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Interannual variability of tropical cyclone systems' landfall over Mozambique and its relationship with atmospheric conditions

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Abstract

Tropical cyclone (TC) landfalls in Mozambique cause recurrent socio-economic devastation, property damage, and loss of life. This study analyzes the interannual variability of TC landfalls and their driving mechanisms from 1971/72 to 2024/25 using RSMC La Réunion and IBTrACS datasets. Atmospheric and oceanic patterns were examined via ECMWF reanalysis data alongside climate indices for the El Niño-Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), Subtropical Indian Ocean Dipole (SIOD) and Southern Annular Mode (SAM). Landfalls occur from December to April, peaking significantly between January and March (accounting for over 85% of total events). Interannual landfall frequency exhibits a linear increasing trend, with multiple landfalls occurring in a single season, particularly post-2000. Composite analyses reveal that high relative humidity emerges over the Mozambique Channel and inland one month prior to landfall, driven by large-scale moisture convergence from the Southwest Indian Ocean (SWIO) and the Atlantic Ocean. Furthermore, SAM and IOD exhibit significant correlations with landfalls, peaking during November-January and January-March, respectively. These climate modes modulate the regional atmospheric steering flow via the Mascarene High and alter SWIO sea surface temperatures (SSTs). Unraveling these predictive mechanisms is vital for strengthening early warning systems and enhancing climate resilience in Mozambique.

Keywords: Tropical cyclones, SWIO region, Mozambique, Landfall, Moisture convergence, Climate drivers.

1. Introduction

Tropical Cyclones are one of the most intense weather hazards of all meteorological phenomena that form over tropical oceans (Fink & Speth, 1998; Bhaskar Rao et al., 2009; Mavume et al., 2010; Tang et al., 2016). During the austral summer (November to April), the SWIO region (0°-40°S; 30°-100°E) experiences high SSTs and weak easterly Vertical Wind Shear (VWS) that are favorable for the TCs genesis (Mavume et al., 2010; Ash &

Matyas, 2012; Burns et al., 2016; Leroux et al., 2018; Manhique et al., 2021). In addition, this basin is one of the major TC formations, accounting for approximately 14% of the total global ocean hotspots, with an average of 12-13 TCs forming each year (Fink & Speth, 1998; Ho et al., 2006; Mavume et al., 2010; Manhique et al., 2021).

Many Southeastern African countries are frequently affected by TCs forming in the western edge of SWIO, known as Mozambique Channel (MC; 10°-27°S; 30°-50°E), associated with approximately 5% of the TCs forming in the SWIO and then crossing Madagascar to make landfall in Mozambique annually (Reason & Keibel, 2004; Mavume et al., 2010; Fitchett & Grab, 2014). The landfall of TCs is associated with substantial heavy rainfall, strong winds, storm surges and severe coastal inundation, which induce damage to infrastructure and agriculture, as well as significant losses of life, especially in low-lying coastal areas (Vitart et al., 2003; Malherbe et al., 2012; Fitchett & Grab, 2014; Bousquet et al., 2021; Eckstein et al., 2021; Mawren et al., 2022; Hooker et al., 2026). Nevertheless, the estimated financial cost associated with the landfall of TCs in the countries comprising the SWIO region has been poorly studied, e.g. (WMO, 2021; Hendricks et al., 2023; Lehtomaa & Renoir, 2023).

The geographic location of Mozambique and extension of its coastline (~2700 kilometres) make it vulnerable to frequent landfalls; TCs forming in the MC are relatively close to land (Matyas, 2015). This is more concerning if one takes into account that more than half of the total population of Mozambique lives in low-lying coastal areas (Lück-Vogel et al., 2012). A single cyclone can make multiple landfalls over this country in one particular season, as recently occurred with Intense Tropical Cyclone Freddy in February and March 2023 (Perry et al., 2024; Ussalu & Manjate, 2026), causing considerable damage to properties, crops, and loss of life in this economically disadvantaged country. Intense TC Idai was another important example, and was deemed one of the deadliest TCs on record in the Southern Hemisphere, affecting Mozambique, Zimbabwe and Malawi in March 2019 (Yu et al., 2019; Kolstad, 2021).

Studies suggest that, despite ongoing human-induced climate change, it remains unclear whether there is a long-term trend in TC frequency in the SWIO. At the same time, there is greater agreement on an increase in the likelihood of category 4-5 TCs (Elsner, 2020; Kossin et al., 2020; Li et al., 2023). Although the overall frequency of cyclones may decrease, the occurrence of intense systems is increasing, resulting in higher wind speeds and increased precipitation, e.g. (Sugi et al., 2017; Roberts et al., 2020). As far as Mozambique is concerned, a recent study of TC landfall shows a significant increase in landfall frequency for the period 2000-2020 as compared to the 1980-1999 period (Chichava et al., 2024). The study suggests that the increase in landfall frequency is associated with warmer SST and low VWS. Nevertheless, this may also be due to decadal variability and improvements in observational records, given the studied time span.

There are also studies indicating that TC cyclogenesis, intensification and track are associated with the large-scale climate modes of variability such as the ENSO, IOD and SIOD. For instance, (Iizuka & Matsuura, 2012) studied the TC activity over the Southern Hemisphere, and they suggested that both ENSO and IOD contribute to the frequency of TC formation over the SWIO, with an increase (decrease) during La Niña (El Niño) and positive (negative) IOD. Several studies have shown links between TC activity in the Southwest Indian Ocean

and these climate modes, e.g. (Mao et al., 2013; Burns et al., 2016; Jury & Matyas, 2022; Ogata, 2023). Additionally, SIOD has been shown to influence TC tracks (Ash & Matyas, 2012).

Whilst several studies have analyzed atmospheric and oceanic conditions behind unusual seasons or particular TC events (Reason & Keibel, 2004; Klinman & Reason, 2008; Chikooore et al., 2015; Mawren et al., 2020; Kolstad, 2021; Jury & Matyas, 2022; Perry et al., 2024; Wang et al., 2025; Ussalu & Manjate, 2026), less research attention has been devoted to understanding the interannual variability of TC landfall over Mozambique on a climatic timescale. Thus, this study has the potential to contribute to the improvement of TC Early Warning System (EWS) and Disaster Risk Management in Mozambique by identifying the distinct atmospheric precursors of TC landfall and hence providing long-lead sub-seasonal forecasts, giving disaster management authorities crucial time to prepare.

This study investigates the interannual variability of TC landfall in Mozambique and its large-scale atmospheric and oceanic influencing mechanisms to enhance TC EWS and disaster risk reduction frameworks. By isolating distinct synoptic atmospheric precursors to TC landfalls, this research seeks to enable long-lead sub-seasonal prognostications, thereby maximizing the operational window for civil protection and emergency preparedness. The mechanisms analyzed here include teleconnections with ENSO, IOD, SIOD and SAM.

The paper is structured in 4 major sections. After the introduction, the paper presents, in section 2, the methodology, which includes the different databases utilized to perform the analysis, and the analyses methods that were performed. Section 3 presents the findings divided into 3 sub-sections. First, the paper presents the general characteristics of the TC landfall in Mozambique, looking at the geographical location of the landfalls and the intra- and interannual variations. The second sub-section analyses the atmospheric variables associated with landfalls with a focus on relative humidity, moisture fluxes, sea level pressure, vertical wind and SST. Finally, sub-section 3 correlates landfalls with Niño 3.4, IOD, SIOD and SaM. Section 4 discusses the findings and concludes the article.

