On the Correlation between EUV Solar Radiation Proxies and their Long-Term Association

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Abstract.

EUV solar radiation proxies, in particular monthly mean Mg II, Lyman α flux, F10.7 and Rz, are analyzed during the period 1979-2020. Their variability is compared through a correlation analysis. When the whole period is considered, the linear correlation is greater than 0.95 between each pair of solar proxies if monthly or 12-month running mean series are used. But, when short sub-periods are correlated this value decreases markedly during maximum and minimum solar activity levels. This result may be due to the random noise part of each series as we show it through a "statistical experiment". Their hysteresis along a solar activity cycle is also reproduced as part of this analysis.

Introduction

The main variation in monthly mean solar activity proxies is that related to the quasi-decadal solar cycle. In particular, in the case of EUV solar radiation proxies, the correlation between them is greater than 0.95 at this time scale, even though in general each index is originated in a different region of the Sun. In addition, their variation along the quasi-decadal cycle in percentage terms is also different.

Based on a work by *Bruevich et al.* [2014], in the present work we analyze the correlation between four EUV solar radiation proxies for sub-periods in order to go through the different phases of the solar cycle. With a simple "statistical experiment" we reproduce some results linked to this correlations analysis, and also to the hysteresis effect which is characteristic of all pairs of the solar indices showing differences during the rising and declining phases of solar cycles [*Bruevich et al.*, 2016].

Data

Four solar activity proxy were considered:

(1) MgII core-to-wing ratio (MgII), which corresponds to the ratio of the h and k lines of the solar MgII emission at 280 nm to the background solar continuum near 280 nm, and serves as a proxy for UV and EUV spectral solar irradiance variability. We used the composite MgII, which combines data from different satellites. It is also called Bremen composite MgII index, available from the University of Bremen [*Viereck et al.*, 2010; *Snow et al.*, 2014].

(2) Lyman α flux (Fα) (in W/m^2 units), which corresponds to the full disk integrated solar irradiance over 121-122 nm, and is dominated by the solar HI 121.6 nm emission. We used the composite Fα, which combines multiple instruments and models, available from the Laboratory for Atmospheric and Space Physics (LASP, University of Colorado) Interactive Solar Irradiance Data Center (LISIRD) [*Machol et al.*, 2019].

(3) F10.7 (in sfu=10^{-22}Ws/m^2), which corresponds to the radio emission from the Sun at a wavelength of 10.7 cm (2800 MHz), and is measured at the Earth's surface at the Penticton Radio Observatory in British Columbia, Canada.

(4) The sunspot number (Rz), from the revised Rz data base obtained from SILSO (Sunspot Index and Long-term Solar Observations), Royal Observatory of Belgium, Brussels.

In the case of MgII and Fα monthly means were estimated from their daily data base, while F10.7 and Rz monthly values were directly obtained from their data source. The period January 1979-December 2020 is considered.

Regarding their source from the Sun, they are: the photosphere for Rz, higher in the chromosphere for Mg II, the transition region to the corona for Fα, and higher chromosphere and corona for F10.7

An additional characteristic which differs among these solar EUV proxies is their sensitivity along the quasi-decadal solar cycle. In fact, in terms of percentage variation, estimated as the amplitude of the decadal cycle relative to the mean value considering a whole cycle, it is, from highest to lowest: ~250% for Rz, ~120% for F10.7, ~45% for Fα, and 10% for MgII.

Correlation analysis

For the correlation analysis we have analyzed the monthly series and also the 12-month running means, that is the low-pass filtered version where intra-annual variability is filtered out. In both cases an almost ideal linear association is noticed when the whole period is considered, with a correlation coefficient above 0.95 in all the cases considering all six pairs between our four indices. It could be said, at least statistically, that they have a common forcing, which we also assume is the same as for the EUV solar radiation.

