Solar Wind Dynamic Pressure and Magnetopause Stand-off Distance before the Instrumental Era

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Abstract. Annual means of a variety of measured and reconstructed solar, heliospheric, and magnetospheric parameters show solar activity signatures at the Hale and Gleissberg cycles timescales. An attempt is made to reconstruct the solar wind dynamic pressure on magnetosphere back to 1873, almost 100 years before the first space measurements, to detect characteristic patterns at that timescale. Also, the consequences on the sunward magnetosphere extension in the solar wind (the so-called magnetopause stand-off distance) are discussed in connection with the variation of the geomagnetic dipole moment in the same time interval.

Keywords: solar wind pressure, magnetopause stand-off distance, long-term evolution

Introduction

The space era has brought a wealth of *in situ* data on the radiative, particle, and magnetic field outputs of the Sun, in which the terrestrial magnetosphere is embedded, creating a data base for space weather studies, when correlated and combined with data on magnetospheric and ionospheric current systems described by various geomagnetic indices as proxy.

The space weather concept, that regards the short-term variations in the different forms of solar activity, their prediction and effects on the near-Earth environment and technology, is evolving on a background offered by the space climate concept, which refers to long-term changes in the Sun, and its effects in the heliosphere and upon the Earth, including the atmosphere and climate. As in situ measurements that started in 1964 cover only a limited time span (cycles 20-23) any study of the long term evolution should resort to reconstructed solar and heliospheric parameters.

Reconstructions of the solar wind (SW) velocity, V, and heliospheric magnetic field (HMF), B, at 1 AU, and of the open solar magnetic flux, F_S, were based on correlations established between these parameters and certain geomagnetic indices (*aa* and equivalents, IDV, SI) for the instrumental period (Feynman and Crooker, 1978; Svalgaard, 1978; Andreasen, 1997; Lockwood et al., 1999; Svalgaard and Cliver, 2005; Svalgaard and Cliver, 2007; Rouillard and Lockwood, 2007; Demetrescu et al., 2010; Lockwood et al., 2010). They could have been extrapolated back to 1868-1870, when the *aa* and, respectively, IDV time series start. All these reconstructions explicitly assume that correlations seen between SW and HMF 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. Other issues related to the correlations mentioned, such as best coupling functions of energy transfer to the magnetosphere, the effects of gaps in HMF and SW data, and the dependence on time scales considered have been surveyed by Finch and Lockwood (2007) (see a detailed discussion in Demetrescu et al. (2010)).

In this paper we reconstruct the evolution of the solar wind dynamic pressure on magnetosphere, *P*, back to 1873, based on the linear correlation with the geomagnetic index *aa* during the time span with instrumental data. A related parameter, namely the stand-off distance of the magnetopause is discussed as well.

Data

As we investigate long-term evolution of P, we first calculated annual means from daily averages available at ftp://nssdcftp.gsfc.nasa.gov/spacecraft_data/omni/, plotted in Fig. 1 together with *aa* annual mean values available at http://isgi.cetp.ipsl.fr/lesdonne.htm. Following a well known debate on *aa* values (see details in Demetrescu and Dobrica (2008); Demetrescu et al. (2010)) and a suggestion by Svalgaard and Cliver (2007), we used a corrected *aa* time series by adding 3 nT to all values before 1957.

Results and discussion

Reconstruction of solar wind dynamic pressure

Both *P* and *aa* of Fig. 1 show 11-year variations. There are, however, significant differences between the two parameters, due to the different physics behind, which results in a weak correlation coefficient, of only 0.70. When the 11-year variations are smoothed out, for instance by means of running 11-year averages (thick lines superimposed in Fig. 1), one gets a very good correlation illustrated in Fig. 2 (correlation coefficient of 0.93) and expressed analytically by the regression line

$$P_{11} = 0.1867 \times aa_{11} - 1.8197 \qquad (1)$$

where P_{11} and aa_{11} are values of the smoothed time series.

