Tropical systems from the southwest Indian Ocean making landfall over the Limpopo River Basin, southern Africa: a historical perspective

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Abstract

The study provides perspective on the contribution of landfalling tropical systems (cyclones, depressions, storms, lows) from the southwest Indian Ocean (SWIO) towards rainfall over the eastern interior of southern Africa, over the period 1948 to 2008. Although these systems contribute to less than 10% of the annual rainfall occurring over the region, their relative contribution to local and widespread heavy rainfall events is shown to be highly significant. About 50% of widespread heavy rainfall events over northeastern South Africa are caused by landfalling tropical systems. Fourier analysis performed on the time-series of rainfall occurring over northeastern South Africa in association with these systems reveals the existence of a quasi-18-year cycle. The cycle coincides with the well-known quasi-18- year Dyer-Tyson cycle in rainfall over the summer rainfall region of South Africa. These results suggest that atmospheric and surface conditions leading to wet phases of the Dyer-Tyson cycle also favour the landfall and subsequent westward movement of tropical systems from the SWIO over southern Africa – and their eventual contribution to rainfall over northeastern South Africa.

Key words: Tropical cyclone, landfall, rainfall cyclicity, southern Africa, Fourier analysis, closed low tracking.

1. *Introduction*

Between 1995 and 2003, a weather system type that has received relatively little attention in the context of southern African climate dynamics was responsible for large amounts of rainfall over the northeastern parts of South Africa, Zimbabwe and Mozambique - sometimes causing devastating floods and record rainfall totals over these regions. This weather system is the landfalling and westward-moving tropical system (cyclone, storm or depression) that develops over the Indian Ocean from where it moves into the eastern interior of the southern African subcontinent. The devastating floods during 1996 over parts of the Limpopo River Basin (Figure 1) were caused by a westward moving tropical depression (Crimp and Mason, 1999). In February 2000, tropical cyclone Eline moved westward over the southern African mainland causing devastating floods over Mozambique and heavy rainfall deeper into the interior (Reason and Keibel, 2004). Heavy rainfall caused by a tropical low located over Botswana during February 2000, but which had its origin over the southwest Indian Ocean (SWIO), is described by Dyson and Van Heerden (2002). The 2007 floods over Mozambique (Padgett, 2007; Klinman and Reason, 2008) were likewise caused by a landfalling tropical cyclone and tropical depression. The westward movement of these systems tends to occur at latitudes where some of the large southern African river basins are found (e.g. Dyson and Van Heerden, 2002) and the effects downstream in terms of flooding can be immense.

On average, eleven tropical disturbances reach tropical depression intensity over the SWIO per year (Jury and Pathack, 1991). Landfall of these systems over the southern African subcontinent does not occur every year, however. In fact, systems approaching the subcontinent usually recurve in the Mozambique Channel and mostly do not contribute to rainfall over the African Plateau (e.g. Dunn, 1985; Jury and Pathack, 1991). Landfalling systems may either track further westward into the southern African interior, or may be deflected towards the south or north. This study investigates the contribution of landfalling tropical systems to rainfall totals and extreme rainfall events over the Limpopo River Basin in southern Africa (Figure 1).

The characteristics of the landfalling systems (e.g. frequency of occurrence and preferred tracks) are also examined. Of particular interest is the possible existence of natural cycles in the frequency of occurrence of landfalling tropical systems over southeastern southern Africa. The existence of such cycles, if sufficiently understood and captured within climate models, would make feasible the skilful prediction of the likelihood of occurrence of westward moving systems at the seasonal to multi-decadal timescales (e.g. Landman and Goddard, 2005; Engelbrecht *et al.*, 2009)

The Limpopo River Basin is located in northeastern South Africa, southern Zimbabwe and southern Mozambique, and is a semi-arid area with an altitude of less than 800 m above sea level and with a mean total annual rainfall ranging between 300 and 600 mm. Within this climatic context, however, the region supports a large rural population dependent on rain-fed agriculture as well as large national parks. The region is therefore vulnerable with regard to the impact of rainfall variability (Vogel and O'Brien, 2003). The eastern escarpment of southern Africa, stretching from the South African Drakensberg in the south northwards over the eastern parts of Zimbabwe and with an altitude that exceeds 1200 m above sea level (Figure 1), receives in excess of 1500 mm per annum over some areas. More than 85% of the rainfall over the eastern interior of the Limpopo River Basin occurs within the summer months (October to March). After dry winters, rainfall increases rapidly only from November and December, and maintains a steady rise during January and February after which it declines rapidly from March onwards (e.g. Schulze, 1965). The peak of the rainy season coincides with the maximum frequency of occurrence in the annual cycle of tropical disturbances that control the summer rainfall season to a large degree (Preston-Whyte and Tyson, 2000). During this time of the year, tropical weather systems invade southern Africa in the form of tropical cyclones, tropical lows and easterly waves (e.g. Karoly and Vincent, 1998). Also, wet spells during summer are pulsed at frequencies that are consistent with the passage of tropical waves over the southeast African and SWIO region (Hayasi and Golder, 1992) while anomalous easterly flow in the 5° – 20°S band in the region of Madagascar leads to increased rainfall over southeast Africa (Mulenga *et al.*, 2003).

When landfalling tropical systems do occur over the eastern interior of southern Africa, the rainfall they produce within a time span of a few days can be a significant contribution to the annual total. Synoptic systems that generate rainfall over the region also include disturbances in the westerlies such as westerly waves and cut-off lows as well as ridging anticyclones (Schulze, 1965; Harrison, 1984; Taljaard, 1985; Preston-Whyte and Tyson, 2000). Quite often, rainfall over eastern South Africa results from tropical-temperate cloud bands, where a westerly wave combines with a tropical trough or low to the north to form a tropical-temperate trough (Harrison, 1984; Preston-Whyte and Tyson, 2000).

Large-scale circulation patterns have been shown to affect the formation and movement of tropical cyclones significantly at the seasonal and inter-annual time scales over different regions of the world (e.g. Elsberry, 1987). A major factor affecting tropical cyclone frequency and tracks globally at the inter-annual time scale is the El Niño Southern Oscillation (ENSO) phenomenon (Chan, 1985; Wang and Chan; 2002; Ho *et al.*, 2006). Over the Atlantic Basin, Goldenberg *et al.* (2001) found that major hurricane activity is oscillatory, modulated by a multidecadal mode of Sea Surface Temperature (SST) variability, namely the Atlantic Multidecadal Oscillation. Certain large-scale atmospheric patterns have also been shown to favour the occurrence of tropical cyclones over the SWIO. During summers with a relatively high number of tropical cyclones forming over the SWIO, upper easterlies and lower westerlies in the equatorial zone to the north of Madagascar form a Walker cell anomaly in conjunction with the east phase of the quasi-biennial oscillation (QBO), providing uplift over the ocean around 50 to 75°E (Jury, 1993). During such summers easterly trade winds strengthen in the subtropics while mid latitude westerlies shift polewards (Jury, 1993).

Local SSTs over the SWIO as well as SSTs in the Pacific Ocean (ENSO) have been shown, through a set of experiments using an atmospheric model, to have an impact on the landfall frequency of tropical cyclones over Mozambique (Vitard *et al.*, 2003). La Niña conditions in the Pacific Ocean, positive SST anomalies over the Mozambique Channel, pronounced SWIO high-pressure anomalies and anomalously high soil moisture conditions and resulting higher vegetation activity over the interior of southern Africa have been reported to favour westward penetration of tropical cyclones into the southern African subcontinent (Reason and Keibel, 2004).

Over South Africa, the existence of a quasi-18-year cycle in the summer rainfall was first noted by Dyer and Tyson (1977), and confirmed in the independent studies of Tyson *et al.* (1975) and Van Rooy (1980). That is, South African summer rainfall shows rainfall variability at a near decadal scale with a period of +/- 9 years with rainfall about 10% above normal followed by +/- 9 years with rainfall about 10% below normal (Taljaard, 1996). The near-decadal scale variability also enhances or opposes the effects of El Niño and La Niña events depending on whether these occur within the drier or wetter parts of the cycle (Kruger, 1999). Although uncertainty exists regarding the origin or forcing mechanism(s) driving the cycle at these time scales, the periods of above normal rainfall display La Niña-like SST anomalies, while the periods with below normal rainfall display El Niño-like SST anomalies (Reason and Rouault, 2002). This is supported by a positive relationship between the Southern Oscillation Index and rainfall over southern Africa (Nicholson and Entekhabi, 1986). The cycle manifests not only periods of above or below-average rainfall, but in sequential periods of about 9 years in length marked by either drought or flood events (e.g. Alexander, 1995). In this regard, it may be noted that devastating flood events that frequent southern Africa, such as the 2000 floods over northeastern South Africa and Mozambique, tend to occur within the slowly varying background of longer-term SST and sea level pressure modes dominated by ENSO-like patterns on various decadal to multi-decadal scales (Reason and Rouault, 2002). During the wetter than average periods over the summer rainfall region of South Africa, anomalously high surface pressures have been shown to occur to the south and southwest of southern Africa, while the Indian Ocean high to the east of the subcontinent weakens (Tyson, 1981). Low pressure anomalies then occur over southern Africa and the Indian Ocean. During such periods, anomalously strong onshore low-level wind anomalies and low-level convergence occur over eastern South Africa, indicating an increase in the advection of moist, maritime air over the region (Reason and Rouault, 2002). Some of these circulation anomalies are also conducive to the landfall of tropical systems over the southern African subcontinent from the SWIO (Reason and Keibel, 2004)

Against this background of an apparent relationship between the wet phase of the quasi-18-year rainfall cycle, an anomalously high frequency in the occurrence of La Nina-like conditions in the Pacific Ocean during such periods, and circulation anomalies over southern Africa and the SWIO favouring the occurrence of landfalling tropical cyclones, this paper also explores the possible cyclicity in the occurrence of landfalling tropical systems from the SWIO over southern Africa.

