Simulations of Southern African climatic change by early-generation general circulation models

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Abstract

Early-generation equilibrium climate models display general agreement concerning possible changes in surface air temperature and mean sea level pressure for the Southern African region under doubled carbon dioxide conditions. There is consensus amongst the models considered that the entire region will become warmer and that tropical, subtropical and mid-latitude circulation systems will weaken and shift southward. Considerably less agreement exists concerning possible changes in precipitation. Encouragingly, though, the broad-scale features of predicted changes are in apparent agreement with the expected circulation changes. Accordingly, northern tropical areas may be expected to become wetter throughout the year. The summer rainfall region may experience wetter summers while wetter summer and drier winter conditions are expected for the winter rainfall region of the SW Cape. However, caution must be exercised in the interpretation of simulated precipitation changes over the subcontinent due to the coarse spatial resolution and simplistic parameterisation of precipitation mechanisms used in the models.

Introduction

General circulation model (GCM) simulations of global climatic change have important implications for regional climates (Gates et al., 1990; 1992). The reliability of regional simulations of climatic change depends largely on the ability of the models to simulate present conditions for a specific region accurately (Grotch and MacCracken, 1991; Karl et al., 1990; Mitchell et al., 1987; Portman et al., 1992). For Southern Africa, GCM simulations of possible future conditions have been presented previously (Tyson, 1990; 1991; 1993). Until recently, however, such predictions have not been supported by an assessment of the ability of the models to simulate present-day conditions for the region. Such an assessment of the present-climate performance of six early-generation equilibrium climate models for Southern Africa has recently been completed (Joubert, 1993; 1994), allowing for the development of more reliable scenarios of regional climatic change than was previously the case. Those models which were shown to simulate present-day surface air temperatures, mean sea level pressures and precipitation most accurately, will be used here to illustrate possible future conditions, given a doubling of the atmospheric carbon dioxide concentration.

Data and methods

The models considered here are all equilibrium climate models linked to mixed-layer slab oceans. In each case, the models are run to statistical equilibrium under present climate conditions, with current levels of atmospheric carbon dioxide (1 x CO_2). Once this equilibrium has been established, the concentration of CO_2 is instantaneously doubled (2 x CO_2) and a new equilibrium is allowed to re-establish. Climatic change may then be estimated as the difference between the mean equilibrium 1 x CO_2 and 2 x CO_2 states. The selection of models for consideration of doubled CO_2 simulations is based on the assessment presented in Joubert (1994). For surface air temperature changes, the 1984 Goddard Institute of Space Studies (GISS) 9-level model (Hansen et al., 1983; 1984), the 1987 11-level United Kingdom Meteorological Office (UKMO) model (Wilson and Mitchell, 1987) and the 1992 9-level Commonwealth Scientific and Industrial Research Organisation (CSIRO9) model (McGregor et al., 1993; Whetton et al., 1993) will be used. Only the CSIRO9 model will be considered for possible changes in mean sea level pressure. A range of models is considered for precipitation changes over the subcontinent. These are the GISS, UKMO, and CSIRO9 models, as well as the 1987 9-level Geophysical Fluid Dynamics Laboratory (GFDL) model (Manabe and Wetherald, 1987).

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Simulated data from general circulation models

Details of the various model experiments are given in Table 1. There is considerable range in the spatial resolution of the four models. The UKMO model has the highest vertical resolution (11 levels) and the CSIRO9 simulation has the finest horizontal resolution (approximately 3.2° meridionally by 5.6° zonally). Several physical processes important for an accurate simulation of present-day Southern African climate and hence for reliable predictions of future climates, are simplistically treated (Joubert, 1994). All models are linked to a simple mixed-slab ocean with no ocean currents, although horizontal heat transport is prescribed in the GISS ocean. Ocean-atmosphere heat exchange in the GISS, UKMO and CSIRO9 models is constrained by the use of a Q-flux procedure which results in an accurate representation of present-day seasonally-varying sea-surface temperatures. However, this correction prevents ocean temperature and sea ice from responding in climatic change sensitivity (doubled CO_2) experiments, thereby excluding a crucial feedback mechanism (Washington and Meehl, 1991).

The parameterisation of convection at model grid points inevitably results in a poor simulation of the magnitude of observed precipitation over the subcontinent, due to the mismatching of scale between observed and simulated events (Gordon et al., 1992). *Simulated changes in total rainfall over Southern Africa must* therefore be interpreted with caution. Cloud optical properties are held constant in both the 1 x CO_2 and 2 x CO_2 runs, effectively preventing the models from adjusting cloud radiative forcing of temperature as a result of changes in radiation associated with

