

Climate of Northwestern South America

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Summary

Northwestern South America (NWSA) hosts one of the rainiest places on Earth and a large suite of tropical ecosystems amid a complex hydroclimate. The hydroclimate patterns of NWSA span from interdecadal to diurnal and sub-diurnal variations. The annual cycle of precipitation and temperature is modulated by large-scale steady circulation patterns such as trade winds, the Intertropical Convergence Zone, and the Hadley and Walker cells. These patterns, in turn, influence regional circulations known as the Choco low-level jet (LLJ), Caribbean LLJ, Orinoco LLJ, and aerial rivers transporting energy and moisture to NWSA. Natural variability in the region is primarily introduced by modulating these steady circulation patterns, resulting in contrasting regions with monomodal and bimodal precipitation distributions. Moreover, diverse natural climate oscillations operating on different time scales play a critical role in modulating these patterns. In particular, the El Niño-Southern Oscillation, the Madden-Julian Oscillation, tropical easterly waves, and nocturnal mesoscale convective systems are especially influential. Recent research emphasizes the importance of land surface-atmosphere feedbacks and moisture recycling in elucidating spatiotemporal hydroclimatic variability. Additionally, factors such as insolation, gravity waves, slopes, anabatic and katabatic winds, topoclimates, and inertial oscillations are significant in explaining the day-to-day variability of the diurnal cycle.

Keywords: climate, hydrology, Northwest South America, spatiotemporal, multiscale

Subjects: Hydrological Cycle, Climate Systems and Climate Dynamics, Climate Impact: Extreme Events, Climate Impact: Terrestrial Ecosystems

Introduction

Northwestern South America (NWSA) constitutes a fascinating geographical setting to study the variability of weather and climate phenomena at a wide range of spatiotemporal scales. This article covers the area from the Caribbean Sea to parts of the tropical North Atlantic and the far eastern Pacific, specifically between 15°N–10°S and 90°W–50°W. Large-scale atmospheric circulation patterns operate over the region, including the Hadley and Walker cells, the Intertropical Convergence Zone, and the trade winds. Also, diverse regional-scale low-level jets (LLJ) and aerial

rivers transport large amounts of water vapor required for precipitation, such as the Caribbean (Amador, 1998; Poveda & Mesa, 1999), Choco (Poveda & Mesa, 2000; Yepes et al., 2019) and Orinoco (Jiménez-Sánchez et al., 2020; Montoya et al., 2001; Torrealba & Amador, 2010) LLJs and mid-tropospheric winds, which link the Atlantic and Pacific Oceans via the Guyanas, the Orinoco, and the Amazon river basins, across the Andes (Arraut et al., 2012; Poveda et al., 2014). The Andes traverse the western portion of the study area, generating significant topographic, climatic, and ecological gradients, which in turn, favor the development of localized wind circulation patterns, contributing to evapotranspiration, condensation, and clouds, thereby creating distinctive topoclimates (Snow, 1976). NWSA includes the world's rainiest area in western Colombia and the eastern Pacific, witnessing large Mesoscale Convective Systems, as illustrated in Figure 1. The region also includes the tropical Andes with glaciers, intra-Andean valleys, rainforests, cloud forests, and dry forests. It also encompasses the northwestern Amazon, the Colombia-Venezuela savannas (*Llanos*), and the Guyana Shield.

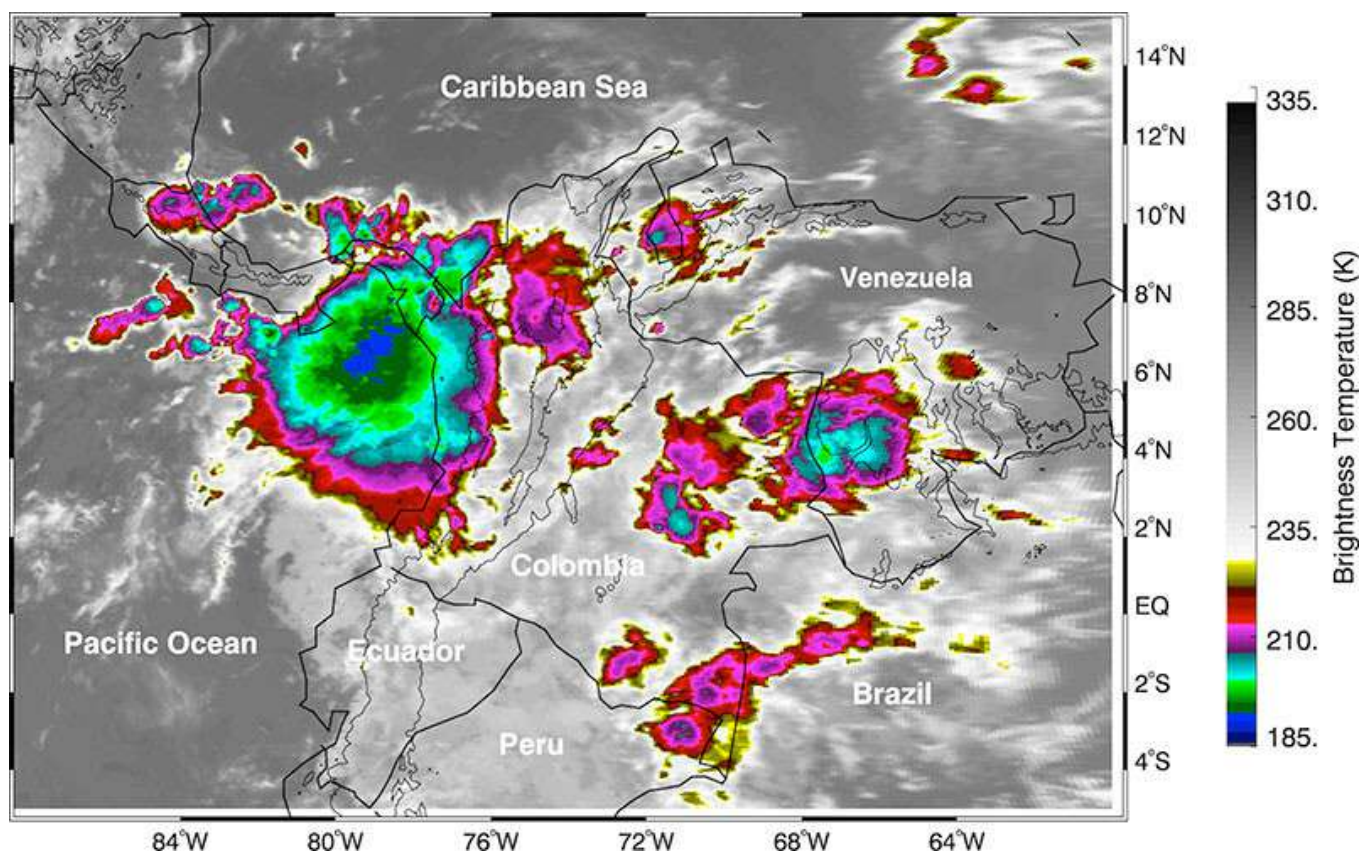


Figure 1. Satellite image of a MCS developed over western Colombia, with rainfall regions extending in Venezuela and Brazil, on August 17, 2012, at 12:00 UTC. The colors denote brightness temperature of clouds, with the most intense red/green colors denoting colder temperatures (around 200 K or -73 °C) emerging from the highest clouds.

Although paleorecords and model projections are crucial for understanding the region's past, present, and future climates, they are beyond the scope of this article and would significantly extend its length. Interested readers may refer to chapters (Arias et al., 2024) and (Flores-Aqueveque et al., 2024) of this encyclopedia.

Long-Term Mean Climatology

This section discusses the main drivers of the long-term mean annual cycle of hydroclimatic variability in NWSA, including precipitation, atmospheric moisture transport mechanisms, low-level jets (LLJs) and a shallow meridional cell, aerial rivers, soil moisture, evapotranspiration, and land surface-atmosphere feedback and river flows.

Precipitation

NWSA features diverse precipitation hot spots and gradients across coastal areas, Andean mountains, the Guiana Shield, forests, savannas, and deserts. Figure 2 depicts the 2001–2023 average seasonal precipitation recorded by NASA’s GPM satellite’s IMERG product (Huffman et al., 2019). Seasonal precipitation distribution follows the north–south movement of the Intertropical Convergence Zone (ITCZ). This leads to widespread rainfall over the Amazon in December–January–February (DJF) and March–April–May (MAM), and localized accumulation in northern South America, the Caribbean, and the Pacific during June–July–August (JJA) and September–October–November (SON). Amazon rainfall features numerous mesoscale precipitative systems with moderate convective characteristics (Cifelli et al., 2002; Nesbitt et al., 2006), akin to oceanic convection (Houze et al., 2015).

Furthermore, deep and intense precipitation systems concentrate in specific areas, notably over western Colombia and the adjacent far eastern Pacific. This region, with a mean annual rainfall of 10,000 to 13,000 mm, ranks among the world’s wettest (Poveda & Mesa, 2000; Yepes et al., 2019), peaking in JJA and reaching a minimum in DJF. These convective elements thrive due to the Pacific cross-equatorial flow, curving toward the coastal landmasses and interacting with the Andes in western Colombia (Mejía et al., 2021; Poveda, 2023; Zuluaga & Houze, 2015). Other precipitation hot spots emerge over the northwestern Amazon during MAM and the Orinoco River basin and the Guyana Shield in JJA. Additionally, significant precipitation gradients form in various inlets and piedmonts of the Andes Cordillera and the Guiana Shield. These gradients are often influenced by the latent heat released through orographically modified precipitation, which further dictates the location of convection (Espinoza et al., 2015; Gomez-Rios et al., 2023). Predictably, the world’s highest lightning activity zones lie within the tropical Andes of Colombia and Venezuela, particularly along the Catatumbo river basin en route to the Gulf of Maracaibo (Albrecht et al., 2016). This area registers a flash rate density of 233 flashes/ km² yearly, substantially impacting human and livestock mortality rates and disrupting power transmission systems.

The seasonal advance of convection during the boreal summer (June to September) in NWSA is a dynamic and complex phenomenon influenced by a variety of climatic factors. This advance is primarily driven by the northward movement of the ITCZ, where the northeast and southeast trade winds converge, causing significant convection and precipitation. As the sun reaches its northernmost point, the thermal equator shifts northward, pulling the ITCZ and the associated convective activity with it. This leads to increased rainfall, especially in coastal areas and the northern Andes of Colombia and Venezuela. In Southeastern Mid-America and Central America, the

rainy season is uniquely characterized by the so-called Mid-Summer Drought (MSD) or “veranillo” (little summer; Magaña et al., 1999). The ITCZ moves to the north during the early summer, enhancing strong convection and rainfall from May through early July. However, late July to August witnesses a strong reduction in rainfall due to the MSD. This feature has been referred to as a “drought” although it does not conform with the definition of a “meteorological drought,” as an extended anomalous precipitation deficit. This is an annual climatological feature and the term “mid-summer minimum” could be more appropriate to characterize it. This period of reduced rainfall occurs as the ITCZ shifts farther north and an eastern Pacific high-pressure system strengthens, reducing moisture transport and suppressing rainfall. Later on, rainfall resumes from late August through October as the ITCZ returns southward. Conversely, the advance and retreat of convection from the Amazon during key months is not symmetric, as the shift in convection back to the Southern Hemisphere occurs during a matter of weeks in October. Such northward shift in the position of strong convection and rainfall is critical due to the projected changes in the width of the tropical belt under different climate change scenarios (Davis et al., 2016; Mamalakis et al., 2021).

The monthly mean rainfall distribution across various locations in NWSA (Figure 3) from 2000 to 2023 mirrors the annual progression, influenced in part by the migration of the ITCZ (Urrea et al., 2019). The northernmost regions, including coastal Venezuela and the Orinoco River basin, experience peak precipitation rates from May to October, while the Guyanas see maximum rainfall from May to July. In the northern Andes of Colombia and Ecuador, as well as certain areas along the Caribbean coast of Colombia, rainfall exhibits a semi-annual pattern with double peaks in April–May and SON, and troughs in DJF and JJA, aligning with the double passage of the ITCZ. Eastern Peru’s Northern Amazonia peaks from December to April (southernmost ITCZ) and dips during July–August (northernmost ITCZ). Andean precipitation varies greatly due to local wind circulations, evapotranspiration, slopes, solar exposure, and cloud formation (Geiger, 1969; López & Howell, 1967; Posada-Marín et al., 2019; Poveda et al., 2005; Snow, 1976; Valencia, Marín, et al., 2023).

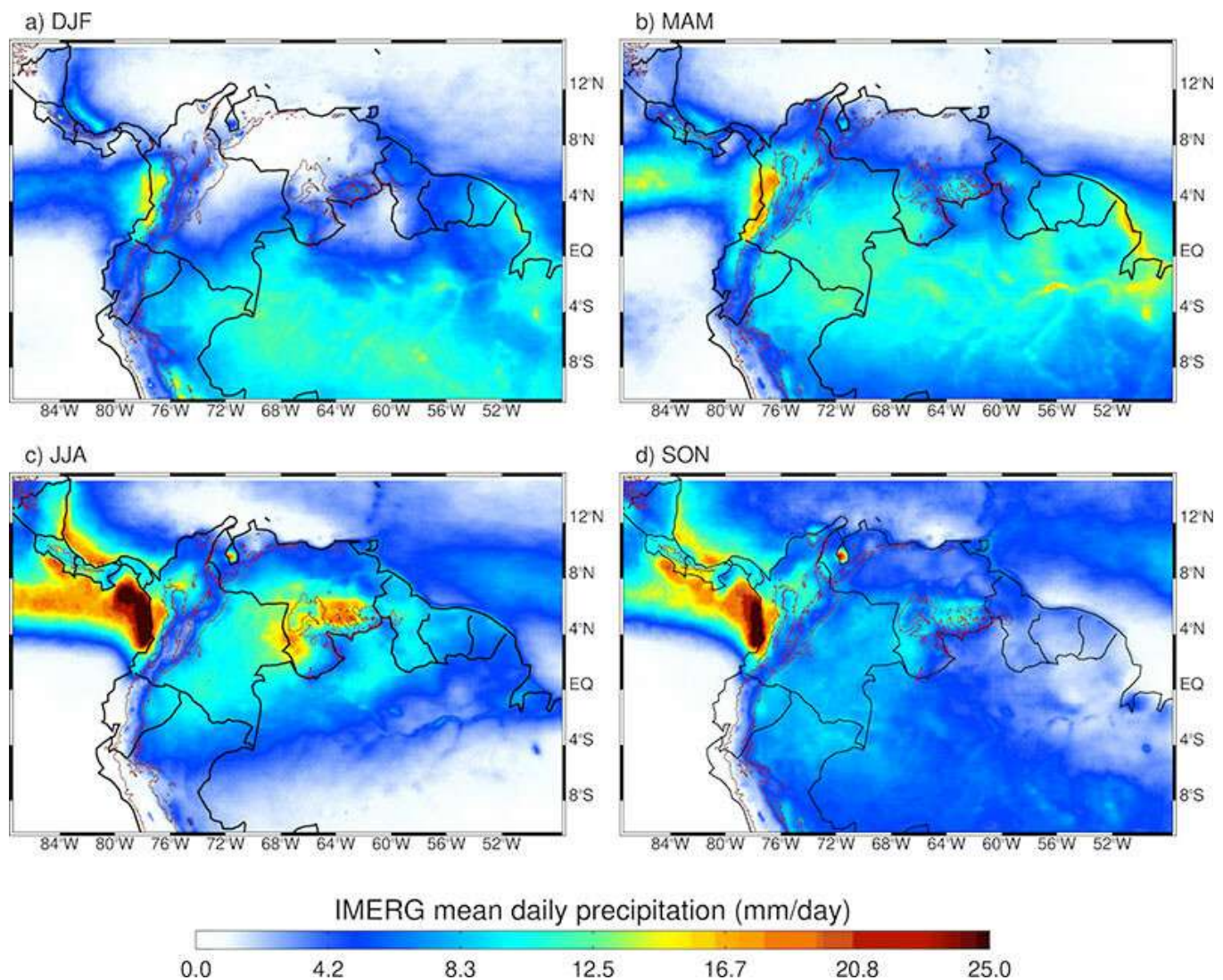


Figure 2. Long-term mean (2000–2023) annual cycle of seasonal precipitation intensity (mm/day) over NWSA. The red contour inside continental regions represents the 1000 m elevation.

Source: GPM-IMERG.

The Colombia–Venezuela *Llano*’s climate features an unpredictable transition between its savannas and the adjacent Amazon rainforest. Mean annual precipitation, usually above 1,500 mm, doesn’t reliably predict this transition, as seen in other forested regions like the Cerrado savannas in the southern Amazon. Instead, precipitation and fire frequency provide better insight into the savanna–forest transition in NWSA (Valencia et al., 2024).

The east–west orientation of the Caribbean coasts of Venezuela and the Guajira peninsula on the northernmost tip of Colombia, along with the prevailing easterlies provide a unique climatic setting. Over the Caribbean, low–level stress–induced divergence results in near–shore upwelling of cold water, leading to extremely dry conditions along the Caribbean coast (Pulwarty et al., 1992).

Venezuela displays three distinct rainfall patterns. In the central and eastern regions, precipitation follows a unimodal pattern, with a rainy season (May–November) and a dry season (November–April), mainly influenced by the ITCZ migration, easterly waves, and the North Atlantic anticyclone (Hastenrath, 1966; Tim & Bravo de Guenni, 2016), akin to Suriname (Nurmohamed & Naipal, 2006). Conversely, a bimodal distribution occurs west of the Andes and in the eastern Venezuelan highlands, with peaks in May–June and September–October, and lows in July–August and November–April, driven by the meridional migration of the ITCZ and influenced by the TNA and tropical eastern Pacific (Poveda et al., 2006; Pulwarty, Barry, Hurst, et al., 1998). A third rainfall regime in Venezuela, identified by Tim and Bravo de Guenni (2016), contrasts the coastal State of Vargas with the inland Bolivar. It features four seasons: early dry (November–January), late dry (February–April), early wet (May–July), and late wet (August–October).

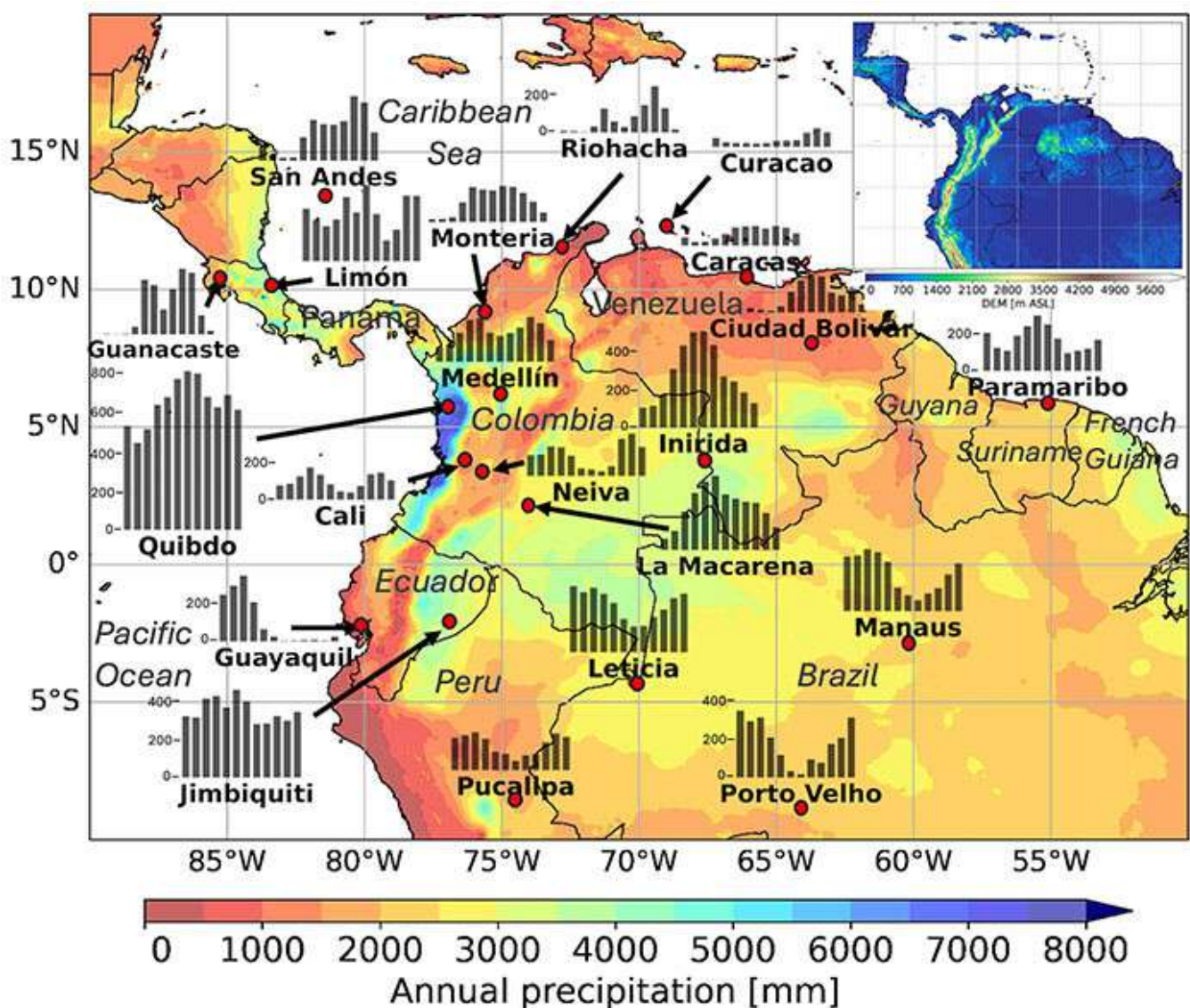


Figure 3. Long-term annual mean (1981–2023) precipitation (contours) and annual cycle of precipitation (mm/month) at selected sites in NWSA. The inset on the top right shows the topography.

Source: Climate Hazards Group InfraRed Precipitation with Station data (CHIRPSv2; Funk et al., 2014).

Atmospheric Moisture Transport

NWSA's hydroclimatology is influenced by diverse water vapor transport mechanisms from nearby oceans and continents. Studies on atmospheric moisture transport, aided by physical water vapor tracers and numerical models, have enhanced understanding of the region's climatic behavior. While various numerical models exist differing in their complexity, they are predominantly employed in NWSA studies. Some of the most used include the Dynamic Recycling Model (Dominguez et al., 2006; Martínez & Dominguez, 2014), the Quasi Isentropic Back-Trajectory model (Dirmeyer & Brubaker, 1999, 2007), the FLEXPART model (Stohl & James, 2004; Stohl et al., 2005), and the Water Accounting Model of 2 layers (WAM-2layers; Bedoya-Soto & Poveda, 2024; Posada-Marín et al., 2023; van der Ent et al., 2014). These models are usually run in offline mode, using as input the states of the atmosphere depicted by reanalysis products, or outputs from global or regional climate models. Despite differing assumptions, shortcomings, and variables, these models estimate atmospheric moisture transport and recycling (i.e., moisture originated as evaporation from the same region). Particularly in NWSA, models concur on dominant moisture sources and sinks, along with interannual variability in moisture transport over the region (e.g., Arias et al., 2015; Bedoya-Soto & Poveda, 2024; Hoyos et al., 2018; Posada-Marín et al., 2023). More recently, observational studies have provided key isotopic measurements that are broadly in agreement with numerical models in terms of the main moisture sources (Ampuero et al., 2020; Escobar et al., 2022).

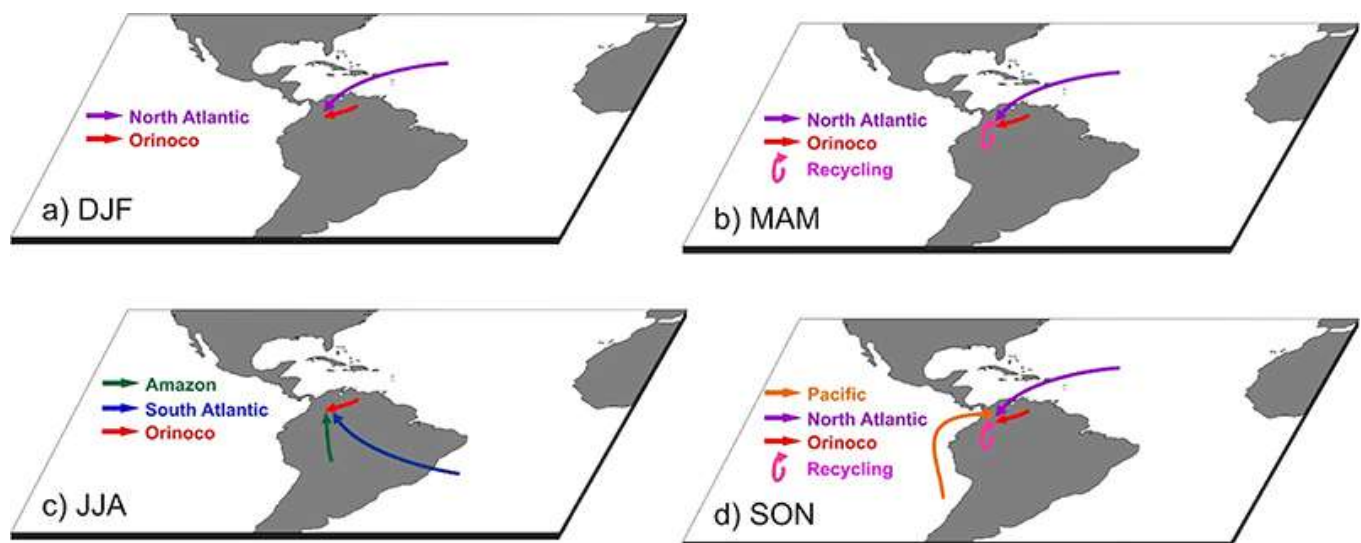


Figure 4. Main seasonal water vapor sources for NWSA.

