

Response to "Comment on the Paper "Characteristic Time Scales of Decadal to Centennial Changes in Global Surface Temperatures Over the Past 150 years" by J. L. Le Mouël, F. Lopes and V. Courtillot"

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REPLY
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This article is a reply to a comment by Cuypers et al. (2021), https://doi.org/10.1029/2020EA001298.

Key Points:

- We find compelling results showing a significant co-variability between sunspot numbers and global temperature
- We do not have a mechanism to explain that forcing: it remains to be found. We do not discuss further the parts of CCC on mechanisms
- The trends of temperature and sunspots (first SSA component) are similar; the second component results in an opposite trend in the last 30 years

Supporting Information:

Supporting Information may be found in the online version of this article.

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Response to "Comment on the Paper "Characteristic Time Scales of Decadal to Centennial Changes in Global Surface Temperatures Over the Past 150 years" by Y. Cuypers, F. Codron, and M. Crepon"

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Abstract We thank the authors (hereafter referred to as CCC) for providing us an opportunity to clarify some points of our original paper. CCC list in their abstract three "key points"that we respond to in this Reply. The first comment is the central one and the most developed. It deals mainly with discussion of features of methods of spectral analysis, mainly SSA. We have quoted the sub-parts of that comment as items 1a to 1k. The replies to comments/key points 2 and 3 are shorter. We disagree with most of the comments by CCC and explain why. We conclude that we have successfully countered CCC's criticism and shown many of their points to be unsubstantiated. The main problem seems to reside in differences concerning the literature on Singular Spectral Analysis and our use of it. Much of our response to the comments can be found in textbooks and review papers on SSA and time series analysis; we quote extensively, both in our original paper and in this response to CCC, Golyandina and Zhigljavsky (2013).

As stated in the original paper by the authors:

(1a) *"the lack of compelling results from the Fourier spectra and SSA estimates which are provided without confidence intervals" "First of all, the standard Fourier spectra of sunspots (ISSN) and HadCrut temperature (simply temperature hereafter) time series provided in Figures 1 and 11 by the authors look very different and do not seem at first sight to share any common significant peak. Moreover, the authors did not provide any confidence interval to allow meaningful conclusions."*

This is not correct. We provide confidence intervals for all the periods we extract on all figures. We do use FT applied not to the full time-series but to individual SSA components in order to obtain a rough evaluation of confidence intervals on the (quasi-) periods. The FT of a real series is complex and even. It has a modulus and a phase. Two spectra with different amplitudes do not imply two signals with different composition: the phase is important.

Figure 1 of our paper presents the (HadCrut) temperature data and the associated Fourier spectrum. Figure 11 is in the same presentation but for sunspots. The temperature series is very noisy, increasingly so when one goes further back into the past. The sunspot series is cleaner with a clear Schwabe oscillation, even if significantly modulated. There is no notion of a noise. It should be no surprise that the amplitude spectra are different. But the FT projects a signal from real to complex space and one should consider the phase in addition to amplitude. One can in some cases (and in our case) estimate an uncertainty on frequencies for instance by taking the half amplitude at half height of individual spectral peaks. In that case the modulus is sufficient. One must recall that two signals with the same amplitude spectra can be different and two different signals can have the same amplitude spectra. In all other cases than Figures 1 and 11, we apply FT only to individual (pseudo-periodical) components extracted with SSA. Another point is that FT acts on the entire signal and in order that spectral peaks be correctly detected the signal must be strictly stationary, which is not the case for many geophysical signals. This is why the raw spectra are different. This is why we have recourse to the SSA filter to regularize the problem.