TABLE 1
SPECIFICATIONS OF THE GCM EXPERIMENTS USED IN THIS INTERCOMPARISON. MODEL RESOLUTION IS GIVEN IN DEGREES (FINITE DIFFERENCE MODELS) OR WAVE NUMBER OF TRUNCATION (SPECTRAL MODELS). CONVECTION IS PARAMETERISED BY MEANS OF THE PENETRATIVE CONVECTION (PC) AND MOIST CONVECTIVE ADJUSTMENT (MCA) SCHEMES. CLOUDS ARE PREDICTED FROM RELATIVE HUMIDITY (RH). ALL MODELS HAVE FIXED CLOUD RADIATIVE PROPERTIES (F). EQUILIBRIUM CO_2 CONCENTRATIONS ARE GIVEN IN PPM. GLOBALLY-AVERAGED WARMING AS A RESULT OF CO_2 DOUBLING IS GIVEN IN °C (AFTER CUBASCH AND CESS, 1990 AND McGREGOR ET AL., 1993)

	GISS (1984)	GFDL (1987)	UKMO (1987)	CSIRO9 (1992)
Horizontal resolution	7.8 x 10.0	R15	5.0 x 7.5	R21
Model levels	9	9	11	9
Seasonal cycle	Yes	Yes	Yes	Yes
Diurnal cycle	Yes	No	Yes	Yes
Cloud scheme	RH	RH	RH	RH
Cloud properties	F	F	F	F
Convection scheme	PC	MCA	PC	MCA
Oceanic Q-flux	Yes	No	Yes	Yes
Number of model years	10	10	15	10
1 x CO_2 concentration	315	300	323	330
Globally-averaged warming °C	4.2	4.0	5.2	4.8

TABLE 2
OVERALL TEMPERATURE CHANGE FOR THE SOUTHERN AFRICAN REGION (2 X CO_2 MINUS 1 X CO_2) EXPRESSED AS A ROOT MEAN SQUARE ERROR (IN °C). THE SIGNIFICANCE OF MEDIAN DIFFERENCES BETWEEN 1 xCO_2 AND 2 x CO_2 SIMULATIONS FOR THE GISS AND UKMO SIMULATIONS IS CALCULATED USING THE WILCOXON MATCHED PAIRS SIGNED RANKS TEST. FOR THE CSIRO9 SIMULATION, STATISTICAL FIELD-SIGNIFICANCE IS INDICATED.

	January		July	
	rms error	**significance**	**rms error**	**significance**
GISS	4.06	99	4.27	99
UKMO	5.35	99	5.75	99
CSIRO9	4.11	99	4.94	99

increasing concentrations of greenhouse gases, including CO_2 (Harrison et al., 1990). Nonetheless, globally-averaged warming predicted by these models (Table 1) falls broadly within the range of 1.9 to 5.2°C described by the Intergovernmental Panel on Climate Change (IPCC) (Gates et al., 1990).

Statistical methods

Grid-point differences between 1 x CO_2 and 2 x CO_2 fields, as well as an overall measure of differences over the field as a whole using a root mean square (rms) error, are calculated. Testing for the significance of differences is, however, problematic (Wigley and Santer, 1990). As mean values only are available for the GISS, GFDL and UKMO models, no estimate of the variability in a given field is available. Tests for the significance of median differences between 1 x CO_2 and 2 x CO_2 simulations using the Wilcoxon matched pairs signed ranks test used here as in Joubert (1994) do not account for the presence of spatial autocorrelation in a given field and hence are likely to over-estimate significance for the field as a whole. Where estimates of the variability in the field are available, as is the case for the CSIRO9 model, the problem may be overcome by using permutation or Monte Carlo methods (Livezey and Chen, 1983) to calculate field significance. Ten years of simulated data for both the 1 x CO_2 and 2 x CO_2 runs from CSIRO9 were available, allowing field significance to be calculated using a pooled permutation procedure (Preisendorffer and Barnett, 1983; Wigley and Santer, 1990). The pooled permutation procedure combines the two 10-year samples and then divides the new subset of 20 years randomly into two new 10-year samples. Test statistics (in this case, a standard t-test) are then recalculated in a series of randomisations, thus generating a null sampling distribution against which the actual test statistic can be compared. The procedure accounts for problems of significance testing associated with spatial autocorrelation, unknown sampling distributions and multiplicity (Wigley and Santer, 1990).

Results

Changes in surface air temperature

Each of the GISS, UKMO and CSIRO9 models simulate widespread temperature increases over the Southern African region (Fig. 1). In both January and July, the consensus between the models is for a warming of 4°C to 6°C over the region as a whole (Table 2). Estimated temperature increases for all three models are highly significant (at the 99 per cent confidence level). For the CSIRO9 model, grid-point t-tests are significant throughout the region, with field significance exceeding 99.9 per cent.