Reanalysis and numerical models suggest the primary moisture sources for NWSA, roughly in descending order: (a) Atlantic Ocean (TNA, TSA, Caribbean Sea), contributing about 50% of precipitation; (b) continental evaporation from Orinoco, northwestern Amazon basins, and Chocó-Darien rainforest in western Colombia, plus recycling, contributing around 30% of precipitation; and (c) tropical and subtropical Pacific, with a smaller annual contribution (e.g., Arias et al., 2015; Escobar et al., 2022; Hoyos et al., 2018; Poveda & Mesa, 2000; Sakamoto et al., 2011). Numerical

model findings regarding water vapor contributions from the Amazon and Orinoco basins to NWSA are supported by isotopic measurements (Ampuero et al., 2020; Escobar et al., 2022; Posada-Marín et al., 2023).

These moisture sources show a clear-cut annual cycle, with enhanced contributions from the TNA and Orinoco sources during SON and DJF, the Pacific sources during SON, the TSA and the northern Amazon basin during JJA, and the recycling of moisture during MAM and SON (Figure 4). The transport of atmospheric moisture is largely modulated by the seasonal changes in the regional circulation, including northeasterly winds during DJF, easterly winds and activity of the ITCZ during MAM, southeasterly winds during JJA, and zonal winds, including westerly flow from the Pacific and ITCZ activity, during SON (Agudelo et al., 2019; Arias et al., 2015; Bedoya-Soto & Poveda, 2024; Gimeno et al., 2012, 2020; Hoyos et al., 2018; Molina et al., 2019; Nieto et al., 2019; Poveda & Mesa, 1999; Sakamoto et al., 2011).

Among the atmospheric patterns contributing to the annual cycle of water vapor transport in NWSA are the LLJs (Gimeno et al., 2016; Poveda & Mesa, 1999) and “aerial rivers” (Arraut et al., 2012; Poveda et al., 2014).

Land cover changes and deforestation, particularly in the Amazon basin, may also affect the region’s water vapor advection and recycling. For example, moisture recycling over the Amazon might be reduced due to deforestation (Agudelo et al., 2019; Ruiz-Vásquez et al., 2020; Ruv Lemes et al., 2023; Sampaio et al., 2021; Staal et al., 2020; Weng et al., 2018; Zemp et al., 2017). Furthermore, alterations in the regional Walker and Hadley cells associated with deforestation can lead to reductions in the contributions of water vapor from the Orinoco and Amazon basins to NWSA (Agudelo et al., 2019; Ruiz-Vásquez et al., 2020). Deforestation scenarios in the Amazon and the Guiana Shield can lead to enhanced moisture advection from the Atlantic sources to NWSA (Bovolo et al., 2018; Ruiz-Vásquez et al., 2020) and the collapse of the cascade of atmospheric moisture over the entire Amazon River basin (Zemp et al., 2017).

A Condensation-Induced Atmospheric Dynamics mechanism, known as the Biotic Pump of Atmospheric Moisture (BPM), has been proposed to elucidate the circulation of winds and rainfall over the tropical forests of South America (Makarieva & Gorshkov, 2007; Makarieva et al., 2013; Pearce, 2020). The theory proposes that forest condensation induces atmospheric dynamics, causing ascending air motions and drawing moist air from the ocean. Observational studies over tropical South America agree with some theoretical predictions of the BPM theory (Molina et al., 2019; Poveda et al., 2014), while other estimates await further research amid the previously discussed mechanisms.

Role of the Andes

The Andes play a key role in influencing rainfall patterns over NWSA. The mountains act as a significant barrier to atmospheric circulation, which results in orographic lifting as air masses are forced to rise over the terrain, leading to cooling and condensation and enhancing precipitation on the windward side. This orographic effect creates a marked contrast in rainfall distribution, with the windward slopes and adjacent lowlands receiving more rainfall, while the interior witness

significantly less, as seen over rainy regions of the Pacific coast of Colombia with respect to the western Andes, and along the piedmont of the eastern Andes of Colombia, Ecuador, and Peru. This complex topographical influence is essential for understanding regional climate dynamics, including variations in weather patterns and climate change impacts across different elevations and latitudes in the Andes (Posada-Marín et al., 2019). To enhance understanding of climate dynamics in the northern Andes, it is essential to consider the differences in vertical lapse rates between the free atmosphere and mountainous terrains (Pulwarty, Barry, & Hurst, 1998). Such differences are critical for both paleoclimate reconstructions and current climate modeling. In mountainous terrains like the Andes, the vertical temperature gradient can be significantly steeper on the mountains compared to the free air. The difference can be explained by diverse microclimatic factors such as radiation, wind exposure, evapotranspiration from intra-Andean valleys and elevation effects. Accurately accounting for these differences is key for reliable climate predictions and for understanding the complex interactions between topography and land surface-atmospheric processes, such as the low-level jets discussed in the following sections.

A key aspect is the placement of the pluviographic optimum (PO) along the slopes of the inter-Andean valleys in the tropical and sub-tropical Andes. Precipitation rises with elevation, peaking at the PO and declining higher up (Oster, 1979). Figure 5a shows the location of the PO (H^*) along the western slope of the Combeima River basin, located on the eastern slope of the central Andes of Colombia (75°W, 4°N), during 1972 and 1973. Figure 5b illustrates the location of the PO around 1,500 m at the eastern slope of the Central Andes of Colombia, and Figure 5c displays the consistent positioning of the PO at 1.5 km altitude, with relative humidity peaking around 700 hPa on the western and eastern slopes of Colombia's Central Andes, based on data from NASA's Tropical Rainfall Measuring Mission (Huffman et al., 2007).

Caribbean Low-Level Jet

The Caribbean low-level jet (CLLJ) is a maximum of easterly zonal winds (larger than 13 m/s) that is observed in the lower troposphere across the Caribbean Sea (about 925 hPa), in the region 12.5°N–17.5°N, 80°W–70°W (Figure 6). This LLJ has a semi-annual variation, having two maxima during boreal summer and winter as well as two minima during boreal fall and spring (Amador, 1998; Poveda & Mesa, 1999; Wang, 2007). The CLLJ is a prominent feature modulating the climate of the Caribbean, southern Meso-America and northernmost South America (Arias et al., 2015; Builes-Jaramillo et al., 2022a; Espinoza et al., 2020; Martin & Schumacher, 2011a; Muñoz et al., 2008; Whyte et al., 2007). Combined with other synoptic disturbances (e.g., tropical easterly waves), it is one of the main moisture sources that explain anomalous wet seasons in the region (Arias et al., 2015; Giraldo-Cárdenas et al., 2022). During dry seasons, the CLLJ has been associated with the MSD (Magaña et al., 1999) and tropical cyclones due to the increase of moisture flux divergence that suppresses the convection, decreasing rainfall, and suppressing the formation of tropical cyclones in the Caribbean region (Wang, 2007). Furthermore, the interaction between the CLLJ and the Choco LLJ (Section “Choco LLJ”) has been associated with hydroclimatic hot spots over NWSA, including the aforementioned rainiest place on Earth over the Colombian Pacific coast. Such interactions also include the Panama and Papagayo gap winds with enhanced low-level moisture supported by increased wind-driven latent heat flux that increases the offshore convergence and

vorticity to sustain convection during the days with strongly propagating precipitation (Dellaripa et al., 2023; Mejía et al., 2021; Morales et al., 2021; Poveda, 2023). Additionally, when the South American LLJ (SALLJ) northern branch is active, the extent and intensity of the CLLJ is more pronounced than during SALLJ occurrences limited to the eastern central Andes (Bovolo et al., 2018; Jones, 2019). Further research is needed to better understand the impact of other intraseasonal processes like the Rossby, Kelvin, or Mixed-Rossby Gravity waves on the CLLJ. Furthermore, additional research is required to examine the influence of other inter-annual processes such as the Pacific Decadal Oscillation, North Atlantic Oscillation, and others.

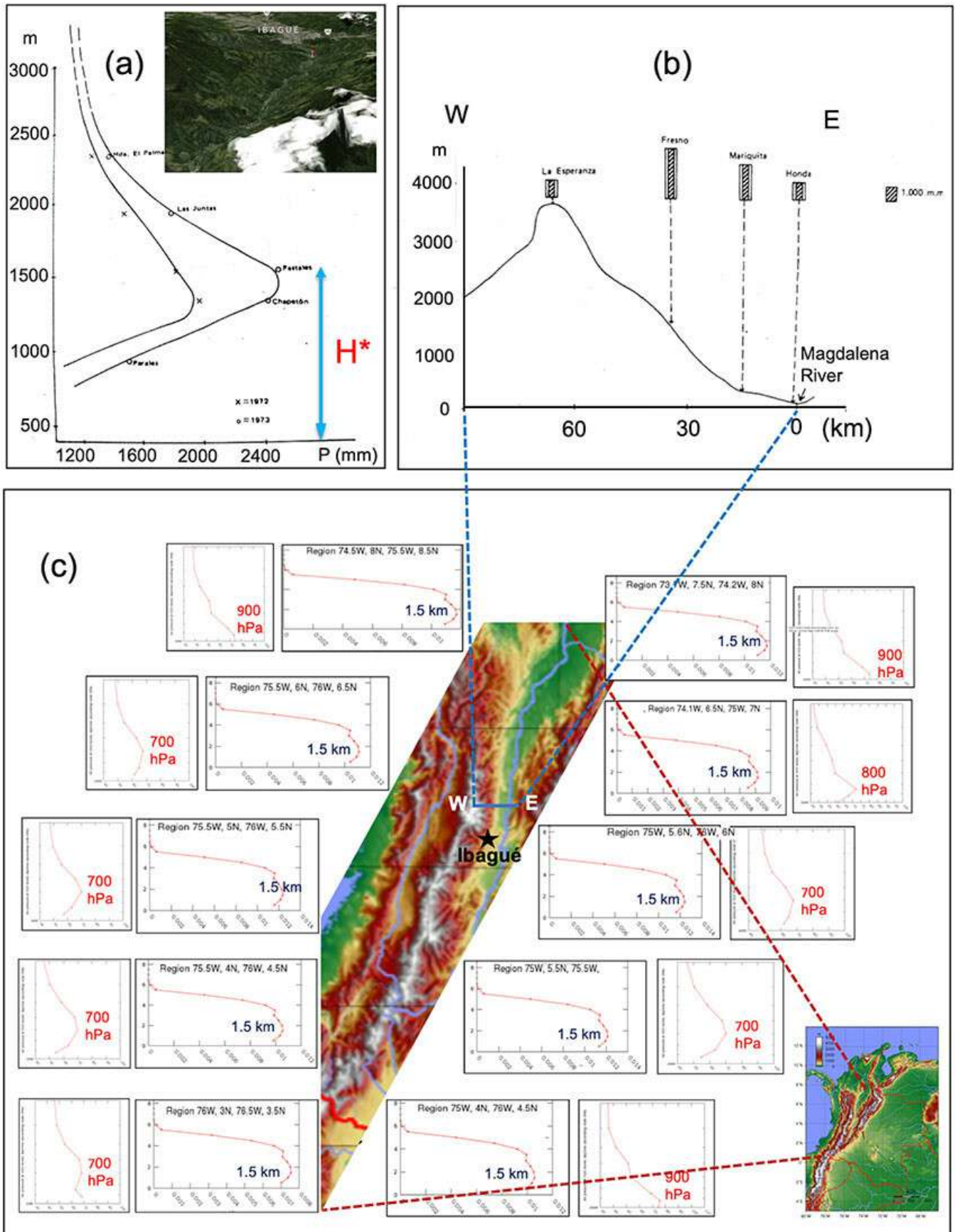


Figure 5. (a) Distribution of rainfall with elevation during 1972 and 1973 along the western slope of the Combeima River basin, located along the eastern slope of the Central range of Colombian Andes. The inset shows the Combeima River valley and the city of Ibagué, denoted with a black star on panel (c), after Google Maps. (b) Distribution of long-term mean annual rainfall with elevation and distance to the floor of the Magdalena River valley along the eastern slope of the Central Andes of Colombia around 5°N (W-E transect on panel (c)). (c) Vertical cross-sections of the long-term mean TRMM rainfall data (3A12 V7), and relative humidity from the Atmospheric Infrared Sounder (AIRS)/Advanced Microwave Sounding Unit (AMSU)/Humidity Sounder for Brazil (HSB) (AIRS for simplicity) Version 6 product (AIRX3STM v006), along diverse transects over the western and eastern slopes of the Central Andes of Colombia, with data from the satellite of the Tropical Rainfall Measuring Mission (TRMM).

Source: (a) Adapted from Oster (1979); (b) Adapted from Oster (1979); (c) Reproduced from Arias et al. (2021) with authorization.

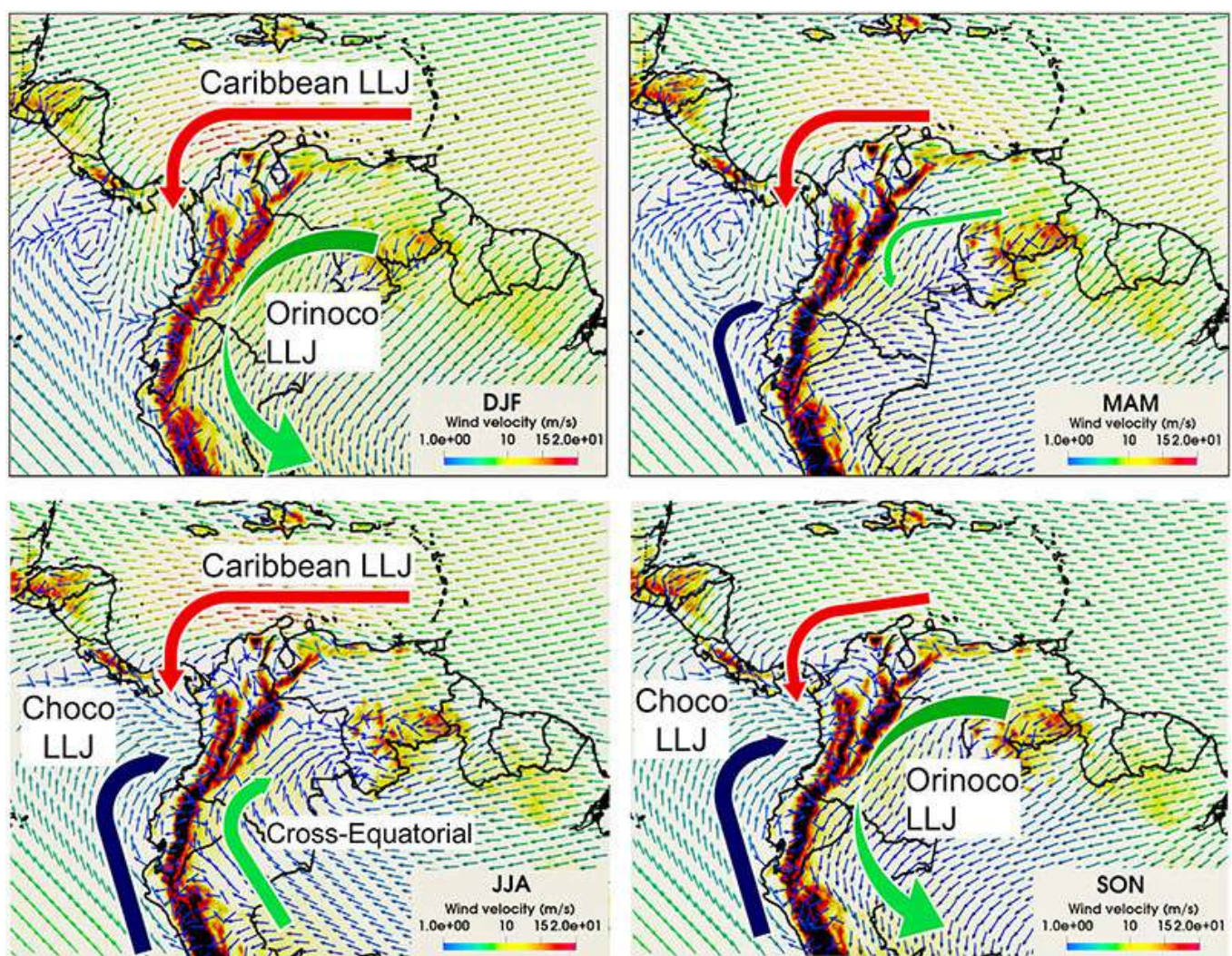


Figure 6. Long-term mean (1980–2022) annual cycle of seasonal wind velocities at 925 hPa over northwestern South America, showing the strength of the regional LLJs.

Source: ERA5 Reanalysis.

Choco LLJ

The Choco low-level jet (LLJ) is a southwesterly flow coming from the Pacific Ocean and reaching NWSA and southern Meso-America (Poveda & Mesa, 1999), with maximum winds at 925 hPa. This LLJ has been identified as one of the mechanisms responsible for the large amount of precipitation in the rainiest region of the world (Mejía et al., 2021; Poveda & Mesa, 2000; Snow, 1976; Zuluaga & Poveda, 2004; Figure 7). This LLJ arises from the difference in sea-surface temperatures between the cooler waters of the Peruvian Pacific and the warmer waters of the Colombian Pacific (Poveda, 2023; Poveda & Mesa, 2000). It has a marked annual cycle with the stronger (weaker) winds during SON (JFM) and values around 4–6 (2–3) m/s (Figure 6; Arias et al., 2015; Gallego et al., 2019; Morales et al., 2021; Poveda, 2023; Poveda et al., 2014). The Choco LLJ transports water vapor originated from regions as far south as the Chilean Pacific coast (Morales et al., 2021; Sakamoto et al., 2011; Sierra et al., 2021) reaching as far as Central America (Durán-Quesada et al., 2017; Sánchez-Murillo et al., 2020). Recently, Yepes et al. (2019) measured the wind magnitude of the Choco LLJ through inland and offshore upper-air observations during extreme seasons. Some of the most significant results show that the Choco LLJ is deeper over land while it is shallower and stronger over the ocean, showing values near those reported by diverse reanalysis in previous works (Poveda & Mesa, 2000).

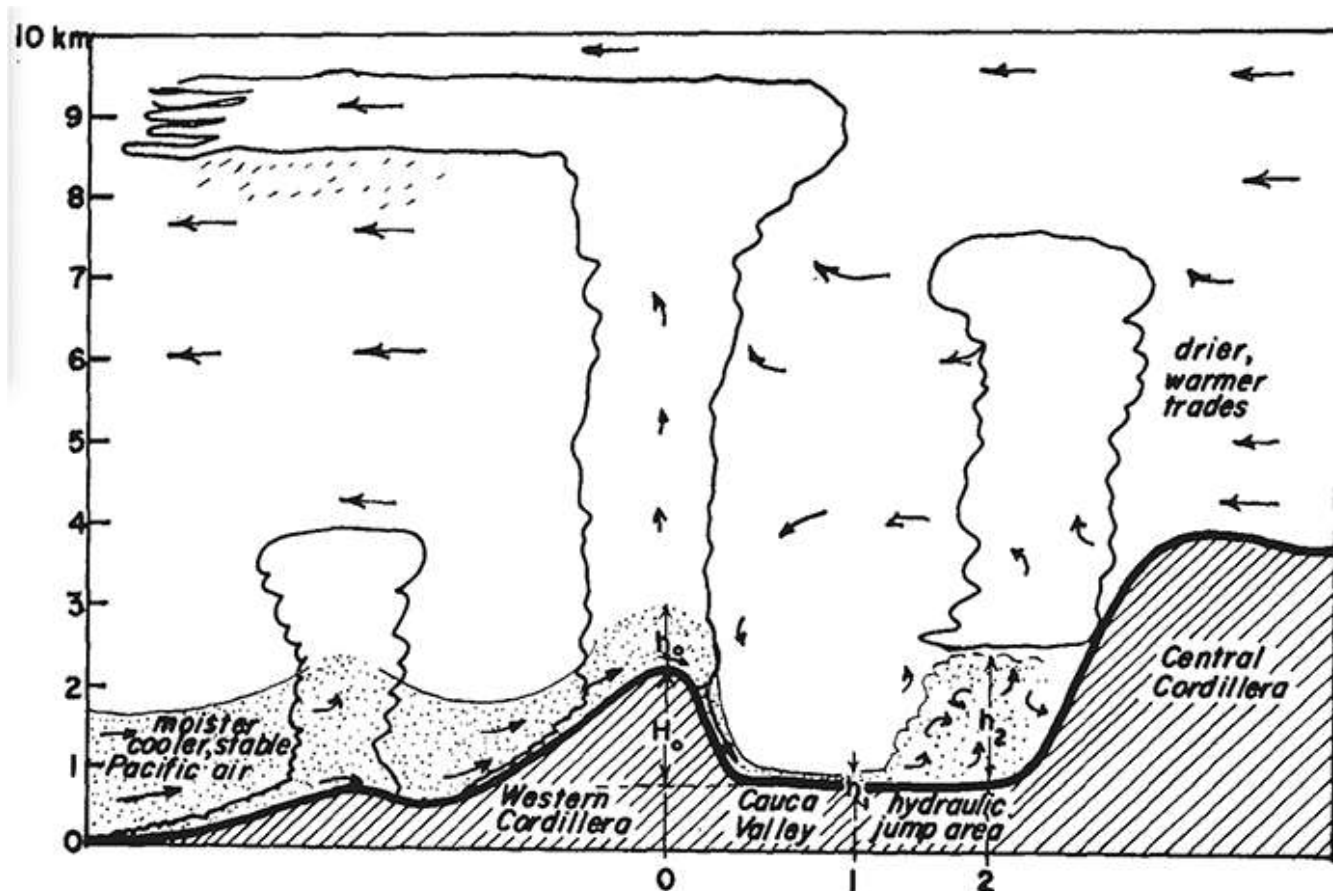


Figure 7. Schematics of the late afternoon flow around 4°N.

Source: Adapted from López and Howell (1967) with authorization.

As the Choco and the Caribbean LLJs (Amador, 2008) transport atmospheric moisture toward NWSA (Hoyos et al., 2018; Morales et al., 2021), they contribute significantly to the formation of Mesoscale Convective Systems (MCS) in the region. The occurrence of MCS over western Colombia, which represents 57% of the total precipitation (Jaramillo et al., 2017), exhibits temporal and spatial variations. Continental MCS tend to occur between 15:00 and 18:00 LST, while oceanic MCS manifest between 00:00 and 03:00 LST (Sakamoto et al., 2011). This diurnal pattern appears to be associated with gravity waves originating from the western Andes, which modulate diurnal precipitation in western Colombia (Mapes et al., 2003). However, Yepes et al. (2020), using regional model simulations, suggested that additional mechanisms related to advection and wind shear play a significant role. Furthermore, during the 2019 OTREC campaign, Valencia et al. (2024) identified the influence of tropical easterly waves in modulating this LLJ. Moreover, Sierra et al. (2021) suggested that the location of the Choco LLJ is intricately linked to the sea pressure gradient between the eastern tropical Pacific and the NWSA landmass.

A Shallow Meridional Cell Formed by the Caribbean-Panama and Choco LLJs

Poveda (2023) revealed a notable interaction between the Caribbean/Panama LLJ and the Choco LLJ when they converge over the far eastern equatorial Pacific. The warmer Panama LLJ rises over the colder Choco LLJ, forming a distinct north/south equatorial frontal system. Its intensity fluctuates annually, peaking from April to November and diminishing from December to March. This interaction gives rise to a shallow meridional circulation cell (SMC; Nolan et al., 2007), characterized by sinking motion between 6°S and the Equator, and rising motion between 5°N and 8°N, confined to the lower atmospheric levels (1,000–700 hPa). Figure 8 illustrates the long-term (1980–2022) mean seasonal cycle of the stream tubes formed by the 3D winds over the region. Notably, the vortex dynamics of the SMC enhance the convergence of the Panama LLJ and intensify deep convection. This intensification is attributed to additional orographic lifting facilitated by the Colombian Andes.

