Changes in rainfall pattern in the eastern Karoo, South Africa, over the past 123 years

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ABSTRACT

Rainfall is a key driver of ecosystem processes, especially vegetation dynamics, in semi-arid regions. Rainfall amount, including droughts and extended wet periods, seasonality, and, possibly, concentration, influence vegetation composition in the eastern Karoo. A monthly rainfall record of 123 years from Grootfontein was analysed to search for evidence of cyclicity in rainfall amount, seasonality, and concentration. Rainfall was substantially higher during the late 1800s and after 1990 than it was during the rest of the 20th century. Extended sequential below-average runs of years characterised the drought periods of the early 20th century and the 1960s. There was strong evidence of an approximately 20-year rainfall cycle, except for spring rain. Additionally, annual and seasonal rainfall showed evidence of a longer cycle, between 44 and 77 years, which may be related to the southern oscillation index. The additive effects of the two cycles described annual and seasonal rainfall with R^2 values typically > 0.5. Rainfall seasonality was also related to the longer-term cycle, while rainfall concentration showed some evidence of having entered a new, more concentrated state since 1988. The analysis reveals that rainfall at Grootfontein is not a random process, but rather appears driven by cyclical processes. Rainfall at the site is predicted to decline over the next approximately 20 years, and the high levels of variation and complex causal factors will make it difficult to discriminate between natural variation and possible effects of climate change on rainfall.

Keywords: semi-arid, rainfall concentration, rainfall seasonality, periodicity, cyclicity

INTRODUCTION

Rainfall is a primary driver of the structure, composition and functioning of semi-arid vegetation communities (Gentry, 1988; Anderson et al., 2007; Belsky, 1990). In semi-arid rangelands rainfall amount may be highly variable over years and decades, although seasonal patterns (e.g., wet summers) may be relatively predictable. High rainfall variability can lead to droughts, which can significantly alter community composition through the die-off of plants (Westoby et al., 1989). Extended periods, rather than single years, of above-average rainfall may induce significant ecological changes, such as the recruitment of woody plants (Kraaij and Ward, 2006), or increased grassiness leading to increased likelihood of fire (Scholes et al., 2003). In the eastern Karoo, South Africa, vegetation composition is strongly related to rainfall amount and seasonality (Roux, 1966; Roux and Vorster, 1983; Hoffman et al., 1990; O'Connor and Roux, 1995). Rainfall amount in semi-arid regions increases plant growth, and rainfall seasonality is a potentially strong driver of vegetation composition in the eastern Karoo (Roux, 1966; Roux and Vorster, 1983; O'Connor and Roux, 1995) because of the differential response of plant growth forms (importantly C_3 shrub and C_4 grass forms) to water availability across seasons (Epstein et al., 1997). Similarly, rainfall concentration (how rainfall is distributed over the year) may control vegetation composition to some extent, as low-concentration rainfall (rainfall spread across much of the year) would presumably favour perennial plants that grow more or less continuously, while high-concentration rainfall (rainfall concentrated within a few months) would favour plants adapted to long periods of dry weather such as succulents and ephemerals. Therefore, changes in rainfall amount, seasonality, and concentration in the eastern Karoo would be expected to have a marked influence on vegetation and ecosystem functioning. Furthermore, understanding cyclical or directional changes in rainfall parameters, especially in the face of predicted increases in rainfall variability (Mason et al., 1999) and amount (Hewitson and Crane, 2006), is necessary for understanding and managing this ecosystem.

In Africa, considerable research effort has been focused on identifying patterns in rainfall over time, and particularly cycles, at continental (Nicholson, 2000), regional (e.g. Tyson, 1971 in South Africa), and local (e.g. Gertenbach, 1980 in the Kruger National Park) scales. In South Africa a range of short-period cycles, in the order of 2–7 years, have been identified (Vines, 1980; Jury and Levey, 1993; Kane, 2009), although of greater interest has been a cycle with a period of approximately 20 years (Tyson, 1971; Dyer, 1975; Dyer, 1976; Hall, 1976; Dyer and Tyson, 1977; Vines, 1980; Jury and Levey, 1993; Alexander et al., 2007; Kane, 2009). Because data series are limited in length (usually <100 years), identifying cycles with a longer period is often impossible, although Kane (2009), using data from 1990, did find evidence of 32–35 and 55–66 year cycles for parts of South Africa. Rainfall patterns have been linked to the Southern Oscillation Index (SOI) (Nicholson and Entekhabi, 1986; Kane 2009), and the sunspot cycle (Dyer, 1976; Thresher, 2002; Alexander et al., 2007), or a combination of the two (Stager, 2007). Sunspots have been identified as having an 11-year cycle, while frequencies ranging from months to a few years (Nicholson and Entekhabi, 1986; An and Wang, 2000), 10–15 years (Sun and Yu, 2009), and 12–20 years (Torrence and

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Webster, 1999) have been found for the SOI. Additionally, the amplitude (variance of the signal) of the SOI signal varies at decade-level time scales (Gu and Philader, 1995).

