

SECTION 1: LONG-TERM TRENDS IN RAINFALL AND RAINFALL VARIABILITY

PREFACE

Section 1 comprises two Chapters as follows:

Nel, W. and Sumner, P.D. 2006. Trends in rainfall total and variability (1970-2000) along the KwaZulu-Natal Drakensberg foothills. *South African Geographical Journal*, 88, 130-137.

Nel, W. Submitted. Rainfall trends in the KwaZulu-Natal Drakensberg region of South Africa during the Twentieth Century. *International Journal of Climatology*.

The first Chapter of Section 1 is a chapter co-authored with Paul Sumner published in the *South African Geographical Journal*¹. The chapter focuses on recent rainfall records along a latitudinal and altitudinal gradient in the KwaZulu-Natal Drakensberg foothills east of the escarpment. South African Weather Services rainfall station data are contrasted with respect to altitude, location in relation to the escarpment and latitude. Rainfall totals are found to be affected by altitude and distance from the escarpment, and this correlates well with findings from earlier work undertaken on the eastern and western side of the escarpment. This paper also presents new findings on the effect that latitude has on rainfall totals and inter- and intra-annual rainfall variability.

The second Chapter, as re-submitted to the *International Journal of Climatology* following inputs from two reviewers, assesses long-term rainfall records in the KwaZulu-Natal Drakensberg east of the escarpment. The study analyses temporal trends of inter- and intra-annual rainfall variability of both annual and seasonal rainfall, and the relationship between summer rainfall in the Drakensberg in correlation to the El Niño/Southern Oscillation

¹ Paul Sumner provided inputs and discussions on the text. The original idea for the paper was mine, and I undertook the text compilation, submission and revision.

phenomenon. Analysis of monthly rainfall indicates an increase in the variability of the distribution of monthly rainfall and the strengthening of rainfall seasonality in the Drakensberg. The El Niño/Southern Oscillation influences summer rainfall variability and a strong correlation exist between summer rainfall and the Southern Oscillation Index for preceding periods. The paper suggests that the lagged correlation between summer rainfall in the Drakensberg and the Southern Oscillation Index could be used as an indicator for seasonal forecasting.

TRENDS IN RAINFALL TOTAL AND VARIABILITY (1970-2000) ALONG THE KWAZULU-NATAL DRAKENSBERG FOOTHILLS

Werner Nel and Paul Sumner¹

¹Department of Geography, Geoinformatics and Meteorology
University of Pretoria
Pretoria 0002
South Africa

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ABSTRACT

South Africa's most valuable source of water is the eastern escarpment region of the KwaZulu-Natal Drakensberg and Lesotho highlands. These upper catchments supply much of KwaZulu-Natal, feed the Vaal River in the interior through two inter-basin transfer schemes and are important conservation areas. Analysis of rainfall and rainfall variability trends can thus contribute to a better understanding and management of the area and yet no recent studies have investigated these aspects. This study assesses the 1970-2000 rainfall period using 13 stations to the east of the escarpment in KwaZulu-Natal and presents a spatial perspective on annual rainfall totals and intra- and inter-annual variability. Altitude and distance from the escarpment eastward are found to influence total annual rainfall with an increase of 41.5 mm per 100 m in altitude between approximately 1100 m and 2100 m a.s.l., and a corresponding decrease of 54 mm for every 10 km eastward from the escarpment. Neither inter- nor intra-annual rainfall variability is influenced directly by altitude or the relation to the escarpment. Latitudinal position is found to have no significant affect on station totals but variability increases from south to north in the Drakensberg, possibly related to the greater seasonal contribution by frontal rains in the south, or more variable annual storm activity in the north.

INTRODUCTION

Rainfall totals and seasonality are crucial in understanding the biotic and abiotic environment. Rainfall trends are critical to the spatial distribution of ecological units (Bailey, 1998), population fluctuation of small mammals (Monadjem and Perrin, 2003), distribution and diversity of insects (e.g. Davis, 2002) and the spatial and temporal patterns of vegetation (Fernandez-Illescas and Rodriguez-Iturbe, 2004). In addition, hydrological aspects such as runoff generation (Winchell *et al.*, 1998), water balance of first order catchments (Everson, 2001) and the timing and magnitude of streamflow events in large watersheds (Koren *et al.*, 1999) are also affected by rainfall trends and variability. In this context, rainfall and rainfall variability in mountainous areas are of primary significance since mountains are typically areas of ecological importance and high altitude sub-catchments regulate discharge, particularly during low-flow conditions.

Recently declared a Trans-Frontier National Park where KwaZulu-Natal borders on eastern Lesotho, the mountainous escarpment region of eastern southern Africa approximates the watershed between the interior catchments that feed the Orange River and the shorter and steeper catchments such as the Tugela, Mooi and Mkomazi Rivers that flow towards the east coast (Fig 1). Given the high rainfall totals known for the area (e.g. Schulze, 1979) there is nearly twice as much total runoff in KwaZulu-Natal per unit of rainfall than for the average of South Africa as a whole, and the province contributes a quarter of South Africa's streamflow (Whitmore, 1970). Given that two inter-basin transfer schemes, the Tugela-Vaal transfer tunnel (TUVA) and the Lesotho Highlands Water Project (Nel and Illigner, 2001), rely on these upper catchments, the area can be considered South Africa's most important source of water.

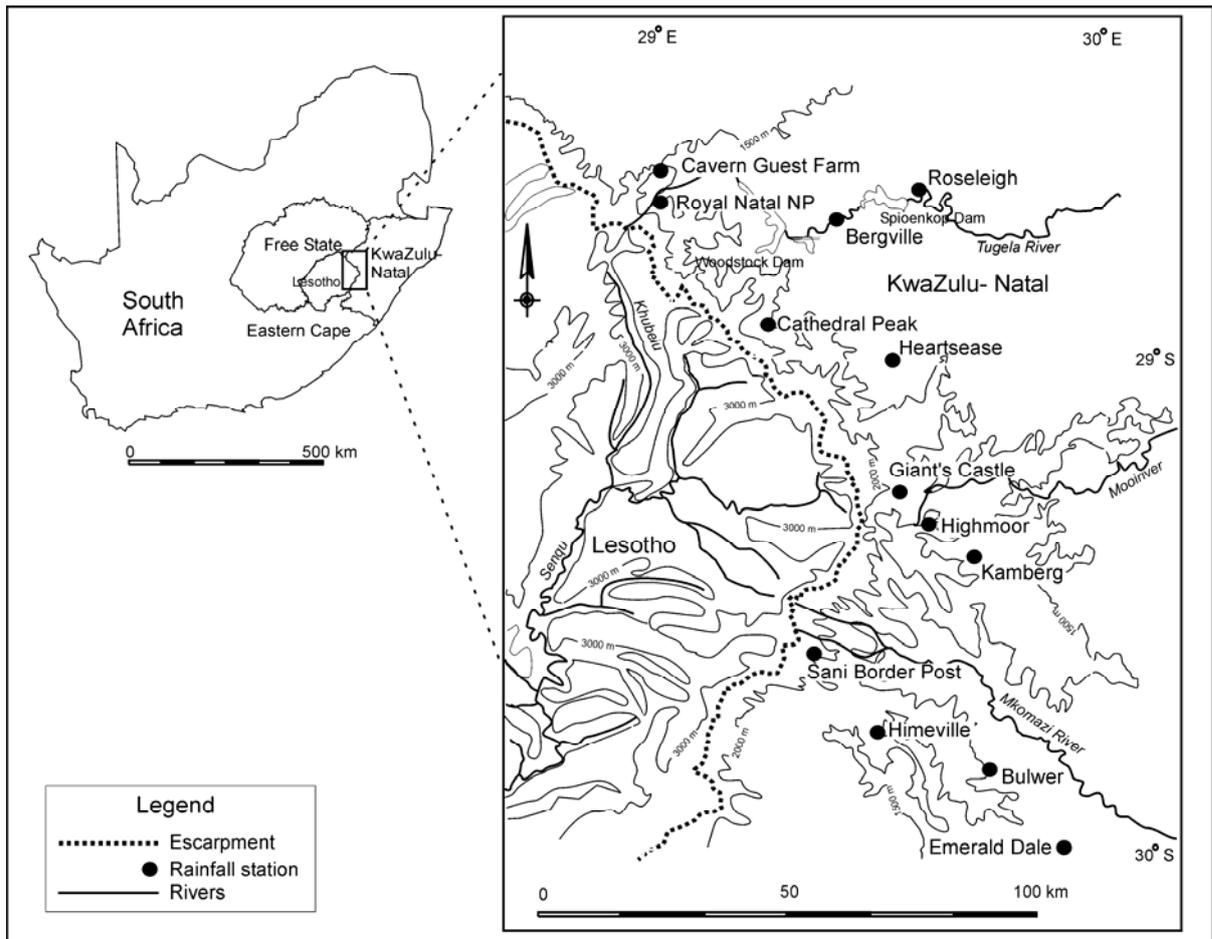


Figure 1: Map of the KwaZulu-Natal Drakensberg and the location of rainfall stations. The escarpment edge corresponds closely to the international border.

Few published assessments exist on total rainfall or rainfall variability for the KwaZulu-Natal Drakensberg area and recent environmental studies still cite trends from the benchmark assessments by Tyson *et al.* (1976) and Schulze (1979). The aim of this study is to assess more recent rainfall records along a latitudinal and altitudinal gradient in the KwaZulu-Natal Drakensberg foothills east of the escarpment. A spatial approach is taken where weather station data are contrasted with respect to altitude, location to the escarpment and latitude.

STUDY AREA

The Drakensberg is part of the Main Escarpment of southern Africa, which extends as a passive margin around the sub-continent and has a highest point of 3482 m a.s.l. (above sea

level) in eastern Lesotho. Typically, the escarpment reaches above 3000 m on the watershed border between KwaZulu-Natal and Lesotho (Fig. 1). Given the remoteness of the eastern Lesotho highlands, few reliable long-term weather stations have been operating in adjacent to and immediately west of the escarpment, and the study focuses on the records available east of the escarpment in what is locally known as the Drakensberg. The main land-use within the Drakensberg area is related to altitude with holiday resorts and conservation areas situated mostly above 1500 m a.s.l. and farmland and small towns found in the lower lying areas. South African Weather Services stations are located in the conservation areas, at resort offices, farms and in towns. Several dams in the northern region on the Tugela River feed the TUVA scheme.

