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Review

Climatology of the Mascarene High and Its Influence on Weather and Climate over Southern Africa

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Abstract: Globally, subtropical circulation in the lower troposphere is characterized by anticyclones over the oceans. Subtropical anticyclones locate over subtropical belts, modulating weather and climate patterns in those regions. The Mascarene High is an anticyclone located over the Southern Indian Ocean and has a vital role in weather and climate variability over Southern Africa. The warm Western Indian Ocean is a major source of moisture for the subcontinent also permitting tropical cyclone genesis. In this study, we review the dynamics of the Mascarene High, its interactions with the ocean, and its impact on weather and climate over Southern Africa. We also review studies on the evolution of subtropical anticyclones in a future warmer climate. The links between SST modes over the Indian Ocean and the strengthening and weakening of the Mascarene High have been demonstrated. One important aspect is atmospheric blocking due to the Mascarene High, which leads to anomalous rainfall and temperature events over the subcontinent. Blocking leads to landfall of tropical cyclones and slow propagation of cut-off lows resulting in severe weather and flooding over the subcontinent. Understanding how expansion of the Mascarene High due to warming will alter trade winds and storm tracks and change the mean climate of Southern Africa is crucial.

Keywords: Mascarene High; Southern Africa; subtropical anticyclones; South Indian Ocean

1. Introduction

Subtropical anticyclones are semi-permanent synoptic-scale weather systems that influence weather and climate over the subtropical regions around the world. They are concentrated around 25° N–45° N and 25° S–45° S in both hemispheres (Figure 1) and occupy about 40% of the Earth's total surface area [1]. Subtropical anticyclones have a vital role in the existence of the world's subtropical deserts [2] mainly due to subsidence associated with their leading edges. They also account for much of the short-term weather variations in extra-tropical regions [3]. The 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 [4].

Semi-permanent subtropical anticyclones surround an area of high pressure, consisting of circulation which is clockwise in the Northern Hemisphere and counter-clockwise in the Southern Hemisphere. They are characterized by mean sea level pressure decreasing from the center to the periphery, anticyclonic wind curl, subsidence, and lower level divergence [5]. These weather systems result from subsidence occurring in the descending limb of the Hadley Cell [4] and owe their existence to monsoonal heating that occurs during the austral summer season over land and they also require air–sea interaction [5–7].

Observations show that weak pressure gradients and light and variable winds are found near the center of subtropical anticyclones, having clear skies due to subsidence [3,4], unlike cyclones, which consist of strong winds near the center and are comparably smaller [3]. Subtropical anticyclone centers are generally located in the eastern portions of the Pacific, Atlantic, and Indian Ocean basins over the Southern Hemisphere. Over the Northern Hemisphere, the Bermuda High is located over the North Atlantic and is referred to as the Bermuda High in summer and Azores High in winter [1]. Over the North Pacific Ocean lies the North Pacific High. In winter, the Bermuda High shifts eastwards and assumes a seasonal name, Azores High [1]. Cooling in Eurasia in the same season, gives strengthening to the Siberian High [8]. In these regions, large-scale subsidence is balanced with strong large-scale low-level divergence at the surface [9], playing an important role in modulating global weather and climate [10]. Over the South Indian Ocean lies the South Indian Ocean High, or the Mascarene High, which plays a major role on the weather and climate of Southern Africa.

The Indian Ocean is the third-largest ocean in all the global oceanic divisions, covering 19.8% of Earth's total surface water (Figure 1) [11]. The Mascarene High lies between the tropical and temperate belts, extending from the region 25–35° S and 40–110° E (Figure 1) [12]. Its movement directly influences weather and climate over the Southern African subcontinent which is characterized by a moderately elevated plateau well above 1000 m (Figure 2). The elevated interior, the low-altitude coastal plain, and mountain systems are the three basic landforms of Southern Africa. The region is largely semi-arid and experiences a variety of climatic regimes, receiving most of its rainfall during the austral summer.