The Grootfontein Agricultural Development Institute (Grootfontein hereafter) lies in the transition zone between the Nama-Karoo (dwarf shrubland) and Grassland biomes in South Africa (Mucina et al., 2007). The boundary between the two biomes is determined mainly by rainfall amount, and possibly season (Rutherford and Westfall, 1994; Mucina and Rutherford, 2006). Therefore, vegetation might shift between Nama-Karoo and Grassland over time, depending on rainfall. A directional change would be anticipated to induce a single biome shift, while rainfall cyclicity might induce alternating biome states. Monthly rainfall data, including the occasional precipitation from snow, have been recorded at Grootfontein since 1888. This record provides a valuable resource for interpreting long-term rainfall, especially within the context of vegetation change which has been monitored on several long-term grazing trials at the site. Site-specific descriptions of rainfall are necessary for interpreting changes in vegetation at that site, considering the high variations in rainfall that can exist among even nearby locations (Kane, 2009).

The aim of this research was to describe ecologically relevant rainfall patterns that have occurred at Grootfontein from 1888 to 2011 in order to provide context for concomitant vegetation changes. We posed the following questions:

- Is there evidence of a directional trend or of cycles in (i) the amount of rainfall and (ii) the seasonality and concentration of rainfall, at Grootfontein?
- Are rainfall parameters correlated with the SOI?

METHODS

Site description

Grootfontein, an agricultural research and training institute developed in 1911, lies in the Eastern Upper Karoo (Mucina et al., 2007). The vegetation is grassy dwarf shrubland dominated by annual and perennial C_4 grasses that grow primarily during summer, and mainly perennial C_3 shrubs that grow throughout the year (other than in mid-winter) depending on water availability.

Rain falls mainly during mid- to late-summer, with March usually recognised as the wettest month (Venter and Mebrhatu, 2005). Average annual rainfall is typical of a semi-arid summer rainfall area in South Africa; O'Connor and Roux (1995) report an annual average of 361 mm, with approximately 27% of the total falling during the cooler months of April to September. For the period 1916–2008, 68 of 86 years (79%) experienced rainfall of between 200 and 500 mm, and 58% of years had below-average rainfall (Du Toit, 2010). In summer, days are warm to hot (30–35°C) and nights are moderately warm (10–16°C). Autumn days are warm (18–23°C) and nights are cool (6–10°C), with occasional light frosts occurring toward the end of the season. Winter days are moderate to warm (14–25°C) and nights are cold (−4–4°C) with frosts common. Temperatures as low as −10°C are usually experienced once or twice in winter. Spring days are warm to hot (28–31°C) and nights are cold to cool (2–8°C). Frosts usually continue until the middle of October. Light snow falls occasionally (absent most years), with heavier snowfalls having been recorded several times over the past century. Rainfall and temperature patterns combine to give 4 basic seasons: a very cold, dry winter, a warm, relatively dry spring, a hot and sometimes wet summer, and a warm and relatively dry autumn. The year can also be divided into a warm season during which grass growth is favoured, and a cool season during which the growth of dwarf-shrubs is favoured (Roux and Vorster, 1983).

Rainfall data set

Rainfall data for Grootfontein (31.4709° S, 25.0286° E) were derived from 3 sources, spatially all within several hundred meters of each other and therefore proximate enough to be treated as a single location. Van Meerten (1927) provides monthly rainfall data from 1888–1926. The South African Meteorological Office provides daily rainfall data from 1916–1997 and from 2004–2008. Grootfontein provides monthly rainfall data from 1995–2012. Periods of overlap provide an opportunity to compare the similarity of the different sets of data on a monthly basis from 1916 to 1926, and 2004 to 2008. A paired t-test was conducted to compare monthly rainfall estimates from 2 sources. For 2004 to 2008, there was no difference between the estimates for the South African Meteorological Office (mean = 32.66, SD = 34.14) and for Grootfontein (mean = 34.03, SD = 33.56) records (t_{81}=-0.721, p=0.473). For 1916 to 1926, there was no difference between the estimates for the Van Meerten (1927) data (mean = 28.95, SD = 34.93) and for South African Meteorological Office (mean = 28.44, SD = 34.24) records (t_{132}=-0.597, p=0.552). Owing to the

TABLE 1
Aggregation of monthly data into seasons of various resolutions of rainfall data at Grootfontein. Within cells horizontal lines circumscribe when the seasons start and finish

<table>
<tr><th>Period</th><th>Jul</th><th>Aug</th><th>Sep</th><th>Oct</th><th>Nov</th><th>Dec</th><th>Jan</th><th>Feb</th><th>Mar</th><th>Apr</th><th>May</th><th>Jun</th></tr>
<tr><td>Spring[1]</td><td></td><td></td><td>|—</td><td>—</td><td>—|</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Summer[1]</td><td></td><td></td><td></td><td></td><td></td><td>|—</td><td>—</td><td>—</td><td>—|</td><td></td><td></td><td></td></tr>
<tr><td>Autumn[1]</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>|—</td><td>—|</td><td></td></tr>
<tr><td>Winter[1]</td><td>—</td><td>—|</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>|—</td></tr>
<tr><td>Cool[2]</td><td>—</td><td>—</td><td>—|</td><td></td><td></td><td></td><td></td><td></td><td></td><td>|—</td><td>—</td><td>—</td></tr>
<tr><td>Warm[2]</td><td></td><td></td><td></td><td>|—</td><td>—</td><td>—</td><td>—</td><td>—</td><td>—|</td><td></td><td></td><td></td></tr>
<tr><td>Annual[3]</td><td>|—</td><td>—</td><td>—</td><td>—</td><td>—</td><td>—</td><td>—</td><td>—</td><td>—</td><td>—</td><td>—</td><td>—|</td></tr>
</table>

