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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.

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Dear reviewer, 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-1a] Although it is to be acknowledged that the paper is submitted as a note and

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conciseness is therefore important, the background provided in the “Introduction” and “Study sites” sections is nevertheless inadequate, being both simplistic and incomplete. There are two main problems. More and better context and literature citation is required, so that a broad hydrologic audience can understand why the technical question under study is important and where they can go for some further information. For example, after the sentence ending with “...end of the glacial influence on outflow (Husset al., 2008)” in the first paragraph of the introductory section, it would be useful to readers of a broad-based hydrology journal like HESS to add something like the following: “Statistical studies of long-term data from glacial and non-glacial catchments has demonstrated that streamflow responses to warming depend on whether glacial ice is present in the basin, and further, that glacial rivers have shown both increasing and decreasing trends, depending on the particular region and where it stands along the aforementioned deglaciation trajectory (Fleming and Clarke, 2003; Stahl and Moore, 2006; Casassa et al., 2009; Moore et al., 2009; Li et al., 2010; Fleming and Weber, 2012; Dahlke et al., 2012). Also, after the last sentence of the first paragraph, I suggest adding something like, “An increasing number of studies have quantitatively explored the potential future impacts of various climate change and glacial recession scenarios upon water resources, using modern glaciological and hydrological modelling techniques (e.g., Stahl et al., 2008; Jost et al., 2012; Clarke et al., in press). These studies and others have demonstrated that glacier change effects are likely to be hydrologically substantial, even in relatively lightly glaciated basins.”

[R-1a] We fully agree. Following your suggestions, the first paragraph of the introduction has been revised. Thank you for the references, they have been included in the text (see below).

[Modified text] In view of accelerated glacier melting worldwide (Lemke et al., 2007; Rabatel et al., 2013; Sakakibara et al., 2013), coupling glacier and glacier-fed hydrosystems evolutions is a timely research thematic (Bradley et al., 2006; Jacobsen et al., 2012). While at the early stages of glacier retreat the reduction in ice volume would

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yield a significant increase in annual runoff (see the conceptual model presented by Baraer et al., 2012), after a critical threshold (depending on the glacier size) the annual discharge would decrease up to the end of the glacial influence on outflow (Huss et al., 2008). Worldwide, glacial river discharges have shown both increasing and decreasing trends, depending on ice cover in the catchment, the study region, and where glacier stands along the deglaciation trajectory (Fleming and Clarke, 2003; Stahl and Moore, 2006; Casassa et al., 2009; Moore et al., 2009; Dahlke et al., 2012; Fleming and Weber, 2012). A growing number of studies have quantitatively explored the potential future impacts of various climate change and glacial recession scenarios upon water resources, using modern glaciological and hydrological modelling techniques (e.g., Villacis, 2008; Stahl et al., 2008; Jost et al., 2012; Clarke et al., 2013). These studies and others have demonstrated that glacier change effects are likely to be hydrologically substantial, even in relatively lightly glaciated basins.

[C-1b] Even more importantly, additional baseline hydroclimatic information is absolutely required about the study area, for readers to properly assess the scientific content and merit of the aper. We need to see basic background information like a graphical presentation of the typical annual cycles in river flow, air temperature, and precipitation within the study region; some basic weather and climatic influences, e.g., the general origins and types of weather patterns affecting the area (frontal vs. convective storms, for instance); and some sense of how the major sources of runoff evolve over the course of a typical year for these rivers (e.g., rainfall, melting of seasonal snowpack, melting of perennial snowfields and glaciers). Providing all of the requested additional background information would only require a few extra sentences and perhaps another figure or two, yet I believe it is key to improving the paper.

[R-1b] Good point. We have now included some information about climate, glacier, and hydrology of the study area in a new sub-section “Climatic, glaciological and hydrological settings” in the section “2. Study site”. Also we now present two graphics showing typical annual cycle in 1) rainfall and temperature and 2) in glacier stream discharge.

