5. General conclusions and Future work

5.1. General conclusions

- The accuracy of the estimation of hydro-climatic anomalies (HyAns) is commonly taken for granted and constitutes an important source of error and bias for subsequent interdependency analysis with other time series or climatic indexes and, consequently there is room for ambiguity in the physical interpretation of results. In Chapter 2, we presented diverse methods to define anomalies and then, we quantified Pearson correlations between ENSO and rainfall anomalies in Colombia. We showed that correlation patterns can change significantly in terms of the sign, magnitude, and timing, depending on the phase of ENSO, and the location in the country. Hence, we took this result into account for subsequent non-linear interdependence analysis using synchronization techniques (Chapters 3 and 4), this in order to check the sensitivity of such synchronization techniques to the HyAns methods.

- We investigate Phase Synchronization (PS) between the El Niño - Southern Oscillation (ENSO) signal and the (inter-annual and annual) cycles of rainfall in Colombia. Our findings show that the positive (negative) HyAns experienced in the Pacific, Caribbean and Andean regions of Colombia, during La Niño (El Niño), are phase-locked with the ENSO signal in the tropical Pacific Ocean, whereas the negative (positive) HyAns experienced in the Orinoco and Amazon regions, during La Niña (El Niño), do not show such phase-locking. Moreover, our results evidence that, at inter-annual time scales, during La Niña, for all quarters, SST3.4 anomalies in the tropical Pacific Ocean lead rainfall anomalies in the Pacific, Caribbean and Andean regions from 1 to 3 months lag whereas, during El Niño, for JJA and SON, SST3.4 anomalies lead rainfall anomalies from 3 to 5 months lag. These results show that, during El Niño, rainfall anomalies exhibit a time-lag longer than during La Niña in relation to anomalies in the tropical Pacific ocean.

- We quantify Phase Synchronization (PS) between the El Niño - Southern Oscillation (ENSO) signal and the annual cycle of rainfall in Colombia. We provide evidence that the ENSO signal is phase-locked with the AC of rainfall in some regions of Colombia, which suggest that the AC plays an important role in the influence of ENSO on Colombian climatology and opens new paths towards the understanding of non-linear feedbacks between hydro-climatic processes. In particular, these links between the inter-annual variability of ENSO and the annual cycle of rainfall over Colombia is possible because of the non-linear basis of the synchonization approach.

- At inter-annual timescales, ENSO exhibits the strongest phase-locking with the annual and inter-annual cycles of rainfall throughout Colombia, although other macro-climatic processes also show significant PS such as the Pacific Decadal Oscillation (PDO) and the North Atlantic Oscillation (NAO). Moreover, we suggest that the highest positive (negative) rainfall anomalies over western Colombia coincide with the strong (weak) PS between the ENSO and the PDO signals.

- We investigate Generalized Synchronization (GS) between the El Niño-Southern Oscillation (ENSO) signal and rainfall anomalies in Colombia. We link the GS results with the dynamics of some physical mechanisms that modulate Colombia's hydro-climatology, including the Caribbean, the CHOCO and the Orinoco Low-Level Jets (LLJs), and the Cross-Equatorial Flow (CEF). Our results confirm those results found using PS, HyAns in the Pacific, Caribbean and Andean regions of Colombia exhibit strong (weak) GS with the ENSO signal during La Niña (El Niño), where hydrological anomalies are positive (negative).

- The GS analysis allows us to identify spatial patterns of non-linear dependence between ENSO and the Colombian's climatology. The mentioned moisture transport sources (LLJs and the CEF) constitute the interdependence mechanism and contribute to explain hydrological anomalies in Colombia during the phases of ENSO. During La Niña (El Niño), GS is strong (weak) for the Caribbean and the CHOCO LLJs whereas GS is moderate (strong) for the Orinoco LLJ. Moreover, moisture advection by the Caribbean and CHOCO LLJs exhibit synchrony with HyAns at 0 to 2 (2 to 4) month-lags over north-western Colombia and the Orinoco LLJ moisture advection synchonizes with HyAns at similar month-lags over the Amazon region of Colombia.

- This work uses a novel approach that reveals new insights regarding the impacts of ENSO given the non-linear nature of the PS and GS methods. First-order approximation of the relation between ENSO and Colombian rainfall anomalies seems to be linear, but it is hardly the whole picture. From our analysis, we can conclude that non-linearity is also important although probably there are other ways to go deeper into this relation but this first step is an important contribution.