[1] *Spring rainfall (September to November of Year t), Summer (December of Year t – March of Year t+1), Autumn (April to May of Year t), and Winter (June to August of Year t).*
[2] *Warm season rainfall (October of Year t to March of Year t+1) and Cool season rainfall (April to September of Year t).*
[3] *Annual rainfall (July of Year t to June of Year t+1; hereafter, a nominal year of, e.g., 1908, refers to rain from July 1908 to June 1909)*

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similarity of the rainfall during the periods of overlap, an uninterrupted monthly rainfall record was constructed from 1888 to 2012 comprising data from Van Meerten (1927) from 1888 to 1916, the South African Meteorological Office from 1917 to 1997, and Grootfontein from 1998 to 2012.

Data analysis

Rainfall seasons

Rainfall data were analysed at a range of resolutions comprising monthly, seasonal (4 divisions (spring, summer, autumn, winter) and 2 divisions (warm, cool)), and annual (TABLE 1). Seasonal and annual periods were defined on account of their relation to plant growth.

Patterns and trends in rainfall amount

To describe trends over time (increases and decreases within or across the data), time-series analysis using polynomial regression was conducted on original rainfall data, specifically for each of the months of September–April inclusive (May to August were excluded because of large numbers of zero values), all seasons (summer, autumn, winter, spring, cool, warm) and annual. First- to fourth-order polynomials ($a + bx + cx^2 + dx^3 + ex^4$, or subsets) were fitted to the data. Higher order models were excluded to avoid overfitting. If more than 1 model was significant (p<0.05), models were selected using Akaike Information Criterion (AIC) values and F-tests. F-tests are appropriate because simpler models here are subsets of more complex models. Either a significant AIC test or a significant F-test warranted the acceptance of a model. Data were not transformed to achieve normality because (i) parametric comparisons were not being made, (ii) transformation would increase the likelihood of a Type 1 error, and (iii) transformation of data would likely result in a reduction of biological realism, because rainfall in semi-arid areas is approximately linearly related to primary plant production.

Unusually long runs of above- and below- average rainfall were calculated, where the probability (P) of an event (an above- or below-average year (x)) occurring sequentially a certain (i) number of times is given as:

$$\overset{i}{P}_x = \left(\frac{n_x}{N_x} \right)^i$$

, where n is the number of events over at total of N years.

Therefore, the number of consecutive events relating to a certain value of P is:

$$i = \frac{\log_{10}(P_x)}{\log_{10}\left(\frac{n_x}{N_x} \right)}$$

Hence, the number of consecutive years of above- or below-average rainfall corresponding to a particular value of P can be calculated, and P values of 0.05 and 0.01 correspond to unusually long runs above or below the mean (1 run in 20 years, and 1 run in 100 years, respectively). The calculated value of i, usually having a decimal component, was rounded up to the nearest integer. This renders the actual P-value slightly lower than the nominal P-value. The number of consecutive years corresponding to the nominal P values was calculated for all seasons and months for above- and below-average rainfall.

Rainfall seasonality and concentration

The time of year at which rainfall peaks (assuming unimodal rainfall, as is the case at Grootfontein) is termed the seasonality. Rainfall usually peaks in mid- to late-summer at Grootfontein. Rainfall concentration is a measure of how rainfall is spread over the year: a concentration of 100% would mean that all rain fell in 1 month, and a concentration of 0% means that all months receive equal amounts of rain (Schulze, 1997). Rainfall season ((1)) and concentration ((2)) are calculated using the technique of Markham (1970), where rainfall amount has a magnitude (in mm), and each month has a direction (position on an arc; in degrees). Concentration values are expressed in terms of mean annual precipitation of the period in question (precipitation concentration index, (3)). Changes in seasonality and concentration over time were calculated using values derived from a 15-year running average.

$$\theta_t = \tan^{-1} \frac{\sum r_i \sin\theta_i}{\sum r_i \cos\theta_i} \quad (1)$$

$$r_t = \sqrt{\left(\sum r_i \cos\theta_i\right)^2 + \left(\sum r_i \sin\theta_i\right)^2} \quad (2)$$

$$P_c = r_t / MAP * 100 \quad (3)$$

where:

θ_t is the time of year (expressed as a direction, in degrees)
r_i is the average monthly rainfall for month i
θ_i is the month (expressed as a direction, in degrees), for each month
r_t is the rainfall concentration
P_c is the precipitation concentration index
MAP is mean annual precipitation

Rainfall periodicity

Spectral analysis is a method commonly used to reveal the temporal frequency at which single or multiple cycles within a time series occur (Dyer, 1975). Monthly and seasonal time series data, as well as annual SOI time series data, were smoothed using a binomial filter of the order 5 (Dyer, 1976). These were subjected to spectral analysis, for which 118 terms were used. Fisher's Kappa statistic was calculated to determine whether the series was simply 'white noise' or had some periodic component (Addinsoft, 2013).

