**Hydrology and
Earth System
Sciences
Discussions**

Interactive comment on "Low-frequency variability of European runoff" *by* L. Gudmundsson et al.

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In any earth science, methodology is an important issue and the comments of the referee M. Mudelsee highlight that a particular choice of methods may alter the outcome of a data analysis. In some cases, however, we have the impression that M. Mudelsee has been too pessimistic concerning the robustness of the analysis. Therefore we take the opportunity of this "interactive discussion" to comment on his major concerns.

1 Choice of time series decomposition method and stability of Φ_X

M. Mudelsee major comments concern the *stability of the estimate* and the *choice of method*. In the following we will comment in detail on his major concerns.

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(1) Stability of the estimates and error bars: M. Mudelsee reflects on the stability of the estimated value of Φ_X. Finite size effects and data-noise may influence the estimated value and M. Mudelsee suggested to quantify the uncertainty of Φ_X with error bars. Further, the estimated Φ_X may depend strongly on the chosen method and its parameters.

(2) Choice of STL parameter λ_{Long}: The choice of $\lambda_{Long} = 19$ follows the recommendations of Cleveland et al. (1990), who show analytically that setting λ_{Long} equal to the *next odd integer* of $(1.5p/(1 - (1.5/\lambda_{Seas}))$ is optimal with respect to a minimal spectral leakage of frequency components associated with the annual cycle, into the low-frequency components. The choice of $\lambda_{Long} = 19$ is closely related to separating the variance of a power-spectrum at a frequency of $f = 1/19$. As this choice of λ_{Long} has a analytic justification we argue against performing a sensitivity study, with varying λ_{Long}. However, we suggest to emphasise the previous points in the revised manuscript.

(3) Choice of method: The STL-algorithm (Cleveland et al., 1990) is one of many time series decomposition techniques that are available. Its principle application is the decomposition of time series into three sub-signals. Other, often more flexible, techniques were considered for the analysis including Singular System Analysis (SSA) (e.g. Ghil et al., 2002), Wavelet based decompositions (e.g. Torrence and Compo, 1998) and Empirical Mode Decomposition (EMD) (e.g. Huang et al., 1998). All these methods have their specific advantages and drawbacks. The final choice for the STL algorithm is pragmatic, motivated by its suitability for the aim of the analysis (isolating low-frequency components from time series) and its algorithmic efficiency.

The focus of these methods is time series decomposition and not a spectral representation of time series. However, in this study we aimed at a parallel analysis of the space-time patterns of the low-frequency components of runoff as well as an analysis of its spectral properties. To achieve this we introduced Φ_X, the fraction of low-frequency variance of the series X, as an albeit simplistic parameter characterizing the shape

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of the power spectrum. M. Mudelsee argues that more specialised methods would be more appropriate to estimate the spectral properties of the time series. We fully agree with this point, however, pure spectral methods do not allow for a direct separation of specific sub-signals.

2 Supplementary analysis

To address the major concerns of M. Mudelsee, we conducted a supplementary analysis demonstrating the stability of our estimation of Φ_Q (the fraction of low-frequency variance of runoff) by comparing it to an alternative approach based on the multi-taper method (MTM). In the following, $\Phi_{Q,STL}$ refers to the estimate that is used in the discussion-paper and $\Phi_{Q,MTM}$ to the new estimate.

$\Phi_{Q,MTM}$ was estimated by first computing the power-spectrum of Q using MTM. (Following the recommendations of Ghil et al. (2002) "discrete prolate spheroidal sequences" (DPSS) - tapers were used). In a second step, $\Phi_{Q,MTM}$ was determined as the fraction of variance explained by frequencies $> 1/19$ months (being consistent with the STL parameter λ_{Long}).

Confidence intervals of both $\Phi_{Q,STL}$ and $\Phi_{Q,MTM}$ were obtained using a boot-strapping procedure. To account for the strong seasonality and high serial correlation in the runoff time series we used a block bootstrap, where blocks of a time series with fixed length are resampled instead of single data points (e.g. Efron and Tibshirani, 1993). There is no standard recommendation on the choice of the block length n_b, and often n_b is set in an ad-hoc fashion. In the present case, the seasonal pattern of the input series needs to be accounted for, requiring a block-length of at least $n_b = 12$ (months). In order to be consistent with the parameter value chosen for the parameter λ_{Long}, the block length was set to $n_b = \lambda_{Long} = 19$. We are aware of that the argumentation for this choice may be simplistic and welcome any constructive suggestions. The bootstrapping was

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based on 1000 replications and the 2.5% and the 97.2% percentiles of the bootstrap sample were used to construct 95% confidence intervals.

Figure 1 summarizes the results. The estimates of $\Phi_{Q,STL}$ and $\Phi_{Q,MTM}$ (circles) are closely related ($R^2 = 0.93$), indicating that the two approaches provide quantitatively comparable results. The gray horizontal and vertical bars are the boot-strap confidence intervals (CI) of each data point and are measures of stability. For both measures, the CIs have comparable magnitudes. Note that the estimates fall outside of the CI in a few cases (STL: 1.6% and MTM: 0.9 %). This may be related to (a) that the "model" introduced by the block bootstrap may not be fully appropriate, and (b) that 5% of the observations are expected to lie outside the 95% confidence-intervals by construction.

