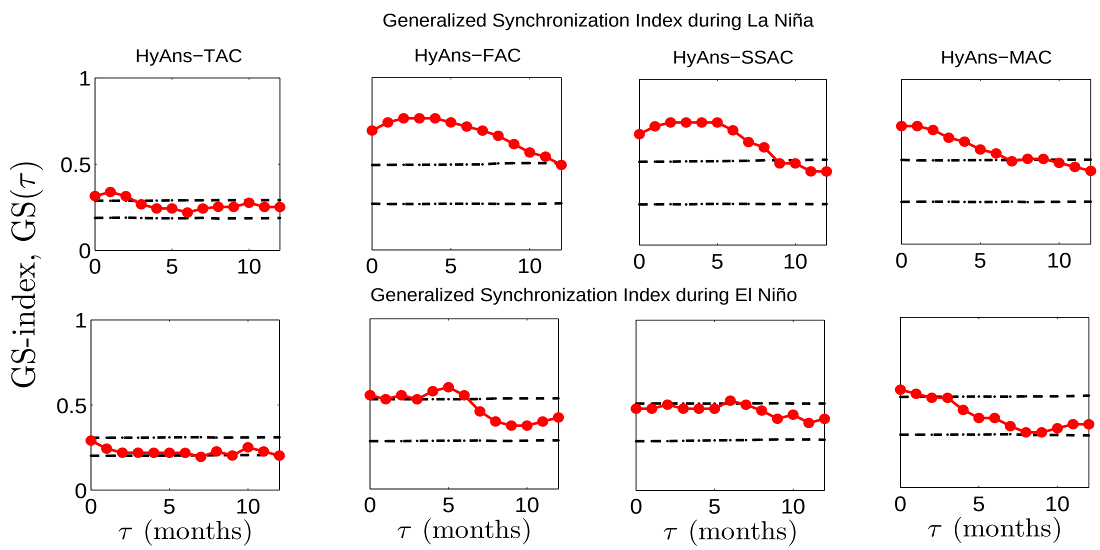
and HyAns–MAC methods suggest a 2 to 4 months-lag whereas, during El Niño, the HyAns–FAC and HyAns–SSAC methods show a 4 to 6 months-lag. Furthermore, the HyAns–FAC and HyAns–MAC methods show time-lag differences during El Niño. As a conclusion, the magnitude of the GS-index is not highly sensitive to the diverse HyAns methods whereas the time-lag between time series could be affected by the HyAns methods.

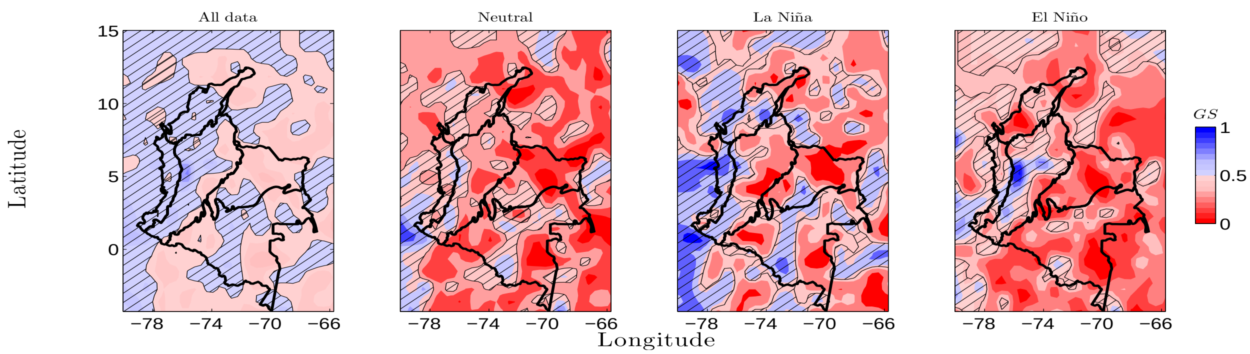
Hereafter, time series are filtered using the F-filtering of the annual cycle by a moving average procedure (HyAns–FAC) in order to remove the intra-annual, semi-annual and annual frequency bands. Furthermore, we verify that the time series only contain information at inter-annual timescales using the test by [*Ahdesmäki, et al.*(2005)].



Figures 4-8.: Generalized synchronization index (GS-index) between the ENSO signal (MEI index) and monthly rainfall anomalies in the Andean region estimated using the four HyAns methods: HyAns–TAC, HyAns–FAC, HyAns–SSAC, HyAns–MAC. (top row) La Niña and (bottom row) El Niño. Period 1976-2015. τ denotes the time lag. (dashed black lines) 95% confidence boundaries.

