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Causal Relationships between Monsoon Systems, the Mascarene High, and Rainfall Variability over Botswana, Southern Africa

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ABSTRACT

Climate change and variability pose significant threats to southern Africa, with projected continuous drought in Botswana. This study examines the causal relationships between African-Indian monsoon systems (East Africa, West Africa, and Peninsula India), the Mascarene High, and interannual rainfall variability over Botswana. Using statistical analysis and mapping techniques (Pearson correlation statistics and convergent cross mapping (CCM)), the authors analysed the impact of these weather systems on rainfall variability from 1979 to 2021. The findings reveal significant negative associations between these weather systems and interannual rainfall variability in Botswana, shedding light on their crucial roles in shaping the region's rainfall patterns. Bidirectional causation between different regions and the Mascarene High was observed, emphasising the interconnectedness of rainfall patterns. Significant findings include the bidirectional causation between Botswana and West Africa rainfall during March–May (MAM) and October–December (OND) seasons. In addition, the authors also observed bidirectional causation between Botswana and Peninsula Indian rainfall during the OND season. The study highlights the potential of these factors in predicting extreme events and assists in planning for potential risks associated with rainfall variability in Botswana to promote community awareness and education on climate change and variability, water conservation, and sustainable livelihood.

Keywords: Pearson correlation; Interannual rainfall variability; Convergent cross mapping; Drought

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1. Introduction

The monsoons affect agriculture and water resources due to the timing and intensity of the seasonal monsoon activities. Farming in Africa is highly dependent on rain-fed agriculture, and the continent is facing increasing vulnerability to climate change and variability, leading to a decrease in agricultural production due to low adaptive capacity [1,2]. These variabilities affect the economic sector, causing food and water shortages due to continuous droughts. These recurrent, severe, and widespread droughts will be a common phenomenon in the future [3] and affect water supply, leading to the unavailability of fresh water and food insecurity. The variability and change will bring severe threats and challenges over eastern and southern Africa due to rising temperatures and varying frequencies and intensities of drought. Rainfall is the most critical meteorological factor in southern, western, and eastern Africa [4,5], driving rain-fed agricultural systems [6–11]. There is a possibility of a rise in the frequency and intensity of extreme climate events, especially those related to precipitation [12,13]. Climate change would lead to an extreme increase in precipitation in wet areas and dry spells in dry conditions [14]. Environmental factors such as the El Nino-South Oscillation or Indian Ocean Dipole, local topography, atmospheric pressure systems or ocean currents influence rainfall variability.

Droughts are a recurring feature of the semi-arid and arid ecosystem, but climate change and variability might worsen the situation because the region depends on natural resources. Drought in southern Africa affects social, economic, and environmental aspects [15]. It is a long-term hydro-meteorological event affecting large regions and different development sectors, especially in Botswana, where the effects are the most noticeable in water resources. There is decreased rainfall, increased cases of drought [16,17], and increased temperatures, leading to stress on evapotranspiration rates [18,19]. Severe droughts are common in Botswana due to erratic, strongly below-average rainfall. They severely affect the country's agricultural sector and water resources. Rainfall decreases due to climate variability, and change is associated with declining regional water supplies, biodiversity, and environmental degradation [20]. According to simulated data from two global climate models (GCMs), CSIRO MK2 and HadCM3, with three IPCC emissions scenarios (A1B, A1FT, and A1T), the southern part of Botswana is projected to have an 11% decline in rainfall by 2050 [21]. These rainfall and temperature pattern analyses often track climate change intensity and size [22–24].

The agro-pastoral production systems in Africa are susceptible to increased climatic variability [20,25]. The cattle industry, as the main contributor to the agricultural sector in Botswana, is susceptible to climate change and drought. The country experienced water scarcity due to extremely low rainfall seasons [26]. Water stress is projected to increase due to climate change and variability, increasing water demand. The increasing water scarcity and drought resulting from climate change and variability might lead to considerable water use, which is expected to occur in tough competition with other sectors of the economy. Sustainable development and climate adaptation measures are needed for water conservation and disaster preparedness to deal with the dynamics of rainfall variability. These can be addressed by anticipating future patterns of rainfall and their effects. Understanding the dynamics of rainfall can assist in creating risk assessment frameworks and scenario-based planning to guide policy decisions and assist community-based adaptation plans.

In the above discussion, there is a lack of interaction between African and Indian monsoon systems on interannual rainfall variability at the country level, where the Mascarene High plays a vital role. Therefore, this paper investigates the interaction between African-Indian monsoon systems through the Mascarene High and their impacts on the interannual rainfall variability over Botswana. There is a need to understand a given country's rainfall distribution and variability to increase the accuracy and reliability of weather forecasting, which is aimed at planning and monitoring extreme events. The study is based on a reduced spatial scale at a country level to ascertain the impacts of Mascarene High on individual countries' weather and climate. The country-level scale will help to monitor the evolution of Mascarene High events accurately and improve the quality of seasonal weather forecasts in the country. Understanding the interannual variability in rainfall is essential for early warnings and forecasts for the community and agricultural production. The correlation methods are used to study atmospheric interactions and rainfall variability but cannot determine the causal relationship between the variables and identify the direction of the cause. However, we must explore the nonlinear coupling causality because nature is a non-stationary and nonlinear space. Therefore, we need causality analysis to identify the causal relationship. The causality method is the convergent cross-mapping (CCM) method [27]. The Pearson correlation was used to study the subsequent interactions, and the CCM was used to analyse the causal relationship and dominant factors influencing Botswana rainfall variability. The researchers widely use CCM to determine meteorological interactions. The CCM method detects causal relationships and weak couplings in complex ecosystems and reconstructs nonlinear pullers in time series data. This study uses the CCM method to analyse the influence of monsoon systems and Mascarene High on the interannual rainfall variability.

