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Versions of Time Series for Classical Solar Indices and an Adequate Description of Solar Activity

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Abstract—This article discusses issues relevant to the 2015 recalibration of the time series of classical solar indices. It shows that the Wolf numbers *WN* and the group numbers *GN* are sensitive to the quality of the observations underpinning the reconstructions of the relevant time series, given the intermittent recordings in the 17th and 18th centuries. The authors suggest that research efforts should focus on the compilation of a long series of total sunspot areas (absolute sunspot magnetic flux), because, on the one hand, this series is less sensitive to poor-quality observations, while, on the other hand, it reflects a clear physical index.

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1. INTRODUCTION

One of the central problems of heliophysics is to understand the dynamics and evolution of solar (magnetic) activity. To solve this problem, we must introduce special parameters, or *indices*, which we then convert into representative time series based on observations and reconstructions and produce a statistical and then a theoretical description.

According to Vitinskii (1973), *solar indices* are global numerical characteristics averaged over a given period that relate either to the entire Sun or a substantial part thereof and describe the features of a concrete solar activity (sunspots, plages, solar flares, protuberances, etc.). We suggest an addition to this definition: a *solar index* is a parameter that reflects the real physics of the system and is uniquely related to the standard basic physical values.

We know three classical indices of solar global sunspot activity (which is the subject of this article): the Wolf number (*WN*), group number (*GN*, or normalized group sunspot number *GSN*), and sunspot area (*A*). The time series of average annual values is 317 years for the first index, 407 years for the second, and, conventionally, 143 years (since the beginning of observations at Greenwich) for the third.

2. RECALIBRATION OF THE *WN* AND *GN* SOLAR INDEX SERIES

In 2015, the General Assembly of the International Astronomical Union in Honolulu discussed the newly compiled versions of the *WN* (Clette et al., 2014) and *GN* series (Svalgaard and Schatten, 2016). The new series were called versions 2.0, as opposed to the classical version 1.0. The very fact of revising the classical series was a profound event: the classical *WN* series had been the backbone of numerous statistical studies, not only in solar physics but also in geophysics, climatology, biology, etc.; the *GN* (*GSN*) series had served, for example, as a scale in the reconstructions of past solar activity from radionuclide contents in natural archives (Usoskin et al, 2014). Nevertheless, the change has happened (see Fig. 1).

At present, an international team of researchers is working to further improve the series (compile the intermittent solar activity observations in the 17–18th centuries). One of their goals is to harmonize the *WN* and *GN* series.

3. *WN* AND *GN* INDICES

In our view, the *WN* and *GN* indices characterize different aspects of sunspot activity, and any comparisons between them are therefore illegitimate. First, we can show that the quantity of large groups with a high *WN* relative to small groups with a low *WN* changes throughout the 11-year cycle (Nagovitsyn and Pevtsov, 2016). Second, if we trace the changes over time in the *WN* per one group from the data of the Kislovodsk Mountain Astronomical Station, Pulkovo Observatory (which provide the number of spots in a group; see Fig. 2), we see that this parameter varies significantly throughout the 11-year cycle; moreover, its distribution is markedly non-Gaussian, and the

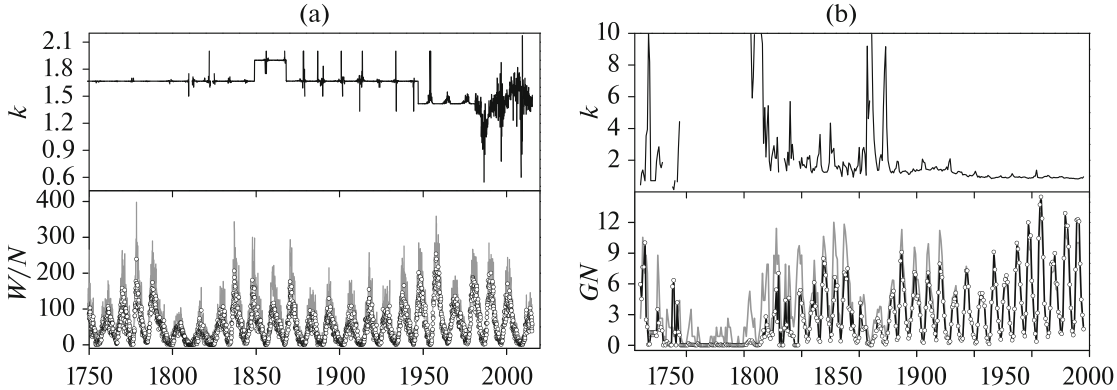

Fig. 1. (a–b) Lower panels: the *WN* and *GN* series. Version 1.0 is shown with circle symbols; version 2.0 is shown with gray color. Upper panels: *k* is the ratio between the version 1.0 and 2.0 indices.