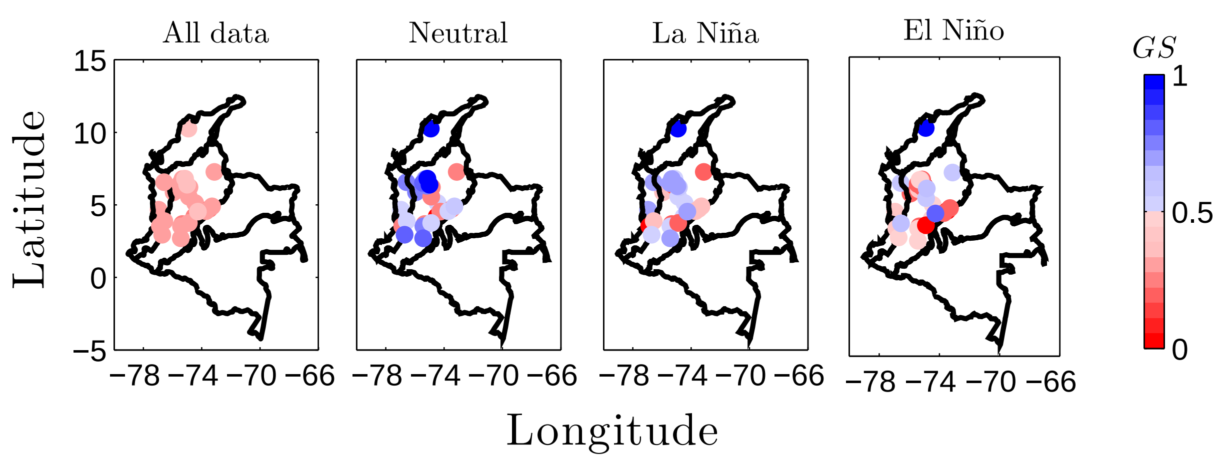
4.5.5. GS between SST3.4 anomalies and hydrological anomalies in Colombia

As a first step, we quantify GS between SST3.4 anomalies and rainfall and streamflows anomalies over Colombia. In general, Fig. **4-9** evidences that rainfall anomalies are in GS with SST anomalies in the central tropical Pacific. In particular, the GS calculation using all data points, regardless of ENSO phases, leads to lower GS-values but whose significant values are consistent with the results considering the Neutral, La Niña, and El Niño. Furthermore, our findings show that the GS is strong (weak) during La Niña where rainfall exhibits positive (negative) anomalies. The lowest GS values are shown in the Neutral condition. During La Niña, the GS occurs mainly over western Colombia, that is the northern and western Andean region as well as the Pacific and the Caribbean regions. In turn, mentioned regions exhibit positive rainfall anomalies. Note that the Amazon region also exhibits significant GS but, during this cold phase of ENSO, rainfall anomalies are negative. During El Niño, the GS is significant mainly over the Pacific and the Andean regions where rainfall exhibits negative anomalies. At this point, our results confirm the influence of both ENSO phases over Colombia [*Poveda and Mesa*(1997),*Poveda et al.*(2010)]. Moreover, our findings confirm that those regions exhibiting strong (weak) phase synchronization during La Niña (El Niño) also exhibit GS (see Chapter 3). Hence, the systems (ENSO and rainfall in some regions of Colombia) exhibit a functional relationship.



Figures 4-9.: Generalized Synchronization Index between SST3.4 anomalies and rainfall anomalies in Colombia, Data set No. 1, period 1975-2006. The hatched contours indicates zones where the GS is significant at 5%.

On the other hand, streamflows are the hydrological response to interactions, at catchment scale, between landscape characteristics (soils, vegetation, geology, the topology of drainage networks, hydraulic properties, etc) and climate and weather events [*Troch et al.*(2013)]. In addition, the catchment plays a filtering role to the high frequency nature of precipitation in association with evapotranspiration and soil moisture dynamics [*Andrés-Doménech et al.*(2015)]. In this sense, it is to be expected that marked long-term patterns of precipitation appear also in long-term characteristics of streamflows. Fig. **4-10** shows the GS index between SST3.4 anomalies and streamflow anomalies. Our results are consistent with those found for rainfall anomalies. First, our findings demonstrate that using all data points, regardless of ENSO phases, leads to lower GS-values. Furthermore, the GS index is higher during La Niña than during El Niño. In particular, streamflow anomalies exhibiting strong GS are located in the Caribbean region and the north-western Andean region. These results could be associated with the GS-patterns between rainfall anomalies and moisture advection from the Caribbean and CHOCO LLJs discussed next.



Figures 4-10.: Generalized Synchronization Index between SST3.4 anomalies and river flow anomalies from the IDEAM and XM datasets, period 1976-2013.

