Hydrol. Earth Syst. Sci. Discuss.,
https://doi.org/10.5194/hess-2018-491-AC1, 2019

Hydrology and Earth System Sciences
Open Access
Discussions

Interactive comment on "Contribution of low-frequency climatic/oceanic oscillations to streamflow variability in small, coastal rivers of the Sierra Nevada de Santa Marta (Colombia)" *by* Juan Camilo Restrepo et al.

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Received and published: 1 March 2019

Anonymous Referee #1 Received and published: 21 January 2019 A review of the paper "Contribution of low-frequency climatic/ocean oscillations to stemflow variability in small, coastal rivers of the Sierra Nevada de Santa Marta (Colombia)" by Juan Camilo Restrepo, Aldemar Higgins, Jaime Escobar, Silvio Ospino and Natalia Hoyos.

The present manuscript addresses an important and current subject in Hydrology. The influence of large-scale oceanographic/atmospheric processes on streamflow variability is a research question of high importance in Hydrology. The understanding of how low-frequency oscillations identified in climate indices can drive the variability in the flow regime in rivers allows us to count on a valuable tool for the construction of statistical models. Spectral analysis was undertaken to determine the nature and magnitude of the relationship between monthly streamflow of 6 rivers and large-scale atmospheric/oceanographic circulation patterns. The study focused on basins that have special characteristics, are small, tropical, coastal mountain rivers localized in Colombia. Continuous wavelet transform and Hilbert Huang transform were the methods selected to identify the modes of variability in the rivers and climatic/oceanographic indices. Cross-wavelet analysis and wavelet coherence that are powerful methods for testing a proposed linkage between two time series were also used by the authors in the paper. The results exhibit that streamflow variability are strong associated with modes of variability in the Atlantic Meridional Oscillation (AMO), Pacific Decadal Oscillation (PDO) and Tropical North Atlantic (TNA).

Due to the complexity that can exist in the teleconnection between climatic indices and flow regime in a river the authors selected the appropriate tools. The tools selected to carry out the study, allows to overcome the problem of linear analysis when evaluating the relationship between low-frequency phenomena and streamflow variability of rivers.

The manuscript is reasonable well-structured, the methods are well described, and the research is within the scope of HESS. However, the manuscript requires a more indepth discussion of the results and it is necessary to be incorporated some missing important information. The paper deserves to be published on Hydrological and Earth Science Systems, after some minor changes. I am reporting below some specific comments, which I hope the authors will find useful while revising their manuscript.

Authors: We appreciate your comments and the overall assessment of the work. It does contribute to improve the quality of the manuscript. Below we provide answers to your specific comments as Author's Response (AR) and Author's Changes in

Manuscript (ACM).

Comments from referees:

(1) It's necessary to highlight the novelty of the work because it's no clear. If this work would not be published, what would the international hydrology community miss? Novelty can reside in a new data set which is of importance to the international hydrology community, in new methodological development, in new conceptual ideas or novel interpretation and insights. The paper applies established methods and it follows the ideas that many papers have developed/applied. The conclusions seem not to add new findings to the already existing knowledge.

(AR) Studies that look at the interplay of multiple atmospheric/oceanographic oscillations on streamflow long-term variability are relatively recent (eg, Shi et al., 2017; Su et al., 2018; Murgulet et al., 2018). The lack of studies on this subject has led to an increase in research looking at how multiple large-scale climatic/oceanographic oscillations, particularly low-frequency, drives streamflow variability (eg, Tootle et al., 2008, Yang et al., 2011, Massei and Fournier, 2012, Boers et al., 2014, Córdoba-Machado et al., 2016, Schulte et al., 2016, Shi et al., 2017; Su et al., 2018; Murgulet et al., 2018). Thus, neither the approach nor the methods applied are novel or unique, since they have been widely applied during the last years. The novelty of this study lies, fundamentally, in the location (Caribbean) and basins' physiography from which the analyzed data come from (Page 2- Line 31, Page 3 - Line 1). These unique charactersitics allowed us to: (1) highlight the influence of low frequency climate indices (ie PDO, AMO and TNA) on the surface hydrology of northern South America (where its effect had previously been minimized - Page 13 Line 1) (2) provide strong evidence that low frequency oscillations are major players on the streamflow variability for this area. Its magnitude is of the same order (or higher in some cases) than that of the ENSO (considered as the main driver of the superficial hydrology of Northwestern Southamerica) (Page 11 Line 3, Page 11 Line 7) (3) show that flow variability is a consequence of the concurrence of different frequency signals, rather than to a specific signal (Labat, 2008, Brabets and Walvoord, 2009, Rood et al., 2016, Valdez-Pineda et al., 2017). This also highlights the modulating effect of quasi-decadal signals (Page 11 Line 16) (4) understand the role of low frequency oscillations in the streamflow of basins with a small drainage area. These signals had shown less intenisty in regional scale studies. (i.e. Murgulet et al., 2017) (Page 11 Line 11). All these aspects will be highlighted explicitly in the introduction and conclusions.

