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RESEARCH ARTICLE

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# Drivers of seasonal rainfall variability over the Angolan and Namibian plateaus

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**Abstract**

Southern Africa has been strongly affected by ongoing climate change in recent decades. Rainfall variability is modulated by regional patterns of moisture advection and convergence in the lower troposphere. Using reanalysis, ground and satellite-based rainfall products and observations from 10 weather stations, we perform a synoptic and climatological analysis focussing on atmospheric circulation, moisture transport and their relationship with rainfall anomalies over the Angolan and Namibian Plateau region. Results clearly show that a stronger (weaker) Zambezi low level jet (LLJ) magnitudes are associated with above (below) normal rainfalls over the main Angolan and Namibian plateaus. With lower confidence, a stronger Limpopo LLJ may also lead to enhanced rainfall over Namibia and southeast Angola. The Zambezi LLJ moisture fluxes are moderately controlled by Mozambique Chanel Trough and Angola Low intensities, while the Limpopo LLJ intensities have very low influence from the Mozambique Chanel Trough and Angola Low, respectively. The Angola Low in its tropical phase is associated with deeper moisture convergence and stronger vertical velocities, leading to higher amounts of precipitable water within the air column, thus enhancing precipitation over the region. It is shown that the major moisture source of rainfall, which is advected to via the Zambezi LLJ, is the Indian Ocean. Meanwhile, the Atlantic Ocean plays a minor role. Given the current lack of observations and projected climate change, further research and investments are urgently needed in the region, for example, regarding the expansion of the surface data network.

**KEYWORDS**

Angola Low, low-level jet, Mozambique Channel Trough, plateaus, rainfall

## 1 | INTRODUCTION

Most sub-Saharan economies rely on basic agriculture, highly dependent on precipitation, due to the lack of a better land management and technology (Branca et al., 2013; Sultan & Gaetani, 2016). These regions are deeply vulnerable to climate variability and change, that is, they are increasingly subject to hazardous weather

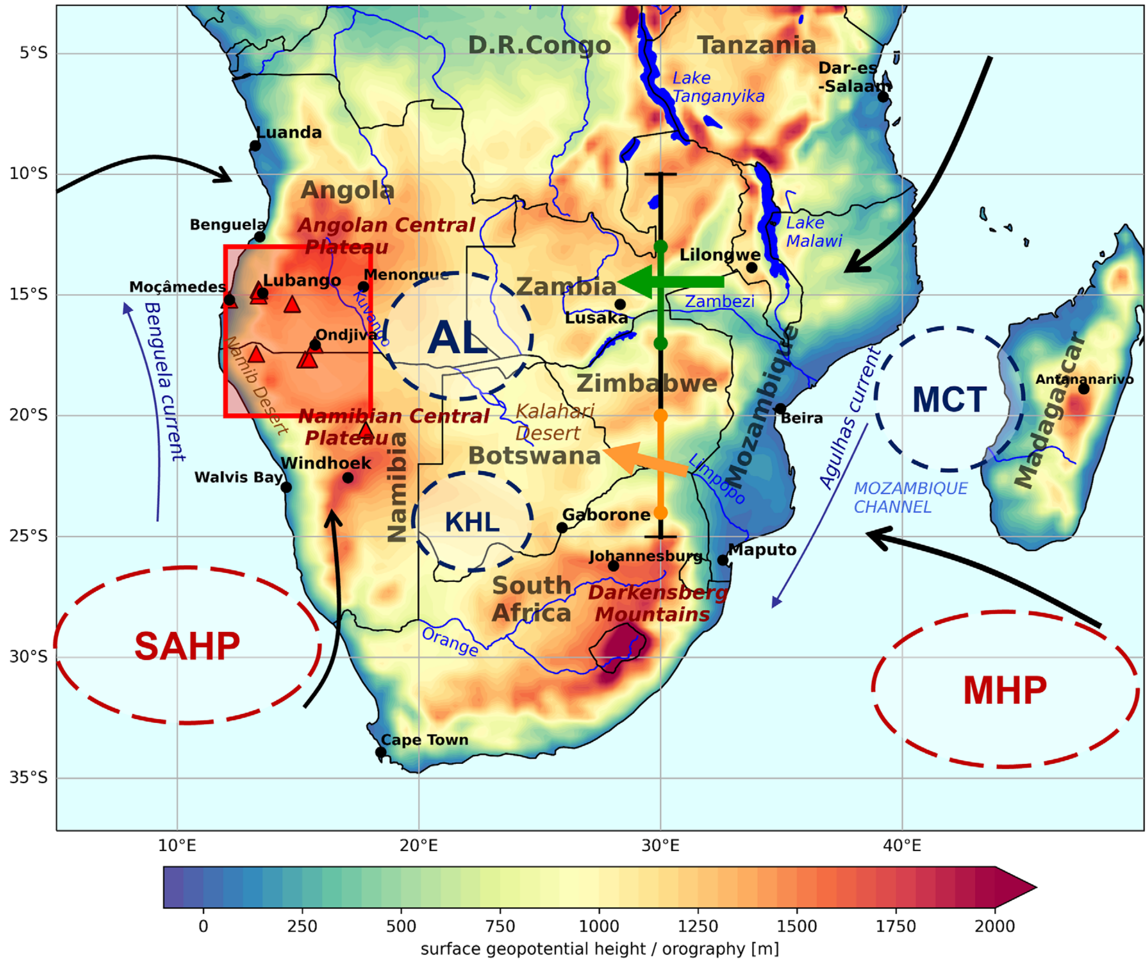


**FIGURE 1** Surface geopotential height (or orography) over southern African subcontinent (colour scale), retrieved from ERA5. Red triangles located in southwest Africa represent the exact location of 10 SASSCAL weather stations. The black line represents the meridional cross section used to produce Figure 4. Values of IVTu for Z-LLJ and L-LLJ were retrieved with respect to green (13°–17°S) and orange (20°–24°S) sections, respectively. Green and orange arrows indicate the mean direction of water vapour via Zambezi and Limpopo LLJ, respectively. The red rectangle represents the study region. Based on Munday and Washington (2017), Barimalala et al. (2021) and Rapolaki et al. (2020), thick black arrows represent the main routes of water vapour transport towards the subcontinent. Important synoptic and mesoscale features are represented with the acronyms AL (Angola Low), MCT (Mozambique Channel Trough), KHL (Kalahari Heat Low), SAHP (South Atlantic High Pressure) and MHP (Mascarene High Pressure). Other important locations are identified, such as main cities, rivers, lakes, deserts, plateaus and ocean currents. [Colour figure can be viewed at wileyonlinelibrary.com]

and climate conditions such as extreme rainfall, floods and severe droughts (Awadallah & Tabet, 2015; Dinis et al., 2021; Luetkemeier & Liehr, 2019; UNDP, 2016). Such extreme events are one major cause of diseases, malnutrition, food insecurity or even mass migrations, leading to high socio-economical exposures to variations in climate patterns and associated extremes (Liu et al., 2015; Sarr, 2012; Wheeler & von Braun, 2013). Southwest Africa is particularly prone to these extreme events, which are aggravated by the limited economic and institutional capacity to respond to severe climate events, most of them still poorly understood and predicted (Limones et al., 2020; UNDP, 2016). Recent literature covering southwest Africa regions projects a widespread warming, an overall precipitation reduction and an ensuing freshwater deficit, increased aridity and a significant loss of biodiversity over the subcontinent, including an exposure of ~70% of livestock to droughts, essentially in the western parts, such as in Namibia and Angola (Carvalho et al., 2017; Collins et al., 2013; IPCC, 2021; Lourenco et al., 2023). Moreover, Angola appeared as a country with the most underreported humanitarian crisis due to droughts and floods, being estimated more than 7 million people needing humanitarian help (CARE International, 2023). Of particular interest is the region that encompasses the Angolan Highlands, which are the headwaters of important rivers like Kunene, Okavango and Kwanza and can be seen as a "water tower" for some arid regions in Angola, Namibia and Botswana (Lourenco et al., 2023).

Angolan Highlands are part of a large interior plateau in southwest Africa, for example, the Namibian and the Angolan Central Plateaus, often laying above 1200 m, cover most of south-eastern Angola and northern-central Namibian territories (Figure 1). The climate in the region is characterized by a dry season that lasts from April/May to October (austral winter) and a rainy season occurring between November and March/April (NDJFM, austral summer). Complex orography plays a key role on spatial distributions of temperature values and rainfall amounts (Huntley et al., 2019), with a very strong east–west height gradient along Namibia and Angolan coasts. Thus, during the rainy season, there are strong precipitation gradients between the coastline and the interior plateau regions, with higher amounts of rainfall inland and over the mountains than at the shoreline (Huntley et al., 2019).Austral summer rainfall occurring across southwest Africa is fed by low-level transport of water vapour, mainly from three sources: Atlantic Ocean, Indian Ocean and the Congo basin (Barimalala et al., 2021; Munday & Washington, 2017; Rapolaki et al., 2020). Over the Indian Ocean, easterly low-level moisture fluxes are generally influenced by the Mascarene High. From the Atlantic Ocean, westerly moisture fluxes onto southern Africa are related to a semipermanent low-pressure system centred near the Angola-Namibian border (named Angola Low, or AL) (Figure 1). The convergence of Indian and Atlantic Ocean low-level moisture fluxes enhances convective processes associated with the ITCZ over the subcontinent, which is placed south of the equator during this time of year, promoting cloud formation and precipitation (Barimalala et al., 2018, 2021; Barry & Chorley, 2003; Huntley et al., 2019). Moreover, the Mozambique Channel Trough (or MCT) is a cyclonic system that occurs in austral summer and is usually placed south of the Mozambique Channel (Barimalala et al., 2020). Transport of humidity can occur can occur within a shallow layer of meandering, fast-moving air within the first kilometre above surface named low-level jets, or LLJs (Algarra et al., 2019; Stull, 1988), being one of the most efficient ways to transport water vapour in the troposphere (Algarra et al., 2019; Payne et al., 2020; Ramos et al., 2016, 2019). In this context, two main large river valleys are associated with intense LLJs responsible for a considerable transport of water vapour from the Indian Ocean towards the southwestern part of the subcontinent: namely the Limpopo River valley low-level jet (L-LLJ) and the Zambezi River valley low-level jet (Z-LLJ). These valleys are located within the East African Rift System, which is a large mountain range covering most of eastern Africa. This set of complex orography contains several other associated orographic LLJs, responsible for water vapour transport towards southern African mainland. This transport characterizes one of the main mechanisms for rainfall to occur in these regions (Munday et al., 2021), thus impacting on the economy, society, and biodiversity of such areas. It is also known that rainfall patterns may considerably vary from year to year. For example, Seregina et al. (2019) developed methodologies to identify the beginning and the end of the rainy season over East Africa, where intra-seasonality is largely influenced by regional features, such as LLJs or local low-tropospheric easterly winds.