Sine wave regression functions comprising 3 parameters ((4)) were fitted to rainfall and SOI data (annual and seasonal) filtered with a 10-year simple moving average and normalised to have a mean value of zero. The three parameters in the equation, a, b, and c, reflect amplitude (height of a peak), period (distance between peaks), and shift (position of the wave along the x-axis) of the wave function. Regressions were accepted as statistically significant if the overall model and each of the three coefficients were $p \leq 0.05$.

Where spectral analysis provided evidence of multiple cycles, a more complex double-wave cosine function ((5)) was fitted to the data to explore whether the data showed evidence of two overlaid cycles (Dyer, 1976). More complex models were accepted based on AIC values.

$$y = a \sin\left(\frac{2\pi x}{b} + c \right) \quad (4)$$

$$y = a + b\cos\left(\frac{2\pi x}{c} + d \right) + e\cos\left(\frac{2\pi x}{f} + g \right) \quad (5)$$

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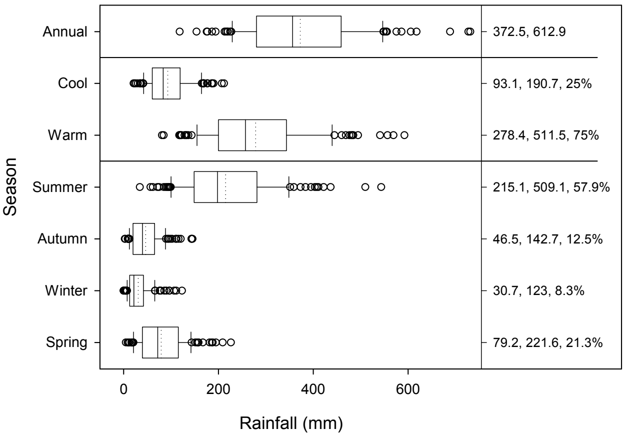

Figure 1
Box and whisker plot of annual rainfall at Grootfontein using 3 resolutions. Boxes bound the 25th and 75th percentiles and show the median (solid line) and mean (dotted line). Whisker bars bound the 10th and 90th percentiles, and outliers are shown as dots. Comma-separated numbers are the mean, range, and per cent contribution to the total average rainfall, respectively.

RESULTS AND DISCUSSION

Rainfall seasons

Average annual rainfall was 372 mm with a wide range, typical of semi-arid areas, from 118 (in 1907) to 731 mm (in 1890) (Figure 1). Average cool season rainfall (93 mm) is approximately one third that of the average warm season rainfall (278 mm). Sixty-eight percent (68%) of the total annual rainfall falls in summer, with the next wettest season being spring. Winter rainfall is approximately 10 mm per month. For all seasons and all months the mean rainfall is higher than the median, reflecting the typical positive skewness of rainfall data in semi-arid regions.

Rainfall amount

Significant trends over time, explaining between 13 and 19% of the variation, were evident for January, 'summer', 'warm season', and 'annual' (Figure 2). In all cases 4th order polynomial models best described the trends (TABLE 2). The most general pattern that emerges is a 'W' shape, where rainfall was high during the late 1800s (annual average = 459 mm from 1889 to 1898), low for the first third of the century (annual average of 319 mm from 1899-1937), rose slightly in the middle of the century (annual average of 401 mm from 1938–1952), dipped until the mid-1980s (annual average of 353 mm from 1953–1984),

