

## ***Interactive comment on “Long-term changes in the North–South asymmetry of solar activity: a nonlinear dynamics characterization using visibility graphs” by Y. Zou et al.***

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We have very much appreciated the comments of the two reviewers to our manuscript and would like to express our thanks for their careful reading and helpful suggestions. In the following, we briefly respond to the main points raised in both comments.

1. Reviewer 1 (A. Hannachi) stated that beyond the contents of our discussion paper focusing on the skewness as one key parameter characterizing the asymmetry of probability distribution functions, other higher-order moments such as kurtosis may play also a role in explaining the dynamical features of visibility graphs (VGs) for the studied solar activity series. We agree with this statement in that VGs are

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generally affected by the PDF of the data under study (as emphasized in our work), and that all higher-order moments are in principle capable of providing key information on such asymmetries. We plan to mention this point more explicitly in our final paper.

Beyond these more general considerations, we have numerically tested the relevance of higher-order moments to the discussed problem of North-South asymmetry in solar activity. Specifically, following the reviewer's recommendation we have computed the time-varying kurtosis for sunspot areas on both hemispheres, as well as their difference, in complete analogy with the skewness shown in the discussion paper. Our results reveal that both skewness and kurtosis show almost identical temporal variability (compare Fig. 3 of the discussion paper with Fig. 1 of this author comment). This fact is easily explained: As can be seen from Fig. 1A,B, sunspot areas are bound to positive values and have distinct tails corresponding to solar activity maxima. The general shape of the associated PDF suggests that not only skewness, but also kurtosis and potentially other (normalized) higher-order moments could have positive values. Specifically, considering the form of such moments as sums over the  $n$ -th power of fluctuations around the mean, it is clear that the higher  $n$ , the stronger large positive anomalies contribute to the final value of the respective moment. Hence, temporal variations of the  $n$ -th moments mainly trace the variability of the distribution tail, and the higher  $n$ , the more this variability will be magnified. In this spirit, considering kurtosis instead of skewness does not provide new information to our specific analysis, but at most magnifies the signals already discussed in our discussion paper.

Given the aforementioned results, we prefer not to discuss other moments of higher order in detail in our final paper.

2. Reviewer 1 further suggests including some didactic example illustrating the difference between VG and HVG. Of course, there are different ways to address this helpful comment. Complying with other papers applying VG or HVG analysis, in

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our final paper we will provide a schematic representation of both graph representations for a small part of the (annually averaged) sunspot number time series illustrating the conceptual differences between both graph representations.

3. Finally, reviewer 1 recommends complementing the presented analysis by comparing it with the outcome of other (standard) techniques of time series analysis. In this regard, we first emphasize the general question of which other technique to choose serving the same purpose as the VG-based analysis, i.e., tracing time variations of nonlinear dynamics characteristics in terms of some running window analysis. Cross-spectral analysis suggested by the reviewer is only partially useful for this purpose, since time scales of relevance might not be covered by our running windows. Wavelet phase coherence has been used for characterizing the asymmetry of hemispheric sunspot areas in terms of a dynamic delay of the respective Schwabe cycles by Donner and Thiel (2007) and Donner (2008), referenced in the discussion paper, and has later been applied to other variables related to solar activity by various other authors. This approach could be extended to wavelet (amplitude) coherence, but some appropriate statistical characteristics need to be defined in order to trace temporal changes in the dynamical properties of sunspot areas at both solar hemispheres relative to each other by just some scalar parameter. We feel that a detailed investigation of this question could provide interesting new results, but would be beyond the scope of the present paper. However, since such an analysis would provide a natural extension of our current work, we will add a brief discussion on the corresponding potentials for future work to our final manuscript.

More generally, we emphasize that given the steadily growing literature on dynamical characteristics of solar activity indicators, a careful discussion of which time series analysis methods (including both classical approaches and modern nonlinear methods such as the one presented in our present work, cross-recurrence plots (Zolotova and Ponyavin, 2006), and others) provide which kind

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of results for different observables calls for a detailed comparison and discussion, which might be subject of a corresponding review paper, but would go far beyond the present work.