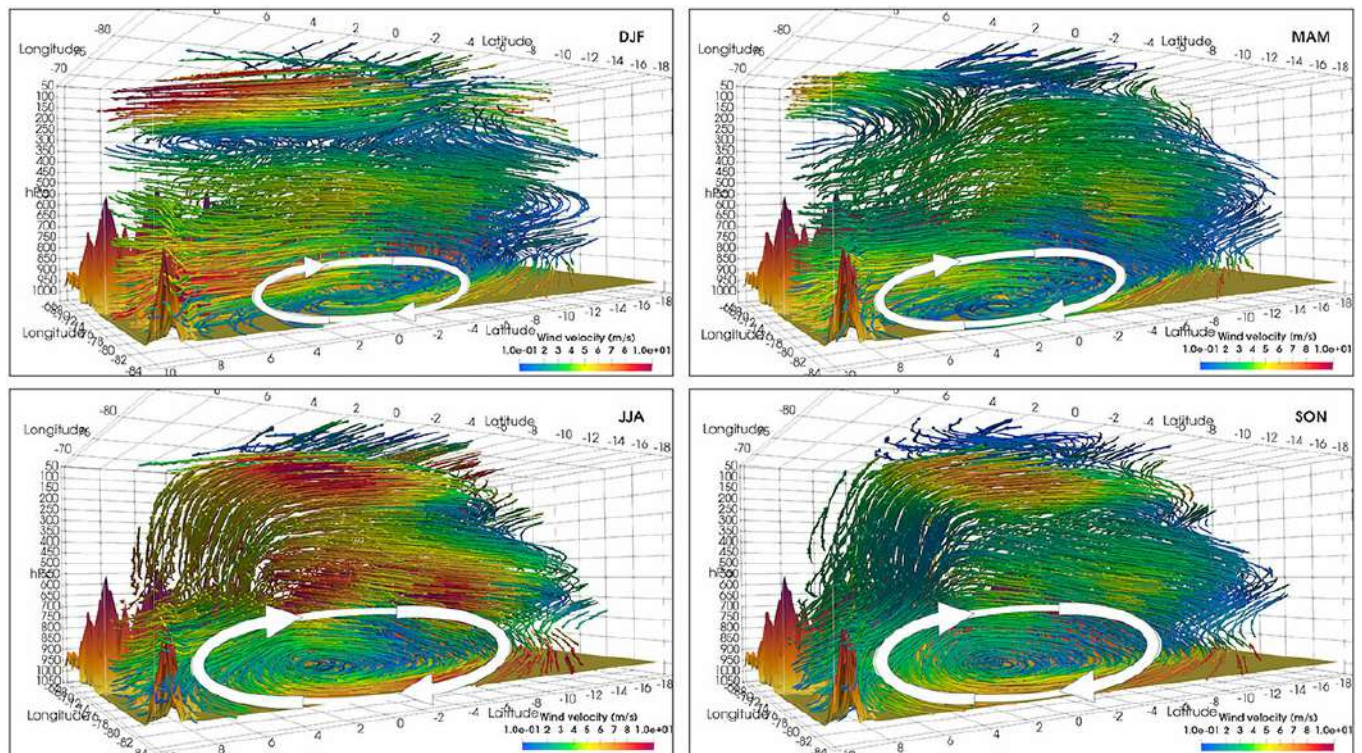


Figure 8. Long-term mean (1980–2022) seasonal cycle of the stream tubes formed by the 3D winds over the far eastern Pacific and western Colombia. White ovals denote the location and vortex movement of the shallow meridional cell between 6°S and 8°N, from 1000 hPa to 700 hPa.

Source: ERA5 Reanalysis.

Orinoco LLJ

The Orinoco LLJ (OLLJ), located east of the Andes Cordillera in the *Llanos* region of Colombia and Venezuela, was first documented in the early 21st century (Amador, 2008; Labar et al., 2005; Montoya et al., 2001; Torrealba & Amador, 2010). It originates from the interaction between the western extension of the North Atlantic Subtropical High and an anomalous low-pressure system over South America (Espinoza et al., 2020; Jiménez-Sánchez et al., 2020). Active during DJF, with peak speeds of 6–8 m/s at 950–850 hPa (Builes-Jaramillo et al., 2022a; Martínez et al., 2022; Rueda, 2014; Figure 6), the OLLJ is associated with the SALLJ, acting as its northern branch (Jones, 2019; Jones et al., 2023), and also with connections with the Amazon LLJ (Anselmo et al., 2020).

At the diurnal scale, the OLLJ attains peak speeds between 4:00 and 10:00 LST along its trajectory from 7.5°N, 64.5°W to 2°N, 73.5°W (Builes-Jaramillo et al., 2022a; Jiménez-Sánchez et al., 2020; Martínez et al., 2022). Regional model simulations indicate that pressure gradient variations induced by changes in Planetary Boundary Layer schemes drive up to a 10% alteration in cross-equatorial moisture transport, potentially resulting in a 30% increase in afternoon precipitation and a 15% rise in the overall mean in the Andes–Amazon region (Martínez et al., 2022). Days with OLLJ wind speeds below one standard deviation from the mean during DJF may lead to a 5–10 mm/day precipitation increase in the OLLJ corridor (Builes-Jaramillo et al., 2022a). At the intraseasonal scale, Jones et al. (2023) showed that the OLLJ (northern SALLJ in their study) is influenced by Rossby wave trains generating positive and negative upper troposphere geopotential height

anomalies, weakening the subtropical jet zonal wind over southern South America. Additionally, Madden–Julian Oscillation convective activity over the eastern Indian Ocean and Indonesia contributes to favoring a stronger OLLJ.

Evapotranspiration and Land-Vegetation-Atmosphere Feedbacks

Estimating evapotranspiration (ET) in South America is challenging due to its diverse landscapes—rainforests, mountains, and coastal regions—with unique land cover and topography. This heterogeneity complicates applying standardized ET estimation methods. Moreover, limited high-quality meteorological, land cover, and soil data introduce uncertainties in understanding and modeling processes. Ongoing land use changes, like deforestation and urbanization, alter surface properties, complicating their integration into ET models. Consequently, numerous regional studies compare ET estimation methodologies and quantify associated uncertainties (Carmona et al., 2021; Melo et al., 2021; Ruhoff et al., 2022; Sörensson & Ruscica, 2018). Figure 9 shows the mean seasonal cycle of ET in NWSA using data from the ERA5 reanalysis. Large seasonal variations are seen over the TNA and the Caribbean Sea (DJF and MAM), but also in the Caribbean region of Colombia (JJA) and in the Colombia–Venezuela *Llanos* and over northwest Amazonia (SON).

The influence of water bodies, abundant in the region, adds an extra layer of complexity, especially in areas like the Chocó–Darién rainforest, the Amazon river basin, and other wetlands. For example, Poveda (2023) provided evidence that oceanic (continental) evapo(transpi)ration is strongly associated with rainfall during the drier (wetter) season over the rainy hot spot of western Colombia and the neighboring Pacific. Also, Fleischmann et al. (2023) explored the interplay between climate, landscape geomorphology, soil, and vegetation, driving ET patterns in South American wetlands. The study confirmed the substantial impact of wetlands on the regional energy balance from temperate to tropical areas, emphasizing their significant role in climate regulation. Notably, wetlands in the Paraná, Iberá, Magdalena, Pantanal, and Pampas regions are identified as major contributors to water loss, moving 13%–29% more water to the atmosphere than adjacent uplands. Seasonal variation in ET differs between temperate and tropical wetlands, with the latter being more susceptible to changes in surface water availability and vegetation activity. Floodable savannas exhibit similar ET rates to nearby forests during flooding, but distinctions emerge during the dry season. The study emphasized the critical role of wetland flooding dynamics in regulating regional vegetation distribution and energy partition. A two-way feedback system operates between wetland vegetation and flooding mechanisms, with ET losses potentially serving as a regulatory feedback.

In the Central Peruvian Andes, Gutierrez et al. (2021) found that ET in the Andes is influenced by water and energy availability, with solar radiation impacting wet-season evapotranspiration and soil moisture affecting dry-season evapotranspiration. The study also evaluated the performance of empirical equations in estimating evapotranspiration and suggested the need to consider soil water content for accurate estimation during the dry season. In the Amazon river basin, Juárez et al. (2007) showed that ET in the southern Amazon region is primarily related to soil water content (water-limited), while Souza Filho et al. (2005) found that evapotranspiration in the northern Amazon region is strongly associated with variations in net radiation (energy-limited).

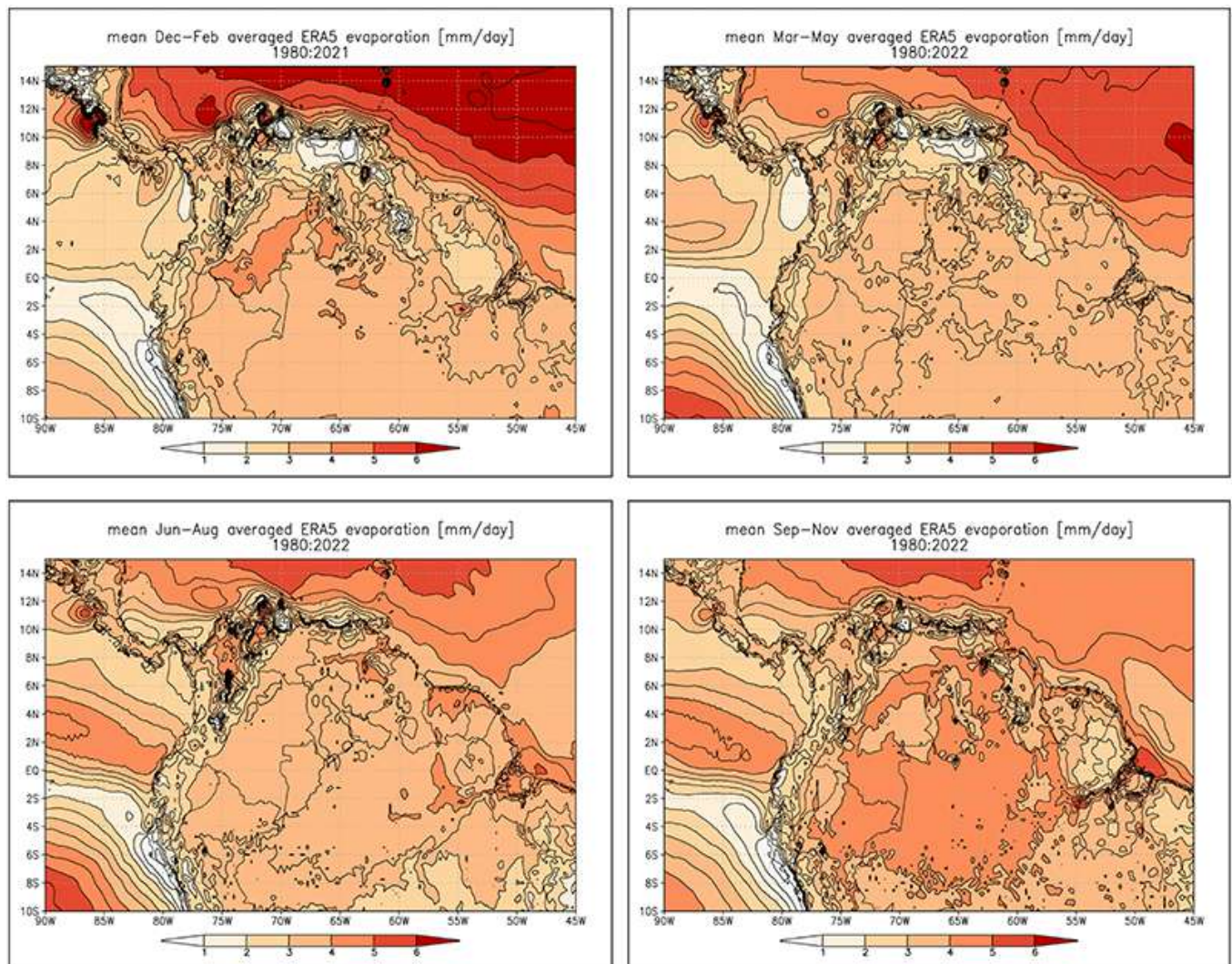


Figure 9. Long-term mean (1980–2022) seasonal cycle of evapo(transpiration).

Source: ERA5 Reanalysis.

A significant aspect of NWSA's climate is its high dependence on Land-ATmosphere Interactions (LATI), in particular Terrestrial Moisture Recycling (TMR) across various timescales, affecting precipitation patterns, soil moisture, ET, and atmospheric circulation. (Baker et al., 2021; Bedoya-Soto & Poveda, 2024; Bedoya-Soto et al., 2018; Bedoya-Soto, Aristizábal, et al., 2019; Bedoya-Soto, Poveda, et al., 2019; Posada-Marín et al., 2023). LATIs involve the exchange of water, momentum, and energy between the land surface and the atmosphere (Baker et al., 2021; Santanello et al., 2018) and they are significantly influenced by the heterogeneous conditions of land surface over NWSA. TMR, a key component of these interactions, involves the transport of moisture from land surfaces to the atmosphere through evaporation and transpiration processes (Staal et al., 2018), followed by subsequent re-deposition as precipitation (van der Ent et al., 2014). This recycling mechanism not only sustains local and regional budget water cycles across NWSA but also contributes significantly to its distribution and intensity of precipitation (Bedoya-Soto & Poveda, 2024; Enciso et al., 2022; Escobar et al., 2022; Hoyos et al., 2018, 2019). This concerns the interplay of trade winds with the Andes and the Amazon forest's role as a significant atmospheric moisture source, creating moisture

conveyor belts (aerial rivers). These LATIs transport large water volumes from the Atlantic Ocean toward the Andes and beyond, traversing the Amazon forest and enhancing the recycling mechanism (Bedoya-Soto & Poveda, 2024; Molina et al., 2019; Poveda et al., 2014; Staal et al., 2018; Zemp et al., 2014). As a result, TMR over the Amazon river basin ranges between 35% and 50% as shown in the precipitation recycling ratio, ρ_c , and more important, over the Andes it reaches values between 70% and 90% (Figure 10a and c), meaning that those percentages of precipitation in those areas originate from moisture evapotranspired on land, mainly in the upwind forests (Posada-Marín et al., 2023; Weng et al., 2018; Zemp et al., 2014). Furthermore, estimates of the continental evapotranspiration recycling ratios, ϵ_c , shown in Figure 10b and d, reach values between 30% and 70% in June–July–August–September (JJAS) and between 30% and 90% in northern South America. These percentages highlight the respective roles of evapotranspiration and transport of water vapor by the atmospheric circulation mechanisms on rainfall in NWSA, pointing out the need of an earth system’s view of the hydrologic cycle and the interconnected risks of deforestation on water resources availability.

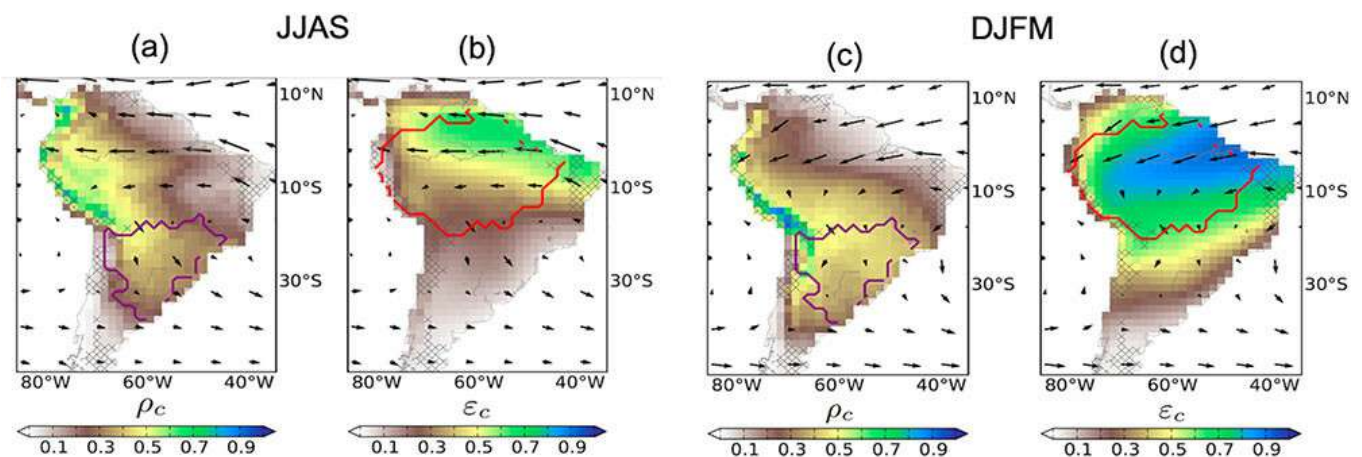


Figure 10. Dry season (left) and wet season (right) distribution of the continental precipitation recycling ratio, ρ_c (a and c); and the continental evapotranspiration recycling ratio, ϵ_c (b and d) over South America. The vectors indicate the horizontal moisture flux field (in $\text{m}^3 / (\text{m}^2 \times \text{month})$ of moisture) and the hatches represent grid cells where annual mean evapotranspiration exceeds mean annual precipitation. The red boundaries delimit the Amazon basin and the purple lines delimit the La Plata basin.

Source: Reproduced from Zemp et al. (2014) with authorization.

At smaller spatial scales over Colombia, seasonal estimates of ρ_c are between 10% and 30% (peaking on the Pacific coast), and ϵ_c between 10% and 80%, peaking over the Andean cordilleras, as shown in Figure 11 (Bedoya-Soto & Poveda, 2024). This means that the higher values of ρ_c (70%–90%) estimated for the Andes by Zemp et al. (2014; Figure 10a and c) are explained by the large-scale water vapor transported by the aerial rivers from the low-lying Amazonia to the tropical Andes. Thus, deforestation of the Amazon also threatens the security of water supply for major cities and hundreds of cities and towns located on the Andes (Poveda et al., 2014; Restrepo et al., 2014).

River Discharges

NWSA boasts mighty rivers. The Orinoco and Amazon, two of the world's largest rivers, traverse the region from Andean origins to the Atlantic Ocean (Figure 12), flowing through its major biomes: the *Llanos*' savannas and the Amazon forest. Additionally, the Magdalena and Atrato Rivers traverse Colombia's intra-Andean valleys, formed by the Andes' branches, discharging over 10,000 m^3/s into the Caribbean Sea. The Atrato River has an exceptionally high water yield, about 0.132 $\text{m}^3/\text{s}/\text{km}^2$, which is more than three times higher than that of the Amazon. As such, it is a terrestrial extension of the Choco LLJ along Colombia's Pacific coast. Combined, these four rivers (Orinoco, Amazon, Magdalena, and Atrato) have an average discharge into the ocean greater than 255,000 m^3/s , roughly equivalent to about 20% of the total discharge from rivers worldwide, estimated at 40,000 km^3/yr (Trenberth et al., 2007). These basins also contain extensive wetlands, covering about 20% of South America, the wettest continent on Earth (Wittmann et al., 2015).

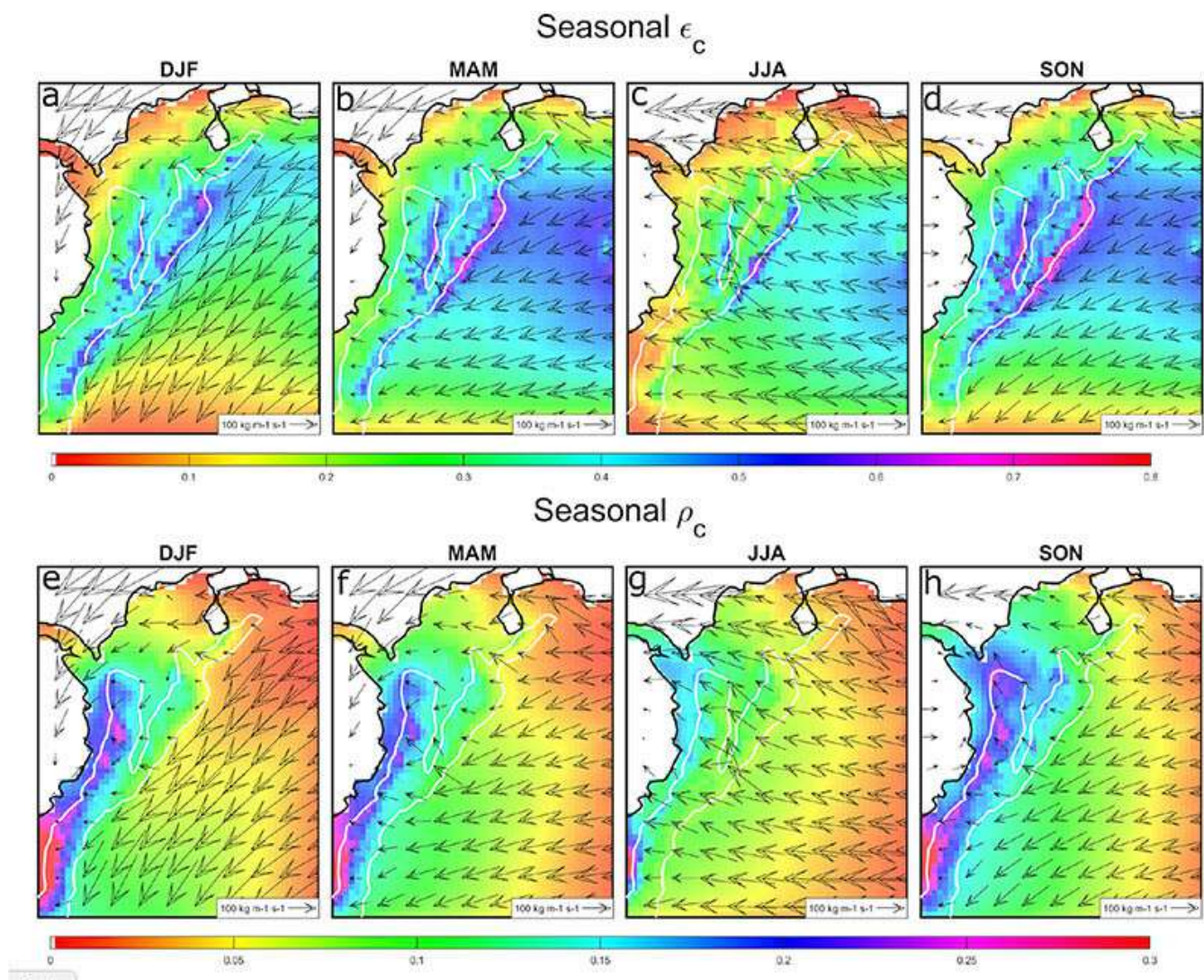


Figure 11. Seasonal distribution of (a–d) ϵ_c and (e–h) ρ_c over NWSA according to WAM-2 using ERA-5 $0.25^\circ \times 0.25^\circ$. Vectors represent the seasonal mean of VIWVF (1980–2020).

Source: Reproduced from Bedoya-Soto and Poveda (2024) with authorization.

Colombia

The Magdalena River drains toward the Caribbean sea and stands as Colombia's most vital fluvial artery, holding paramount socioeconomic significance for the country. It is also considered one of the most important sources of freshwater, sediments, and nutrients in the SW Caribbean Sea basin. Its annual cycle follows that of the rainy annual regimes over the Colombian Andes (Poveda et al., 2014; Urrea et al., 2019) with a bimodal distribution of high water in June and November and low water in February and August (Figure 12). Understanding rainfall–discharge relationships is crucial in NWSA due to heavy reliance on hydropower for electricity generation, with El Niño–Southern Oscillation serving as a major source of seasonal-to-interannual variability (Canchala et al., 2020; Córdoba-Machado et al., 2015; Frappart et al., 2015; Poveda et al., 2011, 2014; Restrepo et al., 2014; Section “El Niño–Southern Oscillation”).

Venezuela

The Orinoco River is the largest river in Venezuela and produces the third largest discharge flow in the world, with mean high waters in August (rainy season) and mean low water in March (dry season; Figure 12; Frappart et al., 2015). Over the entire Orinoco river basin, the study of Paredes-Trejo et al. (2023) found that: (a) long-term surface warming trends increase the evapotranspiration demand, aggravating drought conditions; (b) vegetation greenness remains high despite high surface temperatures, suggesting that temperature alone does not significantly affect vegetation activity and root zone water reserves; (c) a sustained rainfall deficit is necessary to cause observable changes in the vegetation and soil conditions; and (d) droughts severely impact the infiltration–percolation process, affecting the long-term recharge rate of aquifers and their ecological flow contributions. The copious streamflows of the Orinoco River have a discernible effect on fish kills and reef development in the Caribbean as a result of the flooding in the Orinoco basin (Willoughby et al., 2002).