2. *Data and Methods*

In order to quantify the contribution of tropical systems to rainfall over the eastern interior of southern Africa, it is necessary to objectively identify these systems throughout the length of a data record from a number of different data sources. Within this study, the focus is on tropical systems that can be identified as having formed a geopotential minimum (a closed low) in the mid-levels of the troposphere, and that have developed over the SWIO before making landfall over southern Africa. Such systems include tropical low-pressure systems, tropical depressions, tropical storms and tropical cyclones.

The study area is the Limpopo River Basin and adjacent eastern escarpment in northeastern South Africa, southern Mozambique and southern Zimbabwe. Figure 2 gives an overview of the mechanism studied and the study area. In the context of the study, a westward-moving tropical system is identified as having the following properties:

> (1) A closed low (minimum in geopotential height) at 700 hPa and 500 hPa that exists for at least 24 hours, and is replaced by a high pressure system/absence of a low pressure system at 250 hPa.
> (2) The closed low as described above can be identified while the system occurs over the SWIO (but not necessarily when it is present over land).
> (3) The centre of the region of low pressure must make landfall (either in the mid-levels or in the lower atmosphere, but not necessarily in closed low form).
> (4) Responsible for rainfall over the eastern interior of southern Africa – over the escarpment of South Africa and/or the Limpopo River Basin, within South Africa or Zimbabwe.

Various datasets were analyzed in order to identify tropical systems that satisfy the above definition. Synoptic-scale circulation data of sufficient quality and spatial resolution is only available from 1948 onwards, which determined the starting point of the analysis. The systems were identified through the simultaneous analysis of the following datasets:

- 6-hourly National Centres for Environmental Prediction (NCEP) - National Centre for Atmospheric Research (NCAR) reanalysis data (Kalnay *et al.*, 1996). NCEP reanalysis data describes various atmospheric parameters at a spatial resolution of 2.5°, at 6-hourly time intervals, for the period 1948 to present.
- Daily synoptic data and weather maps from the South African Weather Service (SAWS) as contained in the SA Weather Bulletins - available for the period 1950 to present. These data are maps of daily surface pressure and 850 hPa heights for Africa south of 15°S and the surrounding oceans.

- Daily rainfall data covering South Africa (from the Agricultural Research Council – Institute for Soil, Climate and Water (ARC-ISCW) Climate Information System which also contains data from the South African Weather Service) as well as data for a station from the Zimbabwean Meteorological Services. Data for the South African stations are available since the 1920's and since 1950 for the Zimbabwean station.
- La Réunion cyclone tracks data – a database of tropical cyclones and tropical depressions that have occurred over the SWIO region since 1848. The intensity of the system at sea level as well as its location is described in this dataset.

The scarcity of observational data over the Southern Ocean prior to 1979 (when satellite data started to become available) has a potentially serious effect on any attempt to recreate atmospheric analysis for that period (Tennant, 2004). For this reason, the synoptic data from the SAWS, interpolated rainfall fields over South Africa and the La Réunion cyclone track data described above were utilized, in addition to the NCEP Reanalysis data, to identify tropical systems from the SWIO for the entire period under consideration.

As a first step to identify tropical systems, the 6-hourly NCEP data were inspected visually for the period 1948-2008 and all events of land-falling and westward moving low-pressure systems from the SWIO were identified and flagged. The systems identified had to display a geopotential minimum within the 700 hPa height (a condition less strict than required by (1) and (2) above). This served as a broad measure to obtain a large set of tropical systems that would span the set described by (1) to (4).

The visual inspection of NCEP Reanalysis data was followed by the objective identification of closed-low tracks over the SWIO. The closed-low finding-and-tracking algorithm employed is based on the following two-step procedure:

A. The identification of all local geopotential minima (closed-lows) on the desired pressure levels (500 hPa and 700 hPa) for all of the 6-hourly time-levels. A geopotential minimum is defined to exist at a given gridpoint by considering the point as the centre of a 9-gridpoint stencil, and by checking if the geopotential at the centre gridpoint is a local minimum.. In exceptional cases, it was found that up to three adjacent grid points recorded the same geopotential minimum value at a given time-level. For such cases, the stencil was enlarged and the algebraic average of the longitudinal and latitudinal coordinates of the gridpoints sharing the geopotential minimum value were taken as the position of the closed-low at time-level t (e.g. Lambert, 1988; Blender and Schubert, 2000).

B. The tracking of closed-lows in time, is carried out in an iterative procedure where all the height minima identified at time-level *t* are subjected to the tracking criteria that entail the following:

   a) For each height minimum identified at time-level t, all height minima at time-level t+1 that are located within a radius of 700 km from a time-level t height minimum, are considered for the track associated with the time-level t height minimum.

   b) If more than one such a height minimum occurs at time-level t+1, the height minimum at time-level t+1 closest to the time-level t height minimum is considered to be the time- level t+1 realization of the time-level t minimum.

   c) A closed-low track is only constructed if a closed low minimum can be tracked for at least 24 hours (that is, the closed low can be tracked over at least 5 of the time-levels).

This algorithm was employed at 700 and 500 hPa to identify cases where closed lows were present at both these levels simultaneously – with the 500 hPa system, when projected onto the 700 hPa level, occurring within a radius of 355 km of the 700 hPa system. Additionally, it was required that cyclonic circulation was absent at 250 hPa. These requirements describe condition (1) mentioned earlier, and in combination effectively distinguish closed-low systems of a tropical nature from cut-off lows of the westerly wind regime (e.g. Taljaard, 1985). All the output tracks of the algorithm for the period 1948-2008 were analyzed to identify the land-falling systems. All the systems identified by the objective tracker formed part of the larger set of systems identified by visual inspection.

Apart from the NCEP Reanalysis data, the daily weather bulletins obtained from the SAWS were additionally used to independently identify possible cases of westward-moving tropical systems - by studying the more detailed daily sea level and 850 hPa height analyses of the bulletins and comments made by the forecasters. The systems identified from the bulletins to make landfall at the surface also turned out to be, with the exception of one system, a subset of those identified through visual inspection of the 700 hPa NCEP reanalysis data.

The La Réunion cyclone track data describes tropical systems of only tropical depression or tropical cyclone intensity over the southwestern Indian Ocean, and were also used to supplement the analysis of systems identified from the NCEP Reanalysis data and weather bulletin data. Except for two systems, one occurring in 1948 and another in 1960, all landfalling systems from the SWIO identified from the La Réunion data were elements of the set of systems obtained from visual inspection of the NCEP data.

Because the study focuses on tropical systems from the SWIO that had a direct impact in terms of precipitation over the Limpopo River Basin and adjacent escarpment, rainfall data also had to be utilized to select the relevant systems. Daily rainfall data from weather stations covering the entire South Africa were used to construct rainfall images that could be applied to identify the influence of tropical systems on rainfall. Daily rainfall values from between 1500 and 2000 stations throughout the period 1948 to 2008 were interpolated over South Africa with the inverse distance weight method and taking the effect of topography into account (by using the long-term average summer rainfall as a spatial trend). The time series of rainfall surfaces were used to identify rainfall patterns in terms of timing, distribution, amount and direction of propagation that indicated that a land-falling tropical system caused the rainfall over the area. By studying rainfall patterns associated with tropical systems causing rain over the area, a typical rainfall pattern associated with these systems over the northeastern parts of South Africa was identified. This entails a dry period over the area of interest resulting from subsidence to the west of an approaching system (e.g. Preston-Whyte and Tyson, 2000) followed by a westward propagation of rainfall starting over the eastern fringes of the area and intensifying also from the east with highest rainfall amounts occurring over the mountainous eastern escarpment.

If such a characteristic rainfall pattern could be identified from the station data, it was regarded as an additional indication that a tropical system from the SWIO may have made landfall over the area of interest.

The data from all four sources (NCEP Reanalysis, SAWS daily synoptic maps, La Réunion track data and rainfall data) were combined to identify the tropical systems that influenced the area of interest in terms of a contribution towards precipitation. Because the focus is on tropical systems causing rainfall over the interior of southern Africa, the first prerequisite for identifying a system was that at least some measurable rain had to occur at any of the rainfall recording stations over the eastern edges of the area of interest with a record length spanning the entire period. These stations are Musina, Pafuri and Makoholi (Figure 1). Additionally, at least three of the following criteria had to be satisfied:

- Visual inspection identification of landfalling system at 700 hPa.
- Landfalling system identified by objective tracker.
- Typical rainfall pattern associated with tropical systems from the SWIO according to daily rainfall maps.
- Landfall and westward movement of tropical system from the SWIO identified in SAWS daily synoptic charts.
- Landfalling system identified in La Réunion dataset.

All these criteria provide strong indication that rainfall over the area of interest was indeed caused by a tropical system from the SWIO. From the combination of the datasets according to the selection criteria described above, it was finally concluded that 44 tropical systems from the SWIO have caused rainfall over the eastern interior of southern Africa over the period 1948 to 2008. Table 1 shows the complete set of systems identified and also the selection criteria they've satisfied. Figure 3 shows a summary of the number of datasets used to identify the systems as also shown in Table 1.

A third of the total number of systems identified was present in all the datasets considered. Of the 44 systems finally identified, 35 were present in the automatic objective tracker dataset, 31 were present in the cyclone track database from La Réunion and 38 were present in the SAWS daily synoptic weather maps. Only two systems were not present in the dataset from visual inspection of NCEP Reanalysis data. These were tropical storms that occurred in 1948 and 1960 - and they were present in the La Réunion track dataset.

In order to quantify the relative contribution of tropical systems to rainfall over the interior of the subcontinent, data from several stations within South Africa and Zimbabwe with a complete daily rainfall record stretching over the period 1948 to

2008 were analyzed. These stations were chosen to spatially represent the escarpment and Limpopo River Basin with the positions of the stations ranging from 19°S to 26°S and 28°E to 32°E (Figure 1).

