

## DROUGHTS OVER SOUTHERN AFRICA IN A DOUBLED-CO<sub>2</sub> CLIMATE

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*Received 21 February 1995*

*Accepted 5 December 1995*

### ABSTRACT

The southern African region is susceptible to climatic extremes and particularly to extended dry periods. Possible changes in the probability of dry years under doubled-CO<sub>2</sub> conditions are examined using output from the CSIRO nine-level general circulation model. Changes in annual mean rainfall are not expected to be significant. However, the model simulates an increase in the probability of dry years in the tropics, to the south-west of the subcontinent, as well as over the western and eastern parts of South Africa and southern Mozambique, where large percentage increases in the most intense dry spells are indicated. A decrease in the frequency of dry years is simulated over much of the interior of the subcontinent south of 10°S. In regions where the frequency of dry years decreases, the most severe events occur less often. The CSIRO nine-level model indicates a shift in the frequency distribution of daily rainfall events under doubled-CO<sub>2</sub> conditions. A small change in the frequency distribution of daily rainfall events may have further implications for the frequency of mid-summer droughts during the peak summer rainfall period of December–February. Increases in the frequency of mid-summer droughts are simulated over the eastern part of the subcontinent south of 20°S.

KEY WORDS: southern Africa; doubled-CO<sub>2</sub>; drought; extreme events; mid-summer droughts.

### INTRODUCTION

Most of the southern African region south of 20°S is arid or semi-arid, with a high degree of interannual rainfall variability (Tyson, 1986). As such, the region is vulnerable to droughts, which have important agricultural and socio-economic implications for a vast number of its inhabitants (Vogel, 1994). The severe droughts of 1982–1983 (Schulze, 1984), and more recently in 1991–1993 and 1994–1995, are indicative of the vulnerability, particularly of rural communities, to the occurrence of extended periods of low rainfall (Vogel and Drummond, 1993). The last 15 years have seen a procession of droughts over much of southern Africa, adversely affecting agricultural production and water reserves, but there is no evidence of progressive desiccation at least over most of South Africa (Tyson, 1986; Mason, 1995). An exception is over the Lowveld region of the Mpumalanga province of South Africa, where an approximately 40 per cent decrease in expected annual rainfall totals since the mid-1970s has occurred (Mason, 1995).

Given the vulnerability of rural communities in southern Africa to droughts, possible changes in the frequency and intensity of dry conditions, resulting from an increase in the concentration of atmospheric carbon dioxide (CO<sub>2</sub>), could have significant implications. General circulation models (GCMs) are used widely to provide estimates of doubled-CO<sub>2</sub>-induced climatic change, but are unreliable at simulating regional rainfall distributions, particularly where the dominant mode of rainfall production is convective (IPCC, 1990, 1992). Modelled changes in total rainfall resulting from a doubling of atmospheric carbon dioxide therefore should be interpreted with caution.

A range of GCM simulations of precipitation over southern Africa under 1 × CO<sub>2</sub> conditions were considered by Joubert (1995). Of the models considered, the nine-level CSIRO model (CSIRO9) was considered most reliable. The model indicated only small increases in annual rainfall under doubled-CO<sub>2</sub> conditions over much of the subcontinent

(Joubert, 1994; Mason and Joubert, 1997). Other high-resolution GCMs also simulate only small changes in annual mean rainfall for the region (Tyson, 1993). Although the CSIRO9 model has simulated small changes in mean rainfall over much of the subcontinent, even small changes in rainfall climatology can result in large changes in the frequency and intensity of wet and dry years (Mearns *et al.*, 1984; Wigley, 1987; Wigley and Jones, 1987; Katz and Brown, 1992; Katz and Acero, 1994; Mason, 1995). In the Australian region, an increase in the frequency and intensity of extreme rainfall, as well as a decrease in the frequency of low-rainfall events may be expected with a doubling of CO<sub>2</sub> (Whetton *et al.*, 1993). Similar increases in extreme rainfall are indicated for southern Africa (Mason and Joubert, 1997).

