause standoff distance, L, before space era, back to 1870, based on the very good correlation of P with the geomagnetic activity (aa index) during the space era. This paper is an attempt to reconstruct the aa index, the solar wind dynamic pressure, and, implicitly, the standoff distance of the magnetopause to the year 1700, using sunspot number R (1700-2008), aa (1868-2008) and P (1964-2008) available data.

Data

The annual means of the sunspot number were available at ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS/INTERNATIONAL/yearly/YEARLY database. Annual mean values for the 1868-2010 time interval of the geomagnetic index aa were available at http://isgi.cetp.ipsl.fr/lesdonne.htm. Values of the solar wind dynamic pressure (1964-2008) from ftp://nssdcftp.gsfc.nasa.gov/spacecraft_data/omni/ were used. Besides these data, we also used the Earth's magnetic moment that intervenes in the calculation of the magnetopause standoff distance. The geomagnetic dipole moment was determined using the first three Gauss coefficients of the main geomagnetic field model gufm1 (Jackson et. al., 2000), http://jupiter.ethz.ch/~cfinlay/gufm1.html, covering the time span 1590-1990, extended to 2008 with data from the IGRF-11 model (Finlay et. al., 2010) http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html. For the time interval before 1860, for which a linear extrapolation of the magnetic moment is included in gufm1, we also took advantage of the CALS7K geomagnetic model of Korte and Constable (2005), based on arheomagnetic data.

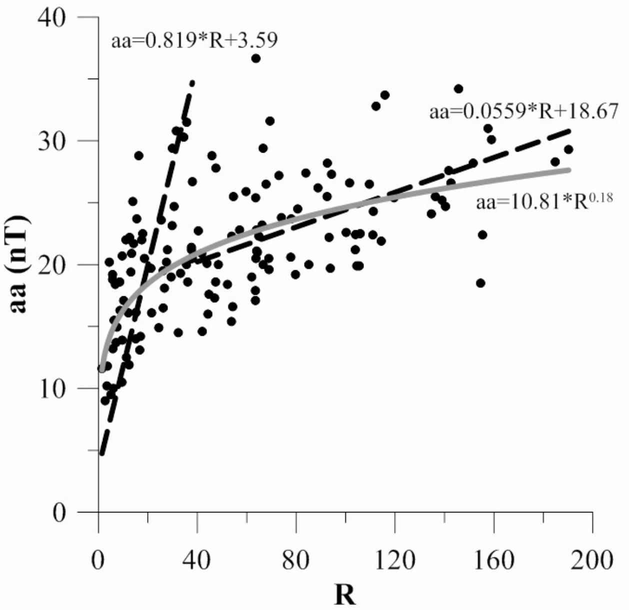

Fig. 1 – Scatter plot of the *aa* and R for the 1868-2008 time interval

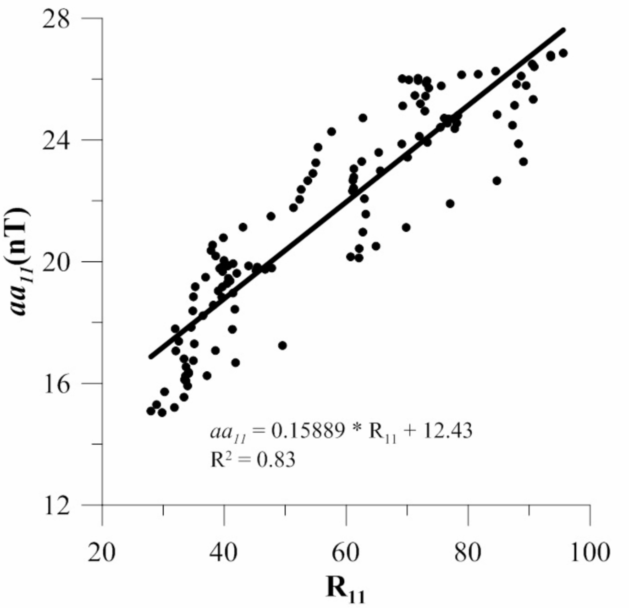

Fig. 2 – Scatter plot of the 11-year smoothed *aa* and R for the 1875-2001 time interval