Rainfall events associated with the tropical systems identified earlier were flagged for further analysis. This was achieved by extracting from the daily rainfall records of each of the 6 stations (Figure 1) the rainfall values associated with tropical systems from the SWIO and calculating the total rainfall associated with each event. Following this procedure, rainfall amounts associated with individual events were summed per year, yielding the total yearly rainfall amount caused by tropical systems from the SWIO for each station, for the period 1948 to 2008. Fourier analysis was applied to identify possible cycles in the occurrence of total yearly rainfall caused by tropical systems from the SWIO, for each of the six stations separately. To emphasize the existence of cycles at periods of several years, the Fourier analysis was performed on the five-year moving averages of the original time series of rainfall, calculated for each station for the period 1948 to 2008. To test for the statistical significance of the peaks in the resulting periodograms, "observed" time series for periods similar to the ones used to calculate the true cycle lengths were randomly created by resampling the real rainfall data through a Monte Carlo process (Livezey and Chen, 1983; Wilks, 2006). A sequence of 5000 time series was randomly created for each case and Fourier analysis was subsequently performed on the 5000 random time series and the amplitudes of the relevant cycles determined. These amplitudes were then ranked and the 4500th and 4750th values determined per cycle. These were then considered respectively to be the values associated with the 90% and 95% levels of confidence. This entire procedure was repeated for the total annual rainfall at the 6 stations separately to identify any relevant cycles in the total yearly rainfall (as opposed to the total rainfall attributed to tropical systems from the SWIO) over the area of interest.

3. Results and Discussion

List of systems identified

Frequency of occurrence of landfalling systems

From the closed-low tracks identified objectively from NCEP data by the automatic tracking system, the frequency of occurrence of tropical closed-lows making landfall from the SWIO is plotted in Figure 4. Note that the systems identified through objective tracking represent only a subset of the total number of tropical systems identified, as some systems that made landfall having lost the property of closed-low circulation at 700 or 500 hPa. The graph shows the number of 6-hourly time intervals during which the centers of tropical closed lows at 700 hPa were located at specific grid points. Figure 4 reveals that the preferred tracks of westward penetrating tropical systems from the SWIO into the southern African subcontinent are in the latitudinal band between and including 17.5 °S and 20 °S, which coincides spatially with the northern half of the Limpopo River Basin. The sharp west-east gradient near the coastline is the result of both the deflection to the north or south of some landfalling systems, as well as the loss of a closed circulation when some systems move westward over land.

Figure 5 shows the time series of the annual number of tropical systems from the SWIO that were responsible for precipitation over the Limpopo River Basin in South Africa or Zimbabwe.

From the graph it can be seen that there were two periods with a relatively high frequency of landfalling systems causing some rain over the area of interest - the 1960s/70s and the late 1990s, separated by a lull in the 1980s. There is also no strong trend visible in the time series, lending weight to the objectivity of the identification process (that is, the suspected lower quality of NCEP reanalysis data for the period prior to 1979 did not induce an artificial increase in the frequency of occurrence of identified systems as a function of time).

Characteristics of rainfall events induced by tropical systems

Of the 44 systems identified, 18 were responsible for daily rainfall amounts greater then 50 mm at one or more rainfall stations shown in Figure 1. This value (50 mm) in a 24-hour period is considered heavy rainfall by the South African Weather Service (e.g. Dyson, 2009). For the systems that caused heavy rain over Entabeni on the escarpment, the average number of rain days per system is 5.6. At Musina, located to the north and therefore closer to the preferred track of closed lows centers, but in the Limpopo River Valley, the average number is 3.3 – resulting in an average value of 4.5 days between these two stations. Another feature of the temporal distribution of the rainfall associated with these systems is a dry period just prior to the commencement of rainfall associated with the systems as a result of the subsidence occurring towards the west of the approaching systems (Preston-Whyte and Tyson, 2000). Therefore, for the analysis of rainfall events typically associated with these systems, a moving period of 5 days with daily increments was used. This ensures that the total rainfall associated with individual systems can be considered and separated from other systems responsible for rainfall. From the data of available stations over South Africa and Zimbabwe (Figure 1), the total contribution to rainfall during the years since 1948 by tropical systems from the SWIO is around 7% over the escarpment (Entabeni) and Limpopo River Basin of northeastern South Africa (Musina, Pafuri) and southern Zimbabwe (Makoholi), with lower contributions further to the south and west. Table 1 summarizes the contribution of these systems to the total annual rainfall and late-summer (here defined as January to March) rainfall for the six selected stations in the northeast of South Africa and southern Zimbabwe.

The westward and southward reduction in total rainfall contribution by tropical systems can be seen from Musina (8% average contribution to annual total rainfall) to Villanora (3%) in the west and Nelspruit (4%) in the south. Table 2 indicates that tropical systems from the SWIO contribute a relatively small portion of the total rainfall over the Limpopo River Basin and adjacent escarpment, with a somewhat higher proportional contribution during late summer (January to March). However, their contribution to extreme rainfall events over the area is quite significant, as will be illustrated below.

The importance of tropical systems from the SWIO over the area of interest in terms of high multi-day total rainfall can be seen in Figure 6. It shows that for both the escarpment (Entabeni) and the Limpopo River Valley (Musina), these systems were responsible for the highest five-day rainfall totals (rainfall summed over 5 days) on record since 1948, and that these systems play a relatively larger role as the magnitude of the rainfall event increases.

The much higher frequency of occurrence of high rainfall totals at Entabeni compared to Musina is the result of the orographic effect on rainfall of the escarpment at Entabeni. It is clear from Figure 6 that tropical systems cause the majority of extreme 5-day rainfall events at both Entabeni and Musina. During individual years, the contribution to the total rainfall by these systems can also be large. During 2000, for example, tropical systems from the SWIO contributed as much as 36% of the annual rainfall at Musina and 38% at Entabeni.

Widespread heavy rainfall events

Three stations were identified in order to consider periods during which precipitation occurred simultaneously over a large area including the escarpment, Limpopo River Basin and eastern Lowveld (the area to the east of the escarpment). These stations are Musina, Pafuri and Entabeni (Figure 1). The area within the triangle connecting these three stations is about 4 400 km^2. Simultaneous rainfall events at all three of these stations were identified and the relative contribution of tropical systems from the SWIO to such events was calculated. Four definitions were chosen (shown in columns 2 to 5 of Table 3) to identify periods during which moderate to heavy rain occurred over all three stations simultaneously. The first two definitions in Table 3 were chosen to mark periods during which more than 50 mm of rain were recorded at all three stations simultaneously within two (column 2 of Table 3) or three days (column 3 of Table 3). The third definition was chosen to highlight periods during which more than 50 mm occurred on any of three consecutive days at all three stations (column 4 of Table 3). The last column of Table 2 shows the percentage of times during which 5-day total rainfall at all three stations simultaneously exceeded a certain threshold amount for all non-overlapping 5-day rainfall totals calculated at the stations. The values show the percentage of events identified that exceeded the limits shown on the left. The data presented in Table 3 were used to identify widespread heavy rainfall events. The threshold values for widespread *heavy* rainfall events in the context of the area were calculated by testing several values and extracting any one value occurring between the 95th and 99th percentiles, shown in ***bold italics*** in Table 3.

Considering widespread, heavy rainfall events, Table 4 puts the contribution of tropical systems into perspective. For only the widespread, heavy rainfall events as identified from the data shown in Table 3 (between the 95th and 99th percentile), Table 4 shows in the first row the total number of occurrences of such events. The second and third rows show what percentage of number of these events occurred during the second part of summer (January to March) and the entire summer (October to March), respectively, while the last row shows what percentage of number of these events was as a direct result of rainfall caused by tropical systems from the SWIO.

Table 4 shows that more than half of the widespread heavy rainfall events occurred during the January-March period (row 2) and about 80 % or more during the summer half-year (October to March, row 3). The importance of the tropical systems from the SWIO is shown to increase from left to right in row 4, as the definition of widespread heavy rainfall becomes stricter. More than half of all cases where daily total rainfall in excess of 50 mm was reported from all three stations within three days and where more than 100 mm of rain was recorded at all three stations within 5 days were caused by these systems.

Cycles in the occurrence of landfalling tropical systems and associated rainfall

Because cycles have been observed in the occurrence of tropical cyclones over various ocean basins (e.g. Goldenberg *et al.*, 2001) and knowledge about cyclicity in the landfalling of tropical systems from the SWIO can improve seasonal and decadal forecasting over southern Africa, a Fourier analysis was performed on the station rainfall data in order to establish whether there exists any cyclic behaviour in the occurrence of rainfall caused by landfalling tropical systems over the area of interest, over the period 1948 and 2008.

Figure 7 shows the annual rainfall contributed by tropical systems from the SWIO at four of the weather stations depicted in Figure 1 during the period under consideration. The rainfall values for each station were rescaled to vary between 0 and 1, by dividing the annual rainfall totals caused by tropical systems from the SWIO for each station by the highest annual value caused by tropical systems at that station within the time series.

Based on the graph (Figure 7), the possible existence of cyclic behaviour with peaks indicated by ovals, can be seen in the rainfall contributed by tropical systems from the SWIO over the area of interest.

Figures 8a and 8b show the periodograms resulting from Fourier analysis for all six stations indicated in Figure 1. On the left-hand side the periodograms for the rainfall caused by tropical systems from the SWIO are shown, while the right-hand side shows the periodograms resulting from Fourier analysis performed on the total annual rainfall at each station. The 90% and 95% confidence levels are also indicated.

The Fourier analysis for rainfall caused by tropical systems from the SWIO at stations over the northeastern part of South Africa reveals the largest peak at 18 or 19 years, while the largest peak occurs at 27 years for Makoholi in Zimbabwe. This quasi-18-year oscillation is statistically significant above the 90% confidence level for all the South African stations (all the stations except Makoholi – Figure 1).