2. Data and Methodology

The TC data used in this study are from La Reunion Regional Specialised Meteorological Centre (RSMC)¹ and International Best Track Archive for Climate Stewardship (IBTrACS)² version v04r01, respectively, for the South-West Indian Ocean from 1970/1971 to 2024/2025. The datasets provide both spatial and temporal information regarding a TC's center position (latitude and longitude) and intensity, recorded at 6-hour intervals. IBTrACS data was utilized as the primary sample, given that it has the longest available record. The RSMC datasets, which are not fully updated, have been used to fill the gaps encountered within the IBTrACS datasets, e.g. (Mavume et al., 2010; Manhique et al., 2021).

To better delineate and analyze the probability distribution of the landfall area during the studied period, the Kernel density estimation (Ramsay et al., 2012) was utilized. The analysis includes systems reaching Tropical Depression status (1-min Mean Sustained Wind (MWS) $>13.9 < 17.4 \text{ ms}^{-1}$) and above. Based on this, months with TC system landfalls (TCL) and those without TC system landfall (noTCL) were identified. To understand

¹ http://www.meteo.fr/temps/domtom/La_Reunion/webcmrs9.0/anglais/index.html#

² <https://www.ncei.noaa.gov/data/international-best-track-archive-for-climate-stewardship-ibtracs/v04r01>

the drivers of TCL, regional atmospheric circulation and oceanic conditions were examined in different lag months prior to landfall for January, February, and March, the peak landfall months.

Monthly mean gridded atmospheric and oceanic fields obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis datasets (Hersbach et al., 2020; Muñoz-Sabater et al., 2021) were used to explore the mean atmospheric and oceanic conditions associated with TCL and noTCL years. The Datasets are the fifth generation (ERA5), available at 0.25° x 0.25° grid size from 1940 to present. The variables considered in this analysis include relative humidity (RH), mean sea level pressure (MSLP), zonal (U) and meridional (V) components of wind, vertical velocity, geopotential height, and SST.

Composite anomaly maps were computed based on months with and without TCL for the months preceding landfall, to gain insight into the atmospheric mechanisms associated with TC landfall. Unless stated otherwise, all anomalies were calculated against the 1981 - 2010 climatological period. To explore the TC landfall links with large-scale climate modes of variability, correlations were analyzed between landfall and Niño 3.4, IOD, SIOD and the SAM indices. The Niño 3.4 and IOD indices were sourced from the National Oceanic and Atmospheric Administration (NOAA) Physical Science Laboratory database³, the SAM index was sourced from the Marshall SAM index database⁴ (Marshall, 2003) and SIOD index was computed using ERA5 data, based on (Behera & Yamagata, 2001) definition. Composite anomaly maps of SST and geopotential height were produced to evaluate the extent to which the correlation results are consistent with the oceanic and atmospheric fields associated with ENSO, IOD, SIOD and SAM.

3. Results

3.1. General characteristics of cyclone landfalls

Regional landfalls

Figure 1 shows the coastal areas of Mozambique where the cyclones make landfall. Most TC landfall is observed in the area spanning parts of northern and central Mozambique between 13° and 24°S, where about 75% of the density of the analyzed TCs made landfall, as measured by the kernel density estimation (KDE).

³ <https://psl.noaa.gov/data/timeseries/month/>

⁴ <https://www.nerc-bas.ac.uk/icd/gjma/sam.html>

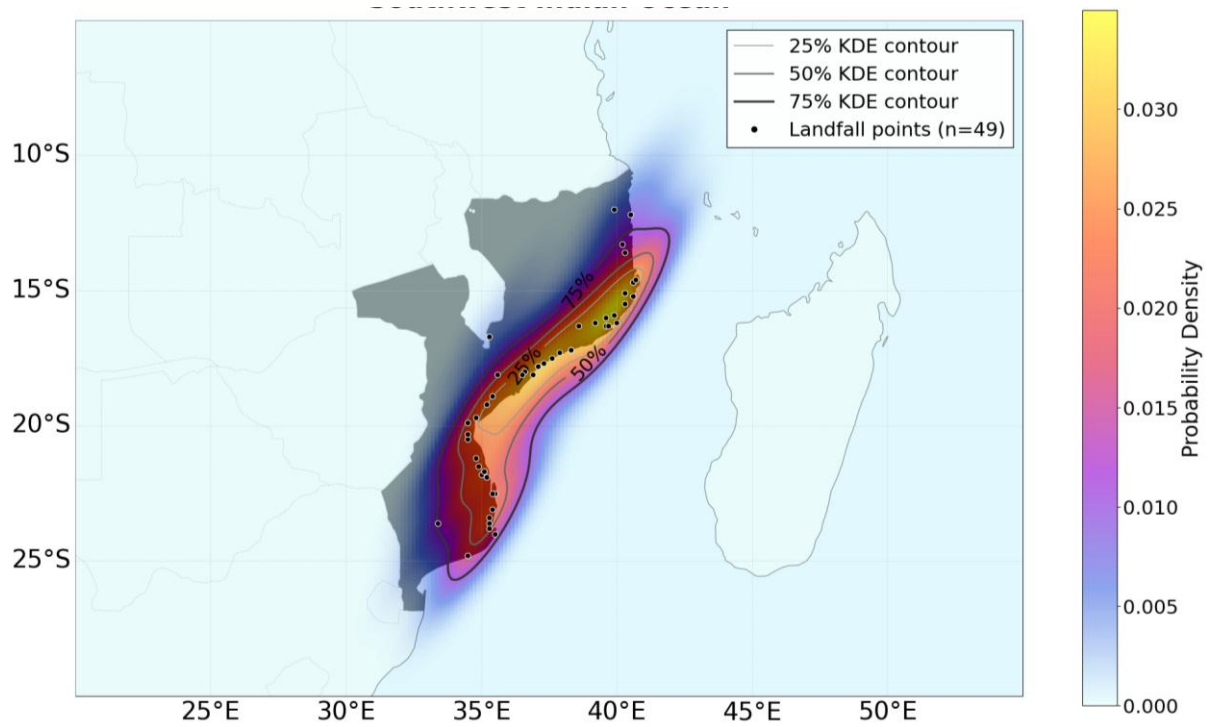


Figure 1. Mozambique map showing landfall points and probability density.

Intraannual landfalls

The monthly landfall frequency graphs (**Figure 2**) show that January, February and March are the months with the most frequent landfall cases (with more than 85%), however, landfalls were also observed in December and April, for the period (1971/72 to 2024/2025) analyzed here. This is consistent with the results from (Mawren et al., 2023), who studied the importance of the Mozambique Channel for the climate of southeastern Africa. After the year 2000, seasons with more than one landfall became more frequent. In some cases, such as those of cyclones Idai and Freddy in 2018/2019 and 2022/2023 seasons, respectively, the same systems made more than one landfall (the cyclones made a first landfall and returned to the ocean, where they again intensified and made a second landfall in another coastal region).