Botswana's background as a semi-arid country with a problem of high rainfall variability and recurring droughts is necessary to understand the characteristics of rainfall variability and its causes. In order to ensure accurate prediction of extreme events in Botswana, information on the extent to which monsoon systems and Mascarene High contribute to interannual rainfall variability may assist in formulating management strategies for sustainable policies. Therefore, identifying and analysing the interactions of the African-Indian monsoon and Mascarene High and their interannual influence on rainfall can improve the prediction of extreme events and develop strategies to mitigate potential impacts on communities' livelihoods. The significance of the study lies in its focus on understanding the interaction between African-Indian monsoon systems through the Mascarene High and their impacts on interannual rainfall variability over Botswana. This understanding is crucial for improving the accuracy and reliability of weather forecasting, which is essential for planning and monitoring extreme events.

2. Materials and methods

2.1 Study area

The study was carried out in five regions; it lies between 25°N–45°S and 45°W–115°E. **Figure 1** shows the spatial distribution of the five regional climate factors used in the analysis. The study area was chosen based on the researcher's interest in linking African and Indian climate systems and identifying a research gap that links the two continents based on the topic specificity. The location as per region is as follows:

a) Peninsula India (Red rectangle) 8°N–22°N and 72°E–88°E [28].

b) East Africa (Black rectangle) 5°S–20°N and 30°–60°E [29].

c) Mascarene High (Blue rectangle) 20°–40°S and 40°–110°E [30].

d) Botswana (Green rectangle) 18°–27°S and 20°E–30°E.

e) West Africa (Orange rectangle) 0°–20°N and 20° W–20°E [31].

Previous research has identified the regions based on their heterogeneity regarding mean sea level pressure, wind, and rainfall variability [9,32]. The areas are classified as monsoon systems and are distinguished by their monsoon-based delineation. Monsoon rainfall is vital to the economy and the societal impacts of the global population. The Peninsula Indian receives most of its rains during the monsoon seasons: the southwest monsoons during June–September (JJAS) and the northeast monsoons during October–December. Indian monsoon onset is accompanied by significant changes in atmospheric circulation and rainfall over Asia and parts of Africa [7]. The monsoon winds blew from the southwest for half of the year and from the northeast for the other half. The wind pattern reverses, accompanied by differing precipitation over India, and is called an advancing and retreating monsoon. Therefore, the wind blew towards India in the summer and to the ocean in the winter.

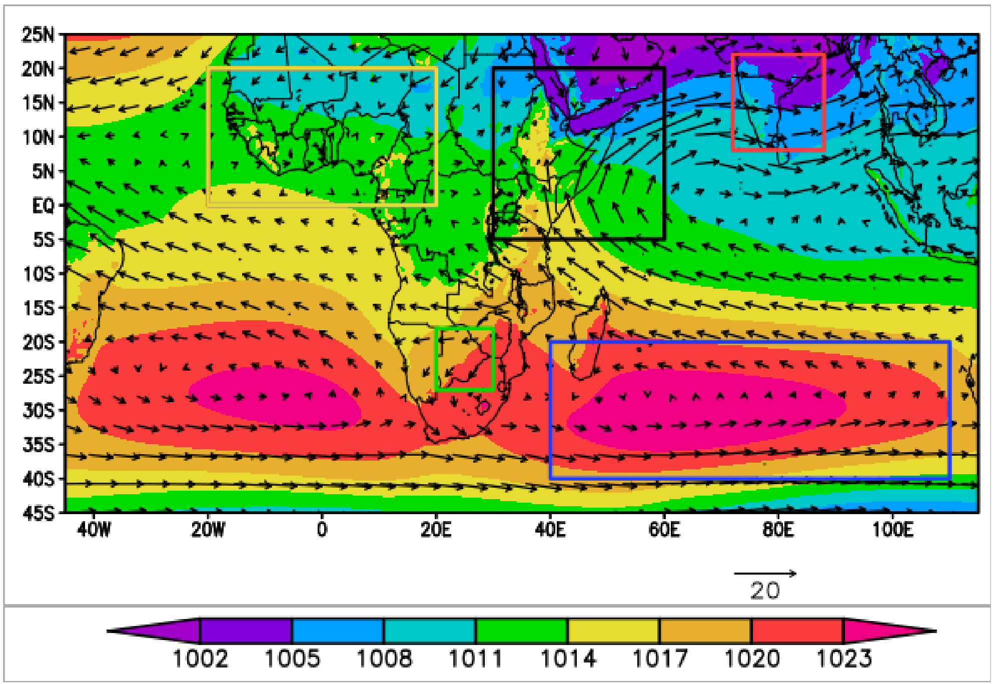

Figure 1. The climatic circulation system for the June–September season from 1979–2021 for Peninsula India (red rectangle), East Africa (black rectangle), West Africa (Orange rectangle), Botswana (green rectangle), and Mascarene High (blue rectangle).

Note: The black arrows show wind vectors @850 hPa superimposed with pressure shown by shaded colour, and the cbar shows pressure levels.

East Africa comprises Kenya, Uganda, Tanzania, Ethiopia, Eritrea, Djibouti, Somalia, South Sudan, Rwanda, and Burundi [29]. Its mean annual rainfall ranges between 800 and 1200 mm, high over the highlands, while northeastern Kenya and Somalia receive low rainfall. Frequent severe droughts occur in these countries [29], and the population heavily depends on rainfall. Floods are also a challenge in East Africa [33]. East Africa has two distinct rainy seasons: long rains during March–May (MAM) when the Inter-Tropical Convergence Zone (ITCZ) is located south of the equator and short rains (OND) in the central, southern, and eastern parts of Africa [29,34]. The two seasons have independent inter-annual rainfall variability and bimodal seasonal rainfall [35]. The variability in short rains is high, while the long rain season has the highest total rainfall [36]. The short-rain inter-annual variability is related to external forcing [37]. The Indian Ocean Dipole circulation patterns [38,39] and the El Niño-Southern Oscillation (ENSO) [40] affect East African rainfall during MAM and OND rainfall [41].