Based on these results we conclude that the estimate $\Phi_{Q,STL}$ is equally robust and comparable to the alternative estimate $\Phi_{Q,MTM}$. Therefore, we can conclude that a change in methodology is not necessary. However, we suggest to report the uncertainty of Φ_Q, Φ_P and Φ_T in the revised manuscript by including maps of the widths of the confidence-intervals (or a related measure). In addition, this supplementary analysis may be of interest to the readership and it may be useful to present it as an appendix (but not in the main text, as it would draw to much attention from the main results).

3   Minor issues

(4) Use the word "river" in the abstract. We will include this in the revised version of the manuscript.

(5) Hyphenation is according to the HESS-D typesetting but we will carefully check for comparable issues in the potential final proof.

(6) We will elaborate on the Hurst phenomenon in the revised paper (as elaborated on in our response to the comment of the Editor D. Koutsoyiannis).

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Currently we are not aware of studies that explicitly investigate "the relative importance of long-term variability as compared to annual or sub-annual variability". Most studies concerned with long-term variability of monthly runoff (e.g. Shun and Duffy, 1999; Hanson et al., 2004; Kumar and Duffy, 2009) focus on the temporal evolution of the sub-signal and only address the question of its relative importance marginally. We are aware of that we may have missed out on some references and therefore we suggest to relax the formulation "little is known" accordingly.

(7) We will define f as a frequency band covering $f_{max} > f \geq f_{min}$.

(8) The daily runoff data come from the same data source as the monthly values. In fact, the monthly values were obtained by aggregating the daily observations. We will state this clearly in the revised paper.

(9) We will define STL as "A Seasonal-Trend Decomposition Procedure Based on Loess".

(10) It is in true that Fig. 2 contradicts the statement that Q_{Seas} may change over time. However, Fig. 2 reflects the choice of parameters elaborated on p. 1710 l. 22 ff in the discussion paper, which enforces annual cycles without trends.

(11) See previous section on methodology (Section 1 issue **(2)**).

(12) More detailed description of the STL algorithm. In our replies to previous reviewer comments we already mentioned the trade-off between the level of detail in method descriptions and the need for a paper to be concise. Most of the chosen methods (STL, ISOMAP, Procrustes Analysis,...) have a relatively high complexity and a full description of all methods would change the focus of the paper from a paper looking at *hydrological phenomena* to a paper concerned with *methods*. Therefore, we chose a rather brief method description. However, to address the demand for more details on the methods in general, we suggest to include an methodological appendix.

(13) Spearman (1904) or Spearman (1987). The version of the paper available to us is

actually a reprint of the 1904 paper published in 1987. See http://www.jstor.org/stable/1422689 for more details. We suggest to cite the paper as follows (Spearman, 1987, reprint from Spearman, 1904) in the text, but only list the reprint in the reference list (which is also more accessible for the majority of the readership).

(14) We will cite von Storch correctly.

(15) We will elaborate on the effect of nonlinear processes on data analysis in an more accessible language. Possibly expanding the example on "distance measurement" in the earth surface.

(16) Including the page numbers where the references are cited in the reference list is part of the HESS-D typesetting.

(17) "remnants of the literature data base". These "remnants" are actually *digital object identifiers (doi)* that are increasingly included into reference-lists, also in HESS-D (see http://dx.doi.org/ for more details).

(18) We will carefully check the reference-list of the revised manuscript for consistency.

(19) see issue **(13)**.

(20) p-values of the Spearman correlations (Table 1). The p-values are computed using the algorithm AS 89 (Best and Roberts, 1975), which does not account for spatial dependence. Currently, we are not aware of well established strategies to adjust Spearman's ρ to spatial dependence. If we should have missed a promising approach we would appreciate an hint to the relevant literature. Otherwise we suggest not to report the p-values and instead use a relatively conservative ad-hoc threshold to select ρ values that we consider to be interpretable. One suggestion would be $|\rho| \geq \sqrt{25} = 0.5$ which corresponds to the case where at least 25% of the variance of the ranks is explained by the correlations.

(21) We will reformat the figure and adjust the coordinate values of the axis.

(22) We will explain the color code as the values of the leading ISOMAP coordinates.

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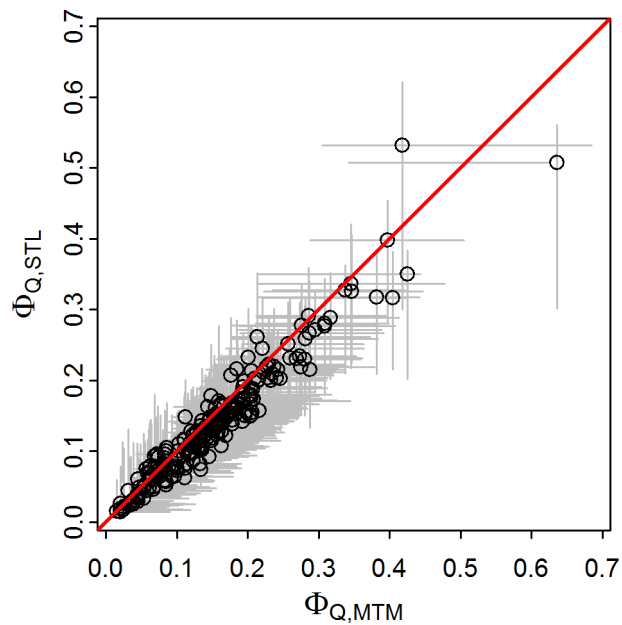Printer-friendly Version

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Fig. 1. Comparison of Phi_{Q,STL} and Phi_{Q,MTL}. Gray bars are 95% confidence intervals based on bootstrap