CLIMATIC CHANGE OVER THE LOWVELD OF SOUTH AFRICA

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Abstract. There has been a 38% decrease in expected annual rainfall totals over the Lowveld, in the eastern part of South Africa, during the last two decades. The downward trend in mean annual rainfall is not replicated in the rest of the summer rainfall region above the escarpment. Rainfall variability over the Lowveld has been increasing since about the 1950s, although the increase in variability appears to have been slowing down in more recent years. Changes in the frequency and intensity of El Niño/Southern Oscillation extreme events are only partly responsible for the observed desiccation and increase in rainfall variability. The CSIRO 9-level general circulation model simulates, for 2 × CO_2 conditions, an insignificant decrease of 10% in the annual mean and a slight increase in the inter-annual variability of rainfall over the Lowveld. Other general circulation models likewise simulate only small changes in annual mean rainfall over the region. However, the simulated increase in rainfall variability by the CSIRO 9-level model is likely to be conservative since the model, being linked to a slab ocean, is unable to represent important features of ocean-atmosphere coupling in the region. Significant changes in the frequencies of extreme drought events and of heavy rains in the Lowveld are likely to occur even with only small changes in the rainfall climatology of the region.

1. Introduction

During the 1980s and the early 1990s many areas of South Africa have received less than the 1951–1980 average annual rainfall, resulting in severe drought conditions that have adversely affected agricultural production and water reserves. Most of South Africa receives a large proportion of its annual rainfall during the months October–March. Hence, the rainfall year is usually defined from July–June. In many areas of the country the 1991/92 rainfall season was the driest on record. During the following season of 1992/93 rainfall was again below average, although the timing of the rainfall was more favourable for crop production and so was not generally perceived to be as serious. Nevertheless, a prolonged period of below average rainfall throughout most of the 1980s and the recent dry years of the 1990s have had a serious impact on water reserves as is evident from the low levels of many of South Africa's larger dams. By September 1993 South Africa's larger dams were an average of only 35% full, with some of the largest dams at even lower levels (South African Weather Bureau, 1993). For example, the Gariep Dam (5670×10^6 m^3) was 24% full and the Vaal Dam (2529×10^6 m^3) was 18% full.

The 1993/94 season brought above average rains over most of the country except for the extreme eastern areas below the escarpment in an area known as the Lowveld (Figure 1). The topographic effects of the interior plateau are responsible for differing climates above and below the escaprment (Preston-Whyte and Tyson, 1987) and so climatic trends in the Lowveld may not be replicated above the

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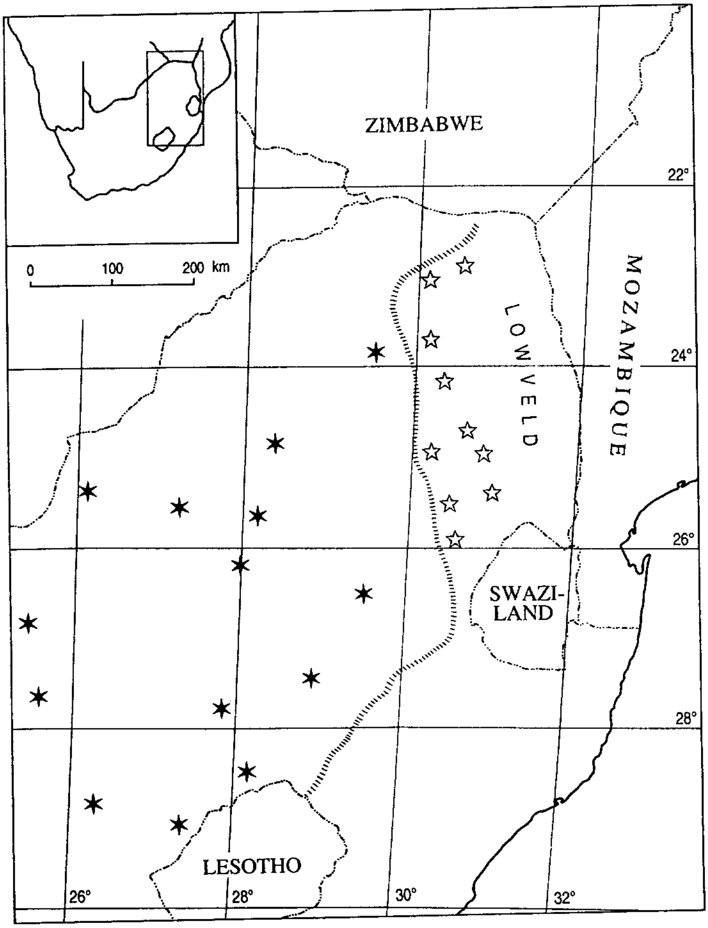

Fig. 1. Location map of the rainfall stations used to calculate regional rainfall indices. The ten white stars illustrate the location of stations used to calculate the index for the Lowveld, and the fourteen black crosses indicate the stations used to calculate the index for the summer rainfall region above the escarpment. The hatched line indicates the top of the escarpment.

escarpment in the rest of the summer rainfall region. Over the Lowveld the 1993/94 season was exceptionally dry.

Because of the generally poor rains of the last few years and the continued dry conditions of the 1994/95 seasons, there is a perception that rainfall over the Lowveld is diminishing. Claims that southern Africa has been getting progressively drier are not new and have been made since at least the middle of the last century (Moffat, 1842; Livingstone, 1857; Wilson, 1865). A history of the study of evidence from instrumental records for a progressive decline in rainfall over South Africa can be found in Tyson (1980) while Vogel (1989) examines the documentary evidence. The general conclusion has been that there is no real evidence for progressive desiccation anywhere in the country. More recently, McLelland (1995) has confirmed that there is no evidence for long term rainfall trends over South Africa. The Lowveld region, however, was poorly represented in the analysis.