4.5.6. GS between the moisture advection by Low-Level Jets and rainfall in Colombia

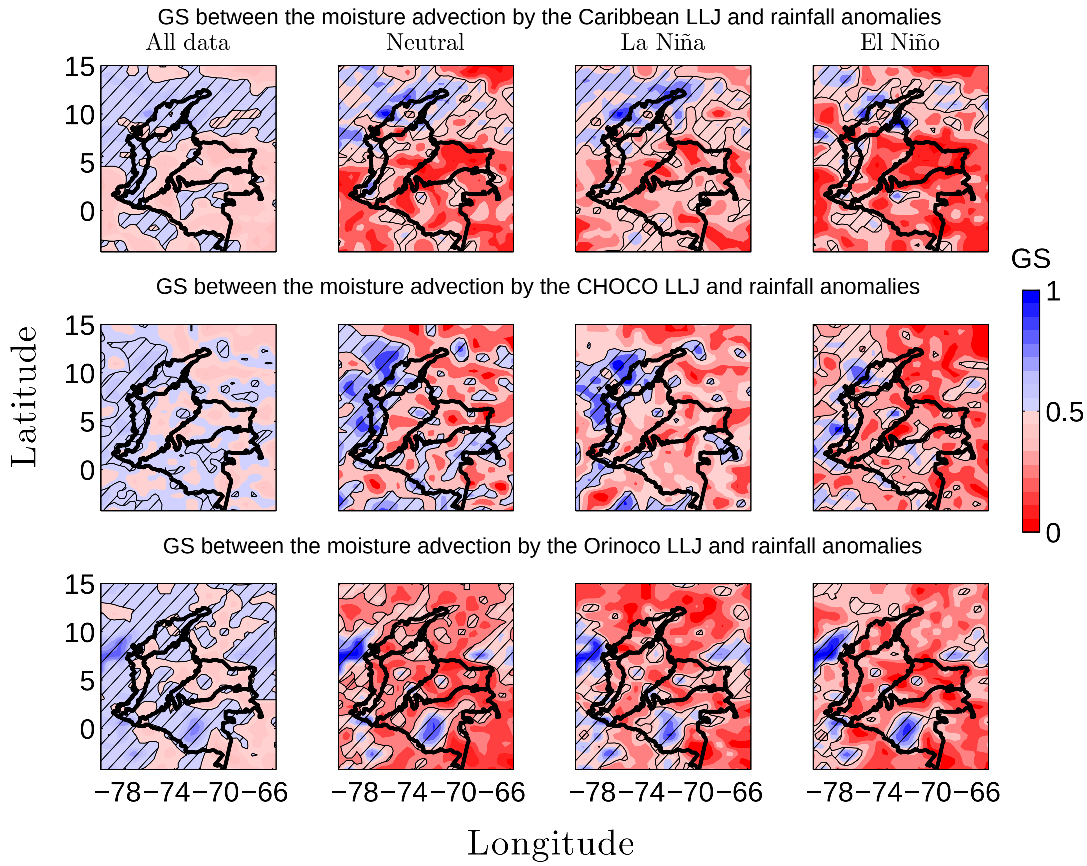
- **GS between the Caribbean LLJ moisture advection anomalies and rainfall anomalies**

Fig. **4-11** shows the GS-index between the moisture advection of the aforementioned low-level jets (LLJ) and rainfall anomalies throughout Colombia, the columns denote the GS-results considering all data and the different samples for the phases of ENSO (Neutral, La Niña and El Niño). Fig. **4-11** (top row) shows the GS-index between the moisture advection by the Caribbean LLJ and rainfall anomalies in Colombia. Our results reveal that rainfall anomalies over the Caribbean, the northern-Pacific, and the northern-Andean regions are related to moisture advection by the Caribbean LLJ. In particular, during La Niña, the GS-index exhibits the strongest values and the largest area, whereas during El Niño the GS-values and area of influence are smaller. These findings are in support of the Caribbean LLJ influence on the hypothesis that the Caribbean LLJ influence the hydro-climatic response over northern South America and, particularly, over northern Colombia [*Wang*(2007), *Martin and Schumacher*(2011), *Arias et al.*(2015)]. Furthermore, these results confirm the influence of the Caribbean LLJ anomalies during ENSO on the positive (negative) rainfall anomalies over northern Colombia. [*Wang*(2007)] and [*Martin and Schumacher*(2011)] showed that during JJA, rainfall in the Caribbean (including the Caribbean region of Colombia) exhibits significant correlations with the Caribbean LLJ index. Moreover, it is postulated that the Caribbean LLJ induces changes in moisture flux divergence in the Caribbean, which enhance convection and increase rainfall [*Martin* *and Schumacher*(2011)]. In this sense, weakening (strengthening) of the Caribbean LLJ winds is associated with increasing (decreasing) rainfall anomalies over northern Colombia [*Arias et al.*(2015)]. Coherently, our findings reveal that positive rainfall anomalies during La Niña coincide with negative moisture advection by the Caribbean LLJ from May to November, which is evidenced as moderate GS. In contrast, our results show that negative rainfall anomalies during El Niño exhibit weak GS (see Fig. **C-11** and Fig. **4-6**a). These results can be explained because the Caribbean LLJ has an opposite relationship with ENSO in the boreal winter and summer. During the winter a weak (strong) easterly Caribbean LLJ corresponds to warm (cold) SST anomalies in the tropical Pacific, whereas during the summer a strong (weak) easterly Caribbean LLJ is associated with warm (cold) SST anomalies in the tropical Pacific [*Wang*(2007)]. Furthermore, during El Niño, the Caribbean and Central America region experiences less precipitation in July-August, suggesting that Caribbean LLJ may modulate precipitation anomalies [Muñoz et al. (2007)].