Climatic, glaciological and hydrological settings From a climatological viewpoint, the Antisana Volcano belongs to the inner tropics (Troll, 1941) with more or less continuous precipitation and homogeneous temperature conditions throughout the year (Figure A). The Antisana's precipitation regime is complex. Although substantial precipitation is observed all the year-round, there is always a period with heavy precipitation between February and June. The beginning of this wet season is however extremely variable. Generally another period between September and November shows high amount of precipitation. These features reflect the different origins of precipitation at the Antisana. First, Antisana receives precipitation from the Amazon basin. The eastern slopes of the Andes are the first obstacles encountered by air masses coming from the east and pushed by the trade winds from the Atlantic (Vuille et al., 2000), creating an ascent of the air and an adiabatic cooling leading to heavy precipitation. Second, the site is located in a border zone with the inter-Andean plateau, thus on Antisana, the precipitation regime of the Amazon regions (a single maximum between June and July and a minimum in February) is mixed with the inter-Andean valley regime (with two wet seasons in February-May and October-November, (Vuille et al., 2000). At inter-annual timescales, there is a general agreement that a significant fraction of the variability of precipitation is related to the El Nino–Southern Oscillation (ENSO) phenomenon (e.g. (Vuille et al., 2000). These studies concluded that El Nino years (warm phase of ENSO) tend to be warmer and drier than the average, while La Nina years (ENSO cold phase) are associated with colder and wetter conditions. From a glaciological point of view, both ablation and accumulation occur all year round on Ecuadorian glaciers (Francou et al., 2004; Rabatel et al., 2013). On Antisana 15 Glacier, (Favier et al., 2004) found that on seasonal timescales, mean ablation rates remained almost constant throughout the year. In addition, albedo appears to be a major determinant in melting. At a daily time step, a close relation was shown between albedo and net radiation (Favier et al., 2004). Changes in albedo go hand in hand with changes in the shortwave radiation balance. Consequently, the frequency and intensity of snowfall, which can occur all year long, play a major role in attenuating the melting processes.

As a consequence, both precipitation and temperature are crucial for the annual mass balance, both during the main precipitation period (between February and May) and the secondary precipitation phase (September–October). Because the 0°C isotherm remains all year round around 4950-5000 m (there is no seasonality in temperature in Ecuador, see Figure A) and glacier snouts are located at about 4850-4900 m, precipitation outside of the glaciers are almost exclusively liquid (except during exceptionally cold conditions during strong La Nina events). As a consequence, there is neither permanent nor seasonal snow cover outside the glaciers. From a hydrological viewpoint, the three main components in the streamflows are: (1) the direct superficial runoff; (2) the snow and ice melting; and (3) the groundwater flows. As shown in (Favier et al., 2008) a groundwater flow originates below the Antizana 15 Glacier and this flux is at the same time groundwater and ice-snow melting. The mean monthly discharge ranges from 0.04 to 0.1 m3.s-1 at Crespo station (1 km from the glacier snout) and from 0.25 to 0.3 m3.s-1 at Humboldt station (8 km from glacier snout; see figure B). The differences in absolute values of outflows are due to the different drainage areas with 2.4 km2 and 14.2 km2, respectively. Two different patterns in the monthly outflows variations can be observed. The mean monthly discharge for the Crespo station shows a perennial flow with the lower values observed between June to August and the higher values form October to May. High discharge values are a consequence of low precipitation over the glacier, which enhances short wave radiation absorption and glacier melting. Low discharge values are a consequence of higher wind velocity that enhances mass losses through sublimation instead of melting (Favier et al., 2004). The correlation between the precipitation and the outflows is weak and the regime is mainly controlled by glacier melting (Fernández, 2010). The outflows at the Humboldt station show low seasonal variations in accordance to the pluviometric regime with glacier contribution during the months of lower precipitation.

[C-2a] Given the operations actually performed to calculate the so-called Wavelet Glacier Signal, it is unclear from the manuscript as written why wavelet analysis is used instead of simpler, standard, Fourier transform-based spectral analysis. On lines

14-16 of page 4377, the authors write, “To compare the spectral power of different stream sites, it was necessary to determine the global wavelet spectrum, which is the average of the local wavelet spectrum at every scale over the whole time series.” This quantity is then used to generate the WGS values lying at the heart of the study.

