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AGROHYDROLOGICAL SENSITIVITY ANALYSES WITH REGARD TO PROJECTED CLIMATE CHANGE IN SOUTHERN AFRICA

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AGROHYDROLOGICAL SENSITIVITY ANALYSES WITH REGARD TO PROJECTED CLIMATE CHANGE IN SOUTHERN AFRICA

by

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ABSTRACT

Climate change resulting from the augmented "greenhouse effect" is likely to have significant effects on the terrestrial hydrological system and the social and ecological systems linked to it. Climate change could potentially affect inputs to the agrohydrological system such as rainfall, temperature and potential evaporation; processes within the system such as vegetation dynamics and crop production; and hydrological responses such as runoff, recharge of soil water into the vadose zone and net irrigation demand. This study outlines the use of a daily water budget model, *ACRU*, and SCENGEN, a climate change scenario generator, to assess potential impacts of global climate change on agricultural production and hydrological responses in southern Africa. This study also considers potential impacts of climate change on plant response which may determine the extent of potential impacts of climate change on agricultural production and hydrological response. Two approaches to climate change impact studies are adopted for use in this study. The first, and more conventional approach considers the impact of a specified climate change scenario, in this case developed with the use of SCENGEN, on the terrestrial hydrological system. The second approach considers the degree of climate change, in this case precipitation change, required to perturb the hydrological system significantly in the various climate regimes found in southern Africa. A comparative analysis of the sensitivity of selected hydrological responses to climate change produced the following results, in ascending order of sensitivity: net irrigation demand < stormflow response < runoff < recharge into the vadose zone. The impacts of a specific climate scenario change on hydrological responses produced unexpected results. A general decrease in mean annual precipitation over southern Africa is predicted for the future with SCENGEN. However, widespread simulated increases in runoff, soil moisture content in the A- and B-horizon and recharge into the vadose zone are obtained. These increases are a product of the CO_2 "fertilisation" feedback, which is incorporated as a maximum transpiration suppression routine, in the *ACRU* model. Net irrigation demand, which is not linked to this routine, is simulated to increase in the future.

PREFACE

The research work presented in this dissertation was carried out through the School of Environment and Development, but within the Department of Agricultural Engineering, both of the University of Natal in Pietermaritzburg, from August 1996 to February 1997, under the supervision of Professor Roland Schulze and co-supervision of Mr Gregory Kiker, both from the Department of Agricultural Engineering, University of Natal, Pietermaritzburg.

I wish to certify that the research reported in this dissertation is my own original and unaided work except where specific acknowledgement is given, and that no part of this dissertation has been submitted in any form for any degree or diploma to another University.

Signed

Kerry L. Lowe

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CHAPTER 1

INTRODUCTION

The natural "greenhouse effect" is responsible for regulating the earth's surface temperature by means of "greenhouse gases" in the atmosphere which block outgoing infrared radiation from the earth's surface while allowing for the penetration of incoming solar radiation through the atmosphere (Sulzman, Poiani and Kittel,1995). An increase in anthropogenic activities such as fossil fuel burning over the past decades has resulted in elevated levels of radiatively active greenhouse gases in the atmosphere, causing a potential increase in absorption of infrared radiation. The global repercussions of these activities include a potential imbalance in the earth's radiation budget, depletion of the ozone layer and acid rain. An anthropogenically induced disturbance of the natural "greenhouse effect", termed the augmented "greenhouse effect", could result in increased warming at the earth's surface, which in turn could affect other climatic variables such as rainfall and evaporation. The rapid accumulation of radiatively active atmospheric gases resulting from human activities and development of the planet has a variety of impacts at every scale: local, regional and global (Graedel and Crutzen,1993).

The objectives of this study are to assess regional impacts of, and sensitivities to, global climate change in southern Africa (defined for the purposes of this study as being the Republic of South Africa plus Lesotho and Swaziland) on agricultural production and hydrological responses by:

i. examining evidence supporting how humanity could be altering the earth's climate (cf. Chapter 2),

ii. considering potential scenarios of future climate change in southern Africa (cf. Chapter 3),

iii. analysing the effects of potential climate change on plant response (cf. Chapter 4),

iv. describing the modelling techniques, system infrastructure and general methodologies used to assess potential impacts of global climate change on a regional scale in southern Africa (cf. Chapter 5) and assessing the potential impacts of global climate change on agricultural production (cf. Chapter 6) and hydrological responses (cf. Chapter 7) in southern Africa.

Two approaches to climate change impact studies are utilised in this study. The first, and more conventional approach considers the impact of a specified climate change scenario, developed in this instance using SCENGEN, on hydrological response and agricultural production. The second approach considers the effect of a change in precipitation on hydrological responses. This approach is adopted to ascertain the sensitivity of the hydrological system to climate change, particularly with regard to precipitation, the magnitude and direction of which is still poorly understood from atmospheric modelling studies.

The need to study the impacts of climate change are well described by Hare (1988) who stated that the impacts of climate change were "..the central environmental problem of our times.." and that its consequences were "..probably more drastic than any other challenge facing mankind..".

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The following chapter describes the natural "greenhouse effect" and how anthropogenic activities are believed to increase concentrations of radiatively active "greenhouse gases" which may augment this effect.

CHAPTER 2
THE GREENHOUSE EFFECT

The "greenhouse effect", a natural process responsible for regulating the earth's overall temperature, is influenced primarily by the concentration of the atmospheric trace gases known as the "greenhouse gases". A consequence of an increase in greenhouse gas levels as a result of human activities is a perturbation of this natural phenomenon, resulting in a possible change in the earth's climate. The consequences of such climate changes are reviewed in the following chapters. This chapter, however, explains the mechanism of the greenhouse effect.

2.1 The Natural Greenhouse Effect

While the possibility of human-induced global climate change remains an issue of much debate, the natural greenhouse effect is a well-established phenomenon based on sound scientific principles. The natural greenhouse effect is the warming of the earth due to the presence of gases that block outgoing infrared radiation from the earth's surface, while allowing the penetration of incoming solar radiation through the atmosphere (Sulzman, Poiani and Kittel,1995). This effect maintains the earth's surface temperature at approximately 15°C and is described in more detail below.

Solar radiation originates from the sun as shortwave radiation (SWR). Radiation of this wavelength range is relatively transparent to atmospheric gases and thus is not absorbed upon entering the atmosphere. Such incoming radiation may, however, be scattered by clouds and dust particles present in the atmospheric layers, thereby preventing a portion of the incoming SWR from reaching the earth's surface. As a result, incoming SWR constitutes only about 32% of the total radiation which warms the earth's surface (Hare,1988).

Infrared radiation originates from the earth's warmed surface as longwave radiation (LWR). All bodies with a temperature above 0°C emit infrared radiation. This is necessary to balance the incoming solar radiation and prevent overheating of the earth's surface. Outgoing LWR is not transparent to certain atmospheric gases, namely the "greenhouse gases". These are primarily carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), chlorofluorocarbons (CFCs), ozone (O_3) and water vapour. Consequently a portion of the outgoing LWR is absorbed by these gases and re-radiated back to the earth's surface. The remaining 68% of the total radiation which warms the earth's surface is contributed by that portion of infrared radiation which is re-radiated (Hare,1988).

The issue of debate is not the natural greenhouse effect itself, but rather the long-term effect of anthropogenic activities resulting in elevated levels of radiatively active greenhouse gases in the atmosphere, which could cause an imbalance in the earth's radiation budget (Sulzman *et al.*,1995). This imbalance is termed the AUGMENTED GREENHOUSE EFFECT and has the potential to initiate changes in climate at a global scale, the extent of which is not yet fully understood.

2.2 The Augmented Greenhouse Effect

Outgoing LWR is emitted primarily in a band from 4-100 μm (Shuttleworth,1994). Water vapour in the atmosphere absorbs radiation in a band from 4-7 μm, and CO_2 absorbs in a band from 13-20 μm. This creates a natural band from 7-13 μm through which 70% of the earth's radiation can escape into space. If the amount of water vapour, incoming solar radiation and CO_2 were to remain constant, then an equilibrium would be reached. Elevated levels of greenhouse gases, particularly over the past century, could have disturbed this equilibrium as these gases have been found to absorb radiation in the band from 7-13 μm. This has the effect of potentially increasing the amount of LWR re-radiated to the earth's surface.

Elevated levels of greenhouse gases result from anthropogenic activities associated with an increasing global population, and include biomass burning, fossil fuel combustion, land use changes such as deforestation, agricultural practices, industrialisation and the use of CFCs for blowing agents, propellants, solvents and refrigerants (Sulzman *et al.*,1995). The ozone layer, an important filter of ultraviolet (UV) radiation from the sun, is destroyed by the products of certain greenhouse gases (Graves and Reavey,1996). Its destruction reduces the atmosphere's ability to filter incoming solar radiation, thus further disturbing the radiation budget.

Initially, the Industrial Revolution in the 17th century was slow to develop and was geographically localised. However, industrial growth has increased exponentially in the 50 years since World War II. This has resulted in an increased demand for energy sources such as fossil fuels to support new industries and to provide for the domestic needs of an expanding population (Graves and Reavey,1996). Consequently, atmospheric concentrations of CO_2 have risen rapidly since the Industrial Revolution and at an exponential rate since the 1950s. CO_2 currently contributes 56% of the augmented greenhouse effect (AGE) and is increasing at approximately 0.5% per annum (IPCC-WGI,1990). The pre-Industrial CO_2 concentration of 280 ppmv is expected to have doubled to 560 ppmv by the 2050s decade (Hulme,1996).

The Earth Summit meeting in Rio de Janeiro in 1992 was an attempt by members of the global community to regulate CO_2 emissions (Graves and Reavey,1996). However, countries with economies in transition, primarily developing countries, are initially expected to increase their emission rate of greenhouse gases as their economy grows and consumer behaviour becomes more closely aligned to patterns in western Europe. Climate change is generally not a major concern in developing countries; rather, it is realised that greenhouse gas emission mitigation will provide benefits in terms of development of new technologies and measures that are often more economically beneficial, whilst also benefitting the environment (Sadowski, Meyers, Mullins, Sathaye and Wisniewski,1996). South Africa's economy is reliant on coal as an energy source. This situation is unlikely to change significantly in the near future. Consequently, the increase in CO_2 emissions from use of coal, coupled with an increase in atmospheric opacity resulting from coal combustion, could cause an increase in the amount of LWR re-radiated to the earth's surface.

CH_4 levels have doubled in the past 300 years and increased by about 53% since the 1940s (Sulzman *et al.*,1995). CH_4 continues to increase at a rate of approximately 0.9% per annum and contributes 11% of the AGE (IPCC-WGI,1990). CH_4 has a half life of approximately 10 years in the atmosphere. Owing to the relatively short half life of CH_4, the beneficial effects of mitigation measures are likely to be apparent within a short period of time (Pipatti, Savolainen and Sinisalo,1996).

N_2O is increasing at a rate of 0.3% per annum (Pearman,1989) and contributes 6% of the AGE (IPCC-WGI,1990). Photolytic breakdown of N_2O in the stratosphere results in the production of nitrogen oxide (NO_2), which participates in the destruction of stratospheric ozone (Pipatti *et al.*,1996). N_2O has a half life of 130-150 years, longer even than that of CFCs.

CFCs, which are entirely human-made and were absent from the atmosphere prior to the 1930s, are divided into two major categories: CFC_{12} and CFC_{11}. Both are increasing at a rate of 4% per annum (IPCC-WGI,1990), but CFC_{12} contributes 6%, whereas CFC_{11} contributes only 3% to the AGE (Sulzman *et al.*,1995). The rate of increase of CFCs was fairly constant during the 1980s, only beginning to decrease in the 1990s, owing to the implementation of the London amendments of 1990 to the Montreal Protocol of 1987, which called for the phasing out of CFCs by 1996 and halochlorofluorocarbons (HCFCs) by 2030 (Brune,1996). However, the half life of these molecules ranges from 75-110 years, and thus they may continue to have an effect on global climate for many decades. CFCs enter the stratosphere where UV radiation and subsequent photochemistry of the molecules results in the production of chlorine monoxide - an ozone destroyer (Brune,1996).