Literature suggests that rainfalls over the LLJs regions are highly influenced by the moisture transport associated with the LLJs themselves (Gimeno-Sotelo & Gimeno, 2023). Both LLJs are mainly induced by horizontal thermal contrasts and are reinforced by the Bernoulli effect via orographic constraints (Barimalala et al., 2018; Munday et al., 2021; Spavins-Hicks et al., 2021). It is plausible that both AL and MCT influence both LLJs intensities, thus modulating rainfalls over the Angola-Namibian plateaus. Understanding relationships between these features is crucial to develop further studies regarding precipitation variability and rainy season onset and cessation. Until now, little attention has been paid on scientific literature on the influence of both LLJs and both AL and MCT on rainfalls patterns across Angola-Namibian plateaus—our study region, defined by the area (13°–20°S, 12°–18°E; Figure 1). This choice is motivated by many of the scientific aspects mentioned above and the availability of new weather station data. With this work, we aim to overcome this gap and pose the following overall research questions:

- What is the influence of both Zambezi and Limpopo LLJs on rainfall over our study region?
- What is the role played by the AL and MCT on the humidity transport via both LLJs and, consequently, on rainfalls across our region of interest?

To try to answer these questions, various rainfall datasets, ERA5 reanalysis and a network of recent surface weather stations data were used. In order to associate rainfall with both AL and MCT, a methodology used by Howard and Washington (2018) based on potential vorticity was important to detect AL and MCT positions along the rainy season, as well as distinguish the AL in two phases—*thermal* and *tropical* low phase.

The study is structured as follows; in section 2, data sources are presented, as well as the methodologies used. In section 3, we show the main results of our study regarding moisture advection and the associated atmospheric drivers that influence regional rainfall over our region of interest. In section 4, we discuss our findings and in section 5, we conclude by presenting the answers to the research questions and what contribution does this study give to scientific knowledge over the region. Limitations of our work and future research perspectives are also presented in the last section.

## 2 | DATA AND METHODOLOGY

### 2.1 | Weather station data

Angola and Namibia regions were severely affected by civil wars, when most existing weather and hydrological stations were destroyed. The surrounding areas were filled with minefields, compromising the access to weather station locations (Lourenco et al., 2023). For instance, over Angola, in 1974, at least 225 "climate posts" covered the entire country. The lack of weather station coverage over the region during the early 2000s contrasts with the late 1960s, when the country had significantly better weather station coverage (Huntley et al., 2019). As a result, nowadays, there is still a critical lack of climate data from surface stations across these places. During the period 2012–2016, a series of new weather stations were installed in southern Angola and northern Namibia regions by the Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL; https://sasscal.org/) program, managed and funded by Germany's Federal Ministry of Education and Research, in cooperation with the University of Hamburg and local meteorological services (Luetkemeier et al., 2018; Posada et al., 2016). Thus, monthly and daily wind ($u$, $v$) and precipitation data from 10 SSASCAL weather stations distributed over southern Angola and northern Namibia was used in this work (http://www.sasscalweathernet.org/). Retrieved daily and monthly data covered the period between the beginning of each station's data report and December 2020 and the locations of those weather station are represented as red triangles in Figure 1. From 10 weather stations, only 3 (placed in northern Namibia) started their recordings in 2012. There is one station located outside the target area, yet it is representative of the region. Stations in Angola were not installed until 2014 thus, only in situ data since 2014 was considered (weather station's details in Table S1, Supporting Information).

### 2.2 | Reanalysis and precipitation datasets

Due to the paucity of surface stations, we utilized other sources of rainfall data: GPCC (Global Precipitation Climatology Centre, gauge-only products with a spatial resolution of $0.25° \times 0.25°$, $\sim 30 \times 30$ km) (Schneider et al., 2008) and a container of uniformly gridded precipitation database named FROGS (Frequent Rainfall Observations on GridS, with a uniform spatial resolution of $1° \times 1°$, $\sim 111 \times 111$ km) (Roca et al., 2019), providing data from various sources: reanalysis-CFSR (Climate Forecast System Reanalysis), JRA-55 (Second Japanese global reanalysis) and MERRA2 (Modern-Era Retrospective analysis for Research and Applications), as well as the gauge-only product CHIRPS (Rainfall Estimates from Rain Gauge and Satellite Observations) and REGEN (Rainfall Estimates on a Gridded Network)—see product specifications in Table 1. All FROGs datasets used ranges from 1980 to mid-2010s and thus 1981–2010 was used as the 30-year reference period. Monthly and daily surface and pressure level data from ECMWF's most recent reanalysis (ERA 5th generation or ERA5) was retrieved for the period of 1981–2020 (Hersbach et al., 2020). Even though ERA5 rainfall improved over previous reanalysis in Africa, such as ERA-Interim (Gleixner et al., 2020; Steinkopf & Engelbrecht, 2022), the rainfall data stem from short-term model forecast, thus being impacted by both relatively few input data for data assimilation and deficits of models with parameterized moist convection.

ERA5 horizontal resolution is $0.25° \times 0.25°$ ($\sim 30 \times 30$ km) and vertical resolution is 25 hPa until 750 hPa level, changing to 50 hPa upwards. To better understand precipitation drivers over Namibia and Angola regions, ERA5 rainfall data was used for the domain (0°N–25°S, 0°W–25°E). Variables retrieved from ERA5 are listed in Table 1.

Negative (positive) values of zonal IVT (henceforth termed IVTu) indicate a *westward* (*eastward*) transport. Even though IVT represents a vertical integration of water vapour transport from the surface until the top of the atmosphere, most of the humidity is transported at the lower levels of the troposphere (>700 hPa), that is, approximately at the same levels as the Zambezi and Limpopo LLJs. For these jets, the IVTu is ∼20–30 times higher than the meridional IVT for the Z-LLJ and ∼2–10 times higher for the L-LLJ (not shown). Thus, from here onwards, to facilitate the analysis, IVTu values are assumed to represent seasonal variations of the amount of water vapour transported across these valleys. IVTu was retrieved over a small meridional section in both river valley regions (at 30°E). Both sections are presented in Figure 2 as an orange (Limpopo; 20°–24°S) and green line (Zambezi; 13°–17°S). Data for our study region was used over the rainy season months (November–March, NDJFM) and for both Z-LLJ and L-LLJ, and the 25th and 75th IVTu percentiles were computed in order to distinguish between a weak or a strong LLJ phases.

**TABLE 1** Monthly averaged and daily retrieved variables (in single and pressure levels) for the period of 1981–2020, their physical units and correspondent pressure level(s).

| Variable | Physical units | Pressure level (hPa) | Dataset | Source | Spatial resolution | Time range |
|---|---|---|---|---|---|---|
| **Single levels** | | | | | | |
| Rainfall | m | - | CFSR<br>JRA-55<br>MERRA2<br>REGEN_all_v1_2019<br>CHIRPSv2.0 | Roca et al. (2019) | $1^\circ \times 1^\circ$, $\sim 111 \times 111$ km | Jan 1981–Dec 2010 (monthly and daily) |
| | | | GPCC | National Oceanic and Atmospheric Administration (Schneider et al., 2008) | $0.25^\circ \times 0.25^\circ$, $\sim 31 \times 31$ km | Jan 1981–Dec 2020 (monthly and daily) |
| | | | ERA5 | Copernicus Climate Change Service (Hersbach et al., 2020) | | |
| Integrated eastward and northward water vapour transport (IVT) | $kg \cdot m^{-1} \cdot s^{-1}$ | - | ERA5 | Copernicus Climate Change Service (Hersbach et al., 2020) | $0.25^\circ \times 0.25^\circ$, $\sim 31 \times 31$ km | |
| Vertically integrated moisture divergence | $kg \cdot m^{-2}$ | - | | | | |
| Total column rainwater | $kg \cdot m^{-2}$ | - | | | | |
| Geopotential height at surface/orography | m | - | | | | Invariable with time |

| Variable | Physical units | Pressure level (hPa) | Dataset | Source | Spatial resolution | Time range |
|---|---|---|---|---|---|---|
| **Pressure levels** | | | | | | |
| $u$, $v$ components of mean wind | $m \cdot s^{-1}$ | 1000–500 | ERA5 | Copernicus Climate Change Service (Hersbach et al., 2020) | $0.25^\circ \times 0.25^\circ$, $\sim 31 \times 31$ km | Jan 1981–Dec 2020 (monthly and daily) |
| Geopotential height | m | 800 | | | | |
| Specific humidity | $kg \cdot kg^{-1}$ | 1000–500 | | | | |
| Potential vorticity | $K \cdot kg^{-1} \cdot m^2 \cdot s^{-1}$ | 800 | | | | |
| Vertical velocity | $Pa \cdot s^{-1}$ | 400–300 | | | | |

*Note*: Data retrieved from reanalysis and mixed satellite and ground-based products.

### 2.3 | Detection of synoptic-scale tropical lows

The determination of the positions and intensities of the main southern African low-pressure systems over time is essential to understand rainfall variability across the region of interest. Previous studies identified AL and MCT systems by geopotential height or relative vorticity minima between 700 and 850 hPa over the regions where they usually form during the austral rainy season

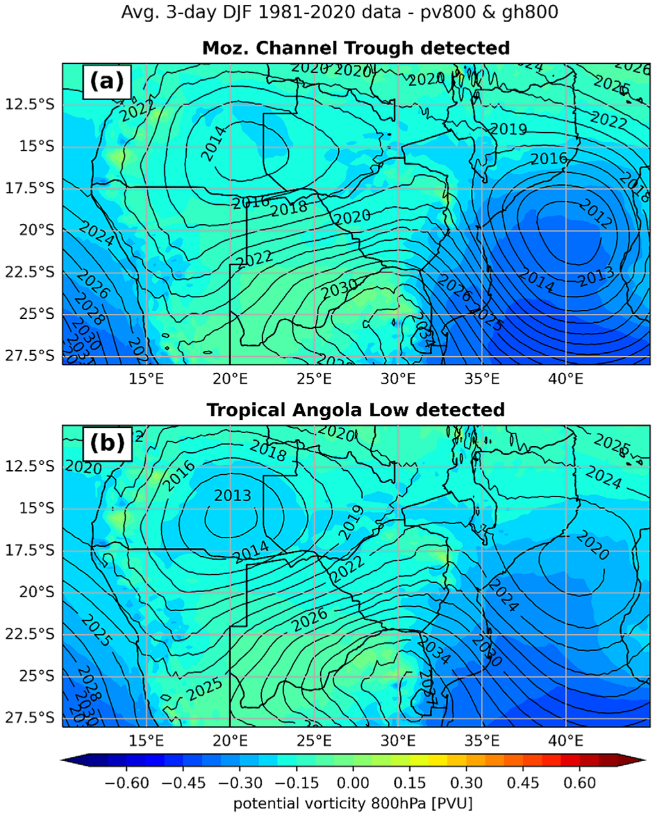


**FIGURE 2** Three-day averaged ERA5 data of geopotential height (contours) and potential vorticity (colour shading) at 800 hPa, for days where an AL was detected. Data from Dec.-Feb. 1981/82-2020/21. Potential vorticity is represented in potential vorticity units (PVU). [Colour figure can be viewed at wileyonlinelibrary.com]

