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Warm tropical oceans and ENSO flavours behind the late Holocene change in hydroclimates in northern South America

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Abstract

At about 4,000 years ago the earth's global climate underwent significant transformations resulting from changes in solar insolation. Manifestations of this change are relatively well known in higher latitudes, however, in the American tropics these are still not fully identified or understood. Recent paleo-environmental reconstructions based on paleolimnological and vegetational histories of two Colombian Andean sites suggest that between ~4,150 and 2,500 yr BP the Eastern Cordillera (EC) witness wetter anomalies, while the Western Cordillera (WC) suffered from drier anomalies between ~3,700 and 1,750 yr BP. Results from analyses of modern precipitation series from weather stations close to the study sites indicate that the long-term mean annual cycle of precipitation in both sites is out-of-phase and that precipitation anomalies on the western (eastern) site are negatively (positively) correlated with sea surface temperatures in the tropical Pacific (Tropical Atlantic). Hence that we propose that both oceans warmed up during the late Holocene, likely from a more active ENSO and ENSO flavours. With the current global rise in atmospheric temperature and the warming of tropical oceans, this study sheds light on possible anomalous effects on precipitation over the northern Andes.

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1. Introduction

At around 4,000 years ago, the Earth's global climate experienced a reconfiguration resulting from changes in insolation and the warming of the Southern Hemisphere (Wanner et al., 2008). Paleoclimatic reconstructions have provided evidences about some of the consequences of this change: the cooling of the Atlantic Sea Surface Temperatures (SST) and a shift to the negative phase in the North Atlantic Oscillation (NAO) and the onset of seasonality in the North American Prairies (Schwalb et al., 2010), a switch in the forcing of the North American Monsoon from the Atlantic to the Pacific (Jones et al., 2015), a decrease in intensity of the Indian Monsoon (Dixit et al., 2014), climate amelioration and diet changes in peoples from the high Andes Puna (Pintar and Rodriguez, 2022), higher variability in the latitudinal migration of the Intertropical Convergence Zone (ITCZ) (Sachs et al., 2018) with an overall migration to the south (Seillès et al., 2016; Ledru et al., 2022), increased precipitation variability in the Caribbean (Cariaco) (Haug et al., 2001), and a warming of the Tropical Pacific (TP) and the intensification of the El Niño Southern Oscillation (ENSO) (Toth et al., 2012, Toth and Aronson, 2019; Seillès et al., 2016; Renseen, 2022), among others. Recent climate models suggest that the location of seas surface anomalies in the TP, known as ENSO flavours, may have had a great influence over precipitation anomalies, thus that ENSO flavours may account for conflicting paleoclimatic reconstructions regarding ENSO during the Holocene (Karamperodou and DiNezio, 2022).

In Colombia, late Holocene pollen records have suggested that around 4,000 calibrated years Before Present (yr BP) climates turned more variable (Marchant et al., 2001) and eventually became more humid (Marchant and Hooghiemstra, 2004). Recent multiproxy paleolimnological and paleoclimatic reconstructions from two strategic sites in Colombia have shed new light on the manifestations of this global event in northern South America. One of the "paleo" records comes from Santurbán-Berlín, a high-altitude dry paramo in the Eastern Cordillera (EC), and the other one is from a mid-altitude wetland, Medellincito, in the Western Cordillera (WC), and close to one of the rainiest places on Earth, the western foothills of the WC (Fig. 1) (Poveda and Mesa, 2000; Yepes et al., 2019). These reconstructions indicate that Santurbán-Berlín, became wet between 4,150 and 2,500 yr BP (Patiño et al., 2020) while Medellincito witnessed very dry conditions between 3,700 and 1,750 yr BP (Jaramillo et al., 2021). This is, eastern Colombia became wet, while the western part turned dry. This response in hydroclimates to the late

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Holocene global change warrants some discussion, not only due to its antiphase character but also because today, average precipitation in Colombia decreases from the west to east (Fig. 1). In this study, we aim to shed light on the effects and manifestations of the 4 ky BP climate event in the tropics based on analyses of today's hydroclimates and to contribute to understand the complex responses of tropical hydroclimates to global phenomena, and thus inform about possible future climate scenarios resulting from warming oceans based on paleo-climate inferences.

2. Modern hydroclimates of Colombia

Colombia's main sources of atmospheric moisture include the Caribbean Sea, the topical North Atlantic and the far eastern Pacific oceans, and also the Amazon region (Arias et al., 2021). Spatial variability of rainfall (magnitude/phase) is controlled mainly by the presence of the three branches of the Andes, splitting the country into five distinctive hydroclimatic and ecological regions, namely: Caribbean, Andean, Pacific, Orinoco and Amazon (Eslava, 1993; Poveda et al., 2006; Alvarez et al., 2011; Urrea et al., 2019). Diverse mechanisms and processes contribute to explain the temporal variability of climate and related variables such as rainfall; e.g. the annual variability is not only controlled by the meridional oscillation of the Intertropical Convergence Zone (ITCZ), but by its interactions with low-level jets and aerial rivers (Poveda et al., 2006; 2014) , while the inter-annual variability is mainly determined by the two phases of El Niño-Southern Oscillation (ENSO): El Niño (warm phase) and La Niña (cold phase), through ocean-land-atmosphere interactions and atmospheric teleconnections, regional low-level jets, and land-surface atmosphere feedbacks and moisture recycling (Bedoya-Soto et al., 2018, 2019, 2019a; Poveda et al., 2005, 2006, 2020; Cai et al., 2020; Builes-Jaramillo et al., 2018, 2022), discussed below.

2.1 Ocean-atmosphere interactions

Annual precipitation in the Andean region has a bimodal distribution due to the seasonal north-south migration of the ITCZ (Espinoza et al., 2020; Arias et al., 2021). At decadal, centennial, and millennial scales, the ITCZ's average latitudinal position, dictated by the location of the warmer hemisphere, has been the main agent controlling the distribution and intensity of regional precipitation in northern South America (Haugh et al., 2001; Byrne et al., 2018; Cai et al., 2020).

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The latitudinal migration of the ITCZ is affected by its interaction with other climatic phenomena such as the Pacific Decadal Oscillation (PDO), ENSO, and the Atlantic Multidecadal Oscillation (AMO) (Trenberth and Hurrell 1994; Moy et al., 2002). For instance, in 2010 the ITCZ was forced to a more northward position due to a warmer than normal Tropical North Atlantic (TNA) which significantly decreased precipitation in Northeast Brazil, triggering droughts and affecting moisture storage in the Amazon Basin (Builes et al., 2018; Marengo and Espinoza, 2016; Cai et al., 2019-2020).