Within the tropics, warming may be expected to be lower than either the global or regional average, varying little with the season. The GISS and CSIRO9 models suggest warming of 2°C to 4°C in both January (Fig. 1a,e) and July (Fig. 1b,f). In contrast, the UKMO model indicates that warming may be as high as 4°C to 6°C (Fig. 1c,d). Over the drier areas of the central subcontinent, simulated temperature increases are larger than within the tropics or the adjacent oceans. In January, the GISS and CSIRO9 models suggest temperature increases of between 4°C and 5°C. Temperature increases in mid-winter are generally larger than in mid-summer over the central subcontinent, with estimates in July by all three models exceeding 6°C (Fig. 1b,d,f). As in the tropics, temperature increases simulated by the UKMO model (in excess of 6°C in both January and July) are larger than predictions by either the GISS or CSIRO9 models.

Over the oceanic areas to the south of the subcontinent, all models simulate large temperature increases (in excess of 5°C) throughout the year (Fig. 1). As over the subcontinent, the temperature increases are also larger in mid-winter than in mid-summer. In July, the UKMO and CSIRO9 models simulate increases greater than 7°C south of 40°S, exceeding 10°C south of 60°S (not shown).

Changes in mean sea level pressure

In January (Fig. 2a) and July (Fig. 2b), the CSIRO9 model simulates a decrease in pressure over the subcontinent and adjacent oceans, with a band of increased pressure over the southern oceans. Estimated pressure changes indicate a weakening of both the South Atlantic and Indian Anticyclones, as well as the mid-latitude westerly circulation to the south of the subcontinent. As a result, the simulated equator-pole pressure gradient is reduced. At subtropical latitudes, grid-point pressure decreases are generally significant (at the 95 per cent confidence level) in both January and July. The increase in pressure over the southern oceans is significant in January, but not in July. The pattern of mean sea level pressure change is also field-significant (above 95 per cent) in January, but not in July.

Changes in precipitation

Changes in seasonal precipitation during the January-March summer and July-September winter season indicate that none of the models simulate spatially homogeneous changes over the subcontinent as a whole (Fig. 3). Furthermore, the GISS, GFDL, UKMO and CSIRO9 models display little inter-model agreement concerning possible changes over all three of the tropical, summer and winter rainfall regions defined by Joubert (1994, his Fig. 5).

The summer rainfall region comprises most of the Southern African subcontinent. During both the January-March (Fig. 3a,c,e,g) and July-September (Fig. 3b,d,f,h) seasons, the pattern of precipitation change over much of the region is patchy. The GISS, GFDL, UKMO and CSIRO9 models all suggest locally-specific increases and decreases in precipitation over the region, but demonstrate little agreement concerning possible changes for the region as a whole. During the January to March season (Fig. 3a,c,e,g), precipitation may generally be expected to increase by 10 to 20 per cent, with increases simulated by the UKMO and CSIRO9 models (Fig. 3e, g) exceeding 50 per cent in certain areas. For the CSIRO9 model, changes in January to March rainfall are not field-significant above 95 per cent, with only individual grid-point increases significant above the 95 per cent confidence level (Fig. 3g). Precipitation averages for the region (Fig. 4) indicate that daily precipitation rates will increase throughout the summer, with strongest increases during the January to March summer season.

Locally-specific precipitation increases of approximately 20 per cent in the summer rainfall

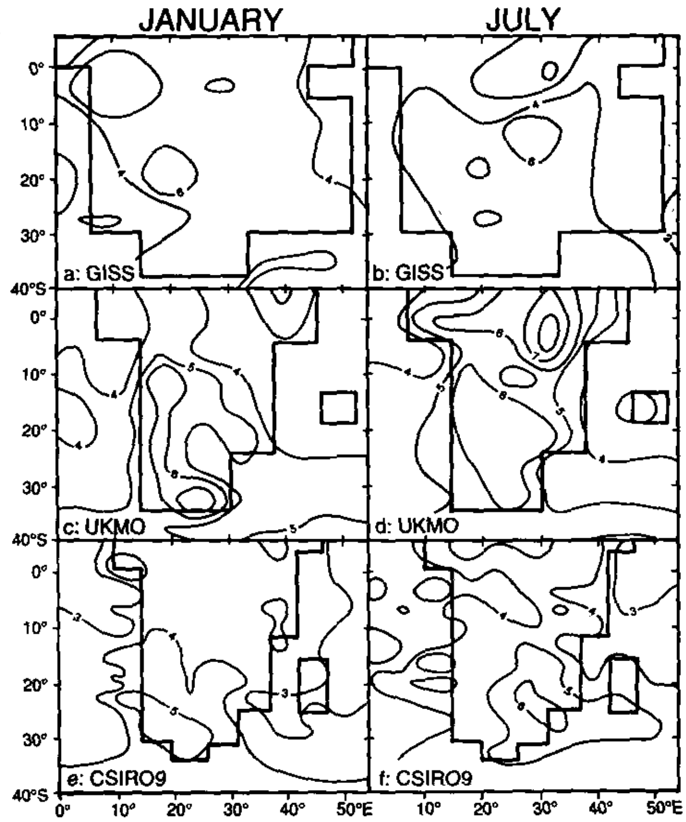

Figure 1

Calculated surface air temperature differences (2 x CO_2 minus 1 x CO_2) in January (a, c, e) and July (b, d, f) for the GISS (a and b), UKMO (c and d) and CSIRO9 (e and f) models, respectively (in °C). For the CSIRO9 model, grid point changes are significant at the 95 per cent confidence level throughout the region and are therefore not shaded.