(Figure 1) (Barimalala et al., 2018, 2020; Crétat et al., 2019; Howard & Washington, 2018). However, as described in Howard and Washington (2018), the AL can be divided in two phases—a *thermal low phase*, characterized by shallow dry convection during October and November, and a *tropical low phase*, mainly defined by deep moist convection and consequent latent heat release, occurring from December to February. The latter phase is dominated by cyclonic, that is, negative in the Southern Hemisphere, values of potential vorticity (PV), whose magnitude increases mainly due to latent heat release within the AL system reflecting that in tropical-like moisture convective features PV is not conserved (Hoskins, 2015). In deep moist tropical convection, maximum latent heat release usually occurs at ~300 hPa (McGee & van den Heever, 2014), leading to a static stability increase, that is, $\frac{\partial\theta}{\partial p}<0\,(\mathrm{km}^{-1})$ and consequently, $\mathrm{PV}<0$ $(\mathrm{s}^{-1})$, as $f<0\,(\mathrm{s}^{-1})$ in the Southern Hemisphere (see Equation (1)). Howard and Washington (2018) work also suggests MCT as an apparent tropical low, mainly during December–February, where deep convection is also associated with moisture and latent heat release, provided by ocean–atmosphere interactions in the Mozambique Channel. Therefore, our focus will be on the MCT and on the tropical phases of the AL which is associated with rainfall. The mathematical expression that defines PV is the Equation (1),

$$\mathrm{PV}=-g(\zeta+f)\frac{\partial\theta}{\partial p}. \tag{1}$$

In Equation (1), $g$ represents gravity acceleration, $\zeta$ the relative vorticity, $f$ the planetary vorticity and $\frac{\partial\theta}{\partial p}$ the vertical gradient of potential temperature, associated with latent heat release (Holton, 2004). Thus, as PV might provide higher accuracy on AL and MCT detection, 1981–2020 ERA5 daily geopotential height and PV fields at 800 hPa (gh800 and pv800), from December to February, were retrieved for areas where the centre of the AL and MCT are typically spotted. The regions of interest for the AL and MCT locations were defined as, respectively (10°–20°S, 12°–25°E) and (15°–30°S, 34°–45°E)—both represented as black and green squares in the inset plot of Figure 3.

Using the retrieved field of daily ERA5 gh800 and pv800 for AL and MCT regions, 3-day averaged fields were computed to reduce noise. Then, a local minimum searching methodology was applied to identify potential local minima. This methodology consisted in finding ERA5 pixels whose surroundings had higher gh800 values. After finding the location of possible gh800 local minimums, the pv800 value for each location of those minima was retrieved. The centre of the system was then defined as the local gh800 minima showing a lower pv800, with pv800 < −0.3 PVU ($1\,\mathrm{PVU}=10^{-6}\mathrm{K}\cdot\mathrm{kg}^{-1}\cdot\mathrm{m}^{-2}\cdot\mathrm{s}^{-1}$). The latter PV threshold for both systems was defined accordingly to the results showed in Howard and Washington (2018) work, which suggested that a threshold of pv800 = −0.3 PVU could be used to classify the AL system as a tropical low (i.e., a "tropical AL") or a thermal low (i.e., a "thermal AL," with pv800 > −0.3 PVU). Averages of gh800 and pv800 when AL and MCT were detected are shown in Figure 2a,b, respectively. Therefore, it is possible to see that MCT and AL regions are characterized by minimums of gh800, as well as low pv800.

# 3 | RESULTS

## 3.1 | Dry and wet season

In this subsection, climatologies in our study region is briefly presented. Figure shows that over southern Angola and northern Namibia, throughout the dry

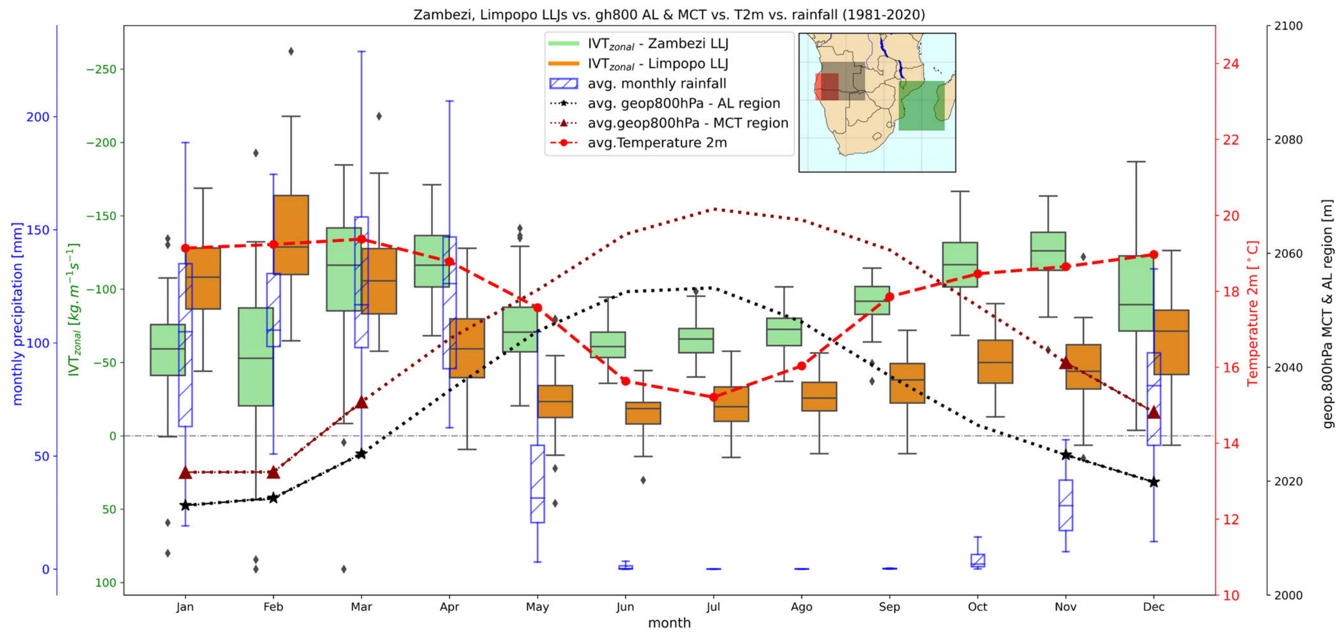


**FIGURE 3** Monthly climatologies of retrieved ERA5 variables (1981–2020 period), over the subcontinent. Green and orange boxplots represent, respectively, monthly distribution of IVTu (across the 41-year period) for Zambezi and Limpopo LLJs. Both LLJs' data were retrieved with respect to sections located in Figure 1 as green (Zambezi) and yellow lines (Limpopo). Dashed grey line marks IVTu threshold between eastward (IVTu >0 $kg \cdot m^{-1} \cdot s^{-1}$) and westward (IVTu <0 $kg \cdot m^{-1} \cdot s^{-1}$) transport of water vapour. The red dashed line and the blue boxplots with stripes show, respectively, 2-m temperature and rainfall monthly distributions, retrieved as an average value over the region of interest (see dark-red square in the inset plot). Values of gh800 for the AL region (dashed black line with stars) and MCT region (dashed dark-red line with triangles) were retrieved, for the rainy season months (Nov–Mar), using, respectively, the average gh800 values over the dark and green boxes (inset plot). [Colour figure can be viewed at wileyonlinelibrary.com]

season, it typically rains less than 20 $mm \cdot month^{-1}$, contrasting with the rainy season, where values of precipitation above 100 $mm \cdot month^{-1}$ are frequently observed (Figure 3). Temperature shows a weak seasonal cycle, with mean monthly air temperatures just below 20°C during the rainy season, and about 16°C in the dry season. Rainy season months are associated with higher values of IVTu associated with both low-level jets. Zambezi LLJ present the following bimodal annual regime—water vapour flux related to the Zambezi LLJ peaks in November and March, decreasing its intensity by June and July. Limpopo LLJ has a unimodal regime, reaching its maximum by February (Figure 3). On average, AL and MCT regions present a minimum signal in the geopotential height at 800 hPa (gh800) fields during the rainy season when compared to those of the dry season, as the latter is dominated by anticyclonic regimes (Figure 3).

## 3.2 | Moisture transport towards southern Africa

A climatological analysis on both Zambezi and Limpopo River valley LLJs is performed to understand their mean spatial and temporal behaviour. Monthly means of November–April 1981–2020, vertically integrated water vapour transport (IVT) and the zonal moisture flux (on pressure levels) from ERA5, are shown in Figures 4 and 5, respectively. At the beginning of the rainy season (November), significant amounts of water vapour from the tropical Indian Ocean enter central and southern Africa via Z-LLJ (Figures 4a and 5a), primarily due to the induced circulation around the Mascarene High. In early austral summer (December), as the latter decreases in intensity, the northeasterly moisture flux, as part of the Indian winter monsoon circulation, gets fully established along the East African equatorial coast and, simultaneously, low-level winds turn to easterly directions in Zambezi and Limpopo river valley regions, advecting large quantities of moisture (Figure 4b). In December, the water vapour is transported via both LLJs towards southwest Africa (Figure 5b).

In January, moisture fluxes related to the monsoonal northeasterlies towards the equatorial East African coast reach a maximum (Figure 4c). Simultaneously, the ITCZ reaches its maximum southward position, and an intensification of the MCT west of Madagascar is observed, which leads to a moisture flux away from the African

