Response to Referee #2

Responses are written in blue.

Referee report on Hydrological signatures describing the translation of climate seasonality into stream flow seasonality by Gnann, Howden and Woods

In their manuscript the authors analyze how long term (seasonal) variations in precipitation time series translate into (long term) variations in stream flow. To do so the authors decompose the precipitation and corresponding stream flow time series into their Fourier modes and analyze the mode corresponding to the annual (seasonal) cycle.

The paper is well written and addresses the problem of signal and forcing from a point of view which is more common in electro-technical engineering than in hydrology. Thus the paper may help to stimulate the field by introducing new methods and alternative approaches to analyze the relation between input-output time series. Below some comments and suggestions which should help the authors to improve and strengthen their manuscript.

We thank reviewer #2 for the helpful and encouraging feedback.

Abstract: "We approximate [..] by sine waves." Input and output signals are not periodic per se, but show recurring patterns. In order to address this point the authors may simply rephrase the above statement with something like: "In order to analyze the seasonality relations between input [...] and output we represent the two time series by their seasonal (annual) Fourier mode." Such a formulation avoids the criticism that the signal itself periodic, while keeping all the rest of the analysis unchanged.

Thank you for the suggestion, we will revise the text accordingly.

Sec 2.2.1: 1 year Fourier mode: It would be interesting to see for an example how the different Fourier modes are represented in the spectrum of the time series. Such a measure would show how "strong" the annual mode is compared to the other modes of the signal.

We did a quick analysis to check how strong the annual mode is in comparison to other modes. We calculated one-sided power spectra and extracted their maxima for all catchments. Two examples (following a copy of Figure 4 from the paper) are shown below (Fig. 2).

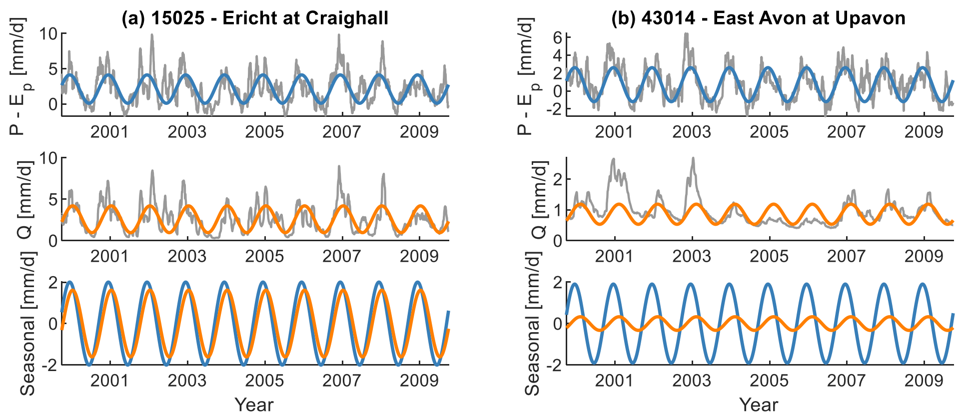

Fig 1. Climate input ($P - E_p$) and catchment output (Q) for two catchments in the UK, and their respective seasonal components. The time series are smoothed using a 30-day moving mean. The Ericht is a rather responsive catchment (BFI =

0.47), while the East Avon has a large baseflow component (BFI = 0.89). Note that for the bottom plots ("Seasonal") the mean values of the sine curves are set to zero. (Figure 4 in the manuscript.)

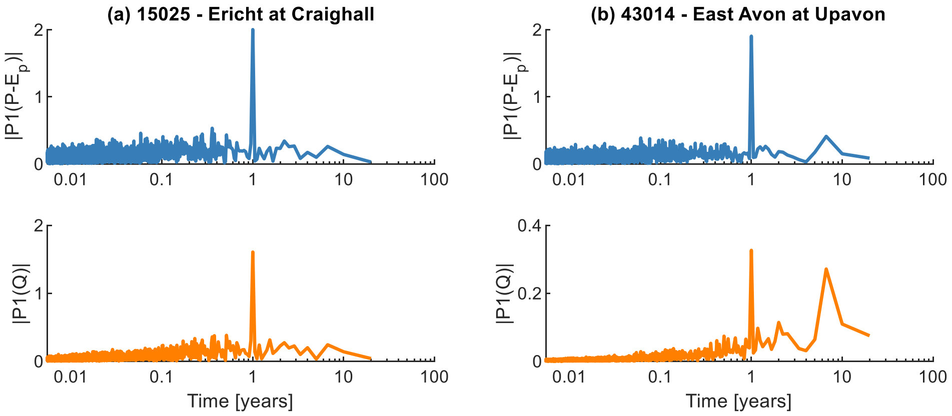

Fig 2. One-sided power spectra of climate input (P - E_p; blue) and catchment output (Q; orange) for two catchments in the UK.