Mascarene High is a semi-permanent subtropical anticyclone situated over the southern Indian Ocean. It is a high-pressure area and plays a vital role in weather and climate by modulating weather and climate patterns. In the austral winter (June, July, and August), it is a component of the Asian-Africa-Australia monsoon system.

The economy of West Africa is based primarily on the West African monsoon, which has a mean annual rainfall of 150–2500 mm. The monsoon occurs during JJAS season when the wind blows southwest from the North Atlantic Ocean, keeping the ITCZ above equatorial Africa [42,43]. The ITCZ crosses West Africa from March to June, bringing wet southwesterlies from the tropical Atlantic to replace the dry, heated, and dusty winds. The Atlantic cold tongue and the Saharan heat-low provide moisture to the continent and combine to generate the southwesterly. The seasonal reversal of wind direction in the lower atmosphere distinguishes the West African monsoon [44]. JJAS (summer months) is the wettest month in West Africa; they account for 80% of the annual total rainfall [45].

Botswana is a landlocked country in southern Africa. Its climate is controlled by semi-permanent subtropical anticyclones (southeastern Atlantic and southwestern Indian oceans) [46]. The country is arid to semi-arid and subject to significant weather variations. It receives more rain in January and February, and seasonal rainfall occurs from October to March. Its economy mainly relies on rain-fed agriculture, and it is driven by mining and tourism, which are equally affected by extreme weather events, especially drought.

2.2 Data collection

Precipitation

The daily precipitation data from 1979–2021 were obtained from the National Centers for Environmental Prediction (NCEP) and Climate Prediction Center (CPC). The data have a resolution of 0.5° by 0.5° and can be accessed through https://psl.noaa.gov. The data include each daily rainfall for the monsoon systems and Botswana. The spatial and temporal precipitation totals were averaged according to the boundary of each region and the individual monsoon season to be used further in correlation analysis as per monsoon season.

Winds

The monthly U & V wind components (m/s) at 850 hPa were sourced from the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5), which has a resolution of 0.25° × 0.25°. The wind data were used as wind patterns across the seasonal spatial and temporal scales to establish a qualitative connection between ocean dynamics, rainfall variability, and distribution. The wind data were accessed through https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels-monthly-means.

Pressure

The mean sea level pressure data from the Copernicus Climate Change Service through Climate Data Store (2023) as per the study area were downloaded. These are ERA5 monthly averaged data on single levels at a resolution of 0.25° × 0.25°. These pressure distributions are used to qualitatively link ocean dynamics to wind patterns and rainfall variability throughout the seasonal spatial and temporal scale. The Mascarene High daily pressure data were delineated per various seasons for correlation analysis with the interregional rainfall. https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels-monthly-means. The area-averaged pressure was aggregated into monthly data for seasonal analysis.

2.3 Method

This paper focuses on coupling patterns between monsoon systems and Mascarene High in different seasons over Botswana rainfall. Botswana's daily precipitation data from 1979–2021 were aggregated into monthly totals based on monsoon seasons to get seasonal interannual variation for MAM, JJAS and OND seasons. The seasonal interannual variation was analysed to understand the variation before further analysis. **Figure 2** shows the study flowchart, the Pearson correlation analysis, which quantifies the relationship and influence of monsoon systems and Mascarene High based on seasonal interannual variations in Botswana rainfall. We used seasonal interregional rainfall (East Africa, West Africa, Peninsula India and Botswana) and Mascarene High pressure for correlation analysis. The relationship between the variables X and Y was determined using the correlation coefficient (r) and whether or not they correlated [47]. To identify the causes and effects, we performed a causality analysis. Significant variables that acquired positive or negative correlations based on the Pearson correlation results were selected for causality analysis.

We used the CCM method to analyse the causality and distinguish the individual influence of monsoon systems and Mascarene High on Botswana rainfall from 1979–2021. The coupling patterns of Botswana rainfall with monsoon systems and Mascarene High in different seasons were performed. The R package for Empirical Dynamic Modelling and Convergent Cross Mapping "rEDM" was used. Empirical dynamic modelling (EDM) is a non-parametric framework for modelling nonlinear dynamic systems, and it is a mathematical theory for reconstructing attractor manifolds from time series data [48]. The "rEDM" package comprises several methods, including simplex projection [49], S-map [50], multivariate embedding [51], convergent cross-mapping [27] and multi-view embedding [52]. From "rEDM", we implemented convergent cross-mapping using the *ccm* function to provide a wrapper to compute cross-map skill for different subsamples of the data. In addition, the spatial seasonal climatology circulations (mean sea level pressure and wind) were plotted to assess the seasonal variation.