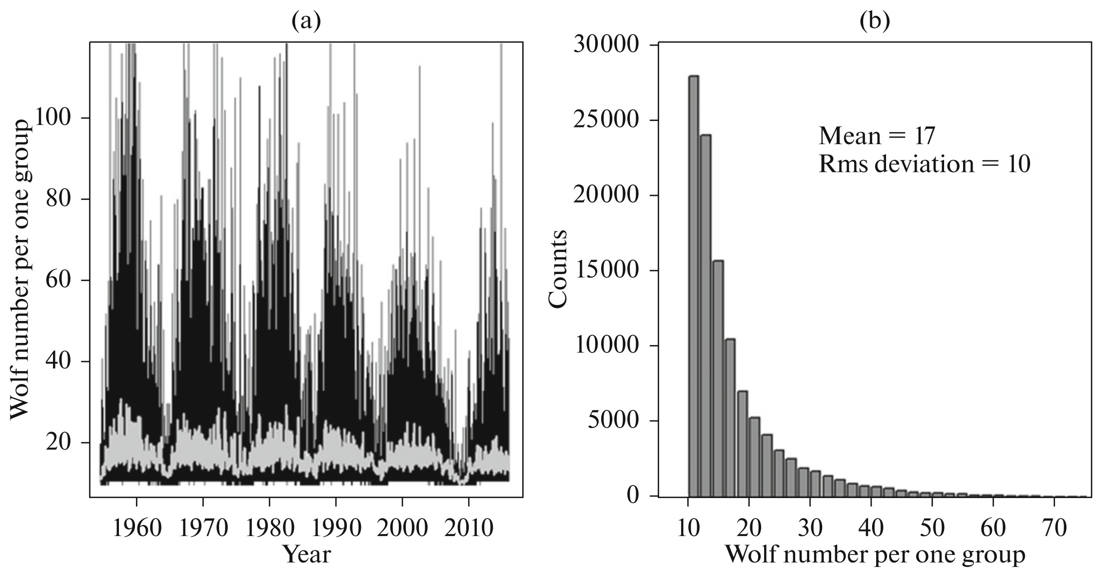

Fig. 2. (a) Change in the *WN* per one group with time (gray color shows a 100-year smoothing); (b) occurrence histogram of this parameter.

mean does not correspond to the maximum occurrence. Thus, the form $WN = bGN$ is statistically unreasonable.

Now, we turn to a few words about the physical sense of *WN* and *GN*. Let us compare two cases with only one small short-lived group and only one large unipolar group on the Sun. Obviously, *WN* and *GN* will be the same in both cases on a given day. However, the magnetic flux in groups with a substantially different area is clearly different. Thus, we conclude that sunspot activity is better described by such parameters as size, area, and magnetic flux, rather than the number of objects.

4. SUNSPOT AREA AND TOTAL SUNSPOT MAGNETIC FLUX

It was shown in (Nagovitsyn, 2005; Nagovitsyn et al., 2016) that the absolute total magnetic flux of sunspots is a physical, rather than statistical, value: the magnetic flux can be expressed through the total sunspot area as $\Phi_{\Sigma}(t)\,[\mathrm{Mx}] = 2.16\times10^{19} A(t)\,[\mathrm{mvh}]$. Thus, the most adequate index of sunspot activity is the total sunspot area *A*, not *WN* or *GN*.

Unfortunately, the classical observational series of the *A* index covers many fewer years than *WN* and *GN*. One of the reasons is the lack of attention as compared with the number-of-objects series. However, we now have available a series of sunspot areas from observations by Schwabe and Carrington (1832–1853 and 1854–1860, respectively, de La Rue's version), which has been reduced to the Greenwich system (Nagovitsyn, 1997); Staudacher's series (1749–1796) (Arlt, 2008); and individual sketches left by observers of the 17th and 18th centuries.