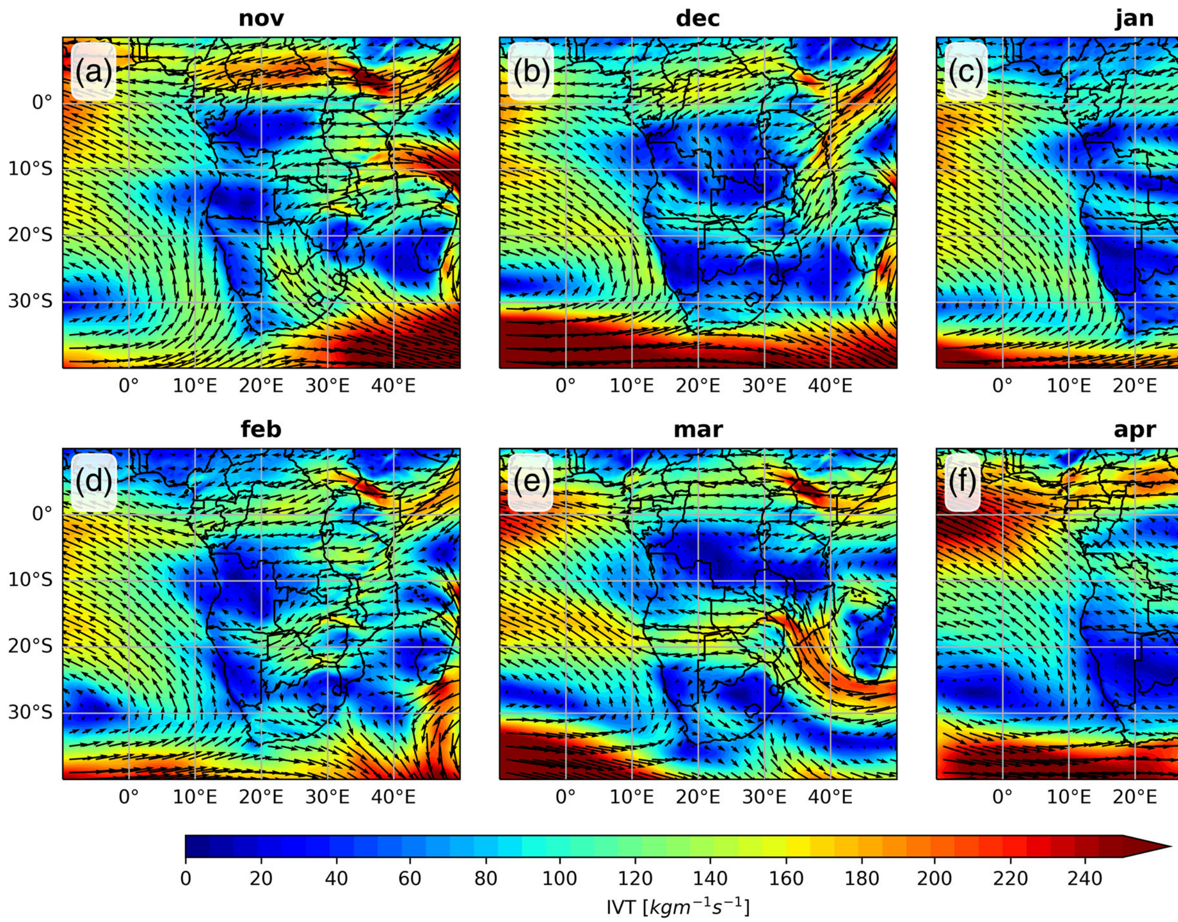


**FIGURE 4** Monthly averaged (1981–2020) integrated water vapour transport (IVT), retrieved from ERA5 reanalysis for the rainy season (November–April), over the southern African subcontinent. Black arrows are spaced by 2° × 2° and represent IVT direction and magnitude. Shaded colours also represent the magnitude value of IVT. Each panel (a–f) represent the following monthly sequence: (a) November, (b) December, (c) January, (d) February and March and (f) April. [Colour figure can be viewed at wileyonlinelibrary.com]

continent at its northern flank, deflecting it from the LLJ entrances in both river valleys. Instead, Z-LLJ and L-LLJ keep receiving water vapour, but now from a southeasterly flux of IVT produced by both Mascarene high and MCT, with some adjustments induced by the presence of Madagascar topography. Thus, in January, a large westward flux of water vapour penetrates the subcontinent through the valleys, with L-LLJ being the most important conveyor of moisture (Figure 5c).

The winter monsoon circulation and the MCT decrease their intensity by February, allowing moisture from tropical Indian Ocean being transported, again, towards eastern and central Africa mainly via Z-LLJ (Figure 4d). However, L-LLJ, mostly receiving humidity from the southeast, still plays a major role on zonal humidity transport towards southern Africa (Figure 5d).

From February to March, the ITCZ begins its seasonal migration back towards the equator (Figure 4e). A pronounced easterly IVT over the Indian Ocean turns to a southeasterly flux towards both Zambezi and Limpopo River valleys. In fact, likely as a result of the presence of Madagascar, zonal humidity transport is higher in Zambezi than in Limpopo valley (Figure 5e). This reflects the meridional displacement of the ITCZ by this time of year, as Zambezi river valley is located north of Limpopo.

During April, the ITCZ continues its northward path, with most of the westward IVT advection happening north of Madagascar, mainly entering in the Zambezi river valley, as the Southern Hemispheric southeasterlies as the first indication of the developing Somali jet appear (Figure 4f). Cross-section in Figure 5f shows a significant decrease of westward moisture transport in Limpopo and a maintenance of the water vapour entrance across Zambezi. Throughout April and in the following months (not shown), higher amounts of zonal moisture transport migrate northward related to the ITCZ movement. In fact, Z-LLJ never ceases its zonal water vapour transport activity during the dry season, unlike Limpopo LLJ.

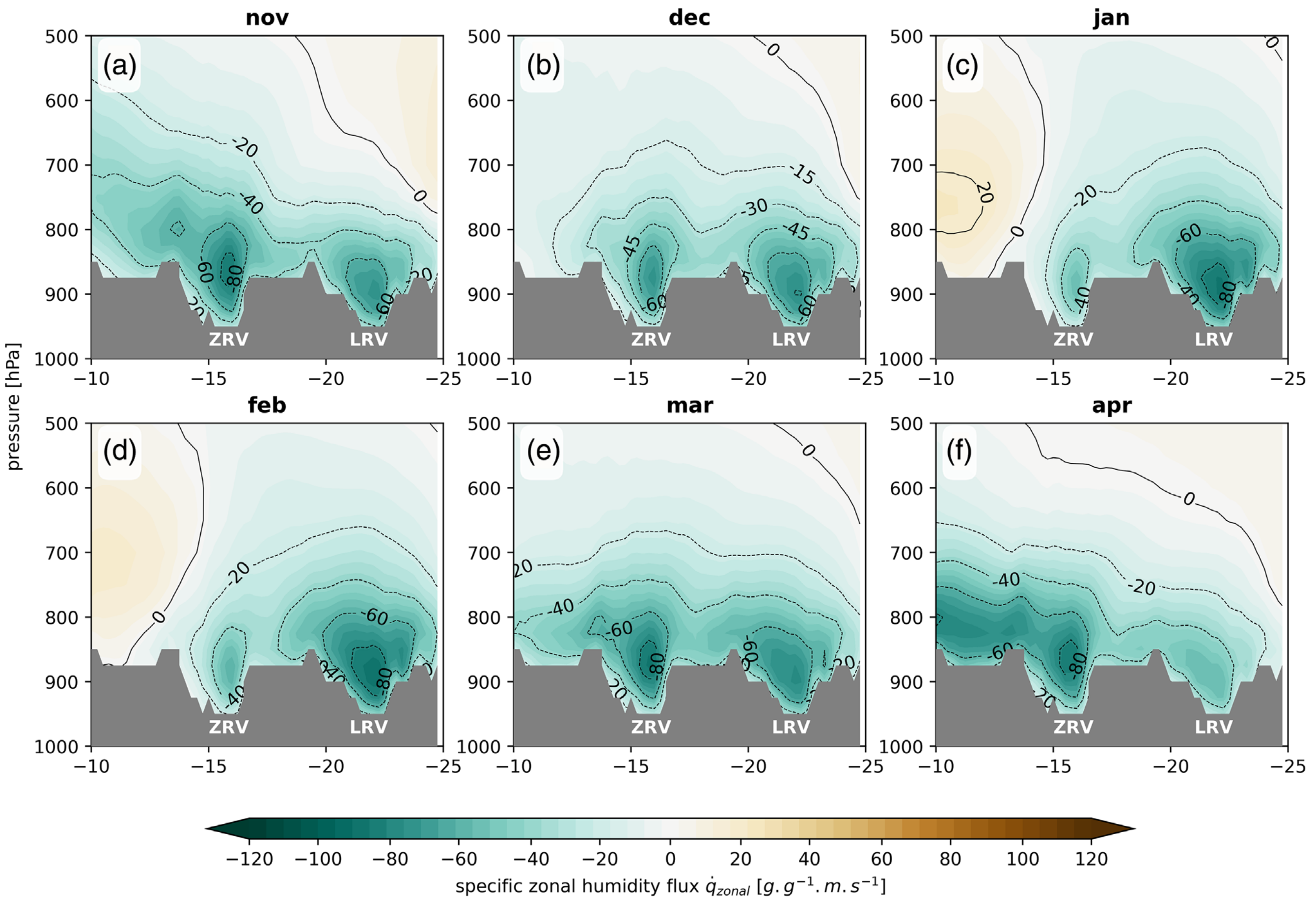


**FIGURE 5** Cross-sections of climatologies (1981–2020) of ERA5 zonal specific moisture flux between 10°S and 25°S at a constant longitude of 30°E (see the black line in Figure 1). The *x* axis in each panel corresponds to latitude. Zambezi (ZRV) and Limpopo (LRV) River valleys are identified in the figure with white acronyms. [Colour figure can be viewed at wileyonlinelibrary.com]

### 3.3 | Impacts of Limpopo and Zambezi low-level jets on rainfall based on ground observations

Limpopo and Zambezi LLJs play a fundamental role during austral summer on moisture transport from the Indian Ocean towards central and western parts of the subcontinent. Thus, it is important to understand the relationship between both LLJs water vapour transports and the precipitation occurring over our region of interest, that is, southern Angola and northern Namibia. To compare monthly precipitation data from SASSCAL weather stations with Zambezi and Limpopo water vapour transports, $IVT_u$ monthly data was retrieved (section 2.2). Figure 6 displays 2014–2020 monthly timeseries of rainfall values (and anomalies) from all 10 weather stations, as well as $IVT_u$ anomalies from both Limpopo and Zambezi river-valley LLJs.

The monthly time series of rainfall anomalies and IVTu over both river valleys (Figure 6) and its respective values of Pearson *R* correlations (*R*) shows that Z-LLJ water vapour flux anomaly can better explain the variation of precipitation anomalies registered in the weather station network than the L-LLJ. In fact, observing each temporal behaviour, it is possible to see that the anomalies of Z-LLJ better fits the weather station rainfall anomalies than the L-LLJ anomalies. This is reflected on *R* values of Zambezi ($R = -0.499$, $p << 0.05$) and Limpopo ($R = -0.082$, $p = 0.46$). Similar correlations were found using ERA5 total rainfall anomalies for Zambezi ($R = -0.47$, $p << 0.05$), even though it slightly improved for Limpopo ($R = -0.14$, $p << 0.05$) (see Figure S3a,b). However, the most negative rainfall anomalies (2015 and 2019) were registered when both LLJs recorded positive IVTu anomalies. Above-normal precipitation was recorded when both LLJs had negative IVTu anomalies (e.g., 2020) or when only the Zambezi had very high IVTu values (e.g., 2016). This result reflects that the variations in the moisture fluxes associated with the jets are not the only seasonal driver of precipitation in our study region.