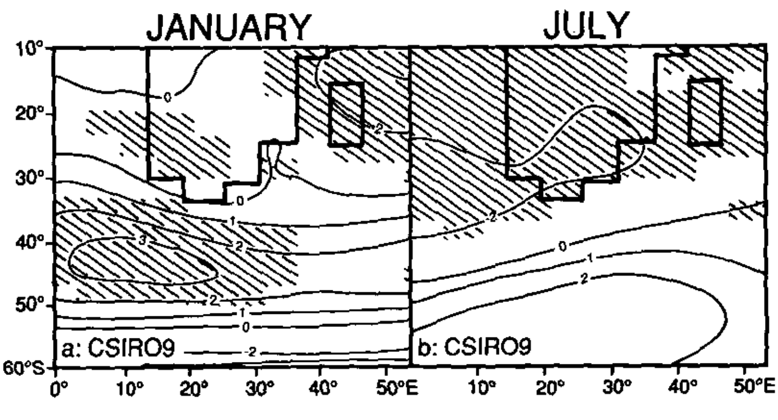

Figure 2

Changes in mean sea level pressure (2 x CO_2 minus 1 x CO_2) in January (a) and July (b) for the CSIRO9 simulation. Changes significant at the 95 per cent confidence level are shaded.

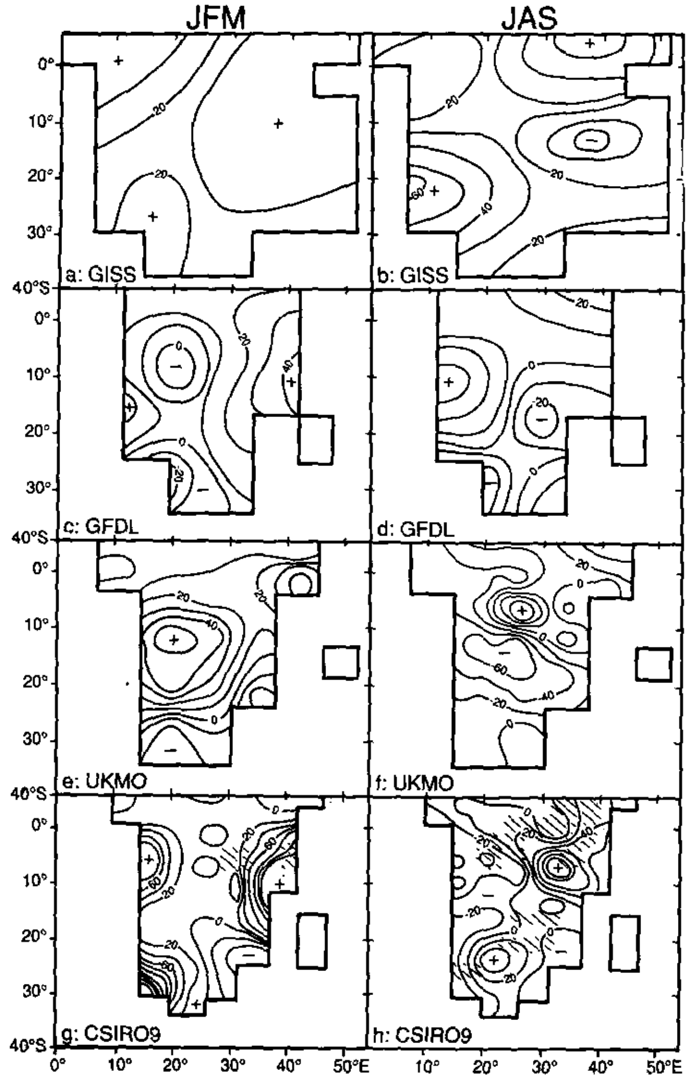

Figure 3
January to March (JFM) and July to September (JAS) seasonal changes in rainfall (2 x CO_2 minus 1 x CO_2) for the GISS (a,b), GFDL (c,d), UKMO (e,f), and CSIRO9 (g,h) models, expressed as a percentage. For the CSIRO9 model, changes significant at the 95 per cent confidence level are shaded.

region are also simulated during the July to September season (Fig. 3b,d,f,h). As in the January to March season, few grid-point increases in the CSIRO9 model are significant (Fig. 3h), and precipitation changes are not field-significant. The simulated increase by the UKMO model (Fig. 3f) is again larger than for the other models. Regionally-averaged precipitation rates for July to September (Fig. 4) reflect the patchiness in the overall pattern of change over the summer rainfall region, indicating relatively small changes in average daily precipitation. Most models predict small decreases in average daily precipitation (less than 0.5 mm/d) during July to September. Such changes are not expected to have a significant impact on regional climate as rainfall receipts remain low during winter and therefore the simulated changes do not represent a change in the annual rainfall cycle nor in the strong summer rainfall maximum for the region.

