Anonymous Referee #2

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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.

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):

(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 índices, the manuscript will be modified as follows (new text in bold and cursive):

<u>Discussion (Page 11 – Line 30):</u> "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 (Fig. 4). ***These results show that the superposition of climatic / oceanographic signals, particularly the modulation of the effects of the interannual signal due to phase changes in long period signals, is a key element within the occurrence of extreme events at sub-regional scale (i.e. Steinman et al., 2014; Shi et al., 2017; Murgulet et al., 2017; Su et al., 2018)."***

<u>Discussion (Page 12 – Line 13):</u> "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 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 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 varibility 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".

Specific 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 telleconections 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 / oceanograhic 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 (ie Einfeld and Alfaro, 1999, Jhonson et al., 2013, Sagarike 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)".***

(2) - Second paragraph: the main idea is confusing. Maybe split paragraphs one for novel statistical methods and another related to the hydrology in Colombia.

(AR) Adjustments will be made on the manuscript.

(ACM) In order to avoid confusión in the ideas expressed in the second paragraph, the paragraph will be split as follows (new text in bold and cursive):

<u>Second paragraph (Page 2 – Line 16)</u>: "Several authors have examined the relationship between streamflow variability in northern South America and large-scale oceanographic/climate indices, particularly those linked to ENSO (e.g. the Southern Oscillation Index [SOI], the Multivariate ENSO Index [MEI], and Niño 1, 2, 3, 4) (Robertson and Mechoso, 1998; Hastenrath, S., 1990; Gutiérrez and Dracup, 2001; Poveda et al., 2001; Restrepo and Kjerfve, 2004; García and Mechoso, 2005). New variables such as SST gradients in the Caribbean Sea and low-frequency oscillations, together with new statistical methods (e.g. Singular Value Decomposition and Principal Components Analyses) are now used in streamflow analysis. These new approaches have improved hydrological forecast models, compared to predictions based solely on El Niño-based indices. ***For example, such an approach allowed to establish that the extremely anomalous wet seasons in northern South America between 2010 and 2012 were not only associated with ENSO anomalies, but also with an enhanced Atlantic Meridional Mode (AMO), a low-frequency oscillation that is independent of ENSO (Arias et al., 2015).*** The new models also reduce the spatial bias of SST, which affects hydrology at regional scales (Tootle et al., 2008; Córdoba-Machado et al., 2016). These studies, however, failed to include representative small basins (area ≤ 5000 km^2) that drain into the Caribbean Sea in northern South America. Furthermore, mountain rivers flowing from the Sierra Nevada de Santa Marta (SNSM) massif (Fig. 1, Table 1) are absent from these models. Pierini et al. (2015) indicated that rivers from the SNSM exhibit a distinctive hydrological pattern, which differs from that of other rivers in northwestern South America. Differences are especially

pronounced between rivers in the SNSM and those with headwaters in the Colombian Andes. The main difference lies in the relatively low contribution from ENSO-related oscillations to the net streamflow variability exhibited by SNSM rivers (Restrepo et al., 2012, 2014). ***Overall, contribution from low-frequency oscillations to streamflow variability is poorly understood, particularly in small, tropical, coastal mountain rivers (Stevens and Ruscher, 2014; Nalley et al., 2016; Marini et al., 2016). These fluvial systems possess low streamflow buffering capacity because of their topographic setting (Milliman and Syvitski, 1992), and they are exposed to regional-scale atmospheric/oceanographic processes (Hastenrath, 1990; Enfield and Alfaro, 1999).*** 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)".

Third paragraph (Page 3 – Line 8): "***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/oceanograpic oscillations and their associated effects on hydrolgy (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)".***

(3) - Third paragraph: to keep the logic of the manuscript the main objectives ought to be aligned with the sub-sections presented in section 4.

(AR) Yes, it is true. The manuscript will be adjusted following this suggestion.

(ACM) In order to align the main objectives and subsequent sub-sections, the manuscript will be modified (Page 3 – Line 8) as follows:

Text to be removed is highlighted in bold and cursive: "The objectives of this study were to: ***(1) study the influence of low-frequency oscillations (linked to large-scale oceanographic/atmospheric processes) on streamflow variability***, (1) explore the temporal characteristics of streamflow variability, (2) estimate the net contribution (i.e.

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 (Table 2) in small, tropical, coastal mountain rivers of the SNSM (Fig. 1 and Table 1)".

New text in the manuscript (new text in bold and cursive): "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)".

(4) - Pag. 4 line 30: explain the main difference between XWT and WTC.

(AR) On Page 5 - Line 13 we present a brief description of the XWT and WTC highlighting their differences. However, based on your observations, we consider it relevant to highlight the difference between these methods on section 3.1

(ACM) In order to reinforce the main difference between XWT and WTC, the manuscript will be modified (Page 4 – Line 29) as follows (new text in bold and cursive):

"We also used Cross Wavelet Transform (XWT) and Wavelet Coherence (WTC) to estimate the correlation between streamflow and eight large-scale climate/oceanographic processes (Table 2). ***The XWT unveils high common powers and relative phases in a time-frequency space; whereas the WTC finds 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 a imprecision 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):

$$\bar{f}(n) = \frac{\int_0^\infty f E_n(f)df}{\int_0^\infty E_n(f)df} \qquad (7)$$

(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 ocurrence 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, interanual and quasi-decadal bands between 19988 and 2002. However, as you stated, the interaction of the cuasi-biennal, annual, interanual and cuasi-decadal bands between 2008 and 2012 is not completely evident, because the cuasi-biennal 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 ocurrence 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 occurred 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)".