Ozone is increasing at a rate of 0.5% per annum and contributes 2% of the AGE (Pearman,1989). Ozone is one of the central species in stratospheric chemistry. It is produced by the photodissociation of molecular oxygen by solar ultraviolet radiation. Several compounds naturally present in the atmosphere play a role in ozone destruction through catalytic reaction cycles. However, the increase in levels of these compounds, coupled with the introduction of CFCs into the stratosphere, has resulted in an increase in ozone destruction (Graedel and Crutzen,1993). Phenomena such as the ozone hole over Antarctica in the winter months and an increase in smoggy conditions may be indicative of the disruption of the atmospheric chemical equilibrium.

Peixoto (1994) states that "....water vapour is the predominant greenhouse gas of the atmosphere". Tropospheric water vapour is a greenhouse gas that absorbs a large amount of incoming solar radiation in a process that is temperature dependent (Sulzman *et al.*,1995). Increases in atmospheric CO_2 levels are expected to raise surface temperatures, thereby increasing the water vapour content of the atmosphere, causing further warming (IPCC-

WGI,1990). Stratospheric water vapour also has a warming effect, but this is not often included in general circulation models (GCMs). The positive feedback effect of water vapour on increased temperature could thus have an even greater effect on warming than current models suggest (Sulzman *et al.*,1995).

Greenhouse gases vary in their ability to absorb outgoing infrared radiation (cf. Table 2.1). Sulzman *et al.* (1995) and Graedel and Crutzen (1993) stated that CH_4 had a global warming potential 20 times greater, and CFCs 12000 times greater than that of CO_2. Pearman (1989) stated that CH_4 had a global warming potential only 6 times and CFCs 18000 times that of CO_2. Despite these differences, it is apparent that the high relative effectiveness of CH_4, N_2O and CFCs as greenhouse gases makes their observed increases a cause for concern. The global warming potential of these trace gases is much greater than that of CO_2, because there is already so much CO_2 in the atmosphere that in many spectral regions absorption is saturated (Graedel and Crutzen,1993).

Table 2.1 Properties and sources of the principal greenhouse gases (Graedel and Crutzen,1993; IPCC-WGI,1990; Pearman,1989)

Gas	Increase (per annum)	Contribution to the Augmented Greenhouse Effect	Global Warming Potential	Primary Sources
CO_2	0.5%	56%	1	Fossil-fuel combustion Land-use changes
CH_4	0.9%	11%	6 / 20	Rice paddies Landfills Wetlands Coal Oil Natural gas
CFC_{11}	4%	3%	18000/ 12000	Blowing agents Solvents Refrigerators Propellants
CFC_{12}	4%	6%	31000	
O_3	0.5%	2%	1	Atmospheric constituent
N_2O	0.3%	6%	350 / 290	Soil and Ocean Processes Land-use conversion Fertiliser use

CO_2 is currently used as the standard for all greenhouse gases to explore the effects of increased absorption of infrared radiation in climate models. However, with the relative contribution of CO_2 to global warming decreasing with time, and that made by the other greenhouse gases increasing, the use of CO_2 as a standard may not be adequate for the long-term (Sulzman *et al.*,1995).

2.3 Mitigation Strategies Regarding Greenhouse Gas Emissions

Industrialised countries currently contribute more carbon to the atmosphere than developing countries. However, developing countries have a higher rate of increase in emissions due to their relatively rapid economic and population growth, when compared with the growth in industrialised countries. Consequently, it is important that members of the global community undertake inventories of greenhouse gas emissions and formulate strategies to mitigate these emissions worldwide (Lee, Zhou, Jung, Wisniewski and Sathaye,1996). Strategies to mitigate greenhouse gas emissions tend to focus on fossil fuels and forest management - currently the major sources of anthropogenic emissions. National policy makers require information on greenhouse gas reduction potential and the costs and benefits of mitigation options in order to make informed decisions which are both environmentally and economically beneficial to the country. Mitigation options may include improving the efficiency of energy use; using less intensive carbon energy sources (IPCC,1995); improved forest management and afforestation (Houghton,1996); improved management of rice paddies and livestock operations to reduce methane emissions, such as the use of new fertilisers and rice cultivars and a change in the nutrition of livestock; and the adoption of suitable alternatives and new technology to reduce emissions of CFCs and other greenhouse gases (Lee *et al.*,1996).

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This chapter has described how increases in the concentrations of greenhouse gases in the atmosphere are believed to be altering the earth's radiation balance, thereby initiating changes in the global climate, such as an increase in temperature and changes in other climatic variables. It has also described the mitigation options that can be considered as a means of reducing global climate change. The following chapter details anticipated changes in certain climate variables in order to assess the potential consequences of climate change in southern Africa.

CHAPTER 3
CLIMATE CHANGE SCENARIOS FOR SOUTHERN AFRICA

Chapter 2 has described how changes in greenhouse gases are projected to lead to changes in climate and climatic variables such as temperature, precipitation and evaporation (IPCC,1995). Research to assess potential impacts of climate change on agricultural production and hydrological responses is dependent on the quantification of anticipated changes in climatic variables. Various methods, which are described below, have been developed for the quantitative determination of potential changes in climate, resulting from the augmented greenhouse effect.

3.1 Definition of Climate Change Scenario

> "A climate change scenario presents a coherent and systematic description of future climate based on clearly articulated assumptions" (Hulme, Jiang and Wigley,1995).

There is a need to generate quantitative descriptions of anticipated future climate for use in climate change impact assessments. This is achieved through the development of a number of plausible future climates - or scenarios (Hulme *et al.*,1995). These scenarios are shaped by the assumptions that they include, such as the emissions trajectory that the world will follow, external forcing of climate and complex feedforwards and feedbacks that will shape global, and regional, response to climate change. Confident predictions of future climate are hampered by the speculative nature of the future and questions such as world population levels in, for example, 2050. Furthermore, how will society impact on the climate? When will the world's fossil fuel reserves be depleted? How will plants respond to changes in climate? The answers to these questions are uncertain. Consequently, confident predictions of climate change effects are impossible. However, environmental managers and policy makers must make decisions now that will affect natural resources in a potentially significantly altered future climate (Sulzman, Poiani and Kittel,1995). Thus they have to make do with coherent, systematic and physically plausible descriptions of future climate, namely scenarios. A climate change scenario is a provisional and contingent description of a possible future climate, subject to adjustment by new scientific information regarding the climate system (Hulme,1996).

3.2 Methods for Developing Climate Change Scenarios

A number of methods have been developed to facilitate the quantitative determination of potential changes in climate in response to the augmented greenhouse effect. These methods provide plausible future climates, or scenarios, but are not yet capable of providing confident predictions of climate changes (Hulme *et al.*,1995).

3.2.1 General circulation models

General circulation models (GCMs) are computerised mathematical representations of the earth's atmosphere and are based on fundamental laws governing atmospheric physics. They describe simplified physical relationships such as the processes governing clouds, precipitation and radiation. GCMs calculate wind, temperature and moisture distribution in the atmosphere and surface climate. These models may also be coupled to other climatic components such as oceans, land surfaces and sea ice. GCMs were originally designed to simulate atmospheric circulation patterns for specified external forcing conditions (Sulzman *et al.*,1995). However, they have been used since the 1970s to provide estimates of the response of certain climatological variables to different levels of greenhouse gas forcing (Joubert and Tyson,1996). These models are capable of simulating low frequency variability such as the El Niño/Southern Oscillation (ENSO) phenomenon (Sulzman *et al.*,1995; IPCC-WGI,1992).

GCMs are limited by the coarse spatial resolution of their output. Most GCMs represent the earth and its atmosphere by a 3-D grid system with horizontal spacing between grid points ranging from 2°-8° latitude and 3°-10° longitude, and with 2-11 vertical layers extending above the earth's surface (Sulzman *et al.*,1995). GCMs can be divided into two types, based on the horizontal resolution of their output, these being low resolution models with a horizontal spacing of, for example, 4° latitude by 5° longitude, and higher resolution models that have a horizontal spacing of, for example, 2.75° latitude by 3.75° longitude (Sulzman *et al.*,1995).

GCMs are used to conduct two types of experiments for estimating future climates, namely equilibrium and transient experiments. Until the late 1980s, GCMs were used in time independent equilibrium experiments, which involved the instantaneous doubling of ambient CO_2 levels and the running of the GCM until an equilibrium climate state was reached (Joubert and Tyson,1996). Equilibrium experiments were generally performed using low resolution atmospheric GCMs linked to simple mixed-layer slab oceans (Joubert and Tyson,1996). Technological advances over the past decade have allowed for the implementation of time dependent transient experiments, where the ambient CO_2 level is increased at a fixed rate, such as 1% per annum, compounded until doubling has occurred (Joubert and Tyson,1996). This fixed rate is higher than the rate at which CO_2 is currently increasing (cf. Table 2.1). Transient experiments are generally performed using high resolution, fully-coupled global ocean-atmosphere GCMs (Joubert and Tyson,1996). Improvements in GCMs over the past decade have resulted in improved simulation of both the present climate and the potential future climate. However, despite their ability to include more complex processes, they still remain simplified representations of the earth's climate (Sulzman *et al.*,1995)

GCMs are particularly limited when modelling atmospheric processes that operate at scales smaller than the grid resolution, such as cloud formation. They also fail to adequately represent the spatial and temporal complexities of the hydrological system. Despite these limitations, the most widely favoured method for scenario development currently is the use of results from climate change experiments generated by GCMs (Hulme,1996; Hulme *et al.*,1995; Sulzman *et al.*,1995). GCM derived climate perturbations can be used as hydrological model input, despite the downscaling required (cf. 3.3.1.3). Scenarios based on GCM results are continually evolving to incorporate new aspects of the climate system (Hulme,1996). SCENGEN, a climate change SCENario GENerator, uses the results from GCM climate change experiments to construct scenarios of future climate (Hulme *et al.*,1995). SCENGEN is discussed in greater detail in Chapter 5.

3.2.2 Historical and paleoclimatic analogues

Historical and paleoclimatic records are analysed statistically to locate a period during which changes are comparable to those anticipated for the future (IPCC-WGI,1990). These records are then developed on the basis of global-scale temperatures during past warm and cold periods, and consist of regional groupings of differences in atmospheric pressure, air temperature and precipitation between the two periods. The scenarios are usually comprised of regionally mapped or gridded anomalies of climate variables.

Information about changes of climatic conditions in the past is available for about the past 570 million years, from the Phanerozoic period (Budyko, Golitsyn and Izrael,1988). During this time, vegetation covered the continents and animals possessing hard tissues were widely distributed. Paleotemperature information is obtained by analysing the isotope composition of the remains of ancient organisms, often found in sediments. In addition to information deduced from fossil evidence, palynological (pollen grain) and sediment deposition studies have also been used to reconstruct past climates (Budyko *et al.*,1988). Warm periods within these climates have been proposed as analogues for future climates.

The ice of Antarctica is also a source of information about the earth's past. Snow falling on the ice cap thaws in the sun, but may subsequently recrystallise. It is during this process that bubbles of gas become trapped in the ice (Graedel and Crutzen,1993). These bubbles are samples of ancient air, which can be extracted and analysed. A number of ice cores have been drilled from the ice cap. A core drilled by a Russian-French team has a data span of 160 000 years and is an important record of the ancient atmosphere.

Evidence of past climate suggests that carbon dioxide and methane records correspond closely to planetary temperature changes. The climate of the past exhibits both warm and cold periods, although the present climate is warmer than most of the period preceding it (cf. Figure 3.1). The changes in temperature shown in these records indicate that the earth's climate is a dynamic system. This prevents scientists from proving, beyond any doubt, that global warming is, in fact, a result of anthropogenic activities and not merely natural climate variability. It must be noted that historical analogues are of limited value because the nature of the climate forcing of the past is different to the climate forcing of the future. The present rate of climate change is considerably quicker than the rate of climate change in the past. Furthermore, climate forcing of the past was potentially influenced by natural events such as volcanic eruptions and meteorite impacts, whereas climate forcing of the future may potentially be attributed to anthropogenic activities such as fossil fuel burning and deforestation which alter the radiation balance in the atmosphere.