While the quasi 18-year cycle dominates the periodograms for rainfall contributed by tropical systems, it also remains the most prominent cycle in the annual rainfall and/or statistically significant above the 90% confidence level for the four stations closest to the centre of the area of interest - Pafuri, Musina, Entabeni and Villanora (Figure 1). It is not present in the data for total annual rainfall at Makoholi in Zimbabwe.

Figure 9 shows the 5-year moving average of rainfall contributed by tropical systems from the SWIO for Musina and Entabeni, as well as the corresponding quasi-18-year wave calculated from the wave coefficients derived from the Fourier analysis.

For both Musina in the Limpopo River Valley and Entabeni on the escarpment, the 18.6-year cycle contributes about 45% of the variation of rainfall associated with tropical systems from the SWIO, over the period 1948 to 2008. Similar results were obtained for the other three stations in South Africa.

Figure 9 also reveals that the peaks in rainfall due to the westward movement of well-defined tropical systems from the SWIO occurred around 1958, 1977 and 1996. These years correspond to the peaks in the quasi-18-year cycle as noted and predicted by Dyer and Tyson (1977). These peaks are also present in the positive values of the 24-month Standardized Precipitation Index values calculated for the northeastern interior of South Africa (Rouault and Richard, 2003). The quasi-18-year climate oscillation, according to Dyer and Tyson (1977), is confined to the subtropical latitudes south of 15°S and is clearest in the band extending from 20 to 30°S across the subcontinent (Tyson *et al.*, 2002). This is also shown by the weakness of this oscillation in the rainfall time series at Makoholi in Zimbabwe compared to the South African stations.

The question arises to what extent periodicities in the rainfall caused by landfalling tropical systems are responsible for the existence of the quasi-18-year cycle in rainfall over northeastern South Africa (and subtropical Africa in general). Figure 10 shows the 5-year moving average of the total annual rainfall for all six stations displayed in

Figure 1, as well as the 5-year moving average calculated for the rainfall caused by landfalling tropical systems (expressed as a percentage of the total annual rainfall). The contribution of tropical systems from the SWIO to total annual rainfall ranges between 0 and 30% when considering the 5-year moving averages. It can also be seen that the influence (relative contribution) of these systems is larger during periods of relatively high rainfall. For the South African stations, three distinct peaks are visible in both annual rainfall and the percentage contribution of landfalling tropical systems to the annual rainfall, with these peaks coinciding with the quasi-18-year cycle of Dyer and Tyson (1977). Figure 11 shows the 5-year moving average annual rainfall averaged over all 6 stations, the 5-year moving average annual rainfall with the rainfall originating from tropical systems subtracted, as well as the 5-year moving average annual rainfall contributed by tropical systems from the SWIO.

It can be seen that the 18-year oscillation is enhanced by the rainfall contributed by the landfalling systems, but that it persists when the rainfall by these systems is subtracted from the time series. The greatest contribution to rainfall by tropical systems occurred during the three peaks of the quasi-18-year cycle. These results, suggest that during wet periods over southern Africa within the 18-year cycle, atmospheric circulation patterns enhance the potential of landfalling tropical systems to cause widespread heavy rainfall events over the region, however it is not the rainfall contributed directly by these systems that drives the quasi 18-year cycle.

The larger contribution to rainfall by tropical systems from the SWIO during the peaks of the 18-year cycle is consistent with the fact that La Niña-like conditions are associated with these multi-year periods of above-normal rainfall over the summer rainfall region of South Africa (Reason and Rouault, 2002), and that La Niña conditions favour the landfall (Vitard *et al.*, 2003) and westward penetration of tropical cyclones into the southern African subcontinent (Reason and Keibel, 2004). The largest contribution to rainfall over northeastern South Africa by tropical systems from the SWIO occurred during the last rainfall peak of the quasi 18-year cycle, between 1995 and 2003. The role that landfalling tropical systems play in contributing to wet years over northeastern South Africa is further illustrated by Figure 12, which shows the difference in the average contribution of tropical systems to total annual rainfall for years with above and below-average rainfall considered for all six stations separately over the entire period.

It may finally be noted that the 18-year peaks in the rainfall data for South African stations represent the contribution of systems that follow a largely zonal (westward) track, whilst the station in Zimbabwe is also influenced by systems that track more northwesterly. For example, during 1962, 1967, 1969 and 1986, tropical cyclones that made landfall moved westward or northwestward over the central parts of Zimbabwe, causing rain over the northern side of the Limpopo River Basin but no rain on the South African side of the Limpopo River Basin. This may explain the relatively smaller contribution of the 18-year peak in the periodogram for Makoholi in Zimbabwe (Figure 8b). Furthermore, the cycle found in the rainfall contributed by tropical systems from the SWIO over the area is not visible in the actual time series of number of tropical systems making landfall and causing at least some rainfall over the area (Figure 3). This is further evidence that the altered conditions during the peaks of the Dyer-Tyson cycle for the period 1948 to 2008 favoured the more zonal movement after landfall of these systems over the interior of southern Africa.

4. Conclusions

Tropical systems from the SWIO contributed less than 10% of the total rainfall occurring over the eastern interior of southern Africa in the Limpopo River Valley over the period 1948-2008. The percentage contribution of these systems to rainfall is highest over the eastern escarpment, from where it decreases to the south and west. When heavy rainfall events over northeastern South Africa are considered, the contribution of tropical systems is far more significant. These systems contribute more than 50% of multi-day heavy rainfall events occurring in the Limpopo Basin (for example, when more than 100 mm is measured within 5 days, simultaneously at three weather stations over the escarpment and Lowveld area of the Limpopo Province in South Africa). The highest 5-day total rainfall values on record both on the escarpment and in the Limpopo River Basin around 30°E are associated with tropical systems from the SWIO.

The contribution to total annual rainfall by these systems over the eastern interior of southern Africa appears to be of a cyclic nature – Fourier analysis of the 5-year moving average of the rainfall time series for the period 1948-2008 shows a statistically significant quasi-18-year cycle in the rainfall contributed by these systems over the northeastern parts of South Africa. The cycle is in phase with the well-known quasi-18-year Dyer-Tyson cycle (Dyer and Tyson, 1977). The quasi-18-year cycle also exists with respect to the total annual rainfall occurring at weather stations in northeastern South Africa, and persists to occur when the rainfall contributed by tropical systems is subtracted from the time series. This result indicates that tropical systems from the SWIO do not as such drive the Dyer-Tyson cycle, but rather that the atmospheric and surface conditions leading to wet phases of the Dyer-Tyson cycle also favour the landfall and westward movement of tropical systems from the SWIO over southern Africa – and their eventual contribution to rainfall over northeastern South Africa. Indeed, the relative contribution of tropical systems from the SWIO to annual rainfall over northeastern South Africa is higher during wet periods within the 18-year cycle. Although the study of underlying factors causing the cyclicity during the study period is outside the scope of this paper, these results emphasize that the types of rain-bearing systems occurring over southern Africa differ in frequency of occurrence and tracks followed between the wet and dry phases identified through the

Dyer-Tyson cycle. These findings can also contribute to the skill of forecasts on the time scale of decadal predictability.

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List of Tables

Table 1 List of all tropical systems making landfall over southern Africa from the SWIO, responsible for rain over the area of interest and datasets containing evidence of the systems

Date of landfall of tropical system responsible for rain over the area of interest	NCEP - Geopotential heights at 700 hPa (Visual Inspection)	NCEP data (Objective tracking algorithm)	La Réunion Tropical Cyclone Database	SAWS daily synoptic maps	Time series of rainfall maps (Distinct rainfall pattern)
20 March 1948			X	N/A	X
02 February 1950	X		X		X
09 February 1950	X	X			X
13 February 1956	X			X	X
01 January 1958	X	X	X	X	X
23 March 1959	X	X			X
31 January 1960			X	X	X
23 January 1962	X	X	X	X	
12 February 1962	X		X	X	X
15 March 1962	X	X	X	X	X
07 March 1964	X		X	X	
05 January 1966	X	X	X	X	X
16 February 1966	X	X	X	X	
08 January 1967	X	X	X	X	
26 January 1967	X	X		X	
23 February 1967	X	X	X	X	X
09 January 1968	X	X	X	X	
21 January 1968	X	X	X		
06 January 1969	X		X	X	
31 January 1969	X	X	X	X	
14 February 1972	X	X	X	X	X
20 February 1972	X	X	X	X	X
27 January 1976	X	X	X	X	X
27 January 1977	X	X			X
05 February 1977	X	X	X	X	X
12 February 1977	X	X		X	X
05 February 1982	X	X	X	X	X
31 January 1984	X	X	X	X	X
19 February 1984	X	X	X	X	X
08 January 1986	X	X	X	X	
03 March 1988	X	X	X	X	
28 February 1993	X			X	X
17 February 1995	X	X		X	X
14 January 1996	X	X	X	X	X
06 February 1996	X	X		X	X
03 March 1997	X	X	X	X	
03 March 1999	X			X	X
03 February 2000	X	X		X	X
22 February 2000	X	X	X	X	X
09 March 2000	X	X	X	X	X
02 March 2003	X	X	X	X	X
04 January 2006	X	X		X	X
23 February 2007	X	X	X	X	X
26 February 2007	X	X		X	X

Table 2 **Average contribution to yearly rainfall at the stations indicated in Figure 1 over the period 1948 to 2008, by tropical systems from the SWIO.**

Station	Nelspruit	Entabeni	Pafuri	Musina	Villanora	Makoholi (Zim)
Annual Rainfall (mm)	847	1795	440	360	421	647
In Jan-Mar (%)	42	54	52	50	49	51
Tropical system contribution - Jan-Mar (%)	**10**	**14**	**14**	**15**	**6**	**14**
Tropical system contribution - All Year (%)	**4**	**7**	**7**	**8**	**3**	**7**

Table 3 Widespread heavy rainfall events according to various cut-off values of rainfall occurring simultaneously at all three stations, for total rainfall during a three-day period (column 1), two-day period (column 2), maximum rainfall during a three day period (column 3) or the total rainfall during a five-day period (column 4) exceeding the thresholds as indicated on the left-hand side. (These statistics pertain to all rainfall events, not only those caused by tropical systems, and were calculated for the period 1948 to 2008.)