Given the fundamental role played by the LLJs, it is expected that, at a daily timescale, wetter days are

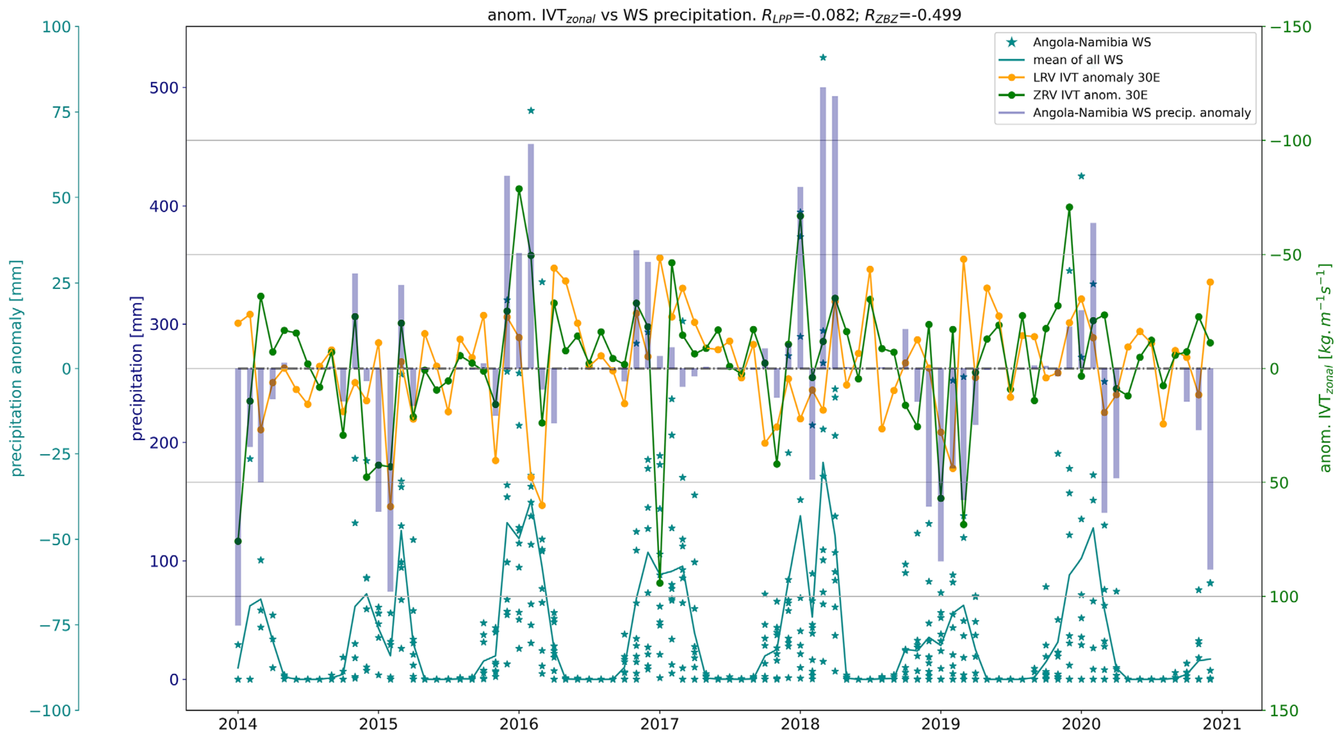


**FIGURE 6** Monthly timeseries (Jan 2014–Dec 2020) of ERA5 IVTu and SASSCAL weather stations data. Every cyan star represents a monthly rainfall value from a different weather station. Cyan line stands for the average of all weather station values within each month (i.e., indicates, in every month, the average precipitation of all weather stations). The bar plot represents the monthly average weather station rainfall anomalies (based on 2014–2020 normal, due to the short weather stations' timeseries). IVTu anomalies (using 1981–2020 normal), were plotted as an average value for two sections presented in Figure 1. Note that positive anomalies of IVTu mean a more eastward (or less westward) moisture advection, and negative anomaly of IVTu, represents a more westward (or less eastward) flux of water vapour. IVTu anomaly axis is inverted for a clearer graphical visualization. Correlation values (figure title) were performed between weather stations' rainfall anomalies and IVTu anomalies from Limpopo ($R = -0.082$, $p = 0.46$) and Zambezi ($R = -0.499$, $p << 0.05$). [Colour figure can be viewed at wileyonlinelibrary.com]

associated with mean winds from east/southeast (Indian Ocean) and to a lesser extent with winds from west/southwest (Atlantic Ocean). Using weather station data, wind roses were calculated to verify daily mean wind frequency distributions across the study region according to two rainfall categories—rainy days (rainfall >1 mm) and dry days (rainfall <1 mm). Figure 7 shows most of weather stations located in the Angolan-Namibian highlands present a bimodal behaviour on wind directions, with wetter days associated with E/SE wind directions and drier days, with a prevalence of winds from E/SE. Thus, results indicate both Zambezi and Limpopo LLJs can be associated with easterly moisture fluxes towards the plateaus, frequently linked to rainier days over the region, as suggested by the wind-rose analysis. Contrary to weather stations over the plateaus, wind roses from weather stations located near the coast have a similar wind regime either in rainy or dry days, suggesting that winds from the Atlantic Ocean dominate the rainy days over places near the coast.

## 3.4 | Rainfall anomalies associated with LLJ intensities

To study the spatial patterns of precipitation associated with both LLJ-related moisture fluxes, monthly means of normalized precipitation anomalies were computed for strong and weak jet situations (Figures 8 and 9). All IVTu values below (above) the 25th (75th) percentile were classified as strong (weak) LLJ months. To account for the well-known uncertainties associated to precipitation datasets over the Tropics (see Figure S1), 1981–2010 monthly averaged data from six data sources—reanalysis and mixed ground-based and satellite datasets of precipitations were used (section 2.2). Negative values of IVTu correspond to westward water vapour transport, that is, the more negative, the stronger the LLJ is transporting water vapour towards southwest Africa and vice versa.

The spatial patterns of the different averaged anomalies of precipitation in Figure 8 show that different datasets mostly agree on the fact that months associated with a stronger intensity of Z-LLJ are related to above-normal

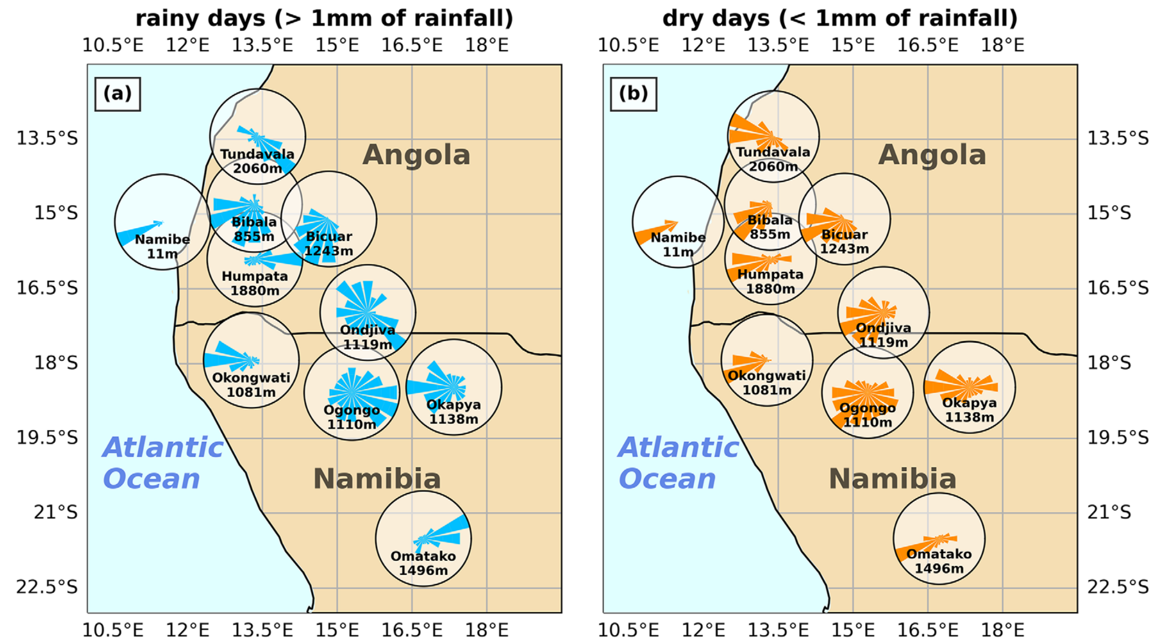


**FIGURE 7** Wind roses representing mean daily surface wind data from 10 SASSCAL weather stations over 2014–2020 NDJFM periods, for (a) rainy days (daily rainfall >1 mm) and (b) dry days (daily rainfall <1 mm). In each wind rose, longer triangles represent higher frequencies of wind from that sector. Weather stations' height above sea level is also shown. Some wind roses locations do not correspond to the exact location of the weather stations as some adjustments were made to have a cleaner presentation. [Colour figure can be viewed at wileyonlinelibrary.com]

rainfalls over the study region. By accessing the percentage of statistical significant pixels over our study region (red box in Figures 8o and 9o), we found that the results with higher percentages of statistical significance were when using ERA5 (78.5%), CHIRPS (75.0%) and REGEN (70.3%) (Figure 8, left panels). By contrast, weaker Z-LLJs (Figure 8, right panels) lead to a pattern inversion with below-normal precipitation values observed across central-southern Angola and over the Namibian territory. However, statistical significance is low in most of the region, except for ERA5 and CHIRPS, who presented statistical significance in 46% and 50% of the pixels over the study region.

When analysing L-LLJ's impact on precipitation patterns over Angola and Namibia, the datasets show stronger L-LLJ phases linked with drier conditions over northern Angola and parts of Democratic Republic of the Congo and wetter conditions over southeast Angola (Figure 9, left panels), however, our study region presents low percentages of pixels with statistical significance (all datasets below 12.5%). Furthermore, all datasets mostly agree in that weaker phases of this LLJ are associated with drier conditions across ANP region, with CHIRPS and ERA5 presenting higher percentages of pixels with statistical significance over that area—93.8% and 60.1%, respectively (Figure 9, right panels).

## 3.5 | Synoptic-scale lows and its implications on low-level jets intensities and rainfall

Both precipitation and IVTu percentiles were recomputed as in section 3.3, but with 3-day averaged data. In Figure 10, gh800 for MCT and AL are shown against the corresponding IVTu from Zambezi and Limpopo LLJs. For the MCT, anticorrelations of $R = -0.47$ ($p << 0.05$) were found with Z-LLJ (Figure 10a), but for L-LLJ, $R$ values were statistically insignificant (Figure 10c). This means weaker MCTs are more likely to be associated to stronger Z-LLJs, but having little influence on the magnitude of the L-LLJ. In Figure 10 blue (red) dots indicate rainy (dry) days, while grey dots mean normal rainfall days. Blue or red dots do not exhibit a clear pattern in Figure 10a, but Figure 10c shows stronger (weaker) Limpopo LLJ is associated with higher (lower) rainfall amounts over the Angola-Namibia plateaus. The latter is in-line with the results from Figure 9. Analysing the influence of AL strength on both LLJs (Figure 10b,d), there is an anti-correlation between AL gh800 and Z-LLJ of $R = -0.43$ ($p << 0.05$), while for L-LLJ, the (positive) correlation is lower ($R = 0.25$, $p << 0.05$). Deeper ALs seem associated to higher rainfall percentiles (blue dots). Another property from MCT and AL is their meridional