Applying Eq. 1 to values of the 11-year running averages of *aa* time series (aa_{11}), we obtain the corresponding 11-year smoothed time series of *P*, P_{11}, plotted in Fig. 3 in comparison with the aa_{11} time series. The thick line superimposed on P_{11} is 11-year running means time series of measured *P* values of Fig. 1. An increase of about 80% is seen between the average 1873-1910 and the average of 1960-2000. Also, before 1900 and after 1950 variations of about 30% around the mentioned averages are present. Using the uncorrected *aa* values would result in significantly lower values, by about 0.6 nPa, of the derived SW dynamic pressure at the beginning of the 20[th] century, as it can be seen in Fig.3, with consequences in estimating the evolution at the 100-year timescale.

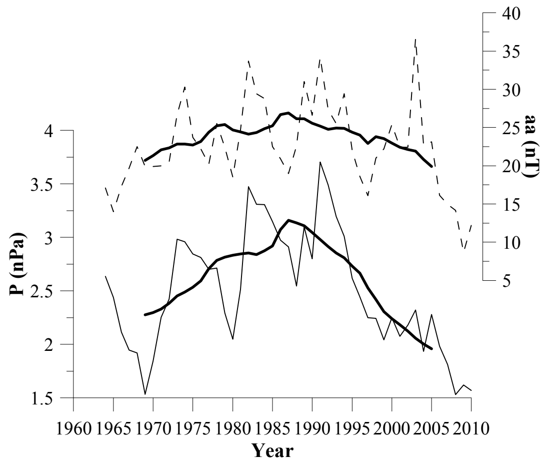

Fig. 1. The evolution of annual means of solar wind pressure at 1 AU (thin solid line) and of geomagnetic index aa (broken line) between 1964 – 2010. 11-year smoothed time series (thick solid lines) are superimposed

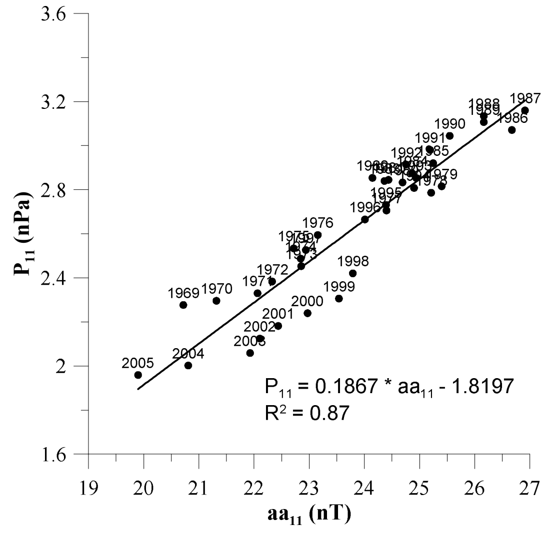

Fig. 2. Scatter plot of 11-year smoothed P and aa for the 1969 – 2005 timespan

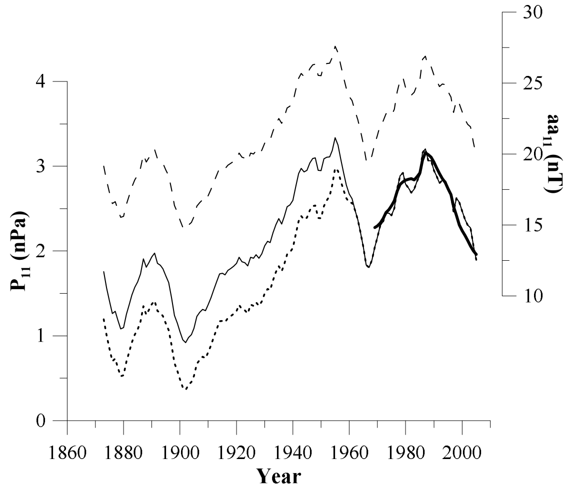

Fig. 3. Reconstruction of the solar wind dynamic pressure between 1873-2005. Thin solid line – reconstruction of P_{11} based on corrected (see text) aa time series (long-dashed line); short-dashed line – reconstruction of P_{11} based on uncorrected aa; thick solid line – P_{11} based on measured values

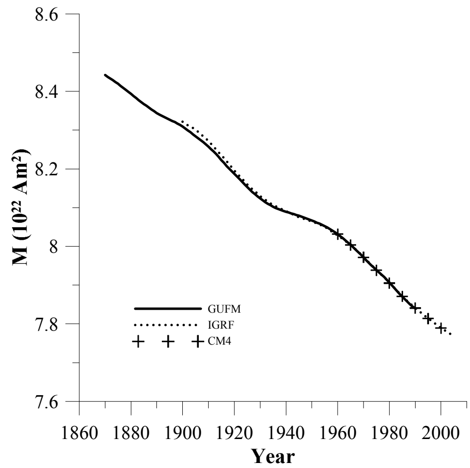

Fig. 4. The variation of the geomagnetic dipole moment given by three geomagnetic models with long timespan, between 1860-2004.