On the other hand, Fig. **4-12** (top row) shows the maximum time-lags in areas of significant GS between moisture advection anomalies by the Caribbean LLJ and rainfall anomalies during the ENSO phases. During La Niña and Neutral phases, synchrony between the Caribbean LLJ moisture anomalies and rainfall anomalies in northern Colombia corresponds to time-lags between 0 and 2 months. During El Niño, such synchrony over northern Colombia occurs at time-lags between 0 and 4 months, suggesting that during El Niño, the time-lag between the Caribbean LLJ moisture anomalies and rainfall anomalies could be longer than during La Niña.

- **GS between the CHOCO LLJ moisture advection anomalies and rainfall anomalies**

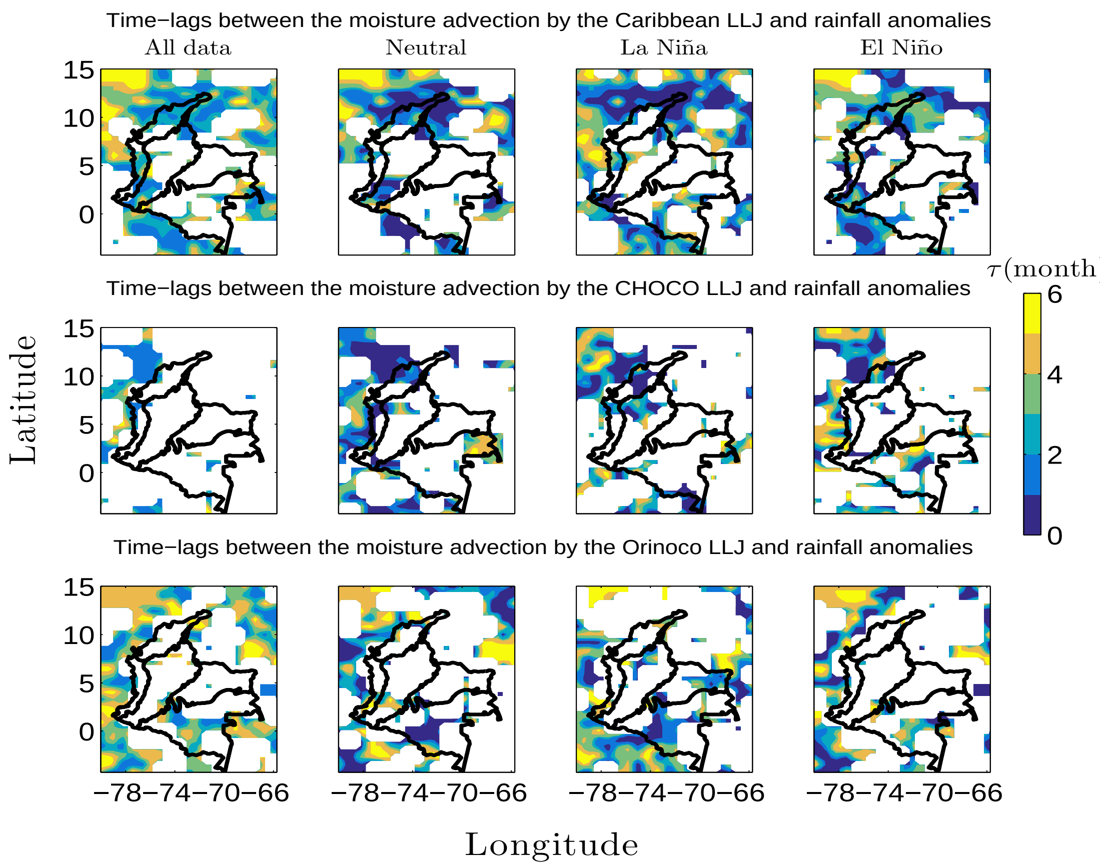
  Fig. **4-11** (middle row) shows the GS-index between moisture advection by the CHOCO LLJ and rainfall anomalies in Colombia. Results evidence that rainfall anomalies over the entire tropical Pacific, the southern Caribbean, and the western Andean regions can be associated with moisture advection by the CHOCO LLJ. During La Niña and Neutral phases, the GS values are higher than during El Niño epochs (in most of places). Furthermore, the GS-significant-areas are larger during the Neutral and El Niño than during La Niña epochs. [*Poveda et al.*(2010), *Rueda and Poveda*(2006), *Poveda and Mesa*(2000)] argue that positive (negative) rainfall anomalies in western Colombia during La Niña (El Niño) can be explained in terms of the increasing (decreasing) moisture advection of the CHOCO LLJ as a result of the increase (decrease) in the temperature gradient between surface air temperatures over the Pacific coast off Colombia and El Niño 1+2 zone during June-July-August and September-October-November. During La Niña, positive rainfall anomalies coincide with positive moisture advection anomalies by the CHOCO LLJ, both signals exhibiting prominent peaks in the same period, which is reflected as strong GS over



Figures 4-11.: Generalized Synchronization Index between the moisture advection of the low level jets and rainfall anomalies throughout Colombia. (top row) Caribbean LLJ. (middle row) CHOCO LLJ. (bottom row) Orinoco LLJ. Dataset No.1, period 1975-2006. The hatched contours indicates zones where the GS is significant at 5%.

northwestern Colombia (see Fig. **4-6**b; Supp. Info. Fig. C-12; Fig.**4-11**, middle row, third column, La Niña). In contrast, during El Niño, GS between negative rainfall anomalies and negative moisture advection by the CHOCO LLJ is weak, although GS is also significant (see Fig.**4-11**, middle row, last column, El Niño). Additionally, we also calculate GS between the sea surface temperature gradient in the previously mentioned regions and rainfall anomalies in Colombia. Our findings confirm the influence of the far-eastern Pacific SST gradient on rainfall anomalies on western Colombia and are consistent with those shown for GS between the CHOCO LLJ and SST3.4 (see Supp. Info. Fig. C-1).

