Hydrol. Earth Syst. Sci. Discuss., 10, C1927–C1935, 2013
www.hydrol-earth-syst-sci-discuss.net/10/C1927/2013/

Hydrology and Earth System Sciences
Discussions

Interactive comment on "Technical Note: Using wavelet analyses on water depth time series to detect glacial influence in high-mountain hydrosystems" *by* S. Cauvy-Fraunié et al.

S. Cauvy-Fraunié et al.

sophie.cauvy@gmail.com

Received and published: 24 May 2013

Dear Bettina Schaefli, Thank you for your very useful and constructive critiques. They were helpful and allowed us to improve our manuscript in many ways. We feel we have addressed all your concerns. Below, you will find the numbered point-by-point responses [R] to your comments [C] and the changes that we would make in the manuscript. Note that we numbered the revised figures with letters (Figure A, B etc...) to avoid confusion with figure in the initial version of the manuscript.

[C-1] I have read in detail the technical note and the review of referee 1. The review

of referee 1 is a very thorough review and I largely agree with all raised points and with the main conclusion, which is that the paper is not acceptable for publication in its current form. I even doubt that major revisions might bring it to an acceptable form. The main reason for this conclusion is that, just as reviewer 1, I do not see why wavelet analysis would be useful for the proposed objective, which is the quantification of the glacier influence on observed stream flow. Why use a "complicated" spectral method with time-resolution if the time-resolution is thrown away for the index calculation? And more importantly: why not simply quantify directly the amplitude of the daily discharge cycles (in the time domain) if this is what the index is supposed to measure? Has this been done before? Before giving some more detailed comments, I would like to emphasize here that continuous wavelet analysis seems a priori a promising tool to analyze glacier stream flow or water level time series - but it remains relatively difficult to make a quantitative use of wavelet power spectra and to quantitatively assess the features that are visible in the spectra. This certainly motivated the use of the global wavelet spectrum in this paper even if it is not clearly stated on p. 4377. This difficulty arises from the expansion of a 1-D signal to a 2-D representation, which includes obviously redundant "information". Any statistical test of whether the features are significant or not has to account for this and is furthermore confronted with the problem of multiple testing. See the work of Maraun et al (2007) and the hydrologic application of Schaefli et al. (2007) for a state-of-the-art of significance testing. An example of how to make a quantitative use of wavelet power spectra for model perfor- mance assessment is presented in the work of Schaefli and Zehe (2007). If the authors want to pursue their idea of using continuous wavelet transform to assess the degree of ice melt influence on streamflow, they should first develop a consistent quantitative method that makes use of the wavelet power spectrum (i.e. not of the global spectrum where time-resolution is lost). I see indeed some potential here (de- tails hereafter) but developing such a quantitative method might be difficult.

[R-1] We fully agree. As suggested by you and reviewer 1, we now propose a complete wavelet analysis of glacier stream level signals. See our response [R-2a-b-c] to reviewer 1.

[C-2] Furthermore, I would like to re-iterate an important critic of reviewer 1: we lack information about the climate and the main drivers of hydrological processes. I wrote the comments below having my mental image of how high alpine glacier systems work, but this might be erroneous for glacier systems in the tropical Andes. How long is the ablation season here? Do the ablation and accumulation seasons overlap? Is there melt the whole year around as suggested on p. 4381? Is ice melt temperature or radiation-driven?

[R-2] OK, climatic, glaciological and hydrological information is now detailed in a new sub-section of the Study site section. See our response [R-1b] to reviewer 1.

[C-3] Potential of continuous wavelet transform to detect ice melt influence The authors state that there is ice melt the whole year around. I would expect that the intensity and the shape of the daily cycles vary throughout the ablation season as a function of the build-up of the glacier drainage system. For Alpine glacier catchments, a wavelet analysis of the time-varying amplitude and shape of daily streamflow cycles (see an example in Fig. 1 hereafter or the discussion in (Baumgartner and Liebscher, 1990, on p. 289)) could potentially be a promising way to detect the influence of a glacier on streamflow (under the hypothesis that runoff processes in the absence of a time-varying glacier drainage system would not lead to such a typical pattern). Devel- oping a quantitative wavelet-based method to quantify this effect seems a difficult task; a time-domain method might well be more suitable.

[R-3] You are totally right. The intensity and the shape of the daily cycles vary throughout the ablation season and our global wavelet spectrum was not giving any information about this. We have now developed two new metrics based on our wavelet analysis (the number of days significant glacier floods and temporal clustering of floods) to take into account such temporal variability (see further details in our response R-2b to reviewer 1).

[C-4] Interest of the method The study discusses that chemical signatures might not be sufficient to detect ice melt influence on streamflow and it reports glacier-influence on locations without obvious glacier cover. Even if I do not think that the proposed method is correct, this result and the potential existence of ice melt water reemergence justifies from my point-of-view the idea of developing a streamflow / water level-based ice melt detection-method. The question whether the reemerged water has the same ecologically-relevant features as direct ice melt remains, however, open.

