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SOLAR ACTIVITY IN THE PAST: FROM DIFFERENT PROXIES TO COMBINED RECONSTRUCTION

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Abstract. Using proxy series that includes ancient observations of sunspots and auroras, concentrations of cosmogenic isotopes ^{14}C and ^{10}Be, we reconstruct sunspot activity level since 850 AD to the present. As a main reference index of solar activity we use the Wolf sunspot numbers, which, as we demonstrate, reflect true levels of the activity in the 18th and 19th centuries better than the Group sunspot numbers. We construct a set of linear and nonlinear inductive models, which are in a good agreement with each other and reproduce the known global solar activity extrema. According to our results, amplitudes of the global maxima are in intermediate positions in respect to estimations of other authors. It follows from our reconstructions that the global maximum of the 20th century is not much higher, if at all, than others.

1. Introduction

Explanation of solar activity behaviour on large (thousand-year) scales is a complex but very important problem. Reliable information about its properties is necessary both for solution of fundamental problems of solar physics and for understanding of regularities of the solar influence upon terrestrial processes. Unfortunately, the duration of regular instrumental observations of the Sun is less than four centuries. That is why indirect sources (proxies) are used for the study of variations of solar activity in earlier epochs. Usually such data as cosmogenic isotopes concentrations (^{14}C and ^{10}Be) (Damon and Sonett, 1991; Bard *et al.*, 1997; Beer, 2000) and data of historical chronicles (Schove, 1955; Nagovitsyn, 1997) are exploited for this purpose. In the last decades new information about these proxies was obtained, which stimulated investigations of this problem (Damon and Sonett, 1991; Bard *et al.*, 1997; Beer, 2000; Usoskin *et al.*, 2004a; Nagovitsyn, 1997). However, as a rule, only one or two proxies from the above-mentioned list are used for reconstructions.

The target of this paper is realization of an approach that is based on an idea about synthesis of information from all available proxies. This approach enables construction of a combined reconstruction of solar activity in the past, thereby increasing its reliability.

2. Data and Methods of Their Processing

Solar activity modulates the interplanetary magnetic field that shields the Earth against the galactic cosmic rays. The latter, in their turn, are sources of atmospheric cosmogenic isotopes, which are collected in tree rings (^{14}C), in marine sediments and polar ice (^{10}Be) and can be used as proxies of solar activity. Here, we shall use two series of ^{10}Be concentration. The first one (BeSP) reflects (for period 850 –1982 with 8-year averaging) concentration of this isotope in Antarctic ice probes (Bard, *et al.*, 1997; Raisbeck *et al.*, 1990). The second series (BeG) represents the yearly means of ^{10}Be concentration in Greenland ice cores for years 1424 –1985 (Beer *et al.*, 1994). We shall build a combined reconstruction of solar activity from the beginning of the longer beryllium series (850 AD). Variations of ^{14}C concentration are estimated with use of the residuals Δ^{14}C that reflect abundances of the isotope in tree rings above a certain zero level. We use the series of Δ^{14}C (Stuiver, Reimer, and Braziunas, 1998) for the period 850 –1900 (*http://depts.washington.edu/qil/datasets/uwten98_14c.txt*).

Another source a of solar activity proxies are historical chronicles. Information about observed middle- and low-latitude aurorae (Au) were recently compiled and extended by Křivský (Křivský and Pejml, 1988) (*ftp://ftp.ngdc.noaa.gov/stp/solar_data/aurorae*) and Silverman (2002) (*ftp://nssdcftp.gsfc.nasa.gov/miscellaneous/aurora*). Another type of historical data are records of naked-eye sunspot observations (WX) that were compiled by Wittmann and Xu (1987). For reconstructions we shall use both these series on the same time interval 850–1900.

