OSCILLATIONS AT SUB-CENTENNIAL TIME SCALES IN THE SPACE CLIMATE OF THE LAST 150 YEARS*

VENERA DOBRICĂ, CRIȘAN DEMETRESCU

"Sabba S. Ştefănescu" Institute of Geodynamics of the Romanian Academy, 19–21, Jean-Louis Calderon St., 020032 Bucharest, Romania, venera@geodin.ro

The 'space climate' and 'space weather' concepts, developed in the last decades, get an increasing significance, as the technological development of humanity, which includes new and new space missions, on one hand, and an increasing need for ground technologies to transport the energy, on the other, is increasing. While space weather affects directly humanity on short terms, the space climate, which refers to long-term solar variability and its effects in the heliosphere and upon the Earth, induces subtler consequences.

Our earlier results regarding the long-term evolution of the solar – terrestrial interactions (*e.g.,* Demetrescu, Dobrică, 2008; Demetrescu *et al.*, 2010) showed that signals at the solar magnetic (MC) and solar Gleissberg (GC) timescales can be found in any of the solar, heliosphere, magnetosphere and ionosphere parameters, and they are quite similar in the heliosphere – magnetosphere environment, pointing to a common pacing source, the solar dynamo.

The present study is focused on the evolution of the coupled system heliosphere – magnetosphere, for the last 150 years, at the timescales of Hale (22 years) and Gleissberg (60–90 years) solar cycles, with a special regard to the low level of solar activity in the last solar cycle. The aim is to bring the information to the present, by using a different methodology, namely Hodrick and Prescott (1997) (HP) type analysis. The results complete the former ones to the present and characterize the space climate in the last 400 years, at the timescales of the Gleissberg and Hale solar cycles.

Key words: Sun-heliosphere-magnetosphere environment, Hale and Gelissberg solar cycles timescales.

1. INTRODUCTION

The space climate concept refers to long-term solar variability and its effects in the heliosphere and upon the Earth. The eruptive processes in the solar atmosphere (flares, coronal mass ejections), electromagnetic radiation (infrared, UV, and X), solar wind (SW), and interplanetary magnetic field (IMF) are aspects of the solar variability. The complex interaction of solar activity outputs with the terrestrial magnetosphere modifies the electric currents of the environment, producing geomagnetic field variations which can be detected from the magnetosphere down to the ground. While the electromagnetic solar radiation creates the charged particles of the ionosphere, contributing to the Sq current system responsible for the regular diurnal magnetic field variations, the particle and magnetic field outputs of the Sun interact with the magnetosphere, producing current systems that are sources of the irregular variations called the disturbance magnetic field that characterizes the so-called geomagnetic activity. The study of geomagnetic activity, characterized by means of geomagnetic indices, has long contributed to progress in solar–terrestrial science because long geomagnetic time series recorded at the terrestrial surface in geomagnetic observatories in the last 150 years have provided means to characterize the Sun–Earth interaction at times prior to the space era (1964 was the starting point for spatial missions from which we have benefitted of *in situ* data on heliospheric and solar wind parameters).

Our earlier results regarding the long term evolution of the solar terrestrial interactions (*e.g.*, Demetrescu, Dobrică, 2008; Demetrescu *et al.*, 2010) showed that signals at the solar

*Paper presented at the 5th GEOSCIENCE Symposium of the Romanian Society of Applied Geophysics, November 20–22, 2020, Bucharest, Romania

 https://doi.org/10.5281/zenodo.5017697

magnetic (MC) and solar Gleissberg (GC) timescales can be found in any of the solar, heliosphere, magnetosphere and ionosphere parameters, and they are quite similar in the heliosphere – magnetosphere environment, pointing to a common pacing source, the solar dynamo. The present study is focused on the evolution of the coupled system heliosphere-magnetosphere, for the last 150 years, at the timescales of Hale (22 years) and Gleissberg (60–90 years) solar cycles, with a special regard to the low level of solar activity in the last solar cycle.