(AMC) In order to highlight the novelty of the work, the manuscript will be modified as follows (new text in bold and cursive):

"(Page 3 – Line 12) To our knowledge, this is the first study to estimate the contribution of low-frequency oscillations to the hydrologic variability at a subregional scale and in these type of watersheds (i.e. small, coastal, and mountainous), and specifically in northern South America, where ENSO has been identified previously as the preeminent driver on streamflow variability (i.e. Gutierrez and Dracup, 2001; Poveda et al., 2001; Córdoba-Machado et al., 2016)".

"(Page 13 – Line 17) Low-frequency oscillations ($\geq$ 8-12 yr) play a significant role in the hydrological variability of rivers in the SNSM (...) In most of the studied rivers, the amplitude of low-frequency components was comparable to, or even higher than the amplitude exhibited by the inter-annual component, which has been considered previously as the main driver of streamflow variability in northern South America at a regional scale. Low-frequency oscillations constitute at least a second-order variability source in these rivers, surpassed in some cases only by oscillations associated with the annual band. Although intra-annual to quasi-biennial modes provide the highest proportion of the global energy spectrum in all rivers (between 43.6 and 83.8%), the contribution from low-frequency modes are > 12%, and reach up to 51% in the Aracataca River, indicating an active effect of such low-frequency oscillations in the streamflow variability at a subregional scale in northern South America. Such effect deserves further studies."

“(Page 14 – Line 1) Previous studies have shown a very low correlation between low-frequency phenomena and streamflow variability in northwestern South America, suggesting minimal effects on regional hydrology. The sub-regional scale approach and the statistical spectral analysis of this study allow to identify and estimate a significant contribution of low-frequency oscillations in the streamflow variability of the SNSM Rivers. Such oscillations, identified as a source of significant streamflow variability in the SNSM rivers, are associated with large-scale climatic/oceanographic drivers, with modes of variability that include quasi-decadal or higher oscillations. The XWT and WTC spectra show that the AMO, PDO and TNA are correlated and coherent with river streamflow at different time scales (. . .) suggesting a link between the shift of these climatic/oceanographic indexes and changes in long-term streamflow variability.

“(Page 13 – Line 24) Periods of intense hydrological variability, in which extreme flows occurred, such as those experienced in 1988-1989, 1998-2000 and 2010-2011, were characterized by the simultaneous occurrence of relatively high-power signals, including low-frequency bands (. . .) Overlapping of different frequency signals can lead to intensification or attenuation of the hydro-climatological cycle, depending on the phase of the different oscillatory components. These pattern highlights the importance of the interaction of different frequency signals and their phase shifting interactions on the streamflow variability of these rivers.”

“(Page 14 – Line 12) Our study highlights the significant role of low-frequency oscillations on the hydrological variability of rivers in the SNSM and potential linkages with large-scale phenomena such as PDO, AMO and TNA. We hypothesize that the location and the physiography of these watersheds (i.e. proximity to the Caribbean Sea, direct exposure to the trade winds and the North Jet Stream, small drainage basins, low basin storage capacity and high relief) make rivers more exposed to sea level pressure (SLP) and sea surface temperature (SST) anomalies; particularly, from the Atlantic Ocean and the Caribbean Sea. Further work is necesary to examine the role of these watershed properties, and others such as basin storage, baseflow index and groundwater residence time, in establishing the relation between low-frequency oscillations and streamflow variability.”

(2) I recommend that the authors specify the type of régimen (natural or altered) in the flow gauge stations. This point is highly important for the results.