Rain producing systems in the Drakensberg consist of two types (Tyson *et al.*, 1976). Large-scale line thunderstorms and orographically induced storms provide the major source of rainfall over the Drakensberg in the extended summer period. Frontal systems develop as closed low-pressure cells in the western Atlantic and move across southern Africa in a west-northwest to east-southeast direction (Tyson *et al.*, 1976). Approximately 43 cold fronts annually affect KwaZulu-Natal (Grab and Simpson, 2000), mainly in winter. Stations in the Drakensberg are known to experience an average of 16 to 18 rain days in the months of December and January, and the summer months November to March account for 70% of the annual rainfall whilst May to August accounts for less than 10% (Tyson *et al.*, 1976).

Snowfalls occur on average eight times a year (Tyson *et al.*, 1976), predominantly in the summit region, although the frequency could be underestimated since localised snowfalls are not taken into account (Boelhouwers and Meiklejohn, 2002). Heavy snowfalls can remain for several weeks on the ground in the high altitude areas (Hanvey and Marker, 1992). Observations by the authors give a water-equivalent of less than 100 mm p.a. on the escarpment (Nel and Sumner, 2005) but the contribution of snow to the water budget in the Drakensberg is unknown.

Rainfall Station	Date	Latitude S (°)	Longitude E (°)	Altitude (m)	Mean (mm)	CV (%)	Abs Dev (%)	PCI
Roseleigh	1957	28.62°	29.55°	1219	844.9	23.7	19.0	16.3
Cavern Guest Farm	1947	28.63°	28.97°	1980	1351.3	24.4	17.8	15.9
Royal Natal NP	1948	28.68°	28.95°	1392	1314.6	24.4	16.9	16.0
Bergville	1931	28.73°	29.35°	1128	767.0	22.8	18.6	16.5
Cathedral Peak	1937	28.95°	29.20°	1448	1220.4	24.5	15.8	15.8
Heartsease	1928	29.00°	29.50°	1167	922.5	21.4	15.4	16.1
Giant's Castle	1948	29.27°	29.52°	1754	1058.0	18.9	12.4	15.5
Highmoor	1955	29.32°	29.62°	1981	1229.0	25.5	20.0	16.1
Kamberg	1954	29.37°	29.70°	1525	1099.1	19.3	16.2	15.3
Sani Pass Border Post	1968	29.60°	29.35°	2055	1180.4	20.2	15.7	15.4
Himeville	1935	29.75°	29.53°	1524	938.3	16.9	11.5	15.2
Bulwer	1923	29.80°	29.77°	1484	1062.4	21.4	17.3	14.8
Emerald Dale	1969	29.93°	29.95°	1189	858.6	21.1	16.1	14.3

Table 1: Spatial distribution, mean annual rainfall and rainfall variability from selected stations in the KwaZulu-Natal Drakensberg, 1970–2000.

With respect to rainfall totals, Tyson *et al.* (1976) propose that mean annual rainfall varies markedly with altitude, and by extrapolating from lower altitude it is estimated that the top of the escarpment receives over 2000 mm of rain annually. Similarly, Schulze (1979) estimates a mean annual rainfall of 1500 mm on the escarpment and a mean January rainfall of 250 mm. However, these annual totals derived for altitudes above 2100 m a.s.l., where few data have been collected in the past, may be overestimates (Nel and Sumner, 2005). More reliable long-term monitoring has been undertaken at altitudes below 2100 m and these records are analysed here.

STATIONS AND DATA ANALYSIS

Rainfall data from 13 South African Weather Service (SAWS) stations in the Drakensberg covering the period 1970 to 2000 for the area between 28.5° and 30° S and 28.5° and 30° E (Table 1, Fig. 1) are analysed. At the stations, daily rainfall is manually measured from a rain gauge at 08h00 by SAWS volunteers; for example police officers (e.g. Sani Border Post),

conservation personnel (eg. Royal Natal National Park; Giant's Castle Game Reserve) and farmers (eg. Heartsease). In earlier reports, a 95-98% accuracy was noted for station data (Schulze, 1979, Dent *et al.*, 1987) but presently, the SAWS do not claim such accuracy from stations (Swart, pers. com). Consequently, only well-established weather stations with long-term unbroken rainfall measurements were considered. Thirteen stations were selected that provided a good geographical coverage of the Drakensberg foothills (Table 1, Fig. 1).

There are many global water resources problems, such as regional water yield studies, for which knowledge of annual or even seasonal rainfall is of little consequence, and an intra-year distribution is required (Schulze, 1979). In the analysis of intra-yearly rainfall trends in the Drakensberg, the seasonality can be described through the monthly rainfall totals as a percentage of the total annual rainfall (Table 2). To define intra-annual variability and to quantify its spatial distribution, a modified version (De Luis *et al.*, 2000; Ceballos *et al.*, 2004) of the precipitation concentration index (PCI) was applied:

$$PCI = 100 \frac{\sum_{i=1}^{12} P_i^2}{\left(\sum_{i=1}^{12} P_i\right)^2} \quad (1)$$

where P_i is the precipitation of the month i . Values below 10 indicate a uniform distribution of rainfall throughout the year. PCI values from 11 to 20 indicate a seasonal trend and values above 20 indicate a considerable variability of the distribution of monthly rainfall (Ceballos *et al.*, 2004). Measures of variability about the mean are of critical importance to water resources, since the greater the variability the more difficult and expensive management of water resources becomes (Klemes, 1973). Inter-annual variability of each station was calculated through the mean coefficient of variation (CV), which is defined as the relationship of standard deviation about the mean as a percentage of the mean as well as the percentage ratio of absolute mean deviation of annual rainfall to mean annual rainfall (absolute

deviation). Data were investigated along a latitudinal and altitudinal gradient and mean annual rainfall and variability plotted in relation to the station's distance perpendicular from the escarpment in an eastward direction. Since the data are normal and the variance constant the Pearson Product Moment Correlation parametric test, as well as linear regression were applied to discern any spatial trends.

Rainfall Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Roseleigh	19	18	12	4	2	1	1	3	4	9	12	15
Cavern Guest Farm	19	18	13	4	2	1	1	3	4	9	11	15
Royal Natal National Park	19	18	13	4	2	1	1	2	5	9	11	15
Bergville	19	18	14	5	1	1	1	3	4	9	11	14
Cathedral Peak	18	20	14	5	2	1	1	3	4	8	11	13
Heartsease	19	17	14	5	2	1	1	2	4	9	11	15
Giant's Castle	19	16	14	5	1	1	1	3	5	9	11	15
Highmoor	18	16	14	4	2	1	1	2	4	10	13	15
Kamberg	19	16	15	5	2	1	1	2	4	8	11	16
Sani Pass Border Post	19	17	14	5	1	1	1	3	5	9	10	15
Himeville	18	18	15	5	2	1	1	2	5	8	11	14
Bulwer	18	15	14	5	2	1	1	3	5	9	12	15
Emerald Dale	15	14	15	5	2	1	2	3	7	9	12	15
Average	18	17	14	5	2	1	1	3	4	9	11	15

Table 2: Monthly rainfall as a percentage of total rainfall, 1970-2000.

TRENDS IN RAINFALL DISTRIBUTION

Tyson *et al.* (1976) and Schulze (1979) found a clearly defined positive relationship between altitude and rainfall. Schulze, (1979) mapped mean annual precipitation and other rainfall statistics in the Drakensberg through the use of trend surface analysis (TSA) with physiographic variables of altitude, distance from a physiographic barrier and alignment of topography. Similarly, more recent data from the stations used in this study indicate a statistically significant ($P= 0.006$) positive correlation ($R^2= 0.51$) between mean annual rainfall and altitude (Fig. 2), and from linear regression an increase of 41.5 mm for every 100 m in altitude can be discerned between the lowest and highest altitude stations (Table 1).