[R-2a] You are totally right, our WGS parameter did not take into account the spectral content over time and we did not take full advantage of the complex wavelet analysis we performed. Several analyses are now provided in the revision to respond to this comment (described below and in R-2b). We now propose the use of "scale averaged wavelet power spectra" over the whole measurement period as a useful tool to better visualize the significance of the diurnal flow variation over time. Technically, for each time series, we calculated the scale-averaged wavelet power defined as the weighted sum of the wavelet power spectrum (over two scales s1 to s2):

where δj is the spacing between discrete scales, δt the time step of the time series, and Cδ the reconstruction factor. The scale-averaged wavelet power permits to examine fluctuations in power over a range of scales (a band) and then take into account potential time lags among sites at different distance from the glacier (Anctil and Coulibaly, 2004; Coulibaly and Burn, 2004; Markovic and Koch, 2005; White et al., 2005). We also determined the 95% confidence level for each time series by calculating the scale-average theoretical red-noise spectrum (see Torrence and Compo, 1998) for more details and Figure C). These spectra allowed us to track seasonal changes in the power at different sites, thereby fully using the wavelet analysis (Figure C). We found that the glacial influence at some glacial sites was highly non-stationary/seasonal (mostly significant over the first period of the year, site 7), and that the glacial influence at groundwater sites may be highly variable (either low but significant over the whole year - site 14, or insignificant, site 13).

[C-2b] Okay, but if that’s all that is needed, then why bother using wavelet analysis – the main advantage of which is to localize spectral content in time, information which it appears is never actually used for anything in the study?

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[R-2b] To further provide a detailed description of scale averaged wavelet power spectra, including the temporal dimension, we further provided three new metrics: (1) the diurnal variation power, (2) the diurnal variation frequency, and (3) the diurnal variation temporal clustering (see Figure D). Note that while the Fourier analysis could potentially permit to calculate metrics #1 (but see below), it does not allow calculating metrics 2 and 3, which are a specific output of the wavelet analysis. (1) Diurnal variation power. We determined the diurnal variation power as the integration of the scale-averaged wavelet power curve corrected by the 95% confidence level (see (Coulibaly and Burn, 2004; Markovic and Koch, 2005). This parameter was moderately correlated with the Fourier power (R2 = 0.539, linear regression, y = 7.18 x) probably because Fourier transform is a relatively inefficient methods for non-stationary time series as it imposes a fixed response interval T into the analysis (Kaiser, 1994, see also R2c). (2) The diurnal variation frequency was calculated as the frequency of days with significant diurnal flow variations in the time series. (3) For the calculation of the diurnal variation temporal clustering (sensus De Vos et al., 2010; Hsu and Li, 2010) we first defined two “hydrological states” corresponding to days with and without significant diurnal flow variation. We then calculated the number of hydrological state changes and divided it by the total number of days in the time series minus one (the maximum number of possible state modifications).

We found a significant positive relationship between the diurnal variation power and the percentage of glacier cover in the catchment (Spearman rank test, $r = 0.93$, $p < 0.001$, Figure D-A). One value (from sites n° 14) laid far above the correlation line. This site presented a highly significant WGS (48.7) while having no glacier cover in its catchment, suggesting infiltrations of water from glacial origin at this site. Overall, there was no correlation between the diurnal variation frequency and %GCC except when the analysis was perform for the Glacier 14 catchment independently (Figure D-B). Last, we found a significant negative relationship between the diurnal variation temporal clustering and %GCC (Spearman rank test, $R = 0.76$, $p < 0.01$, excluding sites without GCC, Figure D-C). This suggests higher number of switches between

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hydrological states (significant water diurnal variation or not) in sites with higher % of GCC.

[C-2c] Why not just use much simpler Fourier power spectra instead, right from the start? Occam's razor seems relevant here. A convincing justification has to be presented as to why to use the more complicated wavelet method (for this particular application).

[R-2c] We agree that this point was not clearly explained in the first version. We have now added a justification to why using wavelet analyses instead of Fourier transform in the Introduction (see added text below and also R-2b).

[Added text] Quantifying hydrosystem flow variability has long triggered the development of numerous methods, most of which are based on time-series analyses (Smith et al., 1998). One fundamental tool is the spectrum analysis in which the time series is decomposed into harmonic components based on Fourier analysis. Series variance is partitioned into its oscillating components with different periods. Peaks in the spectrum indicate which frequencies contribute the most to the variance of the series (Chatfield, 1989). Although very useful for a wide array of applications in hydrology, spectral techniques such as the Fourier transform does not retain the location of a particular event in time or space and make the assumption that the statistical properties of the time series do not vary with time, i.e. are stationary (Smith et al., 1998). However, hydrological processes typically violate the stationarity assumption (e.g. Clarke, 2007; Silva et al., 2012) and there are an increasing evidence of the non-stationary features of glacial rivers, as a result of variations in meteorological conditions (e.g. ENSO, NAO) and inter-catchment differences in runoff regimes (Milner and Petts, 1994; Smith et al., 1998; Lafreneire and Sharp, 2003; Redmond and Koch, 1991), see for example the water level time series of site 7 in Figure C). Wavelet analysis overcomes the problems of non-stationarity in time series by performing a local time-scale decomposition of the signal. This approach allows tracking how the different scales related to the periodic components of the signal change over time (Torrence and Compo, 1998).