Over southern Africa, modelled increases in rainfall intensity are found to be a spatially coherent and an apparently less regionally-dependent signal of climatic change than changes in annual means or the simulated number of rain-days (Mason and Joubert, 1997). For Australia, the CSIRO9 model is also considered to provide more spatially coherent estimates of rainfall change when changes in rainfall intensity are examined (Gordon *et al.*, 1992; Whetton *et al.*, 1993). Widespread increases in the frequency and intensity of extreme daily rainfall events are simulated over much of the southern African subcontinent, most notably over the winter rainfall region of the Western Cape Province. Increases in the intensity of the lowest frequency floods are shown to be particularly severe, suggesting that greenhouse-related climatic change may be most detectable through an increase in extreme flood events rather than changes in long-term means. Similar results are evident when changes in the frequency and intensity of prolonged rainfall events are analysed (Mason and Joubert, 1997). All results are qualitatively similar to those for the Australian region, except that the model's sensitivity to sharp changes in topography over southern Africa is highlighted. The increase in the frequency and intensity of flood events may indicate a change in the frequency distribution of all daily rainfall events in the CSIRO9 model, suggesting that changes in the frequency of dry spells may also be expected. The model is used here to examine possible changes in drought frequency and intensity over southern Africa under doubled-CO<sub>2</sub> conditions.

## DATA METHODS

Daily rainfall data for both the control ( $1 \times \text{CO}_2$ ) and perturbed ( $2 \times \text{CO}_2$ ) simulations of the CSIRO nine-level model were obtained from the Commonwealth Scientific and Industrial Research Organization. The atmospheric component of the model is coupled to a simple mixed-layer ocean and a  $Q$ -flux procedure is applied to ensure accurate representation of seasonally varying sea-surface temperatures (cf. Gordon *et al.*, 1992). The atmospheric model has nine vertical levels with a spectral horizontal resolution of R21 (approximately  $3.2^\circ$  latitude by  $5.6^\circ$  longitude). A comprehensive description of the model is provided by McGregor *et al.* (1993). Annual totals, average number of rain-days per year (a rain-day is defined as a day with 0.2 mm of rainfall or more, after Whetton *et al.*, 1993), and average rainfall intensities were calculated from the daily data for all of the 28 model years available at each of the 108 grid-points representing Africa and the surrounding oceans south of the Equator.

The occurrence of drought is examined in this paper in terms of rainfall deficits only. However, it is recognized that changes in soil moisture and water availability in a doubled-CO<sub>2</sub> climate will be influenced by temperature and other factors, and not just by changes in rainfall. The frequency of occurrence of annual droughts under 1 and  $2 \times \text{CO}_2$  conditions were calculated by identifying the probabilities of the annual rainfall total being less than 90 per cent of the simulated annual means. In the CSIRO9 model climate, an annual rainfall of 90 per cent of the long-term mean represents a fairly severe dry year, typically occurring every 3–5 years over the subcontinent, and in areas of the subtropics, every 20 years. The probabilities of drought occurrence were obtained from the right tail areas of generalized extreme value (GEV) distributions fitted to the annual rainfall totals at each grid-point. The GEV distributions were fitted using maximum likelihood estimation (Prescott and Walden, 1980; Wilks, 1993; Mason, 1995). Percentage changes in drought probabilities were then calculated. Where appropriate, field significance was assessed using a two-tailed binomial test. Spatial correlation was ignored.

Possible changes in the occurrence of dry periods within the peak summer rainfall season (mid-summer droughts) were investigated by examining the frequencies of occurrence of periods of five or more consecutive days with rainfall below 0.2 mm. Differences between 1 and  $2 \times \text{CO}_2$  simulations were considered for the period December to February. The significance of possible changes in the frequency distribution of mid-summer droughts were tested