The problem of recent decreases in rainfall receipts is not confined solely to South Africa. In fact, the 1980s were drier than previous decades over most of the subcontinent (Hulme, 1992; Nicholson, 1993) and in the Sahel progressive desiccation has been occurring since the early 1950s (Nicholson, 1989). In Australia a decrease in austral winter rainfall has been occurring in the southwest since about the 1930s (Nicholls and Lavery, 1992; Allan and Haylock, 1993), although summer rainfall over the eastern half of the country has been increasing (Nicholls and Lavery, 1992).

In light of the recent prolonged spell of dry years over the Lowveld and convincing evidence for climatic change in other parts of Africa, including Zimbabwe and Botswana (Hulme, 1992; cf. Nicholson, 1989), the empirical evidence for a progressive desiccation is reconsidered and possible reasons for the recent dry period are examined. Rainfall scenarios for the Lowveld for the next few decades are considered on the basis of general circulation model simulations of climatic change resulting from a doubling of atmospheric carbon dioxide (CO_2). The implications of the simulated changes in rainfall climatology for drought and flood frequencies over the Lowveld are also considered.

2. Data and Methods

In order to test for changes in rainfall over the Lowveld it is necessary to examine the historical records of annual rainfall totals over the whole area. Monthly rainfall totals for ten rainfall stations were obtained from the Computing Centre for Water Research and the South African Weather Bureau for the 63-year period from July 1930 to June 1993. The ten rainfall stations were selected as being representative of the Lowveld and were chosen to provide as even a distribution as possible. Their locations are illustrated by the hollow asterisks in Figure 1. Unfortunately, few stations are available for the eastern and northern parts of the study area and so the coverage is not ideal. However, although there is a noticeable decrease in mean rainfall from south to north (Tyson, 1986), rainfall variability is fairly coherent over the whole of the Lowveld (Landman, 1994) and so the stations selected should provide a good description of any trends in the area as a whole.

July–June annual rainfall totals were calculated for the period 1930/31 to 1992/93 and converted to percentages of the long term annual mean for each of the ten stations. For each year the mean across the ten stations was then calculated. The presence of missing values in the original station data can affect the variability of the regional rainfall index (Katz and Glantz, 1986). The original station annual totals were 97% complete, however, and so the measured variability of the regional rainfall index can be considered to be fairly accurate and largely unaffected by the few missing values.

Fourteen rainfall stations were selected as being representative of the summer rainfall region of South Africa above the escarpment. The location of the stations is illustrated by the asterisks in Figure 1. As on the Lowveld, the stations were chosen to provide as even a distribution as possible. A regional rainfall index for the summer rainfall region above the escarpment was calculated from the fourteen selected stations in the same way as the index for the Lowveld. Again there were less than 3% missing values and so the index can be considered to be a reliable indicator of rainfall variability. However, a large proportion of the stations had missing data for the last season analysed (1992/93) and so the analysis of rainfall over the summer rainfall region above the escarpment was limited to the period 1930/31 to 1991/92.

Often, long term trends are identified by fitting a linear regression line to the data. Climatic trends are then identified by the slope of the regression line. Simple linear regression, however, is often inappropriate for identifying climatic change since it assumes that any trend evident has been occurring at least since the beginning of the period analysed and that the change in climate has been occurring at a constant rate. Instead a segmented regression line, with the constraint that there is no discontinuity at the change-point(s), has been fitted (Solow, 1987, 1988). Segmented regression allows for the possibility that climatic change began to occur sometime during the period of analysis and can be used to identify when a change in climate has begun. It is additionally able to describe non-linear climatic change better than simple linear regression. Tests for the significance of the improvement of fit of segmented regression over linear regression are detailed in Appendix A.

When a definite optimum change-point value could be identified, segmented regression models have been fitted even when the significance in the reduction in the sums of squares was as low as 60%. Tests for the significance of rainfall trends have rather been based on the trend of individual sections of the segmented regression lines, using standard tests for linear regression (e.g. Montgomery and Peck, 1992). The significance of the individual segments will have been exaggerated, however, because the segments have been defined *a posteriori* to highlight any trend in the time series. Consequently, confidence levels should be adjusted to offset the problem of multiplicity by adjusting for the number of independent tests (Katz, 1988; Brown and Katz, 1991; Katz and Brown, 1991). However, since the identification of the optimum segmented fit does not involve independent tests, use of the Bonferroni inequality will be far too conservative. The true significance level of the individual segments is therefore unknown, but will lie somewhere between the two extremes. Only the *a priori* significance of the trend is indicated and should be read as an overestimate. No account has been taken for temporal auto-correlation in any of the statistical tests, but successive observations are effectively independent ($r_1 = 0.011$ for the Lowveld rainfall index, and $r_1 = 0.014$ for the summer rainfall region above the escarpment) and so significance levels should be unaffected.

Rainfall cycles have been identified using Jenkinson's (1977) method of spectral analysis. Details of the algorithm can be found in Tyson and Dyer (1978).

The coefficient of variation has been calculated for successive overlapping periods of 15 years. Long term changes in rainfall variability have been identified using segmented regression, in the same manner as for the identification of long term changes in the mean. Because of the problems of autocorrelation associated with running statistics, the calculation of significance levels is problematic (Diggle, 1991). Tests for the significance of segmented regression fits (Appendix A) will be inaccurate and so a high confidence level of 99% has been selected to compensate. Significance tests for changes in rainfall variability have not been performed because of the statistical problems involved (Brown and Katz, 1991).