[C-3] There appear to be some technical issues with the way the background spectrum and statistical significance estimates are generated and reported. On lines 18-20 of p. 4378, it states, "Here, we chose the white-noise spectrum (at 95% confidence level) as we were particularly interested in measuring the significance of the wavelet power spectrum at one specific scale, namely 24 h)." There seem to be two technically substantial problems here. First, this statement (as written) is illogical: it seems to imply that the particular period one is investigating determines which background spectrum is to be assumed in the generation of significance levels. That is not at all correct. Rather, that assumption should be guided by the nature of the background noise, on the basis of either empirical or theoretical considerations. Second, the assumption of a white-noise background spectrum is almost certainly the wrong choice. It is well-known that river stage and discharge measurements, particularly those taken at a relatively high sampling rate (hourly or daily observations), such as is the case here, are strongly serially correlated in most rivers (even small, flashy catchments). Consequently, a red-noise background spectrum would seem to be a more justifiable choice for the particular type of application presented in this paper.

[R-3] You are completely right. We made a mistake in using the white-noise. The new analyses have now been performed with red-noise. The statement on lines 18-20 p4378 has been replaced as follows.

[Methods] Torrence and Compo (1998) showed that both the Fourier power spectrum and wavelet power spectrum follow a chi-squared distribution with two degrees of freedom. Assuming a random process, such as red noise, the theoretical background spectrum of a time series can then be calculated. Then, for any significance level from the chi-squared distribution, one can then construct confidence level contours to superimpose on the wavelet power spectrum. We selected the 95% confidence interval for wavelet power as our criteria for significance.

[C-4] Some of the nomenclature and definitions around the so-called Wavelet Glacier Signal (WGS) are problematic. The first issue may be in part a matter of personal preference, but I will flag it anyway: the world doesn't really need yet another three-letter acronym, so please don't call this quantity "WGS." More broadly, every part of the term "WGS" seems slightly dodgy and cumbersome. As noted in point (2) above, the spectral power at the 24 hr band could equally well be determined using Fourier or other techniques, so it's not clear that the "wavelet" part quite captures the basic concept. Also, the Wavelet Glacier Signal doesn't necessarily have anything to do with glaciers at all – see point (5) immediately below – so "glacier" seems a bit off as well. And finally, "signal" doesn't quite describe the mathematical quantity in question here (the ratio of the spectral power in the one-day band to the value it would take on if it was statistically significant at a confidence level of 95%, if I understand the description correctly). I would suggest sticking to terminology which is a little more mathematically descriptive and narrowly correct. Perhaps something like "diurnal variation factor" or "excess diurnal power" might work.

[R-4] We understand your point and have no problem in changing the name of the parameter. As a result of our new wavelet analyses, we now have three parameters that we named so that they describe more precisely the mathematical quantity in question: 1) the diurnal variation power, 2) the diurnal variation frequency, and 3) the diurnal variation temporal clustering.

[C-5] The authors have not, in fact, made a convincing case that the Wavelet Glacier Signal – a measure of the strength of diurnal variability – is indeed a robust and specific measure of glacial influence. Snowmelt-dominated rivers will also show such a diurnal signal, at least up until the prior winter's snowpack is gone. For basins containing mountain glaciers, it is virtually guaranteed that this will be a powerful source of ambiguity. Similarly, rivers in regions which experience regular convective storm activity over at least part of the year, e.g., summer afternoon thunderstorms and associated runoff (perhaps these Ecuadorian basins are an example of such a region, but we can't tell because such basic context is not provided in the paper – see point (1) above) could also have a daily cycle. As a result, the so-called WGS does not appear to be a unique index of glacial influence. If one could rule out those other potential effects on different grounds – using river stage data only from the post-snowmelt season, or finding no evidence for a 24-hr spectral band in rainfall data – only then can WGS be reliably and confidently employed as a glacial influence indicator. Put another way, WGS is really just an index of whether river flows have a strong daily cycle, and it's up to the user to attribute that signal. The authors found a statistically significant association between the amplitude of the WGS and % of the basin covered by glacial ice, but that is hardly surprising given the glacial region they picked and the fact that glacial melt does indeed impart a very strong diurnal signal during the melt season. This outcome is not, therefore, by itself a proof that WGS is a robust, unique, and precise indicator of degree of glacial influence. This issue seems to be a major problem with the work as presented here. However, I could perhaps see how the concepts used in this paper might be modified and evolved into something more useful and robust. A starting point might be to use the full wavelet analysis results (rather than just the time-averaged spectrum) to track seasonal changes in the WGS, and relate these to the major sources of runoff expected at different times of year for the different rivers (see again point (1) above). Another avenue might be to explore how the WGS relates to other data measured for these rivers, e.g., the water quality data listed in Table 1. Perhaps out of these anal- yses one might make some more reliable and defensible inferences about when and how WGS can be used to monitor glacial influence.