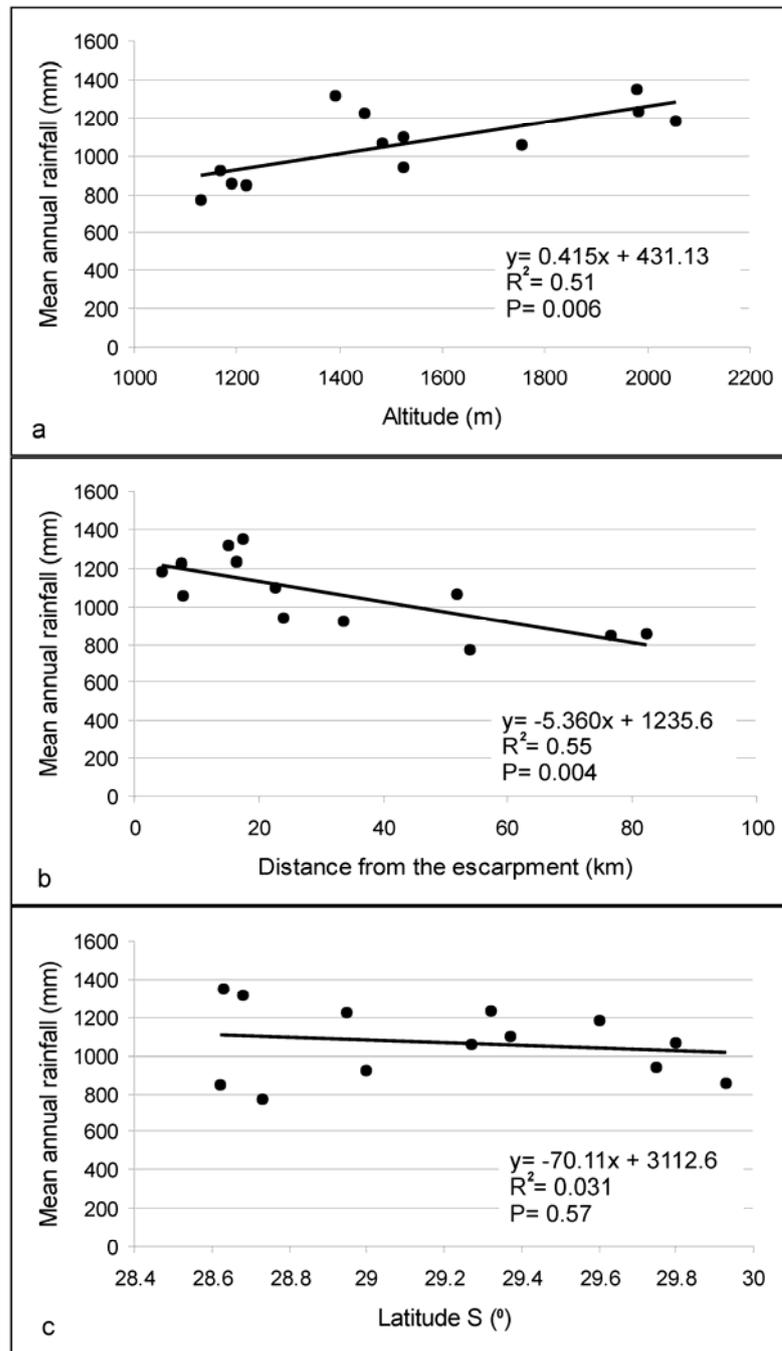


Figure 2: Relationship between mean annual rainfall in the KwaZulu-Natal Drakensberg and (a) altitude, (b) eastward distance from the escarpment and (c) latitude

A strong negative correlation ($R^2= 0.55$) also exists between annual rainfall at the stations and the station's eastward distance from the escarpment ($P= 0.004$) (Fig. 2). Linear regression shows that mean annual rainfall decreases by 54 mm for every 10 km from the escarpment. However, a significant correlation ($R^2= 0.47$; $P= 0.009$) also exists between station altitude and station distance from the escarpment (Fig. 3). This indicates that altitude decrease with an increase in distance from the escarpment in an eastward direction, which is understandable if the topography of the Drakensberg is taken into account (Fig. 1). It is unclear whether the two factors work collectively to affect rainfall totals in the Drakensberg, or if both altitude and the distance from the escarpment influence the spatial distribution of mean annual rainfall independently. Schulze (1979) notes through observations from rainfall maps that rainfall amounts appeared to be influenced by the distance from the escarpment although no mention is made of the correlation in the Drakensberg between altitude and distance from the escarpment.

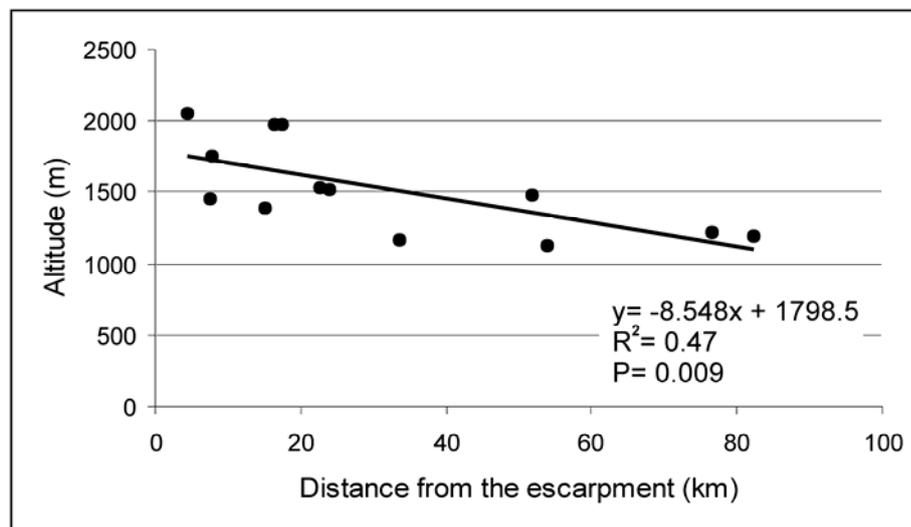


Figure 3: Relationship between altitude and eastward distance from the escarpment in the KwaZulu-Natal Drakensberg.

No significant relationship ($R^2= 0.031$, $P= 0.57$) is found between the latitude of rainfall stations in the Drakensberg and mean annual rainfall (Fig. 2). However, spatial trends in mean annual rainfall appear to be only affected by altitude and the eastward distance from the escarpment.

The five summer months (November to March) account for 75% of the annual rainfall, whilst winter months (May to August) contribute less than 10% (Table 2). This seasonality is also observed in the PCI values, which range between 14.3 and 16.5 (Table 1). Inter-annual rainfall variability, as calculated through the CV, is between 17.0% and 25.5%. The data indicate no statistically significant relationship between altitude and inter-annual rainfall variability, as calculated through the CV and the absolute deviation (Fig. 4). Altitude plays no significant role in affecting spatial trends of variability in the monthly distribution of rainfall in the Drakensberg, as calculated through the PCI (Fig. 4). As with altitude, no significant correlation exists between the eastward distance from the escarpment and inter- and intra-annual rainfall variability (Fig. 5).

Statistically significant linear trends are found when comparing rainfall variability to latitudinal position (Fig. 6). The CV and particularly the PCI show strong negative correlation with an increase in latitude. From linear regression, inter-annual variability as calculated through the CV decreases by 1.7% for every 0.5° increase in latitude ($R^2= 0.40$, $P= 0.02$) between 28.5° and 30°S . Absolute deviation shows the same linear trend, but the correlation is poor ($R^2= 0.18$) and not statistically significant ($P= 0.15$). Intra-annual rainfall variability, as calculated by the precipitation concentration index, shows a strong negative correlation ($R^2= 0.76$) that is significant at $P < 0.001$. The PCI decreases by 0.6 for every half a degree increase in latitude.

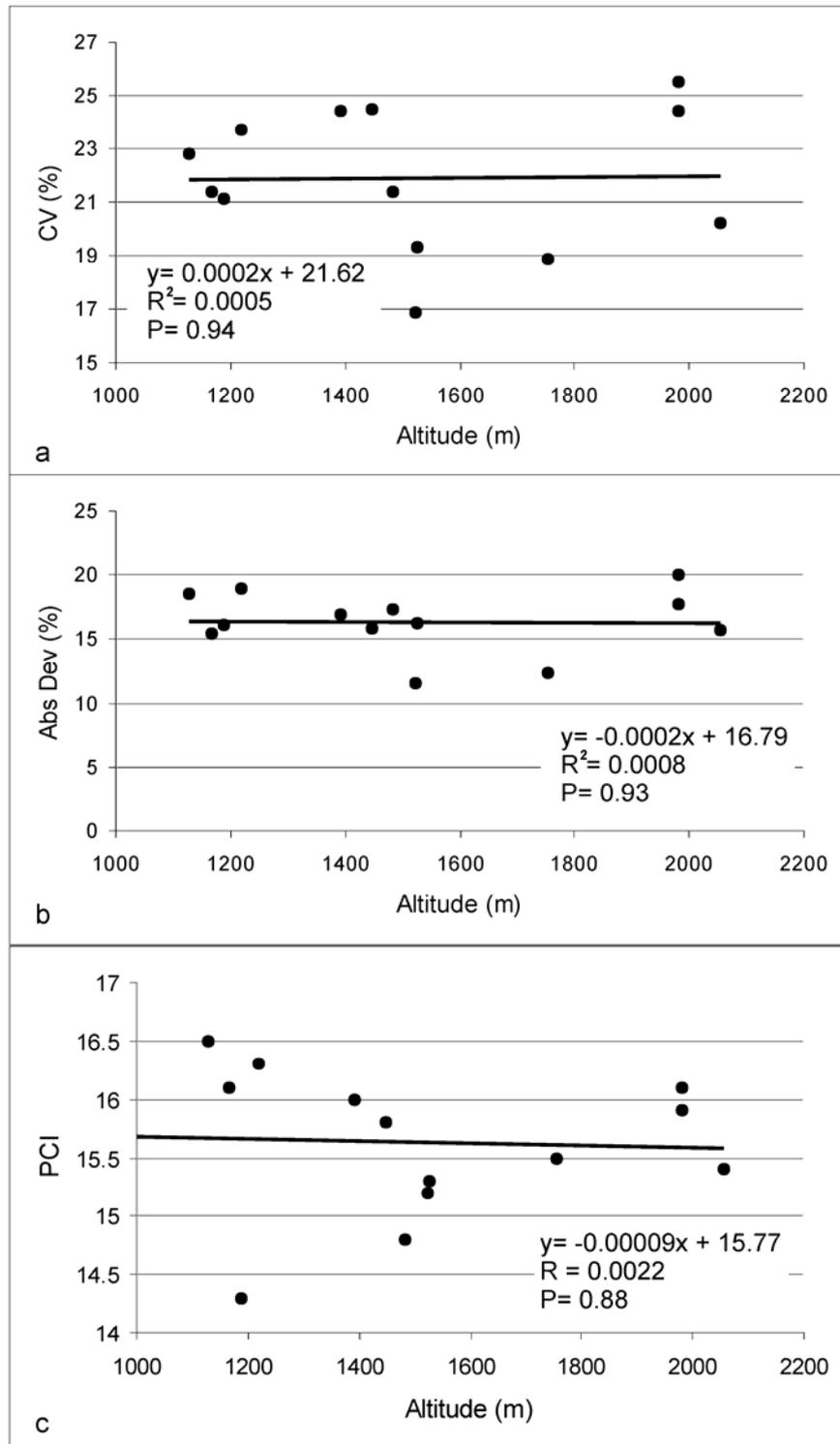


Figure 4: Relationship between altitude in the KwaZulu-Natal Drakensberg and (a) CV, (b) absolute deviation and (c) the precipitation concentration index.