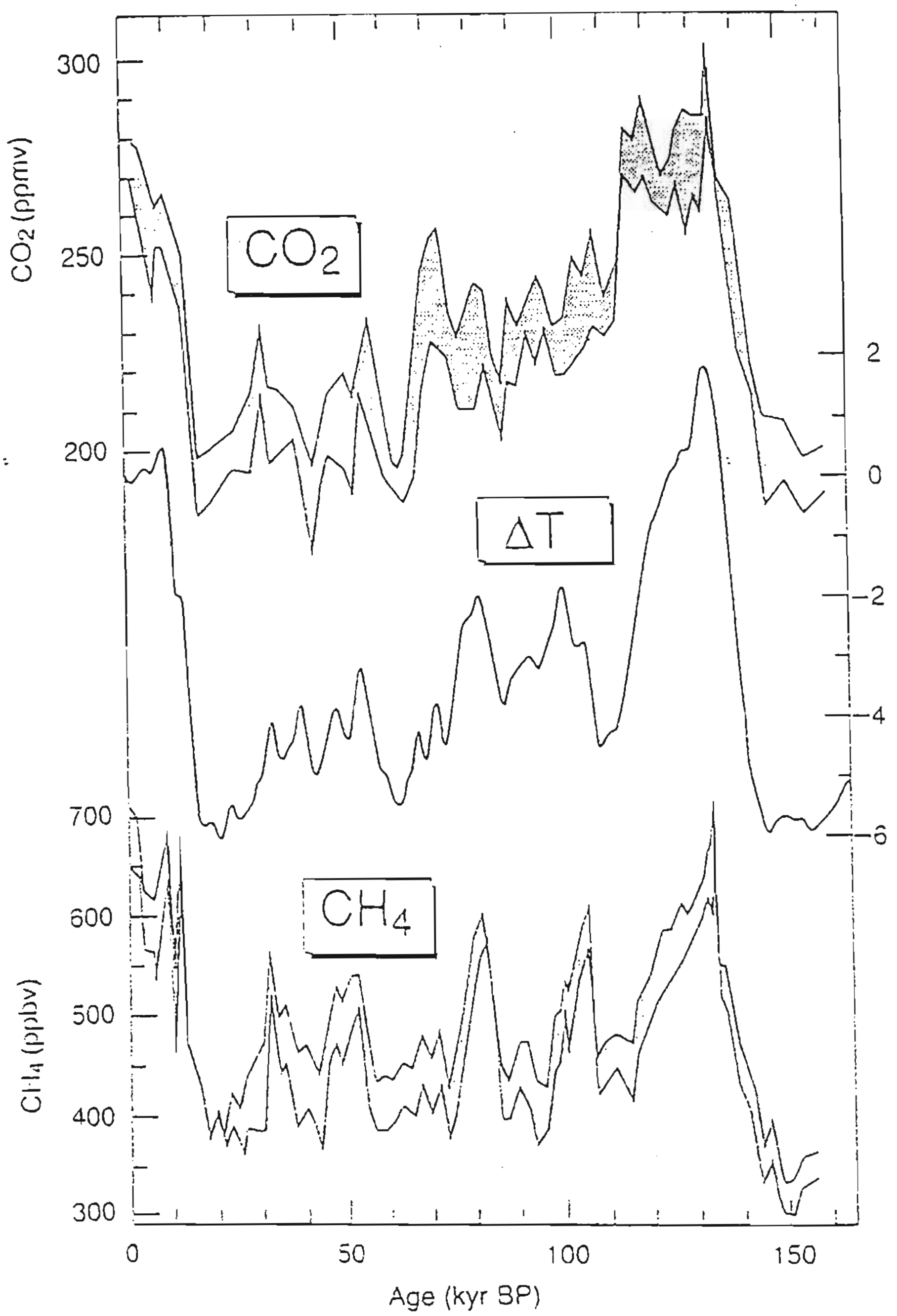

Figure 3.1 Antarctic ice core records of local atmospheric temperature and atmospheric carbon dioxide and methane volume for the past 160 000 years. Present world average, denoted as ΔT= 0 at 0 Kyr BP (Graedel and Crutzen,1993)

3.2.3 Expert opinion

Scenarios can be generated based on "thought" experiments which utilise climatologists' knowledge and understanding of the physical controls of the local or regional climate and their relation to larger scale phenomena (IPCC-WGI,1990). However, caution must be exercised when making use of scenarios derived from expert opinion as they may contain some elements of subjectivity and could be very misleading (Kunz,1993).

3.2.4 Scenario ranges

Many climate change impact studies prefer to consider a range of climate change scenarios. This preference is attributed to the degree of uncertainty associated with the development of scenarios. The range in scenarios is usually defined by an upper and lower limit, which may have been derived from a variety of sources, such as GCM output, paleoclimatic record or expert opinion. Ideally, these limits should encompass the most probable scenarios expected in a future climate. For example, a temperature range of between 2°C and 4°C and a precipitation range of between -20% and +20% may be adopted (Kunz,1993).

3.3 Climate Change Scenarios, with Special Reference to Southern Africa

Hydrology is a dynamic, non-linear, cascading system of complex feedforwards and feedbacks (Schulze,1997). A catchment undisturbed by hydraulic alterations to the natural system, such as dams, may be described by the following simplified hydrological equation (Schulze,1997):

$$Q = P - E \pm \Delta S$$

where, Q = streamflow (mm equivalent)
P = precipitation (mm)
E = total evaporation (mm)
ΔS = change in water storage (mm)

Q is of particular importance in hydrological assessments and impact studies. Thus, the variables driving the equation, P and E, are of particular interest. Changes to these variables will have implications for the response function, Q. Consequently, in order to develop feasible climate change scenarios, the change in P and temperature (T), which directly affects E, must be investigated and presented as change scenarios for consideration in climate change impact assessments (Schulze,1997).

3.3.1 Temperature change scenarios

A range of temperature change scenarios has been developed based on GCM output, interpretation of past analogues, expert opinion and the adaption of overseas studies to southern African conditions. The temperature change scenarios produced are a product of the assumptions and limitations used when deriving them.

3.3.1.1 Assumptions and limitations of temperature change scenarios

i. Temperature change scenarios based on GCM output produce a range of potential future temperatures which are dependent on the type of GCM used. Equilibrium and transient models produce different temperature trends due to the different CO_2 processes inherent in the model structure (Joubert and Tyson,1996). Equilibrium models assume instantaneous doubling of CO_2 levels, whereas transient models assume an incremental increase in CO_2 levels.

ii. CO_2 is currently used as the standard for all greenhouse gases to explore the effects of increased absorption of infrared radiation in climate models. However, with the relative contribution of CO_2 to global warming decreasing with time, and that made by the other greenhouse gases increasing, the use of CO_2 as a standard may not be adequate for the long-term. The use of actual trace gases in climate models will have the effect of increasing the warming expected in some regions (Sulzman *et al.*,1995).

iii. Ozone depletion has a comparable, but opposite, effect to chlorofluorocarbons (CFCs) in the atmosphere (IPCC,1995). The cooling effect caused by the depletion of the ozone layer will potentially counteract a portion of the warming caused by increasing atmospheric concentrations of CFCs. This cooling effect is not included in all climate change experiments.

iv. Localised cooling resulting from sulphur aerosols in the atmosphere which are emitted primarily from volcanoes and power stations will also counteract a portion of the expected greenhouse warming (IPCC,1995). This feedback was not included in climate change experiments in the past (Sulzman *et al.*,1995). However, recent advances in the computational capabilities of computers has allowed for the development of several transient models which incorporate the direct effects of sulphate aerosols on the radiative forcing of global climate (Mitchell, Johns, Gregory and Tett,1995).

v. One of the greatest limitations of GCM projections has been the simplistic representation of feedback processes, namely deep ocean circulation, water vapour, clouds, snow and sea ice, and carbon sequestration by soil and vegetation (Sulzman *et al.*,1995), all of which have the potential to alter temperature change projections. The more recently developed transient models are an attempt to correct this problem by more closely simulating the process of climate change through the incorporation of ocean dynamics, deep ocean mixing and the effect of thermal inertia of the oceans (Joubert and Tyson,1996).

3.3.1.2 Temperature trends from GCM simulations

The following conclusions have been developed from observation of temperature changes simulated with GCMs:

i. Temperature increases are expected to be gradual and linear in response to increases in atmospheric CO_2 and other greenhouse gases (IPCC,1995).

ii. Geographical influence: Minimum warming is expected in the tropics, increasing towards the poles (Joubert,1994). The interior of southern Africa is expected to exhibit a greater degree of warming than the coastal areas (Hulme,1996).

iii. Diurnal changes: Minimum temperatures are expected to increase more than maximum temperatures (Joubert and Tyson,1996).

iv. Seasonal changes: Winter warming is potentially greater than summer warming, especially at higher latitudes (Sulzman *et al.*,1995; Joubert,1994).

v. The occurrence of spells of extreme temperature may also increase the frequency of heat waves. This could have an effect on irrigation, soil moisture availability and drought studies (IPCC Agricultural Impacts,1995).

Latitudinal, seasonal and diurnal temperature changes predicted by GCMs are important considerations when assessing the potential impacts of temperature changes on the agrohydrological system of southern Africa. Recent improvements in spatial resolution of models has led to better simulation of some regional climatic features (Joubert and Tyson,1996). Consequently, GCM output continues to be used in regional impact analyses by means of spatial interpolation or downscaling.

3.3.1.3 Downscaling

GCMs predict significantly different magnitudes of change over southern Africa (Hulme,1996), at a typical spatial resolution of 300 km (Schulze,1997). The most reliable spatial scales of GCMs are continental to global, whereas hydrological impacts models have an ideal spatial resolution of 10 km or less (Schulze,1997). Downscaling GCM output to a level suitable for use by hydrological impacts models may affect the quality of the information obtained from the hydrological models, due to the sensitivity of the hydrological system to changes in climatic variables. Furthermore, the hydrological importance of climatic change increases from global to regional to local scale, whereas the accuracy of climate change predictions generally declines from global to local scale (Schulze,1997). However, Joubert and Hewitson (1996) state that results from initial studies indicate that downscaling can be used to derive accurate regional climate information as a function of atmospheric forcing over much of South Africa.

3.3.1.4 Comparison of temperature changes for southern Africa between selected equilibrium and transient models

Joubert and Tyson (1996) have recently assessed the climate change predictions of six transient models and five equilibrium models, whilst Joubert (1994) evaluated the predictions of six equilibrium models. When analysing the predictions of these models it was found that transient models generally demonstrated different predictions for climate change when compared to equilibrium climate change estimates (Joubert and Tyson,1996).

Both types of model predicted an increase in temperatures throughout southern Africa as a result of the augmented greenhouse effect, with greater warming of the subcontinent compared to the adjacent oceans. These findings were also shown in Hulme's (1996) impacts study of SADC (Southern African Development Community) countries, where a temperature increase of 1.5°C along southern Africa's coast and approximately 2°C in the interior was produced using the UK Hadley Centre's UKTR transient GCM (Murphy and Mitchell,1995).

Studies of the range of absolute warming indicate that transient models predict temperature increases over the subcontinent ranging from 1-2°C, whereas equilibrium models show increases of between 3-4°C (Joubert and Tyson,1996; Joubert and Hewitson,1996). The disparity of results is particularly evident over the southern oceans, where equilibrium models predict increases of 4-5°C, whereas transient models show increases of not more than 1°C.

Studies of the pattern of warming normalised by the global annual average[1] between transient and equilibrium models indicates that transient models exhibit a level of warming greater than the global annual average over the subcontinental land mass, which is generally not the case with equilibrium models. However, equilibrium models tend to exhibit a greater level of warming over the southern oceans compared to the transient models. This is due to the

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[1] Predicted changes in temperature at the time of CO_2 doubling are smaller in the transient than the equilibrium models, even for comparable levels of radiative forcing. This is due to the absence of a state of equilibrium in transient experiments, which are seldom, if ever, run to equilibrium. Consequently, to compare the pattern of climate change predicted for both types of models, predicted changes must be normalised to a global annual average of 1°C. This is achieved by dividing all predicted warming by the global average warming predicted by each model (Joubert and Tyson,1996).

inclusion of the effects of thermal inertia of the oceans and improved representation of ocean dynamics in transient models (Joubert and Hewitson,1996).

It was found that predictions of regional changes by Joubert and Tyson (1996) were generally consistent within the model types, and were also broadly consistent with findings by Hulme (1996), Joubert (1994) and those reviewed by Kunz and Schulze (1993). Joubert and Hewitson (1996) concluded that the best current estimate for regional temperature change in southern Africa using transient models and based on a 1% per annum cumulative increase in CO_2 is 1.5-2.5°C. With this increase, CO_2 doubling is expected to occur around 2050. Using equilibrium models, this estimate, which is also based on an expected doubling of CO_2 by 2050, is between 3-4°C. These estimates fall broadly within the 1995 guidelines of the IPCC which predicts an increase of between 1-4.5°C by 2100.