[R-5] You are right our index did not allow us to distinguish the water sources affecting the flow variation between ice and snow melt (although in our specific study case of the Antisana, it has been shown that snow melt represents only 3% of the melt water contribution, Fernández, 2010). Our index should be employed as an ice/snow melt influence indicator. However to rule out the rainfall as water source assessing diurnal flow variation, one can use additional climatic time series in the studied catchments, on precipitation data. In our study, we now provide a wavelet analysis of precipitation time series measured in the studied catchment (over 2010). Figure E presents seasonal changes in the scale-average power spectra of rainfall time series and the occurrence of significant peaks over a white-noise background. We found low occurrence of 24-hr spectral bands in rainfall data with only 7 significant peaks over 2010, which represents a total of only 19 rainy days with significant diurnal signal. This supports the fact that the diurnal variation power we propose here can be reliably and confidently employed as an ice/snow melt influence indicator in our case (see Favier et al., 2004 for a discussion). To use wavelet analysis on water flow variations as an indicator of ice/snow melt contribution to the stream, we now suggest testing the significance of diurnal signals against precipitation time series. If a significant 24-hr spectral band would be found with precipitation data (which was not the case in our study), a cross-wavelet spectrum analysis on the two time series could then be run (see Torrence and Compo, 1998), so that one can observe whether the water level-precipitation cross spectra mimic or not the general pattern observed in the wavelet spectra of water levels.

[C-6] Nowhere is it clarified why the Wavelet Glacier Signal is a better indicator of the degree of glacial influence on river flows than % of the basin area covered by glacial ice. Percent glacial cover is by far the most common, and almost certainly the easiest to generate and use, measure of glacial influence on watershed hydrology (and that's in all fields of study, including both geosciences and life sciences – note that the second paragraph in the introductory section seems mis-phrased in this respect). There is also a related problem with the second paragraph of the concluding section, which draws all sorts of comparisons except the most important one. Again, this is a key issue with the work presented here – it isn't made clear if or why this approach works better than the most common and probably easiest descriptor. Put another way, it seems the advantages, disadvantages, and potential role of the proposed index have to be thought through a bit more carefully.

[R-6] Good point. We now have included a new paragraph in the introduction which presents the limits of existing indices of glacial influence.

[New paragraph to add in the Introduction]

Existing glacier indices suffer however from several limitations. First, although commonly used, the estimation of glacier cover in the catchment may not be an easy task. For example, in the upper reaches of mountain catchments where accumulation zone of different glacier tongues can be connected, the accurate limits of each individual glacier can frequently be hardly estimated. This is mainly due to the lack of information on the bedrock topography under the glacier and on the ice-fluxes directions. Also, catchment delimitation can be hazardous in places with complex topographies dominated by flats (as in South American páramos) and short-scale steep altitudinal gradients (Verbunt et al., 2003). Second, it may be complicated to determine glacier-influence on stream locations because the apparent absence of glacier cover may not be a reliable indicator of an absence of glacier influence on stream flow because of the complexity of the local geology (Favier et al., 2008). Beyond the well-documented uncertainties related to the glacier volume-area relationships (e.g., Van de Wal and Wild, 2001), melt water infiltrations may strongly affect flow patterns of glacier-fed streams (Bazhev, 1973; Bengtsson, 1982). In glaciers located on terrains with complex geology and ground water reservoirs (e.g. volcanoes, karstic areas), infiltrations are more often the rule than the exception (Favier et al., 2008; Finger et al., 2013). Third, there is growing evidence that water chemical signatures may not be reliable to detect ice melt influence on stream flow as they can be modified by many factors such as climate, bedrock substrates and altitude (Nelson et al., 2011; Zhu et al., 2012). In particular, when glacial meltwater infiltrations occur, water chemistry is likely to be considerably modified during the underground flow routing, depending on the residence time underground, the distance of the underground flow routing and the bedrock substrates (Hindshaw et al., 2011; Nelson et al., 2011). Last, incorporating the high spatio-temporal variability of the different water sources contributions in glaciated catchments requires extensive measurement campaigns (e.g. glacier area measurement, water sampling, and stream habitat measurements), the building of water monitoring structures (e.g. hydrological and climatological stations) or costly analyses (e.g. water chemistry over long time period). While these factors may not appear as major constraints in temperate regions where many monitoring field stations have been established over the last 50 years, most glaciated catchments in the world (e.g. tropical mountains) remain poorly studied due to the difficulties of access and monitoring costs over long time periods (Baraer et al., 2012). However, the global scale of the glacier melting issue calls for the development of cost-efficient methods, and that may allow the hydrological studies of as many glaciated catchments as possible.