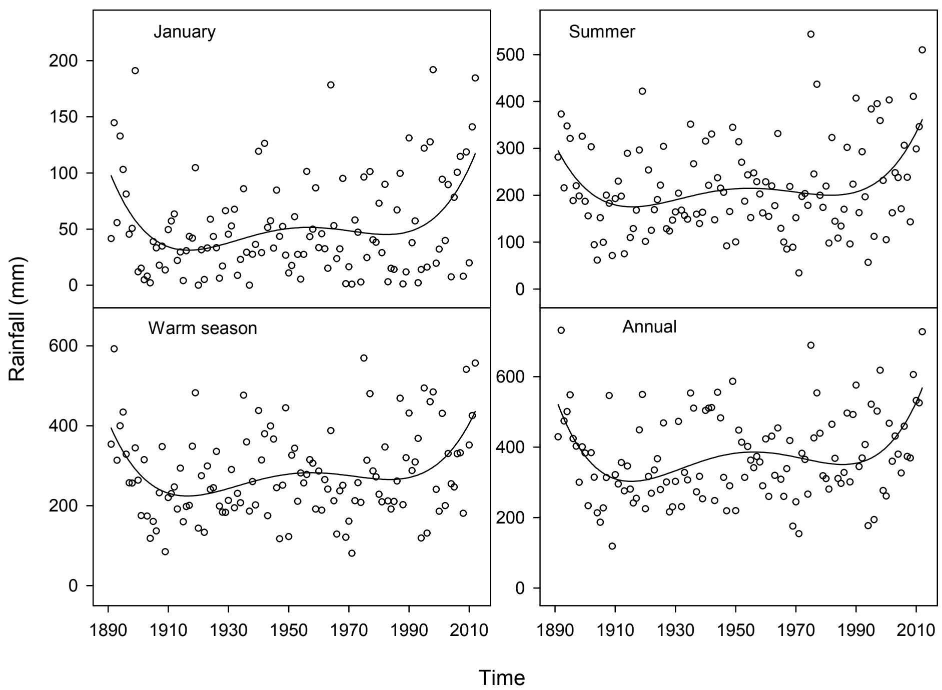

Figure 2
The four time periods that exhibited significant trends over time in rainfall at Grootfontein. Lines are 4th-order polynomial regressions (see TABLE 2 for details).

TABLE 2
Regression and test statistics of polynomial distributions fitted to months September–April, all seasons, and to annual rainfall data at Grootfontein. Only significant regressions are presented.

Model parameters ($y=a + bx + cx^2 + dx^3 + ex^4$)									Comparison with next best model (based on AICC)			
Data	a	B	c	d	e	F ratio	P	R^2	Δ AICC	*P* (AICC)	F ratio	*P* (F ratio)
Jan	104.4	–6.927	0.2187	-2.600×10^{-3}	1.049×10^{-5}	5.38	<0.001	0.155	4.54	0.09	4.36	0.015
Summer	307.4	–13.00	0.4250	-5.220×10^{-3}	2.150×10^{-5}	4.62	0.002	0.136	3.12	0.17	3.64	0.03
Warm	411.4	–17.87	0.5665	-6.702×10^{-3}	2.681×10^{-5}	5.30	<0.001	0.125	5.17	0.07	4.69	0.01
Annual	543.8	–23.78	0.773	-2.600×10^{-3}	2.150 x 10	6.71	<0.001	0.187	10.45	0.01	7.49	<0.001

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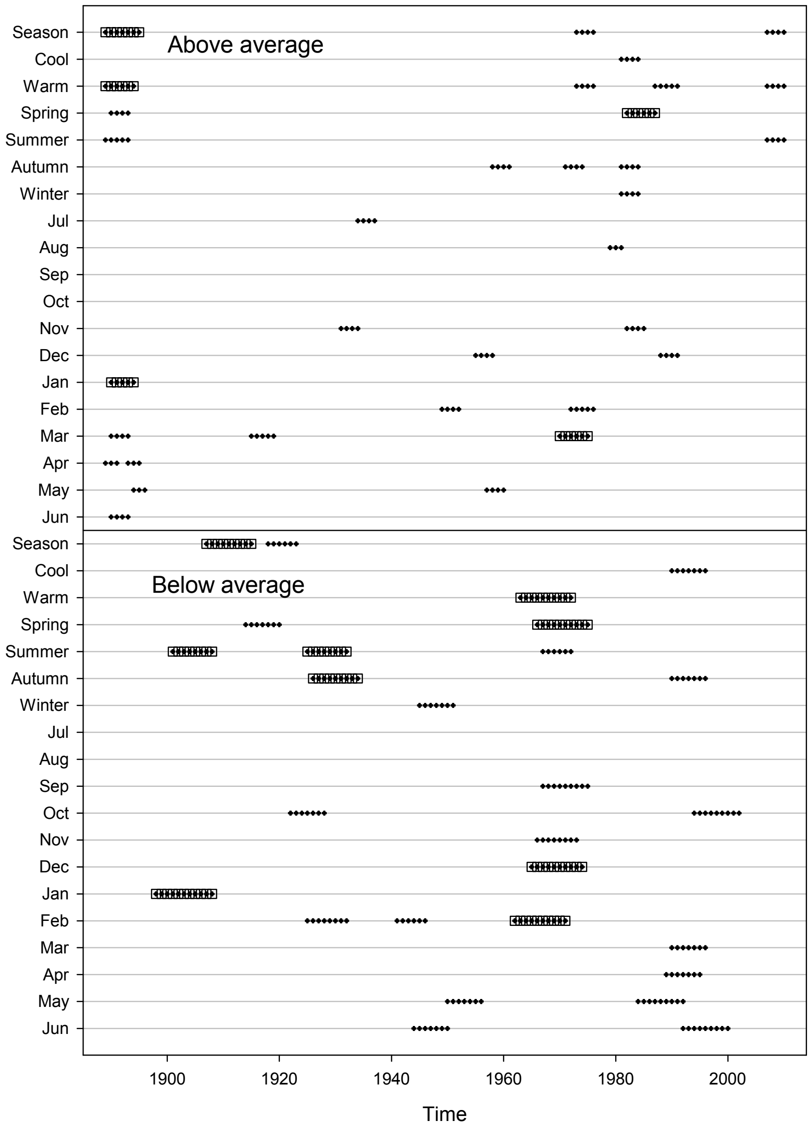

Figure 3
Unexpectedly long above- or below-average runs for seasons and months at Grootfontein. Boxes are p<0.01 (1 in 100 years) and plusses are p<0.05 (1 in 20 years). See text for details.

and rose again until present day (annual average of 426 mm from 1985–2010) (Figure 2). The month of January appears to be important in determining wet years, and this in turn contributes to high totals for 'summer', 'warm', and 'annual' seasons. Of the 20 highest totals for January, 14 (70%) occurred either during the 1890s or since 1985.