ENSO is the most important phenomena inducing climate anomalies at interannual timescales in northern South America (Poveda et al., 2006; Cai et al., 2020). It also affects the global climate system in several ways, but mainly through forcing modes in the Atlantic, Indian and Pacific oceans via atmospheric circulation which in turn trigger different pantropical teleconnections that finally end up modulating the amplitude, spatial structure, and evolution of warm (El Niño) and cold (La Niña) phases of ENSO (Poveda et al., 2001, 2006, 2011; Cai et al., 2019, 2020; Sulca et al., 2018; Espinoza et al., 2020). These changes from event to event known as *ENSO flavours or ENSO diversity* (Tedeschi et al., 2013; Capotondi et al., 2015; Andreoli et al., 2017; Cai et al., 2020) explain why not all ENSO events and their associated impacts are similar. These flavours are in turn affected by the interaction between ENSO and other macroclimatic phenomena such as the PDO, the IPO and the AMO, but also by the location of the main sea surface temperature (SST) anomalies over the tropical Pacific, so that the response to ENSO in a given region is different if the core of the anomaly is located in the Eastern Pacific (EP) or in the Central Pacific (CP). For instance, moisture convergence during La Niña in the Northern Andes is higher when the SST anomaly occurs in the EP than when it occurs in the CP (Cai et al., 2019, 2020). ENSO and its flavors constitute other important phenomena that affect the climate in Colombia at interannual scales. Overall, in most of Colombia, El Niño (La Niña) is generally associated with an increase (decrease) in air temperatures, and with negative (positive) rainfall anomalies (Poveda et al., 2001).

2.2 Ocean-land-atmosphere interactions

Another important source of annual rainfall variability is the interaction between the ITCZ with atmospheric rivers or diverse low-level jets (LLJs, Fig.1) (Poveda and Mesa, 1999; Poveda et al.,

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2014; Durán-Quesada et al., 2017; Espinoza et al., 2020; Gimeno et al., 2020). In Colombia these include the Chocó (over the far eastern Pacific) (Poveda et al., 2000, 2014; Arias et al., 2015; Hoyos et al., 2018; Bedoya-Soto et al., 2019a; Yepes et al., 2019; Sierra et al., 2021), the Caribbean (Poveda and Mesa, 1999; Whyte et al., 2008; Muñoz et al., 2008; Cook et al., 2010), and the Orinoco LLJs (Jimenez-Sánchez et al., 2019; Martinez et al., 2022; Builes et al., 2022), which is strongly connected with the South American LLJ (Espinoza et al., 2020).

Today, the Caribbean and the Chocó LLJs converge into the ITCZ precisely over western Colombia around 5°N (Poveda and Mesa, 2000), whereas the Orinoco LLJ is blocked and deviated to the south-east by the EC (Fig. 1). Both the Caribbean and the Chocó LLJs vary seasonally, and affect the flux of moisture to the foothills of the EC and WC (Poveda et al., 2014; Hoyos et al., 2018). During the austral summer (DJF), the ITCZ is at its southernmost position and, consequently, the Orinoco LLJ peaks (maximum winds but minimum rainfall rates) while the Chocó LLJ is weak. During the boreal summer (JJA), the ITCZ migrates to its northernmost position, and consequently the Caribbean LLJ peaks while the Orinoco LLJ weakens (minimum winds but maximum rainfall rates). During this season, and favored by a strong Caribbean LLJ located north, the Andes are showered by moisture exported from the Amazon Basin and transported by the inter-cross equatorial flows (Fig. 1) (Salas et al., 2020). The Chocó LLJ intensifies during the transit of the ITZC from its northern to its southernmost position during September-October (Poveda et al., 2020).

Moreover, local precipitation is affected by the interaction of the aforementioned LLJs, the tropical easterlies and the complex orography of the Colombian Andes (Trojer, 1959; López and Howell, 1966; Poveda et al., 2005; Giovannettone and Barros, 2009; Posada-Marín et al., 2018; Bedoya-Soto et al., 2019a; Espinoza et al., 2020). For instance, the rainiest places in Colombia such as the foothills of the western slope of the WC and the eastern slopes of the EC and CC are commonly associated with the blocking of moisture carried by LLJs and synoptic disturbances with the Andes (Poveda 2000; Poveda et al., 2014; Espinoza et al., 2020). The fate of the atmospheric moisture transported by the Chocó LLJ is western Colombia including the WC's foothills, however when it is as its peak, is transports moisture inland crossing the WC (Poveda et al., 2014; Gimeno et al., 2020). Conversely, the fate of the atmospheric moisture carried by the

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Orinoco LLJs and the Easterlies is the eastern flank of the EC. All this implies that seasonal precipitation on EC and WC is affected in multiple ways.

2.3 Land-atmosphere

Moisture generated over land is recycled vertically through evapotranspiration-precipitation fluxes and horizontally through advected cascades that connect with the vertical ones (Zemp et al., 2014, 2017). For instance, the Magdalena River valley that divides the EC and CC (Fig. 1), is an important source of moisture from evaporation to higher sites on these cordilleras (Hoyos et al., 2018; Bedoya-Soto et al., 2019a; Escobar et al., 2022).

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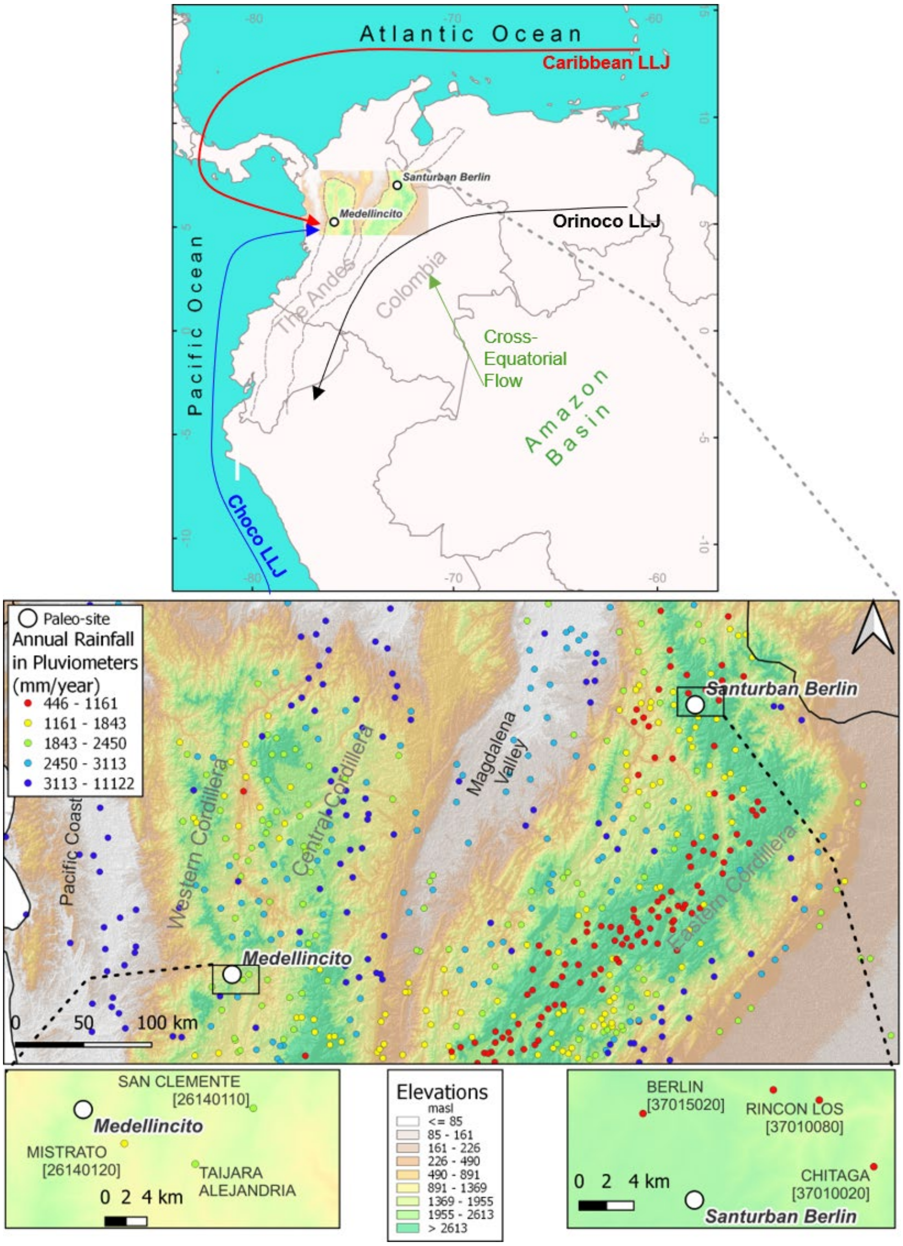