We start with a preliminary processing of the data. First, all the series were interpolated to one-year time step. The long-term trend component of the C14 series, that corresponds to a time scale of more than 1500 years, was subtracted from the series. The aurorae series Au was normalized by dividing by a 200-year running average. Then the series were processed by 13-year running averaging with harmonic weights. The same operations were applied to two known “reference” series that describe solar activity in the instrumental epoch: the Wolf sunspot numbers (WSN) (1700 –1995) and the Group sunspot number by Hoyt and Schatten (GSN) (1610 –1995) (Hoyt and Schatten, 1998). A choice of one of these datasets as reference series would strongly affect results of the modelling. In order to decide between the two series, we did similar smoothing for the annual means of the sunspot areas series (SA) and aa-index of the geomagnetic activity (AA). For this operation we used the sunspot areas series (SA) for the years 1821–1995 that were extended by Nagovitsyn (1997) (*http://www.gao.spb.ru/database/esai/mn_aro.txt*) and the series of aa-index for 1844 –1995 that were prolonged by Nevanlinna and Kataja (1993) (*http://www.geo.fmi.fi/MAGN/K-index*). The series SA and AA were reduced to the scale of GSN by linear regression. As shown in Figure 1, curves “SA $\rightarrow$ GSN” and “AA $\rightarrow$ GSN” are located higher than GSN, despite the fact that the reducing models were built for GSN. It is especially pronounced for

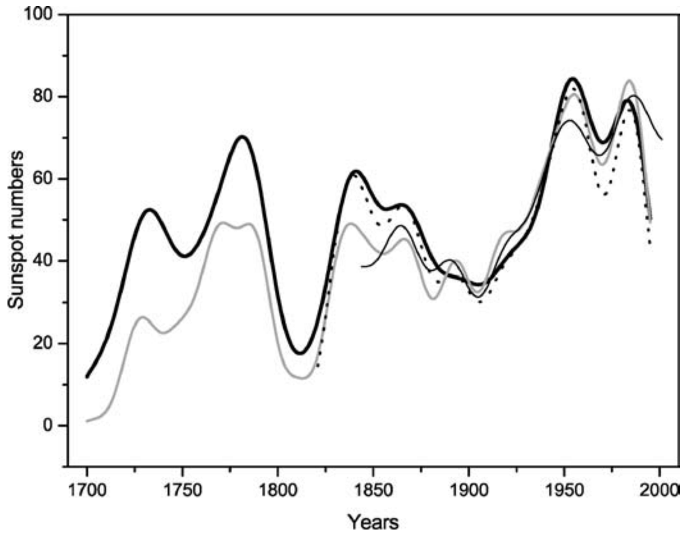

Figure 1. The smoothed WSN (*thick black curve*), GSN (*thick gray curve*), series AA (*thick black curve*) and SA (*dotted curve*) reduced to the GSN scale.

curve "SA → GSN," which has a maximum in the 19th century on a level with WSN.

3. Models and Reconstructions

All series of the proxies have a common time interval with the solar activity series (WSN and GSN) (1700–1900), and we select this interval as a reference one. For reconstructions we used the method of "Inductive Self-organizing Modelling" (ISM) (Farlow, 1984; Madala and Ivakhnenko, 1994), which allows obtaining models of optimal complexity. The reconstructions were built with account for possible time lags (multiple of 5 years) of some proxies relative to solar activity. Despite the fact that nonlinear models participate in the selection of candidates, all models found below proved to be linear.

We start by building models that link the WSN and GSN series with the beryllium ones BeS and BeG. Since the common time interval for these series includes a considerable part of the 20th century, at the first stage the models were obtained for the interval A + B (1700–1970), and "reconstruction" on this interval was made. Afterwards models were built on interval A (1700–1890) and "reconstruction" was made for interval A + B (1700–1970). This procedure was done in order to analyze relative effectiveness of models that are built on "short" (A) and "long" (A + B) intervals. One can conclude (Table I, Figures 2 and 3) that the quality of the models for the WSN proves to be in most cases significantly higher than for the

TABLE I

Relative effectiveness of models for W and GSN that are built with the use of the beryllium series BeS and BeG on the "short" (A, 1700–1890) and "long" ($A + B$, 1700–1970) reference time ranges. The shifted series Be($t + i$) correspond to time lags $i \times 5$ years.