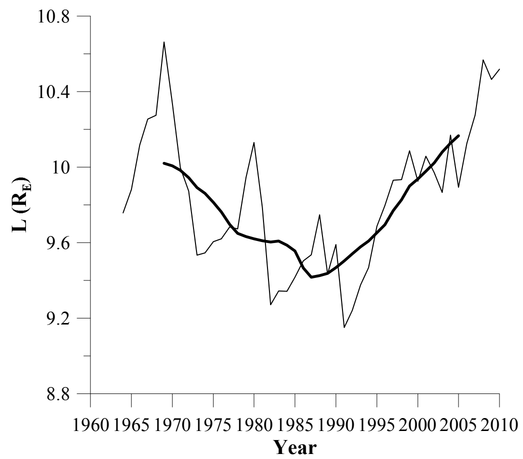

Fig. 5. Evolution of the magnetopause stand-off distance in the space (instrumental) era. Annual values (thin line) and 11-year running averages (thick line).

Reconstruction of the magnetopause stand-off distance

The magnetosphere shape and dimensions (the surface and radius of the magnetosphere cross-section in the solar wind) are a result of the equilibrium between the magnetic pressure of the geomagnetic field and the dynamic pressure of the solar wind in which the Earth and its magnetosphere are embedded (Chapman and Ferraro, 1931). Accordingly, for the sub-solar geomagnetic field B produced by the Earth's magnetic moment M at the distance L where the equilibrium is reached,

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

where f is a constant which depends on the character of the interaction of the solar wind particles with the magnetopause. In this case, f = 2.44. In the international system of units, L would be given by

$$L = \left(\frac{f^2 M^2}{2\mu_o P}\right)^{1/6} \quad (3)$$

where μ_o is the permeability of the vacuum. L is also called 'the stand-off distance of the magnetopause' and is usually commensurate in Earth's radii (R_E=6370km).

More sophisticated models (e.g. Pudovkin et al., 1998 and the references therein) included also the effect of the southward turning of the HMF, capable of shortening the stand-off distance by 0.5-1.5 R_E compared to periods of northward HMF. In this paper we are interested in the long-term evolution of the SW dynamic pressure and magnetopause stand-off distance and consequently deal with annual and 11-year running averages in which these short-term fluctuations are incorporated. A recent review by Shue and Song (2002) discusses the three types of models advanced to describe the location and shape of the magnetopause, namely theoretical, 2-D empirical, and 3-D numerical models.

The magnetic moment of the terrestrial dipole can generally be expressed by means of the first order coefficients of a spherical harmonic model of the main field (e.g. Chapman and Bartels, 1940) as

$$M = \frac{4\pi R_E^3}{\mu_o}\sqrt{\left(g_1^0\right)^2 + \left(g_1^1\right)^2 + \left(h_1^1\right)^2} \; . \quad (4)$$

The coefficients are determined by a spherical harmonic analysis of measured data for a certain geomagnetic epoch, from geomagnetic observatories, repeat stations and geomagnetic surveys – at the Earth's surface, and from dedicated space missions – at altitudes of several hundred kilometers. At present several models describing the evolution of the main field are available (Olsen et al., 2007), of which *gufm* (Jackson et al., 2000), IGRF (Finlay et al., 2010) and CM4 (Sabaka et al., 2004) cover longer timespans: 1590-1990, 1900-2010, and, respectively, 1960-2002. For our study the coefficients of the three models, available at http://www.epm.geophys.ethz.ch/~cfinlay/gufm1/model/gufm1, http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html, and http://core2.gsfc.nasa.gov/cm/ for each year, were used. The evolution of M in the timespan of interest is shown in Fig. 4. It is mainly characterized by a decrease of about 8% in the last 150 years.