4. Reviewer 2 (anonymous) mentions that in their opinion, a more detailed discussion on why VG and HVG provide different results should be provided. In our opinion, such discussion has already been provided in Section 3.4 of our discussion paper, emphasizing that HVGs exclusively trace changes related to dynamical characteristics, whereas VGs mix this type of information with such due to variability in the PDF (as expressed, for example, by the time-varying skewness). Following comment 2 of the first reviewer, we will further illustrate both methods (as well as their differences) by a simple example in our final manuscript.

Unfortunately, from the present analysis, there is not yet much more one could say about the method-intrinsic reasons for the different behavior. In turn, one might speculate about physical mechanisms leading to asymmetries in dynamics and PDF, respectively. However, beyond generally speculating about possible processes leading to strong vs. weak solar activity maxima (asymmetrically on both hemispheres) and thus causing differences in the resulting PDFs, it is very hard to hypothesize about the origins of time variations in dynamical properties. Viewing the solar dynamo as a low-dimensional deterministic system (an assumption that does not appear justified in our opinion), one could attribute such variations to temporal changes in the control parameters or some “external” forcing terms. However, it remains unclear which specific physical variables describing complex processes in the solar interior could be of particular relevance in this case. To our best knowledge, there is no consistent theory addressing this problem, which also responds to the second part of the recommendations of Reviewer 2 regarding some extensive literature search related to possible physical processes. Unveiling the details of such processes is clearly beyond the scope of the present paper, but we agree that this will constitute an important next step.

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In turn, we hope that our findings, especially regarding the dynamical asymmetry pattern revealed by HVG analysis (Fig. 6 in the discussion paper) might help further constraining relevant parameters in the future according to their respective dynamical changes over longer time-scales.

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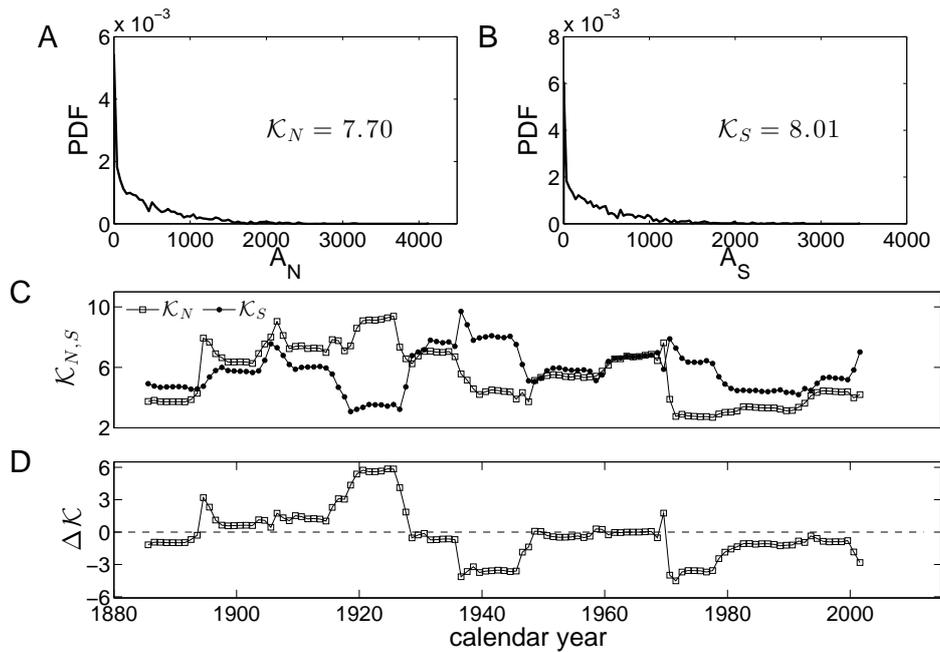


Fig. 1. As in Fig. 3 of the discussion paper for the kurtosis of the sunspot area time series.

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