5.2. Future work

This dissertation opens important research paths that deserve to be investigated in the future, such as:

- We reviewed the concept of climatic 'anomaly' evidencing that linear and non-linear methods to quantify interdependence are affected by how we define anomalies (i.e. the method used to subtract the annual cycle signal). Hence, it is necessary to look total solutions using raw data (without extracting the annual cycle) or quantify the sensitivity and uncertainty of interdependence metrics in relation to the different ways to define anomalies. Some future applications of the uncertainty in anomalies estimation can be: (1) assessing of the false skills in forecasting models (i.e. changes in forecasting through ARIMA models in relation to diverse anomalies methods), (2) identification of general circulation models (GCMs) that show similar variability modes at annual or/and inter-annual scales (i.e. Earth's localities where a group of GCMs show analogous inter-annual variability in association to ENSO or other macroclimatic processes –in terms of sign, timing, and magnitude– for different anomaly methods).

- Our findings evidence that synchronization methods allow revealing that the links among the oscillatory processes play a fundamental role behind the complex hydroclimatic feedbacks. In this sense, it is necessary to implement synchronization techniques using time series derived from a Principal Oscillation Patterns (POPs) analysis [*Von Storch et al.*(1995)], which have a firm theoretical basis that allows reducing multiple time series into their main oscillatory signals that could be useful for prediction purposes.

- Our results show that phase and generalized synchronization techniques have a firm theoretical basis from physical properties of weakly coupled oscillators and non-linear dynamics systems, respectively. Hence, such techniques can be used to quantify non-linear interdependence between oscillatory processes that occur at different time scales (e.g. the interannual variability of ENSO and the annual cycle of Colombia's hydroclimatology). From this point of view, the synchronization framework can be useful to investigate the physical basis behind to scaling properties of hydroclimatic processes. This because synchronization can be thought as a sample space reducing process and, a process that reduces degrees of freedom is a system synchronized. Once a system is synchronized, there will not be much of scaling be visible in the statistics (pers. comm. with Thurner, S.).

- [*Bedoya-Soto et al.*(2019)] shown that the diurnal cycle of rainfall over Medellin's Valley, Central Andes of Colombia, changes with the annual cycle. It is interesting to investigate how the diurnal and annual cycles are connected. However, it is not possible to quantify the interdependence between the diurnal and the annual cycles using the synchronization techniques presented in this work. As we mentioned, phase-locking emerges if there is a relationship between oscillations with relatively small natural integers. For this case, for each annual cycle (AC) there are 365 diurnal cycles (DC), it is not possible to study this phase relationship directly using the PS technique based on phase differences. However, it is important to investigate if there is a phase-locking scaling property that links the DC and the AC. In this sense, further research could study PS between the DC and the 5-10 day variability associated with the Tropical Easterly Waves (TEWs). Then, to explore PS between the 5-10 days and the 30-60 day variability associated with the Madden-Julian Oscillation (MJO). Finally, it is possible to look for PS features between the 30-60 day variability and the semi-annual (6 months) and annual (12 months) variability. The mentioned procedure outlines a way to address the connection between diurnal to annual variability using PS techniques.

- Until now, the literature does not provide a satisfactory explanation regarding the occurrence of different types of ENSO events. In this sense, synchronization techniques could be useful to study the synchronization patterns over the Tropical Pacific Ocean between SST anomalies and wind anomalies. This synchronization approach could provide new clues on the genesis of different flavors of ENSO.

- Synchronization techniques allow studying the non-linear interdependence between processes that occur at different time scales. Recent works by [*Stein et al.*(2011), *Stein et al.*(2014)] and this dissertation show some synchronization features between the ENSO and the annual cycle variability. Other cases deserve to be studied in the future such as (1) synchronization between the MJO and the ENSO variability over the tropical Pacific Ocean, (2) synchronization between the PDO signal and the ENSO signal and, (3) synchronization between the ENSO variability and the inter-annual variability over the Atlantic Ocean (i.e. NAO or AMO).

- This work points out the need to study the Orinoco LLJ anomalies and their relationship with the hydro-climatic response over the Orinoco and Amazon regions of Colombia during ENSO.

- During La Niña (El Niño), the Andean region does not exhibit PS between SST3.4 anomalies and the annual cycle of precipitation in this region during the boreal summer. Hence, further research is needed regarding the role of topography on the phase synchronization features.

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