For almost every catchment in our manuscript (~99%) the strongest forcing Fourier mode is the annual mode. For a few catchments in the US a 0.5y mode is the strongest, yet typically there is also a 1y mode present. Some of the streamflow data show strongest modes different from 1. Yet again, this doesn't mean that there is no annual mode present. For example, in panel (b) below we can see a strong multi-annual mode and the annual mode. We can also see that the groundwater dominated catchment (b) seems to act as a low-pass filter, dampening signals with shorter periods stronger than signals with longer periods. In principle, we could analyse more periods than the annual period and perhaps contrasting different periods might yield other interesting insights. But we have decided to focus on the annual time scale because it has a clear physical meaning (see lines 106-110). We will add the Fourier spectra to the SI.

Line 110: Although notation is an arbitrary choice, I would suggest the authors to use "PET" or at least "E_{PET}" in order to refer to Potential Evapo-Transpiration.

Thank you for the suggestion, but we would prefer to stick with our notation.

Reducing the in-/output signal by putting all weight of the time-series into the single (seasonal) Fourier mode may be problematic for analyzing real world data where: a. It is not per se clear that the overall dominant part of the signal. (Here as mentioned above the spectrum should give insight)

See above for an answer to that question and for Fourier spectra.

b. Additionally the different modes of the input signal do not necessarily need to be linearly coupled with modes of the same frequency in the output. Thus, it should be made clear that the description in section 2.1 relies on the assumption of a single wavelength forcing and a linear response system.

We will state these assumptions more clearly in a revised form of the manuscript.

Note: Due to linearity, all derivations presented in 2.1 should be valid for any Fourier component of the forcing function with F_n=A_n\exp(i*k*t) where A_n is the amplitude of the corresponding mode in the Fourier series.

Yes, the theory is not limited to the annual model. Yet as we've noted above, we focus on the annual mode as it is the dominant mode and as it has a clear physical driving force.

Figure 4: As mentioned before it would be interesting to see, how the blue and orange modes are represented in the corresponding spectra. If the seasonal modes are by far the most dominant frequencies in the signal it could help to justify for the single mode forcing model.

See above for an answer to that question and for Fourier spectra.

Sec. 4.2: Given the heterogeinity of natural systems it is not too surprising that a single linear (reservoir) model is not sufficient.

We agree on that, but we thought we start with rejecting the simplest model.

Fig. 6a and 7a: I would suggest the authors to use a two color divergent color scale to distinguish between negative and positive I_m (blue to white for neg. and white to red for pos values)

We originally intended to stick with the RGB colour schemes introduced by Knoben et al., 2018. We agree, however, that the colour scale is not the best choice in our case. We will change that accordingly.

Another critique of Figs.6/7 is that the high point density can hide variabilities, especially when the points are plotted in a sorted manner, e.g. sorted by amplitude In order to avoid such a situation one could first randomize the sample with respect to the variable of the color bar.

At the moment, the points are plotted based on the list of catchments we've used. That is, neither completely random (the catchment list tends to follow geographical locations) nor sorted by anything specific such as amplitude ratio. We will check whether the plotting order influences the figure and improve the information content of the plot if possible.

Section 4.3 requires some more details how the models were set up and parameters were varied/chosen (This can be added to the SI). Examples are: Line 333: Running IHACRES with 20 000 parameter sets. - Which are the parameters? - What are the parameter ranges that were varied? Line 335: The sentence "Plotting curves [...] produced by a certain set ..." needs some clarification. Questions which may arise here are: - How was the parameter set being chosen? - Was it always the same for all different catchments? - Did the authors perform a parameter sensitivity analysis?

Thanks for pointing out places where we were unclear in the modelling part. We will add more details on the modelling part to the SI.

Line 343: "[...] with varying forcing.": Why do the authors introduce here the aridity index AI=PET/P=1-F/P as a nonlinear transformed quantity of F=P-PET rather than using their definition directly. Alternatively if the aridity dependence is the point to make here the authors should simply say this: "[...] does not vary substantially with varying AI=PET/P=1-F/P."

Thanks for pointing that out. Indeed, using the aridity index here is not necessary. The main purpose was to point out that each line corresponds to a different forcing input. We will change that to the moisture index I_m so that it's consistent with Figures 6 & 7.

— I hope that the authors find my comments & suggestions useful to to improve the manuscript and strengthen their arguments.

Thanks again for reviewing our manuscript!

References

Knoben, W.J., Woods, R.A. and Freer, J.E., 2018. A Quantitative Hydrological Climate Classification Evaluated With Independent Streamflow Data. Water Resources Research, 54(7), pp.5088-5109.