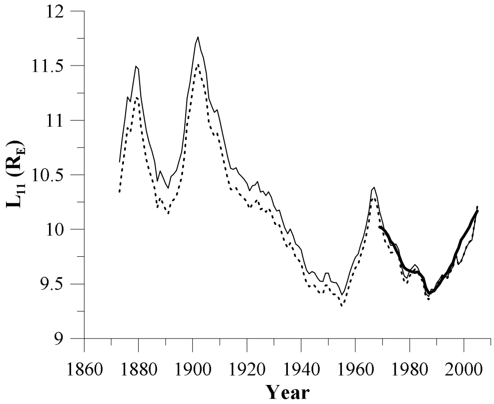

Fig. 6. Reconstruction of the magnetopause stand-off distance between 1873 -2005. Thin solid line – reconstruction of L_{11}; dashed line – reconstructed L_{11} keeping M constant at its value for year 2000; thick solid line – 11-year running averages of the calculated annual mean values based on instrumental data

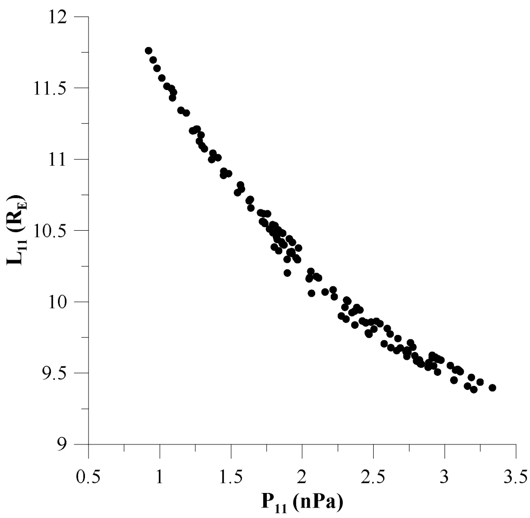

Fig. 7. Dependence of the magnetopause stand-off distance of Fig. 6 on the reconstructed P11 of Fig. 3.

The variation of L, during the time span since *in situ* measurements of the solar wind parameters were performed by various space missions, calculated using Eq. 3, is shown in Fig. 5. It appears that it is dominated by the variation of the SW dynamic pressure (see details in Demetrescu et al., 2011). Accordingly, when P is increasing, L is decreasing, and vice-versa. The superimposed thick line is the 11-year running averages time series of L. 11-year solar-cycle variations amount to 1 R_E peak to trough.

Applying Eq. 3 with reconstructed P_{11} values results in the variation of the smoothed stand-off distance for the 1873-present timespan, shown in Fig. 6. The dominance in L of the P variation over the Earth's magnetic moment one is evident at this timescale too. The weak effect of the 8% decrease of the Earth's magnetic moment is shown in Fig. 6 by the plot of reconstructed L (dashed line) keeping M constant at its value for the year 2000. That effect is of about 2% of the reconstructed values for the end of the 19th century. Variations of about 1 R_E (peak to trough) characterize the 40 years at the end of the 19th and the beginning of the 20th centuries as well as the 40 years after 1957, while a larger variation, of ~1.5 R_E can be seen between the beginning and the end of the 20th century (Fig. 6). In Fig. 7 the dependence of L on P is shown, illustrating the power low dependence of Eq. (3). The variations at the beginning and end of the 20th century show up in Fig. 7 as a range of about 0.12 R_E characterizing L_{11} values for large P_{11}.

Conclusion

The solar wind dynamic pressure on magnetosphere and the corresponding magnetopause stand-off distance were reconstructed based on 11-year running averages of instrumental data. These parameters show the same long-term variation as other parameters of the heliospheric and magnetospheric environment, such as the open solar flux, photospheric magnetic activity, total solar irradiance, cosmic ray flux, heliospheric magnetic field, solar wind velocity, magnetospheric activity (Demetrescu et al., 2010), characterized by the superposition of MC and GC signatures in reconstructed 11-year running averages. A pronounced increase of *P* and a decrease of L in the 20th century by about 80% have been found. Superimposed, a characteristic variation before 1900 and after 1960, with amplitudes of about 30% with respect to the 1960-2000 mean value, is also present.

Results of this paper are a contribution to space climate characterization at centennial timescales.

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