Control and doubled-CO_2 simulated daily rainfall for 28 model years for the CSIRO 9-level general circulation model (McGregor *et al.*, 1993) were obtained from the CSIRO. Annual totals were determined from the 28 years of daily data. Percentage changes in the long term means and differences in the coefficients of variation between the control and doubled-CO_2 simulated climates were then calculated. However, since the CSIRO 9-level model is linked to a slab ocean, it is unable to simulate important features of rainfall variability over the Lowveld associated with ocean-atmosphere coupling (Meehl, 1991). Modelled changes in rainfall variability are therefore likely to be conservative. Simulated rainfall changes for the Lowveld were obtained by averaging results for the eastern half of the summer rainfall region south of 20° S, represented by seven grid points. If it is assumed that there are no fundamental changes in the frequency distribution of rainfall, hypothetical annual rainfall totals under doubled-CO_2 conditions can be obtained by transforming the original station observations. The transformation ensures that the simulated changes in the mean and coefficient of variation are reproduced in the new observations.

The original station data were compared with the hypothetical data to test for changes in the return period of 10-year floods and droughts. In calculating return periods it is necessary to fit a theoretical frequency distribution to the observed distribution. A number of different frequency distributions were fitted to the annual rainfall totals for the Lowveld rainfall stations and the gamma distribution was found to provide the best fit. In addition, the gamma distribution provides a good theoretical fit, being zero-bound and positively skewed. The parameters for the gamma distributions were estimated using maximum likelihood techniques (Appendix B).

3. Evidence for Trends in Annual Rainfall Totals

EVIDENCE FOR ANNUAL RAINFALL TRENDS OVER THE LOWVELD

The changes in rainfall over the Lowveld for the 63 years analysed are illustrated in Figure 2. The year on the x-axis shows only the first year of the rainfall season;

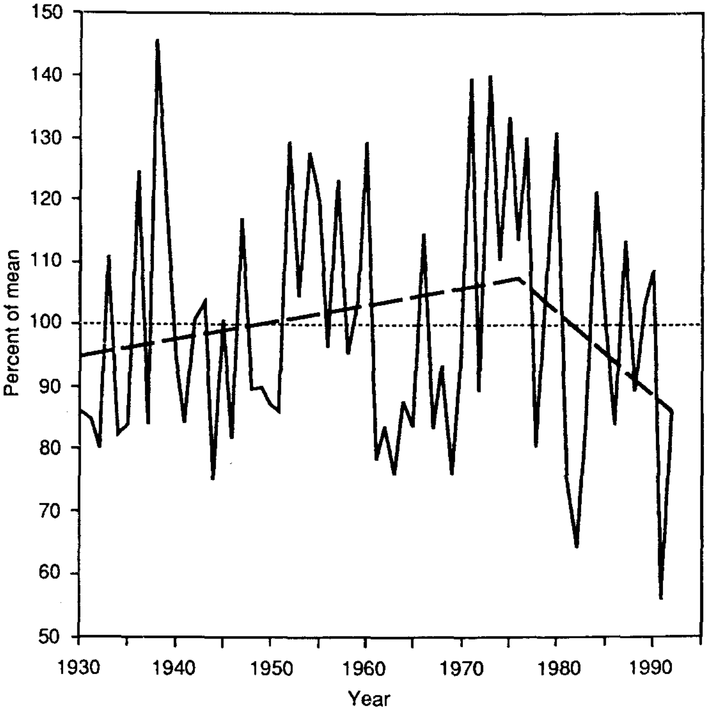

Fig. 2. 1930/31–1991/92 annual rainfall totals for the Lowveld as percentages of the 1930/31–1991/92 mean. The long term mean is represented by the dashed horizontal line at 100%. The two-phase regression line illustrating long term trends in rainfall is also shown. The year labels on the x-axis represent the first year of the rainfall season so that 1930 is the 1930/31 season.

hence, 1930 represents the 1930/31 season. The severe drought of the 1991/92 season is immediately evident as being the driest year during the period of anlaysis and was the only year with less than 60% of the long term mean rainfall. Also evident from the graph is the dry period of the early 1980s and the prolonged wet spell of the 1970s. During the dry spell of the 1960s below average rains were received persistently and only one season received above average rains. The 1960s were preceded by another predominantly wet phase of about ten years.

Superimposed on the graph is the long term trend as described by two-phase regression. Although the two-phase regression is not a significant improvement upon linear regression ($P < 0.36$), it does suggest that rainfall increased gradually from the 1930s until the wet spell of the 1970s and that since the late 1970s there appears to have been a fairly dramatic trend toward drier conditions. Since the mid-1970s a significant trend ($P < 0.06$) toward drier conditions has been occurring, representing a 38% decrease in expected annual rainfall.

It is important to try to explain why this drying trend may have occurred in order to decide whether or not this is evidence of climatic change or simply a temporary phenomenon that can be expected to reverse in the near future. It will