The warm Southwest Indian Ocean and the Agulhas Current region are a major source of moisture for the subcontinent [13] transported by trade winds out of the Mascarene High toward the Angola Low. Tropical cyclones that develop over the Southwest Indian Ocean every summer are steered by the Mascarene High sometimes towards the interior of Southern Africa. Severe weather events such as floods and extreme cold during cut-off low pressure events are linked to atmospheric blocking caused by the Mascarene High [14]. As such, variations in the Mascarene High modulate drought and flood seasons over the subcontinent. A significant amount of the variability of rainfall and temperature over Southern Africa on a variety of time scales is linked to the Mascarene High. An understanding of its climatology and evolution due to climate change is therefore necessary. Most studies have dealt with subtropical anticyclones collectively, but this study focuses on the Mascarene High and will provide a starting point for future studies with a focus on the regional climate.

A systematic review approach [15] employed in this paper identifies and synthesizes research knowledge from individual studies based on subtropical anticyclones and circulations over Southern Africa. In this paper, we focus on the Mascarene High and evaluate existing knowledge while establishing gaps and research questions relating to this weather system and its impact on Southern Africa. This paper is organized in thematic areas, with the next section introducing the general circulation of the atmosphere and subtropical anticyclones. A climatology of the Mascarene High, its seasonal shifts, interannual variability and links to the India Ocean sea surface temperatures (SSTs) are then analyzed. The influence of the Mascarene High on the occurrence of extreme events and climate change projections are considered at the end.

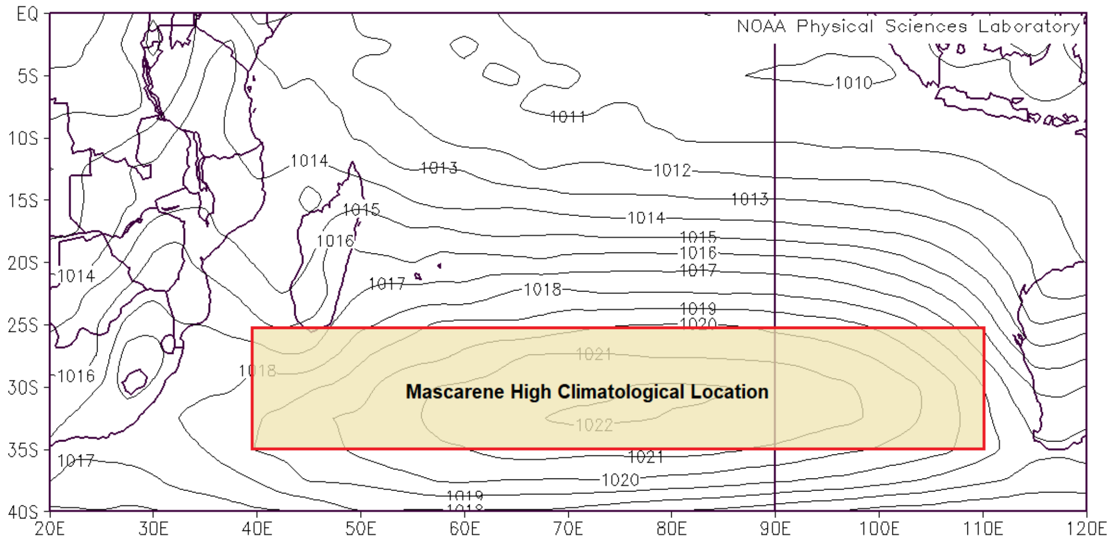

Figure 1. Mean Mascarene High regions over the South Indian Ocean (Generated from NOAA Physical Science Laboratory).