Limit	3-Day total	2-Day total	Maximum in 3 days	5-Day total
>20 mm	18.5%	15.1%	11.5%	24.7%
>50 mm	***3.4%***	***2.5%***	***1.0%***	6.4%
>100 mm	0.4%	0.3%	0.1%	***1.0%***

Table 4 Occurrence of widespread heavy rainfall events over the eastern parts of the Limpopo Province of South Africa and the contribution of well-defined tropical systems from the SWIO to these events.

Definition	3-Day total > 50 mm	2-Day total > 50 mm	Maximum in 3 days >50 mm	5-Day total > 100 mm
Total	33	19	9	7
Jan-Mar	55%	58%	89%	86%
Oct-Mar	82%	79%	89%	86%
Tropical system	**27%**	**42%**	**56%**	**57%**

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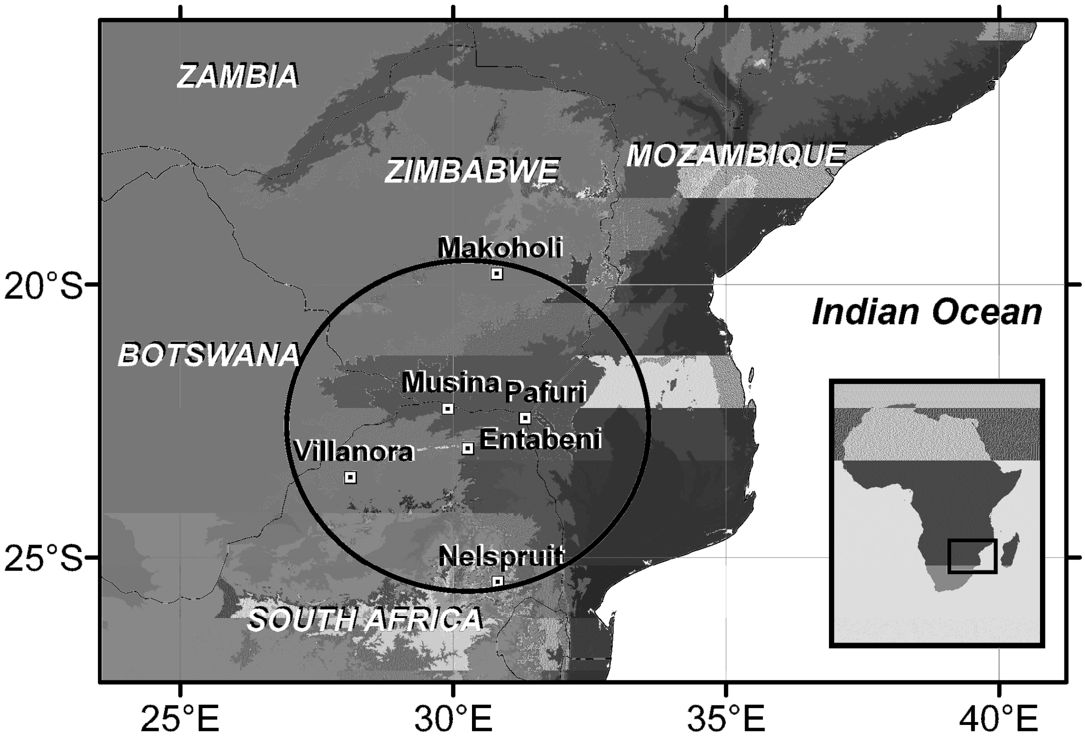

Figure 1 The eastern parts of southern Africa with the Limpopo River Basin clearly visible. Stations in the basin used for rainfall analysis are also indicated.

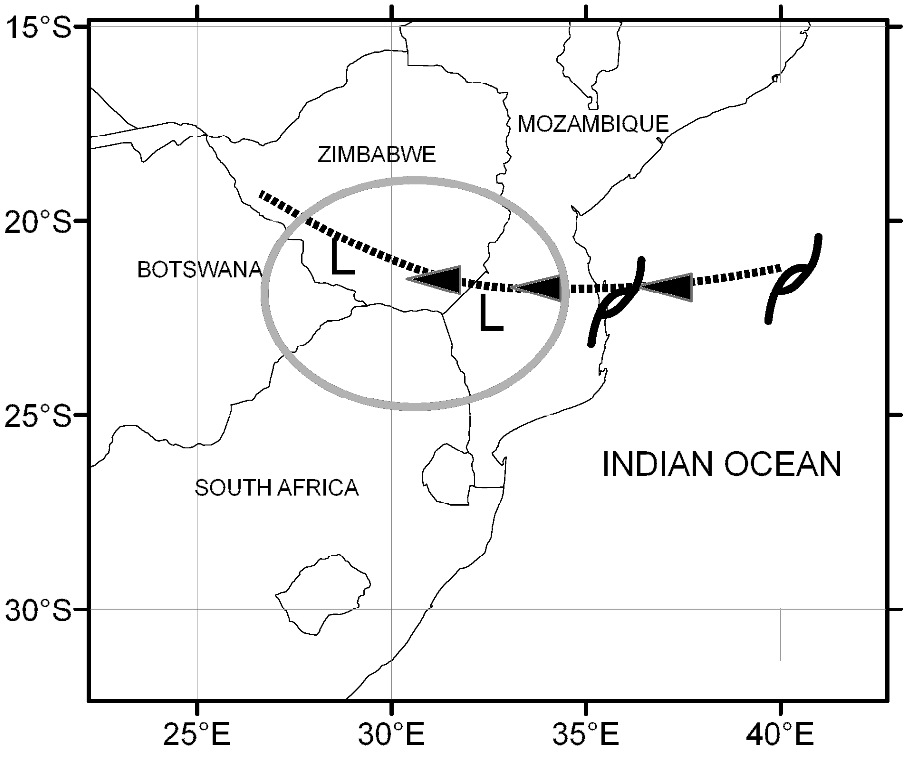

Figure 2 A track followed by several tropical systems from the SWIO making landfall and moving westward over southern Africa.

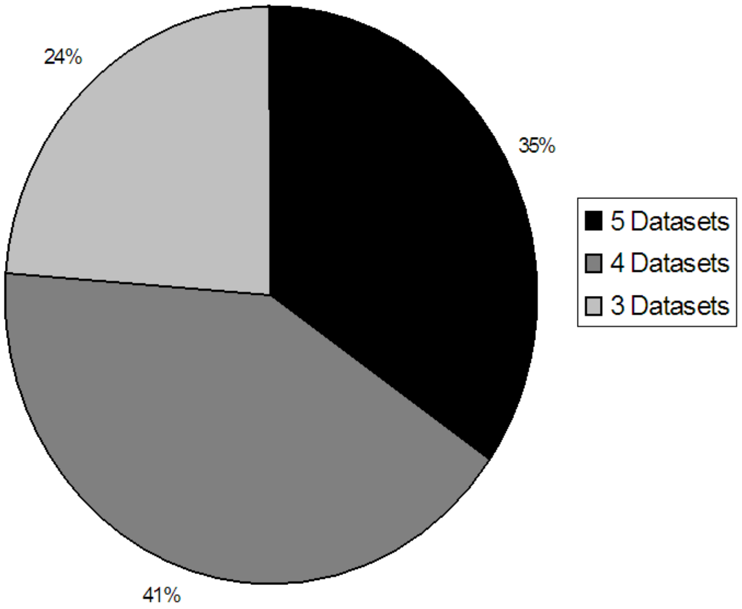

Figure 3 Breakdown of the 45 systems as identified through various combinations of three (light grey), four (dark grey) or five (black) of the following datasets: SAWS synoptic maps, La Réunion track data, objective tracking algorithm applied to NCEP data, visual inspection of NCEP data and a strong indication from rainfall distribution.

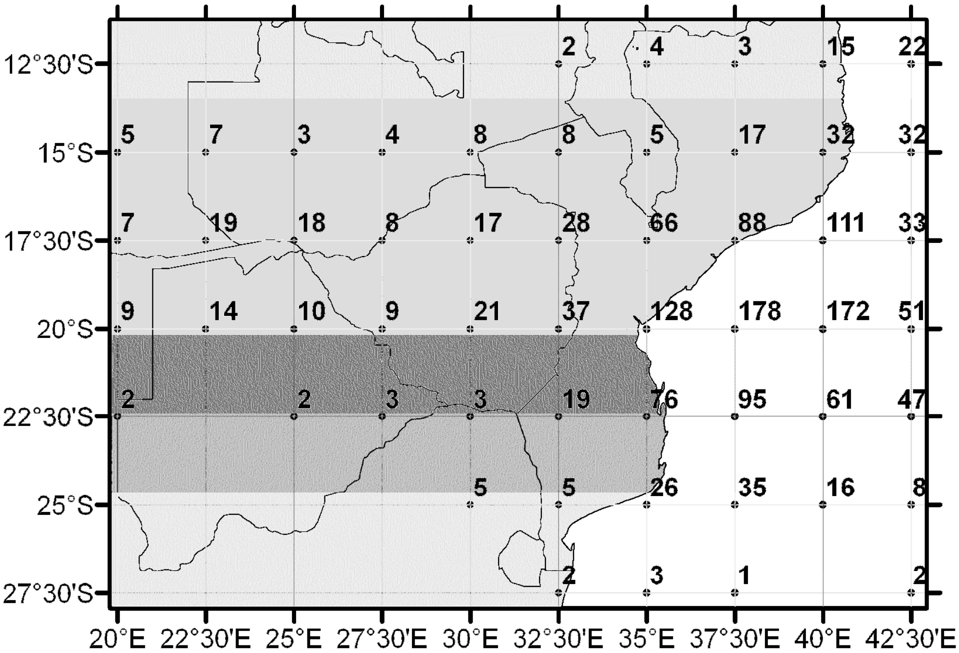

Figure 4 Frequency of occurrence of tropical systems from the SWIO making landfall over southern Africa (units are the numbers of 6-hourly geopotential lows per grid point over the period 1948-2006) as tracked by an objective tracking algorithm applied to NCEP Reanalysis daily 700 hPa Geopotential Height data.