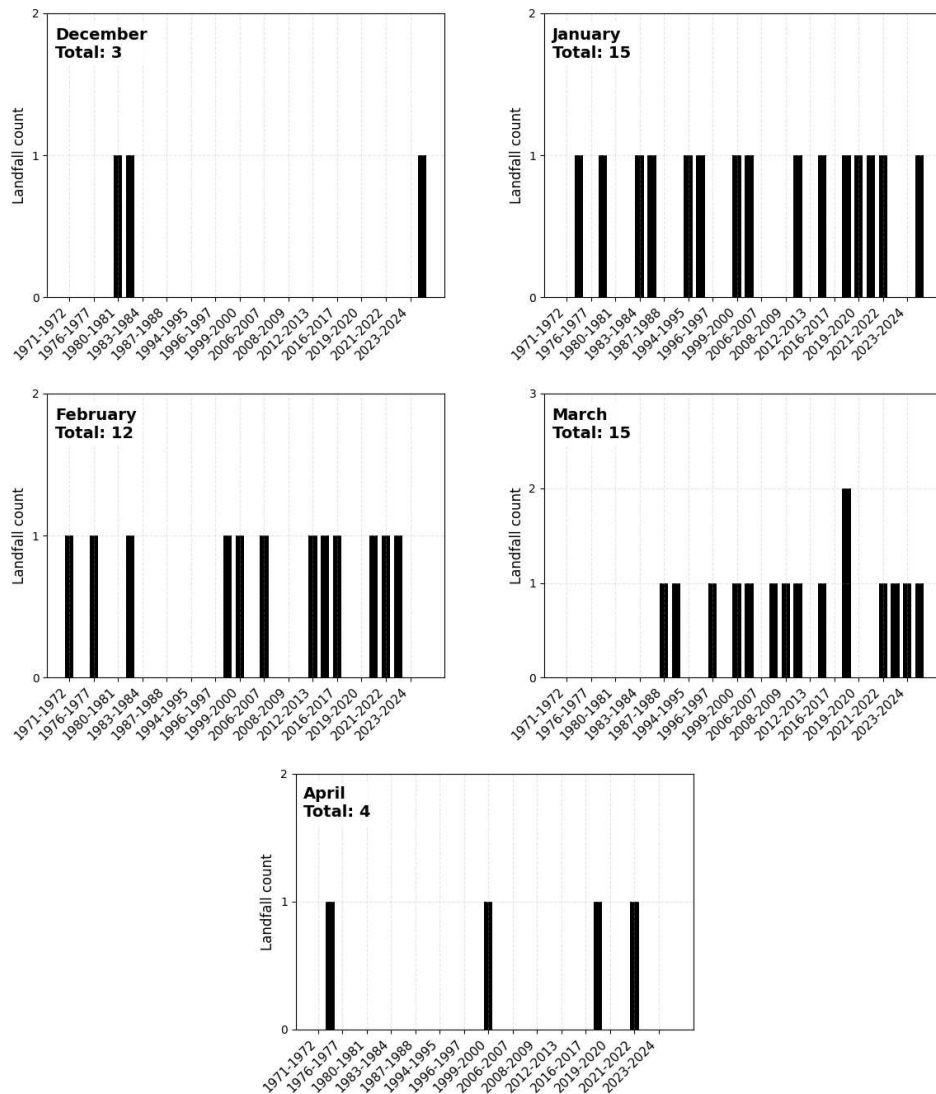


Figure 2. Monthly landfall frequency.

Interannual landfalls

The interannual landfall variability over Mozambique (Figure 3) shows a linear trend with an increasing number of landfalls per season, in accordance with (Chichava et al., 2024) findings, particularly after the season 1999/2000. The seasons 2019/2000, 2019 and 2022 set the record with 4 landfalls (note that tropical depressions were also considered).

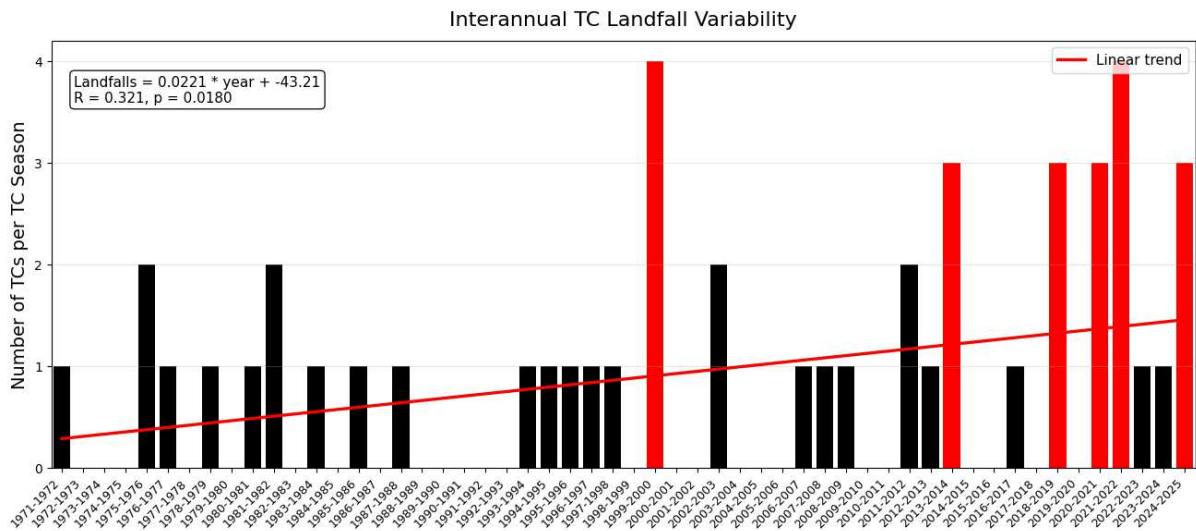


Figure 3. Interannual variability of TC landfall over Mozambique coast (DJFMA). Red bars indicate where more than 2 landfalls were observed in a season.

TC landfall distributions (**Figure 4**) exhibit distinct spatial scales that shift throughout the season, alternating between broad regional corridors and highly localized impact zones. In January (**Figure 4a**), the landfall pattern is characterized by a wider, more diffuse footprint spanning the entire north-south coastline of Mozambique. By February (**Figure 4b**), the spatial distribution narrows significantly, focusing into a high-density cluster concentrated tightly around central-southern Mozambique. As the season closes in March (**Figure 4c**), the footprint expands once again into a broader, more variable band that stretches dynamically between the northern and southern provinces.

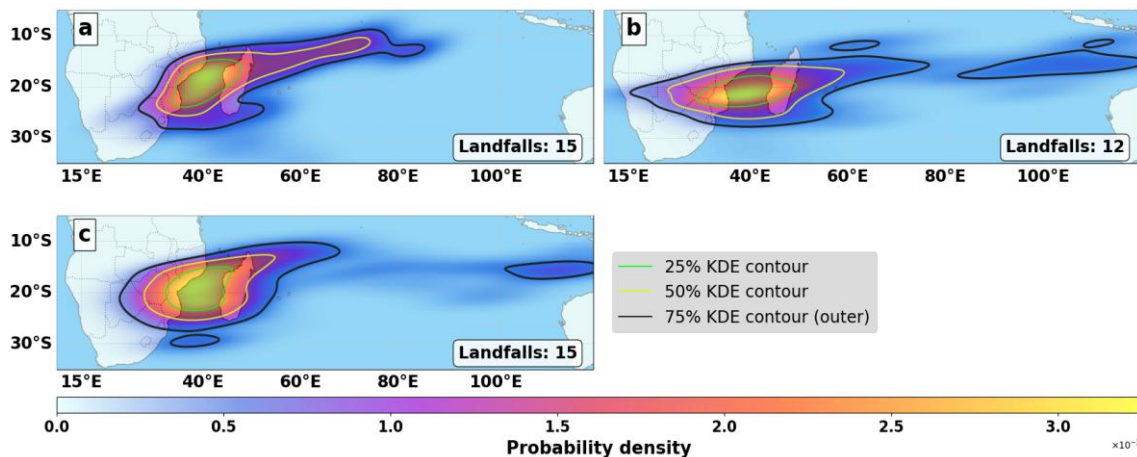


Figure 4. Heat maps showing areas with high landfall density/month, for (a) January, (b) February and (c) March.