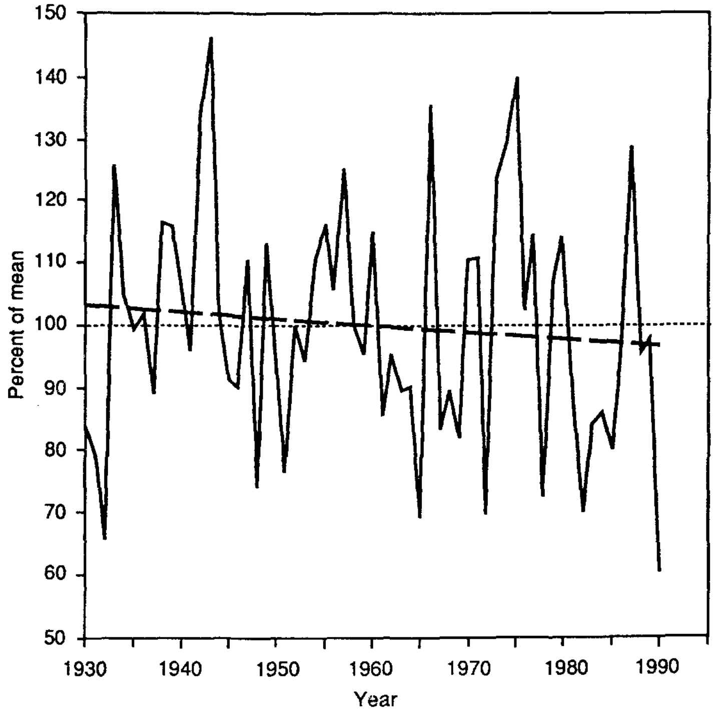

Fig. 3. 1930/31–1991/92 annual rainfall totals for the summer rainfall region above the escarpment as percentages of the 1930/31–1991/92 mean. The long term mean is represented by the dashed horizontal line at 100%. The regression line illustrating long term trends in rainfall is also shown. The year labels on the x-axis represent the first year of the rainfall season so that 1930 is the 1930/31 season.

also be helpful to examine evidence for trends in mean rainfall over the summer rainfall region of South Africa above the escarpment in order to identify whether trends over the Lowveld are a localised phenomenon.

EVIDENCE FOR ANNUAL RAINFALL TRENDS OVER THE SUMMER RAINFALL REGION ABOVE THE ESCARPMENT

Figure 3 illustrates the changes in rainfall that have occurred above the escarpment during the period of analysis. Again the 1991/92 season is seen as being the driest on record but does not appear to have been as severe as on the Lowveld, with a little over 60% of the long term mean rainfall being received. Since more stations were used in the calculation of the rainfall index than on the Lowveld, however, differences in the variance between the two areas cannot easily be interpreted (Katz and Glantz, 1986).

Over the entire 62-year period there is no evidence of any significant trend toward drier conditions. Although the drought period of the early 1980s appears to have been more severe than on the Lowveld, the recent trend toward desiccation has

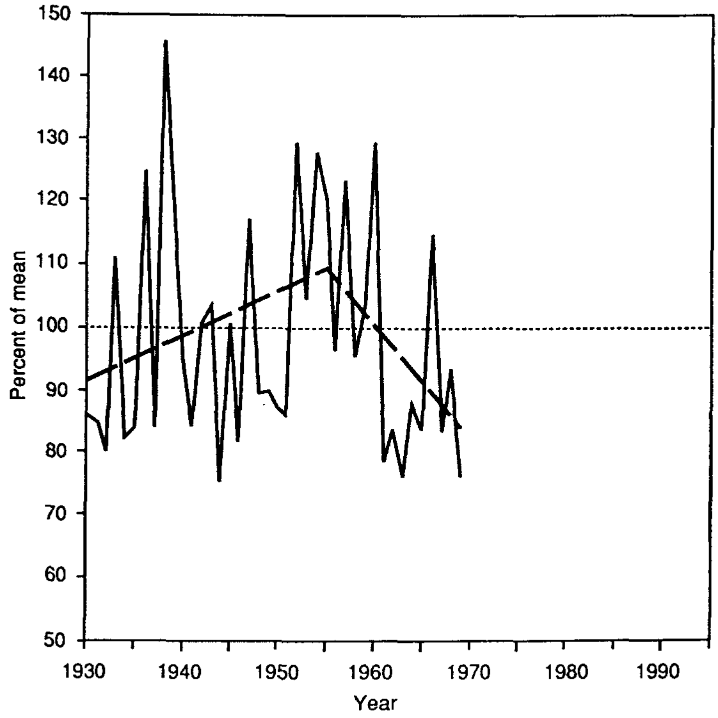

Fig. 4. 1930/31–1969/70 annual rainfall totals for the Lowveld as percentages of the 1930/31–1991/92 mean. The long term mean is represented by the dashed horizontal line at 100%. The two-phase regression line illustrating long term trends in rainfall is also shown. The year labels on the x-axis represent the first year of the rainfall season so that 1930 is the 1930/31 season.

not been identified by the two-phase regression analysis, perhaps largely because of the heavy rains that were received in the 1987/88 season.

DISCUSSION

Apart from the fact that there is no evidence for progressive desiccation immediately to the west of the Lowveld, perhaps the most serious argument against the evidence for desiccation over the Lowveld is that the period over which the drying trend has been observed is too short to constitute unequivocal evidence for climatic change. For example, after a period of good rains in the 1950s, the drought years of the 1960s would have been persuasive evidence of desiccation at that time. The two-phase regression fitted to the Lowveld rainfall index for the period 1930/31 to 1969/70, although again not significant ($P < 0.16$), does appear to suggest that the Lowveld was moving toward a drier climate. From the early-1950s to the late-1960s, expected rainfall decreased by 49% ($P < 0.01$). As is evident from Figure 2, however, the next few years experienced exceptionally good rains.

It is tempting to attribute the recent trend toward drier conditions to a transition from a wet to a dry spell in an approximately 18-year cycle in rainfall that has been well-documented in the eastern and northern Transvaal region (Tyson, 1986). It could then be argued that we should expect a transition toward another wet period to occur in the near future. In fact, the transition to a wet period should have occurred toward the end of the 1980s and, hence, the early 1990s should have been predominantly wet (Dyer and Tyson, 1977) and the Lowveld should now be in about the middle of a wet spell. Clearly this is not the case. Although the 18-year cycle was successfully used to predict the dry period of the 1980s (Dyer and Tyson, 1977; Tyson and Dyer, 1978, 1980) it has not provided warning of the continuation of dry conditions through the late 1980s and early 1990s.