2. DATA AND THEIR PROCESSING

The **data** used in this study concern time series of parameters describing the space climate that characterize media such as the Sun, the heliosphere and the magnetosphere. Their time series are plotted in Fig. 1.

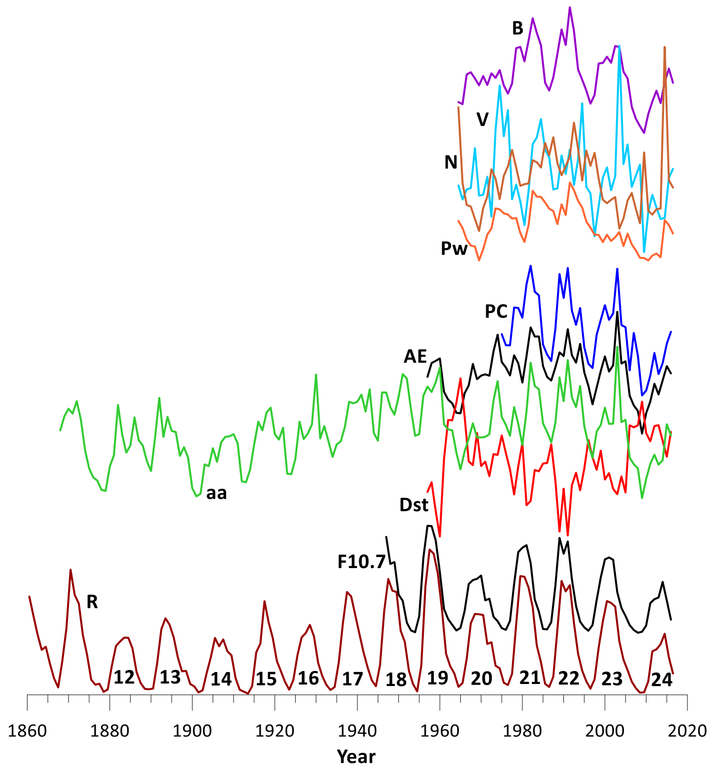

Fig. 1 – Parameters describing the Sun-heliosphere-magnetosphere environment.

Of various indices describing the *solar variability* (Ermolli *et al.*, 2014) we use the international sunspot number (R) and the 10.7 cm solar radio flux (F10.7). The former is a solar index derived from the observations of sunspots on the photosphere, the longest and most commonly used proxy for solar activity. The sunspots observations have been revised by Clette *et al.* (2014), Clette and Lefèvre (2016) and the revisited series are available at http://www.sidc.be/silso/datafiles. The solar radio flux measured at 10.7 cm wavelength, F10.7, whose record extends back to 1947, is the longest record of a physical data that describes the solar activity (Tapping, 2013). It is available through http://www.spaceweather.gc.ca/ solarux/ sx-5-eng.php; http://www.ngdc.noaa.gov/stp/ space weather/solar data/solar features/solar radio/noontime ux/.

The 1 minute *solar wind parameters and heliospheric magnetic field* as measured by NASA's Advanced Composition Explorer

(ACE) spacecraft at the Lagrangean point L1 are available at http://omniweb.gsfc.nasa.gov/. Data for solar wind speed V, particle density N and solar wind pressure Pw, as well as on heliospheric magnetic field intensity B are used in this paper. They are available only after 1964, the beginning of the so-called space era.