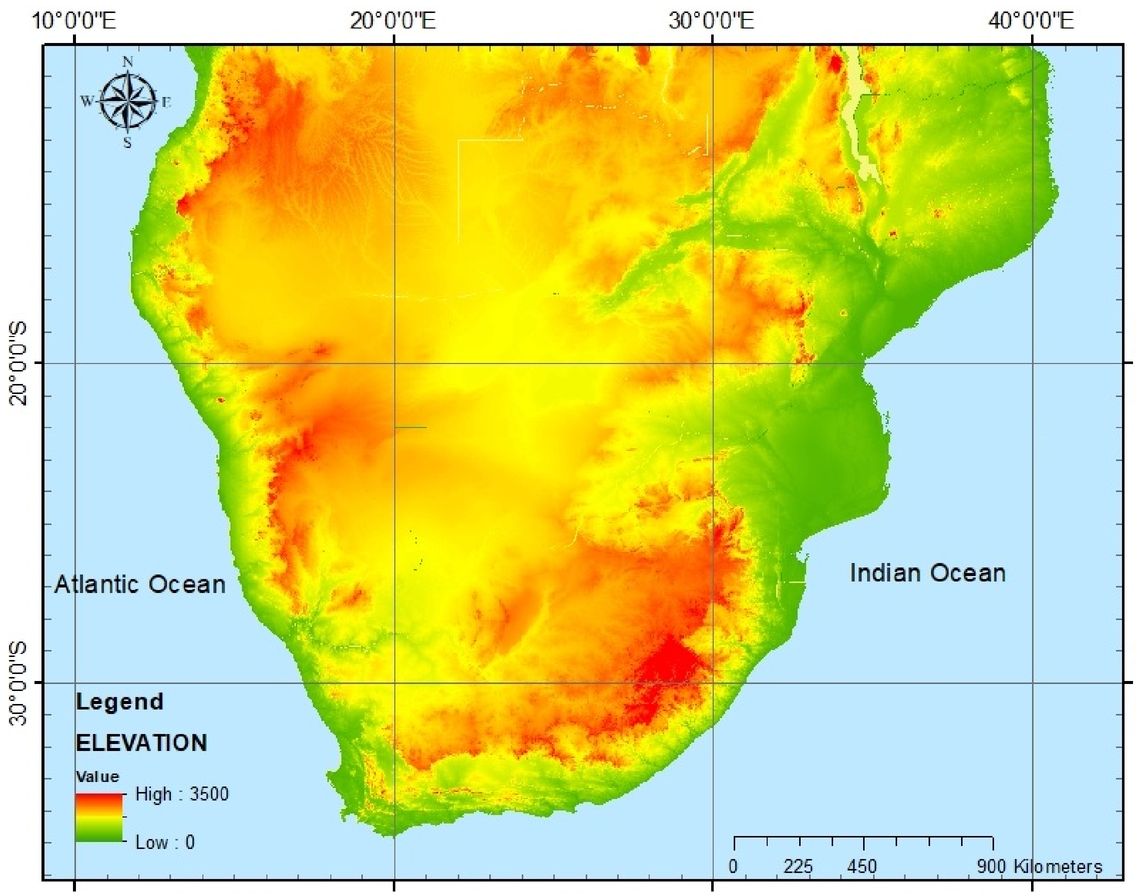

Figure 2. Southern Africa elevation map.

2. General Circulation

Globally, solar heating is a major driving force for large-scale meridional circulation in the ocean and atmosphere [16]. The Earth's surface consists of unevenly distributed solar heating, being greatest near the equator and least at the poles [17] resulting in warmer equatorial regions and cooler poles. Energy is therefore transported poleward through atmospheric and ocean circulations resulting in a weakening of the equator–pole temperature gradient. Circulation of global heat and moisture are a result of the Hadley, Ferrel, and Polar Cells. Global air circulation has one primary circulation cell which is known as the Hadley Cell and is complemented by two secondary circulation cells, referred to as the Ferrel Cell and Polar Cell.