On the other hand, Fig. **4-12** (middle row) shows the maximum time-lags in areas of significant GS between moisture advection anomalies by the CHOCO LLJ and rainfall anomalies during the ENSO phases. During La Niña and Neutral phases, synchrony between rainfall anomalies and the CHOCO LLJ moisture anomalies in north-western Colombia corresponds to time-lags between 0 and 2 months. During El Niño, such synchrony over north-western Colombia occurs at time-lags between 2 and 6 months, suggesting that during El Niño, the time-lag between the CHOCO LLJ moisture anomalies and rainfall anomalies could be longer than during La Niña.



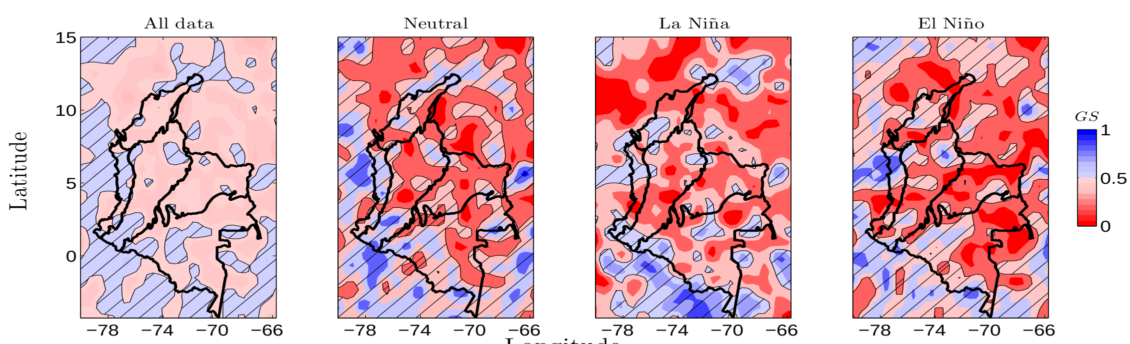
Figures 4-12.: Time-lags between the moisture advection by the low level jets and rainfall anomalies throughout Colombia. (top row) Caribbean LLJ. (middle row) CHOCO LLJ. (bottom row) Orinoco LLJ. Dataset No.1, period 1975-2006. White indicates zones where GS is not significant at 5%.

- **GS between the Orinoco LLJ moisture advection anomalies and rainfall anomalies**

Fig. **4-11** (bottom row) shows the GS-index between moisture advection anomalies by the Orinoco LLJ and rainfall anomalies in Colombia. Our GS-analysis suggests that such positive (negative) moisture advection influences the positive (negative) hydro-climatic anomalies in the Colombian Amazon region during El Niño (La Niña), GS is moderate (strong) and the areas are larger (smaller). In contrast, these GS results can not be easily associated with rainfall anomalies in the Orinoco region (see Fig. **C-11** and Fig. **4-6**c). Hence, these findings point out the need of further research regarding the response of the Orinoco LLJ to ENSO's phases in order to advance the understanding of hydro-climatic anomalies of these regions. Note that the Pacific coast exhibits significant GS, which need to be further investigated. Fig. **4-12** (bottom row) shows the maximum time-lags in areas of significant GS between moisture advection anomalies by the Orinoco LLJ and rainfall anomalies during the ENSO phases. Results suggest a simultaneous relation between moisture by the Orinoco LLJ and rainfall anomalies over the Amazon region. During La Niña and Neutral phases, synchrony between rainfall anomalies and the Orinoco LLJ moisture anomalies in southern Colombia (Amazon region) corresponds to time-lags between 0 and 2 months. During El Niño, such synchrony occurs at time-lags between 2 and 4 months, suggesting that during El Niño, the time-lag between the Orinoco moisture anomalies and rainfall anomalies could be longer than during La Niña.

4.5.7. GS between the Cross-Equatorial Flow and rainfall in Colombia

Fig. **4-13** (top row) shows the GS-index between moisture advection by the Cross-Equatorial Flow (CEF) and rainfall anomalies in Colombia. Our results evidence that rainfall anomalies in the Amazon region are related to the meridional moisture advection by the CEF. Hence, our results support those presented by [*Wang and Fu*(2002)] regarding the influence of the CEF over hydro-climatology of the northern Amazon River basin (southern Colombia).