[C-7] Some additional thought also seems useful around the choice to use river stage rather than river discharge as the basis for calculating WGS, and the implications of that choice. On the one hand, in practice, discharge is usually inferred from stage measurements using a stage-discharge (rating) curve. This inference is subject to error in the rating curve, so that in this sense there is some advantage to using stage data instead. Similarly, stage data are easier to come by than discharge data, being easily obtained using staff gauges or pressure transducers, whereas discharge data additionally require detailed velocity measurements under a range of conditions to generate a rating curve. On the other hand, stage at a certain location is generally determined by both the discharge delivered to that point from upstream, and the local hydraulic characteristics. Thus, it would seem that the local value of the WGS index as calculated in this paper should also reflect local channel geometry, bed roughness, etc. – that is, hydraulic controls entirely unrelated to the degree of glacial influence. Put another way, WGS determined from flow measurements may be more meaningfully comparable between different rivers or different locations on a given river, than WGS derived from stage measurements. Some additional reflection on this potential source of uncertainty seems necessary.

[R-7] As stated by reviewer 2, we do not think that the use of water levels instead of stream discharge would be limiting. In most cases, daily stream flow cycles are quite well preserved in the water level observations as long as (as pointed out by reviewer 2) "the stage-discharge relation is not too strongly non-linear and the cross-sections are not changing their shape throughout the measurement period". Moreover, the use of water level is part of our "methodological package" which aims to provide a simple measure of glacier influence on stream flow (see new paragraph in the Introduction). As you know, water levels are really much easier to measure than stream discharges. Nevertheless to address this issue in the revised version (and as suggested by reviewer 2), we have applied our wavelet method to water discharge data at one of our study sites (Crespo site; see figure B-B for monthly discharges). For both site, discharge- and water level-based analyses gave similar results (see new Figure E in our response R5 to reviewer 2)

[C-8] The last paragraph of the concluding section seems poor. It over-reaches rather severely, I think. The passage also seems to imply that the notion of glacial rivers having diurnal discharge variations, known to scientists for a very long time and to others perhaps much longer, is some kind of relatively new and powerful discovery which must now be capitalized upon. I suggest deleting the passage. More broadly, the concluding section, especially the last paragraph, seems to highlight the general issues with the paper as discussed above. The idea of using empirical time series analysis to generate reliable, objective, and quantitative indices of environmental state is a great one, but the execution here appears somewhat flawed and incomplete – further thought and refinement is required around how the index is calculated, what it means, and how it can be correctly used.

[R-8] We agree with your comment. With the new and more complete wavelet analysis, the conclusion and discussion will be completely changed. We however preferred to wait for your comments on these analyses before re-writing this section.

[C-9] References cited (this is a minimum list - the authors may wish to conduct some additional literature searches as well): Casassa, G, and others (2009), Hydrological Processes, 23, 31–41. Clarke, GKC, and others (in press), Journal of Climate. Dahlke, HE, and others (2012), Hydrology and Earth System Science, 16, 2123-2141. Fleming, SW, and Clarke, GKC (2003), Canadian Water Resources Journal, 28, 69–86. Fleming, SW, and Weber, FA (2012), Journal of Hydrology, 470/471, 36–54. Jost, G, and others (2012), Hydrology and Earth System Science, 16, 849–860, 2012. Moore, RD, and others (2009), Hydrological Pro- cesses, 23, 42-61. Stahl, K, and Moore, RD (2006), Water Resources Research, 42, doi:10.1029/2006WR005022. Stahl, K, and others (2008), Water Resources Research, 44, doi:10.1029/2007WR005956.