3.2 Composite mean analyses of atmospheric variables associated with cyclone landfall over Mozambique

The analyses of atmospheric variables associated with landfall over Mozambique are based on composite anomalies of RH, moisture fluxes, sea level pressure (SLP), vertical wind and SST over the South Indian and Atlantic Oceans, to explore the mean atmospheric conditions before landfall for January, February and March.

These months were selected because they exhibited a higher number of landfalls. Significant patterns were only observed a month before landfall; only these are presented. Plots of RH and moisture fluxes composite anomalies of December (a month prior to January landfall) show a consistent pattern of positive and significant anomalies of RH over south and southeast southern Africa, south of Mozambique Channel and SWIO, eastern of Madagascar, associated with moisture convergence anomalies over southeast southern Africa originating from tropical Atlantic (from the Benguela and Angola currents front region) and SWIO, south of Madagascar (Figure 5a). The RH anomaly pattern contrasts with December composite anomalies when there are no landfalls in January, which show, in general, weaker or negative anomalies of RH (Figure 5b).

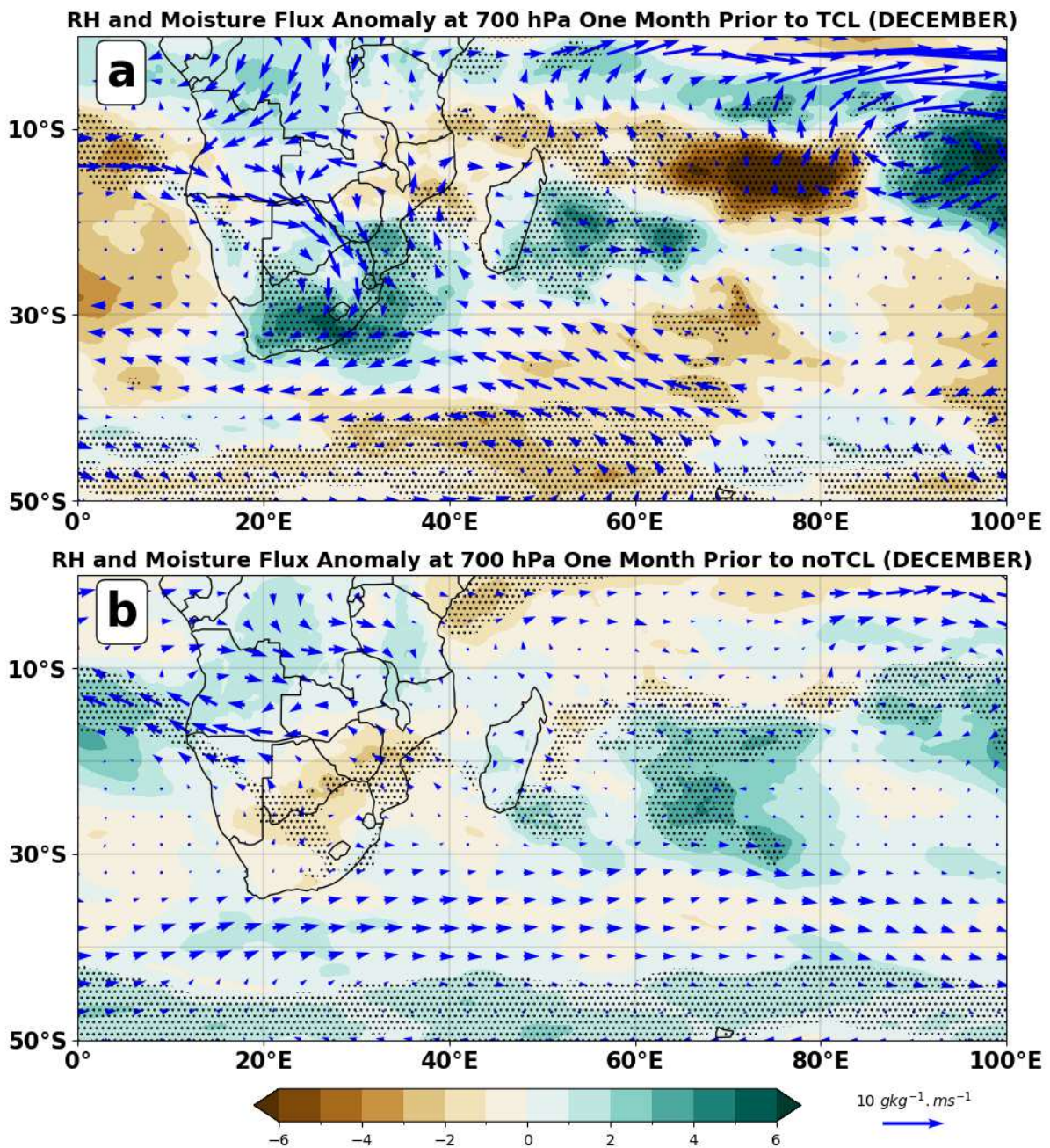


Figure 5. December composite anomalies of relative humidity and moisture fluxes at 700 hPa a month prior to landfall cases (a) and the same period when no landfall is observed (b). Dots indicate areas significant at 95% Student T test.

The plots of RH and moisture flux composite anomalies of January (associated with February landfall cases) show similar patterns with December however, the January RH positive anomalies shift northward and form a diagonal band extending from central southern Africa towards the southeast Indian Ocean (**Figure 6a**). The convergence of moisture flux anomalies is also observed in January composites anomalies, however, the moisture flux anomalies from the SWIO are, in this case, from the tropical Indian Ocean, north of Madagascar, while the tropical Atlantic Ocean moisture flux anomalies show the same pattern as in the previous case (**Figure 5a**). In both December and January, the recycling of moisture fluxes from the continent appears to contribute more significantly to the RH over the southern and central Mozambique and the Mozambique Channel. The February (associated with March landfall) composite anomalies of RH and moisture fluxes also show a pattern of moisture flux anomalies from the tropical Atlantic and SWIO converging over southern and central Mozambique and significant positive anomalies of RH over southern Mozambique (**Figure 6b**). However, different from December and January cases, here the main source of moisture appears to be the tropical Indian Ocean, east of Madagascar and the Mozambique Channel. On the other hand, the RH and moisture fluxes composite anomalies for January and February (when no TC landfall is observed in February and March, respectively) show a similar situation as in **Figure 5b**, i.e., weaker or negative anomalies of RH (figures not shown).