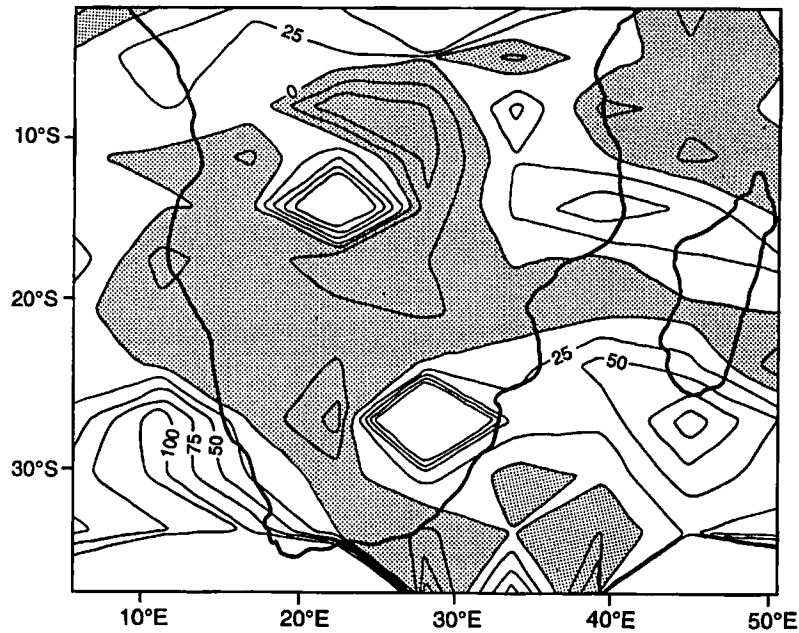


Figure 1. Percentage changes in the probability of dry years, defined as rainfall below 90 per cent of the annual mean. Shading indicates areas of decreased drought probabilities.

using survival analysis techniques, after checking the feasibility of the assumption of independence of dry events via runs tests. The Gehan's generalized Wilcoxon test statistic (Lee, 1992) is calculated based on the combined ranks of the event durations for both 1 and 2  $\times$  CO<sub>2</sub> simulations. The test statistic is compared to chi-squared tables, using one degree of freedom, and was performed separately at each grid-point.

## RESULTS

### *Changes in the severity of annual droughts under doubled-CO<sub>2</sub> conditions*

Except in areas where the control climate simulation is poor, modelled changes in annual mean rainfall over most of the subcontinent are relatively small (Mason and Joubert, 1997). Although it has been shown that changes in the annual mean rainfall are not expected to be highly significant, changes in interannual rainfall variability and the frequency distribution of annual rainfall totals can affect drought frequencies and intensities.

Simulated percentage changes in the probability of dry years (droughts), defined as rainfall below 90 per cent of the annual mean, are shown in Figure 1. Under doubled-CO<sub>2</sub> conditions, decreases in the probability of dry years (shaded) are indicated over a large part of the subcontinent south of 10°S, except over the western and eastern parts of South Africa and southern Mozambique. North of 10°S and south-west of the subcontinent, increases in the frequency of dry years may occur. In areas where dry years are expected to become more frequent, large percentage increases in the most intense droughts are evident. Equally, in areas of decreased drought frequency, the more severe droughts may occur considerably less often. Percentage changes in the probability of dry years are shown to be field significant at the 5 per cent significance level using a two-tailed binomial test and ignoring spatial correlation.

### *Changes in the frequency distribution of daily rainfall events*

The CSIRO9 model simulates widespread changes in the average number of rain-days as well as rainfall totals, thus implying that a shift in the frequency distribution of daily rainfall events over southern Africa will occur (Mason and Joubert, 1997). Such a change has been suggested for the Australian region as well (Whetton *et al.*, 1993). Figure 2 indicates changes in the frequency of varying daily rainfall magnitudes for different regions of the subcontinent. Land grid-points over the subcontinent have been divided into four regions representing the tropics