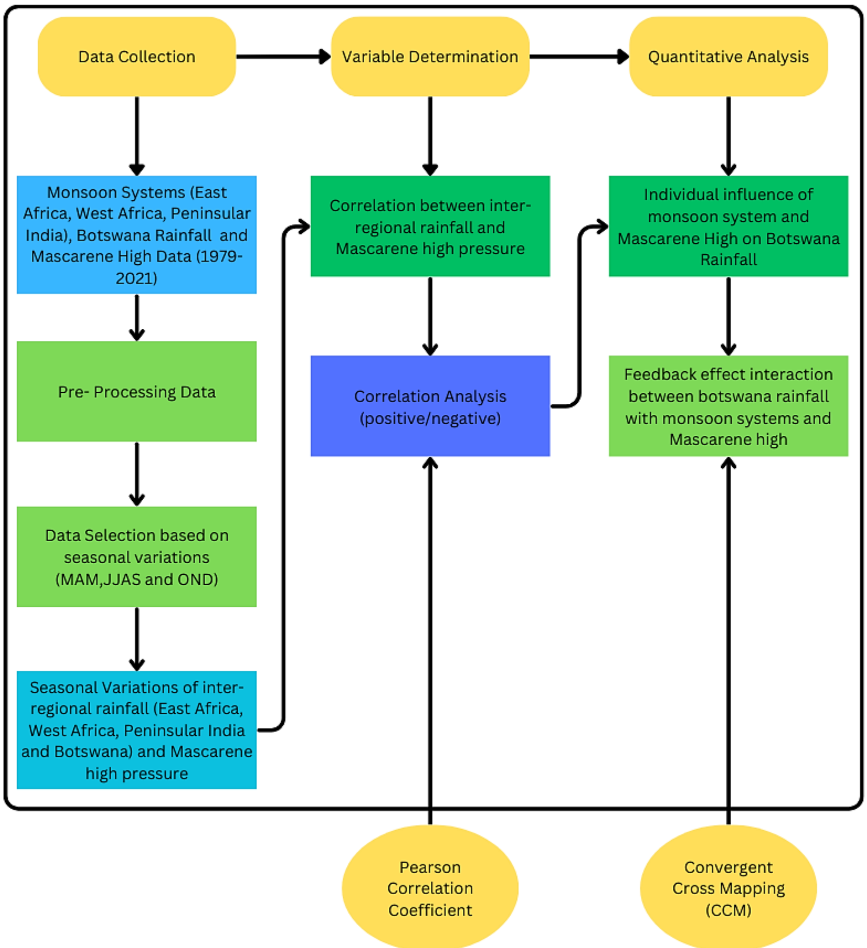

Figure 2. The study framework.

Correlation analysis

The correlation analysis reveals the relationship between pairs of variables [53]. Pearson correlation analysis was used to measure the strength of the linear relationship or establish whether there are any significant relationships between the monsoon systems, Mascarene High and Botswana rainfall. The correlation coefficient values vary between –1 and +1, where values tend to be +1, which means that the two variables are strongly related in a positive linear relationship. In contrast, the values tend to be –1, which means that the two variables are strongly related in a negative linear relationship. The Pearson correlation analysis examined the relationship and influence of monsoon systems and Mascarene High based on seasonal variations in Botswana rainfall variability. The correlation coefficient (r) was used to determine whether there was any correlation between each monsoon system, Mascarene High, and ITCZ rainfall, and, lastly, whether there was a positive or a negative correlation. Since correlation cannot establish a cause-and-effect link, further analysis was done using CCM.

Convergent cross-mapping (CCM) analysis

After finding the correlations, we applied a nonlinear state space method to identify the coupling between Botswana rainfall, monsoon systems, and Mascarene High using the CCM method. It was used to identify the coupling relationships (network) among individual variables in a complex system. **Figure 3** illustrates the $Y = f(X, Y)$ system; according to the Takens theorem, the cross-mapping indicates that the point on the manifold is a variable *My*; hence, the corresponding point *Mx* can be searched simultaneously. We calculated the *Mx* and *My* shadow manifolds that cross the map to the actual manifolds of the system [54]. The manifold is a system overview, where *Mx* and *My* represent X and Y. Therefore, *Mx* can predict *Y* or $\hat{Y}$ | Mx, and vice versa [55]. The CCM method detects weak to moderate coupling; convergent mapping delivers bidirectional causality [27]. For instance, let us say that ρ is a skill prediction and *X* and *Y* are two variables. The influence of variable *X* on variable *Y* was shown by ρ values ranging from 0 to 1. We can predict *X* if X causes Y, *X* causes *Y* and leaves information on *Y* that can be used to retrieve *X* from *Y* if $\rho(X|Y) < 1$ and is high enough [55], and vice versa. Unidirectional causation is denoted by $X \rightarrow Y$. A high value of ρ (X|Y) indicates a good prediction from *X* to *Y*.

On the other hand, poor prediction from *Y* to *X* occurs when ρ (Y|X) is low. Bidirectional causality was denoted by $X \leftrightarrow Y$. Predictions from *X* to *Y* and *Y* to *X* are good if the values of ρ (X|Y) and ρ (Y|X) are high. The CCM method uses nonlinear time series analysis to measure the causes between two dynamic variables based on time series [27].

Climatology circulation analysis

The seasonal climatological variation across the study area was assessed based on seasonality. The spatial seasonal climatology circulation for MAM and OND seasons was assessed based on CCM assessment results. Therefore, the wind and mean sea level pressure were superimposed for MAM and OND seasons to display and visualise the spatial variation during the interactions.

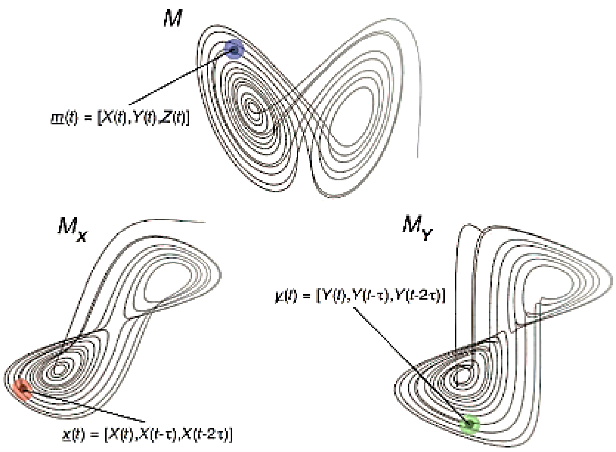

Figure 3. Convergent cross-mapping test for correspondence between shadows manifolds**.**

Source: Tsonis, A.A. et al. [56].