The state of the *magnetosphere/ionosphere* is described by the geomagnetic indices designed to proxy electric currents systems developed as a consequence of the interaction of the Earth's magnetic field with the solar wind and heliospheric magnetic field (Dst, AE, PC), and/or the geomagnetic activity – the general effect of such currents on the geomagnetic field at Earth's surface (*aa*, Ap, IHV, IDV, am, aa_c etc). Such data can be downloaded from dedicated site of the International Service of Geomagnetic Indices (ISGI), the reference service of the International Association of Geomagnetism and Aeronomy in derivation, validation and dissemination of geomagnetic indices (http://isgi.unistra.fr/geomagnetic_indices.php). Due to the observed good correlation of IDV with B (Svalgaard, Cliver, 2005) and of IHV with the coupling function BV^2 (Svalgaard, Cliver, 2007), both B and V could be reconstructed back to 1872 and, respectively, to 1890 by the mentioned authors. A detailed account on these and our own reconstructions can be find in Demetrescu *et al.* (2010).

The **data processing** follows up the Hodrick and Prescott (1997) (HP) type analysis, which is able to separate oscillatory features at smaller (*e.g.*, decadal) time-scales from trends representing variations at larger (*e.g.*, centennial) time-scales, to each considered time series. The HP filter separates a time-series y_t into a trend component T_t and a cyclical component C_t such that $y_t = T_t + C_t$. The function for the filter has the form

$$\sum_{t=1}^{n} C_t^2 + \lambda \sum_{t=1}^{n} [(T_t - T_{t-1}) - (T_{t-1} - T_{t-2})]^2$$

where n is the number of samples and λ is the smoothing parameter. The first sum minimizes the difference between the time-series and its trend component (which is its cyclical component). The second sum minimizes the second-order difference of the trend component (which is analogous to minimization of the second derivative of the trend component). If the smoothing parameter is 0, no smoothing takes place. As the smoothing parameter increases in value, the smoothed series becomes more linear. Appropriate values of the smoothing parameter depend upon the data sampling. In our case data being yearly sampled, we apply a smoothing parameter of 100, recommended by Hodrick and Prescott (1997) and checked by us after a few tests with λ varying between 10 and 1600 with a step of 50 (Dobrică *et al.*, 2018).

Variations at larger time-scales seen in the trend given by HP analysis have been further decomposed in two other oscillations, by applying a Butterworth (1930) filtering with certain cut-offs corresponding to periods of 22 and 78 years, associated to the Hale and Gleissberg cycles known to exist in the solar/geomagnetic activity (*e.g.*, Demetrescu, Dobrică, 2008; Demetrescu *et al.*, 2010). It is important to note that no matter what figure was used in our filter design (except the actual period in data), the filtered time series would show the actual oscillations hidden in the unfiltered time series (Demetrescu, Dobrică, 2014, Appendix).

An example of data processing is given in Fig. 2. The *aa* geomagnetic index has been chosen for this illustration, the longest geomagnetic index. The upper plot shows the *aa* annual means time series (grey) and the so-called trend (black). The next plot from top to bottom shows the so-called cyclic component. The two bottom superimposed plots show the two constituents of the trend, namely the one which we identify as the Gleissberg cycle (GC) component (full line), and the one which we identify as the magnetic cycle (MC) component (broken line) of the trend, that result from high-pass Butterworth filtering of the trend.