Figure 1. Colombia's main sources of moisture and trajectory of main LLJs. Paleo-study sites in the highlighted square (top). Detail of the shaded area showing mean annual rainfall distribution (mm/year in coloured dots) over the Andes (for the period 1976-2015) and location of the closest weather stations to the "paleo" sites (bottom).

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3.Methods

The two "paleo" environmental reconstructions are based on the record from Santurbán-Berlín (7° 6.6'N, 72° 49'W at 3,800 m asl) that covers the last 27,000 yr BP, and studied using diatoms, litho-stratigraphy and element concentrations (Patiño et al., 2020), and the record from Medellincito (5° 19'N, 75° 54'W at 2000 m asl) almost 7,000 years old interrupted by one hiatus from 3,710 to 1,560 yr BP, and analyzed using diatoms, isotope geochemistry, litho-stratigraphy and pollen (Jaramillo et al., 2021). The age models presented here are taken from the original articles (where they are discussed at length), based on Bayesian statistics of fifteen and eight ^{14}C dates for Santurbán-Berlín and Medellincito, respectively, processed through Bacon software (Blaauw and Christen, 2011). Here we present all ages as calibrated ages.

Modern hydroclimate information for the two "paleo" sites was obtained from the national rain gauge network operated by IDEAM, the Colombian Hydrological and Meteorological Institute (http://dhime.ideam.gov.co) for Mistrató and Berlín, the nearest meteorological stations to Medellincito and Santurbán-Berlín respectively (Fig. 1, Table 1). We used monthly rainfall series ranging from 1976 to 2015 and decomposed them using a Seasonal Decomposition of Time Series by Loess (STL) (Cleveland et al., 1990). The STL is based on eigenvalue and frequency response analysis. The seasonal component is the annual cycle, the trend component represents the low-frequency variability including non-stationarities, and the remainder component is the difference between seasonal and trend components (stochastic). All was computed using "R" (R Core Team, 2021).

Table 1. Information of the meteorological stations used in this study

Pluviometer Name (ID Code)	Distance to "paleo" site	Vegetation	Lat (ºN)	Lon (ºW)	Elev (m)	Source
Mistrató (26140120)	10 km Medellincito	Andean Forest	5.29425	75.872	1483	IDEAM
Berlín (37015020)	4 km, Sant.-Berlín	Paramo	7.18694	72.8686	3214	IDEAM

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The trend component associated to the interannual variability for the two stations was correlated with: (i) global SST (HADISST; https://www.metoffice.gov.uk/hadobs/hadisst/) and (ii) the Total Column of Water (TCW; extracted from the ERA5 reanalysis (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5) to elucidate the possible effects of both the Pacific and tropical North Atlantic SSTs variability on interannual and interdecadal precipitation over the two study sites, and to identify other possible agents of rainfall and moisture variability at global, regional, and local scales (Table 2). These correlations were estimated using KNMI Climate Explorer (https://climexp.knmi.nl/).

The parcel trajectory online software *traj3d* (based on the NCAR/NCEP Reanalysis I) was used for the backward tracking of the sources of air moist parcels arriving to the study sites, in a Lagrangian model. This model was obtained from the University of Melbourne Parcel Trajectory Software (http://www.cycstats.org/trajectories/trajhome.htm) and run at 700 mb for October 2010, an anomalously wet month enhanced by La Niña. A discussion of the algorithm is given by Noone and Simmonds (1999) and Barras and Simmonds (2009).

Table 2. Sources for the global climate data used

Climate Data	Period	Data Source	Reference	Source
Sea Surface Temperature (SST)	1871-2022	HADISST	MetOffice	KNMI Climate Explorer
Total Column of Water (TCW)	1950-2022	ERA5	Hersbach et al., 2020	

The wavelet transform was used to quantify the temporal variability of spectral properties of monthly rainfall time series and the temporal cross-coherence between their phases (Daubechies, 1990; Torrence and Compo, 1998). We estimate the wavelet transforms, as well as the wavelet coherence between the monthly series of rainfall at both study sites, to identify the epochs and frequencies that explain the highest portion of the variance between both series, and also their coherence, in order to identify when they were in and out of phase. For practical purposes we employed the continuous wavelet transform (CWT) (Torrence and Compo, 1998) and the cross-

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wavelet analysis (CWA) (Maraun and Kurths, 2004) that involves the wavelet cross-spectrum (WCS), which is defined as the expected value of the product of the single wavelet power spectra of both time series at a certain time, on a scale *s*. We used the Morlet complex wavelet, consisting of a plane wave modulated by a Gaussian, which provides diverse advantages with respect to other wavelets (Yi and Shu, 2012). It was implemented using *waipy*, a python package developed by Mabel C. Costa, available at https://github.com/mabelcalim/waipy, accessed on October 2, 2022.

4. Results

4.1. Study sites' modern hydroclimates controls

Today, annual rainfall in the Colombian Andes decreases from west to east, and upslope, so that mid altitude sites on the WC such as Medellincito (2,000 masl) are generally humid, while high elevation sites on the EC such as Santurbán-Berlín (3,800 m asl) are drier (Fig. 1).

4.1.1 Annual scale of hydroclimate variability

Medellincito (Mistrató station), lies under the moisturizing-air flow of the Chocó LLJ, the recycling of moisture from the Chocó rainforest, and the interaction between the Chocó LLJ and the WC (Figs. 1,2) (Jaramillo et al., 2021). The annual cycle of rainfall is bimodal with two humid (Apr-May and Oct-Nov) and two drier periods (Jun-Jul-Aug and Dec-Jan-Feb) following the seasonal trajectory of the ITCZ (Poveda et al., 2014). This annual cycle ranges between 75 and 180 mm/month with an annual mean rainfall of 1564 mm (Fig. 2).

In the area of Santurbán-Berlín, the annual cycle of rainfall varies from unimodal, mainly in the eastern slope, to bimodal in the western slope. In Berlín station, close to the watershed divide, the annual cycle is specifically bimodal with 696 mm of mean annual rainfall, with maxima during October (150 mm/month) and April (175 mm/month), and minima during January (60 mm/month) and July (100 mm/month) (Fig. 2).