3. Results and discussion

3.1 Botswana's seasonal rainfall patterns and variability

We used Botswana's daily precipitation data from 1979–2021 to prepare monthly averages based on monsoon seasons to get seasonal variation (MAM, JJAS and OND seasons). These seasonal analyses were based on the monsoon activity. It is essential to grasp Botswana's seasonal variation before analysing its correlation with monsoon systems and Mascarene High. As shown in **Figure 4**, Botswana rainfall tends to have high fluctuations during OND and MAM seasons; more rain was received during the OND season and less with fewer fluctuations during the JJAS season from 1979–2021. The MAM and OND rainfall patterns have slit similar fluctuations in opposite directions.

In contrast, JJAS has almost level or constant variability. The mean rainfall value during the OND season can be determined, with a peak of 106.3 mm in 1986 and the lowest value in 1990 at 34.7 mm. We recorded a peak in 1997 at 61.8 mm during the MAM season and the lowest in 1994 at 9.7 mm. The significant difference between them can be caused by Mascarene High variability and monsoon systems.

Rainfall in Botswana's harsh veldt region decreased significantly between 1971 and 2000, with values of –1.097, –0.029, –0.407, and –1.327 mm/year [57]. In contrast, the same patterns throughout the country were confirmed from 1975 to 2005 [17]. The rainfall and temperature changes analyses concluded that between 1926 and 2011 if the trend continues, average annual rainfall will be reduced by around 30 mm by 2050 [58]. The rainfall variability will likely rise as Botswana continues to dry [59,60]. According to the Intergovernmental Panel on Climate Change, rainfall would decline by 30 to 40 percent between 2080 and 2099, with the most significant drops expected during the already dry winter season.

3.2 Seasonal correlation between interregional rainfall and Mascarene High

According to seasonal analysis, we obtained the correlation analysis results in **Figure 5**. The monsoon rainfall (East Africa, West Africa and Peninsula India) and Mascarene High were negatively correlated with Botswana rainfall in MAM and OND seasons. The correlation changed with the season. The correlation between Botswana rainfall and West Africa was the strongest in MAM and OND season, while during JJAS, Peninsula India had a strong significant correlation with Botswana rainfall. The significance of correlation with Botswana rainfall at different seasons was vital except during JJAS, where there is less or no significance.

Figure 5 shows a positive correlation between Peninsula India and West Africa for all seasons. The linkage between the African and Indian monsoons suggests that the Indian monsoon onset significantly affects the West African monsoon onset [5]. It was discovered that there is an interaction between the West African and Indian summer monsoon systems on low-frequency sub-seasonal scales when analysing the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis and Outgoing Longwave Radiation (OLR) data on a pentad basis for three years [5].

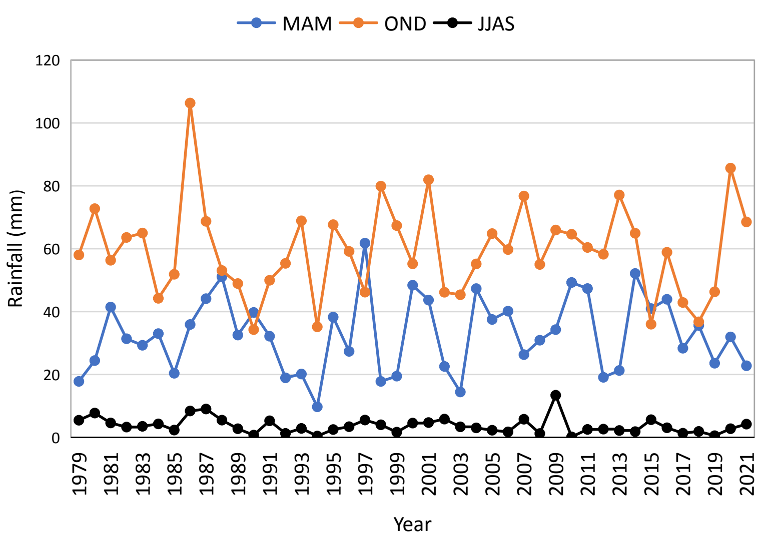

Figure 4. Botswana rainfall variability based on monsoon seasons (March–May (MAM), June–September (JJAS) and October–December (OND) from 1979–2021.

Figures 5b and **5c** show that during JJAS and OND season, East Africa rainfall was positively correlated to Peninsula India. The Peninsula of India positively correlated with East African rainfall through the Tropical Easterly Jet and the zonal pressure gradient that influences low-level circulation [6,61,62]. Furthermore, the East African and Indian rainfall are associated with variations over the northern Indian Ocean and the Arabian Peninsula in low-level height [6].

The rainfall and circulation changes during the Indian monsoon (monsoon onset over Kerala) are associated with a decrease in rainfall over several parts of East Africa (Kenya and northern Tanzania). The monsoon onset over Kerala coincides with the West African monsoon 15-day pause, associated with the Sahel anomalous and culminates for two or three pentads after the monsoon onset over Kerala [7]. The tropical easterly jet stream over the Indian region may influence the mid-tropospheric African easterly jet fluctuations and generate easterly waves to form squall lines over the African monsoon system. The dry spells separate the West African and East African monsoon from JJAS and January–February seasons [63,64]. The Mascarene High drives wind (south easterlies) over the Indian Ocean and transports moisture flux during the long rainy season of JJAS [30].

Figures 5a and **5c** recorded a positive correlation between Mascarene High and Peninsula India during MAM and OND. The previous studies indicate that Mascarene High westward migration influences the intensification of Indian monsoons, the intensification of cross-equatorial flow, and the intensification of the Somali jet [65,66]. The figure also recorded a positive correlation between Mascarene High and East Africa during the MAM and OND seasons. Previous studies show that the East African rainfall variability is associated with Mascarene High during the MAM season [67]. The Mascarene High position and orientation during OND are associated with moisture flux into East Africa; therefore, wetter conditions are linked to weaker Mascarene High in the East. A negative correlation was recorded between Botswana rainfall and Mascarene High during MAM and OND season. The Mascarene High variations modulate droughts and flood seasons in southern Africa and cause significant rainfall variability on various time scales [12] and trade winds from Mascarene High toward Angola Low transport moisture [13]. The mid-tropospheric Botswana High reflects the Mascarene High as the highs tilt northwest with a height, and the Mascarene High also blocks disturbances in the westerlies, resulting in weather anomalies [12].