[R-4] Thank you for this useful comment. We do indeed think that the ice melt water re-emergence issue is an important justification for our developing new ice-melt detection method. This argument is now included in the Introduction, in a paragraph which better justifies the need to develop new methods (see response R-6 to reviewer 1). Concerning the last part of your comment, our team is currently working on the ecology of these re-emerged waters, which tend to have lower species diversity levels than other non-glacial streams (see some preliminary discussion about this in Jacobsen et al., (2012)).

[C-5] Methodology - water level instead of streamflow I am not sure that the use of water level, which is much easier to measure than stream- flow, is really limiting (see reviewer comment 1). The main features of the daily stream- flow cycles might well be preserved in the water level observations - however only if the stage-discharge relation is not too strongly non-linear and if the cross-sections are not changing their shape throughout the measurement period. The first aspect would need some detailed analysis for at least one study location.

[R-5] As proposed we have compared our wavelet analysis on discharge vs. water level data at site 7, which corresponds to the gauging station Crespo (nearby site 7). This analysis is presented in Figure F.

Overall we found a very good correlation between the power spectra calculated with discharge vs. water level time series (see Figure F).

[C-6] Methodology - background spectrum I agree with reviewer 1 that the appropriate spectrum to test against should be a red- noise spectrum. I would, however, give a slightly different motivation. The objective of the significance test of the wavelet power spectrum is to decide whether the visible features could also simply arise from a purely random process. From this point of view, we might want to test against a random process that has similar features as the analyzed process at hand (see Schaefli et al., 2007). This reasoning obviously falls short for a process with strong cycles. In time series analysis, this cycles would typically be removed from the data before estimating the wavelet spectra - since we do not want to detect things that we see already in the time-domain (Schaefli et al., 2007). Reviewer 1 advances the fact that the errors of discharge observations are typically red-noise processes. While I am sure that discharge observations do not have Gaussian errors (given how they are estimated from stage-discharge observations), I am not quite sure whether they are really autocorrelated.

[R-6] As suggested, wavelet analysis has been done with the red-noise spectrum. A justification of the choice of this noise is now given in the Methods (see our response R-3 to reviewer 1).

[C-7] Methodology - Morlet wavelet In its general form, the Morlet wavelet has a parameter that determines its time/scale resolution (e.g Maraun and Kurths, 2004). This parameter also determines the relation between the scale and the Fourier period (p. 4378).

[R-7] Thank you for this information which we have included in the text

[Paragraph on the choice of Morlet wavelet in the Methods] Here, we chose the Morlet wavelet, a nonorthogonal, continuous, and complex wavelet function (with real and imaginary parts), because it is particularly well adapted for hydrological time series analyses (Torrence and Compo, 1998; Labat et al., 2000; Lafreneire and Sharp, 2003). Nonorthogonal continuous wavelet transforms are indeed more robust to noise than

other decomposition schemes and are robust to variations in data length (Cazelles et al., 2008). Moreover complex wavelet functions are well suited for capturing oscillatory behavior whereas real wavelet functions do better to isolate peaks or discontinuities (Torrence and Compo, 1998). Finally the Morlet wavelet function has a high resolution in frequency compared to other continuous wavelets (Cazelles et al., 2008), which was fundamental in our method as we intended to detect the repeated water depth variations at the 24-hour scale. In its general form, the Morlet wavelet has a parameter that determines its time/scale resolution (Maraun and Kurths, 2004). As this parameter also determines the relation between the scale and the Fourier period (period = 1.03 ïĆť scale), the terms period and scale will hereafter be used interchangeably.

[C-8] Terminology [C- 8a] I agree with the critical comment of reviewer 1 on the index terminology.

[R-8a] Ok this has been changed as proposed by reviewer 1.

[C-8b] p. 4387: "power spectrum of a time series" is misleading, it is the estimated power spectrum of the natural process.

[R-8b] OK this will be changed throughout the MS.

[C-8c] I would also suggest to pay attention to clearly distinguish between ice melt and glacier runoff (including all sources of runoff from a glacier). As far as I can see, for the link between climate change and ecological processes (introduction), it is important to separate between water stemming from ice melt, from seasonal snow, perennial snow etc. The proposed method does not allow to separate them. Accordingly the method does not allow to assess the effect of climate warming as suggested in the abstract.

[R-8c] The additional information provided on the hydrological characteristics of the study site (see our response 1b to reviewer 1) should clarify this issue as 1) there is no snow cover outside the glacier in our study area; and 2) the water source identified by our indices includes liquid precipitations on the glacier, and fusion of snow and ice. We agree that the method does not assess the effect of climate warming; the last words "...and assess the consequences of rapid glacier melting." have been deleted from the abstract.