Model	Ref. time range	Correlation A	Correlation A + B
$W(t) = 164 + 0.15$ BeS$(t) + 0.18$ BeS$(t + 2)$	$A + B$	–	0.81
$W(t) = 152 + 0.08$BeS$(t) + 0.22$BeS$(t + 2)$	A	0.87	0.80
GSN$(t) = 153 + 0.18$ BeS$(t) + 0.14$ BeS$(t + 2)$	$A + B$	–	0.73
GSN$(t) = 121 + 0.11$ BeS$(t) + 0.13$ BeS$(t + 2)$	A	0.76	0.72
$W(t) = -68.7 + 60.0$ BeG$(t) + 15.2$ BeG$(t + 2)$	$A + B$	–	0.79
$W(t) = -67.4 + 63.8$ BeG$(t) + 11.4$ BeG$(t + 2)$	A	0.78	0.78
GSN$(t) = -98.2 + 135$ BeG$(t) - 167$ BeG$(t + 1) + 119$ BeG$(t + 2)$	$A + B$	–	0.80
GSN$(t) = -43.8 + 68.5$ BeG$(t) - 17.5$ BeG$(t + 1)$	A	0.64	0.75

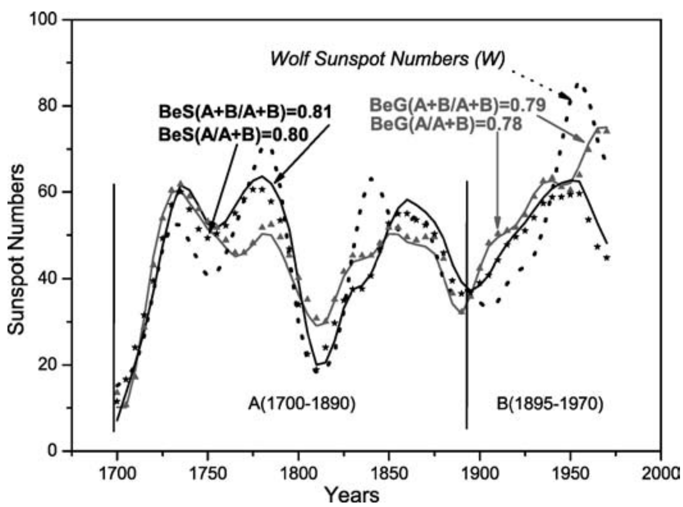

Figure 2. Reconstructions of WSN (*dotted curve*) by models that are built with use of the beryllium series on the "short" (A, 1700–1890) (BeS – stars, BeG – triangles) and "long" (A + B, 1700–1970) (BeS – *black curve*, BeG – *gray curve*) reference time ranges.

GSN models. The models for interval A demonstrate good stability when they are used for interval A + B. The maxima of the obtained "reconstructions" in the 20th century (see Figures 2 and 3) do not reach the actual magnitudes of the WSN and GSN in this epoch. It can be regarded as an indication of some "threshold satiation mechanism" that, possibly, inheres in the ^{10}Be proxy.