Over the subtropical belts, subtropical anticyclones are linked to the descending limb of the Hadley cell [17]. The subtropical belts consist of cool and surface-divergent air that sinks from the upper levels, where air converges, originating from the tropical and temperate belts [4]. For both hemispheres, subsidence is greatest on the eastern sides of subtropical anticyclones and tends be stronger in summer when the Hadley Cell is weaker [18]. Equatorward air ahead of subtropical anticyclones descends on isentropic surfaces warming adiabatically and forming the trade wind inversion. Due to the Coriolis effect, the circulation around subtropical anticyclones is clockwise in the Northern Hemisphere and counter-clockwise in the Southern Hemisphere.

Subtropical anticyclones are also linked to concepts of angular momentum conservation, thermal wind balance, and radiative–convective equilibrium, which explain the structure of the annual mean and zonal-mean Hadley circulation [19]. Rotating turbulences at a large scale are dominated by columnar vortices that are associated with the axis of rotation [20]. Subtropical anticyclones are therefore low-level synoptic scale weather systems that are an important component in the climate system over the subtropics [1].

3. Mascarene High Climatology and Temporal Variability

3.1. Mean Spatial and Seasonal Characteristics

This section focuses mean and seasonal latitudinal and longitudinal boundaries of the Mascarene High, defined based on monthly north–south and west–east mean sea level pressure locations and displacements. Mascarene High boundaries are defined as 25–35° S; 40–110° E (Figure 1) in agreement with earlier studies by [10] and [12]. The boundaries are defined by mapping north–south and west–east limits of the maximum Mascarene High isobar, which is ≤1023 hPa. There is variability in the seasonal location of the Mascarene High which is linked to shifts in the Inter-Tropical Convergence Zone (ITCZ) and South Indian Convergence Zone (SICZ) [21]. Migration of the SICZ is influenced by meridional and zonal wind convergence flow, eddy activities, and moisture advection associated with the Mascarene High circulation. The SICZ, which is a land-based convergence zone, and the ITCZ migrate equatorward (poleward) during austral winter (summer). This migration largely contributes to the equatorward (poleward) location of the Mascarene High during austral winter (summer). Thus, it is vital to consider ITCZ and SICZ seasonal migration and location influences on seasonal Mascarene High displacements. Moreover, during summer (winter), the Mascarene High is displaced southeast (northwest). Thus, the Mascarene High is variable in location and intensity at different times of the year, and these characteristics are expected to change as the atmosphere warms.

3.2. Indian Ocean SSTs and Mascarene High Interannual Variability

Ocean–atmosphere–land interactions over the South Indian Ocean are vital for weather and climate over Southern Africa. Relative contributions of both the Indian Ocean SSTs to rainfall variability over Southern Africa are important because rainfall directly affects the economy of the region via agricultural activities. Variability of Southern African rainfall has been found to be statistically related to the oceans [22]. The summer interannual variability of the Mascarene High is largely influenced by Indian Ocean SSTs [23]. An important mechanism that plays a vital role in the formation of Indian Ocean Dipole (IOD) is the Bjerknes feedback [24], induced by the equatorial easterly wind mechanism of IOD occurrences [25]. Secondly, there is a wind–evaporation–SST feedback that exists over the southeast tropical Indian Ocean. This occurrence is considered as another air–sea coupled process, enhancing the growth of IOD. Thirdly, it has been shown that the Rossby and Kelvin wave track has an oceanic dynamic process during IOD events [26]. The Mascarene High triggers the internal variability of the IOD [27]. IOD occurrences have climate impacts on the surrounding mainland and remote regions such as East Asia, Europe, and South America [28]. It has been found that the positive (negative) phases of the IOD are related to drought (heavy rainfall) over Southern Africa [29]. Whilst the positive IOD mode is related to drought in Southern Africa, it often brings floods to East Africa [30]. The onset of El Niño (linked to major droughts in Southern Africa) is influenced by an extreme positive IOD mode [28,31] such that when the two co-occur, the resulting droughts can be severe. The 2015/16 drought in Southern Africa occurred in the presence of the most intense El Niño and a positive IOD. Other major droughts, such as the 1982/83, 1986/87, 1991/92, 1994/95, and 2002/03 events, also had co-occurrence of El Niño and positive IOD [32]. The upper divergence field was found to be linked to the positive IOD with upper convergence (subsidence) located over Central South Africa and Botswana. Related to earlier studies of coupled atmospheric–ocean interactions, similar to the IOD and El Niño–Southern Oscillation is the Indian Ocean Subtropical Dipole (IOSD) phenomenon, which is influenced by atmospheric forcing and boundary layer circulation [33]. IOSD exists because SSTs in the subtropical Indian Ocean consists of interannual events that are dominant during austral summer [33].

