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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This study evaluates the influence of low-frequency oscillations linked to large-scale oceanographic-atmospheric processes, on streamflow variability in small tropical coastal mountain rivers of the Sierra Nevada de Santa Marta, Colombia. By using spectral analysis and Hilbert Huang transform, the study aims to (1) explore temporal characteristics of streamflow variability, (2) estimate the net contribution to the energy spectrum of low-frequency oscillations to streamflow anomalies, and (3) analyze the linkages between streamflow anomalies and large-scale, low-frequency oceanographic/atmospheric processes.

The main topic of the article is important to Hydrology and water resource management, and deserves to be published in HESS. However, the results need to be discussed in a broader context, comparing the main findings with related literature. The tools applied to address the research questions are adequate and properly applied, however some technical details are necessary to be described. In addition, a deeper explanation about the physical mechanisms linking PDO, AMO, TNA and the basins’ hydrology is necessary. Also, the whole subject is about the possibility of a cause-effect relation between decadal oscillations and streamflow, but the concept of phase locked signals is completely missing in the interpretation of the results and the discussion, which I think is necessary. Thus, my decision is accepted with major revisions.

Authors: We appreciate your comments and the overall assessment of the work. General adjustments will be made in the manuscript and especially in the discussion section (see details below - Author’s response (AC) and Author’s Changes in Manuscript (ACM)):

(AMC) In order to highlight the effect of superimposed signals on streamflow variability, the differences in the phase relationship when comparing high and low frequencies, the phase relationships between streamflow and climatic/oceanographic indices, the manuscript will be modified as follows (new text in bold and cursive):

Discussion (Page 11 – Line 30): “The maximum intensity of the inter-annual signal, which occurred between 1998 and 2002 in most rivers, also coincides with the interval of greater intensity of the quasi-decadal signal (1998-2005) (Fig. 2). Streamflow rates also exhibit inflection points in their trends between the 1990s and 2000s, a period that also coincides with the increase in the amplitude of low-frequency oscillations..."
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 differences in these patterns, suggest that during longer periods, streamflow might be modulated 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 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 or slowly varying phase lag, imply a phase-locked relationship and establish a physically link (i.e. not a casual relationship) between the streamflow variability and each climatic/oceanographic indices (Grinsted et al., 2004; Labat, 2005). Outside the 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.

Discussion (Page 12 – Line 13): “Although robust hypotheses have been put forth regarding the physical relation between the PDO (Poveda, 2004), the AMO (Arias et al., 2015) and the TNA (Enfield and Alfaro, 1999) and the climate of northwestern South America, the physical mechanisms by which these phenomena influence the hydrology at low-frequency scales remains elusive. Understand the specific physical links between streamflow variability and these climatic/oceanographic indices is beyond the aim of this study. Nevertheless, we believe these mechanisms may relate to SST gradients between the Pacific and Atlantic oceans”.

SpecifiAc comments: (1) First paragraph: a more in-depth description on the PDO-ENSO relation is necessary in addition to AMO and TNA relations to inter-annual oscillations.

(AR) Adjustments will be made in the first paragraph to highlight the teleconnections and interactions that exist between these phenomena.

(ACM) In order to provide a more in-depth description of the phenomenon interactions, the manuscript will be modified (Page 2 – Line 2) as follows (new text in bold and cursive):

First paragraph (Page 2 – Line 2): “In the past several decades, streamflow variability has increased (Milliman et al., 2008; Dai et al., 2009), causing frequent and pronounced flood/drought cycles (Hungtinton, 2006). Atmospheric and oceanographic processes are major sources of streamflow variability (Jhonson et al., 2013; Schulte et al., 2016). The El Niño-Southern Oscillation (ENSO) is among the most prevalent oceanographic/atmospheric processes linked to streamflow variability in tropical and subtropical areas (Battisti and Sarachick, 1995; Amarasekera et al., 1997; García and Mechoso, 2005, Labat, 2010). ENSO, however, is also affected by longer-period
changes in the background state (Garreaud et al., 2009; Chowdary et al., 2014). It has been pointed out that its effects can be modulated by the coupling that exists between ENSO phases and long period events, such as the Pacific Decadal Oscillation (PDO) and the Atlantic Meridional Oscillation (AMO) (i.e. Brown and Comrie, 2004; Murgulet et al., 2017; Shi et al., 2017). For example, the 1997-1998 El Niño event occurred during a PDO shift from a warm to a cold phase, but recent warming (2010-2011) in the Pacific occurred during a cold phase of the PDO. Multiple atmospheric / oceanographic oscillations collectively impose a more complex influence on hydrology (Labat, 2010; Nalley et al., 2016; Shi et al., 2016). Thus, changes in the intensity and frequency of extremes events depend on the coupling and teleconnection of these large-scale atmospheric/oceanographic processes. Overall, such interactions occur through changes in the sea level pressure (SLP) and sea surface temperature (SST) gradients, which in turn lead to flux changes in the atmosphere (i.e. Einfeld and Alfaro, 1999, Jhonson et al., 2013, Sagarika et al., 2015, Murgulet et al., 2017, Shi et al, 2017). Such atmospheric and oceanographic interactions, as well as their role in hydrological variability, have gained attention in recent years (Tootle et al., 2008; Arias et al., 2015; Sagarika et al., 2015; Nalley et al., 2016). Thus, a major question in the study of hydrology is the potential effect of longer-period climate modes on the strength of a particular El Niño/Niña event. The interplay that exists between the multiple large-scale oscillations and the regional hydrological process constitutes a complex climate-land coupled system (Steinman et al., 2014; Murgulet et al., 2017).
Furthermore, it has been established that changes in the Caribbean SST gradients affect the amount of rainfall in northern South America (Enfield and Alfaro, 1999), but there is no evidence that such changes affect the hydrological variability of SNSM rivers, which are characterized by a limited ability to filter hydrological signals (Restrepo et al., 2014).