Based on the work by *Bruevich et al.* [2014] we analyzed this correlation for shorter periods in order to detect its variation along the solar cycle. In Fig. 1, the running correlation using a 3-year window for each of the six pairs of solar EUV proxies can be seen, considering monthly mean series (left panel), and the 12-month running means (right panel). The correlation clearly decreases for maximum and minimum periods, which are indicated in the figure by dotted and dashed vertical lines respectively.

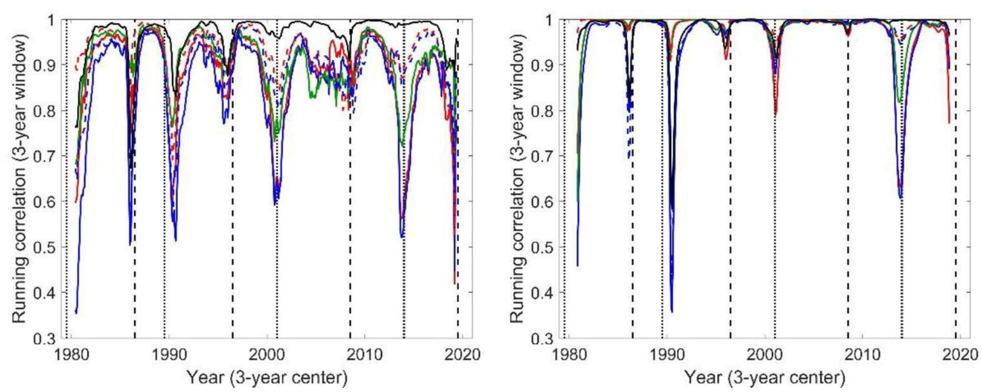

Fig.1. Running correlation (3-year window) between Rz&MgII (red solid), Rz&Fα (blue solid), Rz&F10.7 (green solid), F10.7&MgII (red dashed), F10.7&Fα (blue dashed), and MgII&Fα (black solid), considering monthly means (left panel) and 12-month running means (right panel). Note: solar maxima indicated by vertical dotted and solar minima by vertical dashed lines.

Statistical experiment

In order to analyze the running correlations between each pair of EUV proxies from a pure statistical point of view, we considered two artificial time series, Y_1 and Y_2. They were generated as the sum of a cosine function of 11-year periodicity to simulate the quasi-decadal variation, which we assume common to all of them, and a random noise to simulate the inter-annual variation, which we assume different for each series, that is:

$$Y_1 = 40\times\cos(2\pi t/11) + \varepsilon_1$$
$$Y_2 = 80\times\cos(2\pi t/11) + \varepsilon_2$$

where t is time running from January 1979 to December 2020, with monthly resolution.

Both series share then the same cosine function, with the same phase and only different amplitudes (40 and 80 units respectively), but distinct and unrelated random noises, ε_1 and ε_2, as indicated schematically in Fig. 2.

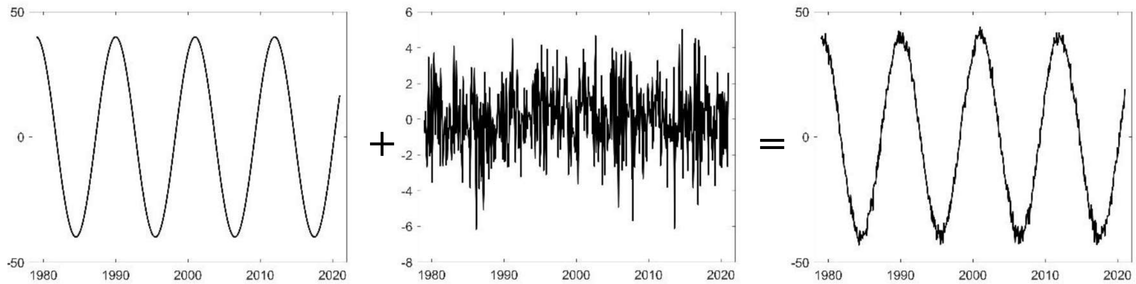

Fig.2. Schematic representation of an artificial series generated to simulate an EUV proxy (right panel), that results from the sum of cos(2πt/11) (left panel) (with 40 units amplitude) and a random noise (middle panel).