3.3.2 Rainfall change scenarios

Scenarios of rainfall changes are much more tentative than those of temperature, due to the high natural intra- and inter-seasonal variability of rainfall in southern Africa (Schulze,1997). As a result, a larger range of scenarios needs to be considered.

3.3.2.1 Assumptions and limitations of rainfall change scenarios

i. Rainfall in southern Africa is influenced by atmospheric processes in both the upper and lower latitudes surrounding the region. Potential changes to weather patterns around the region as a result of climate change remains uncertain. Consequently, it is very difficult to produce rainfall change scenarios for southern Africa that will accurately reflect potential changes to sub-tropical and mid-latitude climates (Lindesay,1992 cited by Kunz,1993).

ii. Rainfall variability in southern Africa is influenced by the El Niño/Southern Oscillation phenomenon, ENSO, and the Quasi-Biennial Oscillation, QBO (Tyson,1992). The effect that climate change has on these phenomena needs to be ascertained so that it can be considered in climate change experiments.

3.3.2.2 Changes in total rainfall amount

Global warming is expected to result in an increase in global average precipitation, shown by global GCM projections to range between 3-15% (IPCC-WGI,1990). This will be caused by an expected increase in sea surface temperatures which will result in an increase in precipitable water in the atmosphere. This increase in atmospheric water content is expected to increase the probability of rain. However, it is important to remember that global GCM results are generally of limited value at the regional scale due to the coarse resolution of the models used and the natural variability of rainfall, which makes it very difficult to predict regional changes with any degree of certainty.

A study undertaken by Joubert and Tyson (1996) predicted the magnitude of change in rainfall seldom being greater than 20%. This is in agreement with paleoclimatic evidence that suggests that in the last Altithermal (7kyBP), when temperatures were also approximately 2°C warmer over much of the subcontinent than at present, as has been predicted by the transient models, precipitation changes were also within the range of 10-20% (Partridge,1996 *pers. comm.*, cited by Joubert and Hewitson,1996). In the summer rainfall regions of southern Africa, decreases in rainfall over the relatively dry winter months are unlikely to be hydrologically meaningful, owing to the small contribution of winter rainfall to the annual rainfall cycle. However, decreases of up to 10% in winter rainfall, predicted in the Hulme (1996) report and supported by Joubert and Hewitson (1996), for the south western parts of South Africa, which is in a winter rainfall region, could have significant hydrological implications for the area.

Joubert and Tyson (1996) found that for summer months, both transient and equilibrium models exhibit rainfall increases over the mid- and high-latitude oceans and the tropics, with decreases over much of the remainder of the subcontinent. However, equilibrium models predict a higher proportion of rainfall increases than the transient models for this period. In summer, Joubert and Tyson (1996) suggest that mean rainfall over the summer rainfall region will decrease by between 10-20%, but with small increases along the eastern coast. Joubert and Hewitson (1996) developed climate change predictions using empirical downscaling techniques. Using a short simulation from the Genesis GCM, they suggest a reduction in summer rainfall of 10-15% over eastern South Africa, with minimal changes for other regions.

Mean annual rainfall amounts obtained by Hulme (1996) using the UKTR transient GCM, indicate widespread decreases over southern Africa of approximately 5%, with reductions of up to 10% in the Western Cape, but with little change over the rest of southern Africa. However, similar studies by Hulme (1996) using other well researched GCMs, for example, the Oregon State University (Schlesinger and Zhao,1989) model, show significantly drier or wetter climates for southern Africa, relative to the climate generated by the UKTR transient model.

Generally over the subcontinent, where rainfall changes are most important for impact studies, little agreement as to the extent of the change in rainfall exists between models. One reason for this could be the diminished warming in the southern oceans observed in the transient models and absent in equilibrium models (Whetton, Pittock, Labraga, Mullan and Joubert,1996, cited by Joubert and Tyson,1996). Joubert's (1994) analysis of six equilibrium climate models also found little agreement between models of the same type concerning possible changes in rainfall amounts for the southern African region.

The lack of inter-model agreement in summer indicates that changes are highly dependent on the individual model selected for use. Consequently, it was concluded that for southern Africa, neither transient nor equilibrium models provide reliable estimates of future rainfall changes (Joubert and Tyson,1996). These findings make it extremely difficult for a reliable assessment of the future water resources of southern Africa to be made. However, provisional impacts assessments can be made, based on results from models that have been validated for use in the region and that show some degree of inter-model agreement.

3.3.2.3 Changes in rainfall intensity

Several GCMs have indicated that under augmented greenhouse conditions there is an increase in convective rainfall. This is supported by Joubert's (1994) analysis of six equilibrium models. He states that precipitation averages for the region indicate that daily precipitation rates will increase throughout the summer. This shift from less intensive non-convective activity to more intensive convective rainfall could have the following important implications for southern Africa (Pittock, Fowler and Whetton,1991):

i. Increased convective activity could increase the frequency and intensity of heavy rainfall events, thereby augmenting runoff and sediment yield.

ii. The decrease in non-convective activity may result in a reduction in large-scale stratiform rain. This will increase the number of dry days between general rainfall events. The resulting effect could be a change in crop yields, disruption of irrigation schedules, a change in soil moisture distribution and recharge of soil water into the vadose zone.

iii. Convective activity could extend towards the higher latitudes, causing a southward shift of the summer rainfall region, which could displace the South West Cape winter rainfall region partially out over the oceans (Kunz,1993).

Changes in rainfall (ΔR) per rainday (RD) can be considered an index of rainfall intensity. However, it must be noted that an increase in rainfall intensity is not synonymous with an increase in total rainfall, because the number of raindays is expected to change.

3.3.2.4 Changes in the number of raindays

Global warming could result in a shift towards more days of heavy, intense rain and fewer days of light rain, with an overall decrease in the number of raindays. This will have serious implications for the hydrology and water resources of southern Africa, especially with regard to irrigation scheduling, runoff production and potential soil erosion (Schulze,1997).

3.3.2.5 Changes in rainfall seasonality and variability

Both transient and equilibrium models simulate present rainfall seasonality in both summer and winter rainfall regions with some degree of accuracy (Joubert and Tyson,1996). Consequently, predictions by these models regarding rainfall seasonality can be treated with a certain amount of confidence. Studies of both model types by Joubert and Tyson (1996) indicate no major changes in rainfall seasonality for the summer or winter rainfall regions.

Hydrologically the inter-annual variability of streamflow is a vital element in the design of dam storage capacities. However, GCMs are not always reliable in determining factors in the climate system which influence inter-annual variability (Hulme,1996). The lack of conformity between results is shown when comparing the findings of Lindesay (1992) to those output by the UKTR model. Lindesay (1992) predicted widespread increases in rainfall variability over southern Africa, whereas Hulme (1996) showed reductions in rainfall variability over some parts of the region.

3.3.2.6 Changes in the frequency of extreme events

The agricultural and socio-economic conditions of southern African make it vulnerable to droughts and floods (Joubert and Hewitson,1996). Consequently, a change in the frequency and intensity of these extreme events could have widespread ramifications for the region and are thus cause for concern.

Pittock (1991) predicted that extreme events will change in magnitude and frequency, resulting in more very hot days, more flood producing events and longer dry periods between rainfall events. These findings concurred broadly with those of Whetton, Fowler, Haylock and Pittock (1993), who used the CSIRO-9 level equilibrium model to study potential changes in extreme events. The lowest frequency floods were expected to be most affected. A decrease in the number of raindays and in the frequency of days with low rainfall indicates the possibility of an increase in dry spells, which is defined here as being a period of 30 days with less than 10 mm of rain. This trend indicates the potential for an increased frequency of droughts (Pittock,1991). Furthermore, the higher temperatures and associated increase in total evaporation could result in an increase in aridity, thereby compounding the effects of the dry spells.

3.4 Reference Potential Evaporation Change Scenarios

Determination of the potential change in evaporation is a very complex process owing to the uncertainty of the potential changes to factors such as cloud cover, windspeed and vapour pressure, which affect evaporation. Air temperature, a factor which has been more widely researched with regard to climate change, is also an important element to consider.

Evaporation (E) can be divided into three components (Schulze,1997):

$E = E_s + E_t + E_w$ where, E_s = soil water evaporation (mm)

E_t = plant transpiration (mm)

E_w = free water evaporation (mm)

Evaporation is, by definition, the conversion of water in a liquid phase to vapour at an evaporating surface and the vertical transport of vapour into the atmospheric boundary layer (Ward,1975). Accordingly, evaporation may be considered an "atmospheric demand", or a "potential", determined by climatic variables such as net radiation, windspeed, vapour pressure and cloudiness (Schulze and Kunz,1995). Changes to these climatic variables will affect atmospheric evaporative demand (Schulze,1997). The accurate estimation of this effect is particularly important in southern Africa, as approximately 91% of the mean annual precipitation in this region is returned to the atmosphere as total evaporation (Whitmore,1971).

Many methods have been devised for estimating a reference for potential evaporation (E_r), which is the forcing function of potential evapotranspiration (Schulze and Kunz,1995). These methods range from complex physically based equations to simple measurements and assumptions based on single variables such as temperature, which is associated with the solar energy forcing function in the evaporation process (Kunz and Schulze,1993). In South Africa there are more climate stations that have temperature records than evaporation records, and they are generally distributed in a spatially more even network covering a wide range of altitudes and physiographic zones. Thus, temperature information is more readily available and can be easily interpolated to other locations due to its relationship with altitude and other physiographic factors (Schulze and Kunz,1995). Temperature change is also a widely researched climatic variable in climate change experiments.

Physically based methods of estimating potential evaporation include the universally accepted Penman (1948) equation which has been widely tested and verified. Penman's objective was to develop an equation for the estimation of surface evaporation that did not require surface temperature information (Penman,1948). Rather, it utilised a mass transfer component based on windspeed and vapour pressure deficits; net radiation based on solar radiation estimations and a psychrometric "constant" to account for the effects of atmospheric pressure, the latent heat of vaporisation and the specific heat of dry air. Consequently, when using the Penman (1948) equation, it is necessary to make certain assumptions regarding potential changes in windspeed, radiant energy and relative humidity. Results of Hulme's (1996) study in the SADC region using output from the UKTR GCM, when applied to the Penman (1948) equation, show a 6% increase in potential evaporation for southern Africa north of 30°S, a 10% increase for the Eastern Cape and increases of between 12-20% for parts of the Western Cape, with no change expected over Lesotho.

These values are at variance with the 2-4% increases expected per °C warming as predicted by Pittock (1991), and which were adapted from Australian GCM results, or the 3% increase expected per °C warming suggested by Kunz and Schulze (1993). The latter study involved the adjustment of the daily A-pan records by a percentage factor only, thereby employing the method of using simple measurements or assumptions based on a single variable, in this instance temperature (Kunz and Schulze,1993). Correcting the A-pan based estimates using temperature alone is a very simplified approach to modelling changes in potential reference evaporation.

Consequently, it was decided that the Linacre (1991) equation for estimating potential evaporation, an adaptation of the original Linacre (1977) equation which is temperature based, would be used for the sensitivity analyses and scenario study described in Chapters 5, 6 and 7. According to a southern African assessment, the Linacre (1977) equation yields the best results when compared to six other commonly used temperature based equations (Schulze and Kunz,1995). This equation is a function of temperature and locational variables (altitude and latitude), yet it also contains, according to Linacre (1977), the generality and universality of the Penman (1948) equation. It is basically a disaggregation of the physically based Penman (1948) equation, which has been reduced to a function of maximum and minimum temperature, altitude and latitude. The end result, according to Linacre (1977), is an empirically based equation that is simple to use, but with a necessary physical base. However, it is important to note that the Linacre (1977) equation estimates net radiation from air temperature. Consequently, changes in temperature directly affect net radiation changes. The close link between temperature and net radiation would suggest that an increase in temperature resulting from global warming will result in an increase in net radiation, which is not necessarily the case. Changes in cloudiness, which also have an effect on net radiation, are uncertain. Consequently, it must be assumed that cloudiness remains constant in a future climate if Linacre (1991) is to be used in the present study. However, the use of the Linacre (1991) equation, with its associated limitations and assumptions is assumed to yield results that are likely to be as useful as those obtained by using the Penman (1948) equation, or any other method.