Results and discussion

Reconstruction of the aa index to 1700

At first sight, there are large differences between the long-term appearance of the time series of the sunspot number R and of the geomagnetic *aa* index, that have long been noticed, of which the two peaks of *aa* in a solar cycle and the increase of the *aa* minimum values in the twentieth century are standing out. A scatter plot *aa*-R is discouraging any attempt to find a simple correlation between the two time series (Fig. 1). Svalgaard et al. (2003) presented a quadratic dependence of IDV(R), while Demetrescu and Dobrica (2010) included the solar cycle 23 data in the analysis and inferred a slightly different dependence, namely IDV=4.52 +0.73$R^{1/2}$ nT. The latter also indicated a possible separation in two populations that can be linearly correlated, reproduced in Fig. 1. IDV (the interdiurnal variability index), derived by Svalgaard and Cliver (2005), is a geomagnetic index that responds to variations in the heliospheric magnetic field strength B. In view of the good correlation between IDV and *aa* (Demetrescu et al., 2010), a tentative power dependence of *aa*-(R) is plotted in Fig. 1. A recent study published by Du et al. (2011) also showed the complexity of the *aa*(R) relationship. The difficulty resides in the physics behind the two time series. Numerous studies (e.g. Richardson et al., 2002; Richardson and Cane, 2012 a; b) showed that the first peak in *aa*, occurring at solar cycle maxima, is a result of solar eruptive phenomena interacting with the magnetosphere, while the second one, occurring in the descending phase of the solar cycle, is mainly a result of the action on the magnetosphere of fast solar wind and of corotating interaction regions in the solar wind. As regards the increase of *aa* minimum values in the twentieth century, Feyman (1982), followed by Ruzmaikin and Feyman (2001) and Georgieva and Kirov (2011), advanced the idea of it being caused by non-sunspot-related solar activity, which, in turn (Georgieva and Kirov, 2011) is related to the evolution of the poloidal solar field. Demetrescu and Dobrica (2008) have previously shown that the increase is the solar Gleissberg cycle signature in *aa* and Demetrescu and Dobrica (2010) showed that (1) other solar outputs, such as the open solar flux, the heliospheric magnetic strength, the solar wind speed and density, the total solar irradiance, and various geomagnetic indices such as *aa*, IDV, IHV, have the same behavior in terms of 11-year averages meant to filter out the solar cycle signature, and (2) that behavior is a result of superimposing in data of the magnetic (Hale) and long (Gleissberg) cycles signatures.

Next, we follow this line of thinking and look for correlations in terms of 11-year averages, as we have already applied in case of our attempt to reconstruct the solar wind dynamic pressure evolution to 1868 (Dobrica et al., 2012). In case of *aa*, in order to reduce the noise in the 11-year average time series aa_{11}, produced by the double peak in a solar cycle, the time series was first smoothed with a 5-year running averages filter. The linear relationship of Fig. 2 is then used to reconstruct the 11-year averages back to 1700. The results are shown in Fig. 3, together with the aa_{11} time series based on the original *aa* time series of annual means (Mayaud, 1972; 1973). The latter was corrected by adding 3 nT to all values prior to 1958, as suggested by Svalgaard and Cliver (2007).

Reconstruction of the solar wind dynamic pressure and the standoff distance of the magnetopause back to 1700

Dobrica et al. (2012) showed that there is a good correlation between the 11-year smoothed series of *aa* index (aa_{11}) and that of solar wind dynamic pressure (P_{11}), shown in Fig. 4. In Fig. 5 the extrapolation of P_{11} based on that correlation is presented along with P_{11} values from instrumental data for comparison. It shows a general increase since 1700, with depressions corresponding to the Dalton Minimum (~1810) and around 1900. Also, pronounced depressions after 1950 and after 2000 are evident. These characteristics correspond to variations seen in other solar and heliospheric parameters (Demetrescu and Dobrica, 2010) and are a result of superposition of Hale and Gleissberg cycles signatures.