Results of the wavelet spectrum of monthly rainfall series at Mistrató and Berlín (Fig. 3 a-b) indicate a much sharper and more predominant semi-annual cycle at Mistrató (WC) and a much weaker signal at the annual timescale, while in Berlín (EC), the annual cycle exhibits a stronger and broader signal that the semi-annual. The cross-power spectra among both time series (Fig. 3c)

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shows an almost non-existent coherence among both rain gauges at semi-annual and annual timescales through the study period. These results indicate that, in spite of the bimodal character of the annual cycle of precipitation at both sites they respond to different processes and mechanisms, beyond the meridional oscillation of the ITCZ over northern South America at annual and semi-annual timescales.

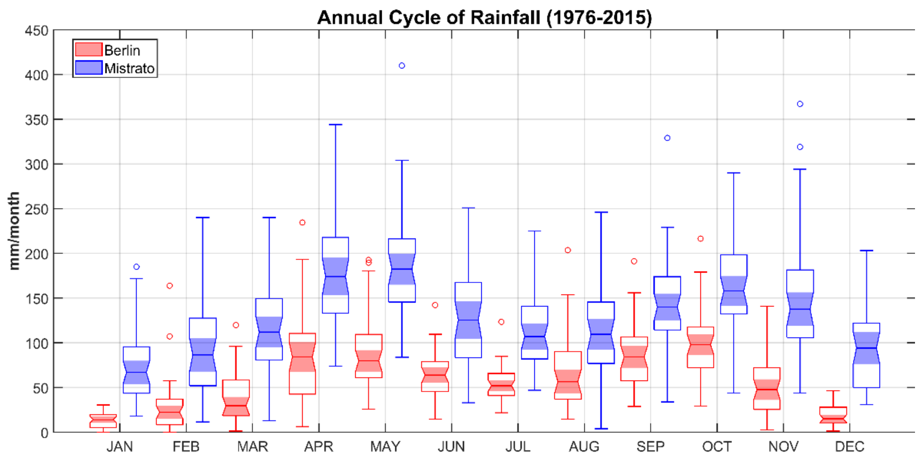

Figure 2. Long-term mean annual cycle of rainfall at Mistrató on the western Andes (blue) and Berlín on the eastern Andes (red).

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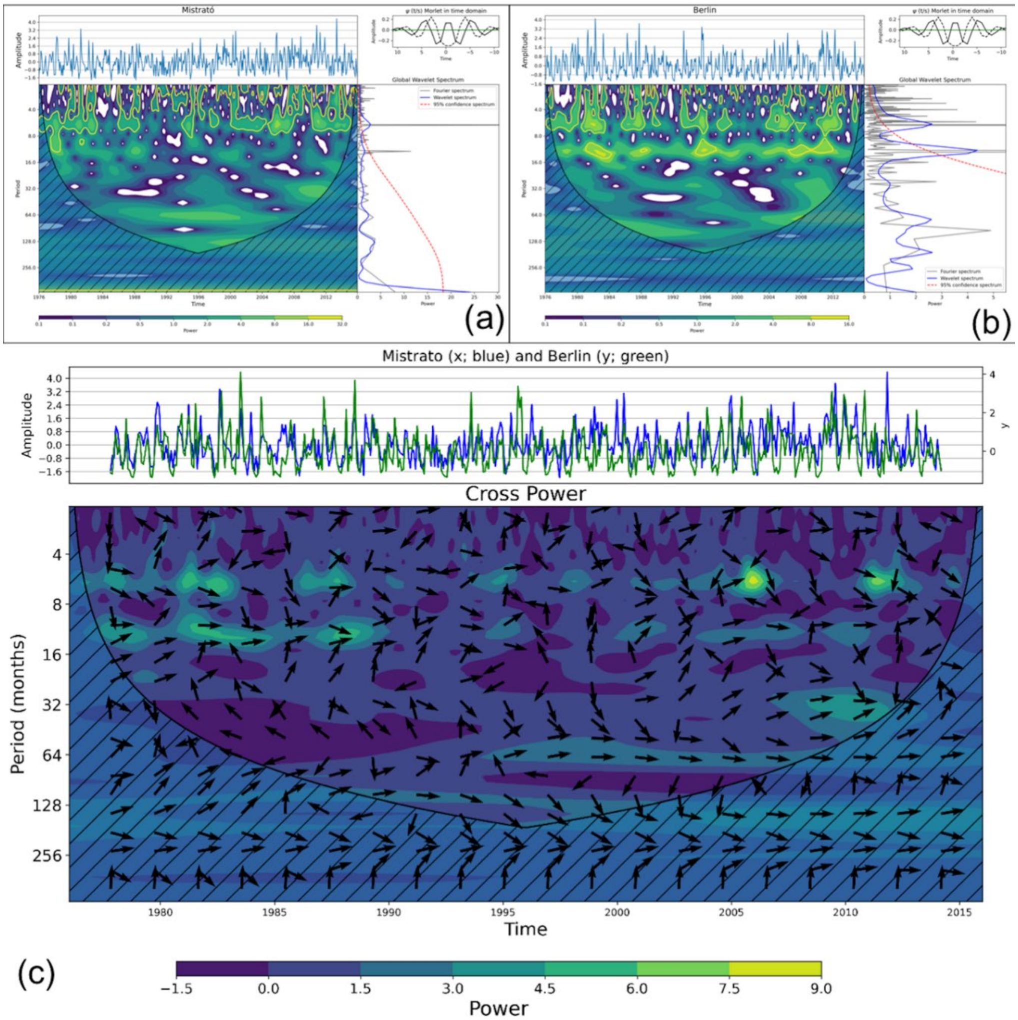

Figure 3. Wavelet spectrum of the monthly rainfall series at Mistrató on the WC (a) and Berlín over the EC (b), along with the cross-power spectra among both series (c).

4.1.2 Interannual scale of hydroclimate variability

Monthly time series were decomposed using the STL into the seasonal component, which reflects the annual cycle, the trend component, which reflects variability in precipitation at

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interannual scales, and the remainder component which is the residual after extracting the seasonal and trend components from each monthly series.

Decomposition results of precipitation series at Mistrató located on the western Andes are presented in Fig S1 (Supplementary Information). Correlations between the trend component with global SSTs (Fig. 4 A, C) and TCW (Fig. 4 B, D) show that during June-July-August, the trend component is negatively correlated with SSTs over the Central TP ($r < -0.6$, $p > 0.05$) and positively correlated with SSTs over the TNA ($r > 0.6$, $p > 0.05$, Fig 4A). This means that El Niño-like warm waters in the TP (TNA) are associated with a decrease (increase) in precipitation at Mistrató (Berlín). Correlations with the TCW depict zonal and meridional moisture flows coming from the TP, TNA, and a cross-equatorial moisture flow coming from the Amazon-Andes (Fig. 4 B, D). The latter acts via the latitudinal migrations of the South Atlantic Convergence Zone (Hu and Fedorov, 2018) (Fig. 4B).