The GISS, GFDL, UKMO and CSIRO9 models display greater consensus in their simulations of precipitation change within the tropical rainfall region (north of 10°S). Simulated increases in precipitation of between 10 and 20 per cent vary only slightly between the models, both spatially and with the seasons (Fig. 3). Each of the models suggest regionally-averaged increases in daily precipitation in the order of 1 mm/d (Fig. 5). The GISS and GFDL models (Fig. 5a,b) simulate increases throughout the year whilst the UKMO and CSIRO9 models (Fig. 5c,d) simulate small decreases during the winter months. No change is expected in the semi-annual cycle of the tropical rainfall region, although the UKMO and CSIRO9 simulations suggest that the amplitude of this cycle may increase.

Little consensus is achieved for estimates of change in the winter rainfall region of the SW Cape (Fig. 3). As this region is represented by no more than two model grid points in any simulation, simulated changes are of necessity locally-specific and must be interpreted with caution. In the January to March season, the GFDL and UKMO models (Fig. 3c,e), estimate decreases in precipitation of approximately 20 per cent, while the GISS and CSIRO9 models (Fig. 3a,g) suggest that rainfall may increase (by in excess of 100 per cent in the CSIRO9 model). During July to September the GFDL, UKMO and CSIRO9 models (Fig. 3d,f,h) each simulate decreases in rainfall of approximately 20 per cent. In the case of the

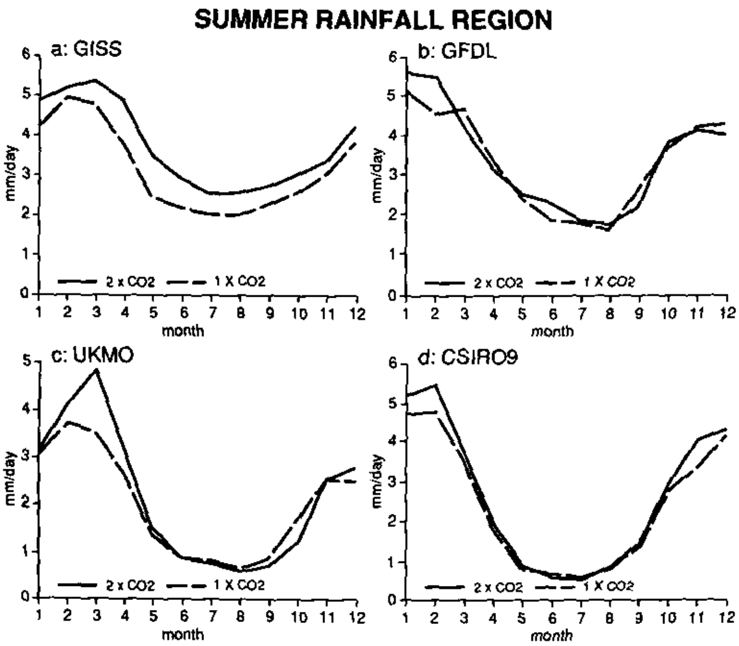

Figure 4
Simulated present-day and doubled CO_2 precipitation rates (in mm/d) for the GISS (a), GFDL (b), UKMO (c) and CSIRO9 (d) models for the summer rainfall region (defined in Joubert, 1994, his Fig. 5).

CSIRO9 model, this decrease is locally significant at the 95 per cent confidence level. In contrast, the GISS simulation indicates an increase in seasonal rainfall of 20 to 30 per cent. Regionally-averaged changes in daily precipitation for the region (Fig. 6) are not well-defined, suggesting both small increases and decreases throughout the year. However, the UKMO and CSIRO9 models (*Fig. 6c,d) both indicate daily precipitation increases in* summer and decreases in winter.

Discussion

The GISS, UKMO and CSIRO9 models agree on the general patterns of surface air temperature change over the Southern African region, simulating temperature increases which range from 4°C to 6°C under doubled CO_2 conditions. This range exceeds the IPCC "Business as Usual" scenario for globally-averaged warming (Mitchell et al., 1990), but is in good agreement with expected warming simulated for the Australian region (Whetton and Pittock, 1991). Overall, simulated warming is greatest for the UKMO model. This model has a higher sensitivity to CO_2-doubling than the GISS and CSIRO9 models (Table 1). Furthermore, a more recent version of the UKMO model with an improved cloud formulation has been shown to simulate much-reduced zonally-averaged warming for the latitude of the Southern African region (Mitchell et al., 1989). It is likely therefore, that warming simulated by the 1987 version of the UKMO model presented here is excessive and unrealistic as an estimate of future conditions.