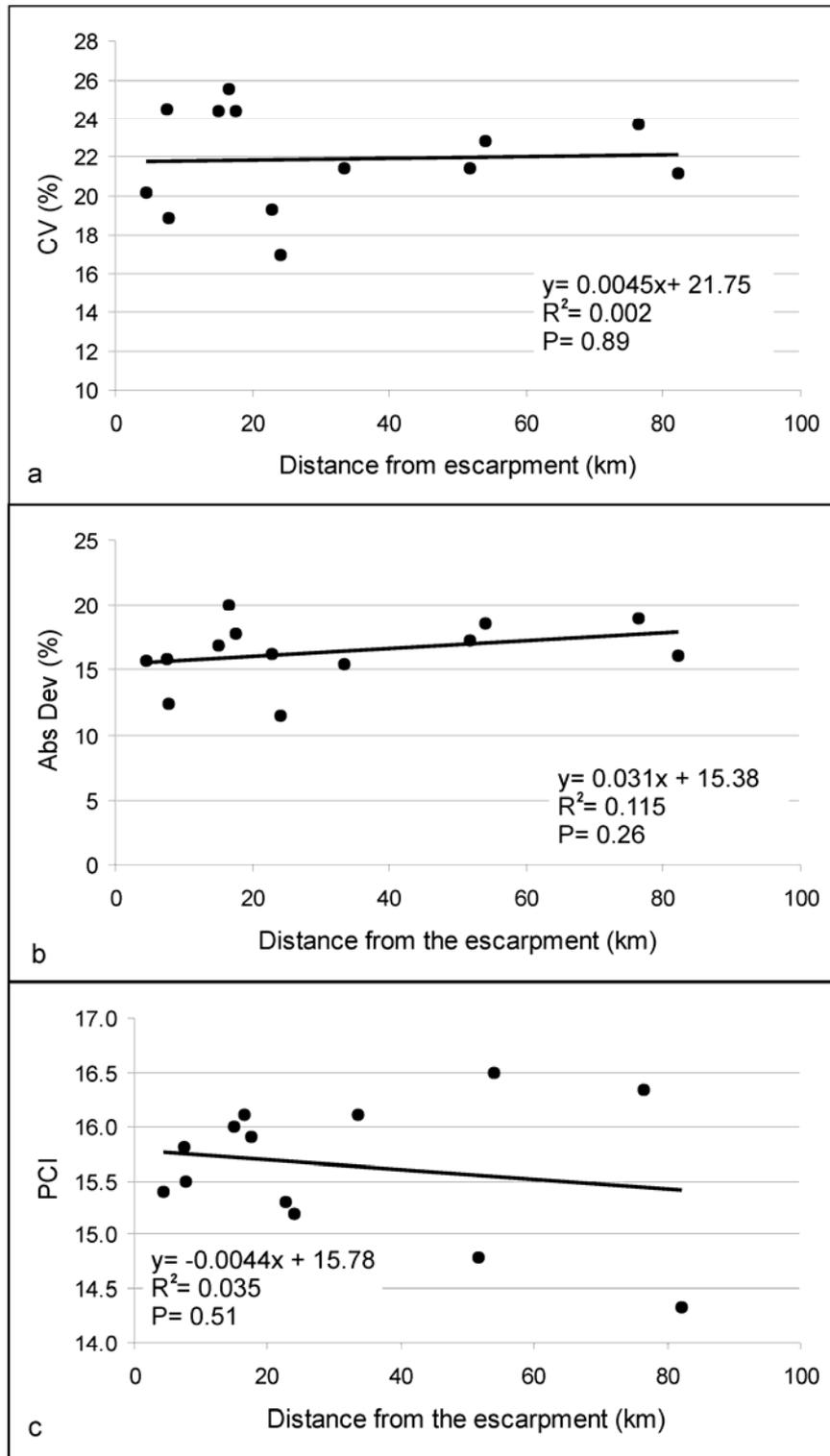


Figure 5: Relationship between eastward distance from the escarpment in the KwaZulu-Natal Drakensberg and (a) CV, (b) absolute deviation and (c) the precipitation concentration index.

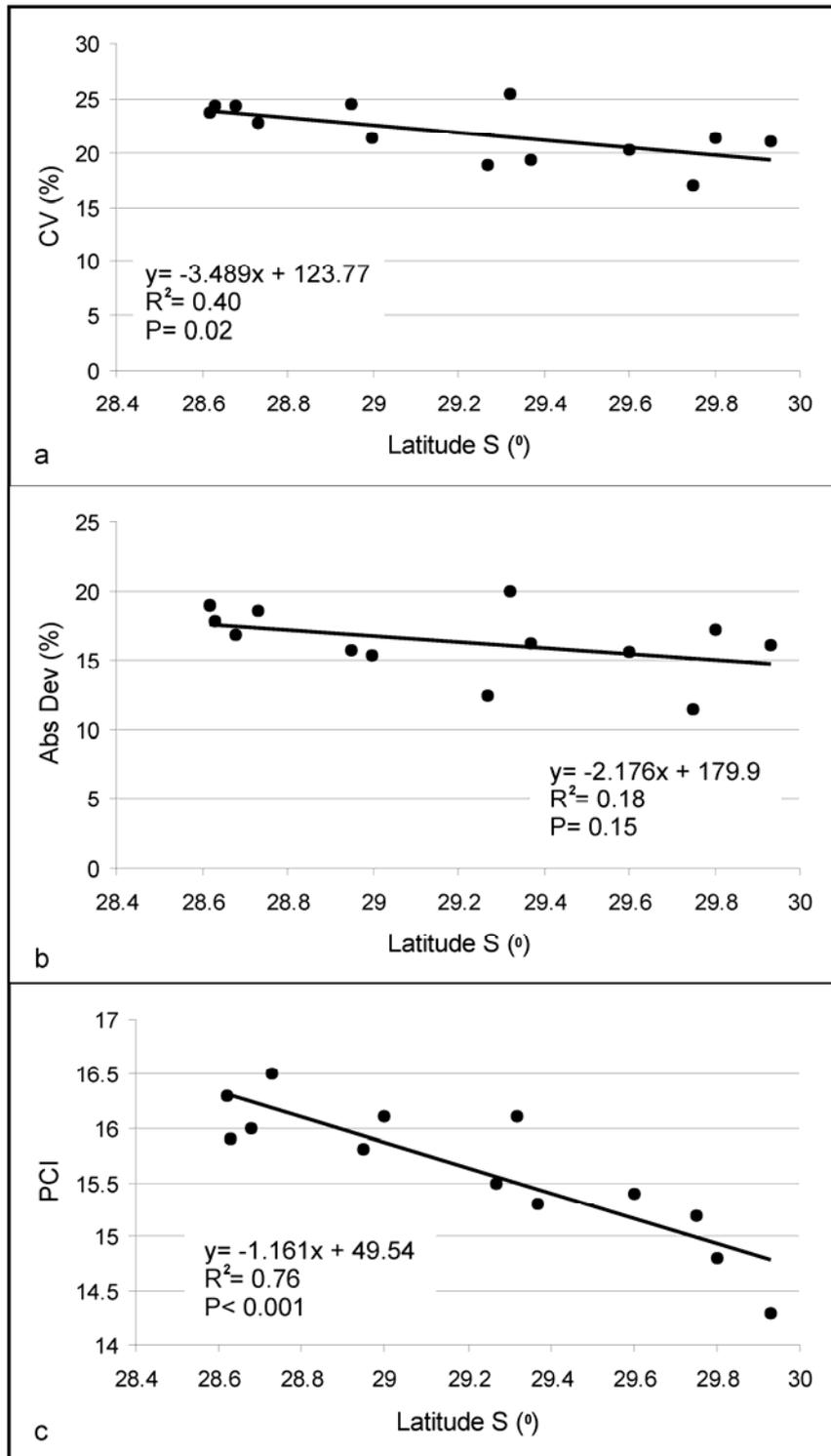


Figure 6: Relationship between latitudinal position in the KwaZulu-Natal Drakensberg and (a) CV, (b) absolute deviation and (c) the precipitation concentration index.

DISCUSSION

A general influence of physiography on the spatial distribution of mean annual precipitation has been long established. Spreen (1947) indicates that altitude accounts for 30% of the variation in mean seasonal precipitation in Colorado (USA), and in the southern Cape of South Africa, Whitmore (1968) showed that a regression equation, which used altitude, aspect, continentality and longitude, could explain most of the variation in mean annual precipitation. More recently, Johansson and Chen (2003) present highly significant relationships between daily precipitation amounts and orography in Sweden. Among the variables selected, the single most important is the location of a station with respect to a mountain range. In the Blue Ridge mountains in the southeastern USA, Konrad (1996) found no significant relationship between heavy rain frequency and elevation alone. In the highlands of Scotland, Prudhomme and Reed (1998) found similar results.

Below 2100 m a.s.l. in the Drakensberg, mean annual rainfall is strongly related to altitude and the location to the escarpment. Above 2100 m a.s.l. where no long-term data are available, the trend of increasing precipitation has been assumed to extend to the escarpment summit altitudes exceeding 3000 m, where rainfall is anticipated to exceed 1500 mm p.a. (Tyson *et al.*, 1976; Schulze, 1979). Similarly, in analysing rainfall trends in the Lesotho Highlands west from the escarpment, Sene *et al.* (1998) found that rainfall is also strongly related to altitude, but it is not clear whether the overall maximum rainfall occurs upwind of or over the crest of the escarpment. Recent data collected from the escarpment above 2800 m a.s.l. (Nel and Sumner, 2005) give lower precipitation values at the escarpment edge and challenge the assumption of increasing rainfall with altitude on the eastern side of the escarpment. Until more data are available, the trend for increasing rainfall towards the escarpment from the east can only be considered to apply to the region below 2100 m elevation as presented in this paper. Similarly, snowfalls and snow cover in the

Drakensberg appear independent of altitude, and there is a strong negative correlation ($r = -0.91$) between snow covered areas and westward distance from the escarpment (Mulder and Grab, 2002) in Lesotho. It is, therefore, suggested that for rainfall estimation in the Drakensberg, greater consideration be given to both the effect of distance from the escarpment, and the relationship between the distance from the escarpment and altitude.