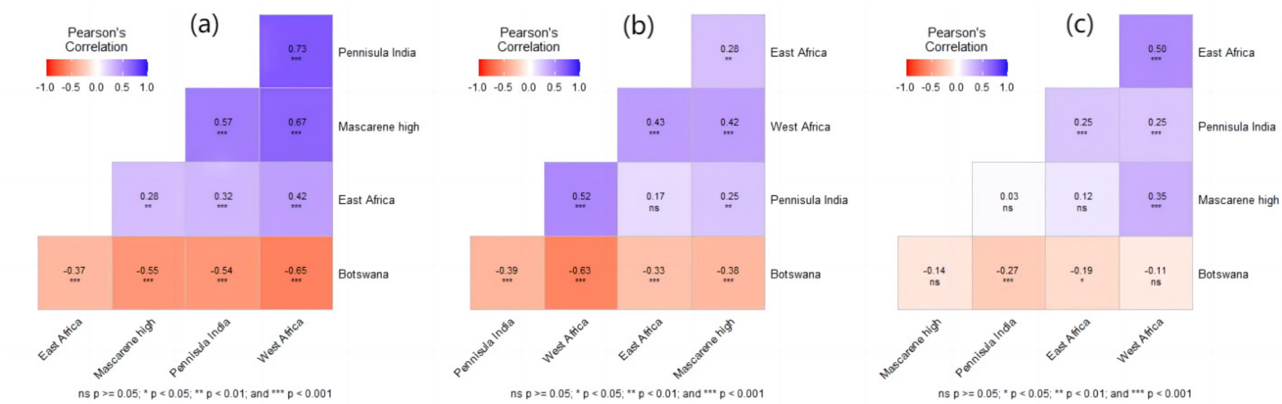

Figure 5. (**a**) March–May (**b**) June–September (**c**) October–December seasonal correlations between individual monsoon rainfall (East Africa, West Africa, and Peninsula India), Mascarene high, and Botswana rainfall. *** Correlation is significant at the 0.001 level (2-tailed), ** Correlation is significant at the 0.01 level (2-tailed); * Correlation is significant at the 0.05 level (2-tailed), and ns correlation is no significant correction at 0.05. Red squares show negative correlations and blue squares show positive correlations.

3.3 Causality between Botswana rainfall, monsoon systems and Mascarene High

The causal relationship and quantitative influence between Botswana rainfall with individual monsoon rainfall and Mascarene High were studied using CCM analysis. From the Pearson correlation results from **Figure 5**, the variables with significant values are adopted for CCM analysis to obtain the individual influence of monsoon systems and Mascarene High on Botswana rainfall variability. Based on different seasons, we calculate the seasonal causality. The CCM result describes the relation of monsoon rainfall or Mascarene High to Botswana rainfall with a value of $\boldsymbol{\rho}$. The results can explain the ability of monsoon systems or Mascarene High to predict Botswana rainfall.

This study reproduces the analysis to identify seasonal causality between Botswana rainfall variability, monsoon systems, and Mascarene High. The ρ values between Botswana rainfall, Mascarene High and monsoon systems are in **Table 1**. The value of prediction skill (ρ-value) ranged from 0 to 1, indicating the influence of one variable on another variable. Higher ρ values indicate more prediction skills. The performance of CCM shows bidirectional and unidirectional causation. During the MAM season, Botswana and West Africa rainfall are deterministic signals; the causal effect equals the inverse direction with bidirectional causation (ρ = 0.51). While Botswana rainfall and Mascarene High experience weak bidirectional causation during the MAM season (ρ = 0.17 and ρ = 0.18). Botswana and East Africa rainfall experience unidirectional causation from East Africa but no causation in the inverse direction during the MAM season (ρ = –0.02 and ρ = 0.24). During the OND season, Botswana rainfall and Mascarene High experience bidirectional causation. However, the causal effect of Botswana rainfall on Mascarene High is stronger than the inverse direction (ρ = 0.46 and ρ = 0.45). In contrast, Botswana and East Africa rainfall experience a substantial unidirectional causation from Botswana rainfall to East Africa but no causation in the inverse direction (ρ = 0.6 and ρ = 0.16).

Botswana and West Africa rainfall also experienced bidirectional causation with a causal effect almost equal to the inverse direction in the OND season (ρ = 0.51 and ρ = 0.50). Botswana and Peninsula India rainfall also experience bidirectional causation. However, the causal effect of Botswana rainfall on Peninsula India is more substantial than that in the inverse direction (ρ = 0.41 and ρ = 0.25).

When comparing CCM causation and Person correlation using **Table 1**, it was observed that when the Pearson correlation coefficient ρ is between –0.55 and –0.65, the ρCCM might be higher; therefore, a higher Pearson correlation may imply substantial causation. When the Pearson correlation ρ is between –0.19 and –0.54, the cross-mapping correlation ρCCM can be either low or high in one direction. Therefore, the Pearson correlation cannot predict the causation between two variables in a time series.

Table 1. Convergent cross mapping of Botswana rainfall with Monsoon systems and Mascarene High based on seasonal variation (March–May (MAM), June–September (JJAS), October–December (OND).