It is interesting to consider the evidence for the 18-year rainfall cycle over the Lowveld in more detail. Figure 5 illustrates the results of a spectral analysis of Lowveld rainfall from 1930/31 to 1985/86, approximately when the current dry period should have begun to come to an end. There is a fairly marked peak in the spectral curve at about 17–19 years which is strong evidence for the 18-year rainfall cycle. If the last seven years are included in the analysis, however, the evidence for the cycle is much poorer. The results of the spectral analysis for Lowveld rainfall from 1930/31 to 1992/93 are illustrated in Figure 6. It is immediately evident that the spectral peak at 18–19 years is considerably dampened, indicating that the cycle is not a robust feature of the climate of the Lowveld.

One of the major influences on inter-annual rainfall variability over South Africa is the El Niño/Southern Oscillation (ENSO) phenomena (Lindesay, 1988). Usually, although not always (Mason and Lindesay, 1993), La Niña and El Niño events are associated with the occurrence of wet or dry years respectively. As evidence, the two driest seasons since the 1930s, of 1982/83 and 1991/92 (Figures 2 and 3), were both strong El Niño years, whilst the good rains of 1975/76 were associated with a La Niña. With a predominance of negative values of the Southern Oscillation Index since about the mid-1980s, a preference for dry years over southern Africa could be expected and may partly explain the recent progressive desiccation over the Lowveld. The correlation between the Southern Oscillation Index, however, is weaker for the Lowveld than for areas further west (Lindesay *et al.*, 1986; Lindesay, 1988; van Heerden *et al.*, 1988) where there is no evidence for a decrease in annual rainfall. Consequently, changes in ENSO activity can only be at best partly responsible for the trend in rainfall over the Lowveld.

4. Evidence for Changes in Inter-Annual Rainfall Variability

Generally, an interest in climatic change is stimulated by a concern about the changing probability of extreme events such as droughts or severe floods because of their implications for dam and bridge construction and agricultural production, for example (see e.g. Glantz *et al.*, 1989). Changes in the frequency and intensity of

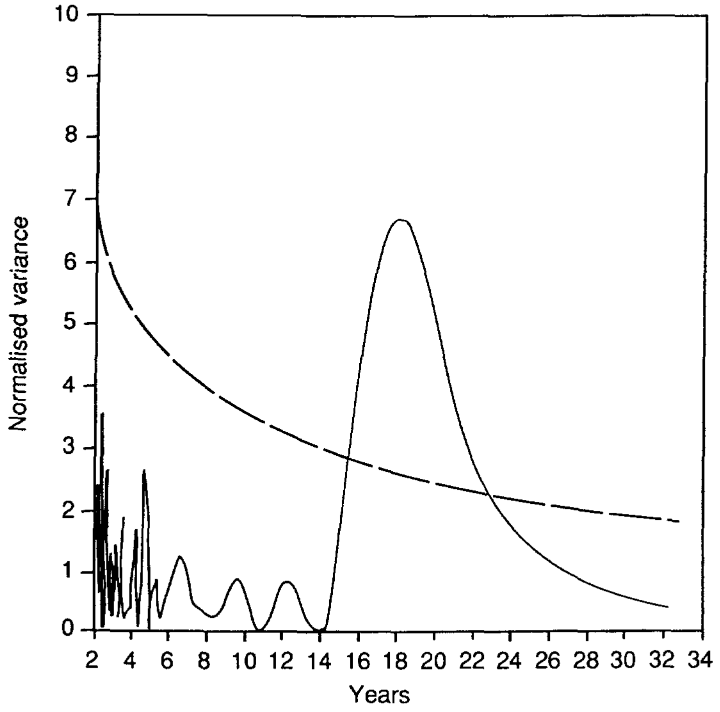

Fig. 5. Rainfall spectra for annual rainfall percentages over the Lowveld for the period 1930/31–1986/87. The 99% significance level is illustrated by the dashed line.

extreme events are highly sensitive to small changes in climatic variability (Mearns *et al.*, 1984; Wigley, 1987; Wigley and Jones, 1987; Katz and Brown, 1992; Katz and Acero, 1994). As a result, it is important to test for a change in the variability of climate as well as the mean in order to identify whether climatic change has occurred.

EVIDENCE FOR CHANGES IN INTER-ANNUAL RAINFALL VARIABILITY OVER THE LOWVELD

Changes in rainfall variability over the Lowveld are illustrated in Figure 7. The year on the x-axis represents the middle year of the 15-year period for which the coefficient of variation was calculated; hence 1937 represents the rainfall variability over the period 1930/31–1944/45. For most of the period of analysis there is convincing evidence for an increase in rainfall variability over the Lowveld, in line with trends in other areas of the world (Bruce, 1994). The increase began in the mid-1940s and since then the expected value of the coefficient of variation has increased by 5.2%. It is possible that the increase in variability has been slowing down recently, although it is difficult to say for certain at this stage without a few additional years of data.

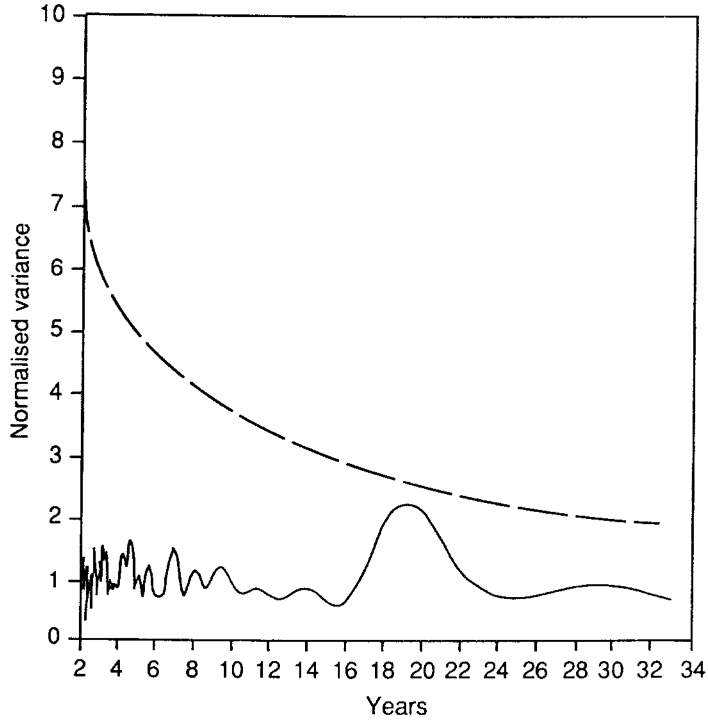

Fig. 6. Rainfall spectra for annual rainfall percentages over the Lowveld for the period 1930/31–1992/93. The 99% significance level is illustrated by the dashed line.