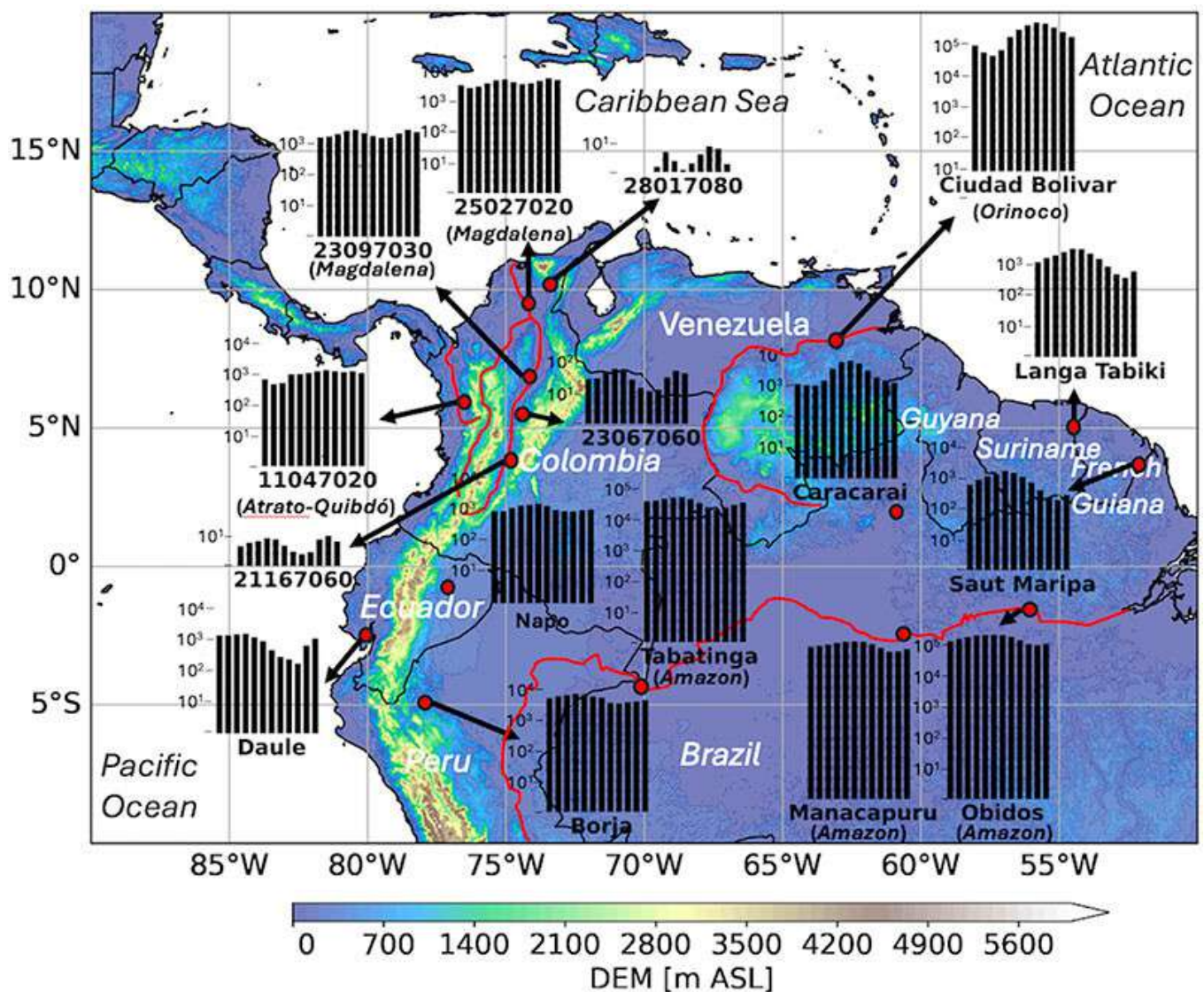


Figure 12. Long-term mean annual cycles of river discharge (y-axis in logarithmic scale— m^3/s). Red lines denote main channel rivers.

Sources: HYBAM international network (L'Observatoire de Recherche en Environnement HYBAM (Contrôles géodynamique, hydrologique et biogéochimique de l'érosion/altération et des transferts de matière dans le bassin de l'Amazonie) <<http://www.ore-hybam.org/>>; Cochonneau et al. (2006)), and Institute of Hydrology, Meteorology and Environmental Studies of Colombia (IDEAM); Monthly discharge for Daule River in Ecuador was adapted from Barrera Crespo et al. (2019).

Ecuador

The mean annual cycle of river discharge in Ecuador exhibits distinct seasonality, particularly to the west of the Andes divide, and is predominantly influenced by seasonal rainfall patterns. Elevated flow discharge levels characterize the wet season (November–May), while a notable dry season occurs from June to November. Illustrating this pattern is the Daule River (Figure 12), serving as the primary tributary of the tidal Guayas River, which feeds into the largest estuary on the Pacific coast of South America. To the east of the Andes divide, drainage is directed toward the Amazon basin, with discharge regimes closely mirroring the regional rainfall patterns (Laraque et al., 2007). The

melting of glaciers and snowpack in the Andes further contributes to water flow into river systems on both sides of the Andes. These augmented flow rates play a vital role in sustaining ecosystems, supporting agriculture, and facilitating hydroelectric power generation across the country.

Andes-Orinoco-Amazon Two-Way Feedbacks

NWSA's hydroclimatology is significantly influenced by the interaction between the Andes Mountains and the two largest river basins in northern South America (Figure 13). The availability of surface water in the Amazon River basin (> 6.06 million km^2) and the Orinoco River basin (~ 1.06 million km^2) depends greatly on their Andean headwaters (Frappart et al., 2012; León, 2005; Marengo, 2005; Moquet et al., 2011). Approximately 50% of the water availability of both river basins originates from Andean sub-catchments. This proportion accounts for 50% of the total area in the Orinoco basin (Figure 13b) and 10% in the Amazon basin (Figure 13c), highlighting the critical role of this water source for the Amazon (Builes-Jaramillo & Poveda, 2018; Builes-Jaramillo et al., 2024). Both basins serve as primary sources of sediments, nutrients, and freshwater for the savannas, rainforests, and the Atlantic Ocean (López et al., 2012; McClain & Naiman, 2008; Meade, 2007; Mora et al., 2020), and act as aerial rivers or moisture transport pathways between the Atlantic Ocean, the continent, and the Pacific Ocean (Builes-Jaramillo, Marwan, et al., 2018; Escobar et al., 2022; Hoyos et al., 2018; Ruiz-Vásquez et al., 2020), via cross-equatorial flow and precipitation recycling (Builes-Jaramillo et al., 2022a; Martínez et al., 2022; Salas et al., 2020; Wang, 2007; Zemp et al., 2014, 2017).

The eastern slopes of the Andes experience orographic convection, leading to extreme weather events (Boers et al., 2015; Espinoza et al., 2015; Martínez et al., 2023; Poveda et al., 2020) and making them one of the primary sources of moisture for both basins (Bedoya & Ramírez, 2023; Paredes-Trejo et al., 2023). These basins support biodiversity hot spots and rainforests, and ET sustains their ecological dynamics (Bovolo et al., 2018; Nobre & Borma, 2009; Zemp et al., 2017). The annual precipitation cycle in the Orinoco and Amazon basins is primarily influenced by the Tropical North Atlantic (TNA) to the north. Both basins exhibit a distinct unimodal rainfall pattern: The Orinoco receives most of its rainfall from April to September (Builes-Jaramillo et al., 2024), while the Amazon's peak period spans from September to April (Builes-Jaramillo & Pántano, 2021). This north-south gradient aligns with moisture transport via the Orinoco LLJ (OLLJ) (Jiménez-Sánchez et al., 2020), South American LLJ (Jones et al., 2023), and Amazon LLJ (Anselmo et al., 2020), which are influenced by atmospheric processes ranging from intraseasonal easterly waves to interannual ENSO events.

Water availability is crucial for the sustainability of these ecosystems and human settlements in the face of climate change, which threatens not only moisture transport from the Andes but also the equilibrium of the Amazon and Orinoco river basins (Arias et al., 2021; Barichivich et al., 2018; Brêda et al., 2020, 2023; Builes-Jaramillo et al., 2024; Falloon & Betts, 2006; Gloor et al., 2013; Miranda et al., 2023; Vilorio et al., 2023). A drier Amazon could result in reduced precipitation and precipitation recycling, potentially tipping the equilibrium of the tropical forest toward savannization (Boers et al., 2017; Flores et al., 2024; Valencia, Salazar, et al., 2023; Zemp et al., 2017), impacting the South American Monsoon System (Bochow & Boers, 2023), increasing temperatures in the TNA (Builes-

Jaramillo, Marwan, et al., 2018), and creating a positive feedback loop with more intense wildfire seasons and droughts (Correa et al., 2024). Reduced precipitation in the Andean slopes, diminished moisture transport to Andean glaciers, drier OLLJ corridors in both directions, decreased moisture transport from the TNA, and less transport from the Amazon via cross-equatorial flow exacerbate droughts in the Orinoco basin and contribute to rainforest loss (Bovolo et al., 2018; Ciemer et al., 2020; Correa et al., 2024; Ruiz-Vásquez et al., 2024; Sorí et al., 2023).

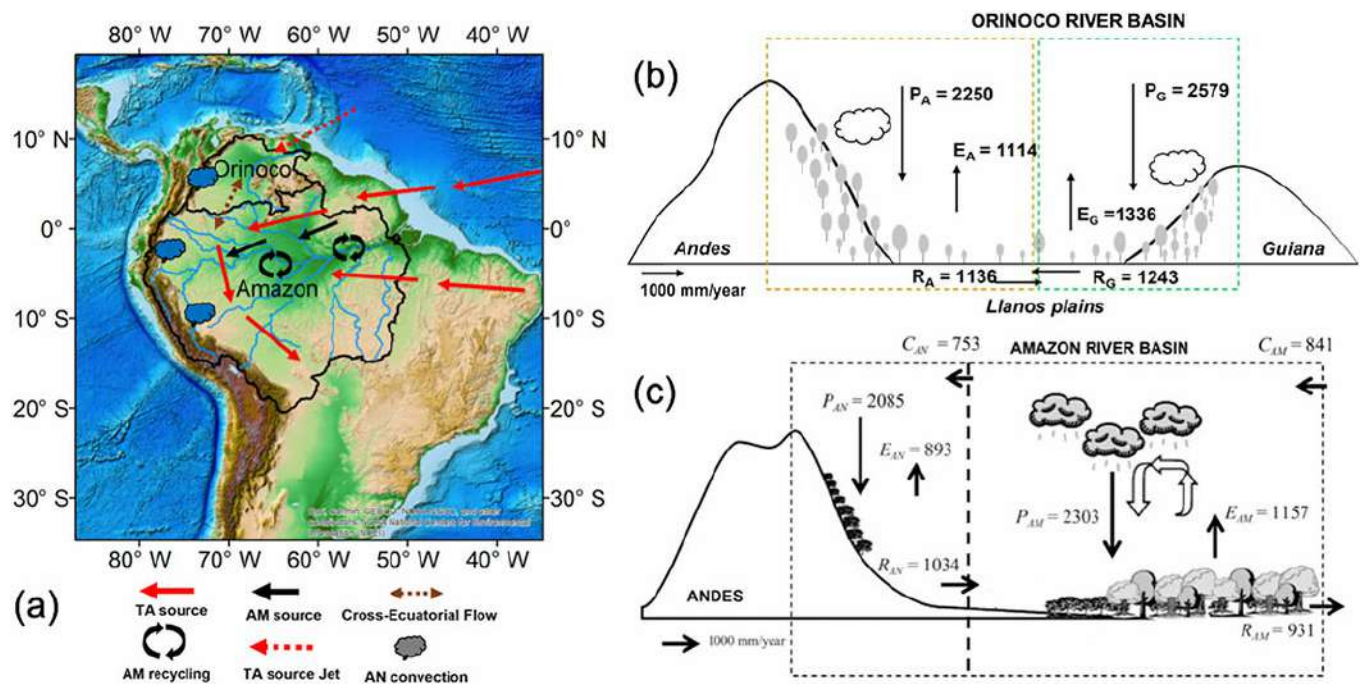


Figure 13. (a) Schematic illustration of feedbacks between the Tropical Atlantic, the Amazon and Orinoco River basins, and the Andes Cordillera. (b) Water balance over the Orinoco River basin, depicting the Andes and Guianese regions. (c) Water balance over the Amazon River basin, depicting the Andes and low-lying Amazon regions.

Source: (b) Reproduced from (Builes-Jaramillo et al., 2024) (c) Adapted from Builes-Jaramillo and Poveda (2018) with authorization from American Geophysical Union. Reprinted by permission from John Wiley and Sons.

Interannual Variability

NWSA's inter-annual hydroclimatic variability is shaped by El Niño–Southern Oscillation (ENSO), and other macro-climatic phenomena including the Pacific Decadal Oscillation (PDO), the North-Atlantic Oscillation (NAO), and the Atlantic Multidecadal Oscillation (AMO), among others (Glantz & Ramirez, 2020; Poveda et al., 2011). Understanding their influence is crucial for diagnosing, modeling, and forecasting extreme hydroclimatic events like intense storms, floods, droughts and heat waves, which have significant socioeconomic and environmental impacts (Cai et al., 2020).

El Niño-Southern Oscillation

ENSO results from the nonlinear coupling between the ocean and the atmosphere over the tropical Pacific. The warm (cold) phase or El Niño (La Niña) is characterized by an anomalous warming (cooling) of sea-surface temperatures (SST) over the central and eastern tropical Pacific (Chen et al., 2019; Timmermann et al., 2018). Furthermore, these phases accompany alterations in the Walker circulation, changes in rainfall patterns over the central-eastern Pacific, and hydroclimatic anomalies around the world (Glantz & Ramirez, 2020; Posada-Marín et al., 2023; Wang et al., 2021). ENSO interacts with many other processes across a wide range of temporal scales from diurnal to annual to multidecadal to centennial, affecting weather and climate patterns with immense socioeconomic, environmental, and ecological impacts worldwide (Glantz & Ramirez, 2020; Poveda et al., 2011). Both phases of ENSO initiate during the boreal spring (March–May) and tend to peak during the austral summer (December–February). El Niño strongly impacts weather and climate patterns in South America, but a clear understanding of its impacts and interactions is an open challenge (Cai et al., 2020).

NWSA is heavily impacted by ENSO but changes in precipitation distribution exhibit large and contrasting spatial patterns. Figure 14 (left) shows that the Oceanic Niño Index (ONI; National Oceanic and Atmospheric Administration, 2019) exhibits negative correlations with precipitation over Colombia, Venezuela, and northeastern Brazil, meaning that SST positive anomalies in the Central Pacific coincide with a decrease in precipitation, whereas positive correlations over the coasts of Peru and Ecuador are associated with an increase in precipitation. Furthermore, Figure 14 (right) shows that surface temperatures also are highly correlated with the ONI index exhibiting the highest correlations in the far-eastern Pacific and Pacific coasts of Peru, Ecuador, Colombia, and over Central America, mainly Panama and Costa Rica. In addition, according to Salas et al. (2024), the ENSO signal is phase-synchronized with inter-annual rainfall and low-level wind variability in NWSA and the far-eastern Pacific. They found consistency in the phase-synchronization between the Central and Eastern Pacific El Niño indices and hydroclimatic anomalies over oceanic and continental regions. Particularly, some areas with significant phase-synchronization do not show significant precipitation anomalies, suggesting that the influence of ENSO on tropical climatology manifests not only in terms of the magnitude of anomalies but also in terms of the phases only.

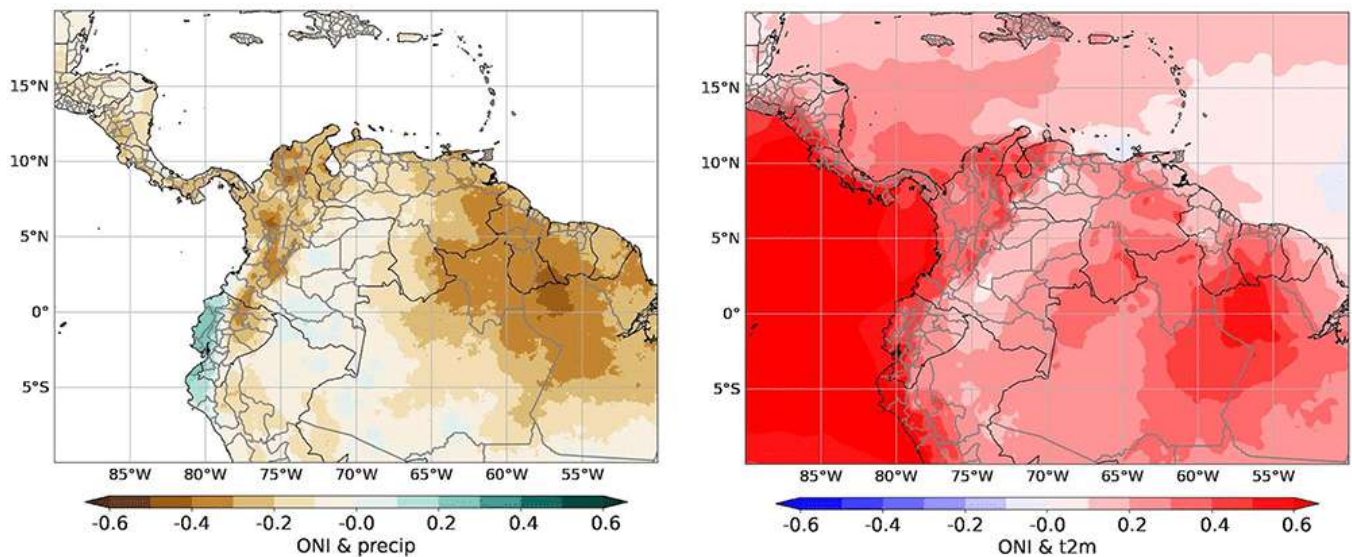


Figure 14. Regression patterns between ONI and (left) precipitation and (right) temperature over northwestern South America for the period 1979–2023.

Source: CHIRPSv2.

ENSO influences climate and weather patterns in NWSA through both long-range atmospheric teleconnections and land-vegetation-atmosphere feedbacks. During El Niño, the following mechanisms (Figure 15a) have been identified (Poveda et al., 2006): (a) A reduction of the SST gradient in the eastern Pacific weakens the Choco jet, decreasing moisture transport inland. This mechanism directly affects the hydroclimate over western and central Colombia: Positive anomalies of precipitation are observed during La Niña and negative anomalies during El Niño. In particular, the location of the Choco low-level jet (LLJ) core is intrinsically associated with the Intertropical Convergence Zone (ITCZ) location (Sierra et al., 2018); (b) Changes in atmospheric circulation mechanisms include the establishment of an anomalous Hadley cell circulation over tropical South America, particularly during December–February; (c) Changes in atmospheric pressures contribute to: (d) the displacement of the centers of convection within the ITCZ in the eastern Equatorial Pacific, shifting them west and south of their usual positions; (e) a reduction in the feedbacks between precipitation and surface convergence in tropical South America, linked to Hadley cell circulation and the Caribbean trade winds; (f) Disruption of land–atmosphere interactions occurs due to the regional coupling between anomalies in precipitation, soil moisture, vegetation, and evapotranspiration. These anomalies travel eastward over time; (g) During the boreal summer of year 0, the northeast trade wind fields intensify during El Niño and weaken during La Niña. However, with changes in surface pressures (as noted in point c), these wind fields reverse in boreal winter of year +1, leading to a shift in SSTs over the Caribbean and tropical North Atlantic; and (h) SSTs and the strength of the trade winds play critical roles in controlling the intensity of tropical easterly waves and tropical storms over the North Atlantic and Caribbean. Also, during El Niño, reduced moisture transport from the Tropical North Pacific leads to drier conditions, disrupting precipitation patterns in teleconnected regions. The weakening of regional circulation, including shifts in the Hadley and Walker cells, promotes subsidence and suppresses convection, which reduces precipitation despite the availability of moisture (see Figure 15b2).

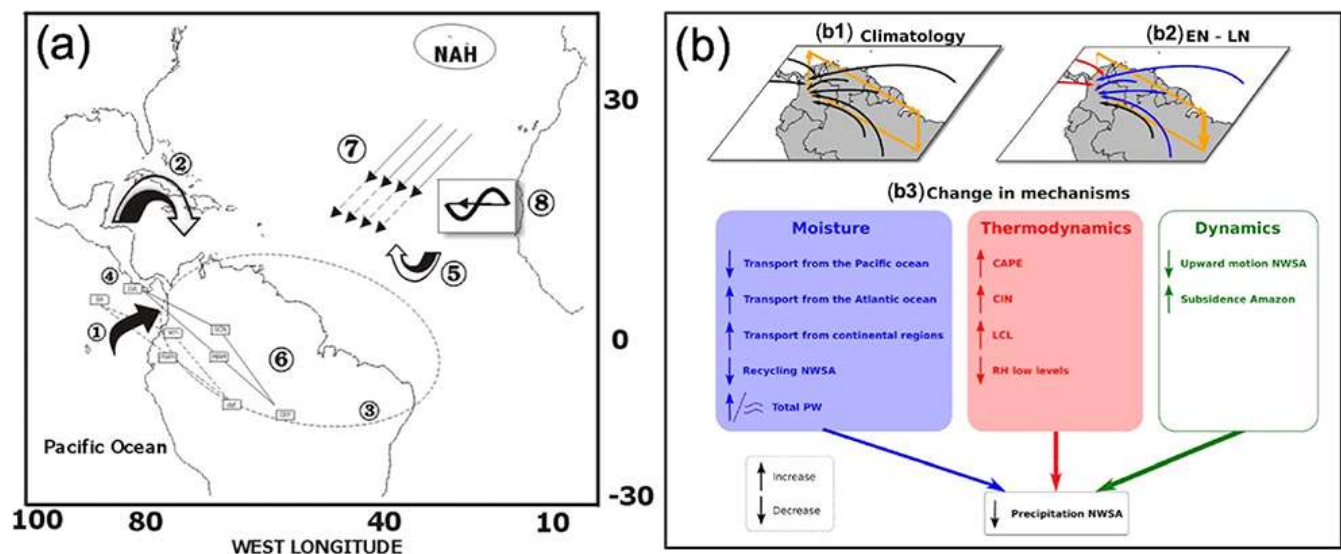


Figure 15. (a) Summary of teleconnections and land-atmospheric feedbacks affecting climate patterns in tropical South America during El Niño. Numbers and symbols correspond to mechanisms and processes listed in the text. (b) Illustration of key changes in atmospheric moisture transport, thermodynamic indices, and regional circulation across NWSA during ENSO events. (b1) Climatology of the atmospheric moisture transport from various sources to NWSA (black arrows) and the regional Hadley cell (yellow arrows). (b2) Differences between El Niño (EN) and La Niña (LN) phases, where red (blue) arrows denote reduced (increased) atmospheric moisture transport while black arrows denote negligible changes. (b3) Summary of significant changes in different mechanisms: atmospheric moisture transport (blue solid rectangle), thermodynamic indices (red solid rectangle), and regional dynamics (green transparent rectangle) over NWSA, where solid (transparent) background color indicates novel (previously known) insights into the mechanisms influencing precipitation in NWSA during ENSO phases.

Source: (a) Poveda et al. (2006) (b3) adapted from Ruiz-Vásquez et al. (2024) with authorization.

In contrast, La Niña events strengthen teleconnections, enhancing ascending motion and moisture convergence (Ruiz-Vásquez et al., 2024), which increases precipitation even when total moisture content may be lower (Figure 15b2). These dynamics, along with feedback mechanisms affecting local temperatures and soil moisture, propagate through the atmosphere, resulting in unexpected climatic outcomes and greater variability in climate impacts across NWSA.

During El Niño events, estimates from tracking numeral models indicate reductions of the water vapor advected from the Pacific (Arias et al., 2015; Gallego et al., 2019; Hoyos et al., 2019; Morales et al., 2021; Poveda, 2023; Ruiz-Vásquez et al., 2024) as well as decreases in the regional recycling of moisture (Posada-Marín et al., 2023; Ruiz-Vásquez et al., 2024). By contrast, moisture advection from the Atlantic Ocean and the Orinoco basin toward NWSA increases during El Niño years (Arias et al., 2015; Hoyos et al., 2019; Ruiz-Vásquez et al., 2024). As a result, the total precipitable water over NWSA during El Niño increases or remains similar in comparison to La Niña (Ruiz-Vásquez et al., 2024), although precipitation decreases during El Niño, as widely shown by multiple studies (e.g., Cai et al., 2020; Cerón et al., 2021; Poveda et al., 2006, 2011). During El Niño, the regional atmospheric thermodynamics inhibits precipitation due to a more stable atmosphere, in addition to

a weaker Hadley cell with reduced ascending motion over NWSA (Ruiz-Vásquez et al., 2024). This is particularly relevant and shows the importance of other processes for the occurrence of precipitation in the region, besides atmospheric moisture transport.

Also, the Caribbean low-level jet (CLLJ) exhibits important variability at interannual timescales. During El Niño, the CLLJ has an opposite relationship in the winter and summer. During the winter a weak (strong) easterly CLLJ corresponds with El Niño (La Niña), whereas during the summer a strong (weak) easterly CLLJ is associated with El Niño (La Niña; Salas et al., 2020; Wang, 2007). In terms of ENSO transitions, a recent work identified that during the transition between El Niño and La Niña (La Niña to El Niño), the low-level water vapor transport changes over the core regions of the Caribbean LLJ, the Orinoco LLJ, and the Choco LLJ, with distinctive patterns during the transition years (Builes-Jaramillo et al., 2023). At intraseasonal timescales, the moisture transport by the CLLJ is modulated by the Madden-Julian Oscillation, which is also associated with modulation of precipitation in the Caribbean region (García-Martínez & Bollasina, 2020; Giraldo-Cárdenas et al., 2022; Martin & Schumacher, 2011b; Perdigón-Morales et al., 2021; Whitaker & Maloney, 2018). Corrales-Suastegui et al. (2020) found an intensification of the CLLJ under climate change scenarios. Furthermore, based on CORDEX-CORE simulations, Torres-Alavez et al. (2021) found a significant increase up to 1.5 m s^{-1} in the strength of the core of the CLLJ, with a strong low-level southerly flow near Central America.

The Orinoco LLJ also varies at interannual timescales. La Niña correlates with Orinoco LLJ (OLLJ) intensification, enhancing its mean wind speed by up to 1 m/s , while El Niño results in a slowdown, reducing it by approximately 2 m/s (Builes-Jaramillo et al., 2022b; Jones, 2019; Jones et al., 2023). Both ENSO phases lead to decreased water vapor flux and precipitation, particularly during El Niño. In rapid ENSO transitions within a year, Builes-Jaramillo et al. (2023) found reduced (increased) water vapor transport through the OLLJ corridor during the La Niña to El Niño (El Niño to La Niña) transition, impacting water availability in the northwestern Amazon. The regional gradients of surface sensible heat flux, near-surface air temperature, and sea-level pressure between the Orinoco basin and the Andes-Amazon transition region are key to controlling changes in the OLLJ intensity (Correa et al., 2024; Martínez et al., 2022). Moreover, Martínez, Arias, et al. (2024) showed that the intensification of the OLLJ can trigger the formation of Mesoscale Convective Systems in the Andes-Amazon transition region of Colombia, as identified during the mudslide that occurred in Mocoa, Colombia, on April 1, 2017, that killed more than 300 people. Additionally, Rodríguez-Gómez et al. (2021) linked the OLLJ to heightened aerosol transport during NWSA biomass burning season, contributing to increased air pollution in cities along its corridor.