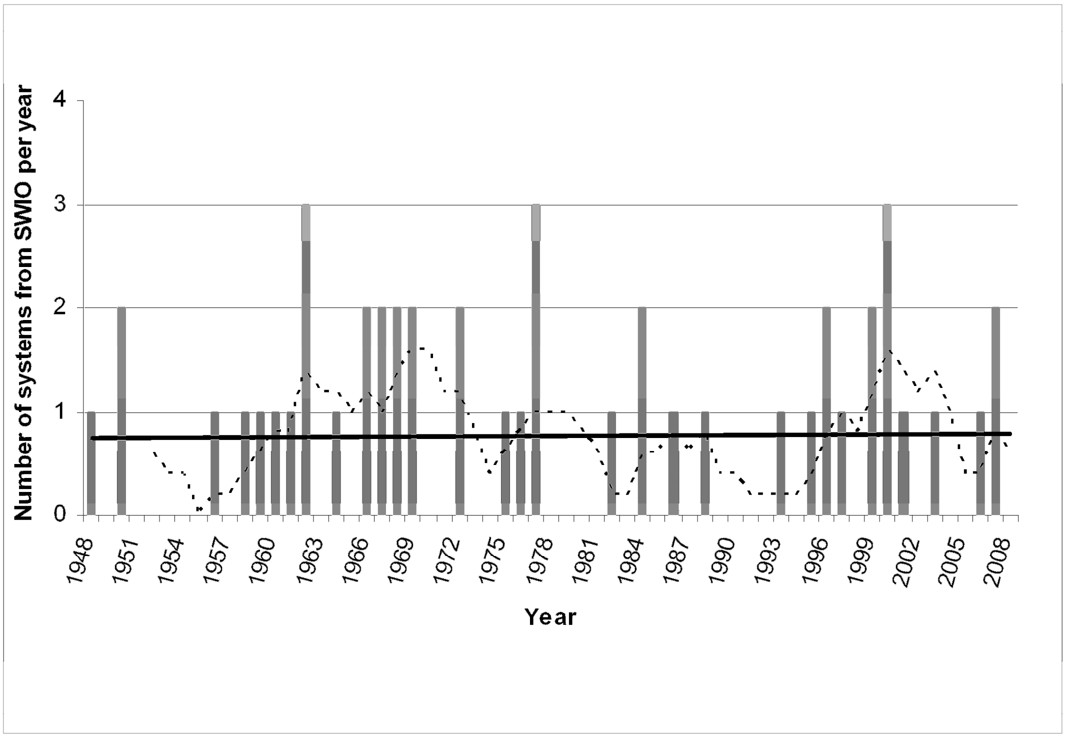

Figure 5 **Number of tropical systems from the SWIO per year, as identified through the combination of synoptic and rainfall datasets, that caused rainfall over the Limpopo Basin (bars) with a linear trend line (solid line) fitted and the 5-year moving average (dotted line).**

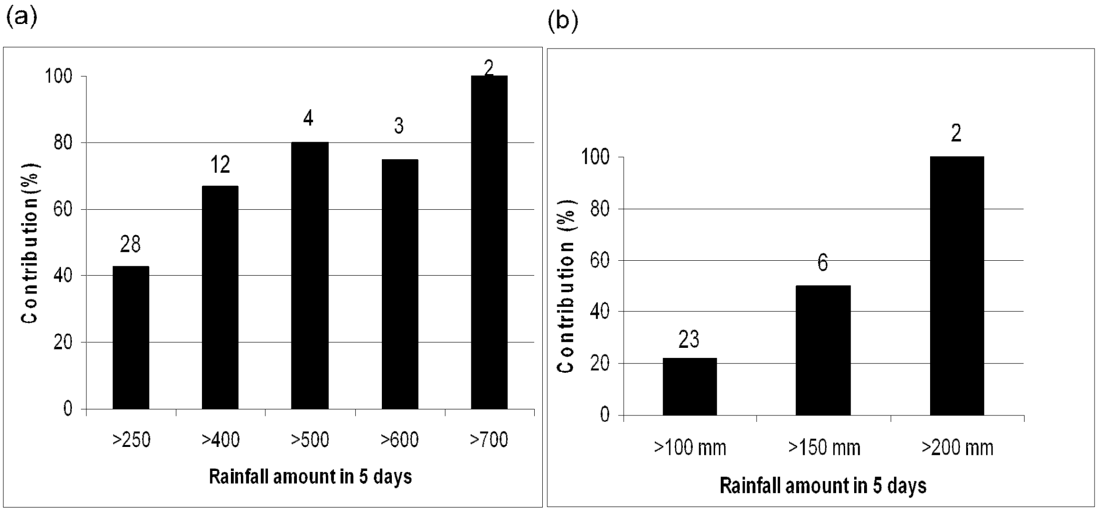

Figure 6 Contribution of tropical systems from the SWIO to 5-day rainfall events exceeding various threshold amounts at Entabeni on the eastern escarpment (a) and Musina in the Limpopo River Valley (b). The figures above the bars indicate the total number of times these rainfall events have occurred since 1948.

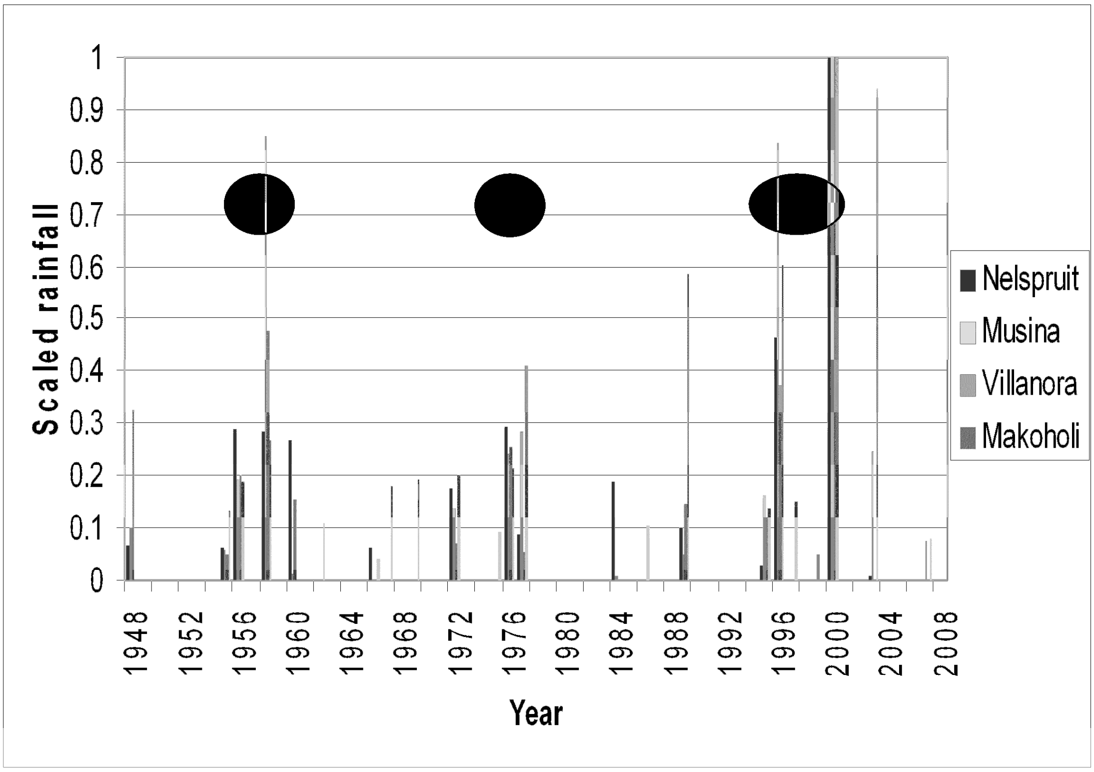

Figure 7 Scaled annual rainfall totals contributed by tropical systems from the SWIO at four locations over the period 1948-2008 (similar results were obtained for Pafuri and Entabeni).