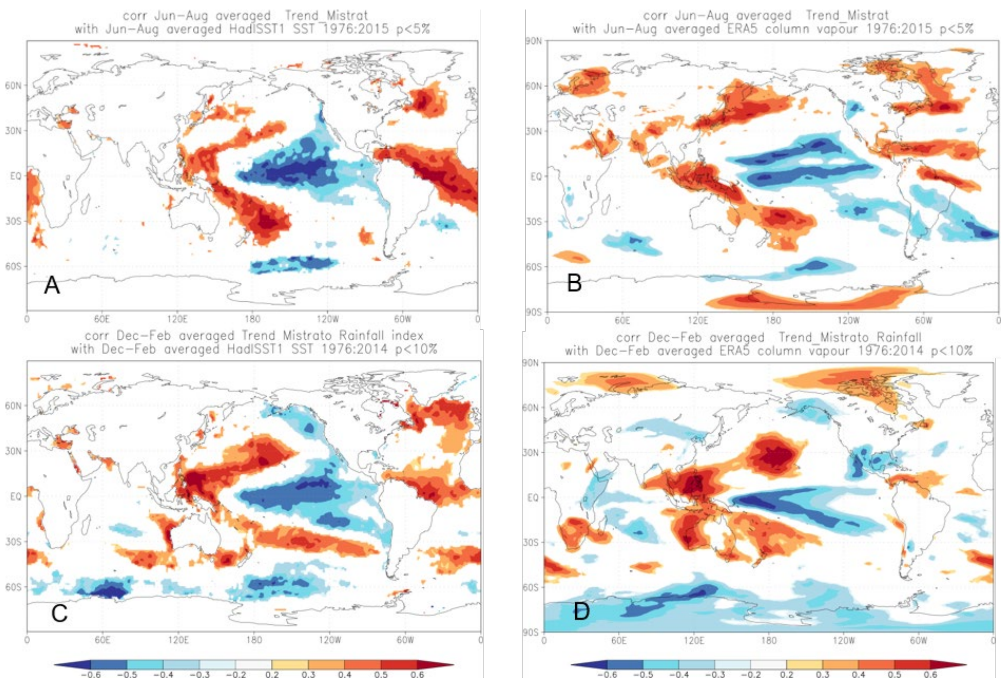

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Figure 4. Global seasonal correlation maps for Mistrató using the trend component for SSTs (HAD1SST) and TCW (ERA-5) during the boreal summer, June-August (A-B) and during the austral summer December-February (C-D)

Decomposition results of precipitation series in Berlín located over the eastern Andes are presented in Fig. S2 (Supplementary Information). Correlation analyses of the trend component with global SSTs (Fig. 5 A,C) and TCW (Fig. 5 B,D) indicate that precipitation is positively correlated with SST in the TNA, particularly during the boreal summer when the ITZC is at its the northernmost position (Fig. 5 A,B) ($r = 0.6$, $p > 0.05$). This means that when the TNA warms up interannually, precipitation in Santurbán-Berlín increases, owing to the zonal effect of available TCW which is constrained to the zonal wind flow including direct connections with the TNA region (Fig. 5B).

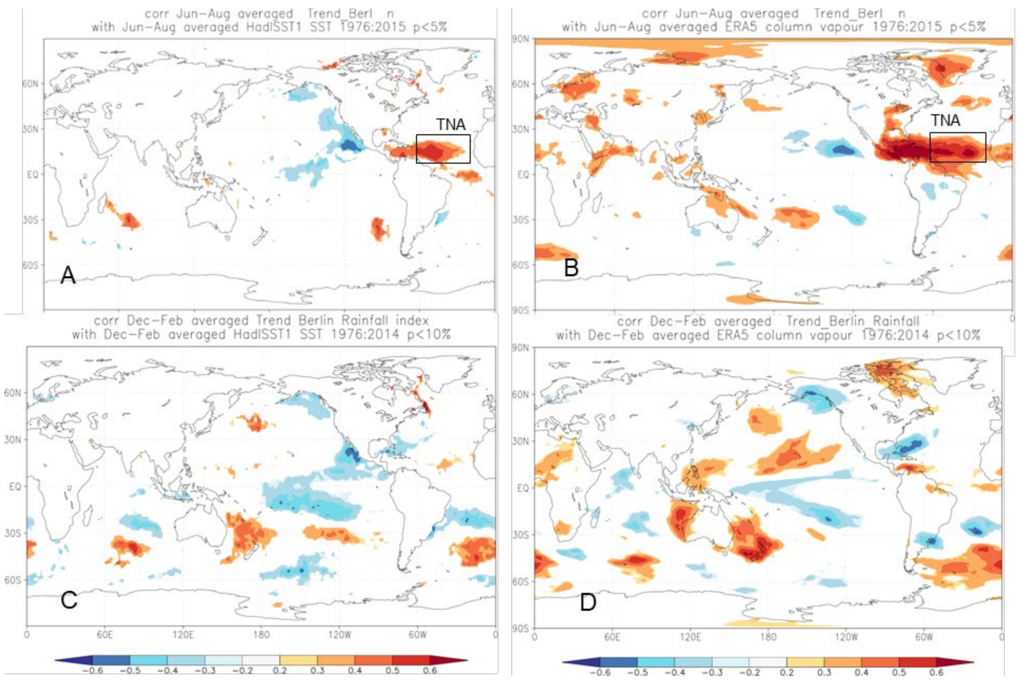

Figure 5. Seasonal correlation maps in Berlín station using the trend component for global SSTs (HAD1SST) and TCW (ERA-5) during the boreal summer, June-August (A-B) and during the austral summer, December-February (C-D)

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Results of the backward-Lagrangian tracking analysis of air parcels at 700 mb for the study sites during a humid period of the annual cycle enhanced by La Niña (October 2010) are presented in Fig. 6. Parcels ending in Berlín originated in the TNA region, traveled predominantly east-west crossing the northernmost part of continental South America before entering Colombia through the north east (Fig. 6A). Air parcels ending in Mistrató, originated in southeastern Pacific and travelled from south to north and east to west just before entering Colombia through the west (Fig. 6B). In spite that both sites are closely located and interconnected by the influence of the three ranges of the Andes, the origin of humid parcels and the physical mechanisms governing rainfall at both sites differ at seasonal and interannual timescales.

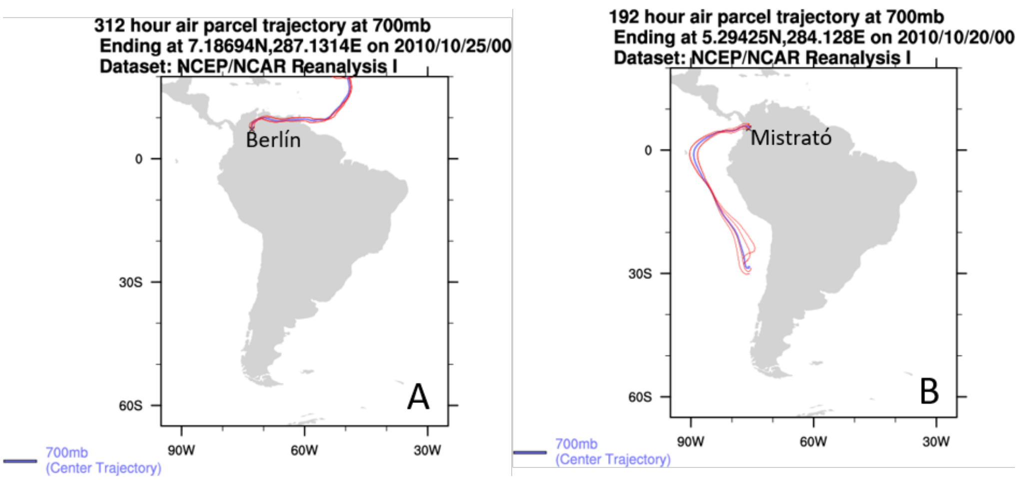

Figure 6. Backward Lagrangian air parcel-tracking during La Niña of October 2010 (an anomalous wet year), showing the different moisture sources at Berlín and Mistrató (6A and 6B, respectively). Image provided by the NOAA Physical Sciences Laboratory, Boulder Colorado from their web site at https://psl.noaa.gov/