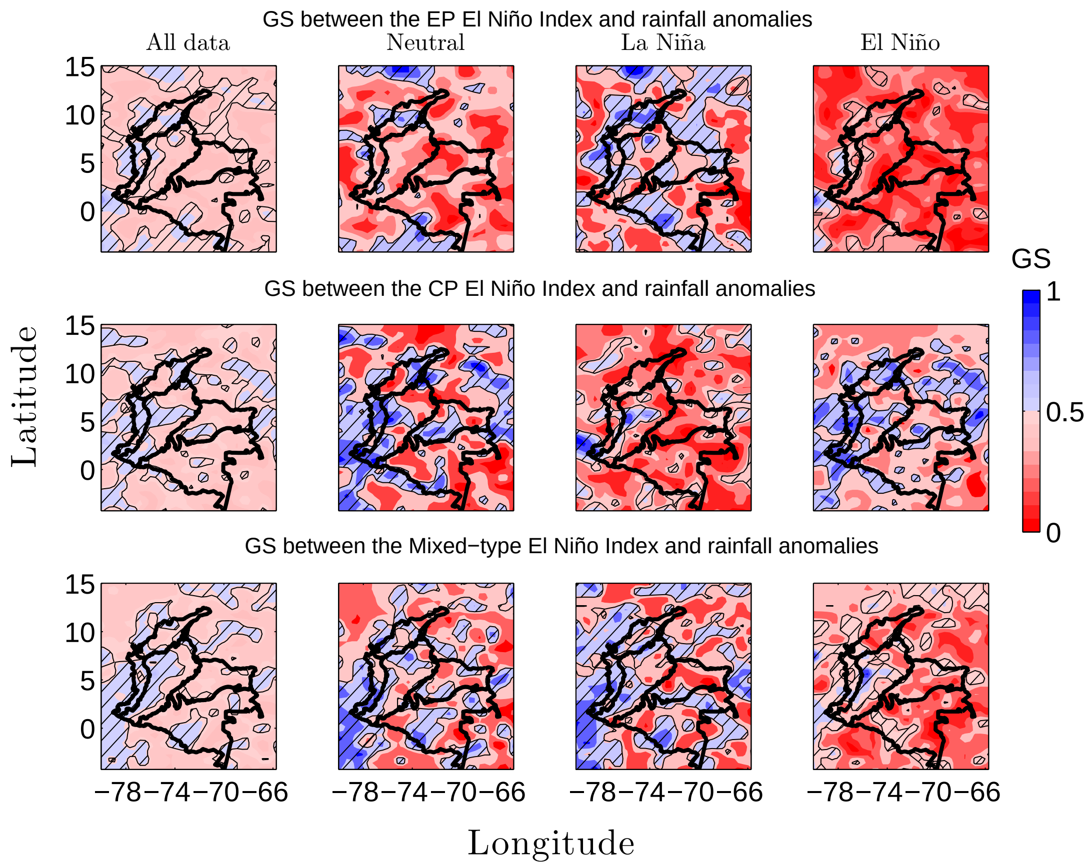
Figures 4-13.: Generalized Synchronization Index between the moisture advection by the Cross-Equatorial Flow and rainfall anomalies. Dataset No.1, period 1975-2006. The hatched contours indicate zones where the GS is significant at 5%.

In addition, our findings show that the GS-significant-areas are larger (smaller) during El Niño (La Niña) as well as the GS is strong (weak) during La Niña (El Niño). In particular, the GS results reveal a connection between the Amazon region of Colombia (north-western most Amazon River basin) and the western Colombia Pacific coast. This result supports the recent works on aerial rivers connecting Amazonia and the Colombian Pacific [*Sakamoto et al.*(2011)], as well as the existence of an Atmosphere-Land Bridge between the Pacific and the tropical North Atlantic through the Amazon River basin [*García-Serrano et al.*(2017), *Builes et al.*(2018)]. In this sense, Fig. **C-11** does not show a clear annual cycle of rainfall anomalies in these regions (see also Fig. C-12 in Supp. Info.). Nonetheless, Fig. **4-6**d evidences positive (negative) southerly moisture advection anomalies by the CEF during La Niña (El Niño) in the austral winter as well as negative (positive) northerly moisture advection anomalies by the CEF during La Niña (El Niño) in the austral summer. This results provide new insights on the influence of the Orinoco LLJ and the CEF winds over the Amazon region as modulators of rainfall anomalies during ENSO. The influence of the Orinoco LLJ seems to be stronger than the influence of the CEF over the Amazon region of Colombia (see **4-11** bottom row). Moreover, our results suggest that the influence of the CEF is stronger in the Pacific region (western Colombia) than in the Amazon region of Colombia. However, further research is needed regarding the CEF dynamics during ENSO and its influence on the Orinoco and Amazon regions of Colombia. At this point, there is not clear evidence on the influence of the CEF over the Orinoco region. Additionally, the analysis of time-lags do not show clear patterns (see Suppl. Info. Fig. C-2, top row).