Fig. 3 shows the running correlation with a 3-year window between Y_1 and Y_2, where again vertical dotted lines indicate maxima periods, that correspond to the cosine crests in this case, and dashed lines indicate minima periods, that corresponds to the cosine valleys.

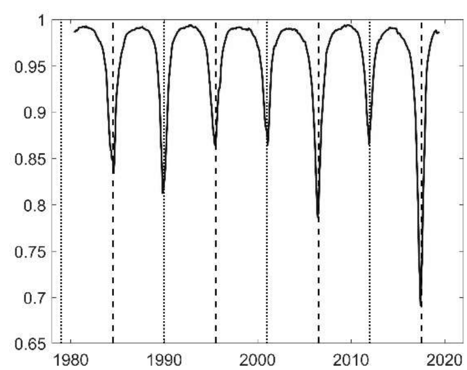

Fig.3. Running correlation (3-year window) between Y_1 and Y_2. Note: crest of cosine component indicated by vertical dotted and valley cosine component by vertical dashed lines.

The same time pattern of the 3-year running correlation behavior between "real" EUV solar proxies, seen in Fig.1, can be noticed in Fig. 3; that is a systematic correlation decrease during maxima and minima periods only, when monthly or 12-month running mean series as well are considered.

We made an additional analysis considering the same artificial series, which consist in their dispersion diagram along a quasi-decadal cycle. Fig. 4 shows Y_1 vs. Y_2, considering their 12-month running means, for a complete cycle, where a hysteresis can be clearly noticed. In fact, the dots in the plot are joined consecutively in time. The hysteresis size increases with the increase of the random noise amplitude relative to the cosine wave amplitude. If pure monthly series are considered, without any smoothing, the hysteresis pattern is completely blurred out.

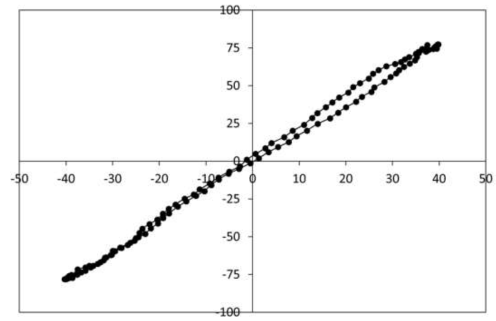

Fig.4. Y_1 vs. Y_2 (12-month running means) along an 11-year cycle.

Discussion and conclusions

The correlation between solar EUV proxies, considering sub-periods approximately spanning a solar minimum or solar maximum period, clearly decreases during maxima and minima, as already shown by *Bruevich et al.* [2014] and in this work in Fig. 1. A reason for this could be purely statistical, as demonstrated in our analysis considering artificial time series. This is due to during minima and maxima periods, the "true" EUV, given by the 11-year cosine cycle, varies too little (first derivatives are zero at these points) and the only variation left is the noise, which is random and consequently unrelated to anything.

Regarding the hysteresis effect [*Bruevich et al.*, 2016], this special pattern can be obtained also considering the dispersion diagram of an 11-year cycle of the 12-month running mean artificial series. This hysteresis disappears if only the cosine terms are considered and it is blurred out if the un-smoothed Y_1 and Y_2 series are used. So, this effect can be also obtained, as in the case of the running correlations, as a statistical by-product, without any physical association or process going on, but due solely to random noise which may always be present in any time series which is the result of measurements, as is the case of EUV proxies, and whose smoothing can generate a hysteresis effect.

Definitely, however, the statistical analysis presented in this work does not rule out a physical underlying mechanism for the correlation decrease during maxima and minima, and for the hysteresis behavior. In fact, in this last the case, for example, the hysteresis is also seen in ionospheric parameters when plotted against solar activity proxies with a convincing physical explanation through the geomagnetic activity effect, which, on average, is higher during the descending than during the ascending phase [*Ozguc et al.*, 2008; *Elias*, 2014].

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