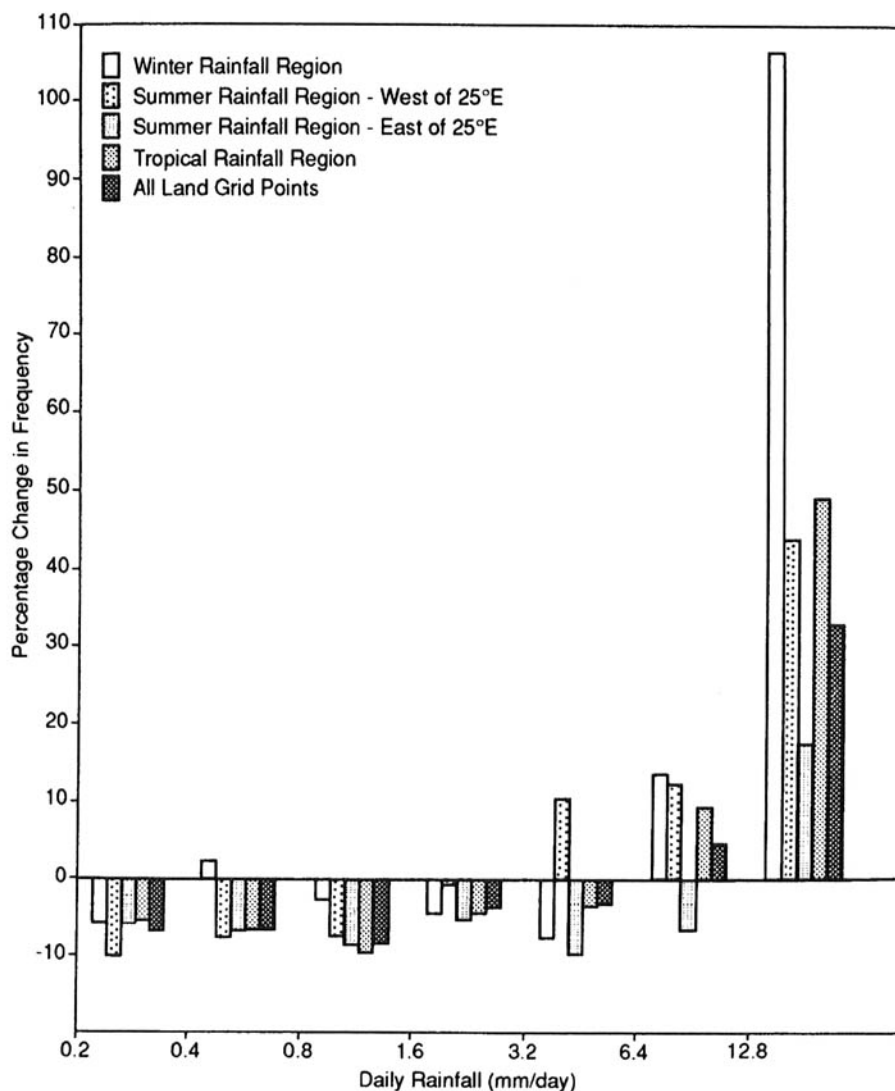


Figure 2. Percentage changes in the frequency of simulated daily rainfall (for rain-days > 0.2 mm) totals for various rainfall classes. Results are illustrated for four regions over the southern African subcontinent (defined in Joubert, 1995, his Figure 4), as well as for all land grid-points.

(north of 10°S), the dry western and wetter eastern halves of the summer rainfall region and the winter rainfall region of the Western Cape Province of South Africa (cf. Joubert, 1995). Based on the model simulations, widespread decreases in the frequency of occurrence of low daily rainfall events (less than 6.4 mm day<sup>-1</sup>) may be expected over almost all of southern Africa (Figure 2). Conversely, large increases in the frequency of heavy rainfall events (above 12.8 mm day<sup>-1</sup>), indicated for all regions (Figure 2), are consistent with the expected increases in the magnitude and frequency of extreme flood events (Mason and Joubert, 1997). There is a possibility therefore of a change in the frequency distribution of daily rainfall events under doubled-CO<sub>2</sub> conditions, with high rainfall events becoming more frequent and low rainfall events occurring less frequently.

#### *Changes in mid-summer droughts*

Serious impacts resulting from drought conditions are not necessarily confined to dry conditions lasting for a number of weeks or longer. The timing of rainfall within the peak rainfall months of December–February is often crucial for crop production. It has been shown that there is often a mid-season hiatus in rainfall, typically occurring some time in January (Harrison, 1986; Olivier, pers. comm.), known as a mid-summer drought. Given a change in