Rainfall in the KwaZulu-Natal Drakensberg displays year-to-year variability, although no relationship between altitude, eastward distance from the escarpment and inter-annual rainfall variability in the Drakensberg is found. Annual rainfall in the Drakensberg is strongly seasonal, as noted in the PCI, with 75% of the annual rainfall occurring between the five summer months from November to March; a contribution that is marginally higher than the value of 70% calculated earlier by Tyson *et al.* (1976) for the period up to 1960. The winter months from May to August give a correspondingly lower total of 3% less than the earlier record of 10%. As with inter-annual rainfall, altitude and distance from the escarpment appears not to affect the variability in monthly distribution of annual rainfall.

A significant spatial trend in rainfall variability is present with regards the station's latitudinal position within the study area. Although this change in variability is not high the trend is significant and it indicates that variation in mean annual rainfall measured from year to year increases from the southern Drakensberg towards the north where the TUVA scheme relies on catchment rainfall in this area. The variability of rainfall does affect streamflow in the Drakensberg (Everson, 2001) with wet years giving higher discharge and dry years low continuous discharge throughout the year and an increase in rainfall variability could present an increase in cost and difficulty in the management of water resources and transfer schemes operating in this area. Latitude also influences the variability in the monthly distribution of annual rainfall as measured at the individual stations. As with inter-annual variability, the variability in the monthly distribution of annual rainfall increases with

decreasing in latitude. Winter rainfall in the Drakensberg is driven by frontal systems that move across southern Africa from the south west (Taljaard and van Loon, 1962; 1963). Rainfall in the southern Drakensberg even though seasonal, thus receives proportionately more rainfall in winter and hence the lower PCI value. Reasons for the higher inter-annual rainfall variability in the northern Drakensberg, however, are unclear. It is possible that orographic induced storms are more variable in the north and that the annual frequency of cold fronts that move north of 30° S are erratic, making the rainfall in the north more variable. More research, however, is required to assess the causes behind the spatial distribution of inter-annual rainfall variability.

CONCLUSION

This study analysed records on annual rainfall totals and intra- and inter-annual rainfall variability trends from 1970 to 2000 in the KwaZulu-Natal Drakensberg foothills and thus updates and extends aspects of the earlier assessments by Tyson *et al.* (1976) and Schulze (1979). Mean annual rainfall on the eastern side of the Drakensberg escarpment is affected by altitude, and this correlates well with findings from earlier work undertaken on the western side of the escarpment (Sene *et al.*, 1998). However, the findings from this study only apply to records obtained from stations below 2100 m a.s.l. and extrapolations of trends to the ecologically and hydrologically important higher catchment altitudes as done in the past do not appear feasible at this stage without further data. More consideration should be given to the eastward distance from escarpment when assessing rainfall totals and this is supported by recent research elsewhere that finds altitude is not necessarily the only important factor influencing rainfall in mountainous areas (e.g. Prudhomme and Reed, 1998; Johansson and Chen, 2003; Konrad, 1996).

In the KwaZulu-Natal Drakensberg, latitude apparently plays no significant role in influencing rainfall totals, but is found to be the single important factor influencing inter- and intra annual

rainfall variability. Rainfall variability increases from the southern Drakensberg to the north where the important TUVA scheme operates. The spatial trend could be related to increased winter frontal activity in the south or greater thunderstorm variability in the north but further research is required to discern the cause.

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**RAINFALL TRENDS IN THE KWAZULU-NATAL DRakensBERG REGION OF SOUTH
AFRICA DURING THE TWENTIETH CENTURY.**

Werner Nel

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ABSTRACT

This study assesses long-term rainfall records in the KwaZulu-Natal Drakensberg, South Africa's most valuable source of surface runoff. Records from 11 stations covering the Drakensberg region indicate that no statistically significant trend in interannual variability exists during the last half of the 20th Century. Mean annual rainfall in the Drakensberg is highly seasonal and analysis of monthly rainfall indicates an increase in the variability of the distribution of monthly rainfall and the strengthening of rainfall seasonality in the Drakensberg through a significant decrease in autumn rainfall. The El Niño/Southern Oscillation influences summer rainfall variability of the KwaZulu-Natal Drakensberg and a strong correlation also exist between summer rainfall and the Southern Oscillation Index for preceding periods. This correlation between summer rainfall and El Niño/Southern Oscillation events suggest that changes in the frequency and intensity of the El Niño/Southern Oscillation should affect the rainfall in the Drakensberg. The lagged correlation between summer rainfall in the Drakensberg and the Southern Oscillation Index could be used as an indicator for seasonal forecasting.

INTRODUCTION

South Africa is predominantly a semi-arid country; and it is only primarily areas in the east that record rainfall above 600 mm (Schulze, 1979). The KwaZulu-Natal Drakensberg is part of the Main Escarpment of southern Africa that extends as a passive margin around the sub-continent. Typically, the escarpment reaches above 2800 m to 3000 m and represents the watershed between the interior catchments of Lesotho and the shorter and steeper catchments of the rivers in KwaZulu-Natal. The province of KwaZulu-Natal contributes nearly twice as much total runoff per unit of rainfall than in South Africa as a whole and a quarter of South Africa's streamflow (Whitmore, 1970) (Fig. 1).

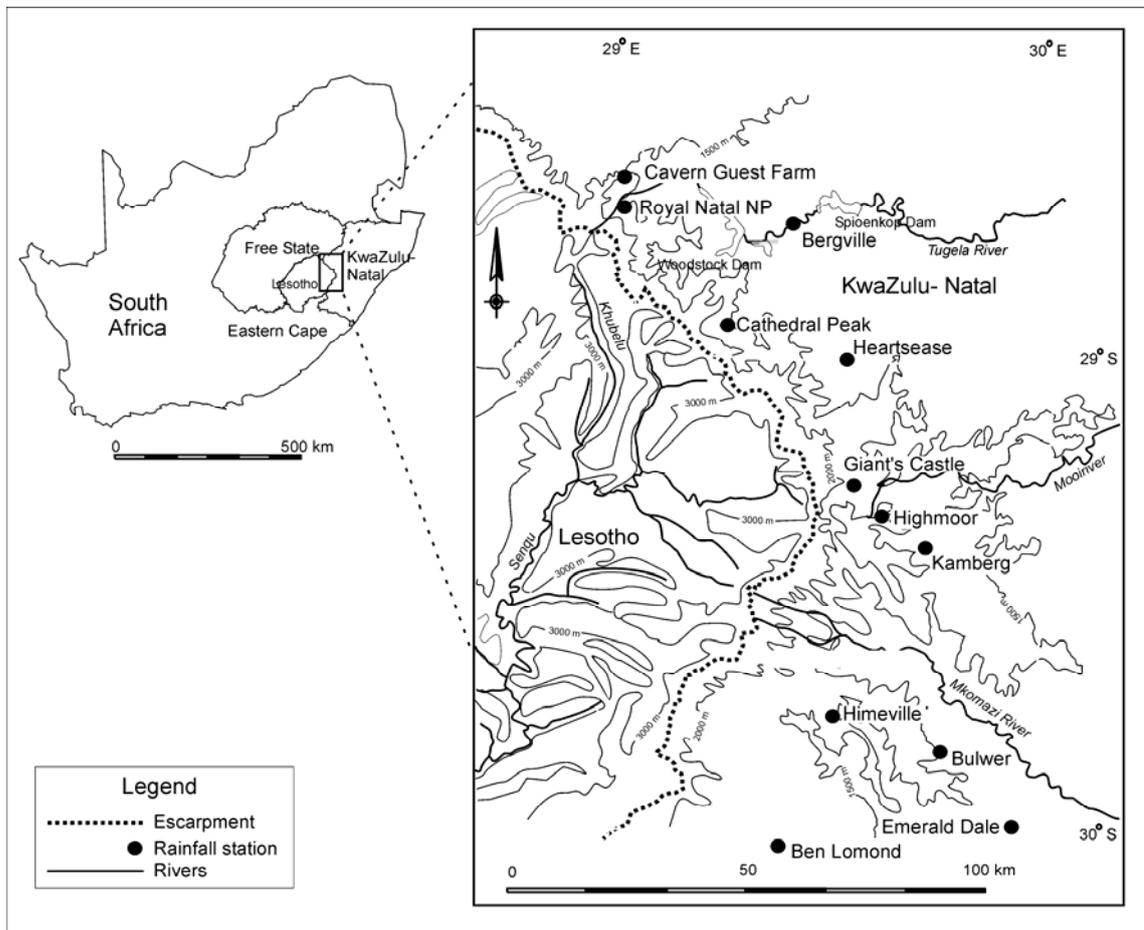


Figure 1: The KwaZulu-Natal Drakensberg region and locations of rainfall stations.

The amount of annual rainfall and its seasonal distribution are crucial factors for understanding the spatial distribution of different ecological units (Bailey, 1998). A whole set of systems such as soil typology and the intensity of geomorphological processes (Ceballos *et al.*, 2004), runoff generation (Winchell *et al.*, 1998), the timing and magnitude of streamflow events in large watersheds (Koren *et al.*, 1999) and the water balance of first order catchments (Everson, 2001) are all affected by rainfall variability. Rainfall trends are also important in the distribution and functioning of fauna and flora and influence for example the distribution and diversity of insects (e.g. Davis, 2002) population fluctuation of small mammals (Monadjem and Perrin, 2003) and the spatial and temporal patterns of vegetation (Fernandez-Illescas and Rodriguez-Iturbe, 2004). Also, population growth and industrial development in South Africa has placed increasing pressure on water resources (Mason and Jury, 1997). For example, in the Johannesburg area in the Gauteng province, South Africa's biggest city, water consumption has more than doubled over the last 30 years (Mason and Joubert, 1995) and it is still rising particularly in dry years (Mason and Jury, 1997). Gauteng province is the economic heartland of sub-Saharan Africa and contains 42% of South Africa's urban population, 50% of the nation's industry and generates 79% of all mining output (Nel and Illigner, 2001). It is predicted that the domestic and industrial water demand in Gauteng is to increase from 980 million cubic metres to 3800 million cubic metres per annum and such a demand will outstrip existing water resources (Waites, 2001). To address this resource problem and to supply water to Gauteng, two inter-basin transfer schemes, the Tugela-Vaal transfer tunnel (TUVA) and the Lesotho Highlands Water Project (LHWP) were developed to transfer water from KwaZulu-Natal and Lesotho to Gauteng (see Bell, 1999; Nel and Illigner, 2001, Waites, 2001). These water transfer schemes rely heavily on the upper catchment areas of the KwaZulu-Natal Drakensberg and Lesotho Highlands for its supply. In this context, rainfall in the mountainous areas is of primary significance because of the ecological importance of the Drakensberg, and also since the high altitude sub-catchments regulate discharge, particularly during low-flow conditions.