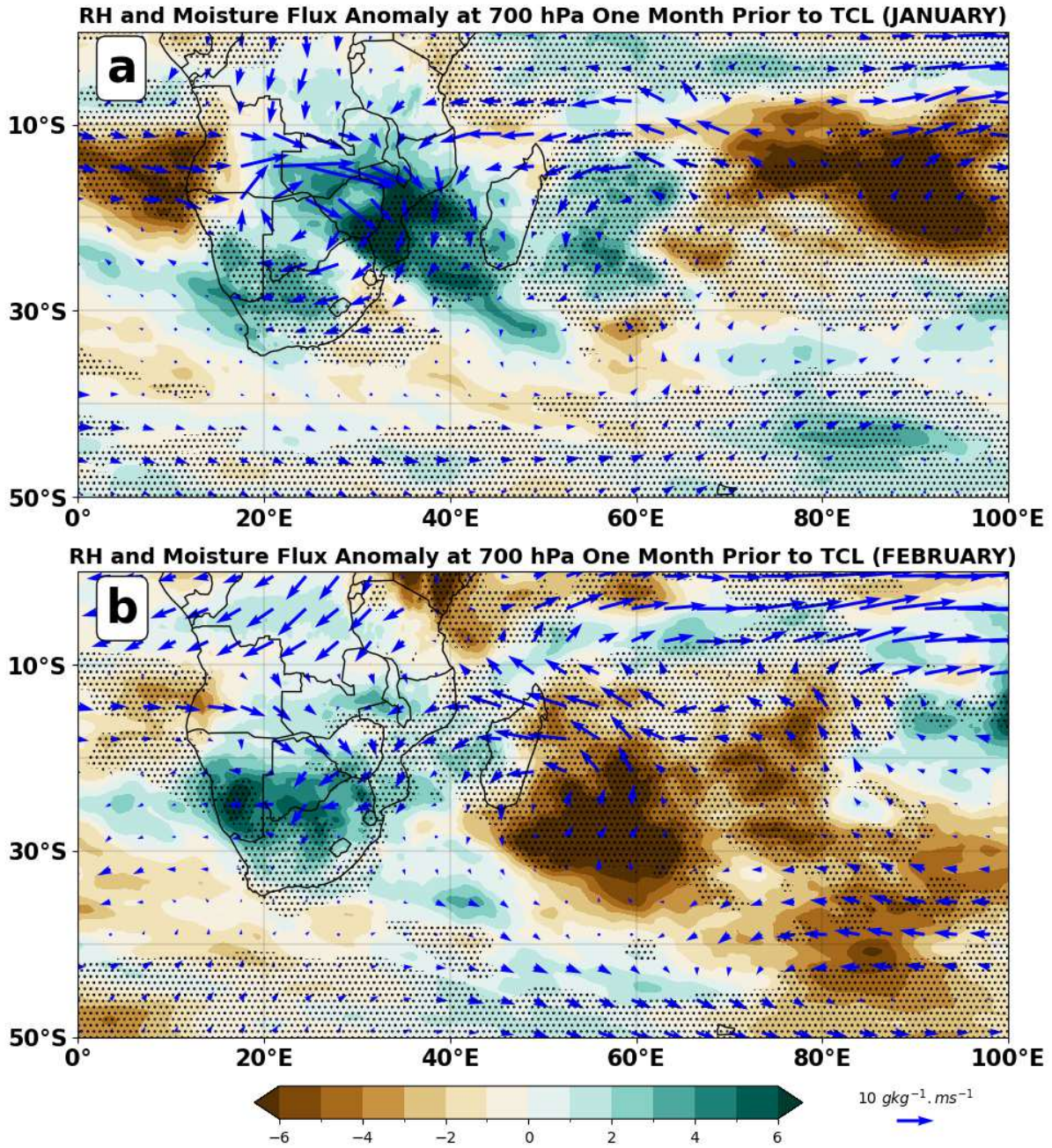


Figure 6. January (a) and February (b) composite anomalies of relative humidity and moisture fluxes at 700 hPa a month prior to landfall cases in February and March, respectively. Dots indicate areas significant at 95% Student T test.

Plots of December SLP composite anomalies (associated with January TC cases over Mozambique) show positive and significant anomalies south to southeast of southern Africa (**Figure 7a**), while the composite anomalies, for the same period, in years without TCs landfall over Mozambique, show negative anomalies of SLP over the same regions (**Figure 7b**). These figures suggest stronger/weaker Mascarene High during years with landfall/no landfall over Mozambique, which is consistent with (Reason & Keibel, 2004; Perry et al., 2024) results.