In the tropics, estimated warming is lower than both the global and regional averages, and does not vary greatly with the season. On theoretical grounds, a lower estimate of temperature increase would result from the fact that the saturation vapour pressure of water increases non-linearly with temperature so that, at higher temperature, proportionally more of the increase in radiative heating of the surface is used to increase evaporation than is used to raise the surface temperature (Mitchell et al., 1990). Surface warming within the tropics is thus reduced relative to both regional and global averages because of enhanced evaporative cooling. Inter-model differences in the pattern of simulated warming in the tropics may be attributed to differences in the treatment of convection (Schlesinger and Mitchell, 1987), the choice of cloud radiative properties (Cess and Potter, 1988) and also the vertical distribution of model layers (Wetherald and Manabe, 1988).

Over the drier areas of the central subcontinent, warming in excess of 5°C occurs in all models in both January and July. Where the land surface is sufficiently dry to inhibit evaporation, further drying leads to a reduction of evaporation and hence evaporative cooling, resulting in further warming of the land surface (Mitchell et al., 1990). Consequently, largest simulated temperature increases occur during the dry winter months. Evaporative cooling is further reduced in the absence of cloud formation, leading to simulated temperature increases by the GISS and CSIRO9 models in excess of 6°C and in excess of 8°C by the UKMO model.

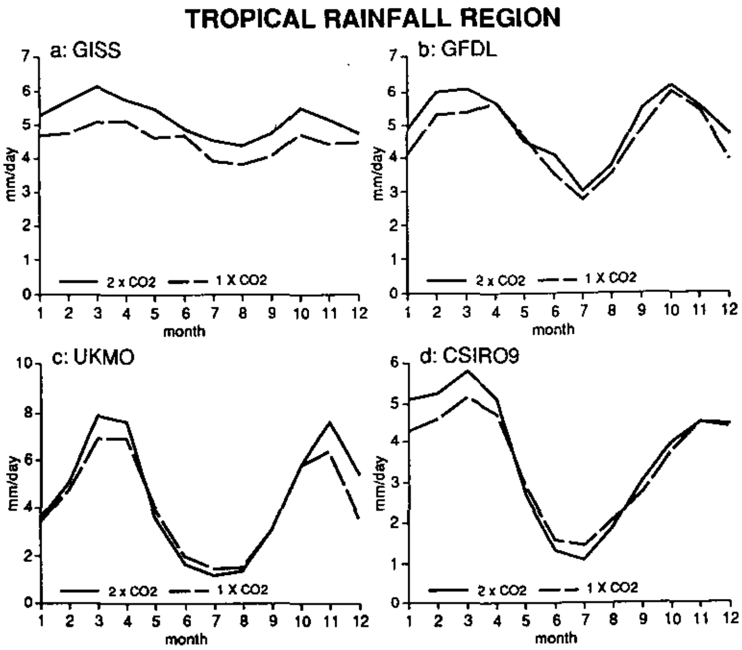

Figure 5

Simulated present-day and doubled CO_2 precipitation rates (in mm/d) for the GISS (a), GFDL (b), UKMO (c) and CSIRO9 (d) models for the tropical rainfall region (defined in Joubert, 1994, his Fig. 5).

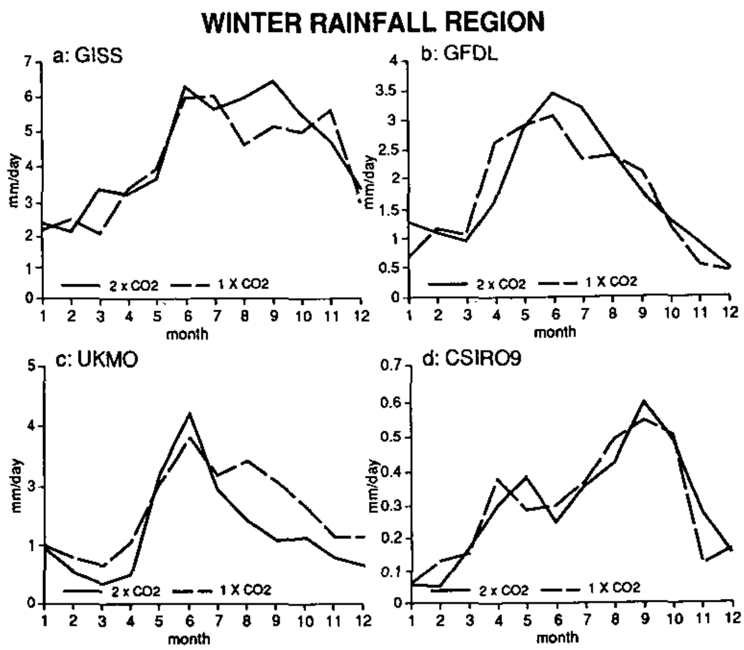

Figure 6

Simulated present-day and doubled CO_2 precipitation rates (in mm/d) for the GISS (a), GFDL (b), UKMO (c) and CSIRO9 (d) models for the winter rainfall region (defined in Joubert, 1994, his Fig. 5).