Colombia

The impacts of ENSO on the hydroclimatology of Colombia have been investigated since the late 1980s with the pioneering studies of Aceituno (1988) and Hastenrath (1990), followed by a large body of literature (e.g., Arias et al., 2015; Cerón et al., 2021; Córdoba-Machado et al., 2015; Giraldo-Osorio et al., 2022; Navarro-Monterroza et al., 2019; Pabón & Montealegre, 1992; Poveda & Mesa, 1993; Poveda et al., 2011; Salas et al., 2020; Waylen & Poveda, 2002). During El Niño (La Niña), Figure 16 shows that the Caribbean, Andean, and Pacific regions experience positive (negative) anomalies

in air temperature and negative (positive) anomalies in rainfall, streamflows (both average and extreme), soil moisture, and vegetation activity (Poveda & Mesa, 1997; Poveda & Salazar, 2004; Poveda et al., 2001, 2011). The impact of ENSO is synchronized with the seasonal cycle, with its effects starting in March–May (year 0), and being more pronounced during December–February (year +1) and less during March–May (year +1). Anomalies in rainfall and river discharges show that the ENSO signal moves in a westerly wavelike manner, being stronger and earlier in the western Andes, and weaker and delayed in the eastern Andes (Canchala et al., 2020; Poveda & Mesa, 1997; Poveda et al., 2011). Hence, as shown in Figure 17, seasonal streamflows over the Andean region are significantly correlated (Poveda et al., 2011) and generalized synchronized with ENSO during both El Niño and La Niña (Salas et al., 2020). Moreover, soil moisture exhibits deficits during El Niño but saturation values during La Niña (see Box 1). Diverse large-scale and regional mechanisms within the ocean-atmosphere-land system explain the identified hydro-climatic anomalies (Arias et al., 2015; Córdoba-Machado et al., 2015; Navarro-Monterroza et al., 2019; Poveda & Mesa, 1997; Poveda et al., 2001, 2011; Salas et al., 2020; Sayol et al., 2022). In addition, the two other major regions of Colombia, the Orinoco and the Amazon river basins exhibit different hydroclimatic anomalies.

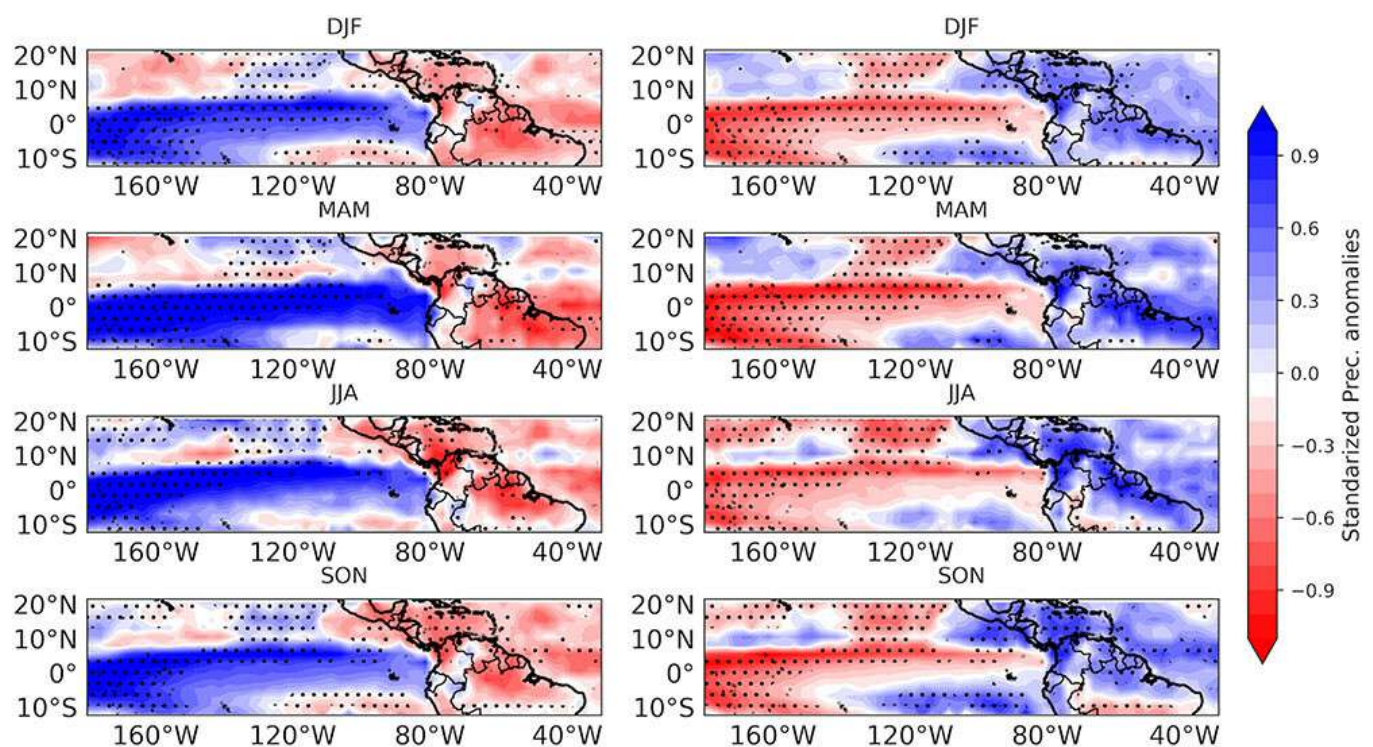


Figure 16. Seasonal precipitation anomalies over Northwestern South America during canonical ENSO phases. (left) El Niño. (right) La Niña. Dots show the significant change in precipitation anomalies at the 0.05 confidence level.

Source: GPCP. Adapted from Salas et al. (2024) with authorization.

Northwestern Amazonia

The impacts of El Niño and La Niña over the Colombian Amazon (northwest of the Amazon river basin) differ from the other regions of Colombia (Poveda & Mesa, 1997; Salas et al., 2020). Figure 18 shows the long-term mean annual cycle of river flows located along the Putumayo river basin in the Colombian Amazonia (Arango-Ruda & Poveda, 2018). They reflect the passage of the ITCZ, with higher streamflows during July and lower flows at the beginning and end of the year, exhibiting negative (positive) anomalies during El Niño (La Niña), mainly during the second half of the year, despite the large error bars. In this sense, Segura et al. (2019) stated that the Andes–Amazon transition zone (8°S – 5°S) does not exhibit its main relationship with ENSO as the main influencing factor (e.g., February–April). They found that the dry events in the transition Andes coincide with the intensification of the eastern branch of the Walker cell. In contrast, wet events can be associated with enhanced convection over the equatorial Amazon.

Venezuela

Large-scale controls on interannual variability of Venezuelan climate are discussed by Poveda et al. (2006) and Tim and Bravo de Guenni (2016). During El Niño, negative anomalies in precipitation and streamflows are witnessed (Guevara, 2006; Paredes-Trejo et al., 2023; Tim & Bravo de Guenni, 2016). During La Niña, positive anomalies are associated with: (a) persistent positive Southern Oscillation Index; (b) below normal SSTs in the eastern Pacific; (c) positive SST anomalies in the Caribbean (in year 0 of ENSO); (d) weaker easterlies between 10°N and 20°N at 200 hPa; (e) negative SST anomalies in the tropical South Atlantic; (f) a northward displacement of the South Atlantic High reaching into Brazil (Pulwarty et al., 1992); (g) stronger ascent of air in January owing to an enhanced Walker cell circulation; (h) an anomalous weaker and northernmost position of the winter Hadley Cell (December–February); and (i) stronger convection associated with positive TNA SST anomalies (Tim & Bravo de Guenni, 2016). The important role of tropical–extratropical interactions on rainfall over northern Venezuela was evidenced in the December 1999 floods, which caused over 30,000 fatalities, in part due to a stationary system that produced heavy precipitation for over 2 days over the northern Venezuelan coast (Lyon, 2003; Rudenstine & Galea, 2012). Rainfall in northwestern Venezuela (Maracaibo region) is also significantly modulated by the eastern Pacific, as it is in the Andes region and the northern Cordillera de la Costa. Coastal regions of Venezuela and Colombia are also subject to the influence of “*nortes*” winds (Pulwarty et al., 1992).

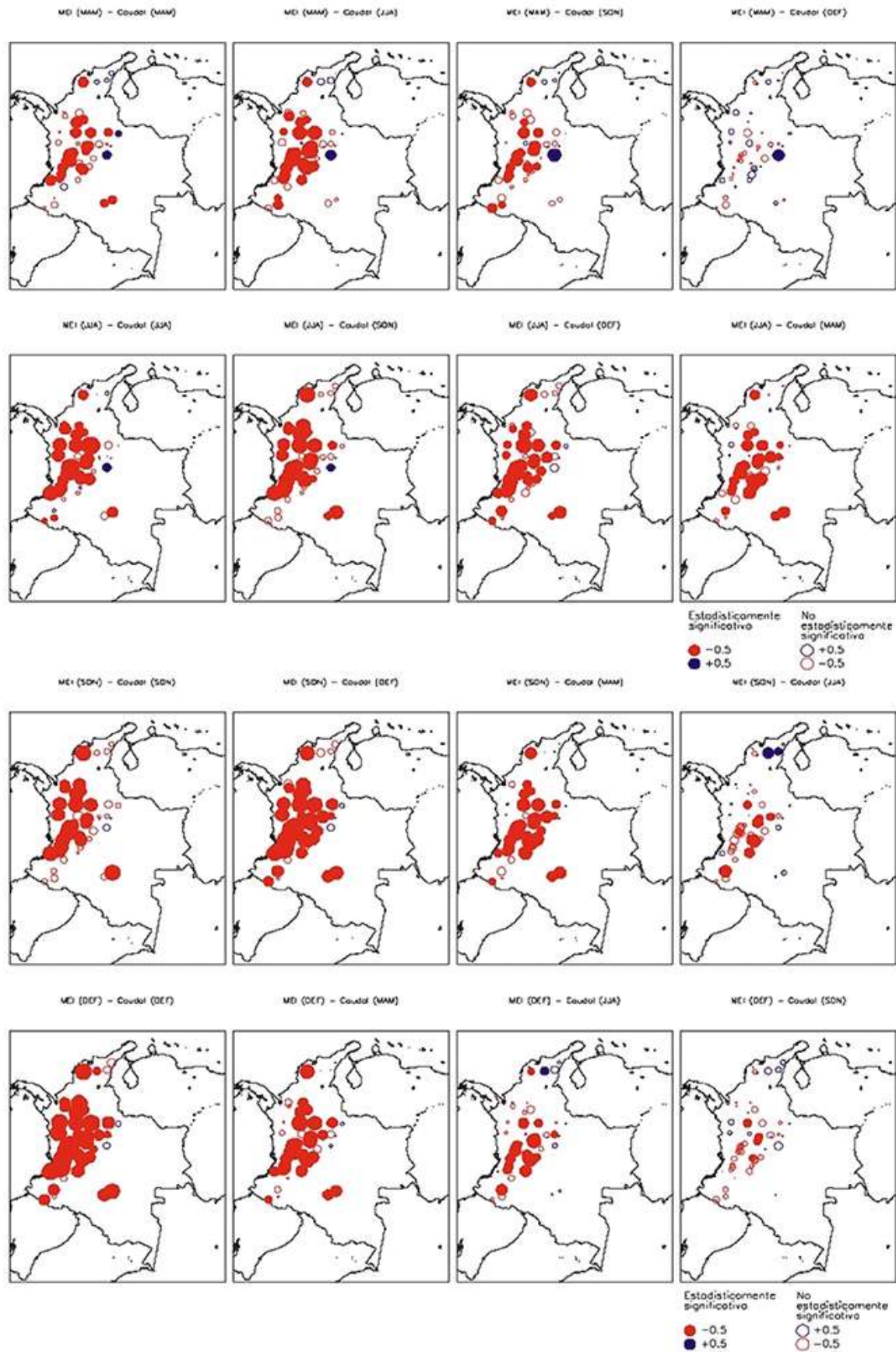


Figure 17. Seasonal lagged correlations between the MEI and river discharges throughout Colombia. First-row MEI in March–May (MAM) versus river flows in MAM and ensuing seasons, second-row MEI in June–August (JJA) and river flows in JJA and ensuing seasons, third-row MEI in September–November (SON) and river flows in SON and ensuing seasons, and fourth-row MEI in December–February (DJF) and river flows in DJF and ensuing seasons. Filled circles denote statistically significant correlations regarding the circles referenced at the bottom.

Source: Taken from Poveda et al. (2011).

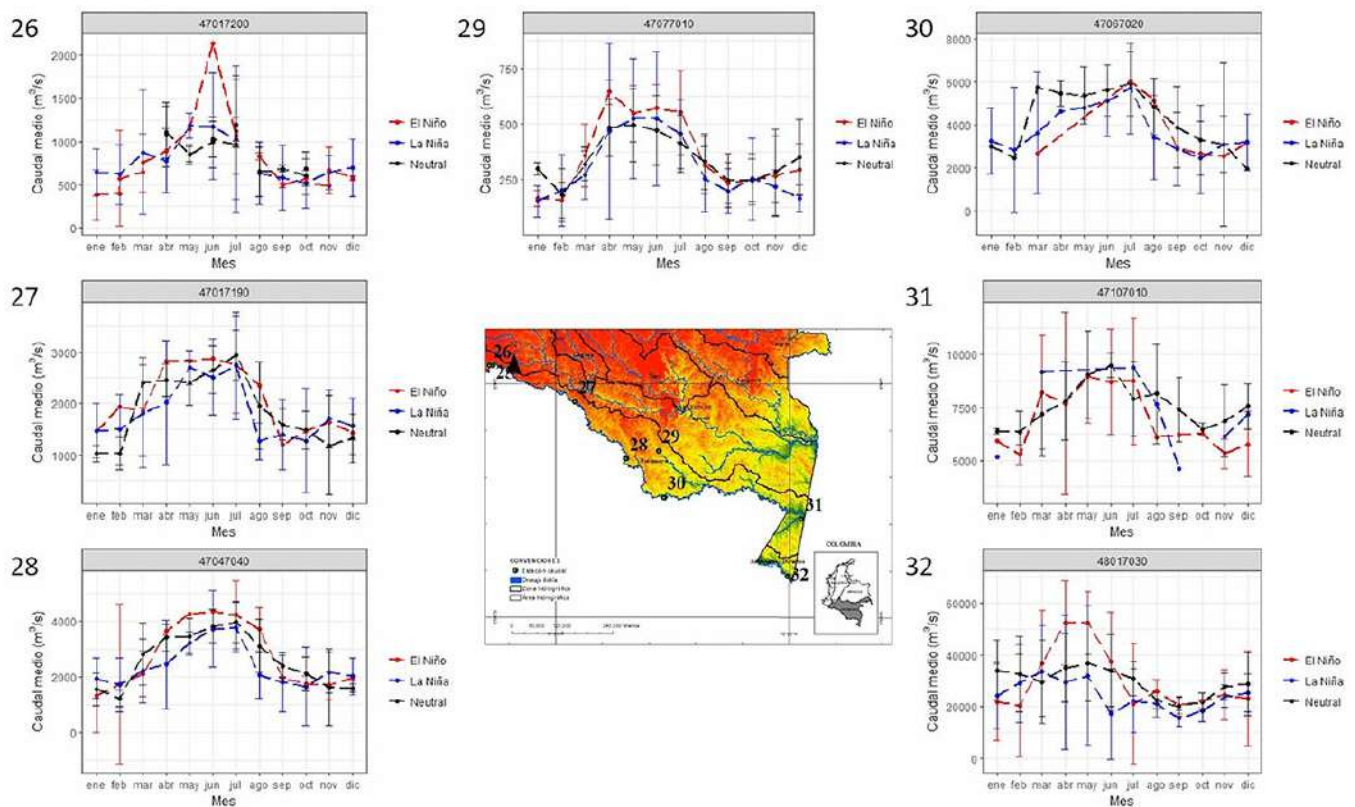


Figure 18. Long-term mean annual cycle of river flows during El Niño (red), La Niña (blue), and neutral (black) years, for some stations located in the Putumayo river basin over the Colombian Amazon. Error bars denote the standard error of the mean.

Source: Reproduced from Arango-Ruda and Poveda (2018) with authorization of Sinchi.

Ecuador

The impacts of ENSO in Ecuador are mixed. One of the most sensitive regions is located over the coastal southern Pacific plains, where severe flooding (droughts) normally occur during January and April of an El Niño (La Niña) event, while the highlands and the eastern slope of the Andes witness anomalously dry (wet) conditions Vuille et al. (2003), although differences from this pattern have been reported by Bendix et al. (2011). Bendix and Bendix (2006) and Kiefer and Karamperidou (2019) showed that positive rainfall anomalies during El Niño mainly affect the coastal plain of Ecuador to the western slope of the Andes at altitudes < 1,800 m, while Pineda et al. (2013) observed ENSO signals at locations as high as 2,700 m. The study of Thielen et al. (2023) also found that in some sectors of the Andes, the ENSO signal could be detected at the 3,200–3,900 m

altitudinal range, depending on distance to the coastline, steepness of the relief, and degree of seasonality. Thielen et al. (2023) found that over the Pacific slope and Galapagos most precipitation extremes occur (Figure 19) during the first semester of the second year of El Niño, with no statistical differences between the two flavors of El Niño (Eastern Pacific, EP, and Central Pacific, CP; Ashok et al., 2007; Kug et al., 2009), and no significant precipitation anomalies were witnessed on the Amazon slope by the occurrences of any type of extreme El Niño: EP, CP, mixed, or coastal (Santoso et al., 2017; Wang et al., 2020).

The study of Zambrano Mera et al. (2018) found that over the coastal region, El Niño is strongly associated with droughts, while the study of Campozano et al. (2016) found that ENSO indicators are useful to estimate the effects of El Niño on precipitation during the January–April wet season, and that Niño 1+2 strong positive anomalies are positively correlated with higher precipitation in the coastal plains of Ecuador and below-average precipitation in the Amazon region. Anomalous warming of the eastern tropical Pacific also exacerbates extreme sea levels over the Ecuadorian Pacific, affecting coastal communities and fisheries Belliard et al. (2021). Also, Quishpe-Vásquez et al. (2019) found that SSTs over the tropical Pacific in DJF affect Ecuadorian streamflows in February–April in two different manners: one associated with the canonical El Niño and the second with El Niño Modoki, with the latter exerting a major influence on February–March–April streamflow over most of Ecuador. El Niño phases in the central Pacific region cause upper-level high pressures and drought conditions in the Andes, while La Niña phases in the eastern Pacific causes droughts in the Western plains through the suppression of westerly flows and convective processes (Vicente-Serrano et al., 2017).

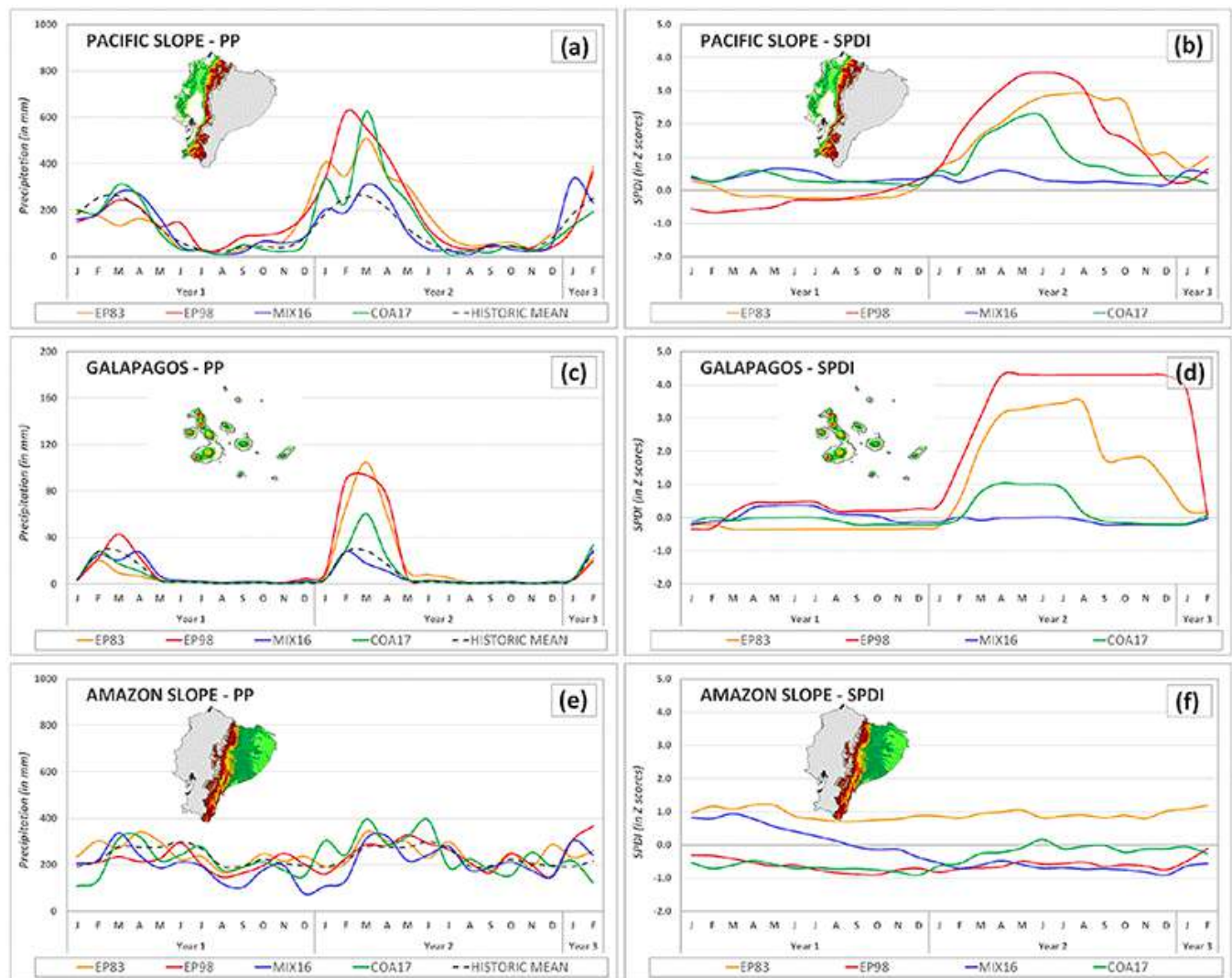


Figure 19. (a) The mean monthly precipitation (in mm) for the main study zones (the Pacific slope, Galapagos, and Amazon slope, correspondingly) for each extreme El Niño event (EP83, EP98, MIX16, and COA17) and Year 1 and Year 2. (b) The resulting mean Standardized Pluviometric Drought Index—SPDI (in Z scores) for each extreme El Niño event (EP83, EP98, MIX16, and COA17) and Year 1 and Year 2.

Source: Thielen et al. (2023).

La Niña, however, has significant and diverse impacts in different regions of Ecuador due to its complex topography and geographic distribution. In coastal regions, La Niña typically enhances rainfall, leading to increased risks of flooding, due to the cooling of the sea-surface temperatures in the central and eastern tropical Pacific (Thielen et al., 2023). In the Andes, the impacts of La Niña are more varied and can depend on specific local conditions. Generally, these areas may experience increased precipitation during La Niña events, but the exact impacts can vary due to the complex topography, which affects cloud formation and weather patterns (Ilbay-Yupa et al., 2021). The Ecuadorian Amazonia typically experiences wetter conditions during La Niña (Moura et al., 2019).

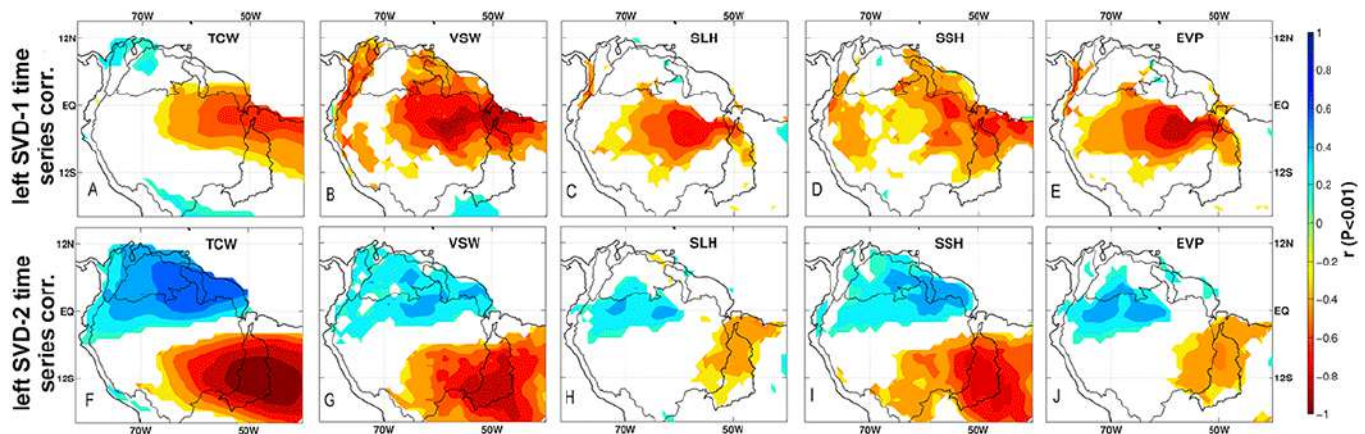


Figure 20. Correlation maps 1986–2013 between the left SVD-1 time series (top) and SVD-2 time series (bottom) of GPCP and 2-m temperature with anomaly fields of total column of water (TCW), volumetric soil water (VSW), surface latent heat (SLH), surface sensible heat (SSH), and evaporation (EVP).