(1b) *"For this reason, we have recomputed the frequency spectra of temperature and ISSN sunspots to compare their relative amplitudes at different periods and provide a confidence interval (Figure A1a and b)." "We used the Thomson multi-tapered method (Ghil et al., 2002) with a time-band width product of 3, a method which is well adapted to a spectrum which exhibits both continuous and singular components."*

The authors probably mean to refer to multi-tapered M-SSA that has been used by Ghil et al. (2002) following Thomson (1982). We use SSA as in Vautard et al. (1992). These authors noted that in order to bridge gaps in a sequence of paleo-climatic data, the FT was not the worst tool. Without going into too much detail, we can say that there is a fundamental difference between SSA and M-SSA: in the former, one analyzes and compares signals and components one by one. In the latter, they are analyzed in groups. Most of these aspects are well documented in Golyandina and Zhiglavsky (Chapters 2.3, 2.4, and 2.5, pages 25 to 71). There is no method that works *ab initio* without adjustable parameters (Kay & Marple, 1981). In SSA these are the size of the analyzing window (that allows one to build the Hankel matrix) and the grouping of Eigen-triplets (Eigen vectors and Eigen values that must be paired). We explain and provide all of these parameters in our paper and figures. In their comment, CCC obtain log-log spectra with the method of Ghil et al. (2002) and a time bandwidth of 3, and they write that this "*is well adapted to a spectrum which exhibits both continuous and singular components"* It is difficult to compare their Figures A1a and A1b, showing PSD as a function of frequency, with our results (Figures A1c and A1d, showing Eigen values as a function of rank).

(1c) *"The only significant peaks that exceed the 95% confidence interval level are the well-known 11-years peak and its harmonic at 5.5 years in the ISSN time series;"*

Where does the 95% confidence come from? Is there an underlying model that allows to establish a confidence distance? All we do is decompose the data to see what they contain.

(1d) *"but there is no corresponding significant peak at the 11 and 5.5 year periods or any other one in the temperature time series"*.

All depends on what is meant by significant. Moreover, the aim of our paper is not to assert that the 11 years Schwabe cycle drives global mean temperature.

(1e) *"The 60-year period shows unsurprisingly more energy in the temperature signal (the temperature, as many geophysical time series, is a "red signal" with more energy at low frequencies)"*.

This is not astonishing: we have known since Laplace (1799) that Earth acts as an integrator. One needs a (sometimes long) time to identify a given effect. Moreover, this remark does not imply a physical mechanism linking sunspots and temperature.

(1f) *"Still, we could not isolate a clear distinctive peak at this period on the temperature spectrum; nor on the ISSN one"*.

These peaks have been found by many authors (Azeem et al., 2007; Henriksson et al., 2012; Le Mouel et al., 2019; Scafetta and West, 2003, 2007; Zotov, 2013). They use different algorithms and can be compared to Ghil et al. (2002). It is certainly true that certain periods we extract by SSA have been found by others. An original side of our work is to have recovered all of them and to have given the components a time varying expression (we believe for the first time). Having both the amplitude AND the phase allows one to start thinking about physics. Figures 3 to 9 show the wave shapes of pseudo periodic components. Their values have in part been already identified by others. Here, we enrich our knowledge of global temperature curves; we hope to be able to propose a model in the future, but this is not yet the case in the present paper.

(1g) *"Can we learn more from the SSA performed by the authors?"*

We had already been asked this by the reviewer and the editor and provided the Appendix, that seemed to satisfy the editor. We can recall that we used an approach that is more modest than Ghil et al. (2002). The classical SSA algorithm we use is described by Golyandina and Zhiglavsky (Chapter 2.1), to which we have added their recommendations in Chapter 2.5 (Sections 2.5.3 and 2.5.4). Again, all parameters, sizes of analyzing windows, regrouping of Eigen-triplets, are given in the text, and the figures (including those borrowed by CCC in their comment).

(1h) *"Unfortunately, the SSA eigenvalues of the temperature and ISSN time-series computed by the authors suggest the same conclusion (Figures A1c and A1d): the dominant frequencies are completely different between the two time series; the temperature SSA is dominated by a 60-years eigenvalue which is simply absent in the ISSN SSA."*

On the contrary, we believe that the eigenvalues have the correct amplitudes. And we take into account the eigen vectors (we are not in the infinite space of Fourier transforms). We do not agree that dominant frequencies are completely different. We see in Figures 2 and 13 that out of the first 10 SSA components of ISSN and temperature, the following six periods are found in both series: 22, 11–12, 8.5–9, 8.1–8, 6.2–6.5, 5.5. They do not have the same amplitude and rank: this is expected for sources that combine in a non-linear way. This is also true for the 60 years component that does exist in ISSN at a larger rank (see Le Mouël et al, 2019b; Le Mouël et al, 2020).