Results of the wavelet analyses at interannual timescales are shown in Figure 7, using the standardized time series at both study sites. As expected, the wavelet spectra at both sites (Figs. 7a and 7b) no longer exhibit significant, strong and well-defined peaks at semi-annual and annual timescales, but a broader signal at interannual timescales, being weaker (stronger) at Mistrató

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(Berlín). The cross-power spectrum (not shown) among the standardized rainfall series at both rain gauges shows a rather weak coherence at interannual timescales (~64 months), but localized in time from 1998 onwards. Given that ENSO is the most important mechanism driving the hydroclimatology of these two Colombian regions, it is relevant to quantify the wavelet power spectrum of the Niño 3.4 index (Fig. 8a), one of the main indices of ENSO, and its cross-power spectra with the standardized rainfall series at Mistrató and Berlín (Figs. 8 b,c). As expected, the wavelet spectrum of the Niño 3.4 monthly series exhibits a broad-band global wavelet spectrum with a stronger signal between 28-64 months, and some other decadal timescales (~128 months). Interestingly, the global wavelet spectrum shows a sharp decrease between 64 and 168 months. The cross-spectra between El Niño 3.4 index monthly series and the standardized precipitation series at Mistrató shows an out-of-phase behavior at 32 months (1995-2015), at 64 months (1985-2005), and longer timescales during the whole study period, albeit most outside the significative cone of influence, which implies that an increase in SSTs in the Central Pacific is associated with negative rainfall anomalies at Mistrató at interannual timescales. On the other hand, the cross-spectra between El Niño 3.4 index and the monthly standardized rainfall series at Berlín (Fig. 8c) shows a coherent in-phase behavior, in particular in the frequency band spanning from 64 to 90 years, which confirms that positive interannual SST anomalies in the Central Pacific (El Niño) is associated with positive rainfall anomalies at Berlin. Similar analyses between the monthly series of the TNA and the monthly standardized rainfall series at both study sites indicate that the TNA exhibits a strong multidecadal signal around 90-100 years (Fig. 9a), and an almost constant out-of-phase association with monthly standardized rainfall at Mistrató (Fig. 9b), mainly from interannual to interdecadal (30-90 years) timescales, which also confirms that positive anomalies in the TNA index are associated with negative rainfall anomalies at Mistrató at interdecadal timescales. On the other hand, the cross-spectra between the TNA and standardized rainfall at Berlin (Fig. 9c) exhibit a coherent in-phase association, mainly at 64-yr and longer timescales, which also confirms that positive anomalies in the TNA are associated with positive anomalies at Berlín at interdecadal timescales.

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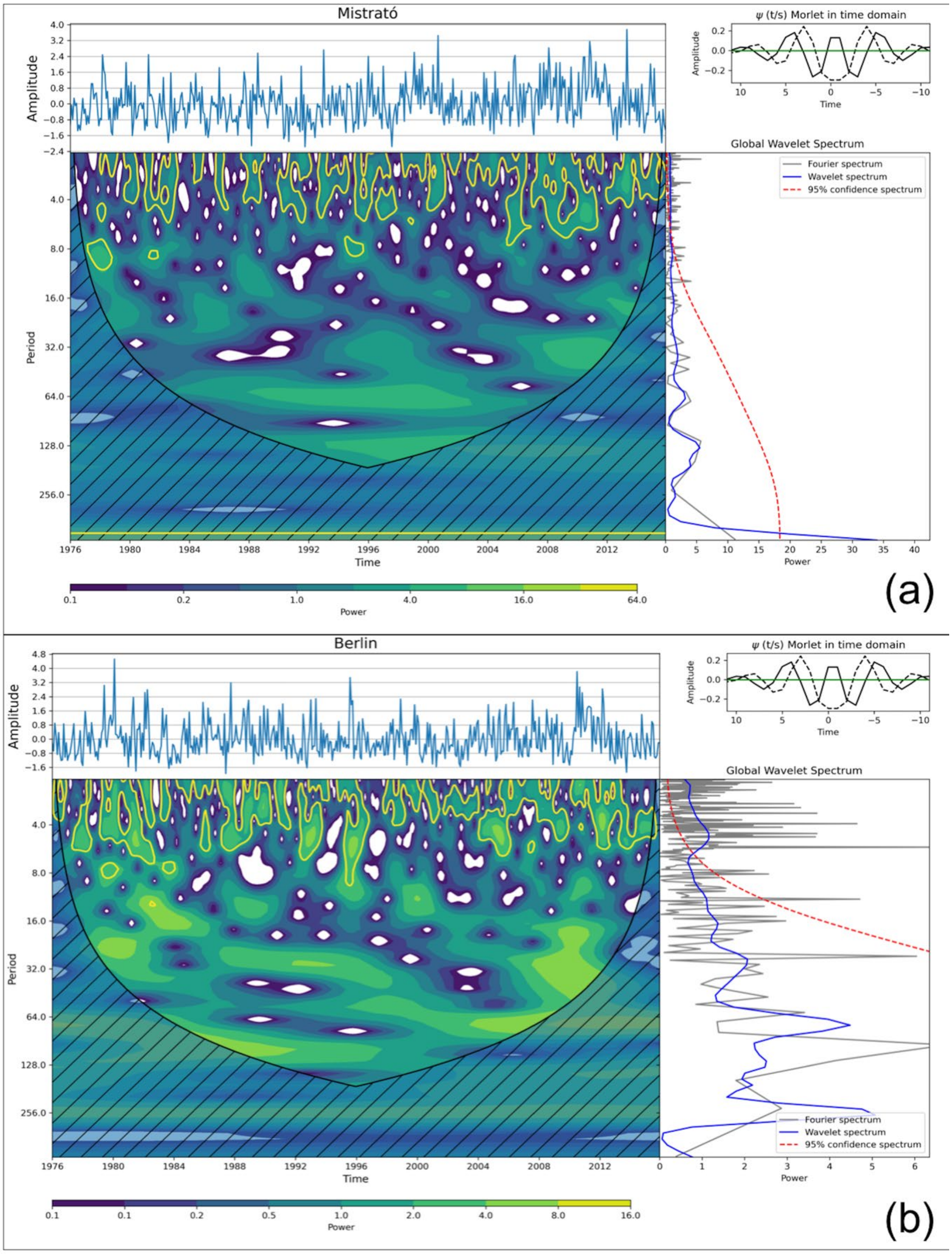

Figure 7. Wavelet spectrum of the standardized monthly rainfall series at Mistrató on the WC (a), and Berlín on the EC (b).