An understanding of the role and occurrence of the IOSD over the subtropical Indian Ocean has increased in recent decades. Subtropical Indian Ocean SST anomalies are characterized by a basin-wide dipole pattern consisting of opposite modes in different austral summers, with these patterns usually referred to as the IOSD modes [33]. The poles of occurrence for the IOSD are found within Australia and south of Madagascar [12]. IOSD phases are identified by the location of warm (cold) SST anomalies in the south-western (south-eastern) subtropical Indian Ocean. The positive phases are characterized by warm SST anomalies in the south-western part and cooler SSTs anomalies in the south-eastern part of the subtropical Indian Ocean. Unlike the positive IOD which is linked to drought and high temperatures in Southern Africa, a positive IOSD is associated with higher than normal rainfall over the subcontinent [34,35]. This happens via enhanced moisture convergence resulting from low sea-level pressure generated by the warm SST anomaly.

Negative phases are characterized by cooler SSTs anomalies in the south-western part and warm SSTs anomalies in the south-eastern part of the subtropical Indian Ocean due to the strengthening of the Mascarene High winds in the east of the subtropical Indian Ocean [12]. The seasonal shift eastwards of the Mascarene High are modulated by the IOSD. The Mascarene High induced by the IOSD significantly influences the behavior of the Indian Ocean southwest–northeast dipole through SST anomalies [36]. Variations in the Mascarene High center location also influence East African rainfall [12,37]. Several studies [33,38,39] have also found phenomena over the tropical Pacific (ENSO) and the Southern Ocean (Antarctic Oscillation) to also modulate the Mascarene High at interannual timescales.

3.3. Moisture Flux, Meridional Pressure Gradient, and the Angola Low

The Mascarene High strongly influences moisture transport from the warm Indian Ocean, affecting rainfall over Southern Africa [12,33]. In summer, moisture convergence over Southern Africa is regulated by a heat low pressure system situated over Angola called the Angola Low [40]. A deep Angola Low and an intense Mascarene High (continental extension) create a steep north–south pressure gradient allowing for transport of moisture onto the subcontinent (Figure 3). During El Niño conditions, there is weakening of the Angola Low and offshore westerly anomalies resulting in a reduced moisture flux and dry conditions over the mainland. The Angola low over Southern Africa is identifiable with loops of half-hourly geostationary satellite images, by locating low-level cyclonic and anti-cyclonic upper tropospheric circulation depicted by the cloud motion.

Moreover, tropical-temperate synoptic scale interactions play a major role in the general atmospheric circulation resulting in cloud bands and rainfall over the subcontinent [41–44]. It has been shown that troughs linking tropical convection having transients in the zonal westerlies are identifiable as cloud bands on visible and infrared satellite imagery. Tropical–temperate troughs and location of the Mascarene High are important in austral summertime rainfall over Southern Africa [45–48]. The tropical–temperate trough extends for 3000 to 8000 km, connecting cold fronts and the ITCZ [48]. On average, an easterly wave is present over the equatorial end of the cloud bands having an important role in the interaction between the ITCZ and the mid-latitude frontal belt.