4.5.8. GS between indices for different types of ENSO and hydrologic anomalies in Colombia

Fig. **4-14** (left column) shows GS between the different types of El Niño indices and rainfall anomalies in Colombia using all data. These results suggest that the three indices exhibit GS with rainfall anomalies over the Caribbean, the Pacific, and the Andean regions whereas the Orinoco and the Amazon regions do not exhibit such interdependence. Furthermore, these results agree with those shown in Chapter 3, which stated that rainfall anomalies are phase-locked with SST anomalies in the Caribbean, the Pacific, and Andean regions, whereas the Orinoco and the Amazon regions do not exhibit such phase-locking. Hence, our GS results suggest that rainfall anomalies in some regions of Colombia (the driven system) are mainly determined by ENSO (the driving system).

Additionally, we quantify GS between each index-type of ENSO and rainfall anomalies in Colombia considering the ENSO phases. We aim to characterize the GS-patterns during El Niño, La Niña and Neutral phases using the same reference periods than in previous analysis as per MEI classification (see Fig. **4-2**). Fig. **4-14** (top row) evidences that



Figures 4-14.: Generalized Synchronization between indices for different types of ENSO and rainfall anomalies throughout Colombia. (top row) Eastern Pacific (EP) El Niño type. (middle row) Central Pacific (CP) El Niño type. (bottom row) Mixed El Niño type. Dataset No.1, period 1975-2006. The hatched contours indicates zones where the GS is significant at 5%.

the EP index exhibits a strong (weak) GS with rainfall anomalies in Colombia during La Niña (El Niño) over vast (small) areas of the continental Colombian territory. Fig. **4-2**a shows that during La Niña (El Niño) phase the EP index shows negative (positive) SST anomalies. This GS-result can be explained because cold (warm) SST anomalies over the Eastern Pacific produces a higher (smaller) temperature gradient between the Pacific Ocean off the Colombian coast and the El Niño 1+2 region that increase (decrease) of the moisture advection by the CHOCO LLJ [*Poveda et al.*(2010), *Poveda and Mesa*(2000)].
In contrast, Fig. **4-14** (middle row) evidences that the CP index exhibits a strong (weak) GS with rainfall anomalies during El Niño (La Niña) phase over vast areas of the continental Colombian territory. Fig. **4-2**a evidences that during El Niño (La Niña) the EP index shows positive (negative) SST anomalies that are higher (smaller) than those experienced in the Central Pacific (Fig. **4-2**a). Hence, we hypothesize that cooling (warming) of SSTs in the far eastern tropical Pacific are more associated with higher positive (negative) rainfall

anomalies in Colombia than the cooling (warming) of SSTs in the central Pacific. The cooling (warming) of SSTs in the Central Pacific seems to modulate rainfall anomalies in Colombia in different ways given that the increase (decrease) of SSTs in the central tropical Pacific are sandwiched by anomalous cooling (warming) over the eastern and western tropical Pacific, which influences the far-eastern tropical Pacific (the Pacific Ocean off the Colombian coast) and the Caribbean sea [Ashok and Yamagata (2007), Ashok and Yamagata (2009), Weng et al. (2009)]. Hence, the characteristics of such anomalous cooling (warming) over the eastern and western portions of the Central Pacific affect the SST gradients between the Pacific Ocean off the Colombian coast and the El Niño 1+2 as well as the response in the Caribbean sea, which affects the hydro-climatic response over Colombia. This result is in agreement with the study of Navarro-Monterroza et al. [*Navarro-Monterroza et al.* (2019)] regarding different effects of CP and EP El Niños on rainfall anomalies in Colombia.
A similar procedure was carried out to quantify GS between the Mixed-type El Niño indices and rainfall anomalies in Colombia. Fig. **4-14** (bottom row) evidences that the Mixed-type El Niño index exhibits strong (weak) GS with rainfall anomalies during La Niña (El Niño) in the Caribbean, the Andean and Pacific regions. These results are comparable with the GS-patterns between the SST3.4 anomalies and rainfall anomalies (see Fig. **4-9**) as expected because both, the Mixed-type El Niño Index and SST3.4 anomalies, are calculated over the same tropical Pacific zone (Niño3.4).
We analyzed time-lags between the different types of El Niño indices and hydrological (rainfall and streamflows) anomalies in Colombia but our results do not show clear evidence of synchrony or temporal propagation of spatial patterns (see Suppl. Info. Figs. C-7 to C-10).

4.6. Final remarks and future work

We use Recurrence Quantification Analysis (RQA) with the aim to study features of Generalized Synchronization (GS) between ENSO and the hydrological anomalies (rainfall and streamflows) over Colombia, taking into account the uncertainty in the non-linear recurrence metrics induced by the different methods to estimate hydro-climatic anomalies (HyAns). Our results suggest that the GS quantifier based on RQA can be significantly affected when anomalies are defined on a constant climatology (HyAns–TAC method). On the other hand, the GS-metric exhibits similar magnitude for the HyAns methods that consider a non-constant annual cycle (HyAns–FAC, HyAns–SSAC, and HyAns–MAC), whereas the time-lags between signals could be sensitive to the HyAns method used.
Our findings allow us to conclude that the hydrology of Colombia exhibits GS with ENSO. Moreover, the physical mechanisms associated with such GS could be different for each region of Colombia. Our results reveal that advection of moisture by the studied Low-Level Jets (LLJs) and the Cross-Equatorial Flow are part of the physical mechanisms influencing the hydrological anomalies in Colombia during ENSO.
We identified that GS-patterns between advection of moisture by each of the three LLJs