(AR) It can be argued that for the surveyed period (Table 3) these rivers experienced a quasi-natural hydraulic regime since there was no damming or major hydraulic structures on the riverbeds. Construction of the only dam located in the study area (Ranchería river) began in the late 2000’s decade and our anlysis do not include this time interval. These basins have experienced, however, significant land-use changes (mainly deforestation and an increase in agriculture). Land-use changes have limited basin hydrologic modulation capacity and favoured changes in hydrological patterns (i.e. ocurrence of extreme events, seasonality length and intensity).

(AMC) In order to clarify the type of regime depicted in the streamflow time series, the manuscript will be modified (Page 3 – Line 24) as follows (new text in bold and cursive):

“In addition, the SNSM rivers exhibit high to very high discharge variability (Qmax/Qmin), high flood regime (Qmax/Q), while possessing drainage areas < 5.0 x103 km2 in mountainous zones (Table 1). Thus, topography is a primary factor controlling flood variability (Restrepo et al., 2014). Except for the Ranchería River with a dam built in the late 2000’s decade, the SNSM rivers have no damming or fragmentation. However, just 15% of the natural forest remains completely unaltered, due to widespread logging and and incease in agriculture. Only 8.5% of the river headwaters remain pristine (Fundación Pro-Sierra Nevada de Santa Marta, 1997). These land-use changes have led to a general loss of hydrologic modulation capacity in the watersheds, which in turn have favoured the occurrence of changes in the hydrological patterns; specifically, an increase of seasonal streamflow extremes (e.g. Pierini et al., 2017; Hoyos et al., 2019)”.

(3) It’s important to know if the flow gauge stations are in the upper, middle or lower

part of the basins. I recommend that the authors should incorporate the spatial location of flow gauging stations in Figure 1A.

(AR) Gauge stations were located in the lower part of the basin, closest to the river mouth. Streamflow time series measured at the mouth of the watershed is considered a valuable integrated signal for drainage basin's water cycle (i.e., precipitation, evapotranspiration, runoff) (e.g., Garcia and Mechoso, 2005; Milliman et al., 2008; Labat, 2010; Pasquini and Depetris, 2007; Probst and Tardy, 1987; Restrepo et al., 2014). Location of the gauge stations will be added to Figure 1A.

(AMC) In order to clarify the gauging stations location, the manuscript and Figure 1 will be modified (Page 4 – Line 19) as follows (new text in bold and cursive):

"Selection of streamflow gauging stations was based on the location and length of records, which had to be sufficiently long to enable analysis of the role and properties of low-frequency oscillations on streamflow variability. Gauge stations are located close to the river mouth, in the lower part of the basin. Streamflow time series measured close to the river mouth are considered a reliable integrated signal for drainage basin's water cycle (e.g., Garcia and Mechoso, 2005; Milliman et al., 2008; Labat, 2010; Pasquini and Depetris, 2007; Probst and Tardy, 1987; Restrepo et al., 2014)…".

(4) Wavelet power relations and phase relations between monthly streamflow of the rivers and large-scale circulation patterns are relatively stable in the longer periods (> 2 years band) and are very unstable in the shorter periods (< 2 year band). This can demonstrate that from longer periods, the monthly streamflow could be controlled by the slowly changing climate. During shorter periods, the monthly streamflow is not only controlled by large-scale ocean–atmosphere patterns.

(AR) This is mentioned on the results section (Page 9 Line 30, Page 10 – Line 14, Page 10 – Line 25). We will highligt this statement in the discussion.

(AMC) In order to highlight the differences in the phase relationship when comparing high and low frequencies, the manuscript will be modified as follows (new text in bold and cursive):

Results (Page 9 – Line 24): "The Cross Wavelet Transform (XWT) and the Wavelet Coherence (WTC) spectrum show that the AMO, PDO and TNA are correlated and coherent with river streamflow over a range of time scales and frequencies. Differences are noticeable, however, for power and phase-relationship when comparing high- and low-frequency signals (Fig. 6-8)".

Discussion (Page 12 – Line 13): "These results suggest a relation between changes of these climatic/oceanographic indexes and long-term streamflow variability, indicating that these watersheds are sensitive to changes in the background climate state. Furthermore, power and phase relationships between streamflow and different índices (Fig. 6-8) were relatively steady for low-frequencies (i.e. > 96 months) but unstable and disperse for high-frequencies (i.e. < 96 months). Such difference in patterns, suggest that during longer periods, streamflow might be modullated by the slowly change in the climate background climate; whereas during shorter periods, the streamflow is not only controlled by large-scale ocean–atmosphere patterns, but also by local short-term phenomena. This result highlights, once again, the significant effect of the superposition of signals of different frequencies in the streamflow variability (eg Pasquini and Depetris, 2007, Labat, 2010, Steinman et al., 2014, Shi et al., 2016 Murgulet et al., 2017)".