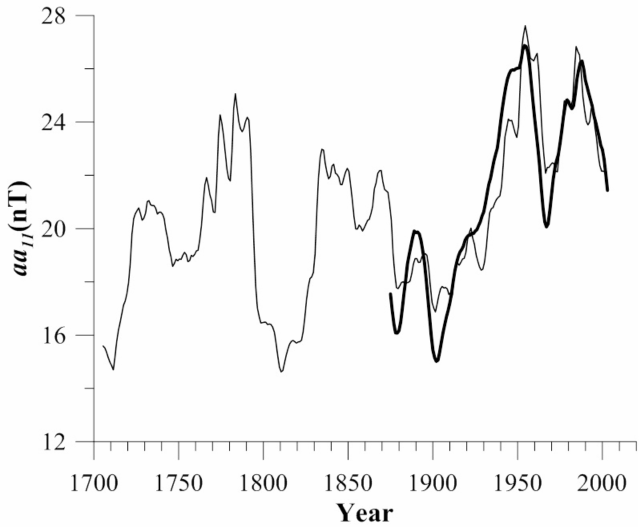

Fig. 3 – Evolution of the *aa11* given by the measured (thick line) and reconstructed data

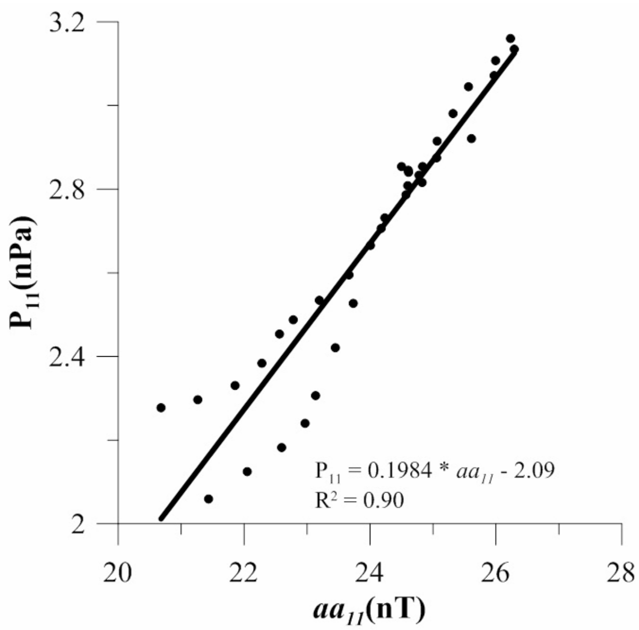

Fig. 4 – Scatter plot of the 11-year smoothed P and *aa* for the 1969-2003 time interval

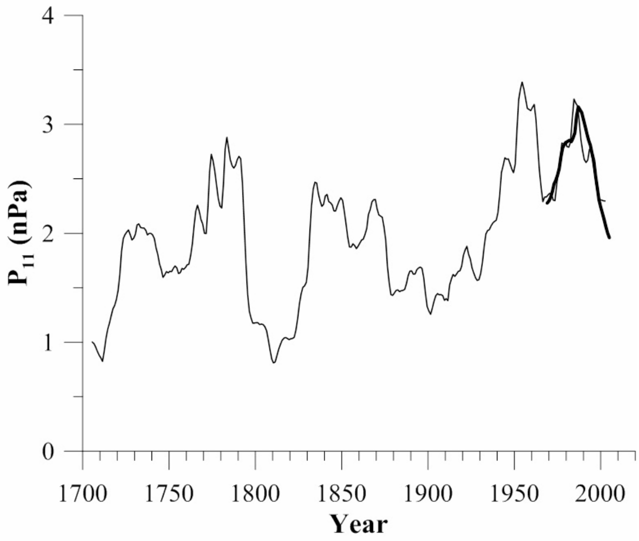

Fig. 5 – Evolution of the P11 given by the measured (thick line) and reconstructed data (thin line)