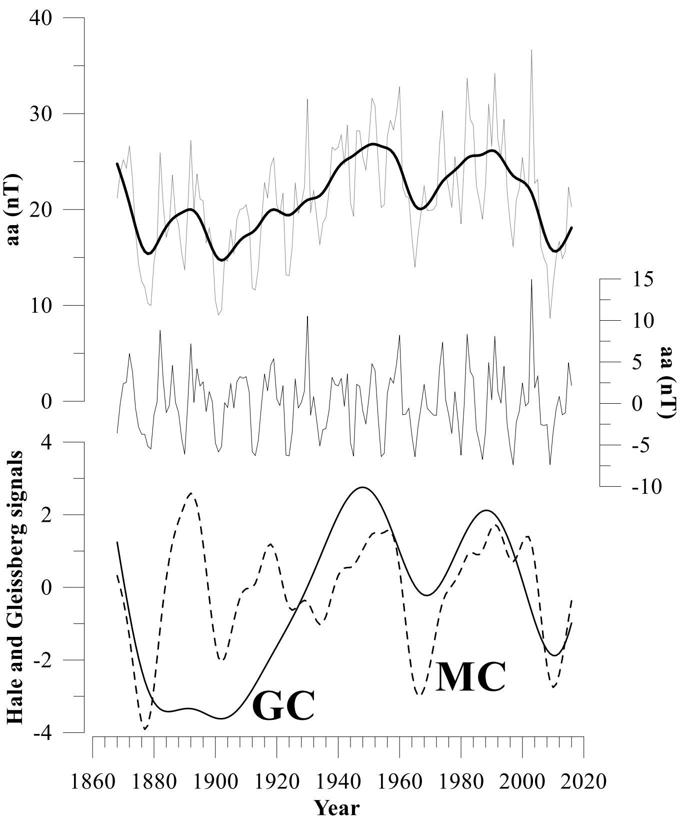

Fig. 2 – HP and Butterworth filtering in case of *aa* geomagnetic index. From top to bottom: geomagnetic index (grey) and the corresponding HP trend (black); HP cyclic component (black); MC (broken black) and GC (full black) signals.

3. RESULTS AND DISCUSSION

By applying the described methodology on data characterizing the three involved environments, the superposition of the trend and cyclic component for all parameters has been plotted in Fig. 3. To make comparable time series plots, the data series of parameters, describing various media and physical processes, have been standardized by taking into account the average values for the common time interval in which they are defined and scaled by their standard deviations about the mean as units. The results have been superimposed in order to better illustrate common features and differences between the parameters. As it was already mentioned, it can be observed, in the upper panel of Fig. 3, the presence of larger time-scales variations in the HP trend of all parameters, while in the lower one the 11 year solar cycle variations. Also, differences in a certain solar cycle between various parameters, such as the peak in intensity of the interplanetary magnetic field, B, after the solar maximum, the high speed of the solar wind, V, in the descending phase of the solar cycle, and the double peak in aa, one during the maximum and the other on the decending phase of the solar cycle, could be noted. More details about latter issue might be found in Demetrescu and Dobrică (2008).

Going further, we filtered out HP trend by a high-pass Butterworth filter with 22 and 78-year cut-offs, to get the variations at the two time scales associated to the corresponding Hale and Gleissberg solar cycles. The results are shown in Fig. 4 for all studied parameters. Similar temporal evolution of the parameters at the two time scales can be seen up to the present. This confirms our earlier thoughts regarding the long-term evolution of the parameters describing the heliosphere-magnetosphere environment, namely: the long-term similarity at the solar magnetic (MC) and solar Gleissberg (GC) timescales, pointing to a common pacing source, the solar dynamo. In addition, the signal at the GC time scale, extended to the present, exhibits besides the minimum of 1900, minima at around 1965–1970 and 2008–2012. The last one contributes to the recent trend of weakening of the solar activity which began with solar cycle 22. We also note that in the same time minima in the signal at MC time scale ocurred.

An overview of our analysis for the last 150 years is presented in Fig. 5. It seems that the evolution of the entire system, the recent trend included, is a result of superposition of the two well known magnetic (Hale) and 80–90 year (Gleissberg) solar cycles variations. Our analysis indicates that the 1964–1965 minimum and the next solar cycle 20, as well as the 2008–2009 one and the following cycle 24 are strongly affected by a minimum in the behaviour of the Sun – Earth system at Hale and Gleissberg cycles timescales. A similar behaviour seems to exist at around 1900 and the solar cycle 14. However, in this case the amplitude of the MC decrease is smaller than in the the two other mentioned time intervals.