(5) One point that is not discussed in depth in the results is the phase changes in the relationship between the time series of flows and the climatic indices. The phase relationship between climatic indices and streamflow is changing in shorter and longer periods. The different phase relationships between AMO, TNA and PDO and monthly streamflow could be show the different influences of variables of the atmospheric system.

(AR) This is correct. This aspect is now discussed in more detail in the discussion section. It is important to keep in mind, however, that the understanding and discussion of the physical links between streamflow variability and these large-scale phenomena, is beyond the scope and aim of this study (Page 3 - Line 8) . Following your suggestions will adjust the discussion.

(AMC) In order to discuss broadly the phase relationship between streamflow and climatic/oceanographic indices, the manuscript will be modified as follows (new text in bold and cursive):

Discussion (Page 12 – Line 13): “These results suggest a relation between changes of these climatic/oceanographic indexes and long-term streamflow variability, indicating that these watersheds are sensitive to changes in the background climate state. Furthermore, power and phase relationships between streamflow and different indices (Fig. 6-8) were relatively steady for low-frequencies (i.e. > 96 months) but unstable and disperse for high-frequencies (i.e. < 96 months). Such differents in these patterns, suggest that during longer periods, the streamflow might be modullated by the slowly change in the climate background state; whereas during shorter periods, the streamflow is not only controlled by large-scale ocean–atmosphere patterns, but also by local short-term phenomena. This result highlights, once again, the significant effect of the superposition of signals of different frequencies in the streamflow variability (e.g. Pasquini and Depetris, 2007; Labat, 2010; Steinman et al., 2014; Shi et al., 2016; Murgulet et al., 2017). For the lower frequencies, in both the XWT and WTC analysis, the phase relationship exhibited a stable phase lag inside the significance common power regions for each river (Fig. 6-8). Such consistent varying phase lag, implies a phase-locked relationship and suggests a physically link (i.e. not a casual relationship) between the streamflow variability and each of the climatic/oceanographic indices (Grinsted et al., 2004; Labat, 2005). Outside areas with significant power the phase relationship changed (Fig. 6-8). We therefore speculate that despite the relatively strong link between streamflow and these indices at specific frequencies (low) and temporal windows (Fig. 6-8), these relationships are highly non-linear and non-

stationary; depending heavily on the phase experienced by these oscillations and their dynamic feedback processes (e.g. Battisti and Sarachick, 1995; Einfeld and Alfaro, 1999; Garreaud et al., 2009). Differences in spectral correlations between rivers from the western and the eastern slopes, and differences in phase relationships observed in some rivers, indicate that further research is required to draw conclusions about the specific drivers of low-frequency variability.

(6) It’s necessary and very helpful for readers to indicate in the cross-wavelet transform and squared wavelet coherence that the relative phase relationship is shown by dark arrows.

(AR) The type of relative phase relationships depicted in the XWT and WTC analyses (Page 5 – Line 19), as well as their statistical significance (Page 5 – Line 30), were explained in Section 3.2. However, a further indication of the meaning of the dark arrows in the XWT and WTC analyses (in the Figures) will improve the manuscript as well as the reader′s ability to interpret results.

(AMC) In order to clarify the meaning of the dark arrows in the XWT and WTC analyses the captions of the Figures 6, 7 and 8 will be modified as follows (new text in bold and cursive):

“Figure 6. Cross Wavelet Transform (XWT) and Wavelet Coherence (WTC) between AMO and the (A) Fundación, (B) Aracataca, (C) Frío, (D) Gaira, (E) Palomino, and (F) Ranchería Rivers. Dark arrows enclosed in the significant regions (thick black contours) represent the angle-phase relationships. For explanation on types and statistical significance of such relationships see Section 3.2”.

“Figure 7. Cross Wavelet Transform (XWT) and Wavelet Coherence (WTC) between PDO and the (A) Fundación, (B) Aracataca, (C) Frío, (D) Gaira, (E) Palomino, and (F) Ranchería Rivers. Dark arrows enclosed in the significant regions (thick black contours) represent the angle-phase relationships. For explanation on types and statistical significance of such relationships see Section 3.2”.