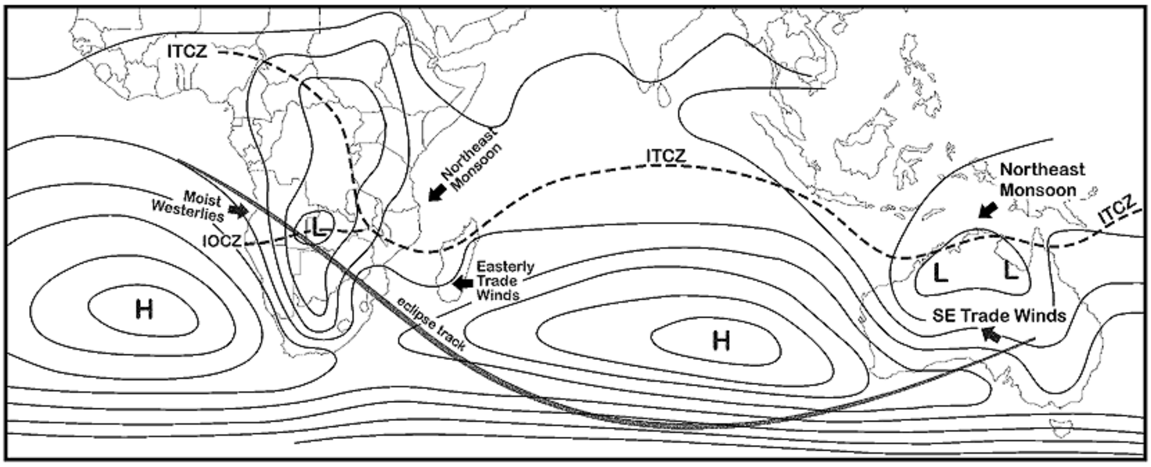

Figure 3. Global pressure and weather systems [49].

3.4. The Mid-Tropospheric Botswana High

The Botswana High is a high-pressure cell existing in the mid-troposphere usually situated over Central Namibia and Western Botswana during late austral summer. It is a reflection of the Mascarene High in the upper air as surface highs tilt to the northwest with height. The Botswana High has been found to impact rainfall over parts of the subcontinent, with a stronger than usual Botswana High usually associated with below-average rainfall (drought) over much of the subcontinent.

For agricultural purposes, it is known that Southern African countries that experience the highest levels of yield variation per unit harvested are generally those that lie on the boundary of the ITCZ. High rainfall periods are characterized by a persistence of the ITCZ while drought is linked with dominance of the Botswana High over the subcontinent. Rainfall variability over Southern Africa depends mainly on the location and strength of the ITCZ and also the passage of upper westerly waves of the midlatitudes. The influence of westerly waves can sometimes be affected by the presence of an intense Botswana High or a persistent Mascarene High block extending from the Indian Ocean.

4. Mascarene High and Extreme Events in Southern Africa

4.1. Mascarene High Blocking

On average, blocking anticyclones frequently form over latitudes that are higher than those where the subtropical anticyclones normally develop or move such that they are often associated with cut-off lows and cloud bands in the lower latitudes [48]. Blocking is regularly associated with a split of the upper westerly jet consisting of two branches. Blocking subtropical anticyclones are also associated with semi-stationary waves that are semi-permanent due to large-scale planetary subsidence of air which is on the poleward side of the Hadley cell circulation [17]. Low-level blocking episodes are identified by central mean sea level pressure exceeding the time averaged by more than 20 hPa [3].

Blocking action of the Mascarene High (or subtropical anticyclones) is generally known as the state of circulation anomaly, having normal zonal flow disturbed by strong and persistent meridional-type flow [3]. This phenomenon slows down west–east ocean–atmosphere circulations over Southern Africa, resulting in blocking of disturbances in the westerlies and weather systems behind the Mascarene High. This occurrence usually consists of above normal pressure and temperature in the troposphere, with pressure in the stratosphere being above normal and temperature below normal [50].