Seasonal Variation	Causality	Mascarene High (ρ CCM)	Pearson (ρ)	East Africa (ρ CCM)	Pearson (ρ)	West Africa (ρ CCM)	Pearson (ρ)	Peninsula India (ρ CCM)	Pearson (ρ)
MAM	$\hat{X}\|My$	0.17	–0.38	–0.02	–0.33	0.51	–0.63	–0.04	–0.39
	$\hat{Y}\|Mx$	0.18		0.24		0.51		0.19	
JJAS	$\hat{X}\|My$			–0.01	–0.19			0.13	–0.27
	$\hat{Y}\|Mx$			–0.04				0.02	
OND	$\hat{X}\|My$	0.46	–0.55	0.6	–0.37	0.51	–0.65	0.41	–0.54
	$\hat{Y}\|Mx$	0.45		0.16		0.50		0.25	

3.4 Climatology circulations during MAM and OND season

Figure 6 depicts the circulation system throughout the MAM season from 1979–2021. The wind vectors (black arrows) are carrying moisture as they rise from the South (high-pressure area) to the north (low-pressure area). Seasonally, the Mascarene High drives south-easterlies wind across the Indian Ocean, carrying moisture flux to the East African landmass and resulting in extended rainy seasons in East Africa [68]. The mean sea level pressure and surface temperature influence the inter-annual timescale of rainfall across East Africa during the MAM season [69]. The Mascarene High moved eastward with intensity between 1014–1020 hPa at a wind speed of less than 10 m/s (shown by the black arrow above the cbar) and the dry south-easterly wind blowing towards Botswana, as indicated by wind vectors.

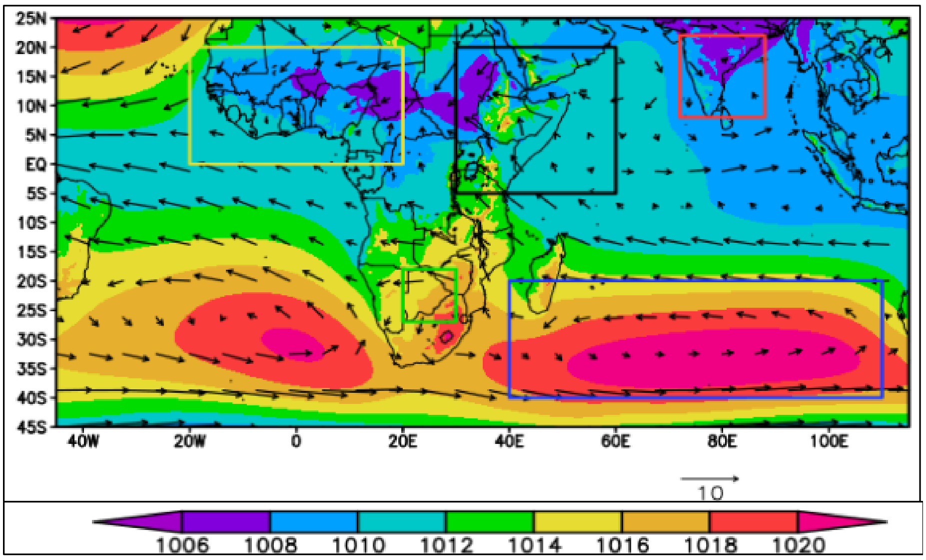

Figure 6. The climatic circulation system for the March–May 1979–2021, Peninsula India (red rectangle), East Africa (black rectangle), West Africa (orange rectangle), Botswana (green rectangle), and Mascarene High (blue rectangle). Arrows show the wind vectors, and the cbar shows pressure levels.

Figure 7 shows the climate circulations during OND season, with the Mascarene High shifted to the East at an intensity between 1016–1021 hPa, creating low pressure over Botswana. The southerly wind rose towards East Africa, converging with the northern east wind towards East Africa. During the season, the zonal wind at 850 hPa shows enhanced easterlies over the tropical western Indian Ocean and northern Mozambique/Zambia, feeding into Southern Africa (Botswana). The tropical western Indian Ocean region is a significant moisture source for southern African summer rainfall [70,71]. The extreme weather occurrences are influenced by the Mascarene High Eastern Ridge [72]. The Mascarene High position and its orientation during the OND season create moisture flux over East Africa. The weaker Mascarene High is linked to wetter conditions that are shifted to the East [73]. The Mascarene High is variable in location and intensity at different times of the year, and as the warm atmosphere changes, so do the characteristics.

When the oceans are cooler than warm land masses, cool winds move towards the land, carrying rain. In addition, during winter, when the land cools faster than the ocean, the wind reverses. In summer, Peninsula India heats up more than the oceans and seas around it, forming low-pressure areas. The southwest summer monsoons carry rain from the Indian Ocean towards the low-pressure area. They converge in low-pressure areas with dry winds from the northeast, forming a cyclonic circulation [74]. These persistent easterly trade winds of the tropics blow out of the subtropical anticyclones and can transport moisture from hot spots over the oceans onto the continents [46].

The northeast monsoon occurs during the OND season, mainly bringing rainfall to India's southern Peninsula. This rainfall is imported chiefly into South India and Sri Lanka. The low-level winds over South Asia reverse their direction from southwest to northeast during summer monsoon withdrawal. It is associated with the continental tropical convergence zone movement to the South and the sub-tropical anticyclone [75]. Monsoon circulations primarily influence Africa's climate across the East and West Indian Oceans [76]. From November to March, the northeast monsoon sweeps over the western Indian Ocean, delivering moisture to east and southern Africa [77]. The rotational components of monsoon flow and the sea surface temperature between the southwest and central Indian Ocean differences significantly influence southern African rainfall [76].