The period of increasing rainfall variability over the last approximately 50 years was preceded by a period of decreasing variability from at least the early 1930s. There is evidence to suggest that a decrease in rainfall variability up to the 1940s has continued since the beginning of the century (Hulme, 1992) and possibly even earlier (McLelland, 1995).

EVIDENCE FOR CHANGES IN INTER-ANNUAL RAINFALL VARIABILITY OVER THE SUMMER RAINFALL REGION ABOVE THE ESCARPMENT

The trends in the variability of rainfall over the summer rainfall region above the escarpment, illustrated in Figure 8, show some similarities to the trends over the Lowveld. One very important exception, however, is that the coefficient of variation has decreased by about 3.5% since the early 1970s. This decrease in variability provides some evidence to suggest that the slowing down in the increase in rainfall variability over the Lowveld is real. From the mid-1950s to the early-1970s there was a sharp increase in the coefficient of variation over the summer rainfall region above the escarpment by 9.3%. Before the period of low rainfall variability during the 1950s, a decrease in variability was observed from at least the early 1930s as also occurred over the Lowveld.

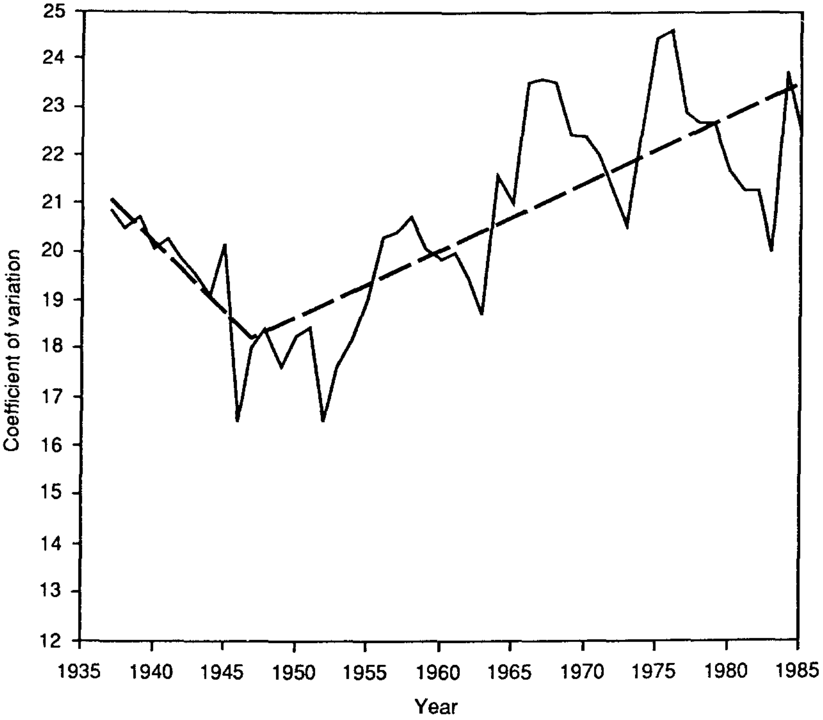

Fig. 7. Coefficients of variation of rainfall over the Lowveld for successive overlapping fifteen year periods centred on the year shown on the x-axis. The coefficient of variation at year 1937 thus represents the measure of rainfall variability over the period 1930/31–1944/45. Long term changes in rainfall variability are illustrated by a two-phase regression line.

DISCUSSION

It may be considered that the decrease in rainfall variability observed in the early part of the century, evident over both the Lowveld and the summer rainfall region above the escarpment, is the result of gradual improvements in data quality. It is, however, unlikely that the decrease in rainfall variability observed in the early part of the century can be attributed solely to improvements in data quality and availability because the extreme rainfall events in the early part of the period of analysis are recorded consistently across all stations. It is likely that the decrease in variability is at least partially real.

Of greater direct interest, however, is the trend toward increasing rainfall variability evident for most of the last half century (cf. Hulme, 1992) apparent over the Lowveld. The implications are that drought and flood events are becoming more frequent over the Lowveld. One possible explanation of this recent trend in variability is that since about the 1950s the frequency and severity of ENSO events is known to have increased (Elliott and Angell, 1988). However, there is again the problem that the correlation between the Southern Oscillation Index is weaker for