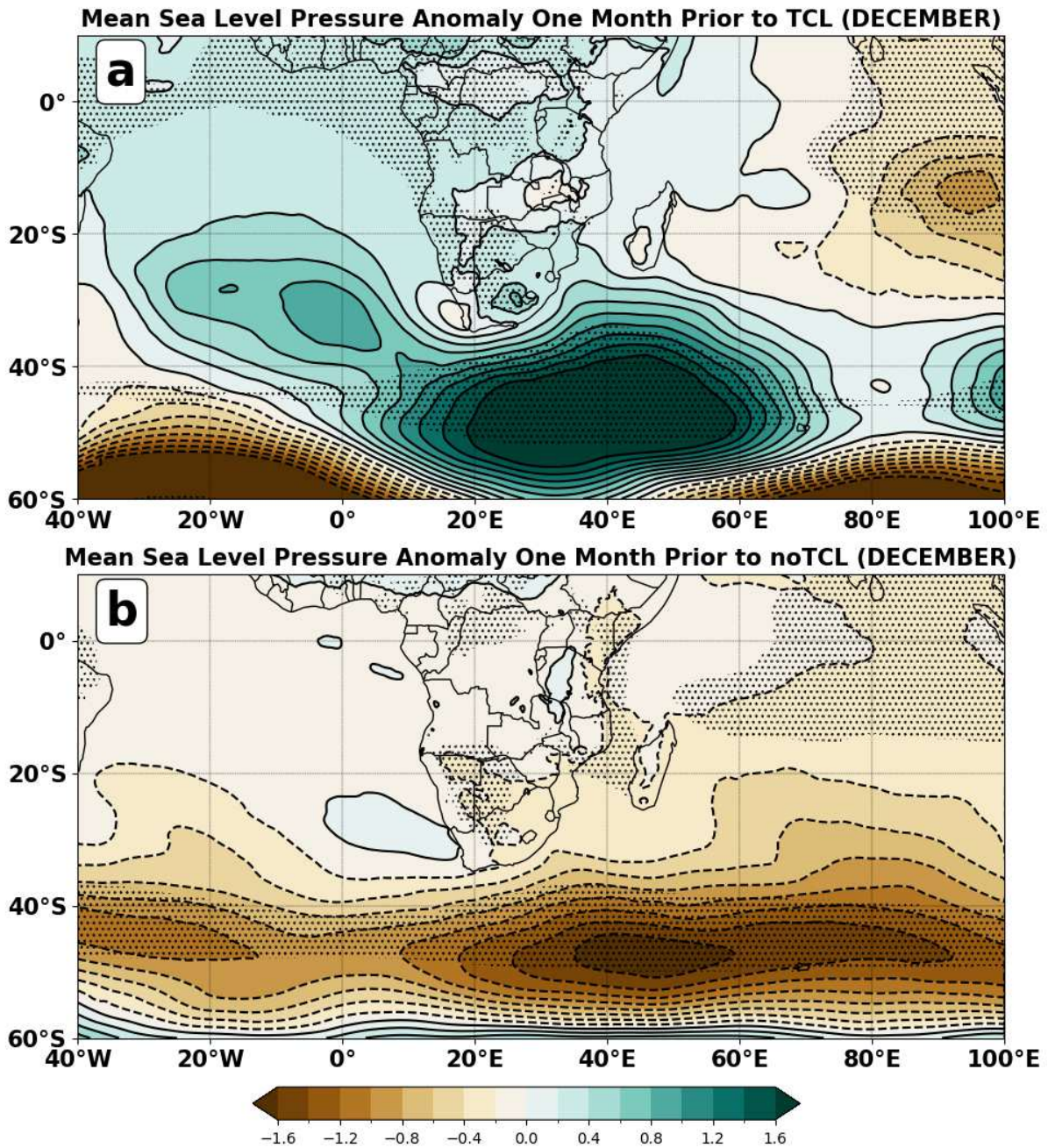
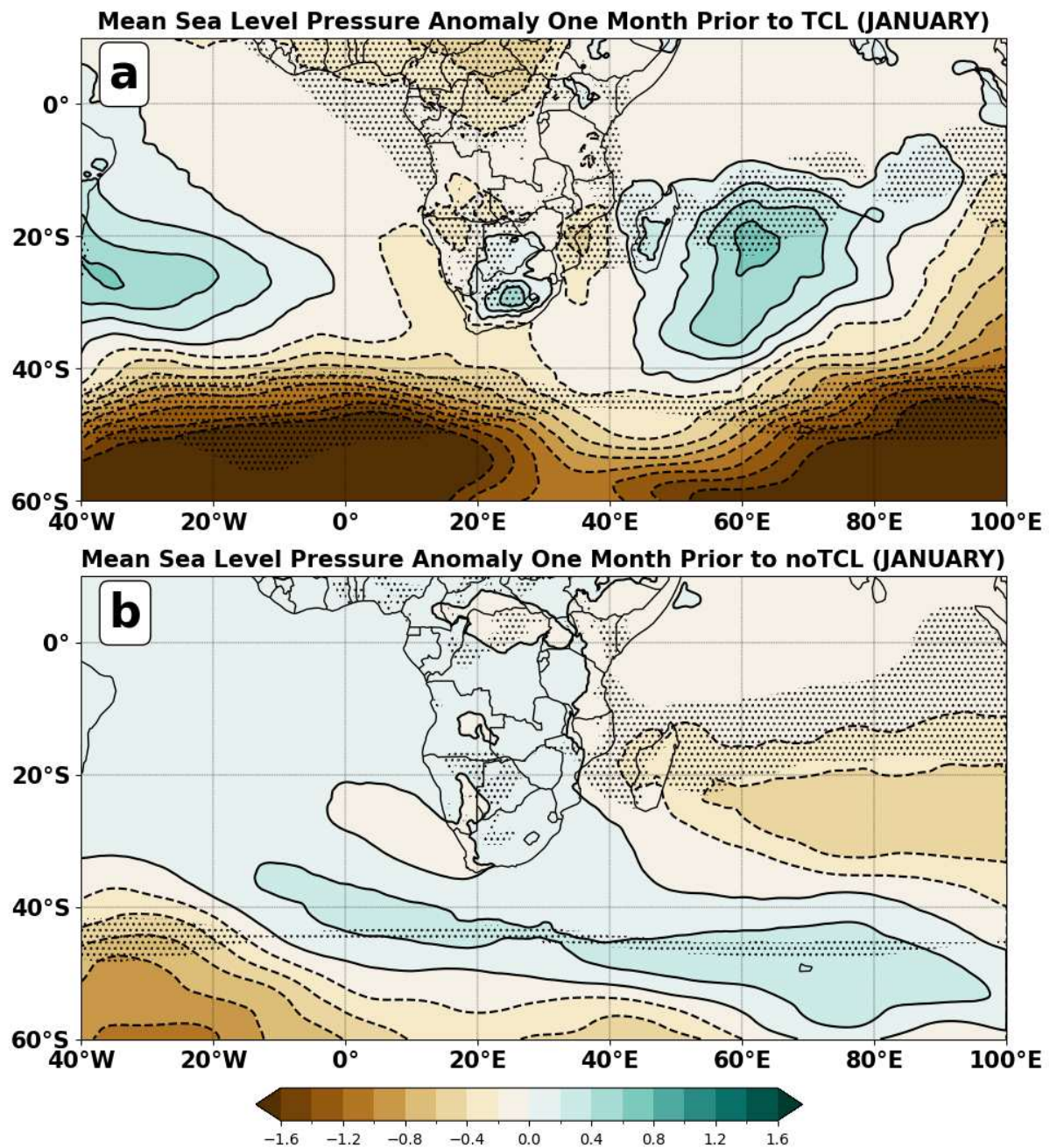


Figure 7. December composite anomalies of mean sea level pressure a month prior to landfall cases (a) and the same period when no landfall is observed (b). Dots indicate areas significant at 95% Student T test.

Plots of vertical wind anomaly for January landfall cases support the patterns observed with SLP anomalies, with strong descending wind anomalies over the south to southeast of southern Africa during years with TC systems landfall, but with ascending or weak anomalies in the same region when there is no landfall (figures not shown).

The January and February SLP anomalies associated with TCs' landfall in February and March, respectively, exhibit a spatial pattern consistent with that shown in **Figure 7**, i.e., strengthened/weaker Mascarene High during years with landfall/no landfall. However, the mean position of the positive/negative anomalies in January

210 and February cases are different. In January, positive/negative anomalies are observed over central SWIO, east
 211 of Madagascar, in years with landfall/no landfall (**Figure 8**).



212
 213 **Figure 8.** January composite anomalies of mean sea level pressure, a month prior to landfall cases (a) and the same period
 214 when no landfall is observed (b). Dots indicate areas significant at 95% Student's t-test.

215 A similar pattern is observed in February composite anomalies associated with March landfall cases, however,
 216 with stronger positive anomalies extending southeastward from eastern Madagascar (**Figure 9**). The vertical
 217 motion supports the patterns observed with the MSLP (figures not shown).