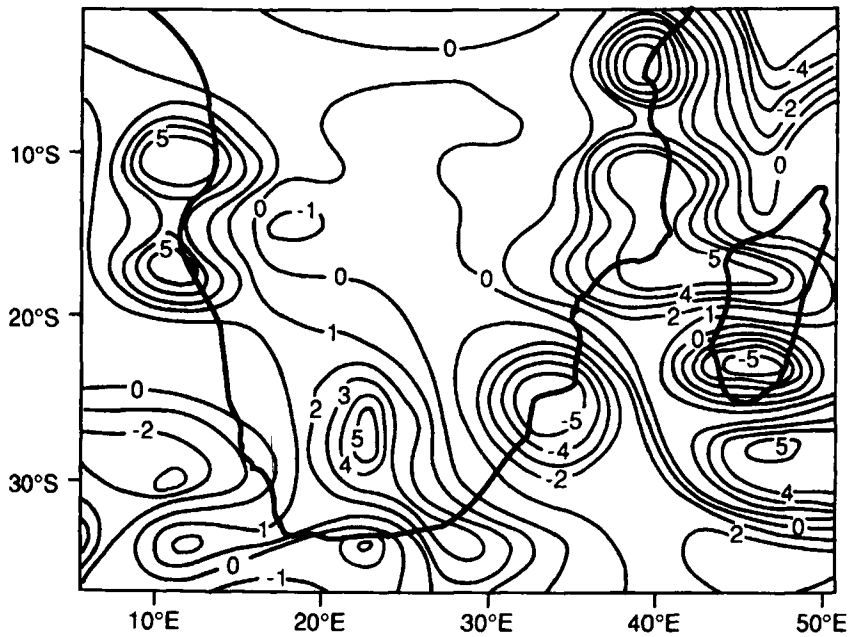


Figure 3. Simulated changes in the average number of rain-days (0.2 mm) during January.

the frequency distribution of daily rainfall events, the possibility that an increase in the occurrence of dry days during the summer rainfall season may lead to an increase in the occurrence of mid-summer droughts is of particular concern. Such a change may have serious implications for crop yields and agricultural productivity in general.

Of key importance to the occurrence of mid-summer droughts is the number of rain-days within the peak few weeks of the wet season (the month of January) of the summer rainfall area. The CSIRO9 model simulates a general decrease in the number of rain-days in January over much of the eastern part of the subcontinent except where the model is sensitive to topography (Figure 3). Over Botswana, Namibia and the northern parts of South Africa (the Kalahari Desert) there is an increase of five in the average number of January rain-days. Over the Lowveld region of the Eastern Transvaal, the simulated number of rain-days in January decreases by about 5 days. Over the north-eastern Free State Province of South Africa, an important maize-producing region, almost no change in the average number of rain-days is predicted. Simulated changes in the number of rain-days in January are not field significant at the 5 per cent significance level. Each of the three regions identified above are examined for changes in the frequency of mid-summer droughts.

The frequencies of mid-summer droughts (defined as a period of five or more consecutive days with rainfall below 0.2 mm) for different starting dates in December to February are illustrated in Figure 4 for three selected regions within South Africa. The probability of a mid-summer drought under control climate conditions, starting within each week after the beginning of December, is represented by the shaded bars and is less than observed because of the overestimation of the observed number of rain-days by the CSIRO9 model (Mason and Joubert, 1997). The hollow bars represent the probability under doubled-CO<sub>2</sub> model conditions. For the Lowveld (Figure 4(a)) a decrease in the average number of rain-days in January by as much as 5 days (Figure 3) is accompanied by a small increase of approximately 10 per cent in the frequency of occurrence of mid-summer droughts throughout the period December-February. Increases are most marked during January and early February. In the Kalahari, a simulated increase in the average number of rain-days, again by as much as 5 days, is associated with a decrease in the frequency of mid-summer droughts, most notably during January and February (Figure 4(b)). Over the maizegrowing region, little change in the frequency of mid-summer droughts is expected (Figure 4(c)) and the probability of occurrence is very low for both control and doubled-CO<sub>2</sub> conditions. The control climate simulation by CSIRO9 is in good agreement with observations, as this part of South Africa is a region where mid-summer droughts occur relatively infrequently.