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This chapter has illustrated that for the southern African region, the augmented greenhouse effect may result in a temperature increase ranging from 1.5-4.0°C, dependent on geographical position, but with additional seasonal and diurnal trends; an unknown change in rainfall and a general increase in reference potential evaporation which is also dependent on geographical position and local temperature change. Chapter 5 describes how climate change scenarios are used to perturb the present climate database to create a possible future climate for use in impact assessments that can shape policy development. Chapter 4 considers the response of plants to climate change. This is an important consideration, as potential changes in climatic variables such as temperature and precipitation may have implications for agricultural production, viz. crop yields, as well as hydrology, viz. changes in net irrigation demand in southern Africa.

CHAPTER 4

THE POTENTIAL EFFECTS OF CLIMATE CHANGE ON PLANT RESPONSE

In agricultural production, an understanding of the potential changes in crop function and distribution is important for maintaining food production in a region. Consequently, the primary aim of this chapter is to serve as a background to Chapter 6, which assesses the potential effects of climate change on agricultural production, viz. maize yield.

The biological impacts of climate change, evident as a change in precipitation or temperature, could range from alterations in metabolism, nutrient requirements and biochemical activities of organisms to changes in patterns of activity within communities and geographical distribution of ecosystems (Bloomgarden,1995). Furthermore, changes in atmospheric CO_2 can affect plant species directly, regardless of changes in climatic conditions. These effects are evident as a change in plant processes such as photosynthesis, stomatal resistance, respiration and transpiration (Bloomgarden,1995). Photosynthesis removes a large amount of CO_2 from the atmosphere, whilst respiration has the reverse effect, as indicated by the following equation (Bouten and Goudriaan,1994):

PHOTOSYNTHESIS : light & chlorophyll

$$CO_2 + H_2O \rightleftharpoons CH_2O + O_2$$

RESPIRATION : energy released

Ultimately, it is the combined effect of CO_2 and changes in climatic variables that contribute to the response of plants to climate change (Bloomgarden,1995).

4.1 The Physiological Effects of Increased CO_2 Concentrations on Plants

The potential change in the rate of photosynthesis in plants is dependent on the concentration of CO_2, in addition to other factors that may limit photosynthesis, such as nutrient availability and light (IPCC Agricultural Impacts,1995). Plant response to changes in CO_2 is also primarily dependent on plant type, which is defined by metabolic pathway.

4.1.1 Two major metabolic pathways of plants

The difference in plant response to climate change can be explained by the differences inherent in the metabolic pathways of plants. There are two major metabolic pathways, namely those of C_3 and C_4 plants, which are described below. These metabolic pathways are hydrologically important, as the degree of transpiration suppression and increase in water use efficiency that particular plant species could display are important factors shaping soil moisture distribution, and thus plant available water as well as net irrigation demand in a future, potentially changed climate.

4.1.1.1 C_3 metabolic pathway

The C_3 pathway is the most common metabolic pathway in plants (cf. Figure 4.1). The complete photosynthetic process occurs in all cells in the leaf (Hulme,1996).The effect of increased CO_2 concentration is influenced by the carboxylation process in the photosynthetic pathway of C_3 plants. This process involves the reaction of CO_2 with the five-carbon acceptor molecule, ribulose biphosphate (RuBP), to produce two **three-carbon** molecules of phosphoglycerate (PGA), which can then be used to manufacture sugars and regenerate a supply of the acceptor molecule, RuBP. The carboxylation reaction is mediated by the enzyme ribulose biphosphate carboxylase/oxygenase (Rubisco). The oxygenation (photorespiration) reaction is also mediated by Rubisco. Consequently, carboxylation and oxygenation are in competition with each other. In the oxygenation (photorespiration) reaction, O_2 occupies the active site of the enzyme instead of CO_2. RuBP is subsequently split into one three-carbon compound, PGA, and one two-carbon compound, phosphoglycollate (PG). A complex reaction converts the PG molecule to PGA. However, energy is expended and CO_2 lost during the reaction, making oxygenation a costly process for the plant. Rubisco has a lower affinity for O_2 than for CO_2, thus compensating for the higher ratio of O_2 to CO_2 in atmospheric gas. The expected increase in CO_2 levels will favour the carboxylation reaction over the oxygenation reaction, thereby potentially enhancing the efficiency of Rubisco (Graves and Reavey, 1996) in a process termed the "fertilisation effect".

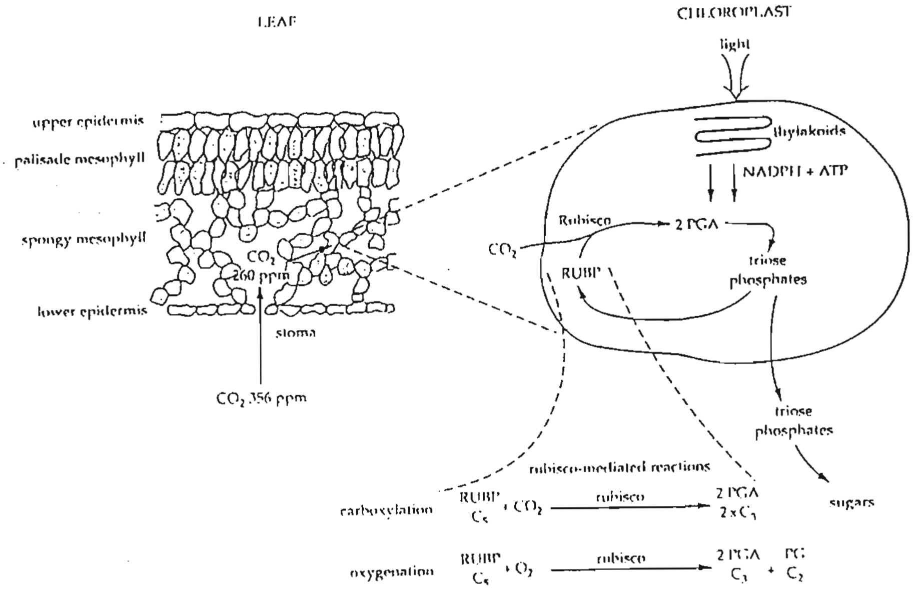

Figure 4.1 **The photosynthetic carbon reduction cycle in a C_3 plant (Graves and Reavey, 1996)**

4.1.1.2 C_4 metabolic pathway

C_4 plants comprise only approximately 5% of the world's flora, but include some of the agriculturally more important species such as maize, millet, sorghum, sugarcane and tropical forage grasses (Graves and Reavey, 1996). The C_4 pathway is more efficient than the C_3 pathway because initial CO_2 fixation only occurs in specific cells (Hulme, 1996). C_4 metabolism comprises two steps, viz.

i. primary carboxylation in the mesophyll of the leaf and,
ii. secondary carboxylation in the bundle sheath cells surrounding the vascular bundles.

Primary carboxylation involves the conversion of a three-carbon acceptor molecule, phosphoenolpyruvate (PEP), to a **four-carbon** compound, oxaloacetate. This reaction is mediated by the enzyme, PEP carboxylase. Oxaloacetate is converted to malate, which is transported out of the mesophyll cells to the bundle sheath cells. Malate is decarboxylated to produce CO_2 and pyruvate. Pyruvate is transported back to the mesophyll cells and recycled as the acceptor molecule, PEP. During secondary carboxylation in the bundle sheath cells, the CO_2 produced during decarboxylation of malate combines with the acceptor molecule, RuBP, to produce PGA (cf. Figure 4.2). The C_4 pathway concentrates CO_2 at the site of RuBP carboxylation in the bundle sheath cells, thereby saturating the active sites of Rubisco. This has the effect of limiting oxidation (photorespiration) to nearly zero. This effect is compounded by the fact that PEP carboxylase has no competing oxygenase activity and low affinity for O_2 (Graves and Reavey, 1996).

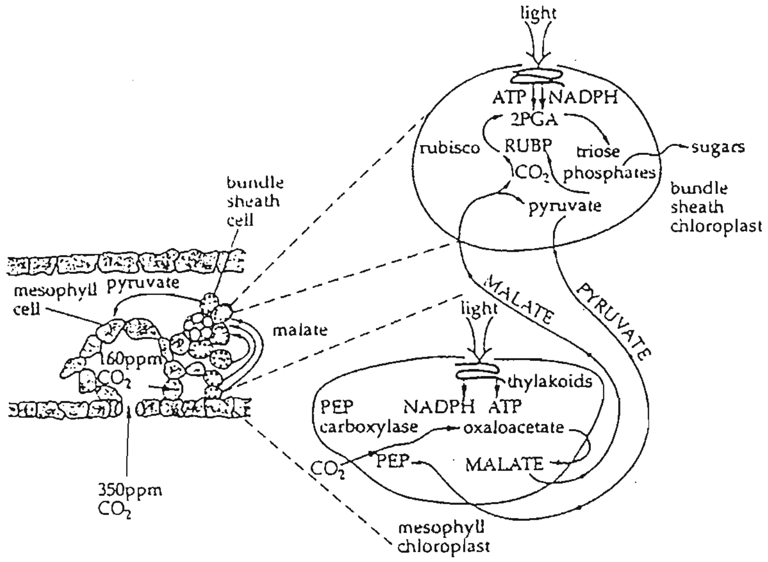

Figure 4.2 **The morphology of the C_4 leaf and the C_4 photosynthetic carbon reduction pathway (Graves and Reavey, 1996)**

4.1.2 CO_2 "fertilisation effect" in plants

Photosynthesis in C_3 plants is saturated when the concentration of CO_2 in the substomatal cavity is 240 ppmv. However, photosynthesis in C_4 plants is saturated when the CO_2 concentration of the substomatal cavity is 150 ppmv (Graves and Reavey, 1996). The ability to operate with a low substomatal concentration of CO_2 implies that C_4 plants are more water-use efficient than C_3 plants and consequently, are more common in drier habitats. This has potential implications for the geographical distribution of C_4 crops should the future environment be more arid. The expected increase in concentration gradient between the air and substomatal space as a result of climate change will have greater significance for C_3 plants, which require a higher substomatal cavity concentration of CO_2, than for C_4 plants. The increase in ambient CO_2 levels raises the photosynthetic rate of the plant, due to suppression of oxidation, a process that occurs frequently in C_3 plants (Hulme,1996). This phenomenon is called the "fertilisation effect" and has the potential to increase plant growth (Kunz,1993). However, it must be noted that non-optimal nutrient conditions in the natural ecosystem could limit the CO_2 "fertilisation effect" (Hulme,1996), as could an increase in C_3 weed competition in an agricultural system (IPCC Agricultural Impacts,1995).

4.1.3 The effect of increased CO_2 levels on transpiration

Plants can only draw water from the soil by losing water from their leaves, via the stomata (Graves and Reavey,1996). This process is termed the "transpiration stream". Exposure to elevated levels of CO_2 causes plants to close their stomata in an attempt to balance the rates of water, CO_2 and nutrient use. This reaction leads to suppression of transpiration. Stomatal closure is more pronounced in C_4 plants than in C_3 plants (Schulze,1991), because in the former, CO_2 released by oxidation is refixed, leading to optimised photosynthetical rates at a lower level of CO_2 saturation than is the case for C_3 plants. The lower level of CO_2 present in the substomatal cavities in the leaves of C_4 plants establishes a steeper gradient from air to leaf cavity than is present in C_3 plants, thus resulting in greater suppression of transpiration.in C_4 plants (Hulme,1996). Schulze (1995c) has included the effects of increased stomatal resistance through suppression of maximum transpiration rates by 22% for C_3 plants and 33% for C_4 plants, in a routine in the *ACRU* model. However, it must be noted that these values are based on the findings of Idso and Brazel (1984) and other literature sources, which have subsequently been superseded by the findings of Goudriaan and Unsworth (1990) and other, more recent, literature sources.

Transpiration suppression per unit leaf area does not imply that total transpiration over the growing season will also decrease. Total transpiration is a function of leaf area in conjunction with transpiration rate. The expected increase in leaf surface area due to changes in plant morphology and growth at elevated levels of CO_2 may compensate for the expected decrease in transpiration rate. Consequently, total transpiration over the growing season could remain stable (Kunz,1993).