[C-9] Method - SAGA Does SAGA provide an algorithm to identify the stream network and the catchment? And if yes, how well does it perform? Any hydrological study published about this? Or should it be compared to a more well-known method such as Taudem (hydrol- ogy.usu.edu/taudem)?

[R-9] Additional information about SAGA is now provided in the MS. Channel network and catchment area was calculated with the SAGA software. Briefly, SAGA derives a channel network based on gridded digital elevation with the specification of the target cells (gauge station), for which the upslope contributing area is identified. The catchment delimitation is based on the multiple flow direction model (Tarboton, 1997) and the extraction of the drainage network uses algorithm described in O'Callaghan and Mark (1984).

[C-10] References Baumgartner, A., and Liebscher, H.-J.: Allgemeine Hydrologie - Quantitative Hydrolo- gie, Gebrüder Borntraeger, Berlin, 694 pp., 1990. Hingray, B., Picouet, C., and Musy, A.: Hydrologie 2 - Une science pour l'ingénieur, Presse Polytechnique et Universitaire Romande, Lausanne, 289-338 pp., 2009. Maraun, D., and Kurths, J.: Cross wavelet analysis: significance testing and pitfalls, Nonlinear Processes in Geophysics, 11, 505-514, 2004. Maraun, D., Kurths, J., and Holschneider, M.: Non-stationary Gaussian Processes in Wavelet Domain: Definitions, Estimation and Significance Testing, Physical Review E, 75, 016707, 2007. Schaefli, B., Maraun, D., and Holschneider, M.: What drives high flow events in the Swiss Alps? Recent developments in wavelet spectral analysis and their application to hydrology, Advances in Water Resources, 30, 2511-2525, 10.1016/j.advwatres.2007.06.004, 2007. Schaefli, B., and Zehe, E.: Hydrological model performance and parameter estimation in the wavelet-domain, Hydrology and Earth System Sciences, 13, 1921–1936, 10.5194/hess-13-1921-2009, 2009

[R-10] Thank you, all references have been considered.

âĂČ References

Cazelles, B., Chavez, M., Berteaux, D., Ménard, F., Vik, J. O., Jenouvrier, S., and Stenseth, N. C.: Wavelet analysis of ecological time series, Oecologia, 156, 287-304, 2008.

Jacobsen, D., Milner, A. M., Brown, L. E., and Dangles, O.: Biodiversity under threat in glacier-fed river systems, Nature Climate Change, 2, 361-364, 2012.

Labat, D., Ababou, R., and Mangin, A.: Rainfall-runoff relations for karstic springs. Part II: continuous wavelet and discrete orthogonal multiresolution, Journal of Hydrology, 238, 149-178, 2000.

Lafreneire, M., and Sharp, M.: Wavelet analysis of inter-annual variability in the runoff regimes of glacial and nival stream catchments, Bow Lake, Alberta, Hydrological Processes, 17, 1093-1118, 2003.

Maraun, D., and Kurths, J.: Cross wavelet analysis: significance testing and pitfalls, Nonlinear Processes in Geophysics, 11, 505-514, 2004.

O'Callaghan, J. F., and Mark, D. M.: The extraction of drainage networks from digital elevation data, Computer vision, graphics, and image processing, 28, 323-344, 1984.

Tarboton, D. G.: A new method for the determination of flow directions and upslope areas in grid digital elevation models, Water Resources Research, 33, 309-319, 1997.

Torrence, C., and Compo, G. P.: A practical guide to wavelet analysis, Bulletin of the American Meteorological Society, 79, 61-78, 1998.

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 10, 4369, 2013.

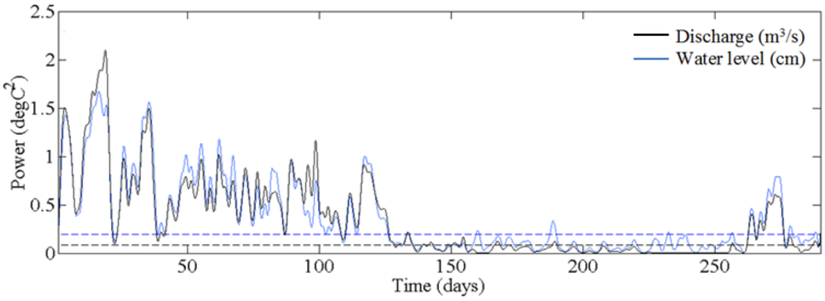

Figure F. Comparison of the wavelet analysis output (scale-averaged power spectrum over the 24 h-band) using discharges (black line) and water stage time series (blue line) at site 7. Dashed black and blue line presents the corresponding 95% confidence levels for the red-noise spectrum for discharge and water level time series, respectively. Discharge data were measured at 30 minute-intervals over the year 2010 at a gauging station.

Fig. 1.