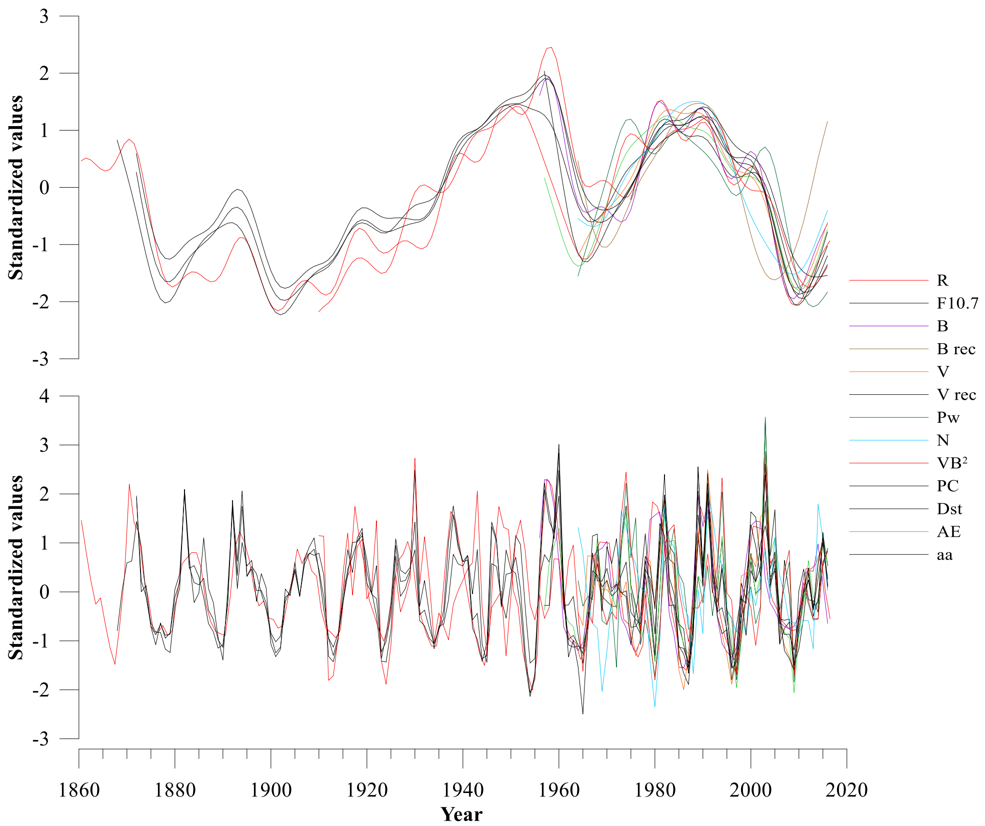

Fig. 3 – The trend (upper) and the cyclic component (lower) for all parameters.