Standard statistical techniques are generally unable to explain the complex interactions, based on non-linear and non-stationary underlying processes, among a wide range of climatic/oceanographic oscillations and their associated effects on hydrology (i.e., Grinsted et al., 2004; Xu et al., 2004; Labat, 2005; Shi et al., 2017). Spectral analyses such as Wavelet Transform (WT) and the Hilbert Huang Transform (HHT) (Grinsted et al., 2004; Labat et al., 2005; Torrence and Compo, 2008; Massei and Fournier, 2012; Schulte et al., 2016) have proven useful to identify the timing of important features of non-stationary signals and to discriminate the relative contribution of signal components, which may change through time. The objectives of this study were to: (1) explore the temporal characteristics of streamflow variability, with emphasis on low-frequency oscillations, (2) estimate the net contribution (i.e., energy spectrum) of such oscillations to streamflow anomalies, and (3) analyze the linkages between streamflow anomalies and large-scale, low-frequency, oceanographic/atmospheric processes (Table 2) in small, tropical, coastal mountain rivers of the SNSM (Fig. 1 and Table 1). 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).
time-frequency space; whereas the WTC ands signiﬁcant coherence even with a low common power, and shows conﬁdence levels against red noise, highlighting locally phase locked behaviors (Shumway and Stoffer, 2004; Grinsted et al., 2004; Labat, 2005).

(5) - Pag. 7 line 10: equation (7) may be wrong.

(AR) Yes, there was an inprecision in equation (7). There is a term in the denominator that must be removed.

(ACM) The manuscript will be modiﬁed in order to adjust equation (7) (Page 7 – Line 10) as follows (new text in bold and cursive):

\[ f \tilde{E}(n) = \frac{\int_{0}^{\infty} \tilde{U}_E a \tilde{U}_n(f) df}{\int_{0}^{\infty} \tilde{U}_E^2_n(f) df} \] (see attached file) (7)

(6) - Pag. 8 line 6-7: from Fig. 2 the statement is not evident for station Frío, please explain.

(AR) This comment is very pertinent. When referring to the simultaneously occurrence of different signal bands, the Frío River exhibits a jointly oscillation of the annual and quasi-decadal bands during 1988 and 1990, and of the annual, interannual and quasi-decadal bands between 19988 and 2002. However, as you stated, the interaction of the quasi-biennial, annual, interannual and quasi-decadal bands between 2008 and 2012 is not completely evident, because the quasi-biennial bands exhibit moderate power (mild yellow) instead of high power (intense yellow) during this period. Also the streamflow record of the Frío River ends in 2009. Thus, is not appropriate to make inferences beyond this date.

(ACM) In order to clarify the examples on the simultaneously occurrence of different signal bands in the Frío River, the manuscript will be modiﬁed (Page 8 – Line 6) as follows:

Text to be removed is highlighted in bold and cursive: “A quasi-biennial oscillation oc-

curred jointly with annual, inter-annual and quasi-decadal oscillations during the 2008-

2012 interval, in the Fundación, Aracataca, Frío and Palomino Rivers (Fig. 2)”.

New text in the manuscript: “A quasi-biennial oscillation occurred jointly with annual, inter-annual and quasi-decadal oscillations during the 2008-2012 interval, in the Fundación, Aracataca and Palomino Rivers (Fig. 2)”.

Please also note the supplement to this comment: https://www.hydrol-earth-syst-sci-discuss.net/hess-2018-491/hess-2018-491-AC2-supplement.pdf


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