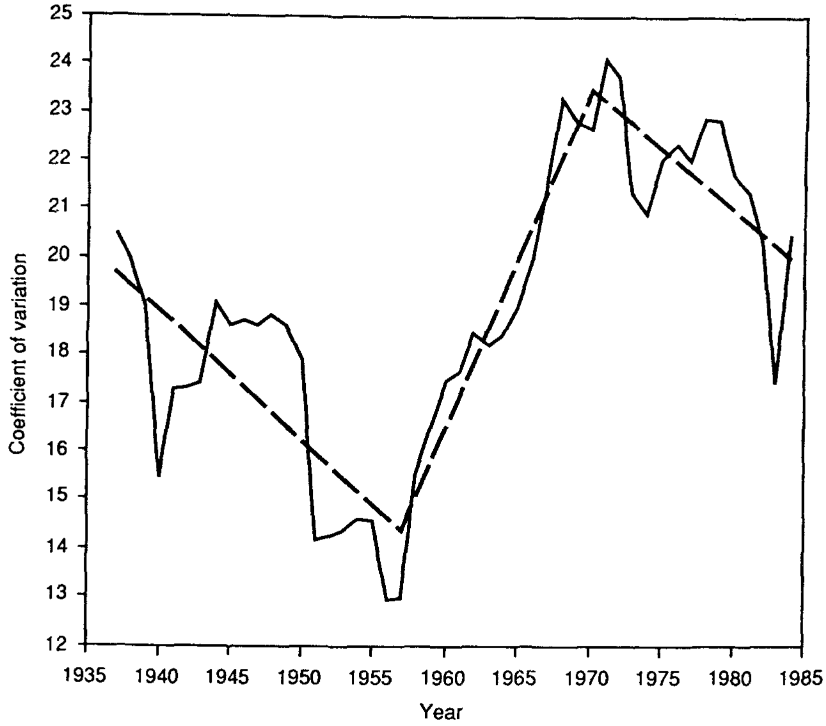

Fig. 8. Coefficients of variation of rainfall over the summer rainfall region above the escarpment for successive overlapping fifteen year periods centred on the year shown on the x-axis. The coefficient of variation at year 1937 thus represents the measure of rainfall variability over the period 1930/31–1944/45. Long term changes in rainfall variability are illustrated by a three-phase regression line.

the Lowveld than for areas further west. As a result, the recent decrease in rainfall variability over the summer rainfall region above the escarpment is unexpected because it has not been accompanied by a corresponding decrease in variability in Pacific Ocean activity.

The El Niño/Southern Oscillation phenomenon is not the only important influence on interannual rainfall variability over South Africa. Sea-surface temperatures in the Indian and South Atlantic oceans have an important influence also (Walker and Lindesay, 1989; Walker, 1990; Jury and Pathack, 1991; Mason, 1995). In both oceans gradual warming in sea-surface temperatures appears to have been occurring this century, possibly as part of the greenhouse warming (Folland and Kates, 1984). Increases in sea-surface temperatures could be expected to result in an increase in rainfall variability because small changes in sea temperatures in warm areas can have a much more significant impact on the atmospheric circulation than strong anomalies in cooler areas since the atmospheric sensitivity to sea-surface temperatures increases over warmer oceanic regions (Rind, 1991; Trenberth, 1991; Hartmann and Michelsen, 1993; Meehl *et al.*, 1993; Zhang, 1993).

5. Rainfall Scenarios for the Lowveld for the Next Few Decades in the Context of Global Climatic Change

It is of interest to compare the observed changes in climate over the Lowveld with the changes that may be expected as a result of an enhanced greenhouse effect. Unfortunately, there is much less confidence in the simulated changes in rainfall resulting from an enhanced greenhouse effect than there is in the changes in temperature. This lack of confidence is partly the result of the fact that changes in precipitation are an indirect consequence of the greenhouse effect but more importantly because of the difficulties in modelling rainfall (IPCC, 1990, 1992; Whetton *et al.*, 1993). Despite the poor ability to model present day rainfall climatology within general circulation models, most of the general features of rainfall distribution and seasonality over southern Africa are modelled by the CSIRO 9-level with an acceptable accuracy (Joubert, 1995). Over the eastern half of South Africa, including the Lowveld, simulated annual rainfall totals and number of raindays are too high, but the respective spatial distributions are reproduced reasonably well (Mason and Joubert, 1995). Of concern, however, is a sensitivity of the model to sharp changes in topography that is particularly evident along parts of the east coast of the subcontinent. Consequently, simulated changes for the Lowveld have been obtained by averaging over a much larger area over the wetter eastern half of the subcontinent south of 20° S.

The CSIRO 9-level general circulation model simulates a decrease in the mean annual rainfall over the eastern half of southern Africa under doubled-CO_2 conditions of about 10% and a slight increase in the coefficient of variation of only 2%. The modelled changes in both annual mean and rainfall variability are statistically insignificant. Other later generation general circulation models similarly simulate only small changes in mean annual rainfall over southern Africa (Tyson, 1993). It is unlikely, therefore, that the severity of the recent observed desiccation over the Lowveld is attributable solely to greenhouse-related climatic change.

The recent trend toward an increase in variability is greater than the model simulation for a doubled-CO_2 climate. However, the simulated increase in rainfall variability by the CSIRO 9-level model is likely to be conservative. The model is linked to a slab ocean and so is unable to simulate the effects of ENSO variability in a doubled-CO_2 climate (Meehl, 1991). Other important features of ocean-atmosphere coupling in the region will also be poorly represented. Consequently, a larger increase in rainfall variability than that simulated by the CSIRO 9-level model is likely (Rind *et al.*, 1989; Rind, 1991; Washington and Meehl, 1991; Cao *et al.*, 1992; Meehl *et al.*, 1993). The possibility that the increase in inter-annual rainfall variability of the Lowveld is partly an indication of greenhouse-induced climatic change cannot be ruled out.

6. Implications for Flood and Drought Events

Although the simulated changes in both the annual mean and the coefficient of variation are statistically insignificant, it is of interest to test the sensitivity of flood-year and drought frequencies over the Lowveld to small changes in the rainfall climatology of the area. Given a 10% decrease in the mean and a 2% increase in the coefficient of variation, changes in the frequency and intensity of 10-year droughts and floods have been calculated.

The ten-year drought throughout the Lowveld is calculated to be about 14% drier in a doubled-CO_2 climate than in the current climate. In the northern Lowveld, the rainfall equivalent of a current ten-year drought occurs about once in every six or seven years in the doubled-CO_2 climate, while in the southern part of the Lowveld occurs about once in five or six years.