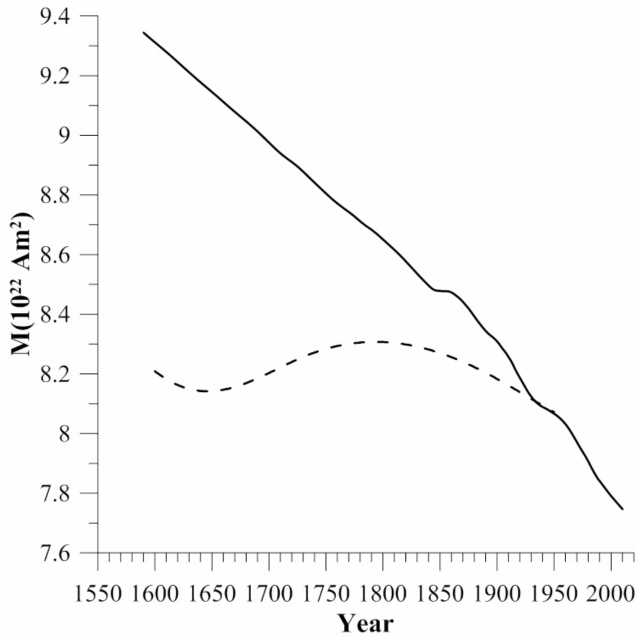

Fig. 6 – Evolution of the Earth's magnetic moment given by *gufm1* and IGRF-11 (continuous line) and CALS7K (dashed line) main field models

The standoff distance of the magnetopause is controlled by the balance of the solar wind dynamic pressure on the magnetosphere and the pressure of the Earth's magnetic field

$$P = \frac{B^2}{8\pi} = \frac{1}{8\pi}\left(\frac{fM}{L^3}\right)^2, \qquad (1)$$

where B is the heliospheric magnetic field strength, P is the dynamic pressure of the solar wind, M is the magnetic moment of the Earth and L is the magnetopause standoff distance. Knowing both the magnetic moment of the Earth and the solar wind dynamic pressure one can determine the standoff distance of the magnetopause.

It is well known that the magnetic field of the Earth is not constant in time. Starting from 1590 the magnetic dipole moment of the Earth has decayed with an average rate of about 5% per century. In Fig. 6 we show the dipole moment evolution as determined from the *gufm1* model of Jackson et al. (2000). The determination of the geomagnetic dipole moment using *gufm1* is more accurate from 1860 on, since the availability of the observatory and satellite provided data; before 1860 the model is based on historical directional data and on linearly extrapolated back in time Earth's magnetic moment. We alternatively used for the interval prior to 1860 the CALS7K model for the dipole magnetic moment as determined from arheomagnetic data by Korte and Constable (2005), also plotted in Fig. 6.

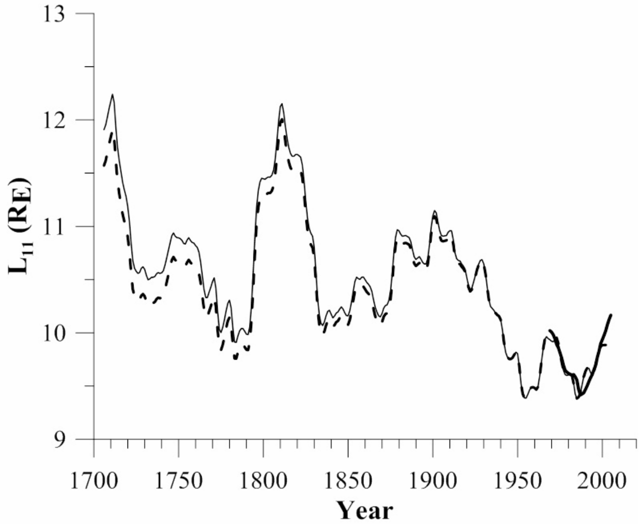

Fig. 7 - Evolution of the L11 as given by the measured (thick line) and reconstructed data using M from *gufm*1 and IGRF-11 (thin line) and from CALS7K (thick dotted line)

Fig. 7 shows the evolution for the period 1700-2005 of the reconstructed standoff distance of the magnetopause, along with the evolution as given by instrumental data. The evolution of the standoff distance of the magnetopause depends rather little on the evolution of the geomagnetic dipole moment. The main influence on that distance is exerted by the solar wind dynamic pressure. In the time interval 1700-2000 the magnetopause standoff distance shows significant variations, from about 12 Earth radii (R_E) to about 9.5 R_E, with variations of ~1.5-1 R_E after 1800 and around 1900, corresponding to variations in the solar wind dynamic pressure.

Conclusion

Based on a good correlation (correlation factor 0.82) between solar-cycle-free time series of the *aa* geomagnetic index and of the sunspot number, we succeeded to get information on the evolution of the geomagnetic activity back to 1700. In turn, the extrapolated *aa* index was used to reconstruct back to the same time the interdecadal evolution of the solar wind dynamic pressure on magnetosphere and of the magnetopause standoff distance.

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