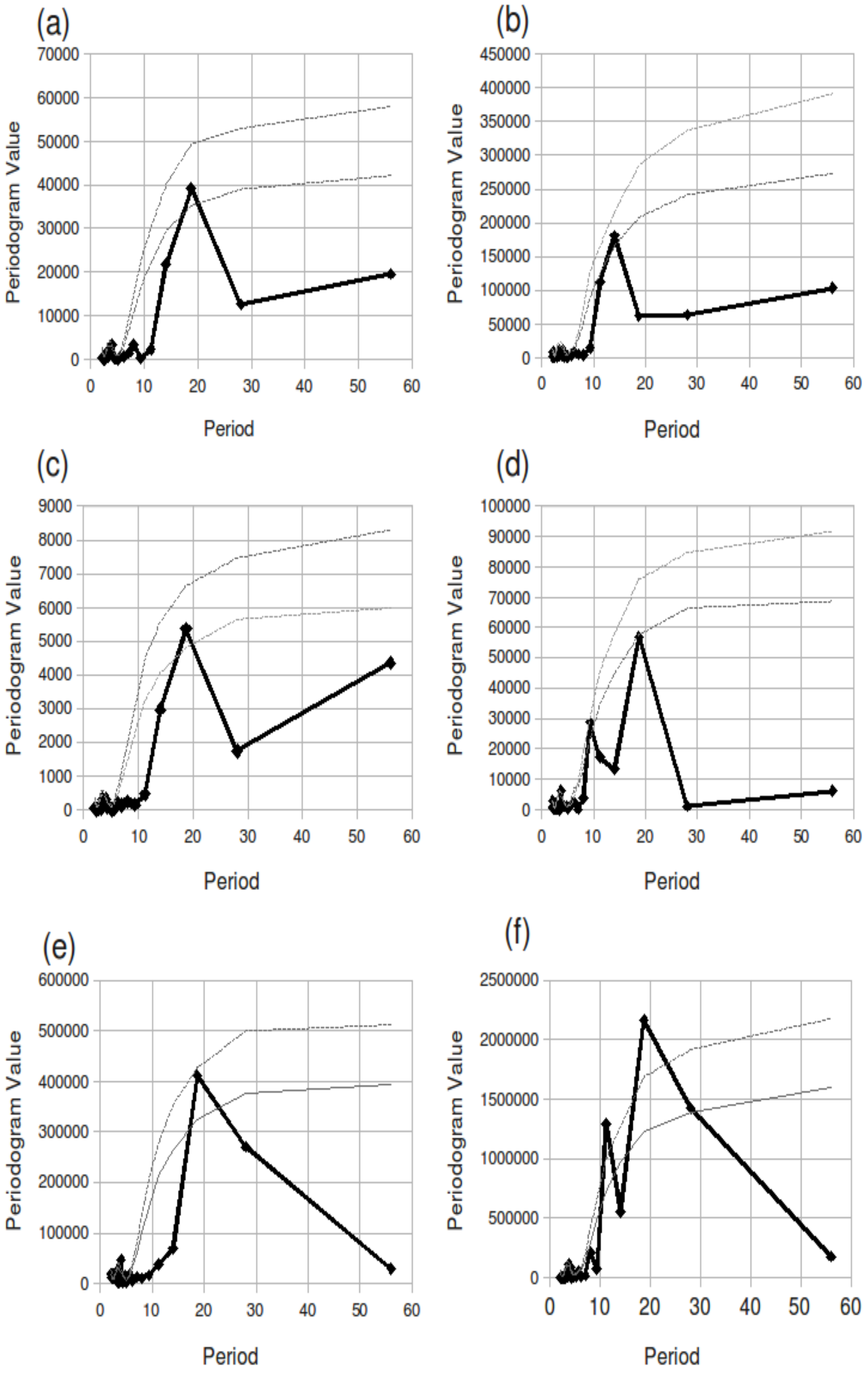

Figure 8 a - f Periodograms obtained for the 5-year moving averages of rainfall caused by tropical systems from the SWIO (left) and for total annual rainfall (right) at Nelspruit (a,b), Villanora (c,d) and Entabeni (e,f). The grey dashed lines indicate the 90% and 95% confidence levels.

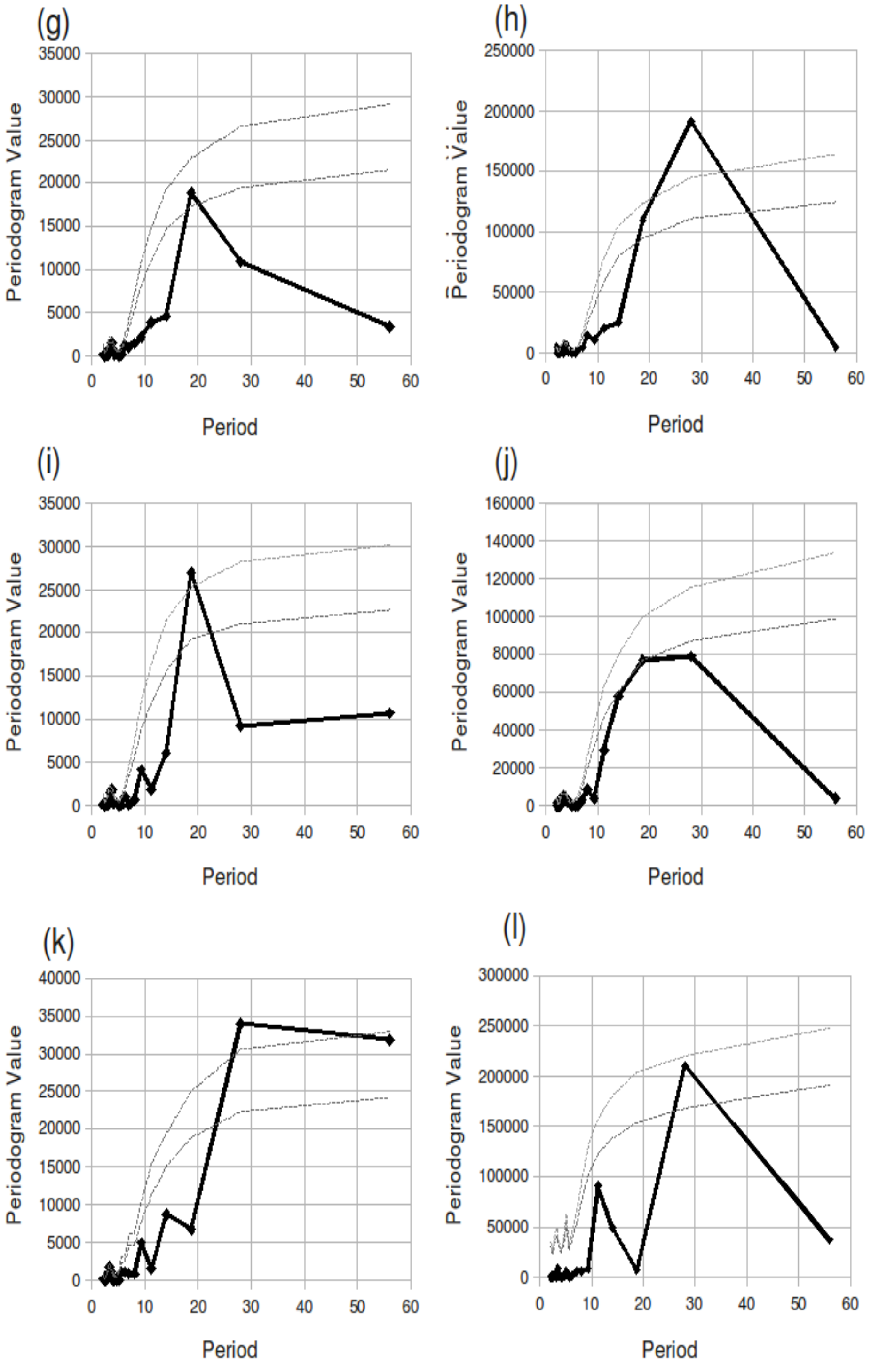

Figure 8 g - l Periodograms obtained for the 5-year moving averages of rainfall caused by tropical systems from the SWIO (left) and total annual rainfall (right) at Pafuri (g,h), Musina (i,j) and Makoholi (k,l). The grey dashed lines indicate the 90% and 95% confidence levels.

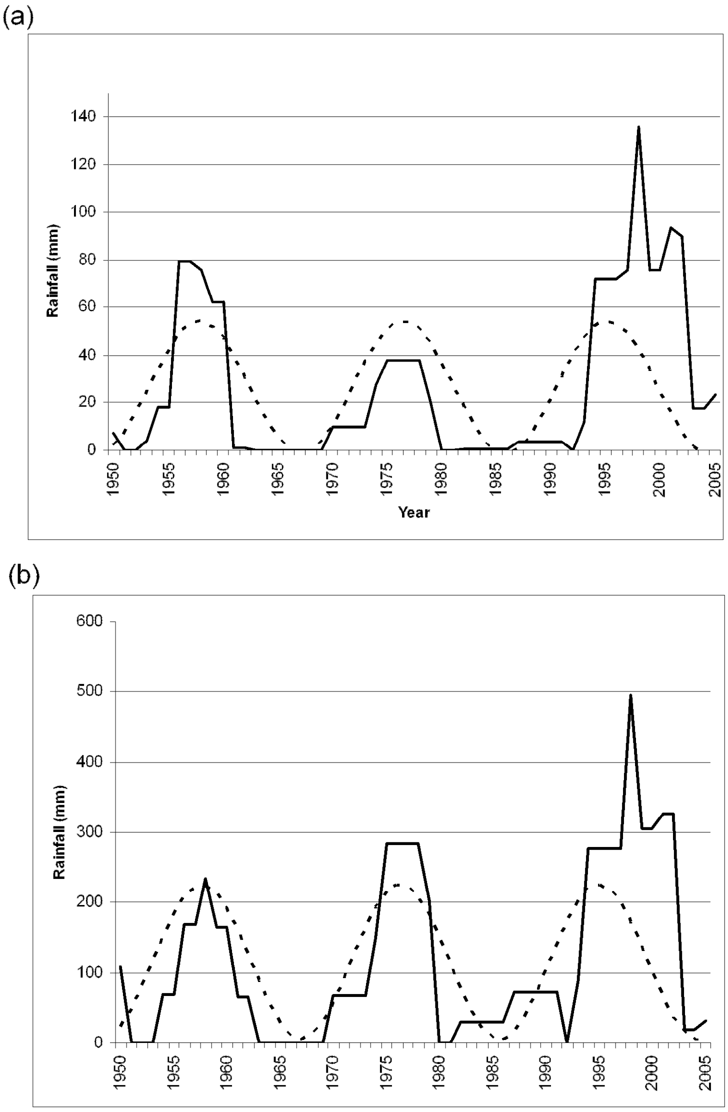

Figure 9 Five-year moving average of rainfall contributed by tropical systems from the SWIO (solid line) at Musina (a) and Entabeni (b) and the 18.6-year cycle calculated from coefficients resulting from Fourier analysis (dotted line).