Source: Reproduced from Bedoya-Soto, Poveda, et al. (2019) with authorization.

Land Surface-Atmosphere Interactions at ENSO Timescales

Understanding Land-Atmosphere Interactions (LATIs) mechanisms in NWSA is crucial for accurately modeling and predicting hydroclimatic variability (Baker et al., 2021), with a particular emphasis on the role of soil moisture (Denissen et al., 2021; Santanello et al., 2018). Bedoya-Soto et al. (2018) highlighted soil moisture's pivotal role in connecting land and atmospheric processes, impacting surface energy fluxes, atmospheric stability, and precipitation formation at interannual scales. This moisture exchange in NWSA governs regional water availability, vegetation dynamics, and climate (Collini et al., 2008). It emphasizes the necessity of integrating LATI into hydrological and climate models for better forecasting of rainfall patterns, droughts, and floods (Baker et al., 2021; Poveda, 2020).¹

LATIs complement well-known teleconnection patterns and atmospheric transport processes in NWSA (Arias et al., 2015; Hoyos et al., 2019; Poveda, 2020). During ENSO, changes in soil moisture influence the atmosphere's response to warming, affecting both precipitation patterns and regional temperature distributions (Bedoya-Soto, Poveda, et al., 2019). This intricate land surface–atmosphere interplay during ENSO events underscores the importance of considering LATIs in understanding and predicting climate variability in NWSA at interannual timescales (Figure 20). During El Niño, the land–atmosphere bridge connects Pacific and North Atlantic SSTs via LATIs over the Amazon, as proposed by Poveda and Mesa (1997), further explored in subsequent studies (Builes-Jaramillo, Marwan, et al., 2018; Builes-Jaramillo, Ramos, et al., 2018; Ramos et al., 2017), showing LATIs' role in ENSO hydroclimatic dynamics in tropical South America.

Box 1. Socioeconomic Impacts of ENSO in Colombia

ENSO-associated hydro-climatic anomalies cause strong socioeconomic impacts in NWSA. Overall, El Niño affects water supply, agriculture and livestock, hydropower generation, human health, forest fires, and air and water quality, which translate into food and electricity shortages, inflation, diseases, and human lives. Also, for the most part, La Niña brings intense storms, landslides, inundation and floods, affecting human lives, infrastructure, crops, and livestock. For instance, Colombia's coffee production is strongly impacted by temperature increase and rainfall decrease during El Niño (Cai et al., 2020; Poveda et al., 2001), as well as during La Niña, as heavy downpours destroy flowering of coffee bushes. Figure 21a shows 10-day average data of volumetric soil moisture during El Niño 1997–1998 and La Niña 1998–1999 in three parcels located over the central Andes of Colombia covered by sunlit coffee, shade coffee, and a secondary forest. Soil moisture experienced significant negative anomalies during the 1997–1998 El Niño, particularly during the two dry seasons of the Colombian Andes. The deficit in soil moisture was particularly severe in the parcel covered by sunlit coffee compared to those covered by forest or shaded coffee. Conversely, during the La Niña event of 1998–1999, soil moisture responded to above-average precipitation conditions by reaching maximum levels throughout the period. Human health is also affected in NWSA during El Niño. Outbreaks of malaria, dengue, and other vector-borne diseases in Colombia are associated with the occurrence of El Niño (Poveda, 2020; Poveda & Rojas, 1997; Muñoz et al., 2021). Figure 21b shows the annual evolution of the Annual Parasite Index of malaria in Colombia during 1959–2023. Malaria incidence exhibits a dual pattern: a persistent upward trajectory, in which climate change might play a significant role, and sporadic outbreaks coinciding with historical El Niño events. The primary climatic factors driving these outbreaks during El Niño are elevated air temperatures and diminished rainfall, which intensify mosquito vector activity and shorten the parasite's reproductive cycle, amplifying the risk of malaria transmission.

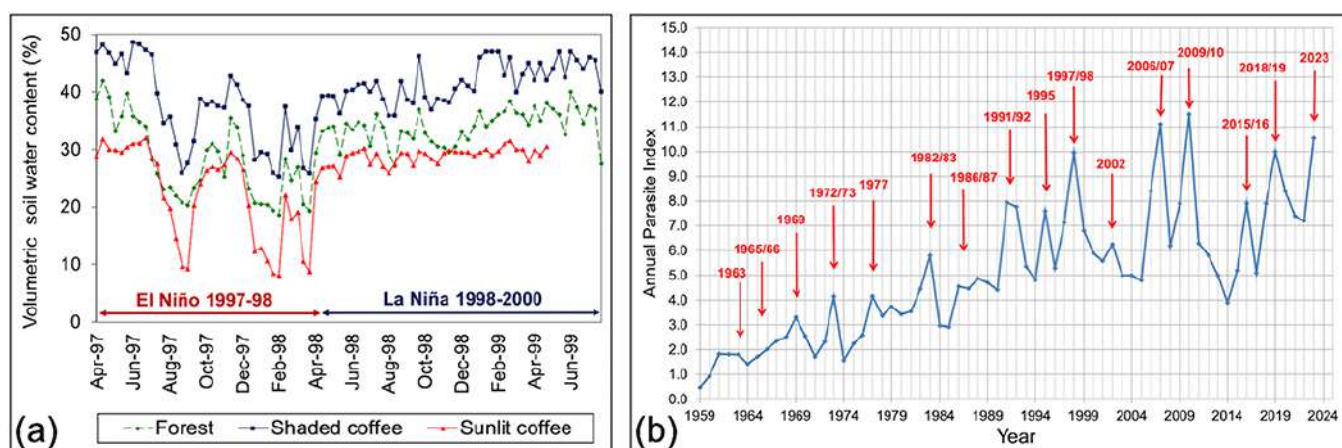


Figure 21. (a) Time evolution of 10-day average volumetric soil moisture measured at 20 cm at three parcels with different land cover types (shaded coffee, forest, and sunlit coffee) during March 1997–August 1999; (b) Time series of the Annual Parasite Index of malaria in Colombia during 1959–2023. Red arrows and years denote the occurrence of historical El Niño events.

Source: (a) Adapted from Poveda et al. (2001) with authorization; (b) Poveda (2020), Colombian Ministry of Health and National Institute of Health.

Other Macro-Climatic Phenomena

Pacific Decadal Oscillation

The PDO primarily affects the North Pacific region but its effects can be felt also near the equator (Mantua & Hare, 2002). Hence, diverse studies have shown that the PDO affects NWSA's hydroclimatology. Poveda, Mesa, Carvajal, et al. (2002) tested diverse statistical methods to forecast mean river flows in Colombia using diverse macro-climatic indices and showed that the PDO is among those that contribute to improving the forecasts. Significant negative seasonal correlations were identified by Poveda and Mesa (2000) between the PDO and streamflows over western Colombia. Also, Rodríguez-Rubio (2013) showed that SSTs, air temperatures, and precipitation over western Colombia and the far eastern Pacific exhibit a second-order relation (34% of variance) with two interdecadal modes associated with the PDO (8–16 yr and 20–30 yr), and may account also for moderate ENSO events. Figure 22 shows seasonal correlations between the PDO index and precipitation (CHIRPS) during 1981–2021. Higher negative correlations are identified over northern SA and the Andes mountains, mainly during December–January–February (DJF), June–July–August (JJA), and September–October–November (SON).

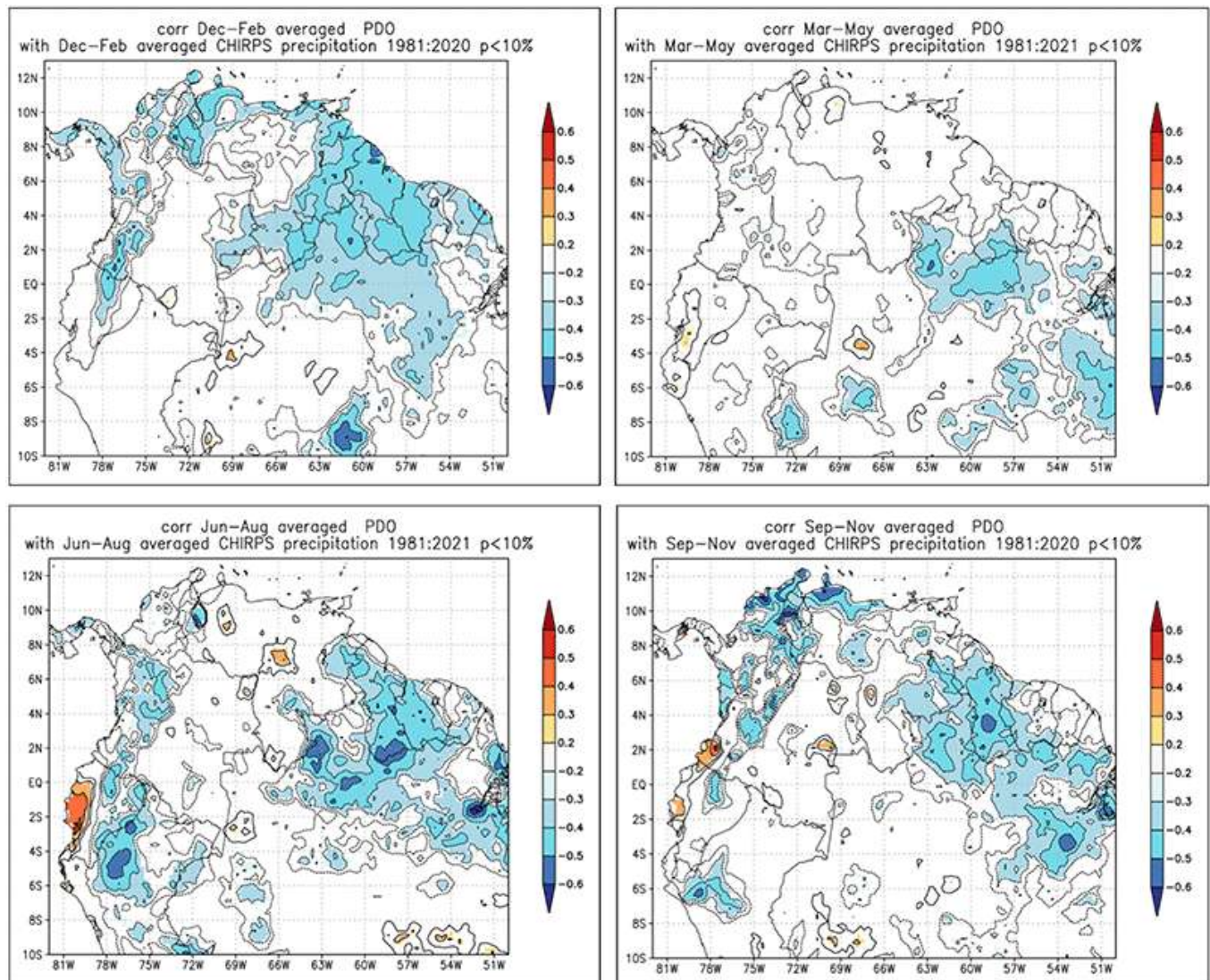


Figure 22. Seasonal correlations between the PDO index (1900–2018, Mantua, U. Washington) and precipitation from CHIRPS for the 1981–2021 period.

The combined effects of the phases of ENSO and the PDO are also evidenced in Colombia's rainfall. Salas (2020) showed that the highest positive (negative) precipitation anomalies over western Colombia coincide with the strong (weak) phase synchronization between the ENSO and the PDO signals. Figure 23 shows that during El Niño and the positive phase of the PDO, rainfall exhibits relative negative anomalies all over the country, with positive anomalies (up to 133%) mostly over the Andes and the northern Caribbean coast. As for La Niña during PDO > 0, rainfall exhibits positive relative anomalies along the Andes and the northernmost Caribbean coast but negative anomalies over the Orinoco and the southern Caribbean coast. Rainfall exhibits clear-cut and strong (> 180%) positive anomalies during La Niña and the positive phase of the PDO over the Andes and the Caribbean coast, and weaker negative relative anomalies over the regions of the Orinoco and Amazon river basins. Likewise, the combined effects of ENSO and the PDO on rainfall in Ecuador have been identified by Vicente-Serrano et al. (2017); Campozano et al. (2020).

North Atlantic Oscillation

The NAO is a key pattern in Northern Hemisphere winter geopotential height, characterized by opposing sea-level pressure anomalies over the Arctic polar cap and the Atlantic Mediterranean sector (Wallace & Gutzler, 1981). It is the most prominent climate variability pattern in mid and high northern latitudes, strongly influencing weather in northeastern North America, Greenland, Europe, and beyond (Hurrell et al., 2003). Studies since Hastenrath (1976, 1997) have shown NAO's impact on the hydroclimatology of northern South America, including Colombia, Brazil, and the inter-Americas seas Hastenrath and Greischar (1993); Poveda and Mesa (1996); Poveda et al. (1998); González-González et al. (2021). Wang (2007) noted that a strong (weak) North Atlantic Subtropical High is linked to stronger (weaker) easterly CLLJ, corresponding to the positive (negative) NAO phase. Salas (2020) found that during La Niña in JJA, NAO is strongly phase-locked with precipitation anomalies in Colombia's Andean and Caribbean regions. Figure 24 shows that, during El Niño and positive NAO, rainfall shows negative anomalies up to 44% across Colombia, while negative NAO sees rainfall drops of up to 52% in the Andes, Orinoco, and Amazon regions, with positive anomalies of up to 119% in parts of the Andes. During La Niña and positive NAO, precipitation anomalies rise to 157% in the northern Andes and the Caribbean, with smaller negative anomalies in the southern Andes. In La Niña and negative NAO, Andes rainfall anomalies reach 253%, while Orinoco and Amazon regions experience negative anomalies up to 32%.

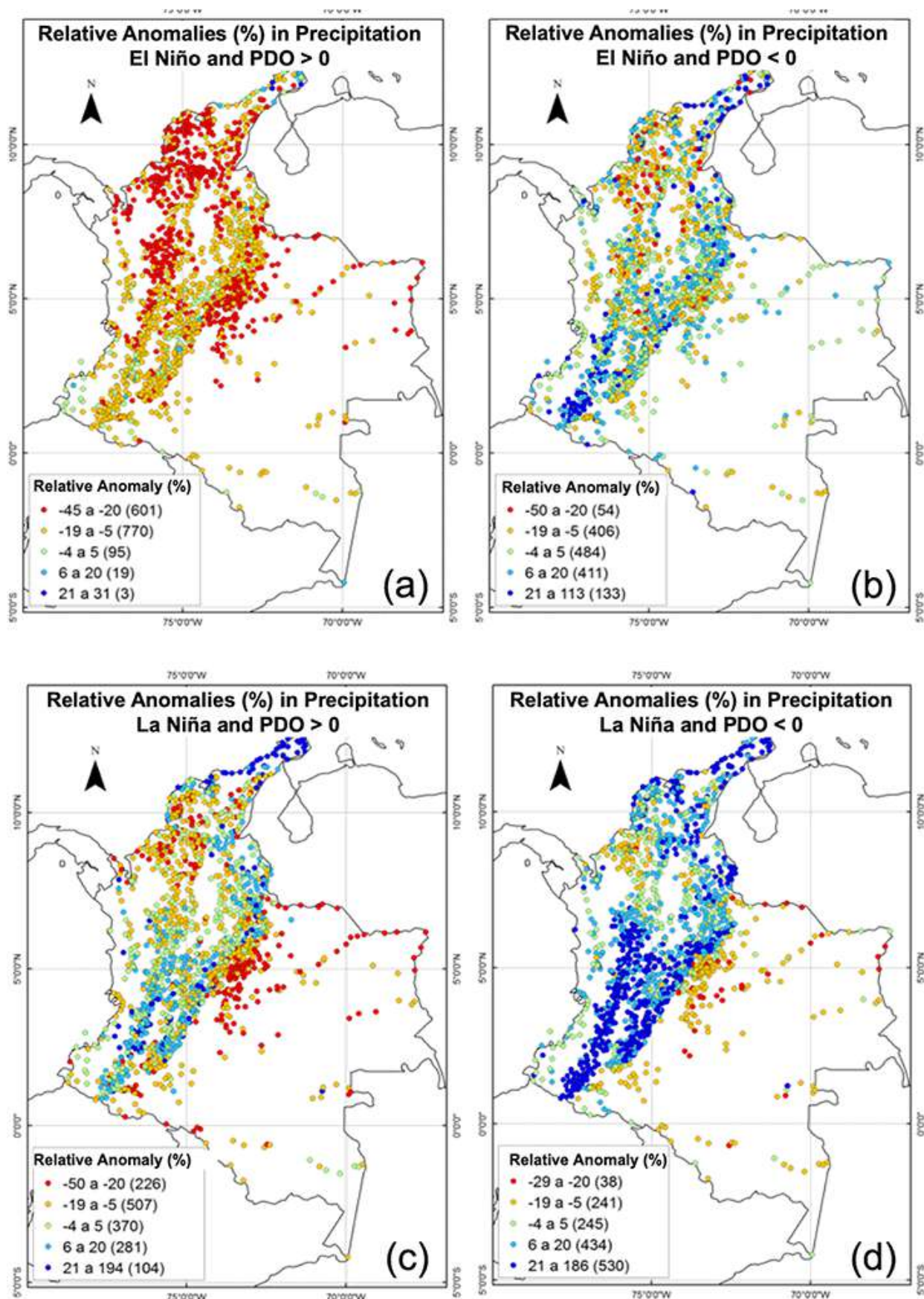


Figure 23. Relative anomalies of precipitation (%) during (a) El Niño and the positive phase of the PDO; (b) El Niño and the negative phase of the PDO; (c) La Niña and the positive phase of the PDO; (d) La Niña and the negative phase of the PDO.

Source: Olarte (2018).

Atlantic Multidecadal Oscillation

The AMO refers to a 65–80-year cycle with a 0.4°C range in North Atlantic sea-surface temperatures, influencing global hydroclimate, particularly in the North Atlantic and North Pacific (Enfield et al., 2001; Kerr, 2000). Loaiza Cerón et al. (2020) discussed how AMO-related SST anomalies impact the Choco and Caribbean low-level jets, with the Choco LLJ weakening (intensifying) and the Caribbean LLJ intensifying (weakening) before (after) 1997. Salas (2020) found AMO is phase-locked with rainfall anomalies in the Amazon and Orinoco during El Niño and La Niña. Maksic et al. (2022) reported increased precipitation in the Amazon and northeastern Brazil during the cold AMO phase, with reduced rainfall in northern South America and the Atlantic, especially during DJF and March–April–May, likely linked to shifts in the Atlantic ITCZ. Figure 25 shows that during El Niño and both AMO phases, rainfall exhibits negative anomalies up to 52% across most of Colombia. During La Niña and positive AMO, rainfall increases up to 270% in the Andes and northern Caribbean coast but decreases over the Orinoco. In La Niña and negative AMO, rainfall drops by 61% above 5°N, while increasing by 236% in the Andes south of 5°N, with negative anomalies over the Orinoco and Amazon basins.

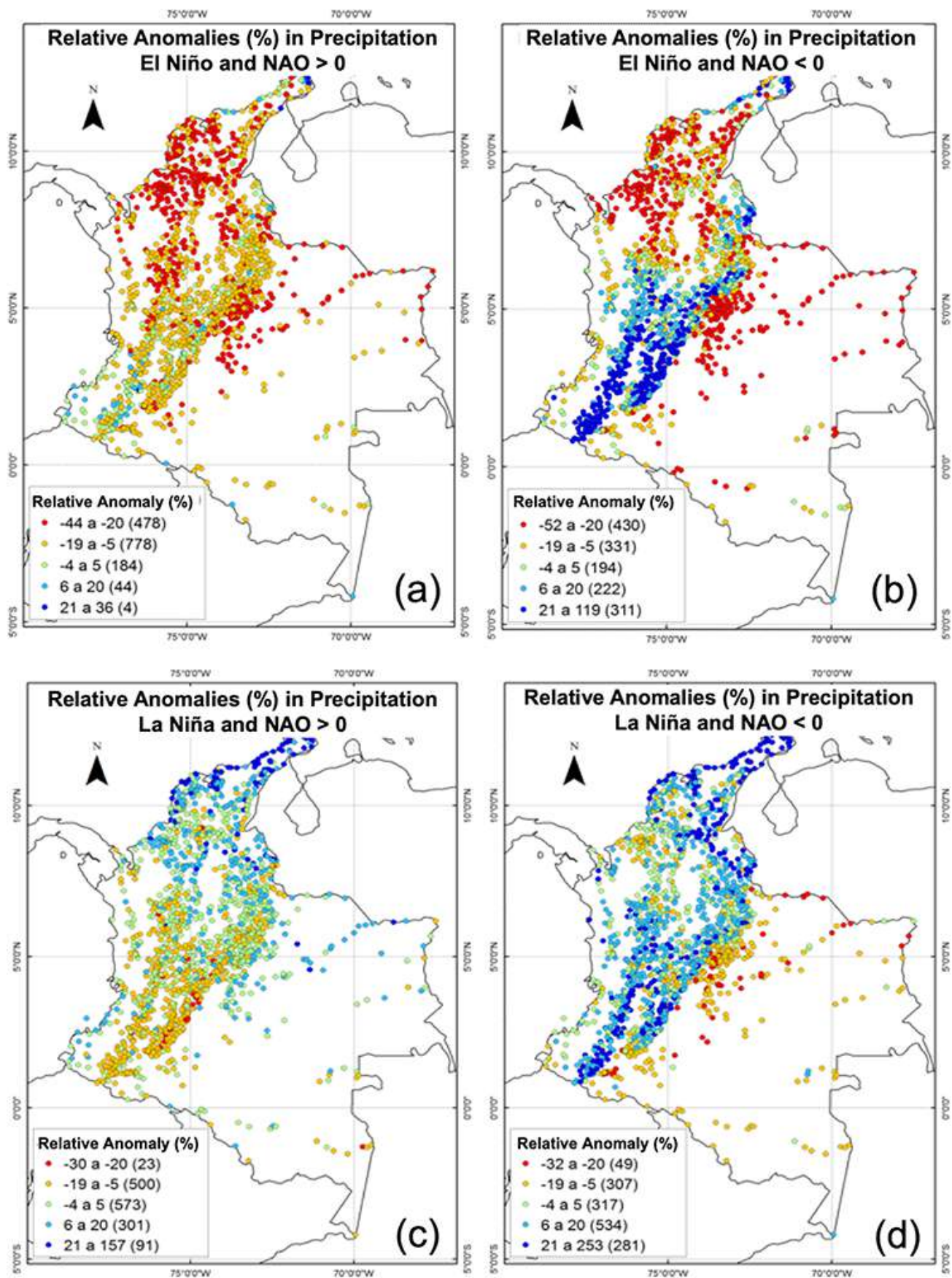


Figure 24. Relative anomalies of precipitation (%) during: (a) El Niño and the positive phase of the NAO; (b) El Niño and the negative phase of the NAO; (c) La Niña and the positive phase of the NAO; (d) La Niña and the negative phase of the NAO.

Source: Olarte (2018).

Intra-annual Variability

Madden-Julian Oscillation

The Madden–Julian Oscillation (MJO) is a large area of deep convection that originates over the Indian Ocean and moves eastward through the tropics, crossing the Maritime Continent, the western Pacific, South America, and Africa, completing its cycle in 30–60 days at about 5 m/s (Kiladis & Weickmann, 1992; Madden & Julian, 1971, 1972, 1994; Weickmann et al., 1985; Zhang, 2005). The MJO is the main driver of intraseasonal precipitation variability in the Amazon basin and tropical Brazil (De Souza & Ambrizzi, 2006; Grimm, 2019; Mayta et al., 2019; Paccini et al., 2018). Recalde–Coronel et al. (2020) quantified its impact on rainfall variability in northwestern South America during the February–April wet season, identifying three mechanisms: (a) modulation of the descending branch of the Pacific Walker Circulation, which is typically located over the region; (b) timing of deep convection, driven by the MJO core rather than equatorial Rossby or Kelvin waves; and (c) a link between coastal sea–surface temperature (SST) anomalies and MJO propagation, with warm SSTs coinciding with enhanced MJO precipitation. Poveda et al. (2005) also found that the MJO influences the diurnal cycle of precipitation in the Colombian Andes, with increased amplitude during active easterly phases and decreased amplitude during less active westerly phases, as shown in Figure 26.