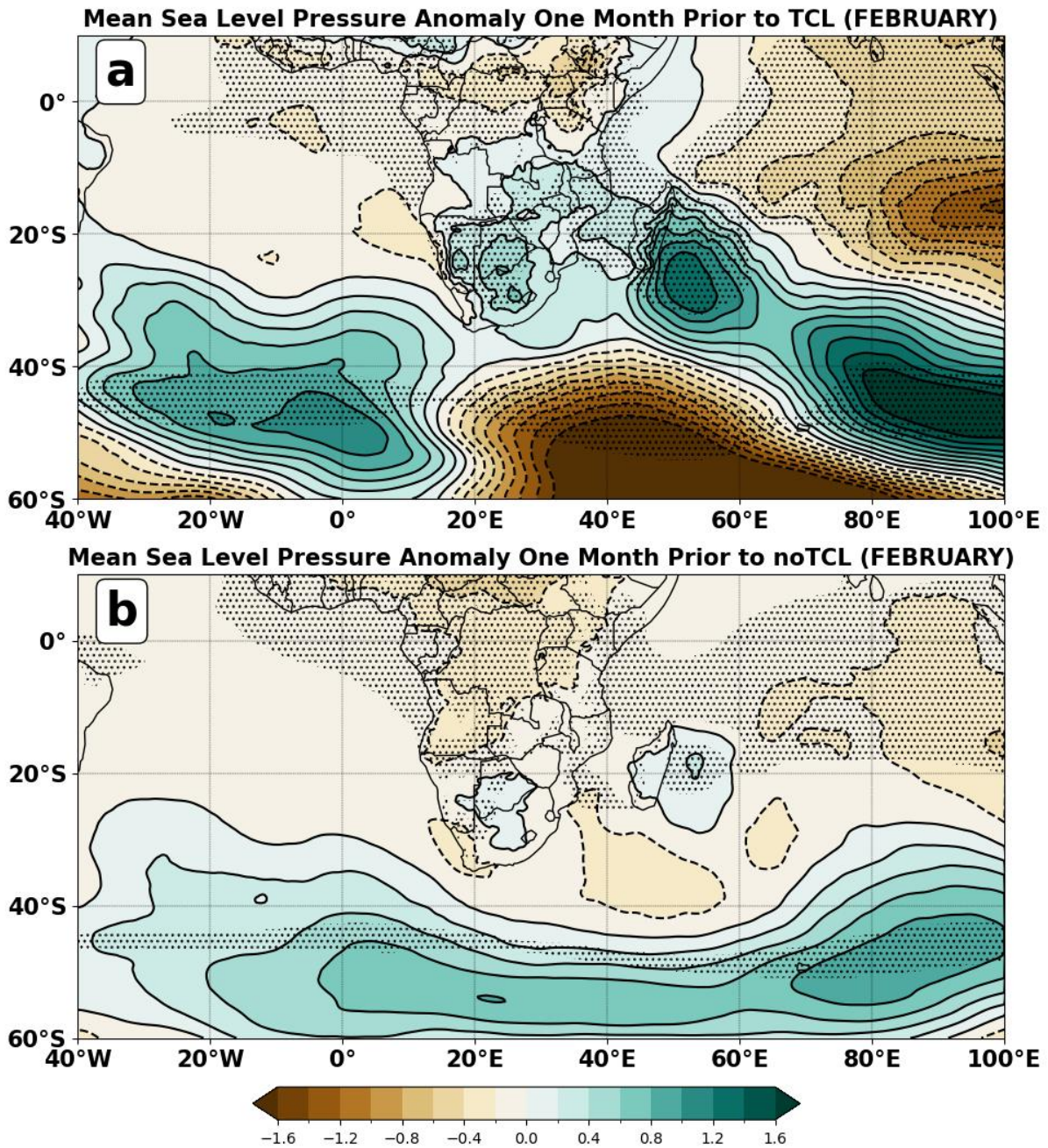


Figure 9. Same as Figure 8, but for February.

3.3 Correlation and composite analysis of TC landfall versus Niño 3.4, IOD, SIOD and SAM

Correlation analyses were explored based on Pearson correlation coefficient with Niño 3.4, IOD, SIOD and SAM indices. The Niño 3.4 index showed consistent negative correlations with landfall however, the correlations are generally weak. The IOD index showed significant correlations with TC landfall for the JFM, FMA and MAM seasons, and the SAM showed significant correlations for OND, NDJ, DJF and FMA seasons (Table 1), with the peak correlations observed in FMA and NDJ seasons, respectively.

Table 1. Correlation coefficients between Niño 3.4, IOD, SIOD and SAM, and TC landfall in Mozambique.

Seasons	Pearson coefficient			
	Nino 3.4	IOD	SIOD	SAM
OND	-0.22	0.09	-0.07	0.36***
NDJ	-0.24*	0.17	-0.07	0.38***
DJF	-0.27*	0.30**	-0.04	0.35**
JFM	-0.28**	0.36***	0.06	0.32**
FMA	-0.28**	0.35**	0.18	0.31**
MAM	-0.25*	0.33**	0.26*	0.26*

Note: (*, **, ***) significant at 90%, 95% and 99% confidence level, respectively.

The SST composite anomalies for TCL years show the positive IOD mode pattern, consistent with the correlation coefficient for JFM and FMA (**Figure 10**). The positive IOD signal is also observed for NDJ and DJF composites, although weaker (figures not shown).

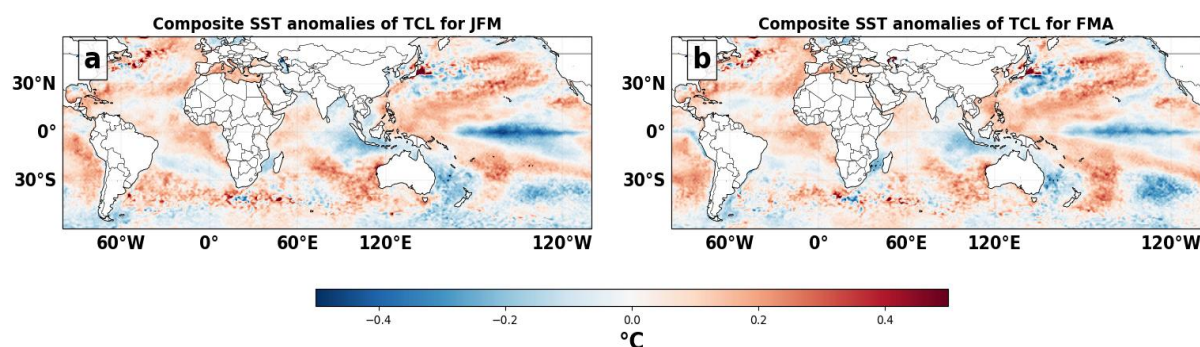


Figure 10. Composite SST anomalies of TCL for (a) JFM and (b) FMA.

Monthly composite anomalies of 500 hPa geopotential height for TCL years show consistent positive SAM for the 3 landfall months analyzed here (**Figure 11a, c and d**). However, composite anomalies for noTCL years show a negative SAM (**Figure 11b**) or a weak positive SAM (figures not shown). The geopotential height anomalies over the SWIO are consistent with the strengthening/weakening Mascarene high during years with

landfall/no landfall over Mozambique, suggesting a Mascarene high modulation by the SAM, which is consistent with the findings of (Ibebuchi, 2024).