4.1.4 The effect of increased CO_2 levels on water use efficiency in plants

One of the most important consequences of growing plants in an enriched CO_2 atmosphere is that they become more efficient in the use of water (Hulme,1996). Water use efficiency (WUE) may be defined as the amount of accumulated carbon per unit of water taken up or lost by the plant (Graves and Reavey,1996):

$$\boxed{\text{WUE} = \text{carbon assimilated / water transpired}}$$

As a result of the increased rate of photosynthesis and CO_2 induced transpiration suppression, plant WUE is expected to increase, provided that temperature remains constant (Beran,1994; Schulze,1991). The expected increase in WUE is primarily attributed to different processes in C_3 and C_4 plants. The improved WUE of C_3 plants can be attributed to both the expected increase in photosynthetic rate (30%) and an increase in transpiration suppression (10-20%); whereas the C_4 response is primarily attributed to an increase (0-25%) in transpiration suppression (Goudriaan and Unsworth,1990). If stomatal resistance is increased to maintain photosynthesis at a constant rate when CO_2 levels are elevated, then there would be a large increase in WUE. If stomatal resistance does not alter, the enriched level of CO_2 will still favour carboxylation and so the amount of carbon assimilated will increase, particularly in C_3 plants. The amount of water lost remains constant under constant temperature conditions. Thus, WUE for both scenarios would increase in an atmosphere enriched with CO_2 (Graves and Reavey,1996).

4.1.5 The effect of increased CO_2 levels on plant morphology and development

CO_2 induced increases in photosynthesis can result in more rapid plant development and growth. Total plant area and biomass, particularly of annual crops, is expected to be reached over a shorter growing period (IPCC Agricultural Impacts,1995). This may result in lower yields in those crops which will not have sufficient time to fill their sinks, such as grain heads, due to the shorter growing season. However, rapid growth of the crop canopy will have the effect of reducing soil evaporation due to earlier shading by the canopy (Bouten and Goudriaan,1994) which, owing to the increased carbon availability, will have thicker and larger leaves. The increase in leaf area will result in greater light interception and total transpiration loss. Rapid plant development may also increase initial water use for the leaf canopy. Consequently, the expected benefits from an increase in transpiration suppression may be cancelled.

4.2 Plant Responses to Increased Temperature

Temperature is a major factor controlling the global distribution of plants. In addition to affecting the geographical distribution of plants, it also affects plant performance within the geographical range (Ennos and Bailey,1995). Plants cannot alter their temperature through metabolism. Consequently, they rely on a number of processes to facilitate heat exchange between the leaf surface and the air. In hot climates, transpiration is an important mechanism for cooling the leaf (Schulze and Kunz,1995).

4.2.1 Photosynthetic response to elevated temperature

Temperature is an important factor regulating the rate of photosynthesis. Species have different optimum, minimum and maximum temperatures for photosynthesis, usually related to their climate of origin (Graves and Reavey,1996). These temperatures are not constant and can change in response to changes in climate by acclimatization. Acclimatization requires an alteration in the thermal stability of enzymes involved in photosynthetic reactions. The range of temperature regimes over which a species can successfully maintain photosynthesis is dependent on genetic variation within the species and the degree to which individual plants can adjust their photosynthetic physiology (Graves and Reavey,1996). This will be an important factor in determining the competitive ability of plants in a changing, natural ecosystem. In an agricultural system, however, crop plants are generally hybrids. This lack of genetic variation requires plant breeders to continually develop new hybrids that can thrive under changing environmental conditions. Consequently, plant breeding and gene manipulation in agricultural production may play an important role in food production in a changing environment.

The process of carboxylation is influenced by temperature, as well as CO_2 enrichment, as discussed previously. An increase in temperature reduces the affinity of Rubisco for CO_2 and decreases the solubility of CO_2. Temperature has a similar effect on O_2, but to a lesser extent. Consequently, the frequency of oxygenation reactions could increase (Graves and Reavey,1996). This is a feedback mechanism, as at high levels of CO_2 the frequency of oxygenation reactions may be reduced. Consequently, an increase in temperature could counteract the effect of enriched CO_2 on the photosynthetic rate to a significant degree.

4.2.2 Change in water use efficiency in response to elevated temperature

If the surface air temperature were to remain constant, then the WUE of plants would be expected to increase with an increase in CO_2. However, a warmer climate by itself results in an increased rate of transpiration. This has the effect of reducing WUE, as the amount of carbon accumulated per unit of water, taken up or lost by the plant, decreases. This counter-active feedback mechanism may cancel or reduce the beneficial effects of transpiration suppression resulting from increased levels of CO_2.

4.2.3 Plant growth and development at elevated temperatures

Increased CO_2 has the effect of increasing plant growth and development, thereby reducing the time the crop spends in the ground. Increasing temperature has a similar effect. The number of heat units required to reach various phenological stages in the crop would thus be attained in a shorter period of time. Furthermore, warmer conditions may reduce the mean start and end dates of frost occurrence, thereby lengthening the growing season. The farmer is thus able to implement avoidance strategies, such as planting earlier or later, to avoid peak periods of pest and disease incidences. A shorter growing season has both additional costs and benefits for the farmer. A shorter season means that the crop has less time to fill its “sinks” (grain heads, cobs and tubers) with carbohydrates. This could result in lower yields for the same amount of land farmed.

Plant growth is also very sensitive to particular temperature ranges during certain stages of growth (Domleo,1990), such as during grain fill or pollen maturation. The increase in temperature may disrupt these stages in the plant's cycle. Warmer winters may also stimulate earlier bud burst and flowering of plants. This could be problematic should a warm period during the winter be followed by a frost resulting in the destruction of vulnerable plant tissues (Graves and Reavey,1996).

An increase in temperature could also change the distribution of plants at higher altitudes (Kunz,1993). The C_4 canopy has a higher optimum temperature for photosynthesis than the C_3 canopy. At higher altitudes and latitudes temperatures are generally lower. Thus C_3 plants grow relatively faster because of their better low temperature performance (Ennos and Bailey,1995). A change in both global and regional temperature ranges could thus alter the distribution patterns of C_3 and C_4 plants worldwide. This could have implications for crop production and weed-crop competition (IPCC Agricultural Impacts,1995).

4.3 The Combined Responses of Increased CO_2 and Warmer Temperatures

Generally, plant responses in natural and commercial agricultural environments remains unclear, but some reduction in transpiration may be expected and there is evidence that senescence may be delayed. Both of these factors indicate that CO_2 enhancement and warming could cause an increase in biomass accumulation (IPCC Agricultural Impacts,1995).

4.4 The Indirect Effects of Climate Change on Plants

Weeds, insects and plant diseases are affected by changes in climate. The resultant changes in the activity and distribution of these crop pests will likely affect crop production (IPCC Agricultural Impacts,1995).

4.4.1 Competition from weeds

Worldwide, crop production is reduced owing to competition from weeds which compete for the same resources essential for crop growth (IPCC Agricultural Impacts,1995). Changes in climate and atmospheric gas composition which will affect the geographical distribution of crops in the future (Ennos and Bailey,1995) will also affect weed growth and weed-crop competition. Most of the world's agriculturally important crops are C_3 plants, whilst the majority of the world's agriculturally important weeds are C_4 plants. As was discussed earlier, CO_2 enrichment is believed to benefit C_3 plants more than C_4 plants. Other factors affecting weed-crop competition, such as temperature and precipitation, will also play an important role in the future. Increasing temperature and changes in precipitation will affect the distribution and growth of weeds. In a drier future climate, agriculturally important C_4 weeds may be more competitive due to their ability to survive in arid areas (Hulme,1996). However, at higher altitudes where temperatures are generally cooler, C_3 crops may be better suited to the conditions than C_4 weeds (Ennos and Bailey,1996).

Uncertainty regarding the magnitude and the potential effects of climate change on agriculturally important weeds remains an obstacle to accurately predicting the potential effects of weeds on crop production (IPCC Agricultural Impacts,1995).

4.4.2 Effect of climate change on insect pests

Insects associated with agricultural systems tend to be r-strategists[2], owing to the unstable nature of their habitat (IPCC Agricultural Impacts,1995). They generally have a broad host range and their geographical distribution is limited primarily by the distribution of their host. Their high rates of reproduction and mobility could enable them to acclimatise rapidly to changes in climate and to migrate, should unfavourable conditions arise.

However, changes in climatic conditions could also adversely affect insect populations. For many insects temperature is an important factor in determining mortality and reproductive

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[2] These species tend to have high rates of reproduction. Traditionally, adults do not rear their young.

rates. A warmer environment may favour the development of certain insect species, resulting in a greater number of life cycles per season. Conversely, those species with lower temperature thresholds for development may be affected adversely. An increase in heavy rainfall events, for example, can drown soil-dwelling insects, in addition to creating a moist environment in which insect predators, parasites and pathogenic organisms such as fungi and bacteria can proliferate.

4.4.3 Effect of climate change on plant diseases

Owing to stratospheric ozone depletion, an increasing amount of ultraviolet-B (UV-B) radiation is currently reaching the earth's surface compared with the levels experienced prior to the 1930s. This, coupled with ozone (O_3) and CO_2, has a direct biological effect on plants (Manning and Tiedemann,1994). The increase in plant canopy size expected as a result of CO_2 enrichment (Schulze,1991) will create a much more humid microclimate within the plant than is currently present. This, coupled with the expected increase in plant biomass which provides an improved nutrient base for pathogens, will favour the incidence of plant diseases such as rusts, powdery mildews, leaf spots and blights. However, the increase in stomatal resistance associated with CO_2 enrichment could reduce the incidence of stomata-invading aerial pathogens such as downy mildews (Manning and Tiedemann,1994). The expected increase in winter temperatures resulting from the augmented greenhouse effect could increase the overwintering potential of certain diseases, resulting in a greater concentration of reproductive spores in the spring, which could have widespread economic implications for agriculture (Agrios,1988).

Ozone adversely affects plant growth and provides pathogenic organisms with an opportunity to colonise the weakened plant. O_3 effects on plant diseases are primarily host plant mediated and have little to do with the effect on the pathogens themselves. Consequently, the exact effect of ozone depletion on plants and their resulting response to plant diseases is, as yet, uncertain (Manning and Tiedemann,1994).

Enhanced UV-B radiation can stunt plant growth, increase branching and canopy size. This would have the effect of increasing the humidity of the microclimate, thereby favouring the development of bacterial or fungal infections. Enhanced UV-B may also reduce net photosynthesis in many plants (Manning and Tiedemann,1994), resulting in a reduction in carbohydrate stores, which will reduce the incidence of high sugar diseases such as rusts and mildews (Agrios,1988).

The effect of plant diseases on world food and fibre production could be devastating. Consequently, the potential effects of climate change on host plants, and therefore on the incidence of plant diseases must be evaluated, so that steps can be taken to ensure food security in a future climate.

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This chapter has described the manner in which plants may respond to changes in climatic conditions, including the potential effects of factors such as weeds, pests and pathogens on plants in a future climate. The potential effects of climate change on agricultural production, discussed in Chapter 6, may be explained by the mechanisms of plant response reviewed in detail in this chapter. The following chapter describes the models used to produce sensitivity analyses and impact studies of the southern African region (cf. Chapter 6 and 7) in response to changes in climate variables, namely temperature, precipitation and reference potential evaporation.

CHAPTER 5

MODELS, DATABASES AND GENERAL METHODOLOGIES USED

5.1 Description of Simulation Models Used

The *ACRU* agrohydrological model (Schulze,1995a) and SCENGEN, a climate change SCENario GENerator (Hulme, Jiang and Wigley,1995), were chosen as suitable tools for use in simulating possible impacts of climate change on agricultural production and hydrological responses in southern Africa. Southern Africa, for the purposes of this study, comprises the Republic of South Africa plus Lesotho and Swaziland. The *ACRU* model has been widely verified and its status as a deterministic model renders it suitable for climate change studies, owing to its physical conceptual structure in representing hydrological processes and its emphasis on inputting physically meaningful parameters (Schulze,1995b). SCENGEN is a computer programme designed to facilitate the generation of global and regional scenarios of climate change, using the experimental results of selected general circulation models (GCMs). SCENGEN was selected for the construction of a climate change scenario for 2050 using results for the southern African region from the Hadley Centre's UKTR transient model (Murphy and Mitchell,1995). These two models are described in greater detail below.