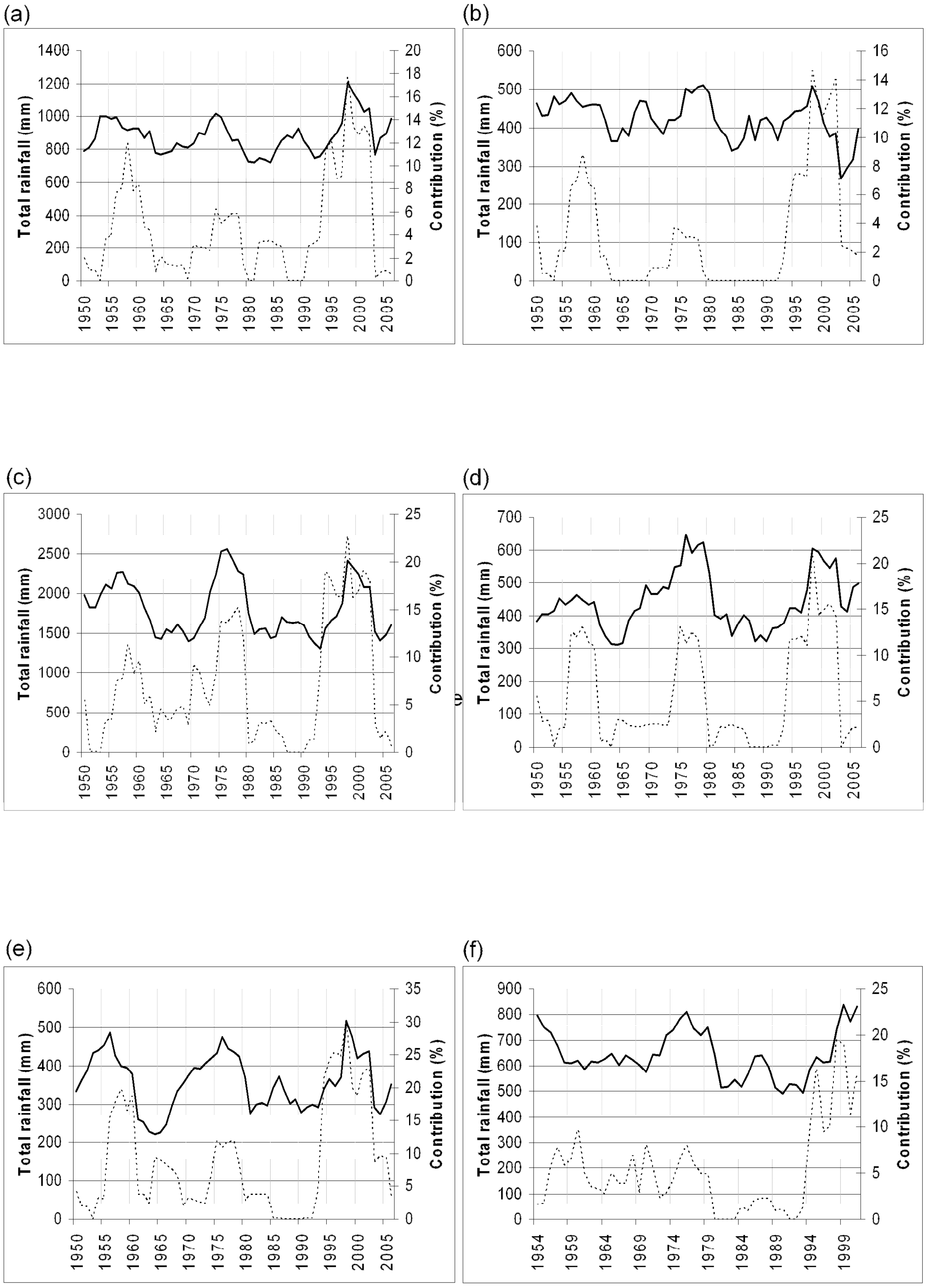

Figure 10 5-year average total rainfall (solid line) and 5-year average percentage of annual rainfall (stippled line) contributed by tropical systems from the SWIO (secondary axis) for Nelspruit (a), Villanora (b), Entabeni (c), Pafuri (d), Musina (e) and Makoholi (f).

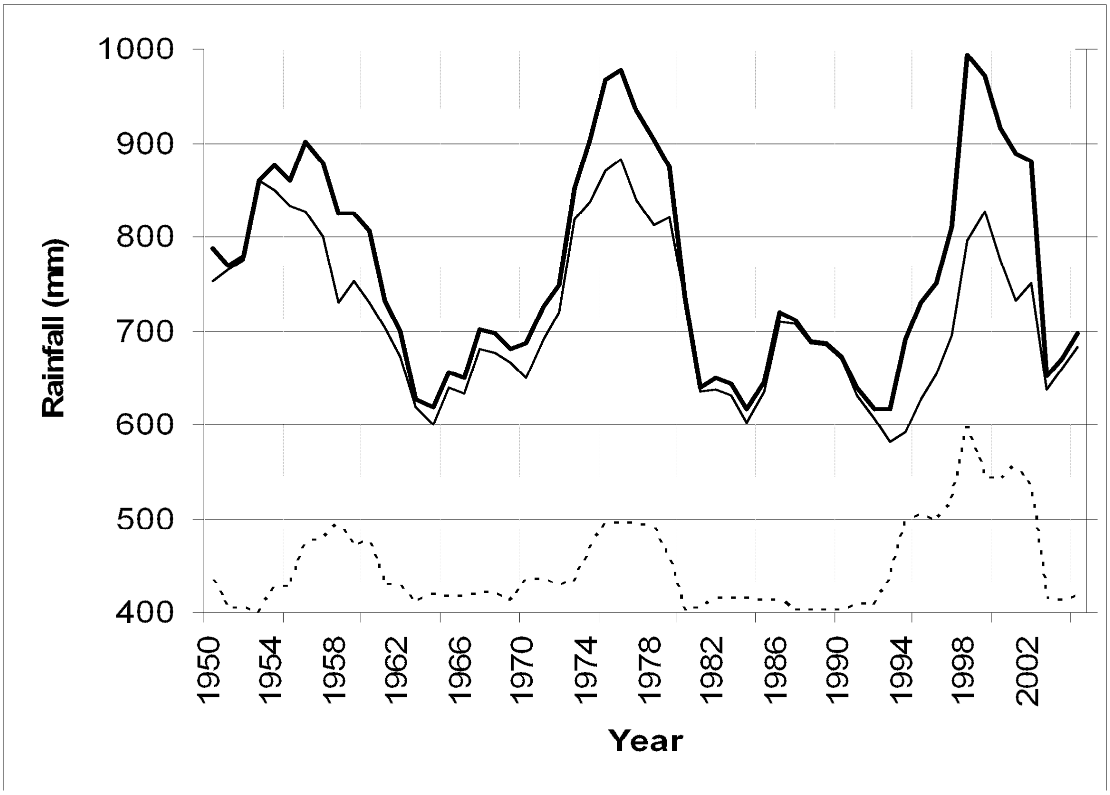

Figure 11 5-year moving average rainfall for all 6 stations accumulated (thick solid line), 5-year moving average annual rainfall when the contribution of tropical systems from the SWIO is discarded (thin solid line) and the 5-year moving average annual rainfall contributed by tropical systems from the SWIO (dotted line).

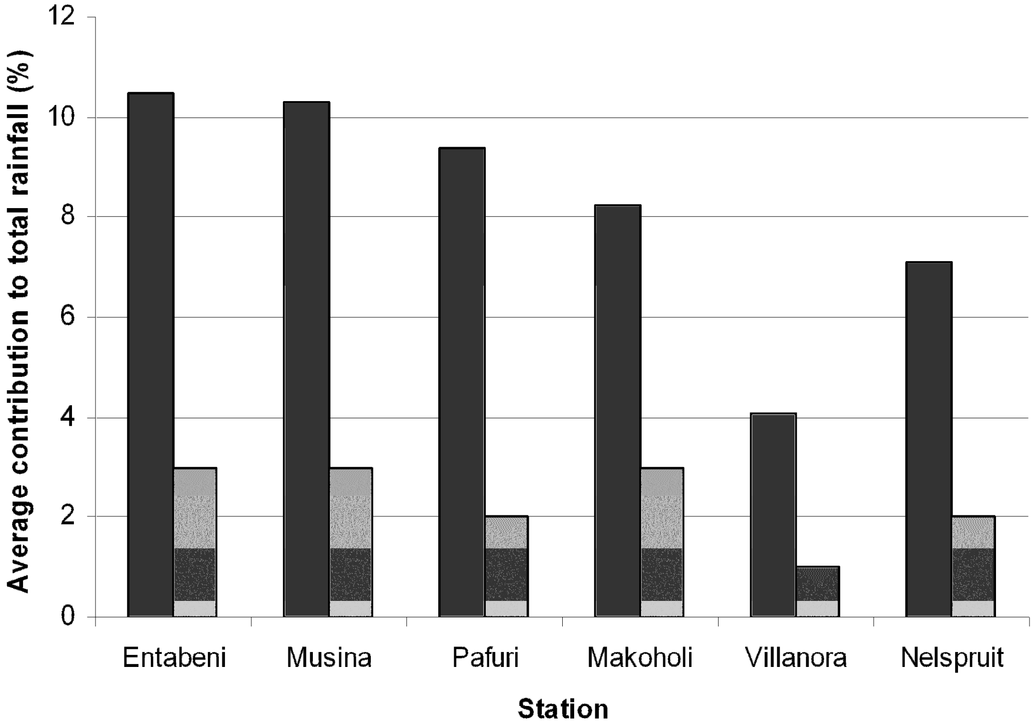

Figure 12 Contribution by tropical systems during above-average rainfall years (black) and during years with below-average rainfall (grey).