“Figure 8. Cross Wavelet Transform (XWT) and Wavelet Coherence (WTC) between TNA and the (A) Fundación, (B) Aracataca, (C) Frío, (D) Gaira, (E) Palomino, and (F) Ranchería Rivers. Dark arrows enclosed in the significant regions (thick black contours) represent the angle-phase relationships. For explanation on types and statistical significance of such relationships see Section 3.2”.

(7) Due to the short length of the flow gauge stations records, it is risky to explore the statistical presence of decadal oscillations. Specifically, the variability mode C8, which do not seem to have enough statistic evidence.

(AR) Yes, we agree. The length of the time series determines the reliability of the analysis, as well as the temporal length of the information that can be obtained from them. For this reason, it was indicated that in order to obtain information on quasi-decadal oscillations, the series evaluated should have a minimum extension of 32 years to comply with the requirements of edge effects (T/2$\sqrt{2}$) and cutoff frequency (T/2) approaches (Page 4 - Line 21). The time series evaluated have lengths that oscillate between 32 and 55 years (Table 3). We can then obtain statistically significant information about oscillations ranging up to 11.3-19.4 yrs and 16-27 yrs, according to the edge effect and cutoff frequency approach, respectively. These time series provide reliable information for all rivers evaluated in terms of the statistical presence of decadal oscillations. It is true also that from these time series it might be risky to explore the presence of higher period oscilations, particularly to those corresponding to the larger MFI modes in the Table 4. This is the specific case for River Fundacion (C7: 21 years) and Gaira (C7: 22 years) (see Table 4). This last aspect needs to be clarified in the manuscript.

(AMC) In order to clarify aspects linked to the presence and the statistical significance of larger period oscillations within the streamflow time series analyzed, the manuscript will be modified as follows (Page 8 – Line 28) (new text in bold and cursive):

“Mode C6 and higher modes correspond to low-frequency oscillations (i.e. quasi-decadal or greater) (Fig. 4 and Table 4). Information on the last IMF mode of Fundación (C7) and Gaira (C7) Rivers must be analyzed cautioulsy as they are outsied the range established for the edge effects approach (Table 4).“

(8) Page 3, line 23: “.....which was designated a RAMSAR site because.....” What is the meaning of RAMSAR?

(AR) In 1971 the Ramsar Convention was first organized to build an international treaty to provide the framework for national action and international cooperation for the conservation and wise use of wetlands and their resources. This Convention considered granting Ramsar status to those wetlands of international importance due to their biological wealth and their role as shelters for seasonal migratory waterbirds (Ramsar, 2019). More than 160 countries have ratified this Convention, and thus it is widely recognized worldwide.

(ACM) In order to clarify the specific meaning of RAMSAR site, the manuscript will be modified (Page 3 – Line 23) as follows (new text in bold and cursive):

“. . .Rivers that run through the western slopes of the SNSM flow into the Ciénaga Grande de Santa Marta (CGSM), the largest Colombian coastal lagoon ($\sim$730 km2) (Fig. 1), which was designated a Ramsar wetland because of its ecological diversity and importance and its role as a shelter for migratory birds (Ramsar, 2019).”

(9) Page 5, line 34: “Data series with a non-normal distribution were transformed prior to applying ......” What type of transformation was used?

(AR) Many statistical analyzes assume that data is normally distributed. Our preliminary analysis showed, however, that the flow series used in this work did not conform to a normal distribution. Therefore, the Wavelet analysis needed a transformation of the probability density functions for the time series to generate reliable results. The transformation of the data consisted of its standardization, the calculation of a zero mean and an unit standard deviation. These are widely established procedures (e.g. Torrence and Compo, 1998, Grinsted et al., 2004, Labat, 2005).

(ACM) In order to clarify the data transformation process, the manuscript will be modified (Page 5 – Line 2) as follows (new text in bold and cursive):

“Data series with a non-normal distribution were transformed prior to applying the CWT, XWT and WTC analyses, using a widely used standardization procedure (zero mean, unit standard deviation) (e.g. Torrence and Compo, 1998; Grinsted et al., 2004; Labat, 2005).”

Please also note the supplement to this comment:
https://www.hydrol-earth-syst-sci-discuss.net/hess-2018-491/hess-2018-491-AC1-supplement.pdf

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Interactive comment on Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-491, 2018.