5.1.1 The *ACRU* model

The acronym *ACRU* is derived from the Agricultural Catchments Research Unit in the Department of Agricultural Engineering of the University of Natal, Pietermaritzburg. This model has been expanded and refined since the early 1980s and is a multi-purpose model which integrates various water budgeting and runoff producing components of the terrestrial hydrological system (Schulze, Angus, Lynch and Smithers,1995a).

This physical conceptual model has been defined by Schulze (1995b) as being:

> "....an agrohydrological modeling system in which the fields of scientific hydrology and applied engineering and water resources related hydrology are integrated and

> interlinked with agrohydrology in terms of the forcing functions and responses of the various components which make up the natural and anthropogenically influenced terrestrial hydrological system"

ACRU uses daily time steps, although some variables such as temperature and reference potential evaporation may be input as monthly values if daily values are unavailable and these are then transformed internally in the model to daily values by Fourier Analysis. Daily multi-layer soil water budgeting forms the core of the model, which is structured to be responsive and sensitive to climate and land use/cover changes on the soil water and runoff regimes (Schulze *et al.*,1995a). In *ACRU*, soil water partitioning and redistribution involves that portion of the rainfall that was not intercepted, or released as stormflow (either quickflow or delayed flow), and which resides in the topsoil, i.e. A-horizon. Once filled to beyond its drained upper limit (i.e. field capacity), the remaining soil water percolates into the subsoil, i.e. B-horizon, as saturated drainage. If the soil water content of the subsoil exceeds its drained upper limit, then saturated vertical drainage into the intermediate or groundwater store occurs. It is from this store that baseflow may be generated as a delay function. In *ACRU*, unsaturated soil water redistribution functions include capillary action.

The *ACRU* agrohydrological modeling system was selected for the simulation of runoff production (cf. Chapter 7) and for the estimation of maize yield (cf. Chapter 6) in a future climate. Net irrigation demand and the soil moisture status of the A- and B-horizons were also selected for study, as were stormflow response and recharge of soil water into the vadose zone (cf. Chapter 7).

Evaporation in *ACRU* occurs from both soil horizons simultaneously, either in the form of soil water evaporation from the topsoil or as plant transpiration from all soil horizons containing actively growing roots (Schulze *et al.*,1995a). It is possible to estimate total evaporation as an "entity" or to compute soil water evaporation and plant transpiration separately within the model structure. The latter option is employed when simulating climate change impacts, so as to be able to account for transpiration suppression in plants resulting from a doubling of CO_2.

In Chapter 4, it was shown that an increase in the atmospheric level of CO_2 may result in an increase in leaf stomatal resistance at maximum transpiration, thereby resulting in an overall increase in plant water use efficiency. To account for the day-to-day effects of this phenomenon, maximum transpiration rates in *ACRU* for a doubling of atmospheric CO_2 levels are suppressed by 22% for C_3 plants and 33% for C_4 plants (Schulze,1995c). It must be noted that these values are based on Idso and Brazel (1984) and other literature sources, which have subsequently been superseded by the findings of Goudriaan and Unsworth (1990) and more recent literature sources (Schulze,1995c). Other effects of climate change on plant response such as direct changes in photosynthetic rates are not included in the model structure. This implies that certain plant characteristics resulting from these changes, such as an increase in leaf area, will remain constant with climate change, except in *ACRU*'s maize yield routines, in which leaf area index is a dynamic response function of accumulated daily growing degrees, which are, of course, changed with enhanced temperatures.

5.1.2 SCENGEN - a climate change SCENario GENerator

Two sets of global warming projections are built into SCENGEN, namely the IS92a and IS92c emissions scenarios. Both of these have been developed for the IPCC, i.e. the Intergovernmental Panel on Climate Change (Leggett, Pepper and Swart,1992 cited by Hulme *et al.*,1995). IS92a was chosen for use in the southern African scenario because it is a mid-range estimate of future emissions and assumes a limited degree of policy intervention to reduce emissions in the future (Hulme,1996). Furthermore, it is used as a reference scenario by the International Negotiating Committee of the UN Framework Convention on Climate Change.

When selecting the IS92a emission scenario in SCENGEN, a choice of three temperature projections is offered (Hulme *et al.*,1995). These temperature projections have been calculated using MAGICC, i.e. the Model for the Assessment of Greenhouse gas Induced Climate Change, and are derived using the IS92a and IS92c emissions scenarios with three values for climate sensitivity, viz. 1.5°, 2.5° and 4.5°C. These temperature thresholds provide an acceptable range of global warming projections. In this study, the MAGICC mid-temperature projection of 2.5°C was chosen, in keeping with the earlier choice of the IS92a emission scenario which is a mid-range scenario, and also because a climate sensitivity[3] of 2.5°C was used for the southern African region in the Hulme (1996) report. This choice is further supported by Joubert and Hewitson (1996) who indicated that a best estimate of temperature change for the southern African region from transient models, following a doubling of CO_2, is between 1.5°-2.5°C.

Global baseline climatologies in SCENGEN include mean monthly surface air temperature (°C), mean monthly precipitation (mm/day) and mean monthly cloud cover (100ths), all at a resolution of 5° latitude by 5° longitude. There is a wider range of variables available at the regional scale. These include mean monthly cloud cover (100ths), diurnal temperature range (°C), mean monthly precipitation (mm), mean monthly minimum surface air temperature (°C), mean monthly surface air temperature (°C), mean monthly maximum surface air temperature (°C), mean monthly vapour pressure (hPa- 24 hour mean) and mean monthly wind speed (m/s at a 10m height). Unlike global baseline climatologies, regional baseline climatologies are present at a resolution of 0.5° latitude by 0.5° longitude. The climatology of the southern African region, defined in SCENGEN as being from 0° to 35°S and 5°W to 55°E, was constructed from station data held by the Climatic Research Unit, University of East Anglia, and station normals from some of the National Meteorological Services in the Southern African Development Community (SADC) region. The interpolation technique used was that developed by Hutchinson at the Australian National University, based on the thin-plate splines approach (Hutchinson, 1991 cited by Hulme *et al.*, 1996).

Results of eleven GCM climate change experiments were included in SCENGEN. These GCM results were validated by Hulme *et al.* (1996) and the models were weighted, based on the outcome of the validation experiment. The UK Hadley Centre's UKTR transient model (Murphy and Mitchell, 1995) had the highest correlation between its precipitation climate and an observed precipitation climatology used for the validation experiment. The UKTR model was therefore chosen for use in this study, based on its reputation as one of the world's leading models (Hulme, 1996). Differences between transient and equilibrium models, which were

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[3] Climate sensitivity is defined as the eventual global warming which would occur as a result of a doubling in greenhouse gas concentrations. The IPCC use a range of 1.5°C (low) to 4.5°C (high) with a mid-range estimate of 2.5°C.

described in Chapter 3, must be considered when interpreting results from a scenario based on a single type of model.

When constructing a climate change scenario for this study, it was decided that the SCENGEN changes in minimum and maximum surface air temperature and in precipitation for the southern African region would be used as input for *ACRU*. However, the resolution of the information was considered too coarse for this study, as the version of SCENGEN used produced a 5° latitude by 5° longitude grid (cf. Figure 5.1) for both the future global and regional climatologies. Consequently, an inverse distance weighted interpolation technique (IDW) was used to scale the GCM output down from 5° latitude by 5° longitude to 0.5° latitude by 0.5° longitude, in a process described in Section 5.2. This 0.5° grid resolution is consistent with that generally used in current southern African climate change experiments, for example, by Hulme (1996) and by Hewitson at the University of Cape Town. It is envisaged that SCENGEN regional outputs for the future will be interpolated down to a 0.5° grid in a new version of the model. This will correspond more closely to the 0.5° grid resolution currently exhibited only by the regional baseline climatologies, and not by the future regional climatologies.

A warming of approximately 1.7°C is expected to occur between the 1961-1990 baseline period and the 2050s decade when using the IS92a emissions scenario together with the results from the UKTR model (Hulme,1996). The atmospheric CO_2 levels associated with this scenario show an increase from the average value of 334 ppmv during the period 1961-1990, to approximately 560 ppmv - an increase of sixty percent. However, this represents an effective doubling of CO_2 relative to the pre-Industrial level of 280 ppmv (Kunz,1993). The 2050s decade was selected as being a suitable time period for this study, because it allowed sufficient time for the potential effects of climate change to become apparent, whilst avoiding the uncertainties attached to long-term projections i.e. time periods greater than 100 years (IPCC, 1990-WGI).

5.1.3 System infrastructure

In order to simulate the potential effects of climate change over southern Africa, the Department of Water Affairs and Forestry's 1946 Quaternary catchments (cf. Figure 5.2),

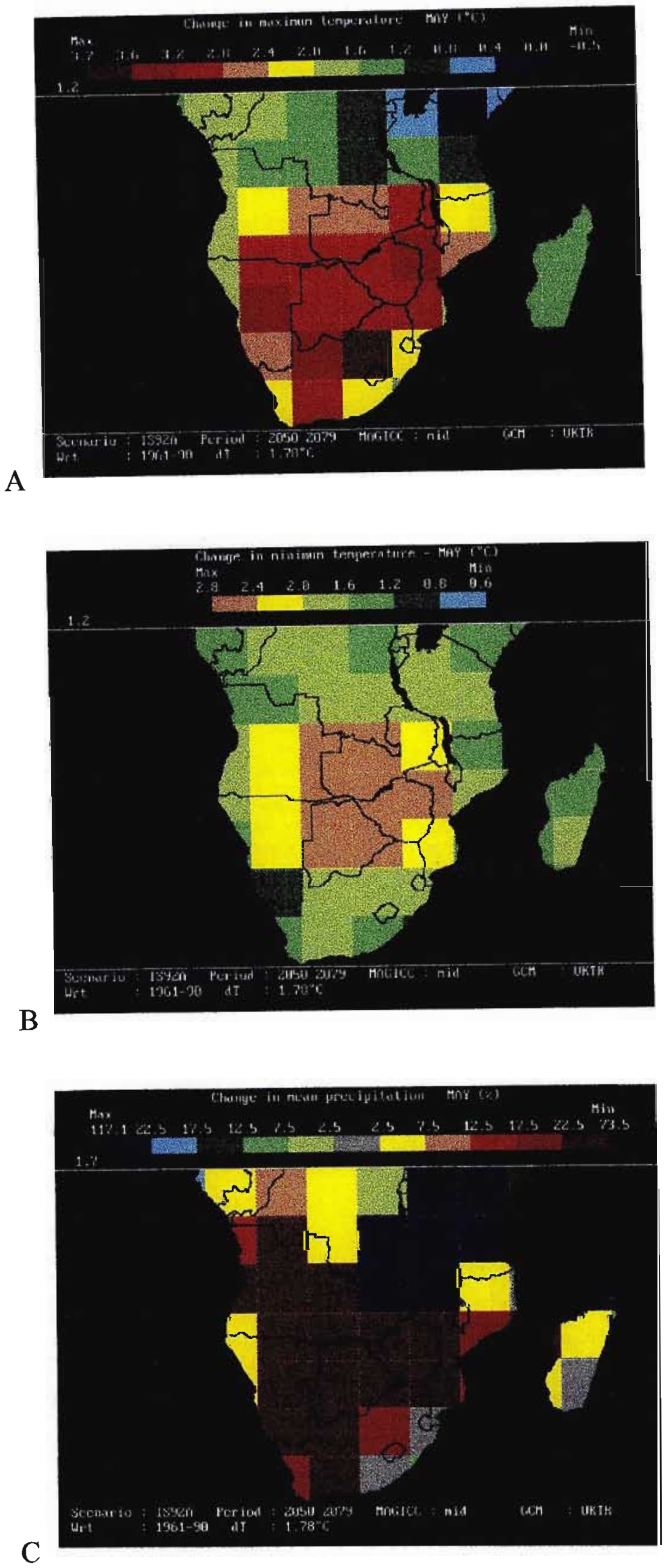


Figure 5.1 **Maximum (A) and minimum (B) temperature as well as mean precipitation (C) output from SCENGEN for southern Africa (5° grids): An example for the month of May**

which are considered relatively homogenous hydrological response zones in southern Africa, were utilised for both the sensitivity analyses and the SCENGEN study. These Quaternary catchment zones have been captured into a Geographic Information System (GIS). The GIS was then linked to vegetation, soils and climate information bases developed for each of the 1946 zones (Meier and Schulze,1995), which are required as input by the *ACRU* model.