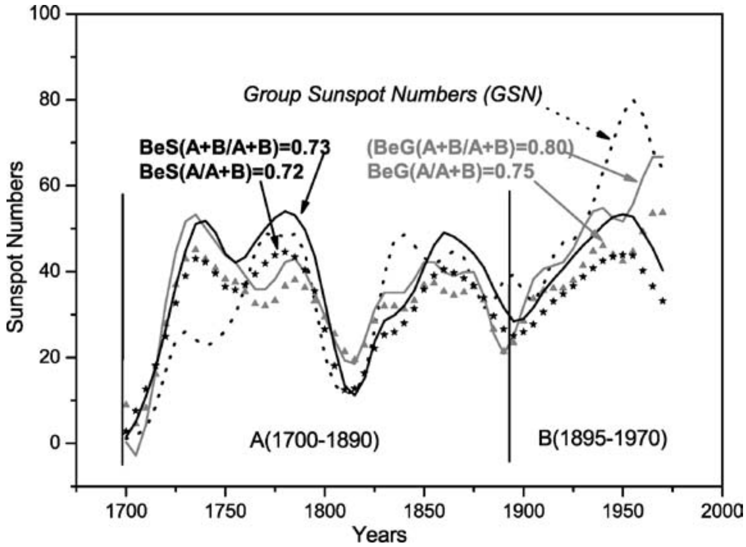

Figure 3. The same as in Figure 2 for reconstructions of GSN.

The results obtained above enable us to make a choice in favour of using the WSN, rather than the GSN, as a main reference index of solar activity.

In Figure 4 we present the WSN reconstructions since 850 AD that are based upon the BeS and BeG series. One can see that the reconstructions by these

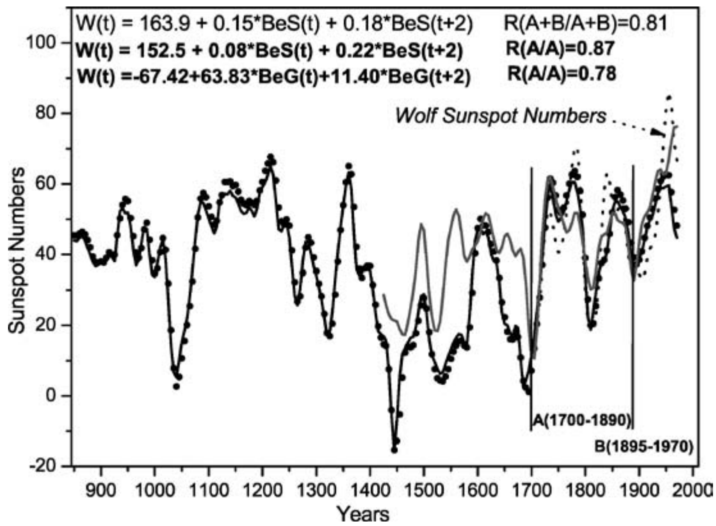

Figure 4. The reconstructions of WSN (*dotted curve*) since 850 AD by models with use of the beryllium proxy series on the "short" (A, 1700 – 1890) (BeS – *black curve*, BeG – *gray curve*) and "long" (A + B, 1700 – 1970) (BeS – *black circles*) reference time ranges.

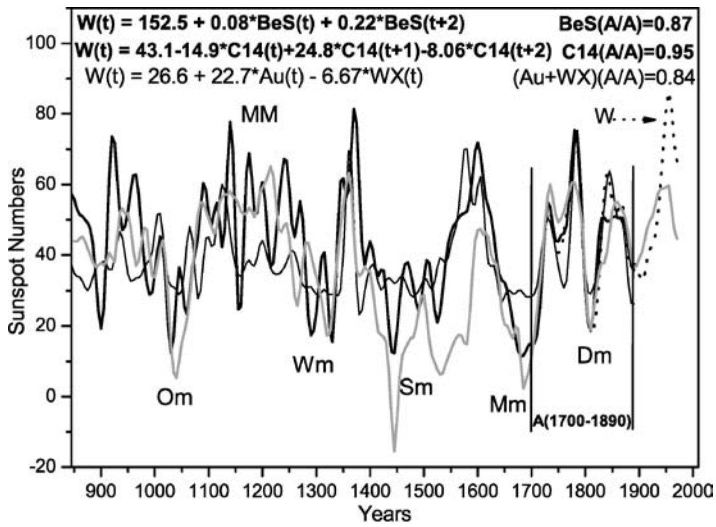

Figure 5. The reconstructions of the WSN (*dotted curve*) since 850 by models on the "short" (A) reference time range with use of the proxy series C14 (*thick black curve*), BeS (*gray curve*) and "Au + WX" (*thin black curve*). The known global minima (Xm) and maxima (XM) of solar activity are marked.

two proxies are in bad agreement. Yet the reconstructions by two models of BeS found for intervals A (black curve) and A + B (black circles) are practically identical.