[R-9] Thank you they are now cited in the text.

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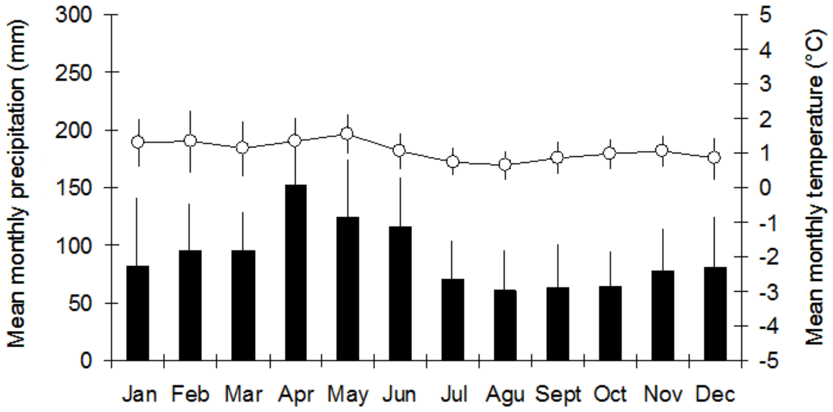

Figure A. Mean monthly precipitation (bars) and temperatures (dots) over one year in the Antisana volcano, Ecuador. The weather station is located on the proglacier margin of glacier 15 at 4850 m. Mean values and standard deviations were calculated over six year (2005-2010).

Fig. 1.

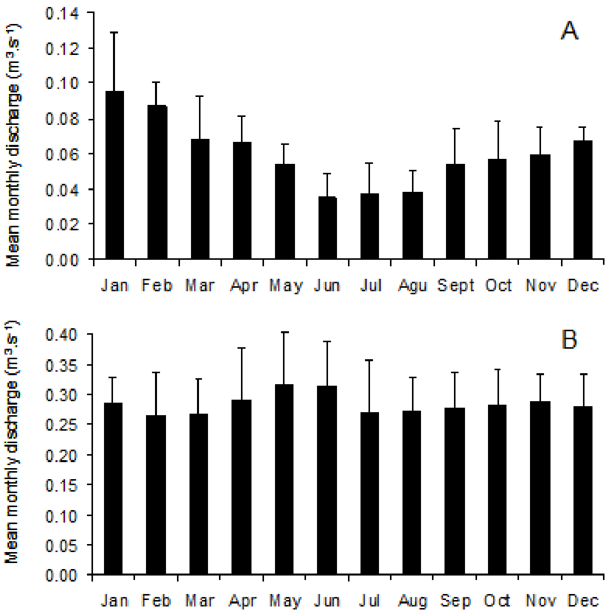

Figure B. Mean monthly discharge data at two gauging stations with high (A, Crespo station, 23.2% of glacier cover in the catchment) and low glacial influence (B, Humboldt station, 8.6% of glacier cover in the catchment) over one year in the Antisana volcano catchment, Ecuador. The gauging stations are located on the Rio Crespo, 1 km from the snout of the glacier Crespo (A) and 8 km from the snout of the glacier 15 (B). Mean values and standard deviations for panel A and B were calculated over five (2006-2010) and eleven years (2000-2010), respectively.

Fig. 2.

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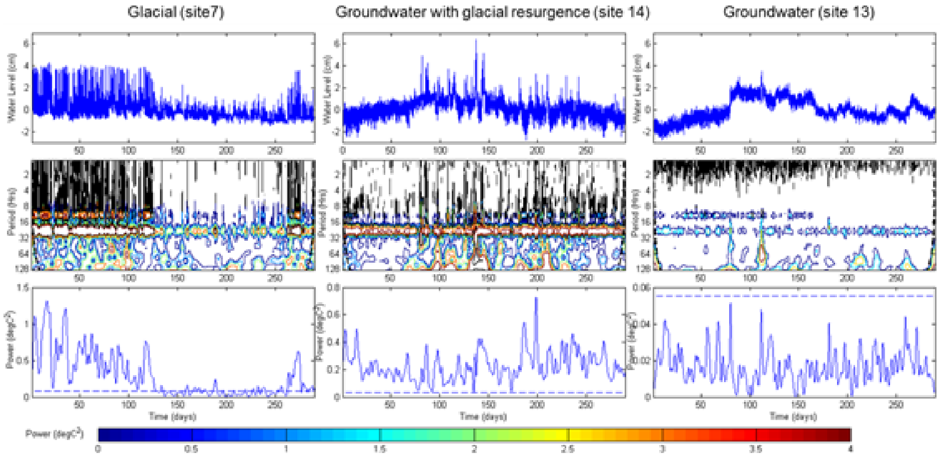