Similar patterns of change in flood frequencies are evident. Throughout the Lowveld the ten-year flood is calculated as almost 10% drier than in the current climate. As a result, in the northern part of the Lowveld, years of high rainfall are less frequent and the rainfall equivalent of a current ten-year flood occurs only once in about 20 years. In the southern part of the Lowveld the ten-year flood occurs about every 25 to 30 years. Hence, the decrease in the frequency of years of high rainfall is more severe than it is further north.

The changes in the rainfall climatology of the Lowveld that are simulated under a doubled-CO_2 climate by the CSIRO 9-level model suggest a deterioration of severe drought conditions in the Lowveld. At the same time, a decrease in the frequency of high rainfall totals throughout the region is simulated. Similar conclusions may not apply to the frequency of extreme daily rainfall events (Gordon *et al.*, 1992; Yu and Neil, 1993; Mason and Joubert, 1995). It should be emphasised that these results are highly sensitive to even small differences in the expected changes in rainfall means and, most notably, variability (Katz and Brown, 1992). Simulations using a coupled ocean-atmosphere general circulation model suggest that drought conditions over southern Africa during Pacific warm events may become more severe under doubled-CO_2 conditions (Meehl *et al.*, 1993). Such an increase in the sensitivity to extremes in the Southern Oscillation would suggest that rainfall variability should increase in the area, which is not simulated by the CSIRO 9-level model. As a result the expected changes in rainfall climatology resulting from a doubling of atmospheric CO_2 as presented in this paper, should be approached with caution.

7. Conclusions

There has been a 38% decrease in expected annual rainfall over the Lowveld during the last 20 years. Although the twenty year period is too short to provide unequivocal evidence of climatic change, it is not possible to attribute the drying trend simply to low frequency variability in the rainfall of the region. Instead, the desiccation may be partly the result of the predominance of negative values of the Southern Oscillation index over the last few years. Lack of evidence for a long term trend in rainfall immediately to the west of the Lowveld and model simulations of climatic change resulting from doubled atmospheric carbon dioxide suggest that the desiccation over the Lowveld may be a temporary phenomenon.

Evidence for an increase in rainfall variability over the Lowveld is stronger than the evidence for a decline in mean rainfall, although the increase in variability appears to be slowing down. Over the summer rainfall region above the escarpment, rainfall variability also increased dramatically from the 1950s but has been decreasing since the early 1970s. The increase in rainfall variability over the Lowveld can be attributed only in part to an increase in the frequency and intensity of El Niño/Southern Oscillation extreme events. The increase may represent evidence of greenhouse-induced climatic change. Although the CSIRO 9-level general circulation model predicts almost no change in the inter-annual variability of rainfall over the Lowveld in a doubled-CO_2 climate, the model is unable to simulate the effects of ENSO variability and other important features of ocean-atmosphere coupling. Consequently, modelled increases in rainfall variability are likely to be underestimated. The CSIRO 9-level model simulates no significant changes in either the mean or the coefficient of variation in rainfall over the Lowveld, but even small changes in the rainfall climatology of the region can result in large changes in the frequency and intensity of flood and drought years.

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Appendix A: Significance Tests for Segmented Regression

If S_2 represents the residual sum of squares of a two-phase regression model and S_1 the residual sum of squares of the linear regression model then the significance of the reduction in residual sums of squares resulting from the use of two phase regression instead of linear regression can be determined using:

$$U = \frac{(S_1 - S_2)/3}{S_2/(n-4)} \,. \tag{A1}$$

The number of data points is defined by n. The statistic, U, follows an F-distribution with 3 and $n - 4$ degrees of freedom (Solow, 1987).

If S_3 represents the residual sum of squares of the three-phase regression model, the significance of the decrease in residual sums of squares resulting from the use of three-phase instead of linear regression can be determined using:

$$U = \frac{(S_1 - S_3)/6}{S_3/(n-8)} \,, \tag{A2}$$

(Hawkins and Galpin, pers. comm.).

Appendix B: Maximum Likelihood Estimation of Gamma Parameters

If the gamma distribution, $g[x]$, is defined by:

$$g[x] = \frac{x^{\alpha-1} e^{-x/\beta}}{\beta^{\alpha}\Gamma[\alpha]} \tag{B1}$$

where $\Gamma[\alpha]$ is the gamma function, the maximum likelihood estimates of the shape (α); and scale (β) parameters are obtained from:

$$L(\alpha, \beta, x_1, \ldots x_n) = \frac{\prod_{i=1}^{n} x_i^{\alpha-1} \exp\left(-\frac{1}{\beta}x_i\right)}{\beta^{n\alpha}\Gamma[\alpha]^n} \,. \tag{B2}$$

It is convenient to calculate the log likelihood so that the parameters are obtained by maximising

$$\ln L(\alpha, \beta) = (\alpha - 1)\sum_{i=1}^{n} \ln(x_i) - \frac{1}{\beta}\sum_{i=1}^{n} x_i - n\alpha \ln(\beta) - n \ln(\Gamma[\alpha]) \tag{B3}$$

(Rohatgi, 1976). Annual rainfall totals for current $T = 10$-year floods, $X_{1,T}$, were calculated from the fitted gamma distributions using

$$X_{1,T} = G_1[T^{-1}], \tag{B4}$$

where G_1 is the cumulative gamma distribution function as fitted to the current rainfall data. The new return periods, under the predicted changed climate, of the current 10-year floods were then calculated using:

$$T = \frac{1}{1 - G_2^{-1}[X_{1,T}]} \,, \tag{B5}$$

where G_2 is the cumulative gamma distribution function as fitted to the hypothetical rainfall for doubled-CO_2 conditions. Rainfall totals for $T = 10$-year droughts and new return periods were calculated by using the complement of the cumulative gamma distribution function in equations B4 and B5.

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