Figure 5 shows reconstructions of the WSN by reference interval A with use of proxies BeS, C14 and the combination "Au + WX". The model using C14 is the most accurate one for interval A. All reconstructions describe well the known epochs of extreme solar activity, but each one has some particular features. For example, the reconstruction by model "Au + WX" gives too high values in global minima, but in maxima it agrees with the reconstruction by C14. On the contrary, maxima of BeS reconstruction turn to be, as a rule, lower than maxima according to C14 and "Au + WX" models. This fact is extra evidence in favour of the "threshold satiation mechanism" of ^{10}Be proxy. We also should note that the models by BeS and C14 include time lags of the input data, but there are no lags in model "Au + WX".

A better agreement exists between reconstructions that are made with the use of combined models including various combinations of the proxies (Figure 6). The most accurate one on interval A is a model that includes three indicators (C14, BeS and Au). The reconstruction by this model is higher than the recent reconstruction of Usoskin *et al.* (2004b) (which uses the GSN as a reference index and is the lowest among others) and lower than in the reconstruction of Nagovitsyn (1997) (which is not the highest among others).

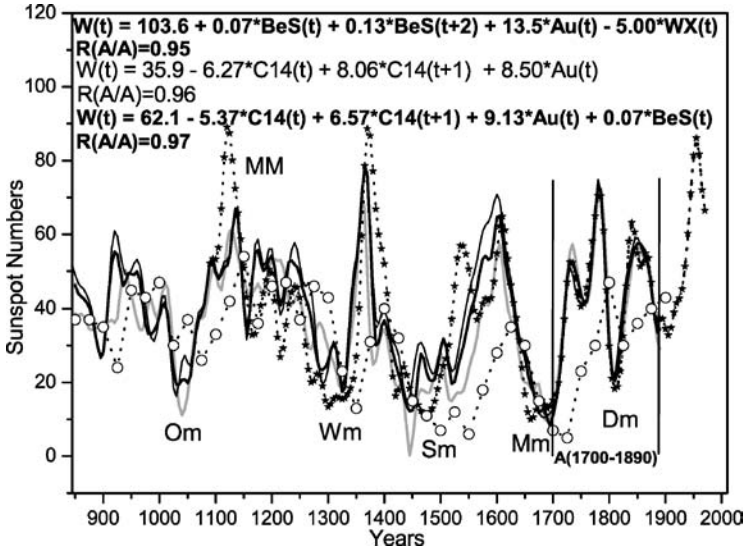

Figure 6. The reconstructions of the WSN since 850 by models with use of the proxy series C14, BeS and Au (*thick black curve*), BeS, Au and WX (*gray curve*), C14 and Au (*thin black curve*) compared with the results of Usoskin *et al*., (2004b) (*dotted curve with circles*) and Nagovitsyn (1997) (*dotted curve with stars*).

4. Conclusions

Therefore, we can conclude that: (I) The method of "Inductive Self-organizing Modelling" allows us to obtain models of optimal complexity. (II) As a reference index of solar activity we select the WSN, since this index is in better agreement with solar activity levels in the 18th and 19th centuries estimated by the sunspot areas and aa-indices. (III) The reconstructions obtained by the combined models proved to be more accurate on the reference interval and to agree better with each other on the interval of reconstruction. (IV) In our solar activity reconstruction by model "C14 + BeS + Au" the amplitudes of global maxima are in intermediate position in respect of estimations of other authors and they are not much lower than the maximum of the 20th century.

Acknowledgements

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