Notably, linear regression analysis ($y=ax + b$) revealed that there were no significant directional trends (although all were positive) for any months or seasons or for annual rainfall over time (all $p>0.08$), consistent with Kane (2009). Dealing with a data set of shorter duration (1881–1950), Vorster (1959) submitted that rainfall in the Karoo was in net decline; similarly a regression of data from 1950 to current day would indicate a directional increase. This highlights the importance of recognising the time horizon needed to assess possible climate change impacts on rainfall.

Unusually long above- or below-average runs were found for all seasons and all months (Figure 3). The high rainfall of the end of the 19th century is clearly evident during summer (January), autumn (March–May), and winter (June). The high rainfall of the late 1800s reflects good rains over much of the country at that time (Tyson and Dyer, 1975). There were scattered above-average runs during the 1970s, generally considered to be a wet decade, while the high 21st century rainfall is associated with above-average 'summer' runs, but not with individual months.

A near-continuous run of below-average years from 1907 to 1923 reflects the droughts that occurred during that period, which at the time prompted an in-depth investigation by the South African Government (Drought Investigation Commission, 1923). Before the respite of the mid-century, further below-average 'summer' and 'autumn' runs, associated with particularly dry Octobers and Februarys, took place from 1925 to 1934. The 1960s was in general a dry decade, with long runs of low-rainfall, 'warm', 'spring', and 'summer' seasons (see also Tyson and Dyer, 1978). While the 1980s are well recognised as a decade of drought (e.g. Nicholson, 1989), there were few long runs of dry years, probably owing to interjections of high rainfall events such as Cyclone Domoina (Mason et al., 1999).

Spectral analysis identified the frequencies of cycles for various seasons and SOI (Figure 4). For 'spring', 'autumn', 'winter', 'warm', 'cool', and 'annual' seasons, the strongest signal was somewhere between 40 and 60 years, which is consistent with findings of Kane (2009). For 'summer', the strongest signal was around 20 years, consistent with the findings of various authors (Tyson, 1971; Jury and Levey; 1993; Kane, 2009), with a

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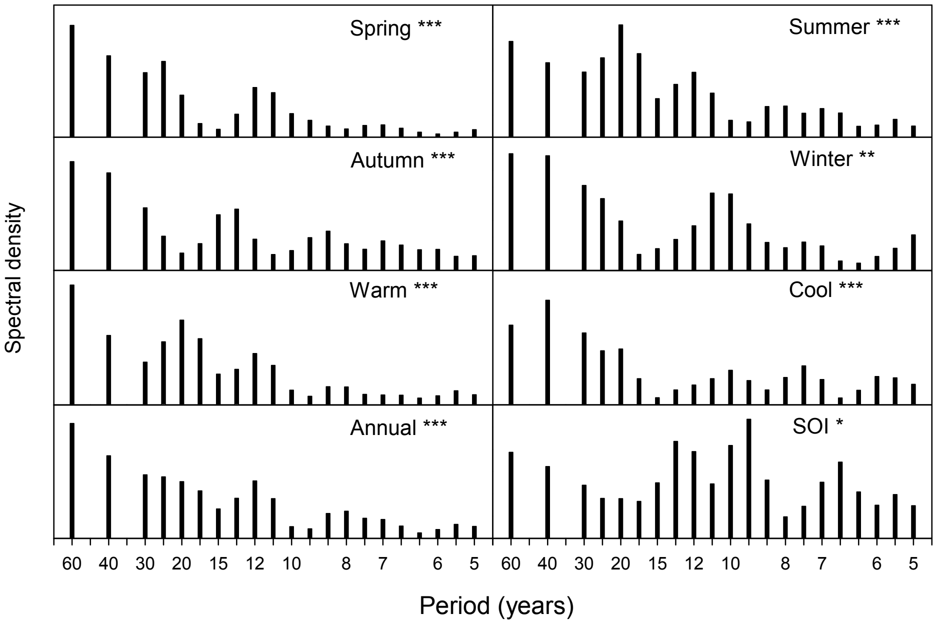

Figure 4
*Variance spectra for climate parameters (rainfall and SOI). Superscripts reflect the probability of the time series being 'white noise', as estimated by Fisher's Kappa statistic (ns: p>0.05; *: 0.01<p≤0.05; **: 0.001<p≤0.01; ***: p≤0.001).*

secondary signal at 60 years. The SOI data also showed a signal at around 60 years, with other signals at about 13 and 9 years.