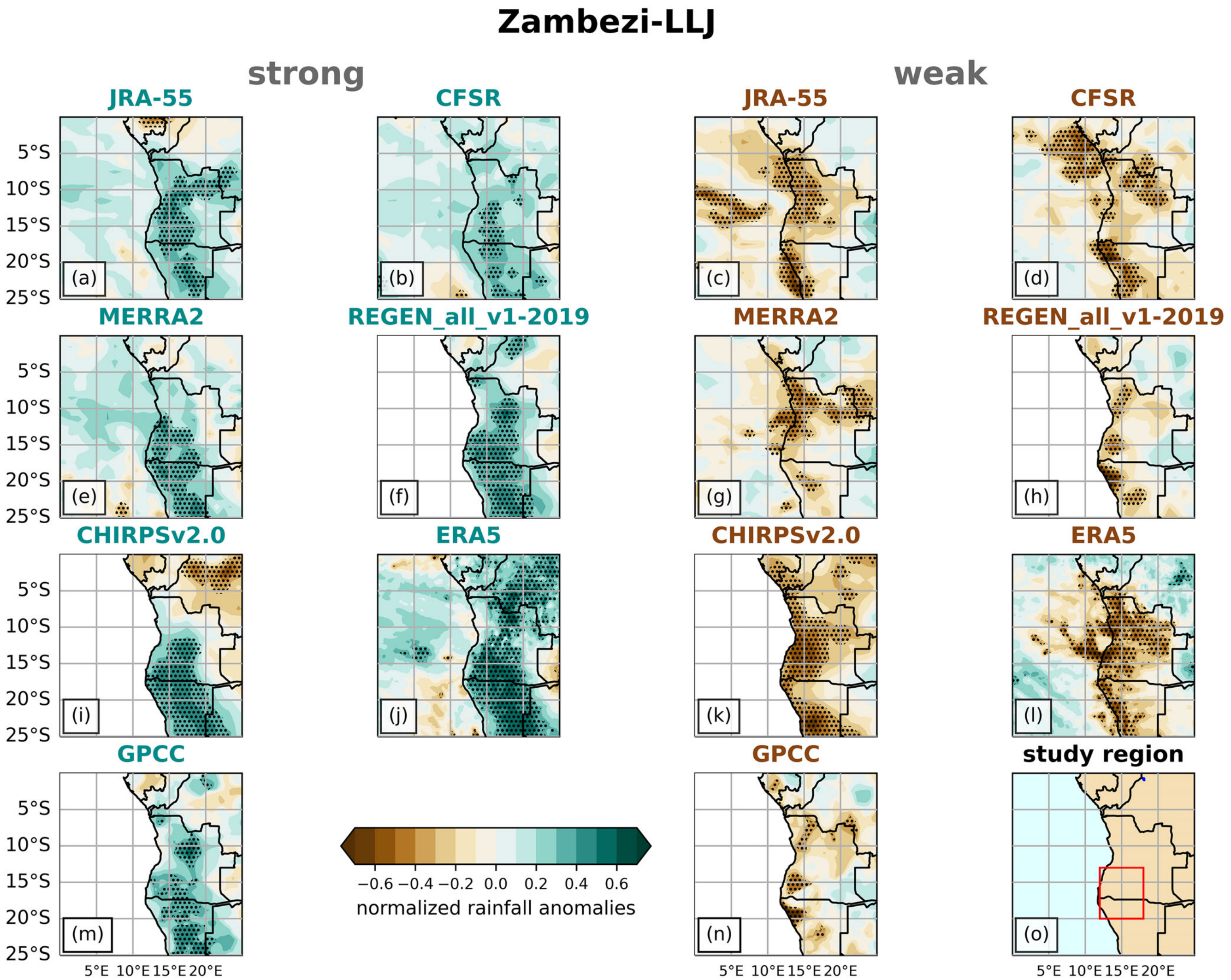


**FIGURE 8** Monthly means of normalized rainfall anomalies (1981–2010) for seven datasets (reanalysis, mixed ground-based, gauge-only and satellite data) according to each Z-LLJ intensity. Strong Z-LLJ cases are presented in the left panels of the figure (a, b, e, f, e, j, m) and the respective titles are written in blue. Weak Z-LLJ are displayed in the right panels (c, d, g, h, k, l, n) and the titles are written in brown. Our target region (region of interest) is presented in panel (o). Each mean was computed using 38 months ($n$ = 38). Normalization of rainfall anomalies was performed by dividing the series of anomalies by its associated standard deviation. Dotted regions represent statistically significant areas using a Student's $t$ test for 95% confidence interval. [Colour figure can be viewed at wileyonlinelibrary.com]

displacements which may impact zonal moisture fluxes associated with the jets. Using the low-pressure detection methodology (section 2.3) for both systems, we tried to verify if there was any relationship between both systems' latitude and IVTu from both LLJs, representing this via kernel density estimations (KDEs). Results are shown in Figure 11, where a preference for higher Zambezi IVTs is shown when the Angola Low is displaced equatorwards (Figure 11a). This is reasonable as the AL enhances the westward flux when it is displaced northwards due to its southern tip being located approximately at the same latitude as the Zambezi river valley. For Limpopo LLJ we cannot identify any tendency regarding AL meridional displacements (Figure 11b). With the MCT, results seem more unclear even though we note a distribution of higher Limpopo IVTu when the MCT is placed northwards (Figure 11d).

Nonetheless it is possible to establish connections between the AL, the MCT and the intensity of both Zambezi and Limpopo LLJs, the link between moisture advection, AL reinforcement and rainfall over the plateau region remains unexplained. Therefore, the low-pressure detection methodology (section 2.3) to detect the AL centre was combined with ERA5 pv800 information to classify the local gh800 minimum as “tropical AL” or “thermal AL.” After separating all the gh800 minima found within the 1981–2020 ERA5 data into “tropical AL” and “thermal AL,” the following variables were analysed, including: (a) Zambezi IVTu, (b) Limpopo IVTu, (c) vertically integrated moisture

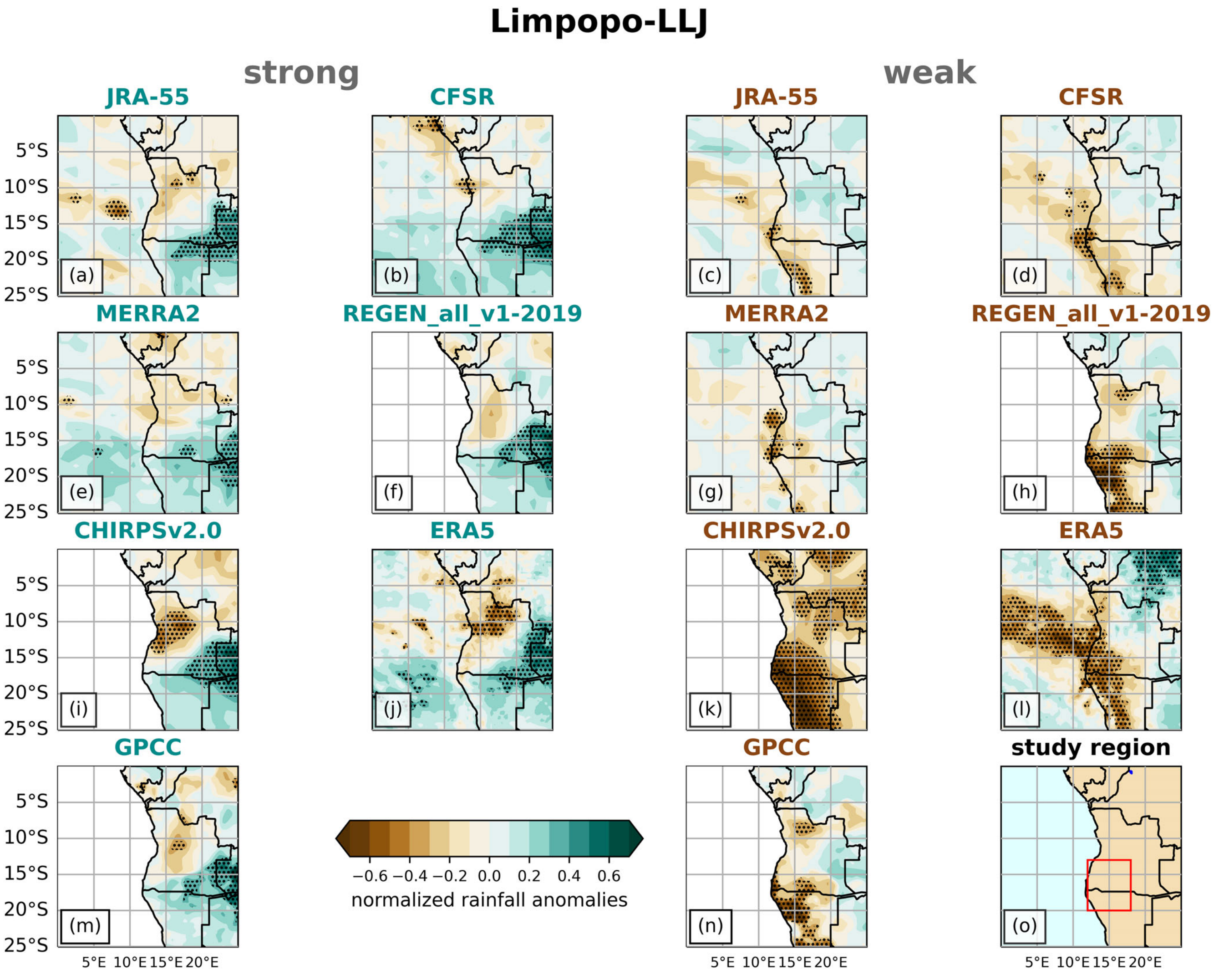


FIGURE 9 Same as Figure 8 but with L-LLJ intensities. [Colour figure can be viewed at wileyonlinelibrary.com]

divergence, (d) 300–400 hPa vertical velocity, (e) total accumulated column rainwater (including all condensed species) and (f) accumulated precipitation on the ground (Figure 12). This analysis allows establishing a relationship between AL activity and moisture convergence, as well as assessing its effectiveness in producing rainfall. Even though IVTu from Zambezi and Limpopo do not change direction significantly depending on the "tropical AL" or "thermal AL" presence (Figure 12a,b), higher moisture convergence is generally observed for "tropical AL" cases (Figure 12c). However, the more significant differences are found in total rainfall, in total column water and in vertical velocity within the system. Figure 12d,e shows higher vertical velocities at 300–400 hPa and larger amounts of total column rainwater for "tropical AL" when compared to "thermal AL" events. When inspecting total rainfall, the same is observed, with tropical AL systems associated with higher precipitation amounts than in cases where AL is on its thermal state (Figure 12b).

## 4 | DISCUSSION

The aim of this study was to understand the influence of the Zambezi and Limpopo low-level jets and quantify the role of the Angola Low and Mozambique Channel Trough on rainfall patterns over the region of interest, that is, Angolan-Namibia plateaus, using reanalysis, gauge-only products, satellite and ground-based data.