and hydrology change, in terms of magnitude and spatial distribution, depending on the phase of ENSO (La Niña and El Niño). In this sense, there are three main results, which advance our understanding about the hydrological anomalies in Colombia at interannual timescales: *(i)* rainfall anomalies in the Caribbean, northern-Pacific, and northern-Andean regions are mostly related with moisture advection by the Caribbean LLJ. During La Niña (El Niño), rainfall and streamflows in these regions exhibit positive (negative) anomalies, and GS is strong (weak) with the largest (smallest) areas of significant correlation; *(ii)* rainfall anomalies in the entire Pacific region, the southern Caribbean region, and the western Andean region can be associated with the advection of moisture by the CHOCO LLJ. During La Niña (El Niño), hydrological variables experiment positive (negative) anomalies and, GS is strong (weak) whereas the significant spatial GS-areas are small (large); *(iii)* rainfall anomalies in the Colombian Amazon region are correlated with the advection of moisture by the Orinoco LLJ. During La Niña (El Niño), the Amazon and Orinoco regions experience negative (positive) hydrological anomalies but only the Amazon region shows weak (strong) GS.

We provide evidence of propagation patterns over Colombia regarding the influence of the LLJs and CEF over the studied hydrological anomalies: *(i)* During La Niña, the Caribbean LLJ moisture anomalies exhibit synchrony with rainfall anomalies in northern Colombia at 0-2 months lags. During El Niño, the Caribbean LLJ moisture advection leads rainfall anomalies at 2-4 months lags. During Neutral and La Niña conditions, time-lags are similar. *(ii)* During La Niña, the CHOCO LLJ moisture anomalies exhibit synchrony with rainfall anomalies over north-western Colombia at 0-2 months lags. During El Niño, CHOCO LLJ moisture anomalies lead rainfall anomalies at 2-4 months lags. During Neutral and La Niña, time-lags are similar; *(iii)* the Orinoco LLJ exhibits synchrony with rainfall anomalies over the Amazon region (not so over the Orinoco region); *(iv)* north-western Colombia (the Caribbean region and the northern Pacific region) experiences a conjoint influence of the Caribbean LLJ and the CHOCO LLJ.

We also study the GS between the moisture advection by the Cross-Equatorial Flow (CEF) and rainfall anomalies in Colombia. Our results indicate that rainfall anomalies in the Colombian Amazon region are correlated to the CEF. During La Niña (El Niño), GS is strong (weak) whereas the GS spatial patterns are small (large). It is remarkable that our GS results reveal a connection between the Amazon region of Colombia (west-northernmost Amazon River basin) and the western Colombian Pacific coast. This result can be associated with aerial rivers connecting the Pacific and the Amazon River basin, which had been stated in several previous works [*Sakamoto et al.*(2011), *Poveda et al.*(2014), *Builes et al.*(2018)]. In particular, the Orinoco LLJ exhibits stronger GS in the Amazon region of Colombia than the CEF and the analysis of time-lags do not show clear synchronous evolution of signals, which requieres more research.

We quantify GS between three indices for the different types of El Niño (EP and CP) and hydrological variables in Colombia. Our results suggest a strong (weak) GS between negative (positive) SST anomalies in the Eastern Pacific and rainfall anomalies in Colombia. In contrast, our results exhibit a strong (weak) GS between positive (negative) SST anomalies in the Central Pacific and rainfall anomalies. These findings evidence a different influence of the types of ENSO on hydrologic anomalies in Colombia. Further research is needed regarding the effects of the different types of El Niño on physical mechanisms influencing Colombian hydro-climatology.

This work uses a novel approach that reveals new insights regarding the impacts of ENSO given the non-linear nature of the GS method. 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. In particular, our findings contribute to explain the hydrological anomalies over Colombia in terms of diverse physical mechanisms of moisture transport during ENSO. Furthermore, we take into account the uncertainty in the analysis with respect to different ways to define anomalies, which is a fundamental procedure to avoid biases in the interpretation of results for climatological purposes at inter-annual timescales. Notwithstanding, further research is needed regarding the seasonal spatio-temporal patterns of GS at inter-annual timescales, the differences in results considering the different flavors of ENSO, and the differences in the estimation of time-lags in relation to the HyAns methods.

Further research is needed regarding the effects of the different types of El Niño on physical mechanisms influencing Colombian hydro-climatology, e.g. How do the different types of ENSO affect the dynamics of low-levels jets surrounding Colombia? How do the different types of ENSO affect the dynamics of the Cross-Equatorial Flow from the Amazon River Basin? How do the different types of ENSO affect diverse land surface-atmosphere interactions at continental, regional and local scales? How do synchronization patterns change with seasons? These topics are outside the scope of this investigation and need to be further investigated.

4.7. Acknowledgments

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CRP Toolbox for MATLAB developed by N. Marwan and available at http://tocsy.pik-potsdam.de/CRPtoolbox.