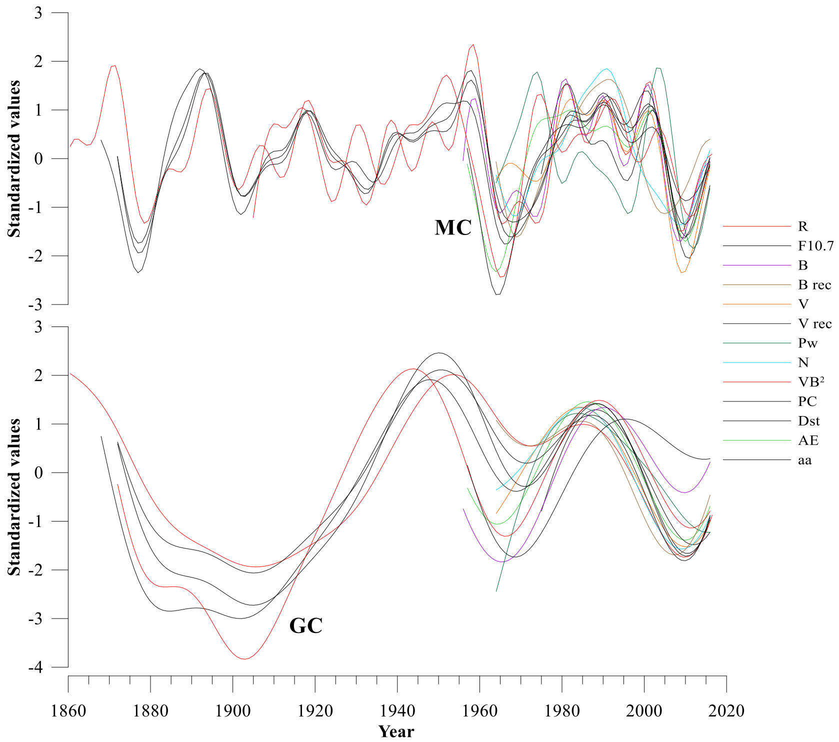

Fig. 4 – The inter-decadal (MC) (upper) and sub-centennial (GC) (lower) signals from HP trend for all parameters.

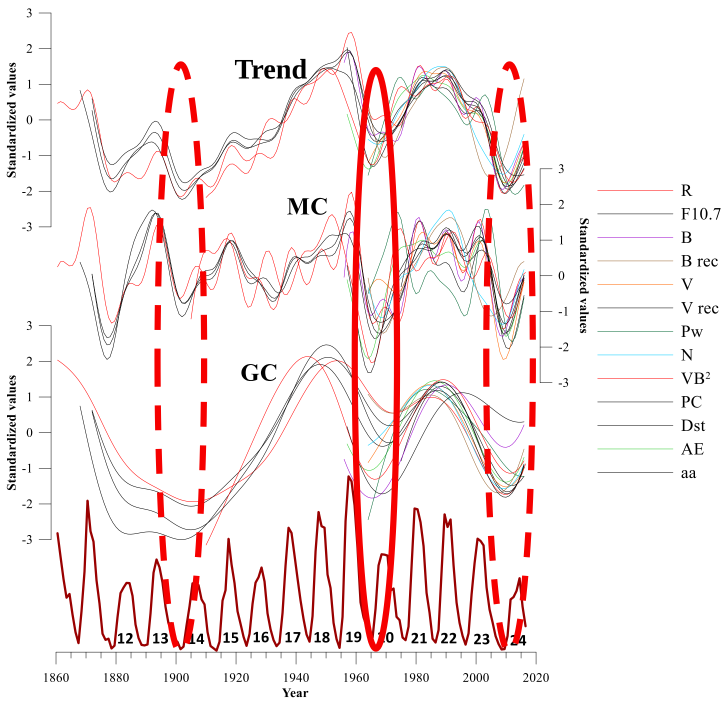

Fig. 5 – The trend (upper), the inter-decadal (MC) (middle) and sub-centennial (GC) (lower) signals in studied parameters together with the sunspot number evolution (lowermost). The solar cycles are numbered. The red ovals denoted three similar aspects in the temporal evolution for the last 150 years.

4. CONCLUDING REMARKS

The evolution at MC and GC timescales in parameters characterizing solar activity, heliosphere and magnetosphere was shown, by using Hodrick and Prescott (HP) type analysis and Butterworth filtering. Confirming our previous studies, the present analysis, covering the last 150 years, shows the MC and GC signals are quite similar in the heliosphere – magnetosphere environment, pointing to a common pacing source, the solar dynamo.

At the MC and GC timescales, the deep 23/24 solar minimum and the cycle 24 are similar with both the 19/20 minimum and the cycle 20, and the 13/14 minimum and the cycle 14.

The study of the long-term solar and geomagnetic activity evolution would bring new insights regarding the behaviour of the magnetic solar cycle during the next minimum that is expected by the solar-terrestrial community with an occurence probability in solar cycles 24–26.

Acknowledgements. The study has been supported by the Institute of Geodynamics (Project 3/2017, 2018, 2019, 2020). The results of this study have been partially reported at VarSITI 2017 and GEOSCIENCE 2020 Symposium.

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Received: February 24, 2021
Accepted for publication: March 15, 2021