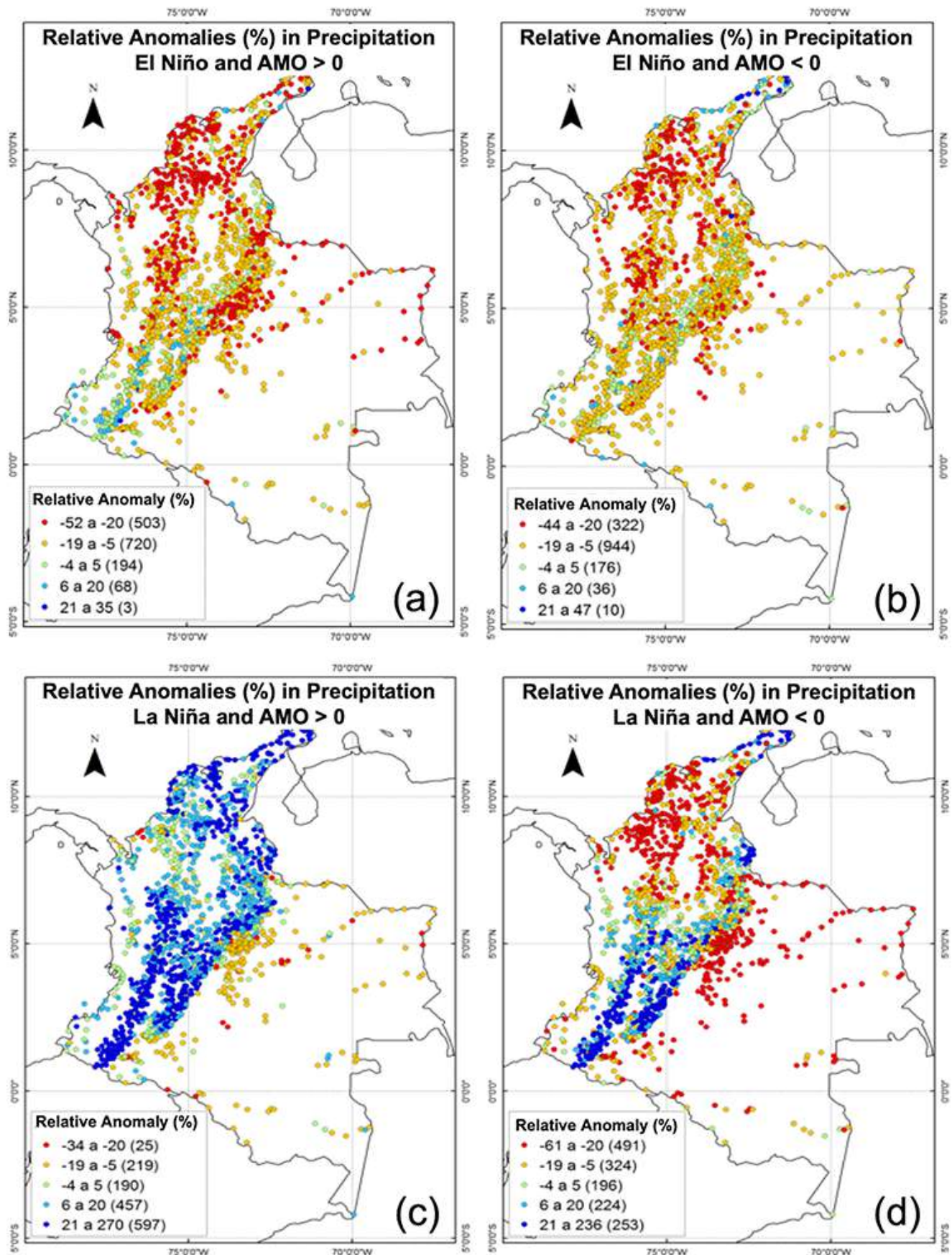


Figure 25. Relative anomalies of precipitation (%) during: (a) El Niño and the positive phase of the AMO; (b) El Niño and the negative phase of the AMO; (c) La Niña and the positive phase of the AMO; (d) La Niña and the negative phase of the AMO.

Source: Olarte (2018).

Tropical Easterly Waves

Among the synoptic phenomena influencing NWSA climate are the Tropical Easterly Waves (TEW; e.g., Dominguez et al., 2020; Espinoza et al., 2020; Giraldo-Cárdenas et al., 2022; Hollis et al., 2024). TEWs are westward-propagating off-equatorial waves that are typically convectively coupled, contributing important amounts of precipitation within the tropics (Kiladis et al., 2009). Tropical depressions, tropical storms, and hurricanes over the TNA and the Caribbean are borne from TEWs, as those shown in Figure 27. Over the Americas, TEWs contribute up to 50% of seasonal precipitation in the Caribbean and NWSA (Dominguez et al., 2020). The influence of the TEWs in NWSA is modulated by large-scale phenomena. For instance, the contribution of TEWs to precipitation interannual variability becomes more important during ENSO neutral phases (Dominguez et al., 2020). Also, the convective phases of the MJO over NWSA favor the passage of TEWs over the region, enhancing precipitation (Giraldo-Cárdenas et al., 2022). More recently, Valencia et al. (2024) showed a connection between these synoptic disturbances and the Choco LLJ. In particular, the Choco LLJ strengthens and becomes more southerly during the occurrence of convectively coupled TEWs, in association with a northward displacement of the Intertropical Convergence Zone, favoring precipitation over the western Caribbean and drier conditions in the northern Colombian Pacific (Valencia et al., 2024).

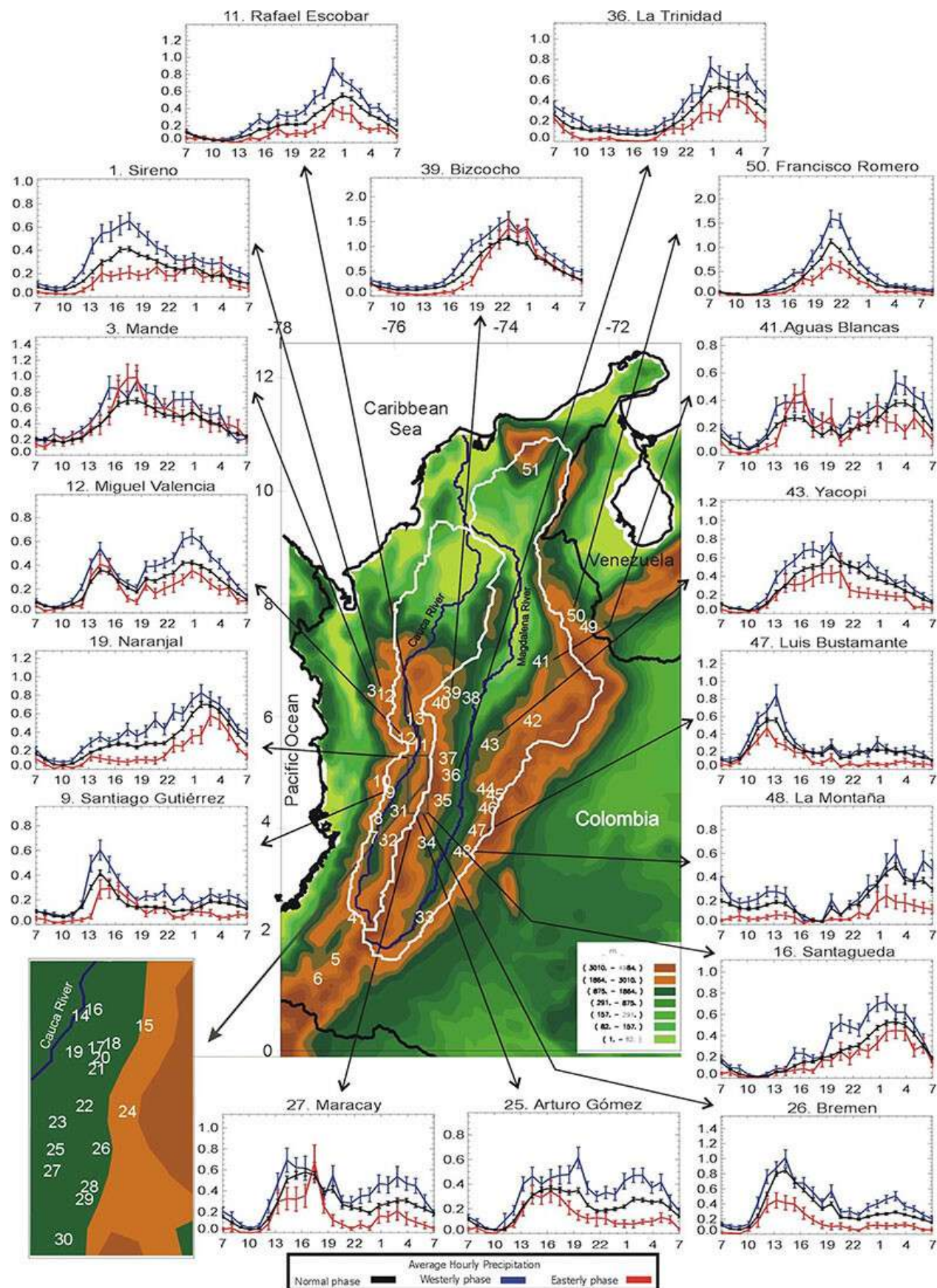


Figure 26. Average diurnal cycle of precipitation rates (mm/h) during the westerly (blue), normal (black), and easterly (red) phases of the MJO, for diverse rain gauges in the Colombian Andes.

Source: Reproduced from Poveda et al. (2005) with authorization.



Figure 27. A series of tropical storms distributed from the west coast of Africa to the Caribbean Sea in August 2012.

Source: Image from NOAA's GOES 13 satellite. Credit: NASA Goddard Space Flight Center/Flickr, CC BY 2.0.

Interestingly, Giraldo-Cárdenas et al. (2022) found that about half of the TEWs passing through NWSA are identified as dry waves, inhibiting the occurrence of precipitation. Furthermore, the synoptic timescales associated with the TEWs, corresponding to frequency bands with periods of 3–12 days and 6–18 days, were also identified in daily precipitation and streamflows of 47 river basins over northern South America (Salas et al., 2022). They found that the variance explained by the TEWs in rainfall over each catchment is greater than the variance explained by streamflows, which suggests that catchments efficiently filter out this variability. Moreover, the percentage of variance of TEWs explains from 5% to 20% of streamflow variability for catchments ranging from 1,000 km² to 5,000 km².

Mesoscale Convective Systems

Precipitation patterns in NWSA, along with their spatial and temporal variability, are closely tied to Mesoscale Convective Systems (MCS). These systems, the largest and most intense convective ones, significantly influence weather, rainfall, and large-scale circulation in tropical regions (Houze et al., 2015; Laing & Fritsch, 1997; Zipser et al., 2006). Diverse studies have investigated the spatial and temporal distribution of MCS over NWSA to provide a record of their occurrences. For example, Velasco and Fritsch (1987) described the location of large convective systems for the Americas and

found that these elements of organized deep convection maximize near or over continental regions during the nighttime hours and occur where low-level nocturnal jets frequently develop, in particular over the Pacific coast of Colombia, with clear-cut life cycles.

These findings have been deepened to include a broader extension of the convective cloud population that makes up a great part of the characteristic MCS. Zuluaga and Poveda (2004) utilized satellite data to pinpoint prevalent MCS locations in NWSA, highlighting peaks in western Colombia and the adjacent far eastern Pacific, with widespread convective systems in the Amazon region. Also, Mejía and Poveda (2005) analyzed reanalysis products, identifying conditions conducive to MCS formation in the same area, characterized by heightened convective available potential energy, reduced convection inhibition, and moderate vertical wind shear. Regional analyses of the convective elements that make up part of a typical MCS showed that low-pressure systems at mid-levels were prevalent during the occurrence of deep convective cells that have aggregated in the low-level lands north of the Andes, while over the Colombia–Panama coast, orographic lifting where the Choco jet encounters the Andes further enhances the occurrence of MCS in their middle and later stages of development (Zuluaga & Houze, 2015). Further analyses of the convective cloud population that makes up part of the life cycle of MCS typical of NWSA show that the deep, intense convective stages are predominantly concentrated over continental regions close to the orography, while the upscale aggregation of convective entities that constitute part of the well-developed MCS tend to migrate away from the topography toward oceanic regions (Jaramillo et al., 2017; Zuluaga & Houze, 2015).

Figure 28A shows the probability of the TRMM Precipitation Radar detecting a wide convective core (WCC), defined as areas with reflectivity above 40 dBZ over 1,000 km², during June–July–August (JJA) 1998–2003. WCCs are mainly concentrated along the Pacific coast of Colombia and Panama, the northern Colombian Andes, and parts of the Orinoco and Upper Amazon basins. In later MCS stages, some convective systems evolve into Broad Stratiform Rain areas (TRMM echoes over 50,000 km²; Figure 28B), mostly over the eastern Pacific near Colombia, with fewer occurrences in the Orinoco and Upper Amazon regions. Very deep convective cores also develop, especially during JJA, peaking over the northeastern Andes of Colombia and Venezuela (Figure 28C), associated with severe weather like lightning and flash floods.

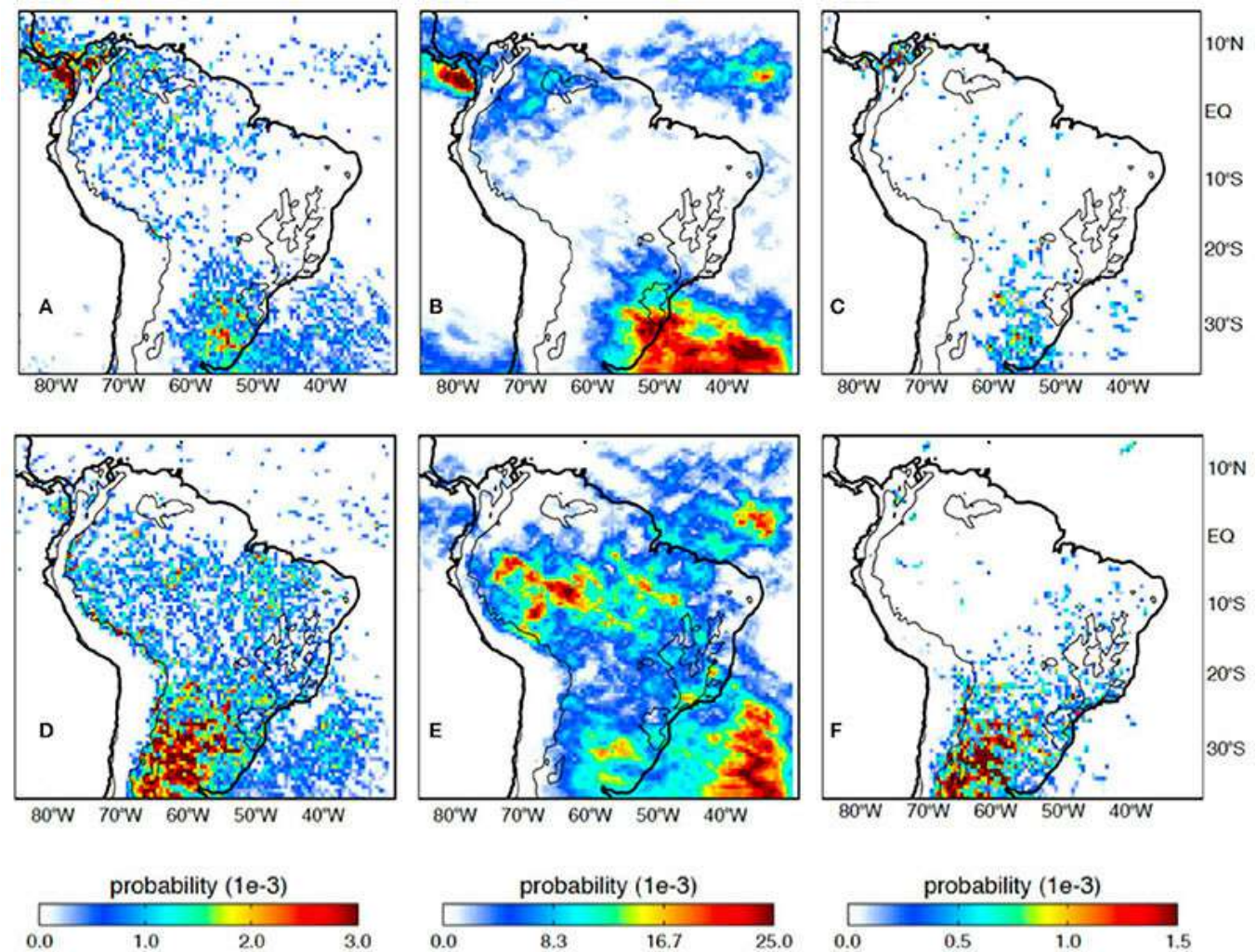


Figure 28. Geographical distribution of the probability of finding (A) a wide convective core; (B) a broad stratiform region; and (C) a deep convective core during JJA from 1998 to 2003. (D) same as (A); (E) same as (B); and (F) same as (C) but for DJF, respectively. The black contour inside the continental regions represents the 700 m elevation.

Source: Reproduced from Poveda et al. (2020) with authorization.

Precipitation systems within MCSs over the Amazon region exhibit a more modest convective nature, distributed across the vast rainforest. The diurnal cycle of MCS convective elements peaks during late night and early morning near the coast and over the ocean (Figure 29), while deep convective systems peak in the late afternoon and midnight over land. MCS contribute about 57% of rainfall in western Colombia and the eastern Pacific (Jaramillo et al., 2017). However, MCS contribute less to rainfall in the tropical Amazon compared to regions west of the Andes, due to the more maritime nature of precipitation there (Houze et al., 2015; Rasmussen et al., 2016).

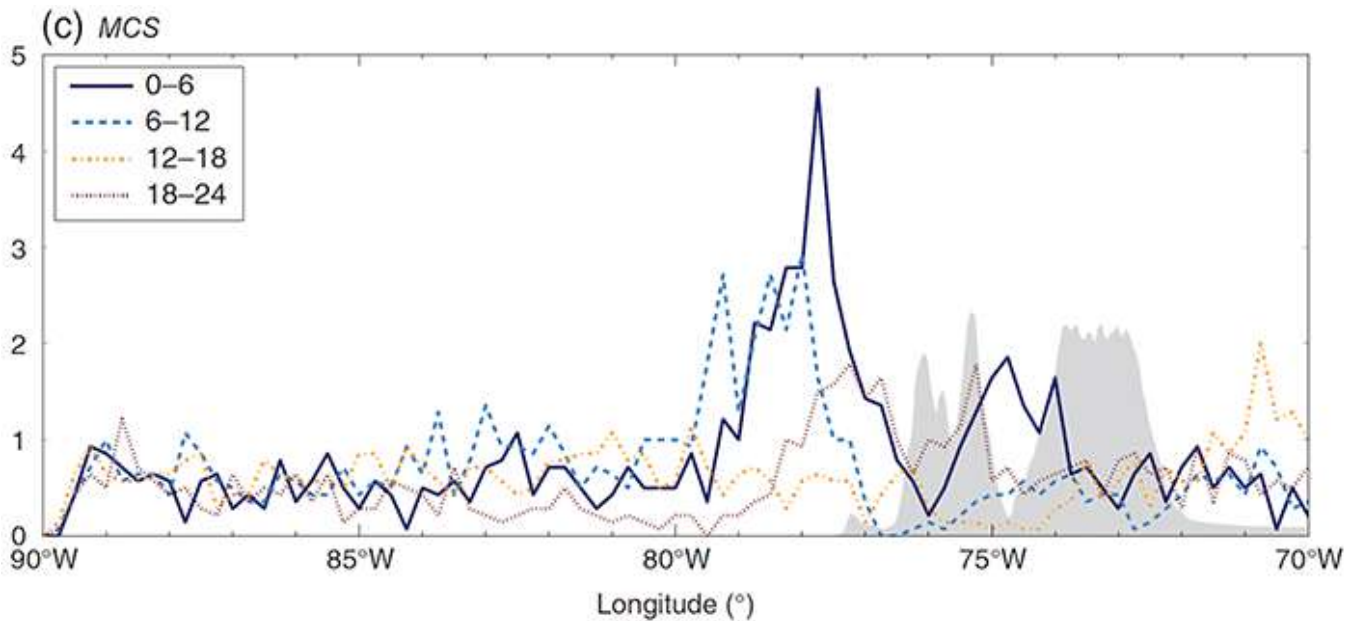


Figure 29. Composite cross sections of the diurnal cycle (in local time) of the mean annual number of MCSs, averaged over meridional bands between 2°N and 8°N. Gray shading represents the average topographic relief between 5°N and 6°N.

Source: Reproduced from Jaramillo et al. (2017) with authorization.

Diurnal Variability

In the tropics, local to mesoscale day-periodic processes and circulations dominate regional weather, unlike higher latitudes where the diurnal cycle is much smaller than the annual due to radiation geometry. In tropical land regions, land-sea breezes and mountain circulations drive the diurnal patterns of cloudiness, rainfall, and weather (Hastenrath, 2012). In mountainous areas, orography and insolation create local wind circulations (anabatic and katabatic) and sharp contrasts in surface heat budgets, influenced by variations in heat capacity, albedo, vegetation, surface roughness, and evapotranspiration, affecting the atmospheric boundary-layer dynamics.

The Colombian Pacific coast and the adjacent ocean, the Andes, and the Amazon basin are among the areas with the most prominent diurnal cycles of precipitation in South America, with afternoon convection triggered by moisture advection, surface net radiation, latent and sensible heat fluxes, evapotranspiration, plus coastal and topographic effects (Giles et al., 2020). For instance, the winds of the Choco, Caribbean, and Orinoco LLJs exhibit clear-cut diurnal cycles (Figure 30). The Caribbean and the Orinoco LLJs are stronger at 12:00 UTC, and weaker at 18:00 UTC, while the Choco LLJ is nearly opposite with stronger winds at 18:00 and 00:00 UTC and weaker at 12:00 UTC.

Over the Pacific coast of Colombia, higher precipitation intensities occur between 09:00 and 21:00 hours UTC (04:00–16:00 hours LST), with the highest at 18:00 UTC (13:00 LST) and lower values between 00:00 and 03:00 hours UTC (19:00–22:00 hours LST). Rainfall is very much concentrated over land between 18:00 and 21:00 UTC (13:00–16:00 LST) and migrates offshore into the adjacent Pacific during the midnight and early morning hours (03:00–12:00 UTC or 22:00–07:00 LST). Such

westward movement of rainfall has been attributed to gravity waves that emerge in the high Andes owing to the afternoon heating that propagate offshore during midnight and early morning hours (Dellaripa et al., 2023; Houze, 2004; Mapes et al., 2003; Mejía et al., 2021; Yepes et al., 2020), as illustrated in Figure 34. The study of Dellaripa et al. (2023) found that days when thunderstorms move farther away from the Colombian coast are characterized by higher levels of moisture near the surface, facilitated by enhanced Choco and Caribbean–Panama LLJs. In turn, rain over this region can occur in intense bursts (showers) or in extended periods of less intense rainfall (rains). The latter regime often produces more total rain than the former. Rains require a very moist atmosphere but can occur with weak atmospheric instability, whereas showers occur in drier atmospheres but require stronger instability (Raymond et al., 2024).

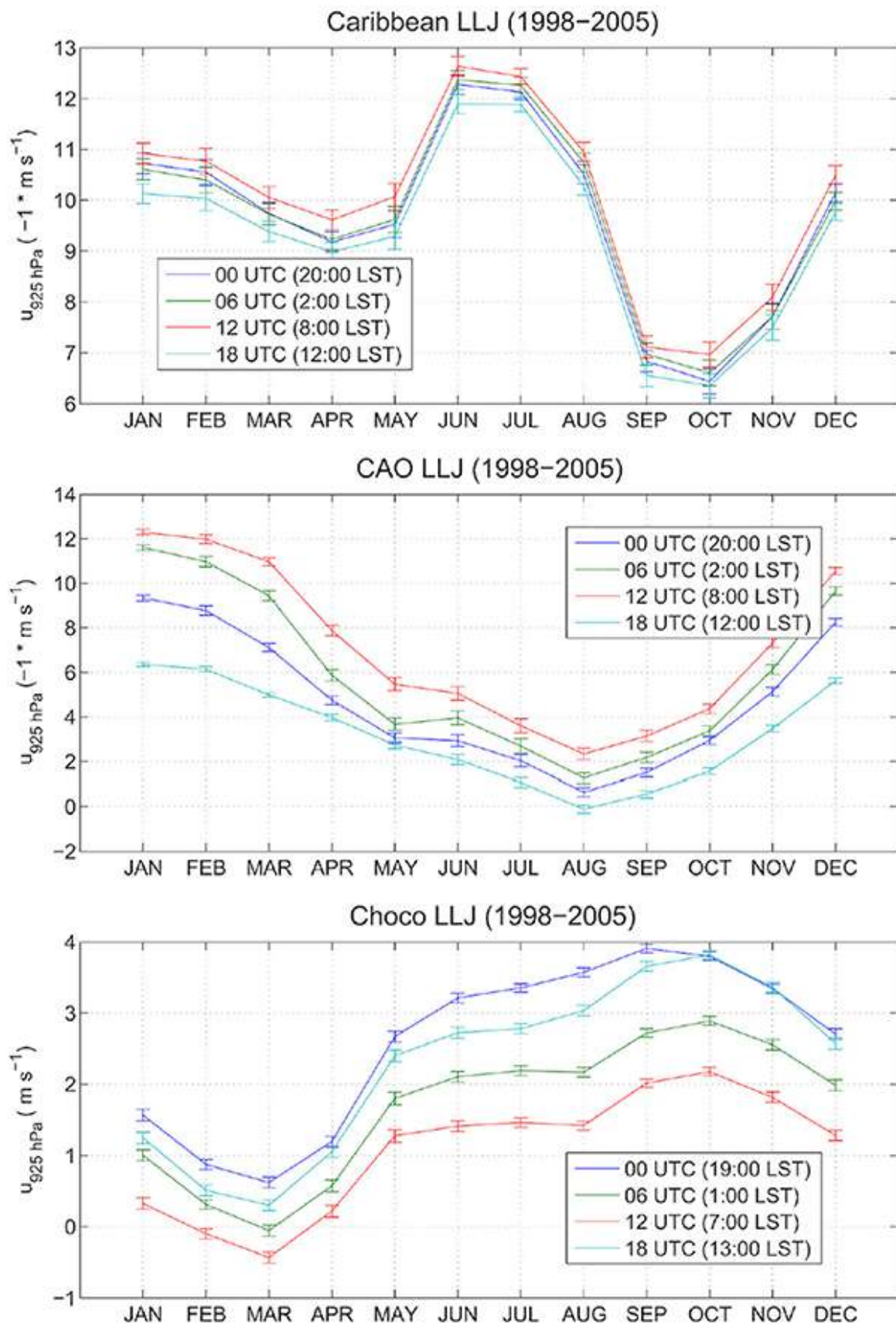


Figure 30. Average diurnal cycle of the zonal winds at 925 hPa through the annual cycle for the period 1998–2005, at the core of the Caribbean (top), Orinoco (CAO, middle), and Choco (bottom) LLJs. Error bars denote the standard error of the mean.