To the best of our knowledge, we analysed for the first time the relationship between both Limpopo and Zambezi LLJs intensities and surface rainfall data from local weather-stations in southern Angola and northern Namibia (Figure 6). Even though Limpopo and Zambezi LLJs are important contributors of humidity advection coming from the Indian Ocean towards central and western parts of the southern African subcontinent (Munday et al., 2021), including Angolan and Namibian plateau regions (Figures 4 and 5), our results show only a clear relationship for the Zambezi LLJ for our study region

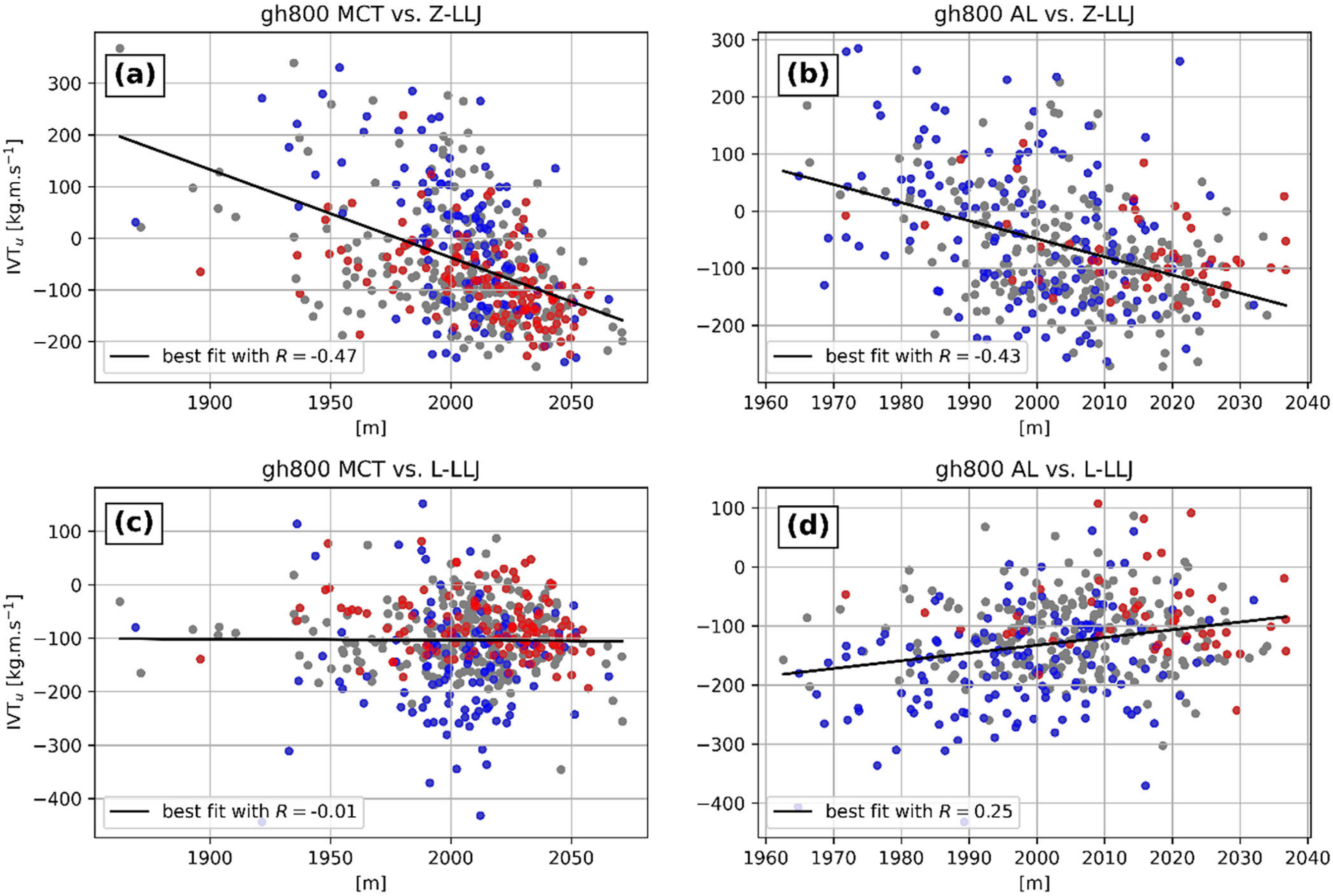


**FIGURE 10** Scatter plots of 3-day averaged ERA5 data (1981–2020, December–February) for AL and MCT gh800 versus Limpopo and Zambezi IVTu intensities. (a) gh800 MCT versus Zambezi IVTu; (b) gh800 AL versus Zambezi IVTu; (c) gh800 MCT versus Limpopo IVTu and (d) gh800 AL versus Limpopo IVTu. Days with values of precipitation >75th percentile, were classified as rainy (blue dots); <25th percentile were classified as dry (red dots) and days with rainfall between the 25th and 75th percentile represented normal rainfall days (grey dots). Black line corresponds to a linear regression performed using all the dots, with $R$ values displayed in each graph. Values of gh800 for the AL and MCT were computed via local minima searching methodology presented in section 2.3. Rainfall data corresponds to an average over the region of interest (red rectangle in Figure 1). [Colour figure can be viewed at wileyonlinelibrary.com]

(Figures 8 and 9). We consider these results as key findings over a region working as a "water tower" of main Angolan and Namibian rivers and feeding some arid regions of Angola, Namibia and Botswana (Lourenco et al., 2023).

Wind-roses using weather-stations' surface wind data showed a prevalence of easterly/southeasterly winds associated with rainy days, particularly at stations located over the Central Angolan and Namibian plateaus, as well as a prevalence of westerly winds associated with drier days, increasing our confidence on the importance of the easterly advection of humidity on local rainfalls (Figure 7). We gave a first insight on how weaker (stronger) LLJs intensities are related with below (higher) than normal rainfalls over the plateaus. The result was supported by Figures 8 and 9, which showed a pattern of a wetter region of interest during higher LLJs intensities. Rainfall and $IVT_u$ anomalies from both LLJs showed higher statistical significance in the Zambezi case (Figure 8) than in Limpopo (Figure 9). These results are in line with Munday et al. (2021) who found a relationship between stronger East African LLJs (including Zambezi and Limpopo), enhanced dryness over the eastern parts of the subcontinent and higher precipitation amounts over southwest Africa. Using a regional model, Barimalala et al. (2021) found that a blocked Z-LLJ would significantly reduce moisture availability and rainfall over the subcontinent during most of the rainy season. This is consistent with our results, showing weaker Zambezi LLJs in regions with negative rainfall anomalies (right panels of Figure 8).

Barimalala et al. (2021) results regarding MCT intensity and associated rainfall over Africa in austral summer showed less precipitation over southwest Africa during weaker MCT phases. Such result is similar to those described in section 3.4, where drier periods over

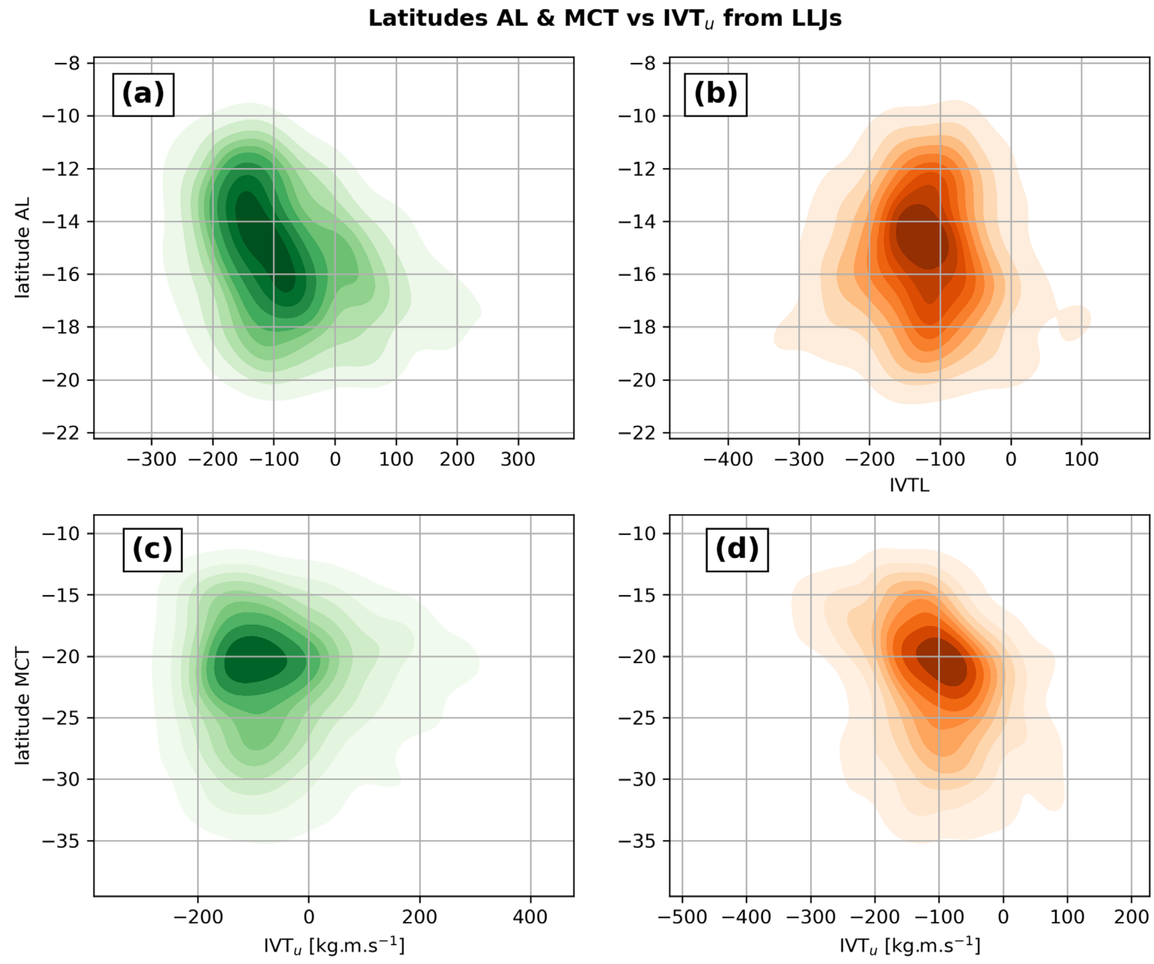


**FIGURE 11** Kernel density estimation (KDEs) plots using 3-day averaged ERA5 1981–2020 data and local minima detection methodology (section 2.3) to compare Angola Low latitudes with (a) Zambezi IVTu and (b) Limpopo IVTu, and to compare Mozambique Channel Trough latitudes with (c) Zambezi IVTu and (d) Limpopo IVTu. [Colour figure can be viewed at wileyonlinelibrary.com]

southwest Africa are linked with a weaker MCT. The Angola Low has also been studied in recent literature, with Munday and Washington (2017) stating that the AL explains ~40%–60% of austral summer rainfall variability over Africa, mostly over Angola-Mozambique cloud band zone. Our results regarding the AL intensity and associated rainfall are consistent with Munday and Washington (2017) findings, where a deeper AL seem to be related with periods of larger amounts of rainfall over southwest Africa (Figure 10b,d). Correlations of $R = -0.47$, $p << 0.05$ (Figure 10a) and $R = -0.43$, $p << 0.05$ (Figure 10b) between Z-LLJ and MCT and AL were found, respectively.