Even though the area is crucial for runoff generation, no studies have investigated the long-term trends of rainfall and rainfall variability for the Drakensberg region and only a few published assessments exist on total rainfall or rainfall variability for the area (for example Tyson *et al.*, 1976; Schulze, 1979). The aim of this study is to assess long-term rainfall records in the KwaZulu-Natal Drakensberg east of the escarpment. The study analyses the temporal trend of inter- and intra-annual rainfall variability of both annual and seasonal rainfall and the relationship between summer rainfall in the Drakensberg and its correlation to the El Niño/Southern Oscillation.

STUDY AREA AND DATA

Given the remoteness and inaccessibility of the eastern Lesotho highlands and the escarpment area, no long-term, reliable weather stations have been operating in the past few decades in this area and the study focuses on the records available from 11 selected South African Weather Services (SAWS) stations in the KwaZulu-Natal Drakensberg region east of the escarpment. The stations are well established, with long-term rainfall data covering most of the last century and provide a good geographical coverage of the Drakensberg between 28.5° and 30° S and 28.5° and 30° E longitude (Table 1, Fig. 1). At the stations, daily rainfall is manually measured from a standard raingauge at 08h00 by SAWS volunteers that include farmers, police officers and wildlife conservation personnel.

The major source of precipitation over the Drakensberg is large-scale line thunderstorms and orographically induced storms developing mostly over the extended summer period (Tyson *et al.*, 1976). Also, during winter, approximately 43 cold fronts affect KwaZulu-Natal annually (Grab and Simpson, 2000), which develop as closed low-pressure cells in the western Atlantic and move across southern Africa in a west-northwest to east-southeast direction (Tyson *et al.*, 1976) bringing widespread rainfall to the Drakensberg and occasional snow. The contribution of snow to the water budget in the Drakensberg is unknown. It is estimated

through observations that snow gives a water-equivalent of less than 100 mm per annum above the escarpment (Nel and Sumner, 2005). At lower altitudes precipitation falling as snow is minimal. Below 2100 m a.s.l. in the Drakensberg, mean annual rainfall is strongly related to altitude and the location to the escarpment (Nel and Sumner, 2006). Above 2100 m a.s.l. where no long-term data are available, the trend of increasing precipitation has been assumed to extend to the escarpment summit altitudes exceeding 3000 m, where rainfall is anticipated to exceed 1500 mm per annum (Tyson *et al.*, 1976; Schulze, 1979). Similarly, in analysing rainfall trends in the Lesotho Highlands west from the escarpment, Sene *et al.*, (1998) found that rainfall is also strongly related to altitude, but it is not clear whether the overall maximum rainfall occurs upwind of or over the crest of the escarpment. However, recent research suggests that the estimates of annual totals derived for altitudes above 2000 m a.s.l. may be overestimated and challenge the assumption of increasing rainfall with altitude above 2100 m on the eastern side of the escarpment (Nel and Sumner, 2005). At altitudes below 2100 m a number of more reliable long-term monitoring sites exist (Table 1) and it is these rainfall records that are analysed here.

Table 1: Spatial distribution of selected rainfall stations in the KwaZulu-Natal Drakensberg.

Rainfall Station	Historical record	Latitude (S)	Longitude (E)	Altitude (m a.s.l.)	Mean (mm)	CV (%)	PCI
Cavern Guest Farm	1947-2000	28° 38	28° 58	1980	1354.5	21.5	15.4
Royal Natal National Park	1948-2000	28° 41	28° 57	1392	1314.0	21.8	15.6
Bergville	1934-2000	28° 44	29° 21	1128	754.9	23.1	16.1
Cathedral Peak	1941-2000	28° 57	29° 12	1448	1260.9	21.5	15.6
Heartsease	1928-2000	29° 00	29° 30	1167	919.0	19.5	16.2
Giant's Castle	1948-2000	29° 16	29° 31	1754	1045.8	17.0	15.2
Highmoor	1955-2000	29° 19	29° 37	1981	1227.3	23.3	15.8
Kamberg	1955-2000	29° 22	29° 42	1525	1061.8	19.3	15.2
Himeville	1935-2000	29° 45	29° 32	1524	935.7	15.4	15.3
Bulwer	1955-2000	29° 48	29° 46	1484	1034.5	21.9	15.0
Ben Lomond	1921-2000	30° 06	29° 22	1432	848.7	16.9	15.0

TRENDS IN INTERANNUAL RAINFALL VARIABILITY

To study rainfall trends in the lowlands of Lesotho, Eckert (1980) computed a Lowlands rainfall series 1920/21-1978/79 as an arithmetical mean. Hydén, (1996) showed that this method gave almost identical results as with using weights as outlined by Thiessen (1911). In this context, to test for trends in annual rainfall, the data at each station for the period 1955-2000 were used to calculate an arithmetical mean for the region and this mean for each year was plotted (Fig. 2). Mean annual rainfall in the study area range from 750 mm to 1350 mm (Table 1), but no linear trend in mean annual rainfall in the Drakensberg from 1955 to 2000 is evident (Fig. 2).

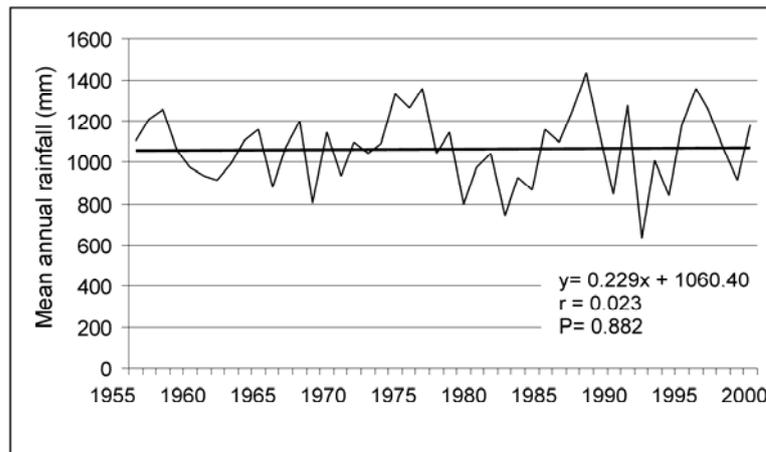


Figure 2: Time series of mean annual rainfall for eleven stations in the Drakensberg region for the period 1955 to 2000.

Analysis of annual rainfall as measured at the three longest running stations (Ben Lomond in the southern Drakensberg, Heartsease in the central and Bergville in the north) indicate that at Heartsease and Bergville a slight non-significant increase in annual rainfall over time exist

and the 2-year moving average of the annual rainfall shows cyclic oscillations between approximately 10 and 20 years (Fig 3). Much of the summer rainfall area of South Africa does experience a quasi 20-year rainfall oscillation and previous research has shown that the Drakensberg falls in the area that has rainfall oscillations between 16 and 20 years (Tyson *et al.*, 1975). Tyson *et al.*, 1976 also found minor rainfall cycles in the Drakensberg between 2 to 3 and 3 to 4 years and rainfall cycles of 3.5 to 6 years are also detectable over southern Africa, which are associated with the El Niño/Southern Oscillation phenomenon (Mason and Jury, 1997).

Interannual rainfall variability in South Africa is high with the coefficient of variation (CV) exceeding 40% in the dry western areas (Tyson, 1986). Previous research indicate that interannual rainfall variability in the Drakensberg region as calculated through the CV, range between 16.9 and 25.5% and decreases from north to south, possibly due to the greater seasonal contribution by frontal rains in the south or more variable annual storm activity in the north (Nel and Sumner, 2006).

To analyse the long-term trend in interannual rainfall variability at each station for the period 1955-2000, the absolute deviation of annual rainfall from mean annual rainfall (absolute deviation) were analysed (Fig. 4). The Pearson Product Moment Correlation parametric test as well as linear regression was applied to all data to discern any temporal trends with the related degree of significance. Even though all stations show an increase in the variability of annual rainfall measured from the mid 1950's to the end of the century, none of the linear trends of interannual rainfall variability are statistically significant at the 95% confidence level.