Source: ERA-Interim Reanalysis. Reproduced from Bedoya-Soto, Aristizábal, et al. (2019) with authorization.

The diurnal cycle of precipitation in the Colombian Andes exhibits strong spatial variability, with unimodal or bimodal behaviors, peaking at different hours, even at very small spatial scales (Poveda et al., 2005). Generalized common features are the daily minimum between 07:00 and 11:00 LST and the midnight maximum along the eastern slope of the Central range of the Colombian Andes. Figure 32 shows the long-term mean monthly march of the diurnal cycle at selected stations in the tropical Andes of Colombia. Some rain gauges show consistent peak rainfall at a fixed hour yearly, while others vary seasonally (shifting-phase). Some have a two-peak cycle during transition periods, as shown in Figure 33 for Medellín's valley, discussed by Bedoya-Soto, Aristizábal, et al. (2019). Such combination of seasonally shifting-phase uni- or bimodal diurnal cycles has also been identified in four distinctive groups of rain gauges located over a transect from the Andes to the Amazon in Ecuador by Ruiz-Hernández et al. (2021). They concluded that diurnal precipitation variations are influenced by local topography and wind patterns, including katabatic and anabatic winds (Trachte & Bendix, 2012; Trachte et al., 2010). This was also observed in the Colombian Andes (Arias et al., 2021; Bedoya-Soto, Aristizábal, et al., 2019; Giles et al., 2020; López & Howell, 1967; Mapes et al., 2003; Warner et al., 2003). Other mechanisms affect the diurnal cycle of rainfall in the tropical Andes such as both phases of ENSO and the Madden-Julian Oscillation, tropical easterly waves, hurricanes in the Caribbean and the northeast tropical Pacific, but not so the moon phases (Poveda, Mesa, Agudelo, et al., 2002). Also, Saharan dust events affect the seasonal and diurnal cycle of rainfall in the Caribbean and the Amazon river basin (Morales-Medina et al., 2024; Swap et al., 1992).

Furthermore, Land-ATmosphere Interactions (LATIs) impact the diurnal variability of precipitation, particularly in the Central Andes (CA) of Colombia, shedding light on Terrestrial Moisture Recycling (TMR) mechanisms driving regional climate patterns (Bedoya-Soto & Poveda, 2024; Bedoya-Soto, Aristizábal, et al., 2019). The region's complex topography and heterogeneous land surfaces create microclimatic conditions that are strongly influenced by LATIs. TMR mechanisms are vital for regional climate, as land surface evaporation fuels convective processes and precipitation (Bedoya-Soto & Poveda, 2024; Escobar et al., 2022; Hoyos et al., 2018, 2019). In the CA, the diurnal cycle of rainfall exhibits distinct phases, influenced by variations in atmospheric and soil moisture sources (Bedoya-Soto, Aristizábal, et al., 2019). LATIs, including TMR, contribute to the observed midnight/early morning peak in precipitation during certain seasons, such as June–July–August.

Over Lake Maracaibo in Venezuela, precipitation exhibits a strong diurnal cycle, peaking at night (land breeze) and reaching a minimum during the day (lake breeze; Biasutti et al., 2012; Mapes et al., 2003). In northern Amazonia, rainfall peaks around noon near the Atlantic coast, with the diurnal phase shifting later as precipitation moves inland toward the southwest, as shown in Figure 31 (Hayden et al., 2023), reaching a late afternoon peak in western Amazonia (Angelis et al., 2004; Giles

et al., 2020; Hayden et al., 2023; Tai et al., 2021). This pattern is linked to sea breeze disturbances near the coast that propagate inland, helping to trigger MCS under favorable conditions for convection (Hayden et al., 2023; Tai et al., 2021).

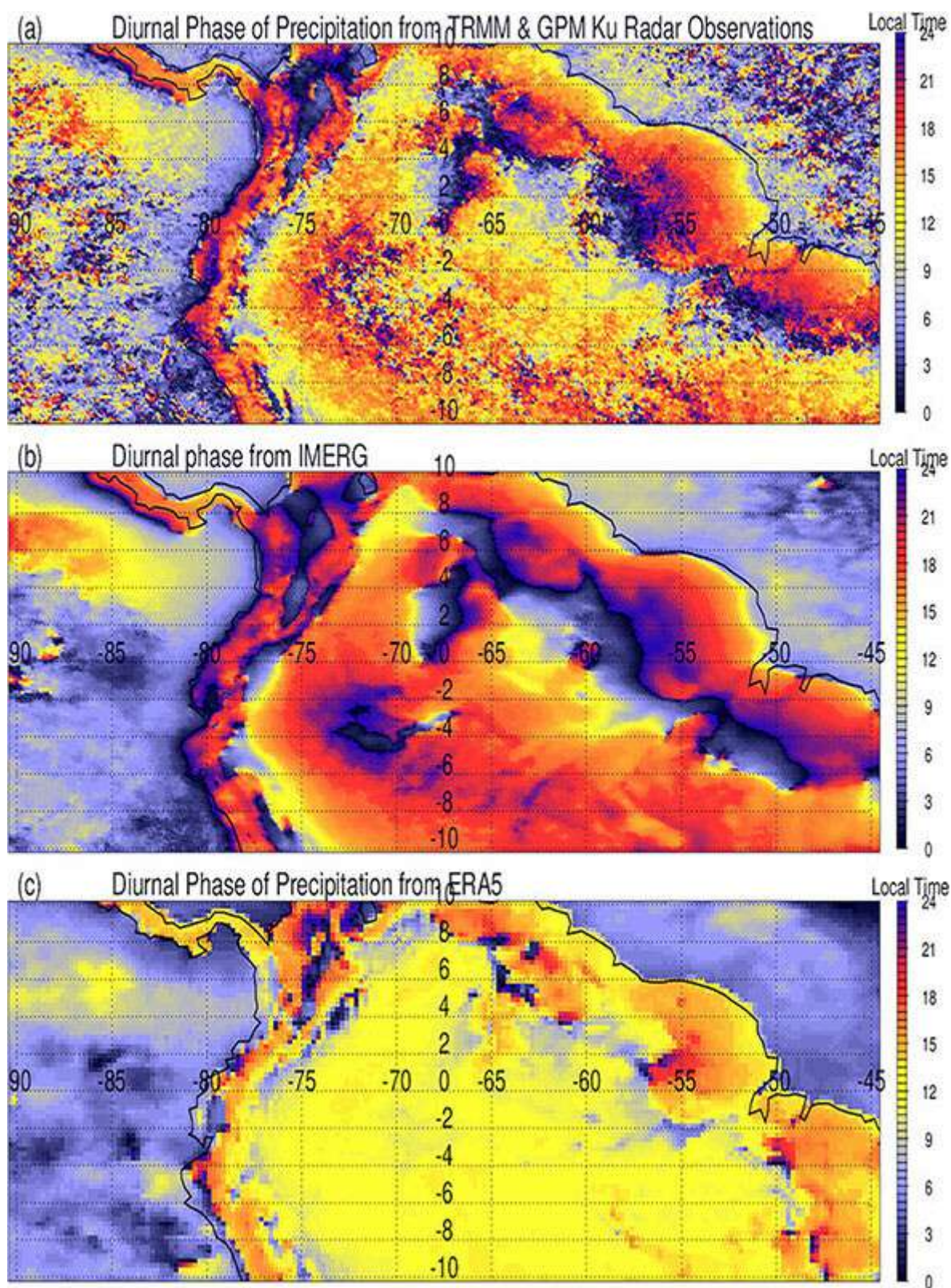


Figure 31. Diurnal (first) harmonic phase of hourly precipitation (2001–2018) observed by (a) Ku radar and (b) IMERG at $0.1^\circ \times 0.1^\circ$ resolution, and (c) ERA5 at $0.25^\circ \times 0.25^\circ$ resolution.

Source: Hayden et al. (2023).

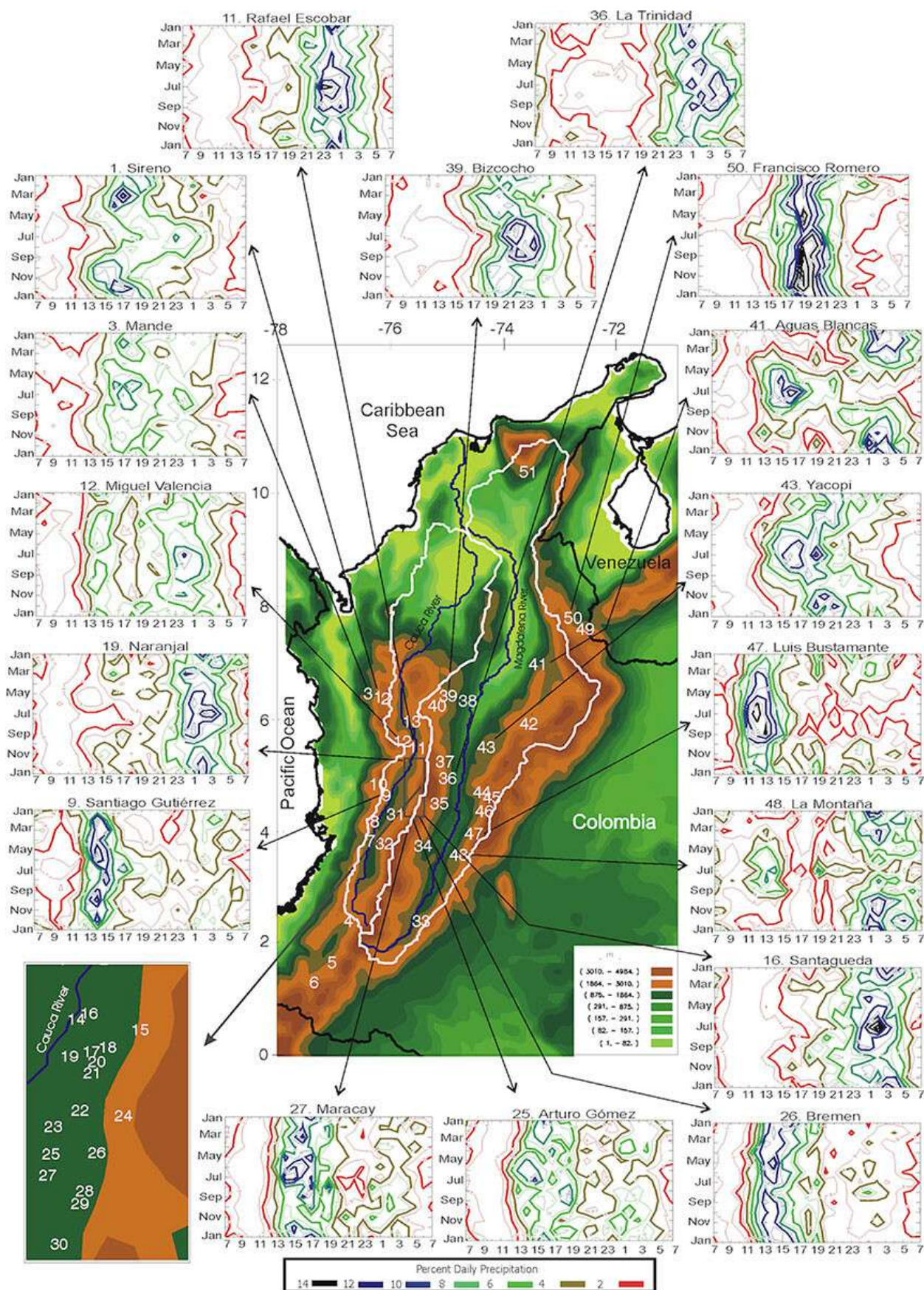


Figure 32. Monthly march of the diurnal cycle of rainfall at 17 selected stations in the tropical Andes of Colombia. The diurnal cycle is defined from 07:00 to 07:00 LST, and interpolated isolines indicate percent of total daily rainfall, with the color scale shown at the bottom. Boundaries of the neighboring Cauca (left) and Magdalena (right) River valleys are shown in white. The inset at the bottom left shows details of rain gauges located in the western flank of the Central cordillera.

Source: Reproduced from Poveda et al. (2005) with authorization.

Concluding Remarks and the Way Forward

Climate and weather patterns discussed in the present article highlight the complex ocean–land–atmosphere interactions involved in NWSA. With neighboring oceans, the Andes, and the Amazon and Orinoco basins, the area showcases diverse topoclimatic variations and climate gradients. Further advances in observation and monitoring networks, isotopic analysis, remote sensing, and modeling studies will deepen understanding of the described climate. Focus areas include unraveling the multiscale spatiotemporal dynamics for better predictability, from near-term nowcasting to subseasonal and interannual forecasting (Arias et al., 2021; Espinoza et al., 2020; Poveda et al., 2020).

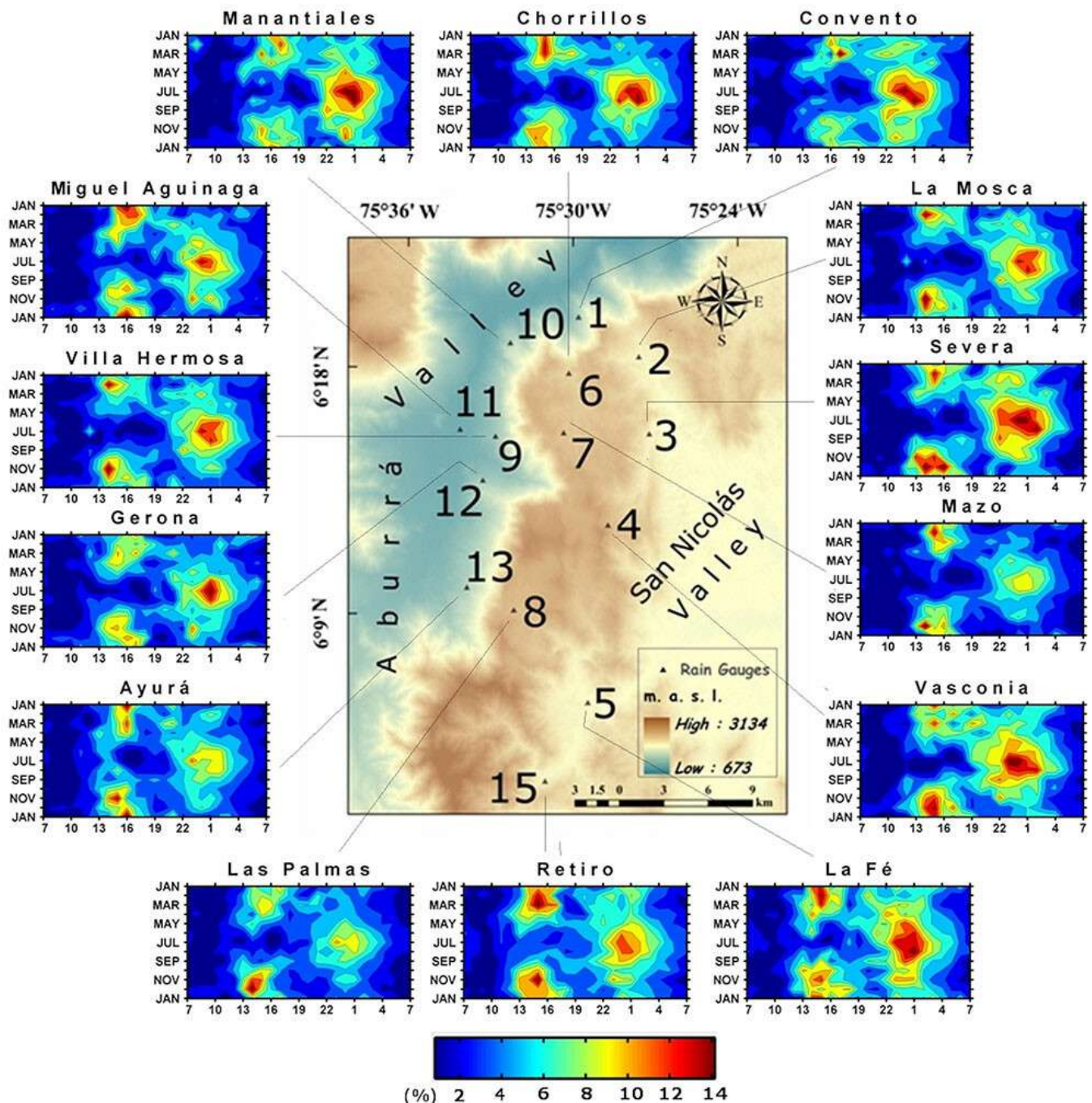


Figure 33. Monthly march of the diurnal cycle of rainfall (hourly percent of the daily precipitation) at diverse rain gauges located in the Medellín Valley and the adjacent San Nicolás plateau, along the Central range of the Colombian Andes.

Source: Adapted from Bedoya-Soto, Aristizábal, et al. (2019) with authorization.

Numerical modeling for NWSA faces challenges due to the resolution required to represent various atmospheric systems and the configuration of model physical parameterizations. The Andes impose strong forcing on atmospheric flow, with weather and climate influenced by small-scale motions, particularly between the micro-alpha (0.2–2.0 km) and meso-beta scales (20–200 km; Orlanski, 1975). However, typical global models for Numerical Weather Prediction (NWP) use grid spacings

around 10 km, with effective resolutions over 50 km, meaning most convection and some atmospheric systems (e.g., in intra-Andean valleys) are missed. Grid spacings for seasonal-to-subseasonal (S2S) models are even coarser, posing challenges for representing regional variability. Additionally, most atmospheric models, such as the Weather Research and Forecasting (WRF) model from National Center for Atmospheric Research, are developed outside the tropics, meaning some parameterizations (e.g., cloud microphysics or boundary layer processes) may not be optimized for tropical conditions (Martínez-Castro et al., 2018; Zhang & Wang, 2017).

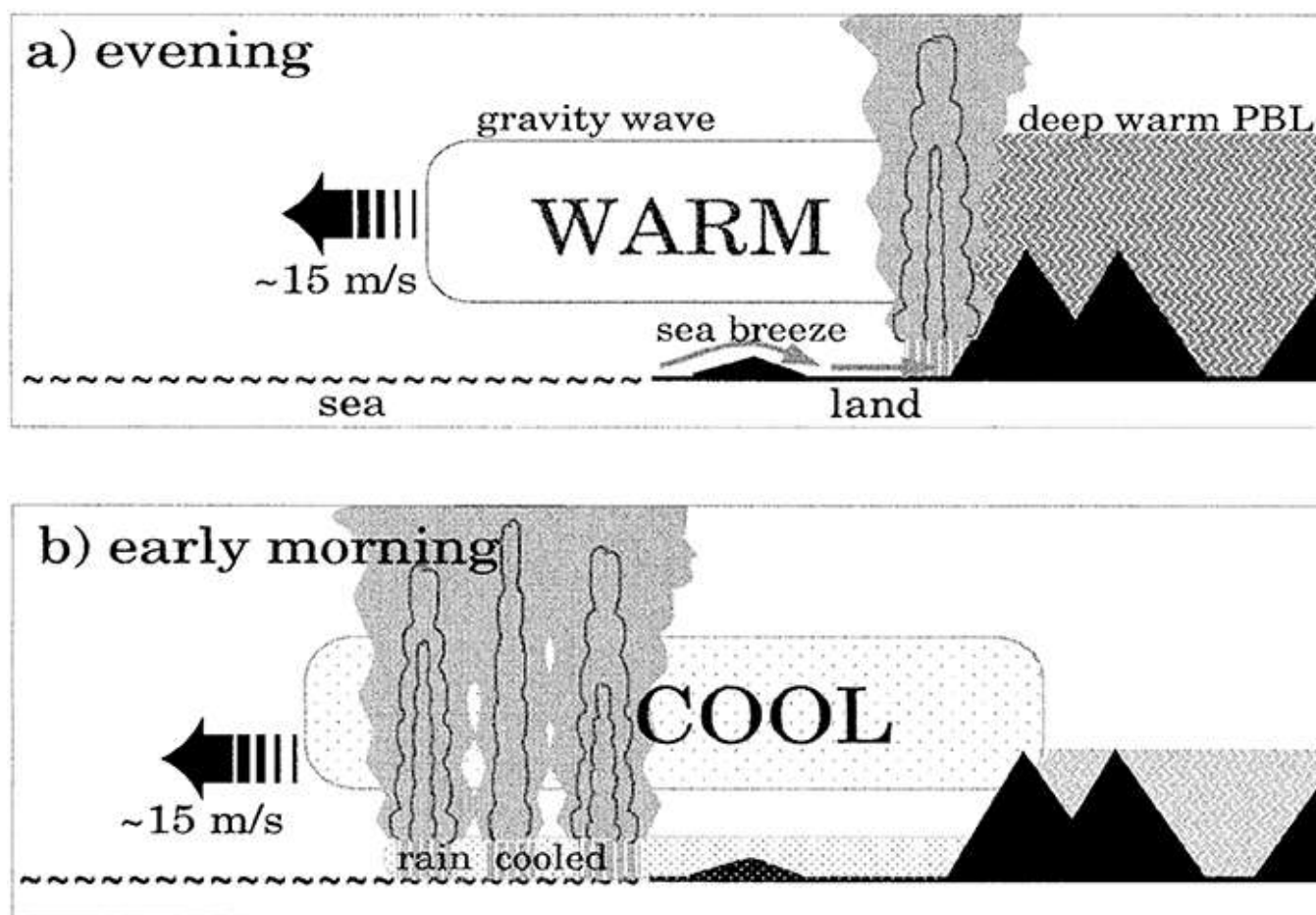


Figure 34. Schematic depiction of diurnal gravity waves emitted by the mixed layer over mountainous terrain, and associated deep convection.

Source: Reproduced from Mapes et al. (2003) with authorization.

Modeling at “convection-permitting” resolutions (e.g., grid spacing of 3–4 km) for NWSA has helped with understanding regional and local characteristics, but challenges remain, such as biases in simulated precipitation and organized convection (Gomez-Rios et al., 2023; Martínez, Rendón, et al., 2024; Yepes et al., 2019, 2020). Better models may be needed to capture important land-vegetation-atmosphere feedbacks (Martínez et al., 2022) and fully coupled atmospheric-ocean simulations (Martínez et al., 2019). Limitations in simulating mesoscale circulations, convective organization, and surface-atmosphere couplings with the ocean, land, and vegetation can impact

long-range effects of NWSA on downstream regions, crucial for accurate S2S forecasts. Comprehensive model evaluation would benefit from diagnostics like statistics on Mesoscale Convective Systems (e.g., trajectories, size, lifespan), low-level jets (Choco-Jet, CLLJ, OLLJ), and the diurnal precipitation cycle. Further research is needed on model validation, focusing on tuning and parameter calibration for tropical mountainous environments like NWSA.

Such modeling efforts require parallel advancements in monitoring a wide range of variables and their assimilation into models, both at the surface and across atmospheric levels. This is particularly challenging due to the region's sparse data availability (Condom et al., 2020). In-situ soil moisture data sets, surface energy balance measurements, and atmospheric boundary layer data are almost nonexistent across NWSA. Radiosonde data are limited, available at few locations and only once per day, while high-resolution rainfall intensity measurements from radars are extremely scarce. This data gap is especially critical in the Andes and the wet Pacific coast of Colombia, where satellite precipitation estimates need significant improvement to accurately represent in-situ rainfall (Vallejo-Bernal et al., 2021). This highlights the need for more field campaigns, like those for the Choco Jet (CHOCO-JEX; Yepes et al. (2019)), or those proposed by ANDEX <<https://www.andex-rhp.org/>>, a regional hydroclimatic program of GEWEX focused on the Andes.

The fragile ecosystems and vulnerable populations dependent on this region's natural resources need better climate products, targeted risk assessments, and bottom-up governance strategies that support sustainable practices. This is crucial in addressing the current and future combined impacts of deforestation, land-use changes, pollution, and climate change.

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Notes

1. Reflections on advances in health and environment research in the context of the COVID-19 pandemic.