Southern Africa region has a distinct wet and dry season, and the amount and timing of rainfall affect ecological processes, agricultural cycles, and water availability. The interactions between the Mascarene High and monsoon systems influence the monsoon behaviour and the timing of rainfall in Southern Africa. The Mascarene High can affect weather systems, causing cloud bands, cut-off lows, and tropical cyclones that affect the region's precipitation. Southern Africa's rainfall distribution and variability are influenced by the location and strength of the Mascarene High, which is responsible for guiding air masses loaded with moisture into the region. The position and strength of Mascarene High variations influence the spatiotemporal variability in rainfall over Southern Africa and affect both short-term weather events and long-term climatic trends. Due to atmospheric blocking caused by Mascarene High, Southern Africa may experience anomalous rainfall events marked by wet or dry spells that deviate from standard seasonal patterns. Temperature anomalies and heatwave conditions are linked to Mascarene High variation and might influence southern Africa's climate in the future. Climate models and satellite observations are used to study and monitor Mascarene High and rainfall variability to improve climate forecasting and prediction, promote climate-resilient decision-making, and improve early warning systems for extreme weather events. They are also used to study the complex interactions between monsoon systems, the Mascarene High and their influence on rainfall patterns over Southern Africa. The study employs the CCM to explore causality between Botswana rainfall, monsoon systems, and the Mascarene High. However, the specific mechanisms that influence each system must be thoroughly explained. We recommend future research to investigate the physical

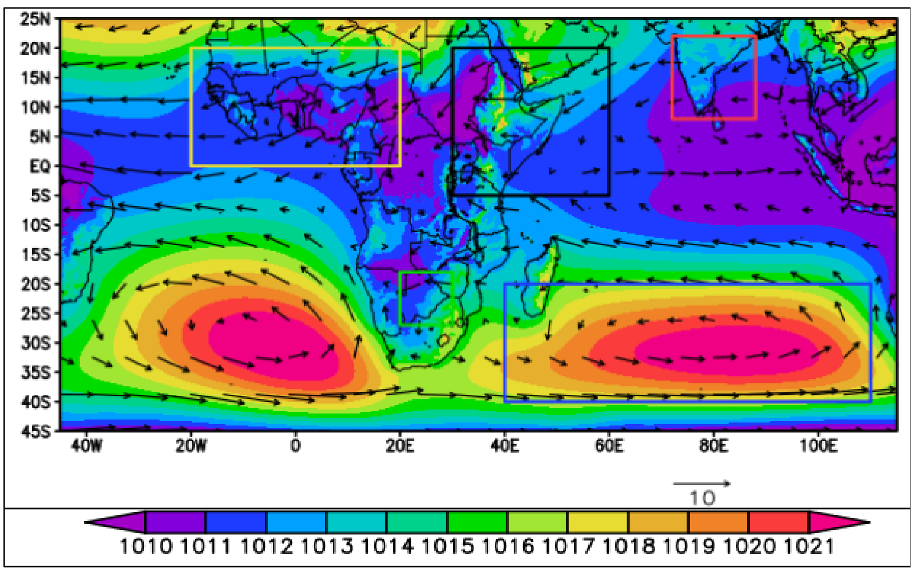

Figure 7. The climatic circulation system for the October–December 1979–2021 monsoon system, with Peninsula India (red), East Africa (black), West Africa (orange), Botswana (green), and Mascarene High (blue), The wind vectors shown by arrows and cbar show pressure levels.

mechanisms driving these interactions.

The implications of this study are significant. Understanding the causal relationships between monsoon systems, the Mascarene High, and rainfall variability in Botswana can lead to improved prediction of extreme events and the development of strategies to mitigate potential impacts on communities' livelihoods. By recognising the crucial roles of these weather systems in shaping rainfall patterns, we can better prepare for and respond to droughts and other extreme weather events. This knowledge can also aid in promoting community awareness and education on climate change and variability, water conservation, and sustainable livelihood practices. Ultimately, the findings of this study have the potential to empower local stakeholders to actively participate in resilience-building efforts and contribute to the overall resilience of the region in the face of climate change.

4. Conclusions

This study analysed the temporal patterns of seasonal rainfall in Botswana from 1979 to 2021. It uncovered the intriguing connections between monsoon systems, the Mascarene High, and the variability of rainfall in Botswana. The results show that Botswana negatively correlates with monsoon systems and Mascarene High and varies from season to season. The causality analysis using the CCM method also demonstrated that the influence on Botswana's rainfall varied between seasons. The study found a positive bidirectional relationship between Botswana and West African rainfall during the MAM and OND seasons, indicating that the West African monsoon system can predict rainfall variability over Botswana during these seasons. Botswana rainfall and Mascarene High exhibited weak bidirectional causation during the MAM season. During the OND season, they demonstrated moderate bidirectional causation. The results imply that Mascarene High can be used to predict rainfall variability in Botswana during the OND season. In addition, there is a significant unidirectional causation between Botswana and East Africa's rainfall, suggesting that East Africa's rainfall cannot be used to predict rainfall variability over Botswana during the OND season. In contrast, bidirectional causation is observed between Botswana and Peninsula Indian rainfall, signifying that Peninsula Indian rainfall can be employed to predict rainfall variability in Botswana during the OND season. Monsoon systems and Mascarene High had no seasonal influence on Botswana's rainfall variability during the JJAS season.

The study identified the seasonal variations in the influence of monsoon systems and Mascarene High on the interannual rainfall variability in Botswana. Notably, the negative association between West African rainfall and Mascarene High to Botswana rainfall during the MAM and OND seasons may contribute to Botswana's heightened interannual variability. This variability is associated with the adverse effects of climate change and extreme events, such as recurring droughts in Botswana, emphasising the need for informed decision-making and policy interventions to enhance adaptive capacity.

Author Contributions

Both authors contributed to the study's conceptualisation and design. Lydia Frank handled the material preparation, data collection, and analysis. She also wrote the first draft of the work, and both writers offered feedback on earlier drafts. Thus, both authors read and approved the final paper.

Conflict of Interest

No conflict of interest.

Data Availability Statement

The data that support the findings of this study are openly available in the links below:
https://psl.noaa.gov
https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels-monthly-means.

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