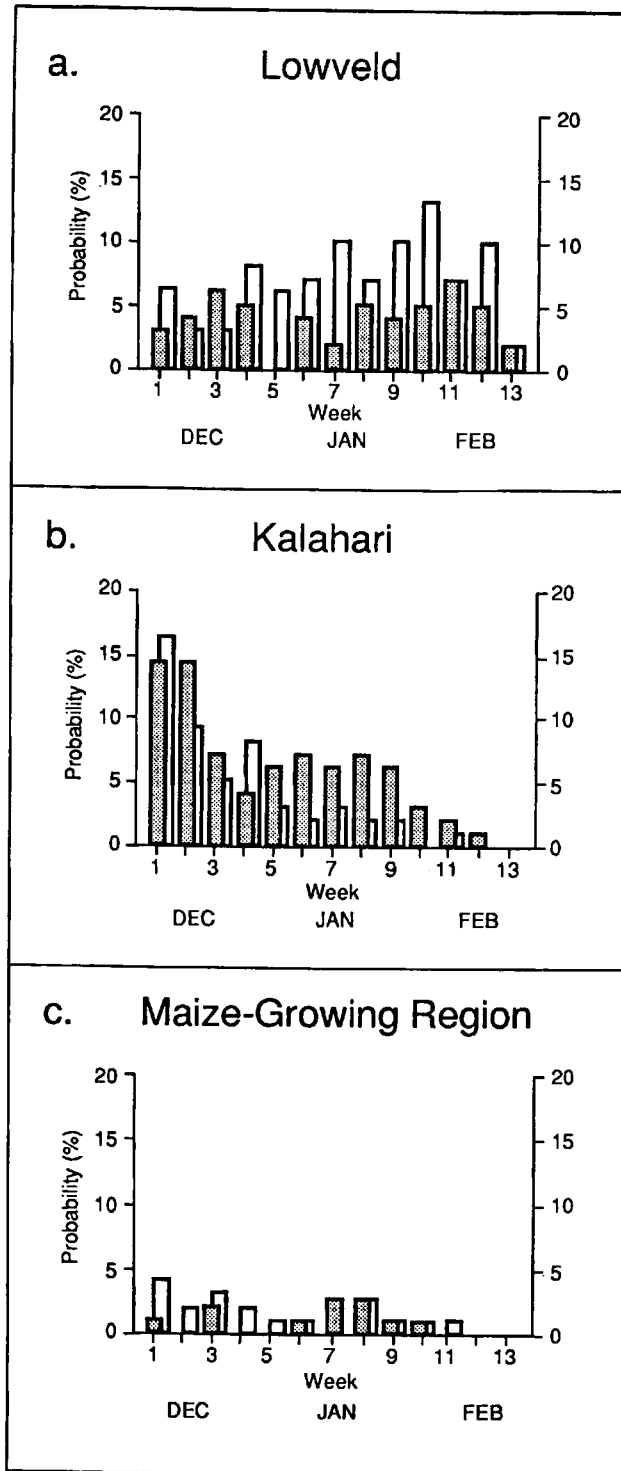


Figure 4. Simulated frequencies of mid-summer droughts (defined as a period of five or more consecutive days each with rainfall below 0.2 mm) for different starting dates in December to February for (a) the Lowveld, (b) the Kalahari Desert, and (c) the maize growing region of South Africa. Shaded bars indicate probabilities under present climate conditions. Hollow bars indicate probabilities under doubled-CO<sub>2</sub> conditions.

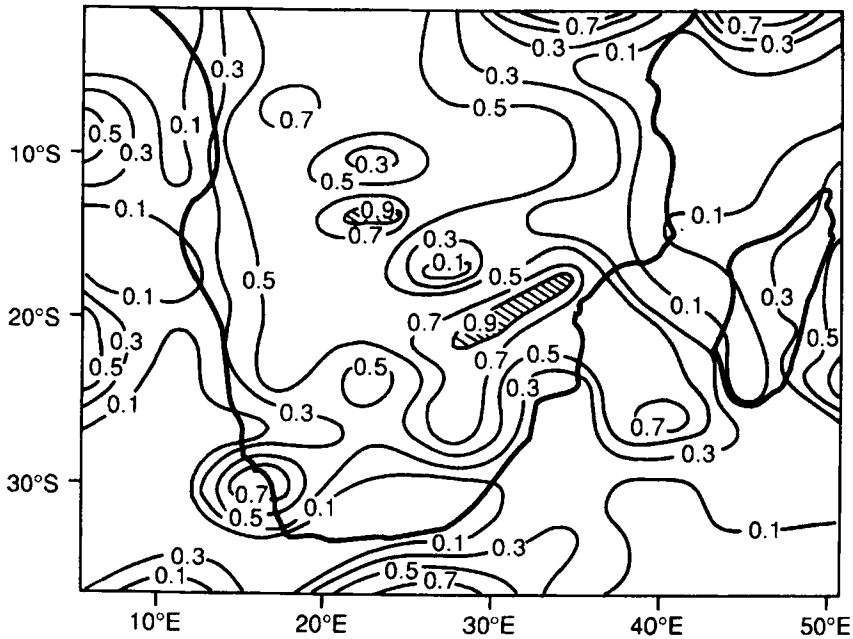


Figure 5. Chi-squared probabilities for the Gehan generalized Wilcoxon test statistic, calculated at each of the grid-points. Areas with  $P > 0.9$  are shaded.