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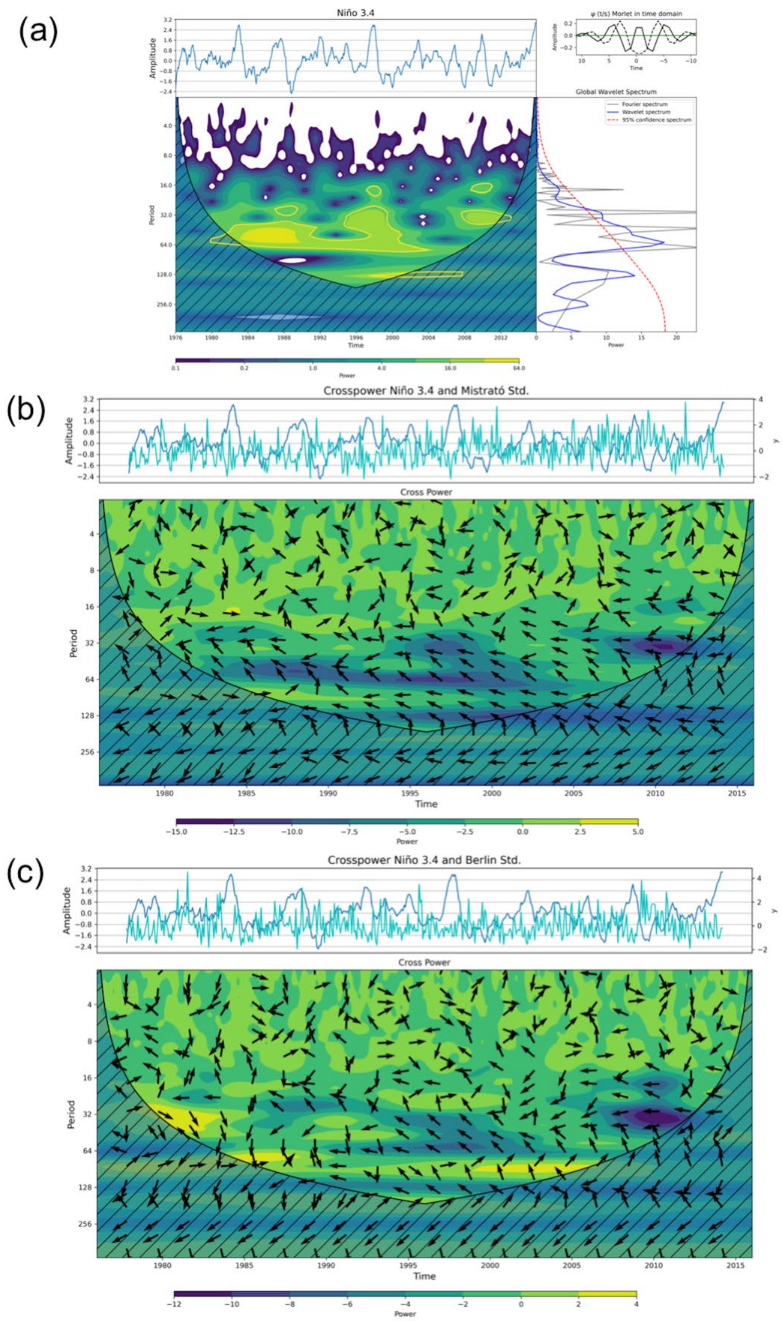

Figure 8. Wavelet spectrum of the monthly series of the Niño 3.4 index (a). Cross power spectra between the monthly series of the Niño 3.4 index and the monthly standardized rainfall series at Mistrató and Berlín, respectively (b and c).

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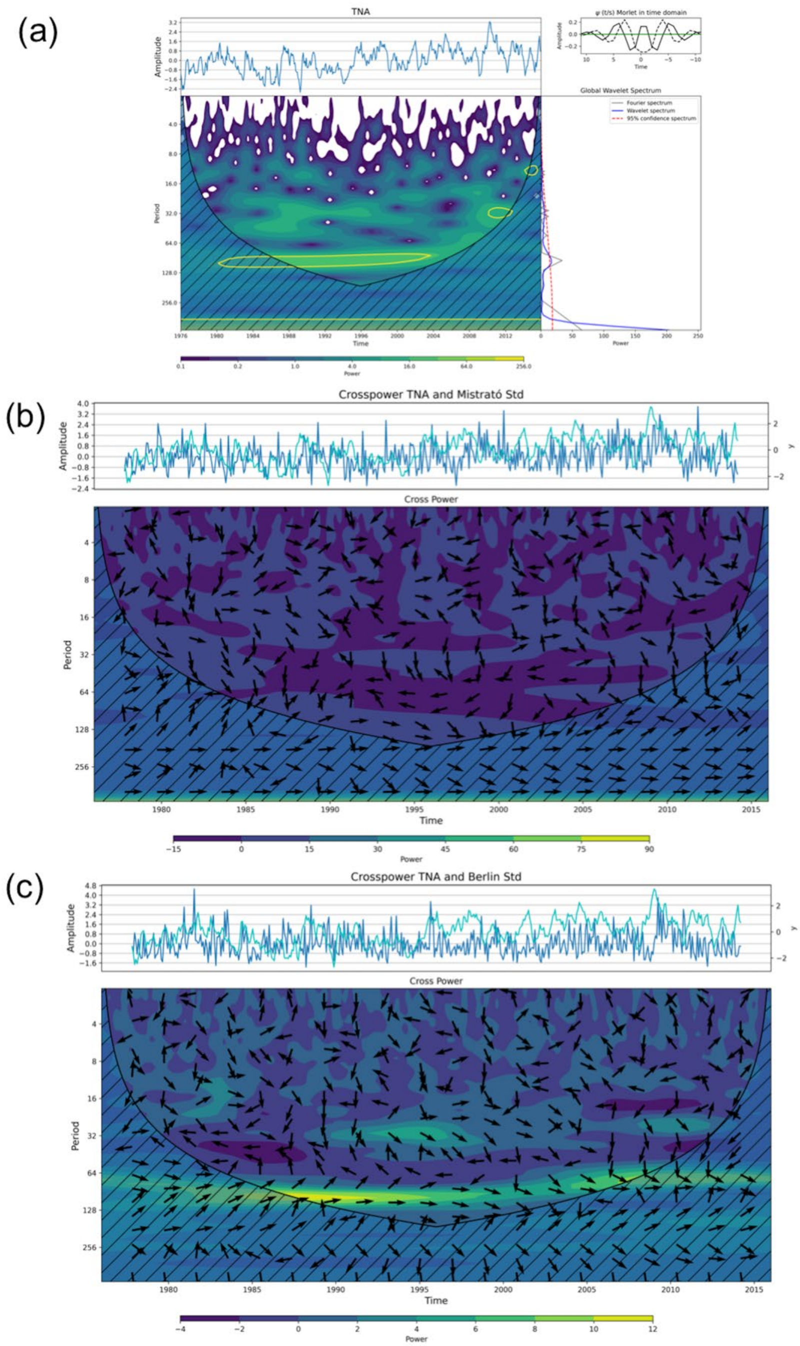

Figure 9. (a) Wavelet spectrum of the monthly series of the TNA index (a), Cross power spectra between the monthly series of the TNA index and the monthly standardized rainfall series at Mistrató and Berlín, respectively (b and c).