Figure C. Wavelet analysis outputs at three stream sites (7, 13, 14) with contrasting glacial influence (site 7 is glacier-fed while site 13 and 14 have no superficial connection to the glacier - but site 14 has glacial resurgence as indicated by significant diurnal flow variation). First row of panels: averaged normalized water level time series. Second row of panels: wavelet power spectrum normalized by their standard deviations. The black line delineates the areas where the power is considered significant (i.e. exceeds the 95% confidence level of a red-noise process), the dashed black line delineates the cone of influence that delimits the region not influenced by edge effects. Third row of panels: normalized scale-averaged wavelet power spectra at 24-h. The dashed blue line shows the corresponding 95% confidence levels for the red-noise spectrum. On each panel, day one corresponds to the 1st January 2010. The colour-bar shows the legend for the different colour, blue and red for low and high wavelet power, respectively.

Fig. 3.

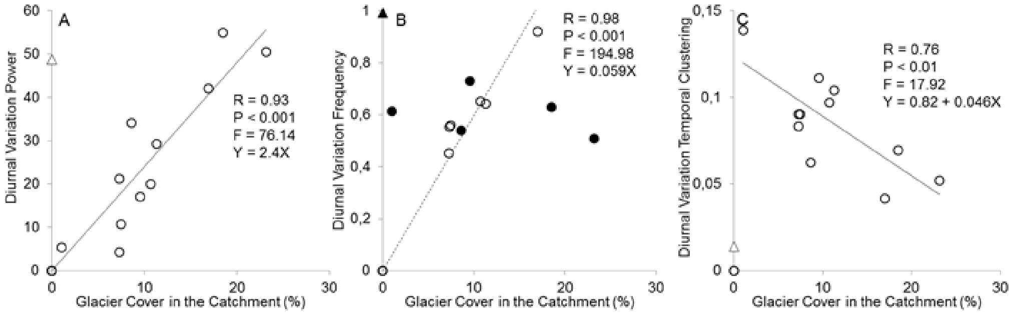

Figure D. Scatter plot of (A) diurnal variation power, (B) diurnal variation frequency, and (C) diurnal variation temporal clustering vs. the percentage of glacier cover in the catchment. In the three panels the triangular dot represents site 14. In panel (B) black dots represent stream sites located in the “Crespo” catchment and open dots stream sites in the “Glacier 14” catchment. The full regression line excludes site 14 in panel (A), sites localized in the “Crespo” catchment in panel (B) and sites with no glacier cover in the catchment (including site 14) in panel (C).

Fig. 4.

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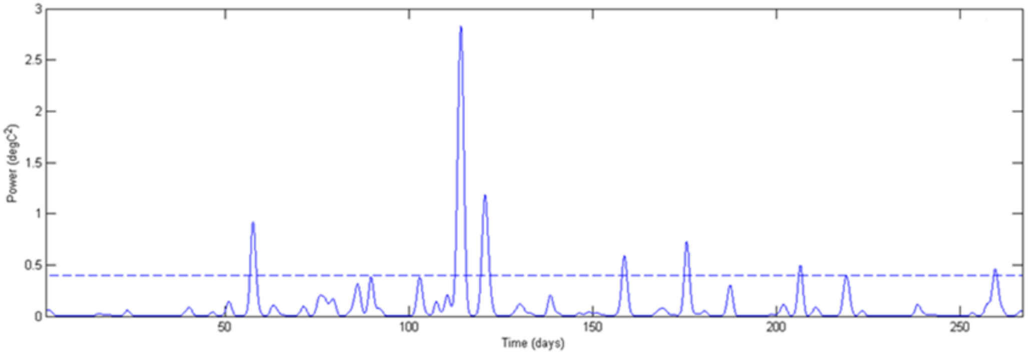

Figure E. Scale-averaged wavelet power (24h) resulting from the wavelet analysis on rainfall time series. The dashed blue lines correspond to the 95% confidence levels.

Fig. 5.

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