Differences in the frequency distribution of mid-summer droughts between the 1 and  $2 \times \text{CO}_2$  simulations are not significant over much of the interior of the subcontinent. Figure 5 shows isopleths of the probabilities for the Gehan tests at each of the grid-points. In view of the fact that the data at the grid-points are correlated, it is not appropriate to consider tests at the simple 5 per cent or 10 per cent levels (Livezey and Chen, 1983). True significances will lie somewhere between the simple and Bonferroni levels (Brown and Katz, 1991). However, differences between the two distributions are significant (cf. Figure 1) only in regions where the control simulation of rainfall is known to be poor (Mason and Joubert, 1997), including the coastal areas of Angola, the west coast of South Africa and the southern coastal regions of Mozambique. This result suggests that caution needs to be exercised when interpreting the practical implications for changes in mid-summer droughts as simulated by the model. Again, it serves to highlight the caveat for all GCM simulations of possible changes in rainfall totals, frequencies, and intensities. The representation of physical processes responsible for rainfall production, most notably convection, requires improvement.

## CONCLUSIONS

General circulation model predictions of regional changes in rainfall differ considerably from model to model, and regionally-specific changes from a single model therefore may not be reliable. It is preferable to consider several GCMs when assessing regional climate change and the use of only the CSIRO9 model implies that the results presented here should be interpreted with caution. There is some consensus amongst GCMs that only small changes in annual mean rainfall may occur over the subcontinent. Although changes in annual mean rainfall with a doubling of atmospheric  $\text{CO}_2$  over southern Africa are not expected to be highly significant, even small changes in interannual rainfall variability and the frequency distribution of annual rainfall totals can affect drought frequencies and intensities.

The CSIRO9 model predicts that dry years (droughts), defined as rainfall below 90 per cent of the annual mean, will become less frequent over much of the subcontinent between  $10^\circ$  and  $25^\circ\text{S}$  under double- $\text{CO}_2$  conditions. By contrast, increases in drought frequency are indicated in the tropics, to the south-west of the subcontinent and in parts of South Africa and southern Mozambique. In regions where the frequency of dry years decreases, the most severe droughts occur less often. Equally, in regions where increases in the frequency of droughts are indicated,

large percentage increases in the most intense droughts are expected. For the Lowveld, a decrease of up to 5 days in the average number of rain-days in January is accompanied by a small (10 per cent) decrease in the frequency of occurrence of mid-summer droughts during the period December–February. An increase in the number of rain-days of a similar magnitude over the Kalahari is associated with a decrease in the frequency of occurrence of mid-summer droughts during January and February. Few mid-summer droughts occur over the maize-growing region of South Africa, as simulated correctly by the CSIRO9 model under  $1 \times \text{CO}_2$  conditions, and little change under doubled- $\text{CO}_2$  conditions is predicted. Overall, expected changes in extreme flood events and droughts imply a shift in the frequency distribution of daily rainfall events in the CSIRO9 model. Widespread but small decreases in the frequency of occurrence of low daily rainfall events may be expected over almost all of southern Africa. Large increases in the frequency of heavy rainfall events, indicated for all regions, are consistent with expected increases in the magnitude and frequency of extreme flood events.

#### ACKNOWLEDGEMENTS

This research formed part of a Special Programme on South African Climatic Change: Analysis, Interpretation and Modelling (SACCAIM) funded by the Foundation for Research Development. Data for the CSIRO9 model were provided by the Commonwealth Scientific and Industrial Research Organization Division of Atmospheric Research, Australia. Mr B. Rajaratnam assisted with certain statistical calculations. Mr. P. Stickler drew the diagrams.