(1i) *"... (by construction, the SSA method will produce peaks at single frequencies even in a purely random noise time-series)"*.

Although this may be true for the Fourier Transform (e.g., the *sinc* function examples given in books) and Maximum Entropy Spectral Analysis, it is not for SSA (Golyandina & Zhigljavsky, 2013). By the way, a "true" numerical noise does not exist since all algorithms start with constants in the address files that help start the randomization (see the MatLab *rand* function).

(1j) *"Although the SSA significance is not straightforward to assess, it could be have been tested using a Monte Carlo SSA test* (Ghil et al, 2002)*"*.

SSA (and also FT, spherical harmonics, wavelets,...) is a tool that allows one to decompose signals on orthonormal bases, that have no physical significance a priori. These algorithms must verify the property that applying them twice to the signal, one should recover the original signal within the numerical resolution of the computer. If CCC ask whether our components can be given a physical meaning, the question to be asked is what is the separability of components extracted by SSA. Golyandina and Zhiglavsky's Chapters 2.3.3 and 2.5.4 deal with this subject. So there are other methods available, besides Ghil et al. (2002); moreover, the Monte-Carlo method is purely statistical whereas the rotation of the Hankel matrix associated with the Varimax allows one to optimize the distribution of energies in eigenvectors, and therefore to come closer to the (unattainable) perfect separability.

(1k) *"Since this crucial information is lacking, we can attempt to select the significant components by locating the slope break in the temperature SSA (Ghill et al,* 2002*): the idea being that there is a sharp break between the highest (significant) eigenvalues and the lowest un-significant ones. This suggests that all components shorter than 60 years period are not significant for the temperature, a conclusion that is consistent with the frequency spectral analysis"*

The paper that CCC refer to treats only of FT and spectral randomization. CCC's criticism would then apply to Golub and Reinsh (1971) (father of Singular Value Decomposition), to Vautard et al. (1992) for SSA, to Mallat (1989) for the pyramidal algorithm used in wavelet theory,... CCC must agree with our spectrum in Figure 1, since they use it as an argument in their first sentence: all periods below the 60 years peak would be insignificant. The sum of all energies below the 60 years period should be much smaller than the energy of the peaks above. This is not the case, as shown by our SSA analysis.

(2) "*the small radiative forcing associated with the sunspot variability*"

We do not claim to have found a mechanism: we suggest that the SSA components of ISSN and temperatures that share the same characteristics could be linked in some way. But we conclude "*The trend itself could, at least in part, be a segment of a much longer, multi-centennial solar period. In conclusion, SSA has revealed modulated components that can reasonably be assigned to solar variability for most and even possibly all of them. Naturally, mechanisms should be sought to account for these observations and hypotheses.*»

(3) "*the simple evidence that the slowly varying components of the temperature and sunspots time show opposite trends in the last 30 years*"

We do not agree. All depends on the way the trend is defined. SSA provides the trends (component 1) shown in Figure 20 of our paper. These trends are not opposite but rather similar. When adding the next (oscillatory) SSA components, the "opposite trends" that are seen from 1980 in 2020 in CCC's Figure A2 result. The opposite slopes do not come from the SSA trend but from failing to separate the following oscillatory component(s).

In conclusion, our three key points may read:

- We find compelling results showing a significant co-variability between sunspot numbers and global temperature
- However, we do not have a mechanism to explain that forcing: it remains to be found. Therefore, we do not discuss further the parts of CCC discussing mechanisms
- The trends of global temperature and solar sunspot numbers (defined as their first SSA component) are similar in the last 150 years; the slow second SSA component is responsible for an opposite trend of the two series in the last 30 years

Data Availability Statement

All data are freely available from public web sites as listed in the acknowledgements of our original paper.

Acknowledgment
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