Blocking subtropical anticyclones occur when upper westerly flow becomes detached, and this results in a long-lived blocking subtropical anticyclone at the surface.

Mascarene High blocking movements are relatively slow from day to day during prevalence, and this may be associated with occurrences of anomalous weather conditions [51]. Blocking may persist over the South Indian Ocean for several days, and its duration in the Northern Hemisphere tends to be longer than blocking in the Southern Hemisphere. Variations in distribution, characteristics, and intensity of the St. Helena High (South Atlantic) and the Mascarene High play an important role in rainfall distribution over Southern Africa. Therefore, the slow movement and distribution process of the weather system can easily be identified. Mascarene High blocking is known to cause the development of long atmospheric waves which are stable from commencement until they dissipate.

4.2. Steering of Tropical Revolving Systems

Steering of tropical revolving systems (tropical storms, depressions, or cyclones) towards Southern Africa from the Southwest Indian Ocean and the Mozambique Channel is largely determined by trade winds [52]. These systems are notoriously destructive because they occur with strong winds, heavy rainfall, and abnormally high tides that they generate. For instance, tropical cyclones may cause massive inundation in low-lying areas that are near the coast due to storm surges. Trajectories of tropical cyclones are mainly influenced by the flow of easterly trade winds that generate from the Mascarene High, resulting in their general east-to-west movement. Thus, tropical cyclones are steered by advection of planetary vorticity by the large-scale environmental flow which are the trade winds.

Reference [53] investigated the 2011/12 season (Jan–Mar) for tropical cyclone occurrences over the Mozambique Channel and found that the Mascarene High can induce an easterly steering flow over the Mozambique Channel that guides weather systems onto the plateau of Southern Africa. This is important because the loss of human lives over Southern Africa due to tropical cyclone landfalls may be reduced by communication of weather forecasting and pre-warning mechanisms.

4.3. Cut-Off Lows

A weather system largely affected by a blocking Mascarene High is an intense form of westerly trough known as a cut-off low. Cut-off lows are deep low-pressure systems, strongest in the middle troposphere, forming in the steering levels at about 500 hPa [54]. This is when the upper air system separates from the principal westerly flow of the mid-latitudes and is then said to be "cut off" from this westerly flow, forming a cut-off low [54]. However, it needs to be noted that the definition of the cut-off low weather systems varies to some extent through literature. Here, it is defined as a low-pressure system that separates from a planetary circulation that spins off autonomously as it is no longer linked to the westerly wave.

This weather system is identifiable because it loses all its momentum and can locate over a region for a number of days or propagate slowly before dissipating. Cut-off lows are linked with instability in the mid-troposphere and deep convection and can also bring anomalous weather patterns over a region. This was evident in the cut-off low event of April 2019 over Eastern South Africa (Durban), when flooding killed at least 85 people, displacing thousands. Cut-off lows are one of the main drivers of damaging floods and consist of semi-annual variation, having peaks between March to May and September to November. Whilst they are least frequent during December to February, it is then they are mostly associated with blocking Mascarene High blocking [54]. Cut-off lows located over the 2.5° E–32.5° E/20° S–45° S regions are more likely dump rainfall over the mainland. Mascarene High blocking triggers a stagnation in the propagation of the westerly wave and this can enhance formation of a cut-off low, which spins independently from the westerly wave causing additional blocking over Southern Africa [55]. A fully developed cut-off low circulates independently causing additional blocking from Mascarene High blocking. Cut-off low blocking is another form of quasi-stationary west–east tracking, causing unsettled weather over the subcontinent for an extended period in the process.