#### REFERENCES

- Brown, B. G. and Katz, R. W. 1991. 'Use of statistical methods in search for teleconnections: past present and future', in Glantz, M. H., Katz, R. W. and Nicholls, N. (eds), *Teleconnections Linking Worldwide Climate Anomalies: Scientific Basis and Societal Impact*, Cambridge University Press, Cambridge, pp. 371–400.
- Gordon, H. B., Whetton, P. H., Pittock, A. B., Fowler, A. M. and Haylock, M. R. 1992. 'Simulated changes in daily rainfall intensity due to the enhanced greenhouse effect: implications for extreme rainfall events', *Climate Dyn.*, **8**, 83–102.
- Harrison, M. S. J. 1986. *A synoptic climatology of South African rainfall variations*, Unpublished PhD thesis, University of the Witwatersrand 341 pp.
- IPCC (Intergovernmental Panel on Climate Change) 1990. *Climate Change: the IPCC Scientific Assessment*, Houghton, J. T., Jenkins, G. J. and Ephraums, J. J. (eds), Cambridge University Press, Cambridge, 365 pp.
- IPCC (Intergovernmental Panel on Climate Change) 1992. *Climate Change 1992: the Supplementary Report to the IPCC Scientific Assessment*, Houghton, J. T., Callander, B. A. and Varney, S. K. (eds), Cambridge University Press, Cambridge, 200 pp.
- Joubert, A. M. 1994. 'Simulations of southern African climatic change by early-generation general circulation models', *Water S.A.*, **20**, 315–322.
- Joubert, A. M. 1995. 'Simulations of southern African climate using early-generation general circulation models', *S. Afr. J. Sci.*, **91**, 85–91.
- Katz, R. W. and Acero, J. G., 1994. 'Sensitivity analysis of extreme precipitation events', *Int. J. Climatol.*, **11**, 505–513.
- Katz, R. W. and Brown, B. G. 1992. 'Extreme events in a changing climate: variability is more important than averages', *Climate Change*, **21**, 289–302.
- Lee, E. T. 1992. *Statistical Methods for Survival Data Analysis*, 2nd edn, Wiley, Chichester, 482 pp.
- Livezey, R. E. and Chen, W. Y. 1983. 'Statistical field significance and its determination by Monte Carlo techniques', *Mon. Wea. Rev.*, **111**, 46–59.
- McGregor, J. L., Gordon, H. B., Watterson, I. G. and Dix, M. R. 1993. *The CSIRO 9-level Atmospheric General Circulation Model*, CSIRO Division of Atmospheric Research, Technical Paper No. 26, CSIRO, Canberra, 89 pp.
- Mason, S. J. 1995. 'Climatic change over the Lowveld of South Africa', *Climate Change*, **32**, 35–54.
- Mason, S. J. and Joubert, A. M., 1997. 'Simulated changes in extreme rainfall over southern Africa', *Int. J. Climatol.*, accepted.
- Mearns, L. O., Katz, R. W. and Schneider, S. H. 1984. 'Extreme high-temperature events: changes in their probabilities with changes in mean temperature', *J. Clim. Appl. Meteorol.*, **23**, 1601–1613.
- Prescott, P. and Walden, A. T. 1980. 'Maximum likelihood estimation of the parameters of the generalised extreme-value distribution', *Biometrika*, **67**, 723–724.
- Schulze, B. R. 1984. *Climate of South Africa. Part 8: General Survey*, WB28, 5th edn, South African Weather Bureau, Johannesburg, 330 pp.
- Tyson, P. D. 1986. *Climate Change and variability in Southern Africa*, Oxford University Press, Cape Town, 220 pp.
- Tyson, P. D. 1993. 'Recent developments in the modelling of the future climate of southern Africa', *S. Afr. J. Sci.*, **89**, 494–505.
- Vogel, C. H. 1994. '(Mis)management of droughts in South Africa: past, present and future', *S. Afr. J. Sci.*, **90**, 4–5.
- Vogel, C. H. and Drummond, J. 1993. 'Dimensions of drought: South African case studied', *Geojournal*, **30**, 93–98.
- Whetton, P. H., Fowler, A. M., Haylock, M. R. and Pittock, A. B. 1993. 'Implications of climate change due to the enhanced greenhouse effect on floods and droughts in Australia', *Climate Change*, **25**, 289–318.
- Wigley, T. M. L. 1987. 'Impact of extreme events', *Nature*, **316**, 106–107.
- Wigley, T. M. L. and Jones, P. D. 1987. 'England and Wales precipitation: a discussion of recent changes in variability and an update to 1985', *J. Climatol.*, **7**, 231–246.
- Wilks, D. S. 1993. 'Comparison of three-parameter probability distributions for representing annual extreme and partial duration precipitation series', *Water Resources Research*, **29**, 3543–3549.