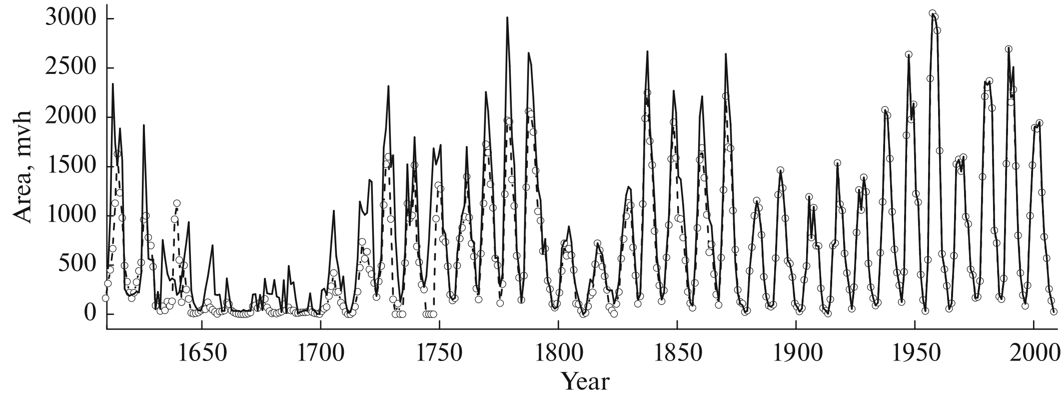

Fig. 3. *A* series. The circles and dashes indicate version 1.0; the solid line shows version 2.0.

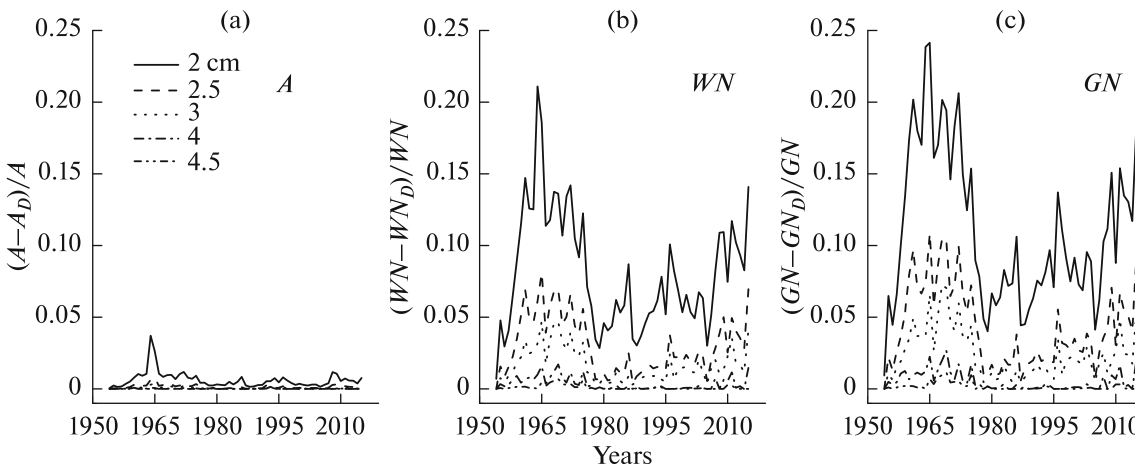

Fig. 4. Information loss function estimates for (a) the average annual *A*, (b) *WN*, and (c) *GN*.

It should be noted that Nagovitsyn (2005) used the so-called primary index approach to show that the three indices being discussed are linked by the relation

$$A^2 = aSN \cdot GN - bGN^2.$$

Thus, if we have the *WN* and *GN* series, we can derive the *A* series. Solving this problem was the goal of Nagovitsyn (2005) and Nagovitsyn et al. (2016). The results for versions 1.0 and 2.0 are shown in Fig. 3.

However, it would be desirable to obtain data on *A* for the 17th and 18th centuries from direct, albeit sparse, observations by individual authors. It should be noted here that, as compared with *WN* and *GN*, the *A* index is less prone to selection due to imperfect observational instruments. Let us assess this factor.