Rainfall cycles were apparent in annual rainfall and during all individual seasonal classes, and for the SOI (Figure 5). For all seasons other than spring, a double-wave cosine model provided a better fit, and was statistically more acceptable based on AIC values (for all models p<0.001). In all cases, the shorter cycle lay between 18 and 24 years, consistent with the approximately 20-year cycle found by others. The longer cycle ranged from 44 to 77 years, which is in general agreement with Kane (2009). These findings are consistent with the prediction of Dyer (1975) that several interacting cycles may influence southern African rainfall. Evidence of a long-term cycle of 44 years was suspected by Dyer (1975) for winter rainfall in South Africa, although that data record was too short to be certain. This may correlate with the winter rainfall here (43.5 years).

This record is 123 years which allows the longer cycle to be identified, but its magnitude remains unclear. For example, for annual rainfall a short-term cycle of 21.7 years and a long-term cycle ranging from 45 to 80 years (the approximate range of long-term cycles found over all seasons) provide statistically significant (p<0.02) fits to the data (Figure 6). This indicates that a long-term cycle, in the order of 45–80 years, may be common to all seasons, and this correlates to similar fluctuations in the SOI. Long-term correlations between rainfall and SOI have been found elsewhere (e.g. Nicholson and Entekhabi, 1986).

Rainfall seasonality and concentration

Seasonality of precipitation fluctuated over time, with peak rainfall ranging from 23 December (in 1993) to 7 February (in 1973). Until 1970, peak

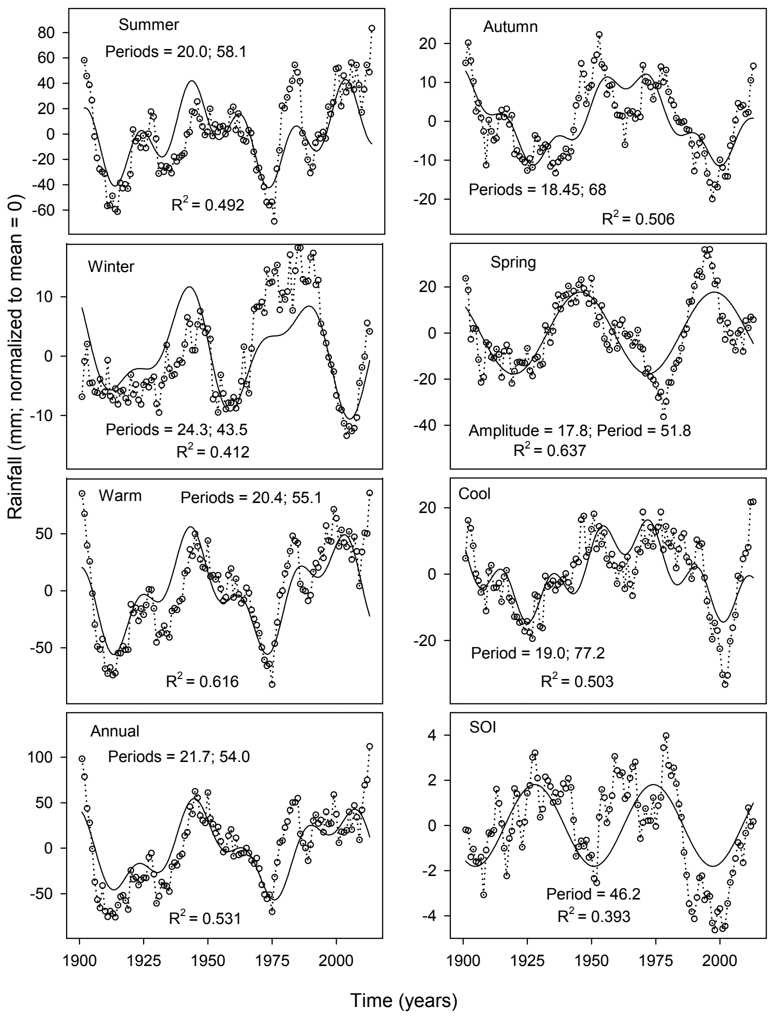

Figure 5
Rainfall and SOI data filtered using a 10-year simple running mean (open markers and dotted lines) fitted with single sine or double cosine wave regressions (solid lines). All regressions and all parameters' coefficients are significant (all F-values>21.7; all p<0.0001). Each dot represents the previous 10 years' data.

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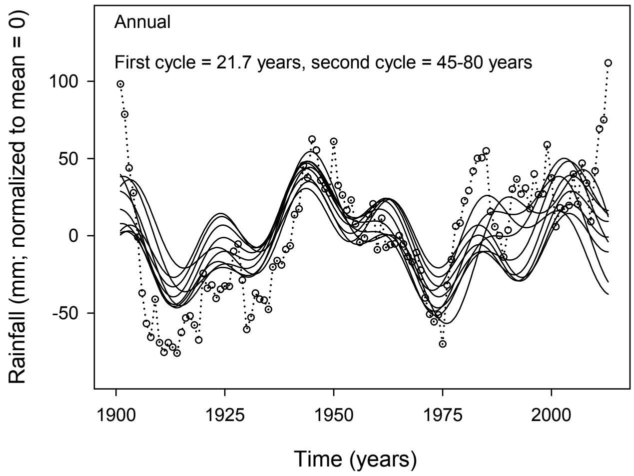

Figure 6
Annual rainfall data filtered using a 10-year simple running mean (open markers and dotted lines) fitted with double cosine wave regressions (solid lines) with a constant short-term cycle and a long-term cycle ranging from 45–80 years. All regressions are significant (all F-values>2.6; all p<0.02). Each dot represents the previous 10 years' data.