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4.2 Paleo-climate archives

In Santurbán-Berlín a decrease in detrital input, an increase in lake water levels and or an extension of the wetland and an increase in runoff, interpreted as an increase in precipitation and wetland productivity (Patiño et al., 2020) is dated between ~4,150 and lasted ~2,800 yr BP. This change was inferred from a sharp change in core lithology from pale silt to organic mud, a peak in *Aulacoseira* spp, a planktonic diatom previously absent from the record, and an increase in Ti:Ca (Patiño et al., 2020; Fig. 10). In Medellincito-Mistrató, a change to dry conditions was inferred from a hiatus, an increase in sand content, open vegetation, aerophil diatoms and an excursion in nitrogen and carbon isotopes (Fig. 10) between ~3700 and 1270 yr. BP (Jaramillo et al., 2021). The absence of pollen indicative of anthropogenic activity in both records indicates that these changes are non-anthropogenic and that both sites were affected by natural agents e.g. climate variability. The climate configuration of Colombia during the late Holocene, wet in the high elevations of the EC and dry in the WC, are opposite to conditions reigning today (Fig 1).

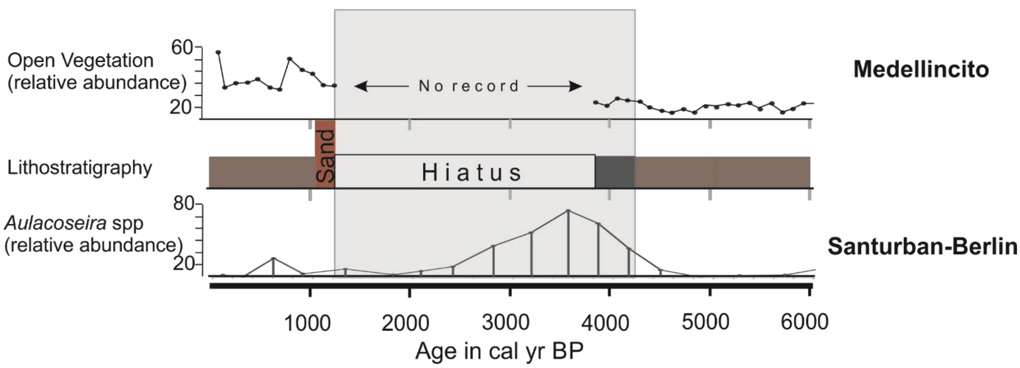

Figure 10. Records from the "paleo" sites. From bottom to top: relative proportion of planktonic diatom *Aulacoseira* spp in the record interpreted as increase in precipitation in Santurbán-Berlín. Lithostratigraphy, hiatus and relative proportion of open vegetation indicating a dry period in Medellincito-Mistrató. Shaded areas indicate the period of climate change recorded at the two sites.

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5. Discussion

Results from our analyses indicate that the SSTs and TWC in the TNA and TP have significant effects on today's precipitation in our study sites (Figs. 4 and 5). In Mistrató, decreases (increases) in precipitation are correlated with warm waters in the TP (TNA), whereas when the TNA warms up precipitation increases in Santurbán-Berlín. Our results also confirm that monthly precipitation at both sites are out of phase, and that the main sources of moisture are the TNA for Santurbán-Berlin and the tropical Pacific for Medellincito-Mistrató. Based on this, we propose that the late Holocene change in Colombia was caused by the increase in SST in the TNA and TP.

The out-of-phase character of the late Holocene climate change in both study sites is confirmed by other climate inferences. For instance, the Central Cordillera which is affected by moisture coming from the Chocó LLJ, turned dry between ca. 5,900 and 3,200 yr BP (Berrio et al., 2002), and the eastern savannas and lake La Cocha, a high-altitude lake on the southern part of EC, became more humid after about 4,000 cal yr BP (Gonzalez-Carranza et al., 2012; Hooghiemstra and Flantua, 2019). Other paleoclimatic records and climate models have also suggested that TP SSTs warmed up in the late Holocene (Seillès et al., 2016), and that ENSO events became more frequent and intensified until about 1800-1200 cal yr BP (Moy et al., 2001; Donders et al., 2008). An increase in ENSO frequency would explain the late Holocene change to dry conditions in Medellincito, but wouldn't necessarily explain the shift to wetter conditions over the eastern regions of Colombia, confirming that in addition to the TP becoming warmer, the tropical Atlantic also warmed up, as suggested by the analysis in this study. The warming of the two tropical oceans during the late Holocene is explained by ENSO flavors or the pantropical interconnections that occur during some ENSO events suggesting that in addition to ENSO intensifying, it also became more diverse. This finding is in agreement with recent climate modelling suggesting that during the late Holocene event frequency increased in the Eastern Pacific and decrease in the Central Pacific and Coastal (ENSO flavours) as a result of orbital forcing (Karamperodou and DiNezio, 2022). Today's ENSO teleconnected regions located either outside or in the tropics started to be more variable at around 5,000 (4,000 cal yr BP), including continental South America (Donders et al., 2008). The increase in ENSO's frequency and amplitude in the late Holocene is attributed to changes in Northern Hemisphere's insulation and subsequent changes in the Pacific trade winds (Moy et al., 2008) and also from extra heating of the Indo Pacific Warm Pool (Donders et al., 2008) that triggered

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cyclicity. Generally speaking, ENSO frequency increased after 5,000 yr BP, reached a peak in variability between ca. 3,000 and 1,800 yr BP (1,200 according to Donders et al., 2008) declining afterwards (Moy et al., 2001; Toth et al., 2012, 2019). The change in our records to modern like conditions after 1250 in the WC converges with this pattern (the record from the EC after 2,500 cal yr BP is of very low resolution to be able to record this change).

It has been proposed that during the late Holocene the ITCZ migrated south and maintained a more southern position (Haug et al., 2001; Seillès et al., 2016; Ledru et al., 2022). Our results confirm this as this ITCZ southern shift would have weakened or shifted south the Chocó LLJ reducing moisture in the WC (Mistrató), at the same time that it would have allowed the easterlies to enter the EC (Berlín), increasing precipitation.

In summary, modern analyses of today's precipitation series indicate that precipitation in the study sites is out-of-phase, that the sources of moisture for Berlín (Santurbán-Berlín) and Mistrató (Medellincito) originate in the TNA and the Pacific, respectively, and that interannual variability of the global sources of moisture generated in the TP and TNA modulate the amount of moisture feeding the ITCZ and thus precipitation over the Andes, that with their complex orography, end up altering further local precipitation. Hence that besides the fact that the two "paleo" sites are less than 400 km apart, and that the ITCZ governs precipitation in both sites, there are other factors that induce complexity to the system and end up altering precipitation. TNA and TP have a significant effect on today's precipitation in our study sites (Figs. 4-9).

Conclusions

Out-of-phase precipitation anomalies in the western and eastern cordilleras of the Colombian Andes during the late Holocene, can be explained by the warming of the Tropical Pacific and Tropical North Atlantic likely from an increase in ENSO and ENSO flavours events.

Given that current global warming is affecting the SST of the tropical oceans and consequently the temperature gradient between the NH and SH, there likely be consequences on the average position of the ITCZ, and precipitation distribution in the Colombian Andes, the most densely populated region of Colombia that depend on the water resources maintained by the current precipitation regimes.

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Author contribution

MIV and JMB designed the investigation. MIV supported the "paleo" component of this research. JMB and GP provided modern hydroclimate analyses. All authors contributed to the analyses and discussion of results and to the writing of the manuscript.

Competing interests

We declare no competing interests.

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