Assuming that a critical resolution for the discernment of a pore with diameter *d* is the Rayleigh resolution δ of a telescope with a lens diameter of *D*: $\delta['']=14/D[\mathrm{cm}]$, we can calculate the loss function, specifically, for the annual average value of the index *I*, overlooking pores and spots with diameters of less than *d*. We used the Kislovodsk data in the calculation. Figure 4 illustrates the function of relative losses in the index values $fl=(I-I_D)/I$ for a range of small telescopes with a lens diameter of *D*. Here, we use the following notation: I is the true value of the index and I_D is the value for a telescope with diameter *D*; $I = A, WN, GN$. Evidently, the index of sunspot areas is less susceptible to losses due to the small pupil of the instrument: at $D = 2$ cm, the maximum value $fl \approx 4\%$, whereas the maximum *WN* value at this *D* is $fl \approx 20\%$ and that for the group number is even higher, $fl \approx 25\%$. Here, it is important to keep in mind that the effective aperture for telescopes with low-quality optics may be less than the actual lens diameter; the value $D = 2$ cm does not seem odd for observations in the 17th century.

Figure 5 also shows the *fl* values for average monthly values of *GN*. Evidently, the maximum *fl* values for this averaging are rather high. Naturally, if we consider the daily values, they will be even higher (perhaps, sometimes close to unity). Hence, we conclude that if activity reconstructions for the 17th century

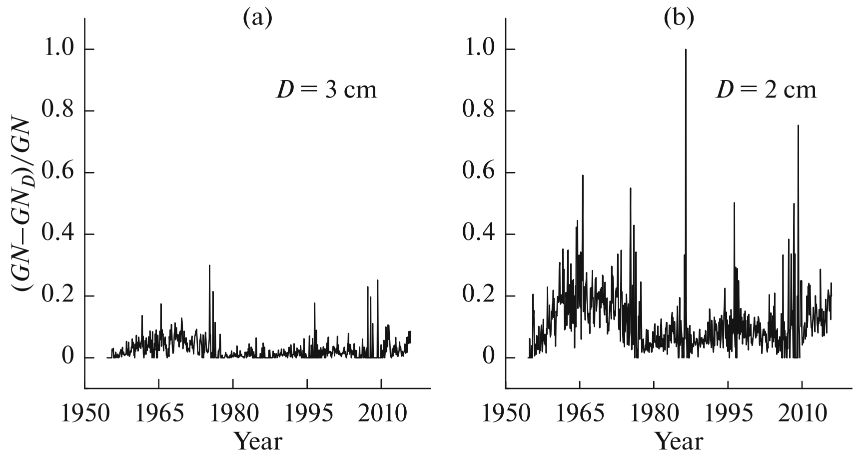

Fig. 5. Information loss function estimates for the average monthly *GN* at (a) $D = 3$ and (b) $D = 2$ cm.

employ isolated irregular observations from poor-quality telescopes, the reconstructed monthly and annual average *GN* values will be inevitably underestimated (see also (Ogurtsov, 2013)). Therefore, the conclusions by Zolotova and Ponyavin (2015) about substantial activity during the Maunder minimum are, despite the convincing arguments of their opponents (Usoskin et al., 2015), not so far from reality. Another confirmation is the remarkable results obtained by Kudryavtsev et al. (2016), who found that the level of activity during the Maunder minimum was comparable to that during the Dalton minimum. It should also be noted that, according to Nagovitsyn et al. (2010), the north–south asymmetry and spatial distribution of activity are related to its level; hence, we would need accurate estimates for these indices at the Maunder minimum to reconstruct these characteristics too. On the other hand, if we reconstruct past solar behavior from such sources as chronicle records of sunspots observed with naked eye (Nagovitsyn, 2001; Vaquero, 2002) or the number of auroras (Schove, 1983; Nagovitsyn et al., 2015), we need to understand that these data exploit primarily large sunspots, which make the main contribution to the total sunspot area as a solar activity index.

5. CONCLUSIONS

Thus, we showed that, in light of the information losses associated with observations obtained from small telescopes in the 17–18th centuries, the total sunspot area index *A* is more beneficial than the *WN* and the *GN*. The losses of annual average values for the *A* index are no more than 4%, whereas *GN* has an error of up to 25%; *WN* also gives a large loss function, up to 20%.

We pointed out that the available estimates for the monthly and annual average values of *GN* and *WN*, which were derived from a limited number of observations with small-aperture telescopes, may be much lower than the actual values.

The main conclusion reached in our article is that efforts should be made to compile a representative series of sunspot areas—a truly physical index of solar activity.

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