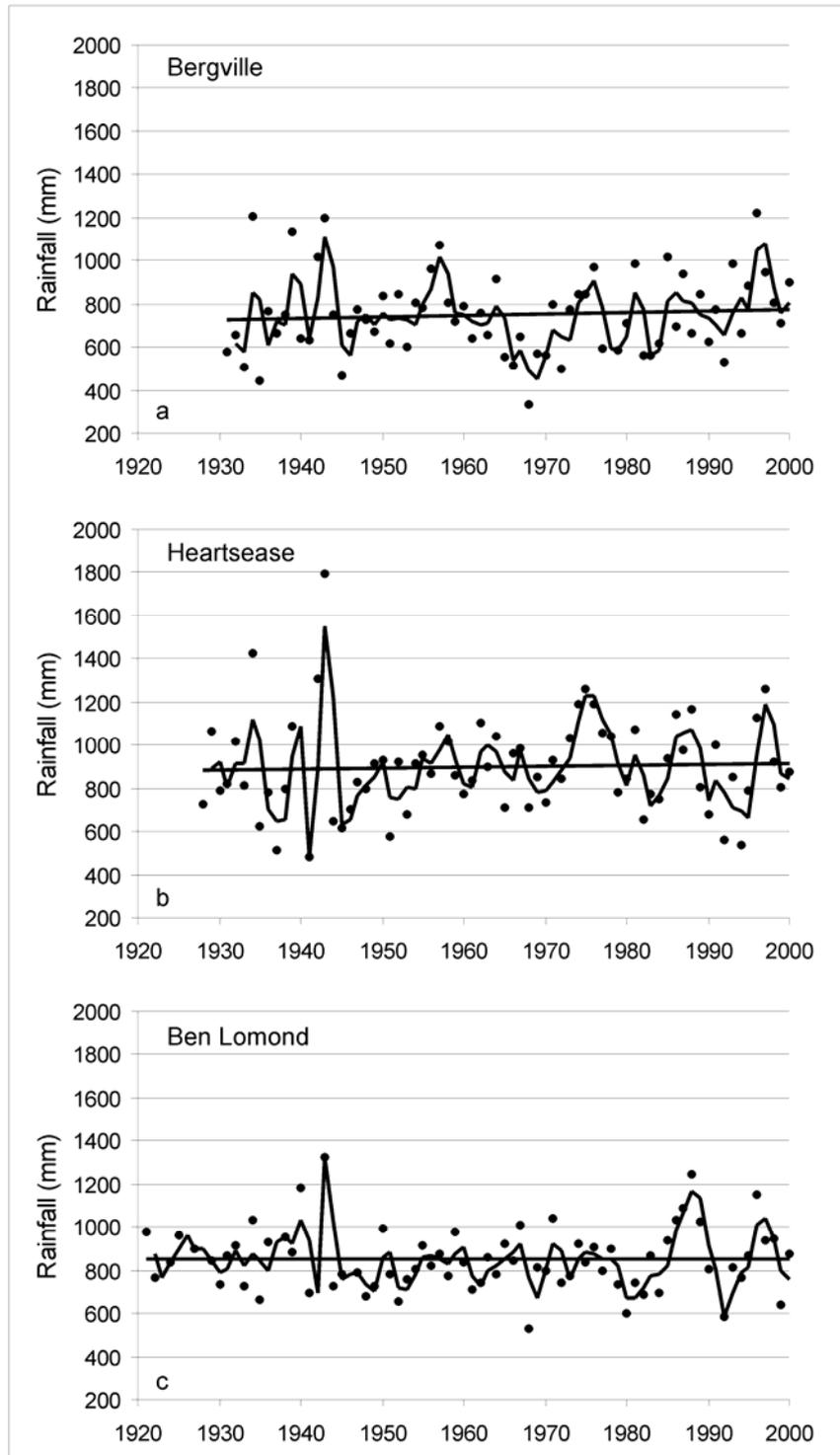


Figure 3: Linear trend and 2-year moving average of annual rainfall measured at a) Bergville, (b) Heartsease and (c) Ben Lomond.

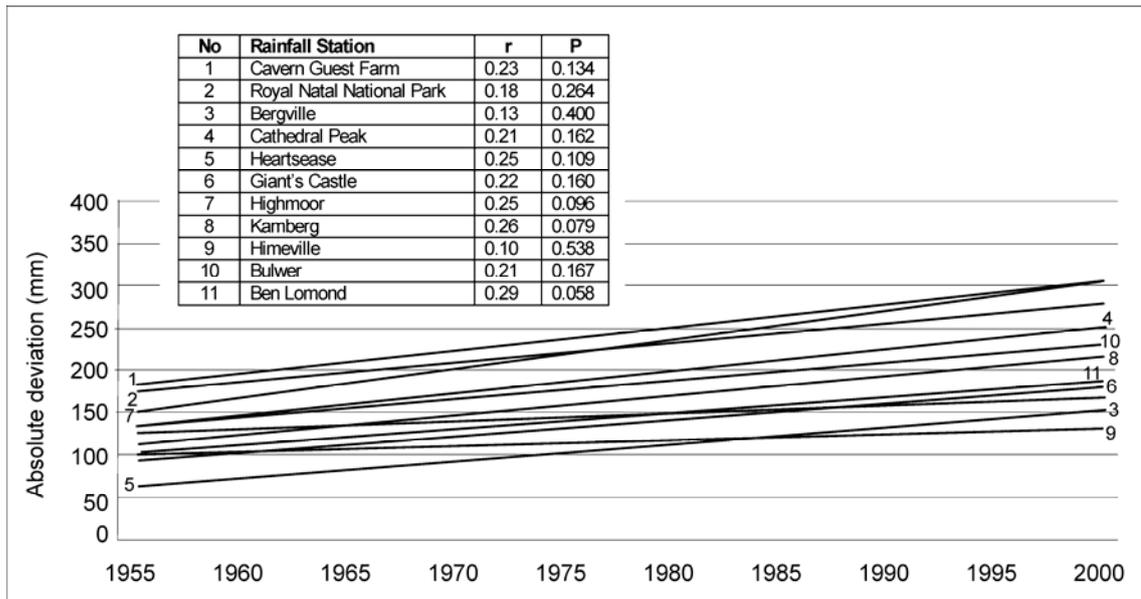


Figure 4: Linear trends of the absolute deviation of rainfall measured at each individual station for the period 1955 to 2000.

TRENDS IN INTRA- ANNUAL RAINFALL AND SEASONAL VARIABILITY

Rainfall in the Drakensberg is seasonal, and the seasonality can be described through the monthly rainfall totals as a percentage of the total annual rainfall (Nel and Sumner, 2006). However, to define the intra-annual variability and its temporal trends a modified version (De Luis *et al.*, 2000; Ceballos *et al.*, 2004) of the precipitation concentration index (PCI) was applied:

$$\text{PCI} = 100 \frac{\sum_{i=1}^{12} P_i^2}{\left(\sum_{i=1}^{12} P_i\right)^2} \quad (1)$$

where P_i is the precipitation of the month i . Values below 10 indicate a uniform distribution of rainfall throughout the year. PCI values from 11 to 20 indicate a seasonal trend and values above 20 indicate a considerable variability of the distribution of monthly rainfall (Ceballos *et*

al., 2004). Therefore, an increase in the PCI value over time indicates an increase in the variability of the distribution of monthly rainfall.

To analyse the long-term trend in intra-annual rainfall variability the PCI was calculated for each station from 1955 and the linear regression plotted (Fig. 5). Pearson correlation coefficient was applied to the station data to quantify any trends with the related degree of significance. All stations, except Bulwer, show an increase in PCI values from 1955 to 2000 indicating an increase in the variability of the distribution of monthly rainfall. The increase in PCI over time at Cavern Guest Farm, Giant's Castle, Highmoor and Kamberg stations are statistically significant at the 95% confidence level. From linear regression the PCI increased from 14.3 to 16.6 at Cavern Guest Farm, 14.2 to 17.2 at Highmoor and 14 to 16.5 at Giant's Castle and Kamberg from 1955 to 2000 (Fig. 5). An increase in PCI values indicates an increase in the seasonality of monthly rainfall in the Drakensberg. Since rainfall in the Drakensberg is strongly seasonal this increase in PCI values could suggest an increase in summer rainfall and a decrease in winter rainfall. To test the hypothesis of an increase in seasonality and to quantify the changes in seasonal rainfall the mean summer (November to March), winter (May to August), spring (September and November) and autumn (April) rainfall measured at each station for the period 1955-2000 was analysed and plotted for each year. As expected from the PCI an increase in summer and spring rainfall and a decrease in winter rainfall from 1955 can be observed (Fig. 6), but the trends are not significant. However, a statistically significant ($P= 0.009$) decrease in autumn rainfall can be discerned. In the Drakensberg region, rainfall falling during autumn decreased by approximately 30 mm from 1955 to 2000. However, it must be noted that the use of monthly values of rainfall to define a seasonal regime is "suspect" (Jackson, 1977) because the onset or end of a rainfall season, either on average or individual years seldom coincide with calendar months (Schulze, 1979). Since for this study only temporal trends are analysed this delimitation is purely a functional one.

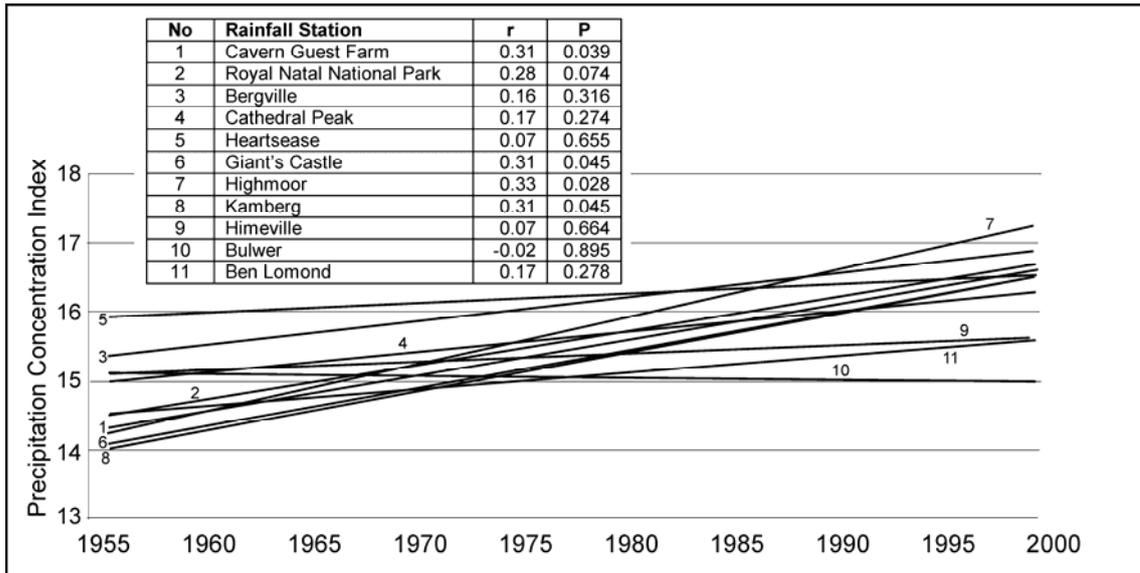


Figure 5: Linear trends of the Precipitation Concentration Index measured at each individual station for the period 1955 to 2000.