It was demonstrated that the AL is a key atmospheric feature controlling rainfalls over Angola-Namibia plateau region, essentially when the latter is in its tropical low stage, enhancing the necessary dynamic and thermodynamic conditions for moisture convergence to occur therein. An analysis on vertically integrated moisture divergence fields in the centre of both tropical and thermal AL phases highlighted the role of moisture convergence, the associated upward air motion and production of relatively large amounts of condensate within the air column during a tropical AL stage, consequently linked with effective rainfalls (Figure 12). Therefore, we conclude that the action of both the MCT (over the Mozambique Channel) and the AL (typically anchored over SE Angola) controls humidity advection inland, where MCT also plays an important role for the precipitation patterns observed over the plateaus. MCT helps the advection of water vapour via Zambezi LLJ, feeding deep convection within the tropical AL.

Uncertainty regarding the relative estimates of each source of advected moisture towards southwest African regions remains an issue. Barimalala et al. (2021) and Munday et al. (2021) result shows confidence on the statement that the Indian Ocean is the main source of atmospheric humidity, whose transport is facilitated by Limpopo and Zambezi LLJs—key features of water vapour advection towards the central-western parts of the

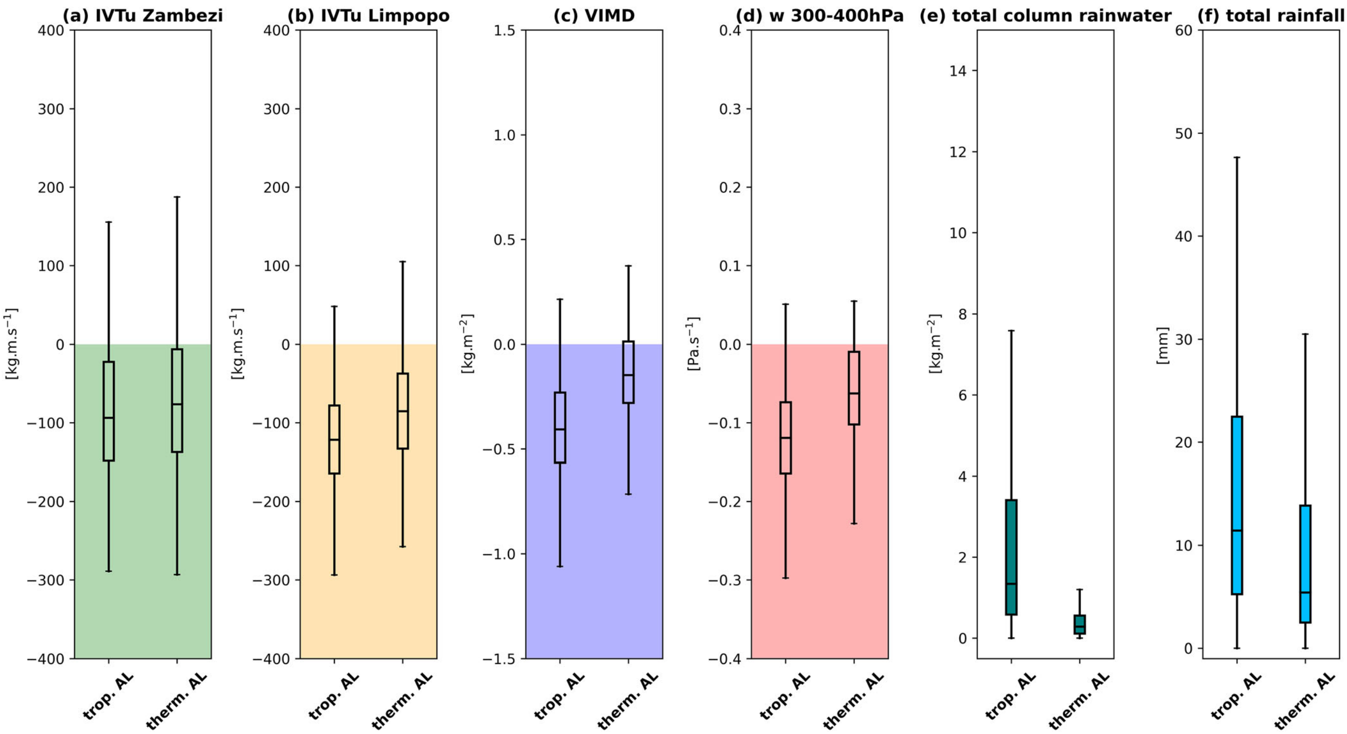


**FIGURE 12** Boxplots of 3-day aggregated ERA5 1981–2020 data. Each panel corresponds to the following variables: (a) Zambezi LLJ IVTu and (b) Limpopo LLJ IVTu, (c) vertically integrated moisture convergence, (d) vertical velocity between 300 and 400 hPa, (e) total accumulated column rainwater and (f) total accumulated rainfall on the ground. Using local minima searching methodology presented in section 2.3, each gh800 minimum was classified as "tropical AL" or "thermal AL" according to the established threshold of PV < −0.3 PVU. Each panel has two boxplots associated with the distribution of each variable for the "tropical AL" and "thermal AL" cases. In panels (a–d), coloured regions mark negative divergence, positive vertical velocities and westward IVTu values, respectively. [Colour figure can be viewed at wileyonlinelibrary.com]

subcontinent. However, it is also known that warmer eastern South Atlantic sea surface temperatures are related to moisture availability along coastal southwest Africa, often associated with large-scale periodic ocean surface warming offshore Angolan-Namibian coast—a phenomenon named *Benguela Niño* (Imbol-Koungue et al., 2019). Results regarding moisture advection shows little influence of Atlantic Ocean on our study region when compared with both Limpopo and Zambezi LLJs (Figure S2). Some literature reports a strong influence of large-scale modes of variability (e.g., El Niño–Southern Oscillation, Subtropical Indian Ocean Dipole) on rainfall and geopotential anomalies over the subcontinent (Crétat et al., 2019; Hoell & Cheng, 2018; Pascale et al., 2019), even though these interactions are yet to be fully understood. As an example, Crétat et al. (2019) related AL meridional displacements and intensities with ENSO phases (El Niño or La Niña) and Hoell and Cheng (2018) found a relation between La Niña (El Niño) phases and higher probabilities of wet (dry) rainy seasons across the subcontinent. Thus, as ENSO and SIOD are likely to be responsible for AL strength and latitudinal shifts over the years, it also might have an impact on both LLJs interannual variability as well as on MCT dynamics.

Our results on Figure 11 show northward ALs related to higher Zambezi LLJs intensities. On the other hand, MCT meridional displacements do not fully relate with both LLJs strengths. Following Munday et al. (2021), East African LLJ representations should be performed on spatial grids with <60 km resolution. Our work used the *state-of-the-art* ERA5 reanalysis to analyse Limpopo and Zambezi LLJs, with a vertical discretization of 25 hPa until the 750 hPa level, and a spatial grid of ∼30 km—higher than what was suggested by Munday et al. (2021). Even though our analysis on precipitation behaviour over southwest Africa was complemented with additional seven different sources of rainfall data and a local weather-station network, uncertainty on precipitation amounts and variability over the region still persists. Physical aspects regarding the AL and its influence on rainfall over southwest Africa were also accessed using ERA5, such as vertically integrated moisture divergence, vertical velocity and total column rainwater. However, in the future, using finer resolution atmospheric models or more sophisticated reanalysis products could improve the representation of these systems, either horizontally or vertically.

## 5 | CONCLUSION

This study assessed the role of different atmospheric drivers on moisture advection towards Angolan and Namibian plateaus, as well as local rainfalls. The main focus of this study was on two low-level jets placed in two East African river valleys—Zambezi and Limpopo—as well as two low-pressure systems—the Mozambique Channel Trough and the Angola Low.

Our main conclusions for each one of our research questions are as follows:

- What is the influence of both Zambezi and Limpopo LLJs on rainfall over our region of interest?

A strong relationship between Zambezi low-level jet and rainfall anomalies over the Namibian and Angolan plateaus is found. This is only partially the case for the Limpopo low-level jet. When assessing rainfall anomalies using local weather-stations, the Zambezi low-level jet moisture flux anomalies show a strong anticorrelation (statistically significant), unlike Limpopo (not significant). This is also true when using different rainfall datasets with high spatial resolution to quantify the statistical significance on rainfall anomalies in the region.

- What is the role played by the AL and MCT on the humidity transport intensity via both LLJs and, consequently, on rainfalls across the southwest African plateau regions?

A reasonable relationship between both AL and MCT and Zambezi LLJ was found (both statistically significant). In Limpopo's case, anticorrelations are very low and not significant. Thus, while AL and MCT might contribute to the intensification of Zambezi LLJ, this is not true for the Limpopo's LLJ intensity. Also, northward AL shifts, mostly influenced by large-scale interannual variability, are also linked with Zambezi LLJ intensifications. The advected water vapour is converted in rainfall due to the presence of the AL, mainly in its tropical low phase during mid to late rainy season, as it associates with deep moisture convection where large amounts of air moisture are converged and condensed, producing rainwater within the air column.

Regarding future work, it became evident from this study, that investments in scientific research across the region is needed, namely by installing and properly maintaining more weather stations and organizing field campaigns (e.g., to study vertical atmospheric profiles over both Zambezi and Limpopo River valleys) to understand the details of regional dynamics of both LLJs, their effects on rainfall across Africa in austral summer and to enhance the surface database of this area. The lack of weather stations and, consequently, the inexistence of long timeseries of atmospheric data over the region, contributes to a significant lack of scientific knowledge about the weather dynamics of southern Africa. FRESAN project (https://fresan-angola.org/) and its associated missions to southern Angola are trying to compensate this lack of weather-recording instruments by installing and fixing existing weather stations across the country, whose data will be freely available soon (by the end of the project, in 2025). Yet, it is still not enough to provide an acceptable coverage of the entire subcontinent, whose precipitation variability play a key role on the agricultural-based economies of most of the sub-Saharan countries. Thus, a better understating on rainfall variability drivers and a development of efficient methods to improve rainfall forecasts over the region will certainly help these populations in becoming more resilient to hazardous agricultural seasons. A few studies have investigated the influence of tropical cyclones over the Mozambique Channel and rainfall over eastern parts of the subcontinent (Malherbe et al., 2012; Mawren et al., 2022), however, to the best of our knowledge, there is no study reporting the influence of such systems on humidity advection and rainfall anomalies over southwestern regions of Africa in austral summer. This requires further research, especially accounting for the increasing number of such cases over recent years (e.g., cyclones Idai and Kenneth in 2019 and Freddy in 2023).

## AUTHOR CONTRIBUTIONS

**Carlos A. Pereira:** Conceptualization; investigation; writing – original draft; writing – review and editing; visualization; methodology; formal analysis; software. **João P. Martins:** Conceptualization; methodology; writing – review and editing; visualization; formal analysis; supervision. **Andreas H. Fink:** Supervision; formal analysis; writing – review and editing; visualization; methodology; conceptualization. **Joaquim G. Pinto:** Writing – review and editing; visualization; formal analysis. **Alexandre M. Ramos:** Conceptualization; writing – review and editing; formal analysis; supervision; methodology; visualization.

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## CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request. Python codes and weather station data are available from the corresponding author. By 2025, FRESAN project intends to make weather stations publicly accessible.

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## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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