The considerable warming at high latitudes observed in all three simulations is a manifestation of errors in the specification of sea-ice albedo feedback, and a strong winter temperature inversion which limits warming to the near-surface layer in each of the models (Mitchell, 1989). Under actual conditions of increasing CO_2 concentration, such high latitude warming is unlikely. In more recent simulations with coupled ocean-atmosphere models (Cubasch et al., 1993; Manabe et al., 1991; 1992; Meehl et al., 1993; Stouffer et al., 1989; Washington and Meehl, 1989) this problem has been overcome due to the formation of deep water in the oceans, resulting in considerably reduced warming at higher latitudes (Gates et al., 1992). Nonetheless, an important consequence of the high-latitude warming simulated by equilibrium climate models linked to mixed-layer slab oceans is the significant decrease in the meridional temperature gradient under doubled CO_2 conditions. The weaker latitudinal temperature gradient implies a weaker north-south pressure gradient and thus a weakening of the mid-latitude westerly circulation, both at the surface and in the upper atmosphere (Mitchell et al., 1990).

Important uncertainties remain in the simulation of surface air temperature changes under doubled CO_2 conditions. In particular, the models considered here all provide a highly simplistic treatment of cloud radiative feedbacks, holding cloud optical properties fixed in both their present-day and doubled CO_2 simulations. This effectively prevents cloud radiative feedbacks from reacting to changes in cloud microphysics and hence changes in radiative forcing as a result of increasing CO_2 concentrations (Cess et al., 1990; Harrison et al., 1990). The sensitivity of regional climatic change simulations to the treatment of physical processes may be illustrated with reference to the recent UKMO run discussed earlier, which included an improved cloud formulation (using a variable cloud water scheme) and cloud radiative properties (Mitchell et al., 1989). The modified UKMO model demonstrated considerably reduced globally-averaged warming. By implication therefore, the more sophisticated treatment of cloud radiative forcing of temperature in the 1989 UKMO model may be expected to alter and possibly reduce estimates of regional temperature change. Furthermore, as this more sophisticated parameterisation may result in lower temperature increases, the estimates by the simpler models considered in this analysis must be interpreted with circumspection.

The CSIRO9 simulation suggests a weakening of both the subtropical anticyclones and the mid-latitude circulation under doubled CO_2 conditions. The resulting southward migration of the subtropical high pressure belt and associated trade winds and mid-latitude westerlies occurs in response to the large high-latitude warming and consequent decrease in the meridional temperature gradient (Pittock and Salinger, 1982). These results closely resemble doubled CO_2 changes predicted by the CSIRO 4-level model for the Australian region (Whetton and Pittock, 1991) and are consistent with expected changes for the entire Southern Hemisphere (Mitchell et al., 1990). More recent equilibrium climate simulations, also using mixed-layer slab-ocean models which similarly include increased horizontal resolution and a gravity wave drag term, produce doubled CO_2 estimates of mean sea level pressure change which are similar to that of the CSIRO9 model (Mitchell, et al., 1989). In addition, whilst transient simulations with fully coupled ocean-atmosphere models simulate less high latitude warming and therefore improved meridional temperature and pressure gradients, simulated changes in mean sea level pressure are generally similar to the estimates by the CSIRO9 model considered here (Gates et al., 1992).

The approach adopted in this paper has been to examine grid-point changes in mean sea level pressure. An alternative approach is to use the present-day mean sea level pressure field to develop empirically-derived relationships between the large-scale circulation and climate (Hewitson and Crane, 1992). Accurate transfer functions which describe the circulation-temperature relationship over North America in the GISS 4° x 5° GCM have been developed (Hewitson and Crane, 1992). Attempts to describe similar circulation-temperature and circulation-precipitation relationships for the Southern African region have proved more difficult due to the relatively poor simulation of mean sea level pressure by the GISS model in this region (Hewitson, 1993). However, the application of observed circulation-climate relationships to the doubled CO_2 circulation does not rely directly on accurate grid-point simulation of present mean sea level pressure conditions and may prove more successful in the development of reliable regional-scale climatic change predictions as a whole.

Simulated changes in seasonal rainfall patterns are generally consistent with predicted circulation changes over Southern Africa by each of the GISS, GFDL, UKMO and CSIRO9 models. The southward shift of the tropical rainbelt observed in, for example, the GISS model (Hansen et al., 1984), leads to rainfall increases over tropical Southern Africa. On a theoretical basis, increased precipitation in the tropics may be expected as a consequence of the generally moister tropical atmosphere expected under doubled CO_2 conditions (Mitchell et al., 1990). Warming of the lower atmosphere within the tropics results in an increase in the moisture-holding capacity of the atmosphere. The increased moisture leads to an increased moisture flux into regions of low level convergence (such as the Intertropical Convergence Zone) and therefore increased precipitation. Subsequent rainfall increases during the late summer over the central subcontinent are due to increased moisture availability from the tropics. In addition, possible drier conditions during winter over the SW Cape may be associated with the southward shift of the mid-latitude storm track. This pattern of precipitation change is consistent with predictions by this generation of models for the Australian region (Whetton and Pittock, 1991) and for the Southern Hemisphere as a whole (Mitchell et al., 1990).