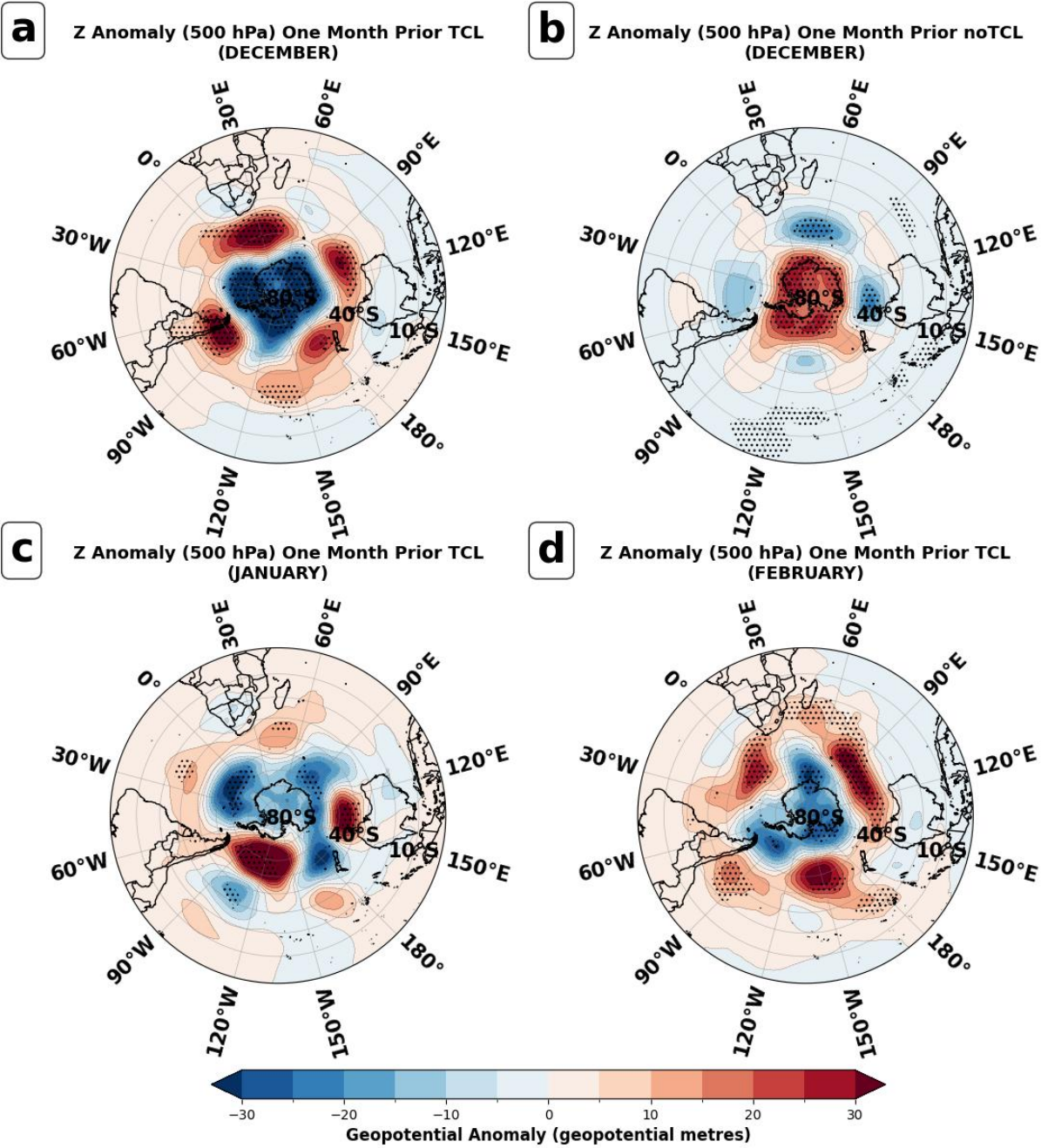


Figure 11. Composite anomalies geopotential height at 500 hPa.

4. Discussions and Conclusions

The main objective of this study was to investigate the interannual variability of TC landfall over Mozambique and the associated atmospheric and oceanic conditions prior to landfall. Landfall showed spatial variability within the TC season. The landfalls in early and late months (December and April) are mainly concentrated over northern and central Mozambique however, with few cases for the analyzed period (3 and 4, respectively), January and March landfalls are mainly concentrated over central Mozambique and the February landfalls are

concentrated over southern Mozambique. January, February and March are the months that showed the highest number of landfalls during the analyzed period (12 or more, in each month). March was also identified as the month with the highest number of landfalls in Mozambique by (Mawren et al., 2023), who also reported that more intense TCs (Category 3 and above) occur further south in the Channel in this month. Consequently, there is also a relationship with the intensity of the cyclone. The interannual frequency showed an upward trend, with an increasing number of landfalls in a single year (two or more, with cases of two landfalls by the same TC system), consistent with (Chichava et al., 2024) findings. The analyses of the associated atmospheric and oceanic conditions were based on composite analyses of relative humidity, moisture fluxes, sea level pressure, geopotential height, vertical wind and sea surface temperature, in years with landfall compared to years without landfall for months that showed higher landfalls (January to March). The results show significant positive anomalies of RH over the Mozambique Channel and landfall domain, one month before landfall in all three peak months. In contrast, for the years without landfall, the monthly RH anomalies are, in general, weak or negative. Previous studies have shown that moisture is a key factor for TC intensification, size and overland maintenance, e.g. (Hill & Lackmann, 2009; Wu et al., 2015; Wakefield et al., 2021). The high RH is associated with moisture flux convergence from the Atlantic and Indian Oceans over the landfall region and Mozambique Channel. Composite anomalies of SLP show mainly positive values over the southwest Indian Ocean, south to southwest Madagascar in years with landfall, while in years without landfall, SLP anomalies are negative or weak. This suggests stronger/weaker Mascarene High during years with landfall/no landfall, particularly in January and February. Stronger Mascarene High enhances the moisture fluxes towards the Mozambique Channel and inland southern Africa, hence the increase in relative humidity. However, in December and January, continental moisture fluxes appear to contribute more to the increase in relative humidity. SAM exhibits significant correlations in the early season, with a peak in NDJ, while IOD exhibits significant correlations in the late season, with a peak in JFMA. The correlations with Niño 3.4 index were consistently negative, although not significant. (Iizuka & Matsuura, 2012) identified an increase in TC system formation during La Niña and positive IOD, which may suggest that the landfalls that co-occur with these modes of variability are also associated with a higher number of TC formations over the SWIO, as suggested by (Chichava et al., 2024). The results of this study suggest that the landfall over Mozambique is supported by higher-than-normal relative humidity over the continent and the Mozambique Channel, which is associated with significant moisture fluxes from the Atlantic and Indian Oceans. The moisture fluxes over the Indian Ocean appear to be driven by a stronger Mascarene High, which is in turn modulated by a positive SAM, consistent with findings of (Ibebuchi, 2024). However, seasonal shifts of the Mascarene high appear to play a role in the spatial distribution of landfall along the Mozambique coast, as shown here by the spatial variability of landfall along the Mozambique coast. While this study provides critical insights, the robust identification of long-term trends is inherently challenged by the relatively small sample size of historical TC landfall events. This statistical limitation is further compounded by data uncertainties between 1970 and 1990, a period when less reliable observational records may have led to the underreporting or omission of events within the IBTrACS dataset. Despite these data constraints, this work offers significant novelty; while the influence of the Mascarene High on individual TC tracks toward Mozambique is well-documented, this study elevates the analysis to a climatological timescale, uncovering how this high-pressure system modulates regional atmospheric humidity and large-scale moisture fluxes over longer periods. These results will contribute to the improvement of TC

EWS, disaster risk management and improve the implementation of anticipatory actions in Mozambique. By identifying the distinct atmospheric precursors of TC landfall a month before, meteorological agencies can issue localized, long-lead sub-seasonal forecasts, giving disaster management authorities crucial time to prepare. Furthermore, these findings empower policymakers to transition from reactive disaster response to proactive, climate-resilient development. This includes strategically updating zoning laws, designing infrastructure tailored to specific regional wind and surge thresholds, and allocating some emergency resources.

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454 **Data Availability**

455 The tropical cyclone track and intensity data used in this study were obtained from the WMO La Réunion
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