THE SOUTHERN OSCILLATION AND SUMMER RAINFALL

The Southern Oscillation influences the rainfall variability of the southern hemisphere and research has shown that the Southern Oscillation in turn is connected to the El Niño/La Niña phenomenon (Hydén and Sekoli, 2000). Many authors have studied the effect the El Niño/Southern Oscillation (ENSO) has on the Southern African rainfall. (eg. Lindesay *et al.*, 1986; Lindesay, 1988; Van Heerden *et al.*, 1988; Jury *et al.*, 1994; Mason, 2001) and that ENSO warm events (negative values of the Southern Oscillation Index) are frequently associated with less than average rainfall and drought over much of southern Africa (eg. Tyson, 1986; Ropelewski and Halpert, 1987; Janowiak, 1988; Van Heerden *et al.*, 1988; Mason and Jury, 1997). During an El Niño low phase (warm event) the cloud- band convergence zone moves offshore and with it the highest rainfall. Cold events (La Niña) as expressed by positive values of the Southern Oscillation Index (SOI) bring increased rainfall because of the location of the cloud band over southern Africa (Tyson and Preston- Whyte, 2000). For a full review of the mechanisms by which change in the tropical Pacific Ocean

affects the atmosphere over southern Africa see Mason and Jury (1997); Mason and Tyson (2000); Tyson and Preston-Whyte, (2000) and Mason (2001).

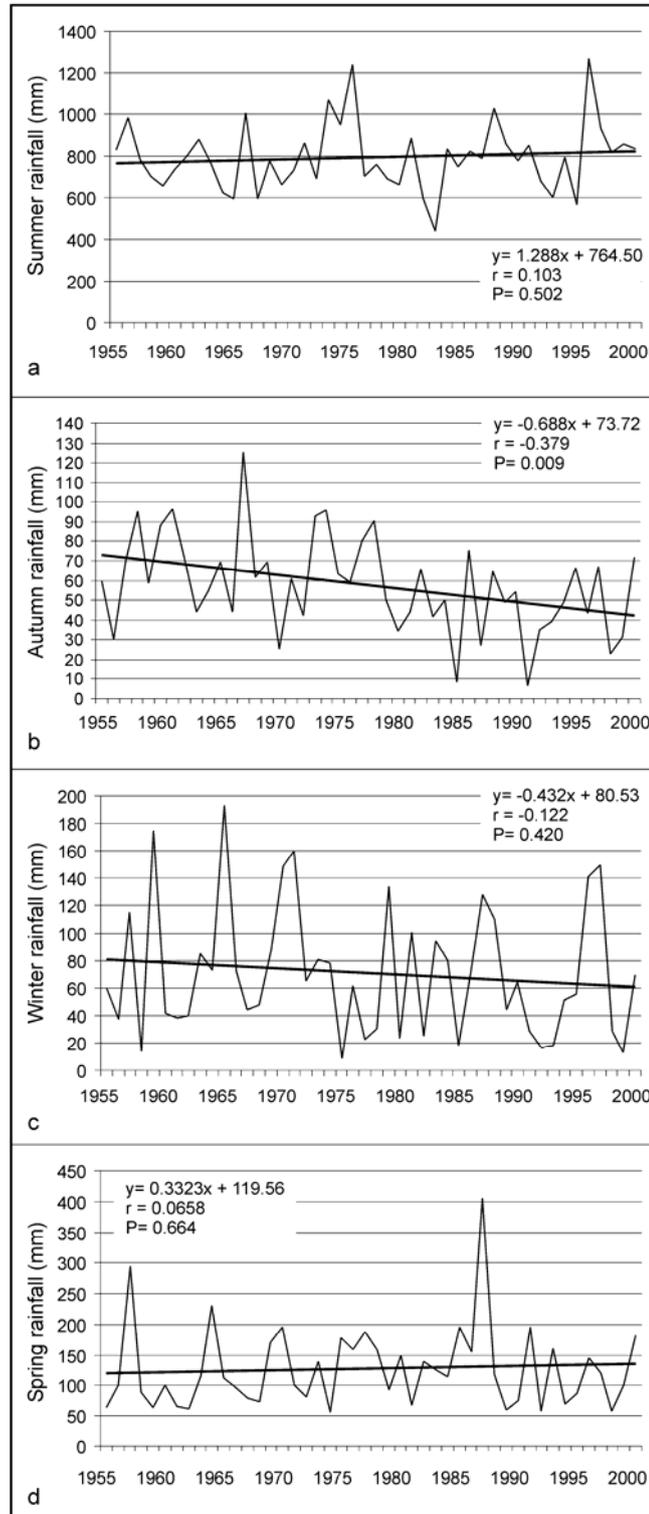


Figure 6: Time series and linear trends of (a) summer, (b) autumn, (c) winter and (d) spring rainfall for eleven stations in the Drakensberg region, 1955 to 2000.

The influence of ENSO events is strongest during the summer rainfall months of December to March when the El Niño/La Niña events have reached maturity (Mason and Jury, 1997). Van Heerden *et al.* (1988) found a strong relationship between summer monthly SOI values and corresponding summer monthly rainfall in South Africa. These findings make it likely that there exist a simultaneous, non-lagged relationship between the ENSO and rainfall in Southern Africa (Hydén and Sekoli, 2000). However, due to this persistence of the ENSO equally significant correlations were found between winter three-month mean SOI values and individual summer month district rainfall (Van Heerden *et al.*, 1988). This indicated that lagged correlation between the SOI and summer rainfall existed. Hydén and Sekoli, (2000) successfully used this lagged correlation to forecast early summer rainfall from preceding months SOI values in the Lesotho lowlands.

To investigate the effect the ENSO has on summer rainfall totals in the KwaZulu-Natal Drakensberg, the regional summer rainfall (November to March) has been determined annually for the period 1955-2000 as an eleven station arithmetical mean. To calculate the SOI, the method used by the Australian Bureau of Meteorology is the Troup SOI, which is the standardised anomaly of the Mean Sea Level Pressure difference between Tahiti and Darwin. The SOI data were retrieved from the Internet on February 21 2005 from the Australian Bureau of Meteorology's website. To test if there is a non-lagged relationship between summer rainfall and the SOI the average of November to March SOI was compared with the summer rainfall (November to March) of the Drakensberg region (Table 2). The Pearson Product Moment Correlation parametric test was applied to test the strength of the relationship with the related degree of significance. A statistically significant correlation ($r=0.52$, $P=0.003$) exists between summer rainfall in the Drakensberg region and the contemporaneous SOI (Table 2). Also, summer rainfall correlates well ($r=0.54$, $P=0.002$) with spring and early summer SOI (September to January). To forecast early summer rainfall from SOI values in the Lesotho lowlands, Hydén and Sekoli (2000) assume that one-month is needed to model the forecast, distribute the results and act on them. Therefore, the SOI

was computed for preceding periods lagged at least one month. A similar methodology was used to test if there is a lagged relationship between the SOI and the summer rainfall in the Drakensberg and if this correlation is strong enough to be used as an indicator for seasonal forecasting (Table 2). All lagged correlations that were tested are significant for $P < 0.01$. The correlation coefficients between summer rainfall and preceding months are all above 0.4 (except May+Jun+July+Aug+Sept SOI) with the highest lagged correlation ($r = 0.50$) from the four months preceding the start of the summer rainfall season (July to October).

Rainfall period	Period of SOI values (non- lagged)	r	P	
November-March	Nov+Dec+Jan	0.52	0.0003	
	Nov+Dec+Jan+Feb+Mar	0.52	0.0003	
	Period of SOI values (lagged)			
	May+Jun+Jul+Aug+Sep	0.39	0.0076	
	Jun+Jul+Aug+Sep	0.44	0.0022	
	Jun+Jul+Aug+Sep+Oct	0.47	0.0012	
	July+Aug+Sep	0.47	0.0010	
	Jul+Aug+Sep+Oct	0.50	0.0006	

Table 2: Correlation coefficient r with the relevant level of significance P between regional summer rainfall and the mean SOI values for certain periods.

DISCUSSION AND SUMMARY

Mean annual rainfall in the study area range from 750 mm to 1350 mm and no increase or decrease in mean annual rainfall during the last half of the 20th century in the Drakensberg could be discerned. However, annual rainfall does show cyclic variation of between 15 and 20 years. This compares well with previous findings (Tyson *et al.*, 1975; Tyson *et al.*, 1976) that suggest that the Drakensberg falls in the area that has a quasi 20-year rainfall oscillation. Historical records indicate that interannual rainfall variability over South Africa is increasing (Mason, 1996) but in the Drakensberg region all stations show a non-significant change in variability of annual rainfall. Mean annual rainfall is highly seasonal with 75% of the total rainfall measured during November to March and although no change in annual

rainfall can be discerned in the Drakensberg (1955-2000) an increase in the variability of the distribution of monthly rainfall can be seen. The increase in PCI over time at four stations in the Drakensberg region is statistically significant at the 95% confidence level and indicates an increase in the seasonality of monthly rainfall in the Drakensberg. Trend analysis of the four different rainfall seasons indicates a statistically significant decrease of rainfall during autumn. In the KwaZulu-Natal Drakensberg the active crop-growing season is from October to April (Schulze, 1979). If this decrease in autumn rainfall persists it could affect the late crop-growing season in this crucial area.

The Southern Oscillation influences the summer rainfall variability of the KwaZulu-Natal Drakensberg with a strong statistically significant correlation existing between summer rainfall in the Drakensberg and the contemporaneous SOI. This correlation between summer rainfall and ENSO events suggest that an increase in the frequency and intensity of ENSO should negatively affect the rainfall in the Drakensberg. Due to the persistence of the SOI (Hydén and Sekoli, 2000), there also exists a statistically significant correlation between summer rainfall and the SOI for preceding periods lagged at least one month. The highest lagged correlation ($r= 0.50$) between summer rainfall and SOI is obtained from the SOI values for July to October. This is in the same order as the correlation found by Hydén and Sekoli (2000) between November and December rainfall in the Lesotho Lowlands and the SOI values of July to September ($r= 0.51$). The lagged correlation between summer rainfall in the Drakensberg and SOI could be used as an indicator for seasonal forecasting.

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