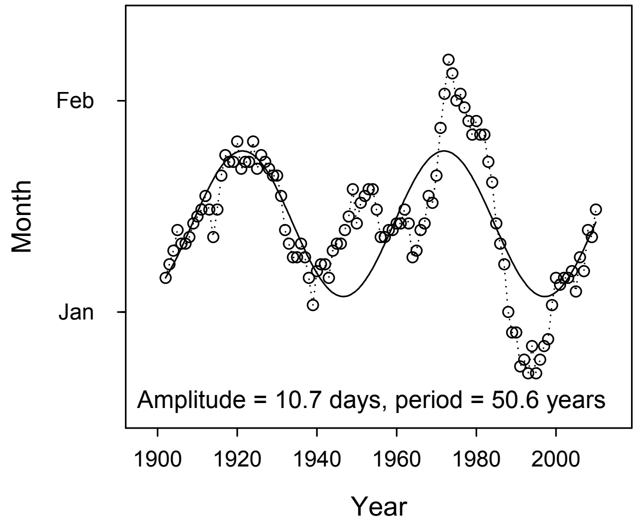

Figure 7
Rainfall seasonality over time. Each point reflects average values from the previous 15 years. The solid line is a sine wave regression ($F_{2,106} = 72.0$, $p<0.0001$, $R^2 = 0.576$).

rainfall was always during January; during the mid- to late-1970's the rainfall season shifted into February, followed by a sharp shift over during the late 1970s and 1980s to a late-December season. More recently, rains have returned to a mid-January season (Figure 7). The frequency of the cycle (50.6 years) is in general agreement with the long-term cycles found for rainfall amount and SOI (Figure 5).

Segmented regression analysis revealed two distinct trends in rainfall concentration over time (Fig. 6). First, concentration decreased slightly over time until 1988, whereafter it increased rapidly ($F_{1,106} = 81.3$, $p<0.01$). This indicates that before 1988 rainfall became progressively but slowly more evenly spread over the year but since then it has become more concentrated. There is also evidence that there is a cycle to rainfall concentration of approximately 26 years, although this value does not match the cycles of seasonal rainfall.

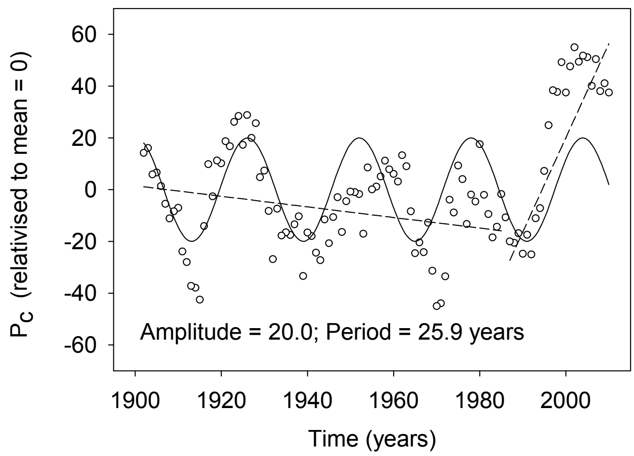

Figure 8
Rainfall concentration index (P_c) over time and segmented regression (dashed line). The solid line is a sine wave regression ($F_{2,106} = 29.6$, $p<0.0001$, $R^2 = 0.358$).

CONCLUSION

All analyses indicate that the rainfall amount, concentration, and seasonality are not random processes. The general theme that emerges is one of cyclicity, where rainfall parameters are explained as single or double cycles, often related to a period of either approximately 20 years, or in the region of 40–60 years. The only apparent shift, or directional change, appears to be rainfall concentration, which has increased significantly since 1988.

Rainfall over the past 30 years (1981–2010) was considerably higher (annual mean = 413 mm) than for the preceding 81 years (annual mean = 347 mm; 1899-1980). While this does not signal a net increase in rainfall, it has been associated with significant increases in grassiness on some long-term trials (unpublished data). In contrast, regressions predict that total rainfall will decrease until about 2025 to levels similar to those experienced during the droughts of the 1910s and 1960s. This would coincide with rain falling later in the season, and possibly with increased winter rainfall. Ecologically this should induce a shift towards lower biomass production (and lower livestock carrying capacity), reduced grassiness, and increased abundance of shrubs.

The analysis of the Grootfontein rainfall data provides a detailed description of the patterns of precipitation at a site, and could act as a precedent for investigating precipitation history at other sites. Such further analyses would provide detailed and comparable descriptions of rainfall history which could then be aggregated to provide a more general understanding of rainfall at a spatial scale. The analysis also reveals that assessing possible effects of climate change on rainfall in semi-arid climates may be difficult unless (i) such effects are of significant magnitude, (ii) effects are novel (e.g. a shift to winter rainfall at Grootfontein), or (iii) significantly longer data sets are available.

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