5. Climate Change Impacts

The climate system is changing because of the increase in concentration of anthropogenic greenhouse gases. Projections of the climate system on global and regional scales are mainly based on dynamic model applications which use the laws of physics applied to the Earth system with a set of complex partial differential equations [56]. A variety of models are used to make projections, these include Earth system models and coupled ocean–atmosphere models, as well as atmosphere-only models [9]. Statistical and dynamical downscaling techniques are used to provide high resolution detail over an area of interest. Thus, an understanding, as well as projections of, the Mascarene High is crucial to global climate research and local societies for future adaptation [1]. Although projections of dynamic climate models are increasingly being used to inform climate change adaptation studies, they are sometimes criticized as not being verifiable [57]. The argument is that it will only be possible to verify the reliability of the projections several decades into the future [56]. The models are generally verified using present-day climate, and an assumption is made that if they simulate present-day climate well, their future projections are usable.

The Mascarene High is an important climate control over Southern Africa, and its behavior in the future climate should be studied and projected. Models are projecting the expansion of tropical regions in the future due to global warming [58–60] and southward expansion of the Hadley Cell and storm tracks [5]. This expansion is expected to cause poleward migration of the Mascarene High and the cold fronts. There is a growing evidence suggesting long-term changes are occurring in the boundaries of the Hadley Cells [61]. Changes in the circulation system will result in a change in the weather and climate over Southern Africa which include shifts in the subtropical dry zones and significant changes in mid-latitude rainfall. These changes may result in vital societal and ecological consequences.

There are documented, observed changes in the position and intensity of global subtropical highs due to climate change [18,19]. However, there has been no focus on the future projections of the Mascarene High. Most papers treat them as Southern Hemisphere Subtropical Highs collectively. Findings on expansion of the tropics and shifts in the Hadley Cell [61,62] are either based on anthropogenic greenhouse gases and warming of the oceans, but also on the stratospheric ozone hole over Antarctica. However, it needs to be emphasized that observed and projected shifts are not uniform from region to region, and these changes and intensification will lead to corresponding changes in subtropical rainfall and also storm tracks equatorward and poleward of the Mascarene High.

6. Conclusions

The ability of Southern African countries to adapt to a changing climate may be hindered by widespread poverty, political instability, and civil war. These are major issues, as a number of numerical climate models project a general increase in temperature and a decrease in rainfall amounts. This indicates that there will be an increase in climate and weather-related challenges in the future. A better understanding of physical processes that influence temperature and rainfall variability, changes, and trends over Southern Africa such as the Mascarene High may help with understanding the expected future climate, especially where large uncertainties exist. This may also improve the reliability of forecasting anomalous events caused by Mascarene High blocking, which could lead to positive implications for quality of life, economic well-being, and growth over Southern Africa.

This paper has presented a review of the influence of the Mascarene High over Southern Africa, most importantly, movement and characteristics of the weather system over the Indian Ocean. The Mascarene High exists over a non-continuous subtropical belt, punctuated by landmasses. The importance of the ocean–atmosphere interactions of the Mascarene High on weather and climate over Southern Africa was also presented. From the review it can be concluded that the Mascarene High is known to drive moisture fluxes onto the Southern African region via the trade winds. The strength of the trade winds largely depends upon the north–south pressure gradient from the Mascarene High to the austral summer Angola Low over the interior. The mid-tropospheric Botswana High lies over the subcontinent and is a reflection of the Mascarene High as surface highs tilt northwest with height.

There is large-scale flow from the Mascarene High, steering tropical revolving systems in the Southwest Indian Ocean westward. Another important aspect is that the Mascarene High occasionally blocks the passage of disturbances in the westerlies which results in anomalous weather.

Throughout the literature, there is minimal work done on Mascarene High blocking and its projections. Therefore, there is vast significance in studying the causes of Mascarene High blocking in a changing climate. [5] performed a regressing analysis on present-day climate data for the St. Helena High over the South Atlantic Ocean and found that there is a projected future climate expansion and displacement of the weather system. This is a vital finding because similar projections are expected for the Mascarene High in a changing climate.

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