The use of four different precipitation simulations has allowed intercomparison of a range of predictions. Considerably less inter-model agreement exists concerning changes in precipitation over the subcontinent than for changes in surface air temperature. Gates et al. (1990) suggest there are two reasons for this. Firstly, precipitation changes are the indirect result of several different processes in the models, many of which are not resolved at model resolution, whereas temperature changes are primarily a direct response to increased radiative heating. Secondly, changes in precipitation represent fairly small deviations from the natural variations and are therefore more difficult to detect, given the short sampling period (only 10 years) available for this study.

Estimated changes over much of Southern Africa south of 10°S have been shown to be grid-point specific, suggesting that the accuracy of such simulations is adversely affected by the coarse horizontal resolution of the models. Given the coarse horizontal resolution and simplistic parameterisation of precipitation mechanisms (particularly cumulus convection) used in this generation of models, changes in precipitation of convective origin (predominant over the central subcontinent during summer) cannot be accurately simulated for specific regions (Gates et al., 1990; 1992). In summary, therefore, little certainty can be expressed in predictions of precipitation for Southern Africa by the models considered for this analysis.

A more valuable approach to predicting changes in rainfall may be to examine changes in rainfall intensity and not total rainfall

(Gordon et al., 1992). Two studies using the 4-level (Gordon et al., 1992) and 9-level CSIRO (Whetton et al., 1993) models respectively, suggest that changes in rainfall intensity provide more spatially homogeneous signals than do changes in total rainfall. Both studies indicate that an increase in the frequency of extreme rainfall events combined with a shorter return period for extreme events, as well as a decrease in the frequency of low-rainfall events may be expected with CO_2 doubling. Similar studies remain to be performed for the Southern African region.

While the early-generation general circulation models considered in this analysis exhibit considerable agreement concerning possible changes in surface air temperature and mean sea level pressure under doubled CO_2 conditions, predictions of regional precipitation change have been shown to be less reliable. However, the analysis has identified uncertainties associated with the parameterisation of physical processes which are important for prediction of climatic change over Southern Africa.

More recent general circulation model simulations with improvements in spatial resolution as well as the parameterisation of regionally-important physical processes have resulted in more accurate representations of global climate and global climatic change. Greater reality has been achieved in the simulation of the global climate system and of the processes responsible for climatic change. The most notable development of this kind has been the use of transient simulations with gradually-increasing CO_2 concentrations, linked to fully coupled ocean-atmosphere general circulation models (Cubasch et al., 1993; Manabe et al., 1991; 1992; Meehl et al., 1993; Stouffer et al., 1989; Washington and Meehl, 1989; 1991). These more sophisticated simulations generally confirm the predictions of global change of the early-generation equilibrium climate models (Gates et al., 1992). Predictions of globally-averaged warming fall within the range of the IPCC "Business as Usual" scenario based on the earlier simulations and the large-scale patterns of change predicted by the fully coupled models are similar to those of the equilibrium experiments presented here (Gates et al., 1992). As there is a need to make predictions of global climatic change specific to the Southern African region, further studies such as these presented here, but based on the newer generation of models, need to be performed in order to develop more reliable estimates of regional climatic change for Southern Africa.

Conclusions

The four equilibrium models considered in this paper display general agreement concerning possible changes in surface air temperature and mean sea level pressure for the Southern African region under doubled CO_2 conditions. It appears fairly certain that the entire region will become warmer and that tropical, subtropical and mid-latitude circulation systems will shift southward. Considerably less certainty exists concerning possible changes in precipitation. Encouragingly, the broad-scale features of predicted changes in precipitation are in apparent agreement with predicted circulation changes. Accordingly, tropical areas may be expected to become wetter, with wetter summers for the summer rainfall region and possibly drier conditions for the winter rainfall region of the SW Cape. However, large uncertainties in the simulations of precipitation change are related to the coarse horizontal resolution and simplistic parameterisation of precipitation mechanisms over the subcontinent by the early-generation general circulation models considered here.

More recent general circulation models incorporating improved physical parameterisations, increased spatial resolution and more realistic simulations of the process of climatic change may be expected to simulate future conditions with greater reliability than was hitherto the case. In particular, transient simulations with gradually increasing CO_2 concentrations, linked to fully coupled ocean-atmosphere models, represent a significant advance in the modelling of climatic change. The development of reliable predictions of climatic change for the Southern African region will benefit by extending the analysis presented in this paper to the more recent generation of general circulation models.

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