5.1.3.1 Climate databases

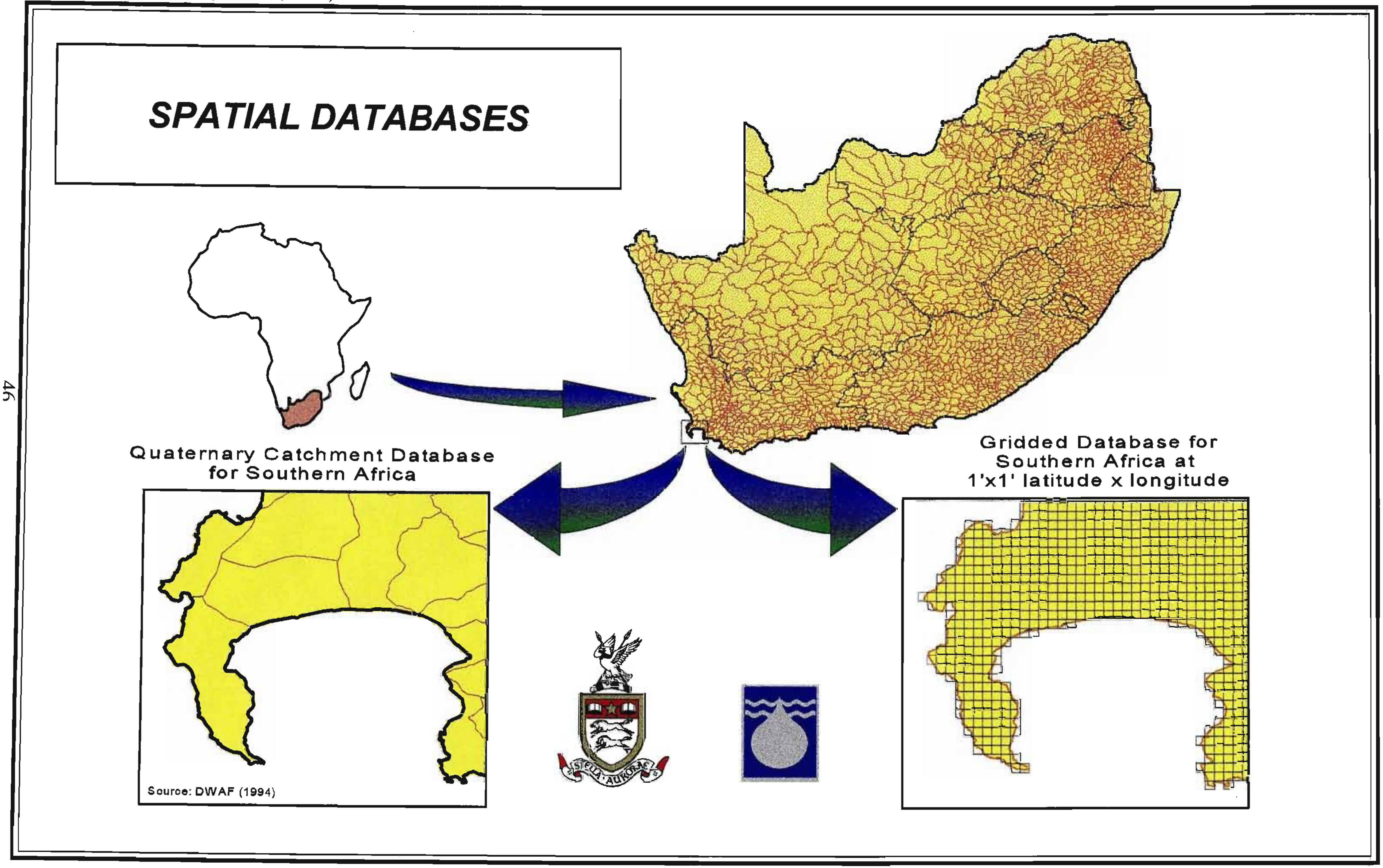
i. Rainfall - A representative rainfall station for each zone was selected, based on a minimum record length of reliable daily rainfall for the 43 year period 1951-1993. The daily values of some stations' daily rainfall were adjusted, particularly when stations on the edge of a Quaternary catchment were selected, to best represent the rainfall across the whole zone.

ii. Air temperature - From a 1 minute × 1 minute of a degree latitude/longitude grid of monthly means of daily maximum and minimum temperatures developed by Schulze (1995a), representative monthly values were derived by GIS for each of the 1946 Quaternary catchments.

5.1.3.2 Soils information base

Soils information for southern Africa was originally obtained by Schulze and Lynch (1992) from the Institute of Soil, Climate and Water which has identified 84 broadly homogenous soil regions. The boundaries of their soil map have been geocoded into a GIS, with the relevant soil parameters for the *ACRU* model for each of the 1946 response zones computed (Meier and Schulze,1995). Soil parameter information includes soil water retention constants at permanent wilting point, drained upper limit and porosity, as well as horizon thicknesses for a two-horizon soil profile. The initial soil water contents of the topsoil and subsoil at the start of the simulation is expressed as a percentage of the plant available water capacity. In this study, both of these values were set at 50% (Schulze,1996 *pers. comm.*).

Figure 5.2 Representation of spatial database, used in the study (Schulze,1997)



5.1.3.3 Assumptions included in the study

i. No changes in relative humidity, windspeed or the earth's energy balance were incorporated into the model.

ii. Changes in anticipated long-term averages only, and not of detailed daily temporal or spatial distribution patterns for rainfall, temperature or reference evaporation were considered.

iii. All soil properties were assumed to be unaffected, despite indications that soil cracking, infiltrability and surface runoff response may change with climate change.

iv. No changes in land use or natural vegetative cover were considered, although climate-induced changes in catchment vegetative cover could potentially alter processes such as interception and infiltration. Rather, it was assumed that the vegetation in all zones was veld in good hydrological condition. Furthermore, it was assumed that veld in good condition could have a basal cover of 70% (Schulze,1996 *pers. comm.*). The surface cover routine was incorporated into the model for the SCENGEN study.

v. The crop coefficient, which gives the ratio of "maximum" evaporation from the plant at a given stage of plant growth to a reference potential evaporation, is input into *ACRU* as monthly values (Schulze, Lecler and Hohls,1995c). In this study, the values illustrated in Figure 5.3 were given as crop coefficients representative of veld in good hydrological condition. The decline in winter months is indicative of senescence, brought about by plant die-off with frost occurrence and soil water stress.

vi. Month-by-month canopy interception loss (mm/rainday) estimates were provided for estimating daily interception loss values on a rainday. Figure 5.4 indicates how the month-by-month values chosen mimic intra-annual differences in interception loss, depending on the stage of growth or dormancy of the vegetative cover (Schulze *et al.*,1995c).

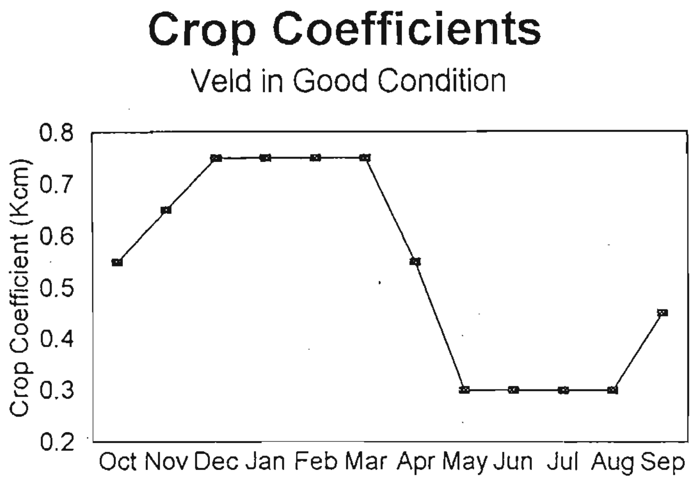


Figure 5.3 Crop coefficients for veld in good hydrological condition

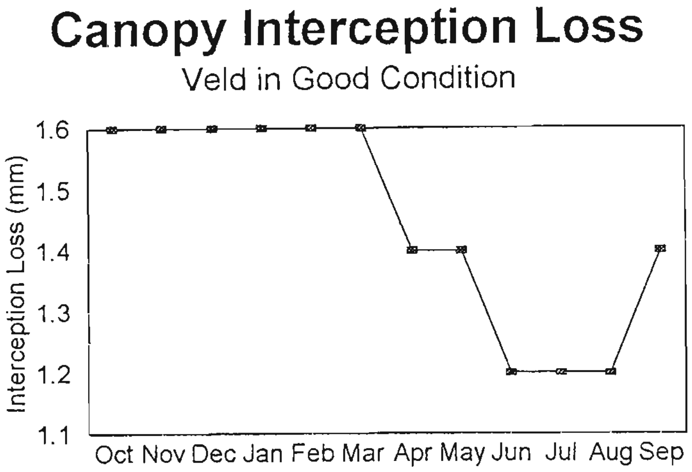


Figure 5.4 Canopy interception loss estimates for veld in good hydrological condition

vii. It was assumed that the active root system of grass is concentrated in the topsoil horizon, particularly in winter when water uptake is reduced, owing to a generally lower atmospheric evaporative demand. Consequently, the fraction of the active root system in the topsoil was maintained at around 0.9, in the summer months, and 1.0 in the winter months.

viii. The critical leaf water potential of veld in good condition was set at -1000 kPa (Schulze,1995c).

ix. The potential effects of weeds, pathogens and insects were not considered in the simulation, because of the complex feedforward and feedback mechanisms associated with biological systems that are yet to be understood fully.

5.2 Method Used to Link SCENGEN Information to *ACRU*

A number of 5° grids were produced for the southern African region following the development of the climate change scenarios from SCENGEN. Owing to the fact that the climate change grids were at a very coarse resolution, it was decided to apply an inverse distance weighted interpolation technique (IDW) to scale the 5° grid values down to 0.5° grid values. IDW enables the user to "control" the significance of known input points upon the interpolated values, based on their distance from the point of interpolation (Arc/Info User's Guide 6.0,1991). This implies that points which are close to the control point are programmed to be influenced to a far greater degree by the control point value in the interpolation than points which are further away. This has the effect of representing an element of localised climatic trends, which are greatly influenced by geographical features and position. The characteristics of the interpolated surface can be controlled by limiting the number of input points in the IDW process. The SCENGEN grids were scaled down using a radius of 5 degrees, rather than the sample method which delimits the number of points to be used. This will maintain spatial variation in the representation of climate and will prevent points that are too far from the point of interpolation, and thus having little influence on the local climate, being included in the IDW process.

Caution must be exercised when implementing the IDW process. IDW is an inverse distance weighted AVERAGE (Watson and Philip,1985 cited by Arc/Info User's Guide 6.0,1991). The implications of this are that the values obtained cannot be higher than the highest or lower than the lowest input. Hence, by implication, extremes in climate relative to localised geographical features such as mountains or valleys must have been reflected in the original input points in order to be reflected in the interpolation. Furthermore, the influence of an input point on an interpolated value is distance related. Consequently, IDW may smooth out features such as ridges and valleys. However, a sufficiently dense sampling of input points will produce a suitable representation of the desired surface.

In total, twelve 5° interval points in southern Africa were used to scale the SCENGEN point information down to 0.5° grids for use in the *ACRU* model. This is not a very dense distribution. However, the climate change trends exhibited by the UKTR model (Murphy and Mitchell,1995) are generally well preserved by the IDW process (cf. Figure 5.5). Grid values obtained by this process were then incorporated as "front-end" routines for *ACRU* (Kiker,1996 *pers. comm.*).

5.3 Methodology Used For Climate Change Impact Studies

The approach to climate change impact studies adopted for the SCENGEN study involves the analysis of results with the intention of elucidating the potential impact of a specified climate change on agricultural production and hydrological responses in southern Africa. This approach is in contrast to that adopted for the sensitivity analyses (cf. Chapter 5.3.2), where results are analysed with the intention of identifying the sensitivity[4] of a system to climate change and also the "critical level" of change, which is the boundary between a change that the system can accommodate, and one that it cannot (Parry, Carter and Hulme,1996).

5.3.1 Methodology used for the SCENGEN study

The following methodology was used to estimate the impact of a specified climate change on agricultural production and hydrological responses in southern Africa:

The *ACRU* model, linked to the 1946 Quaternary catchments database, was used, together

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[4] Sensitivity, in this context, is the degree to which a system will respond to a change in climatic conditions (IPCC,1995).

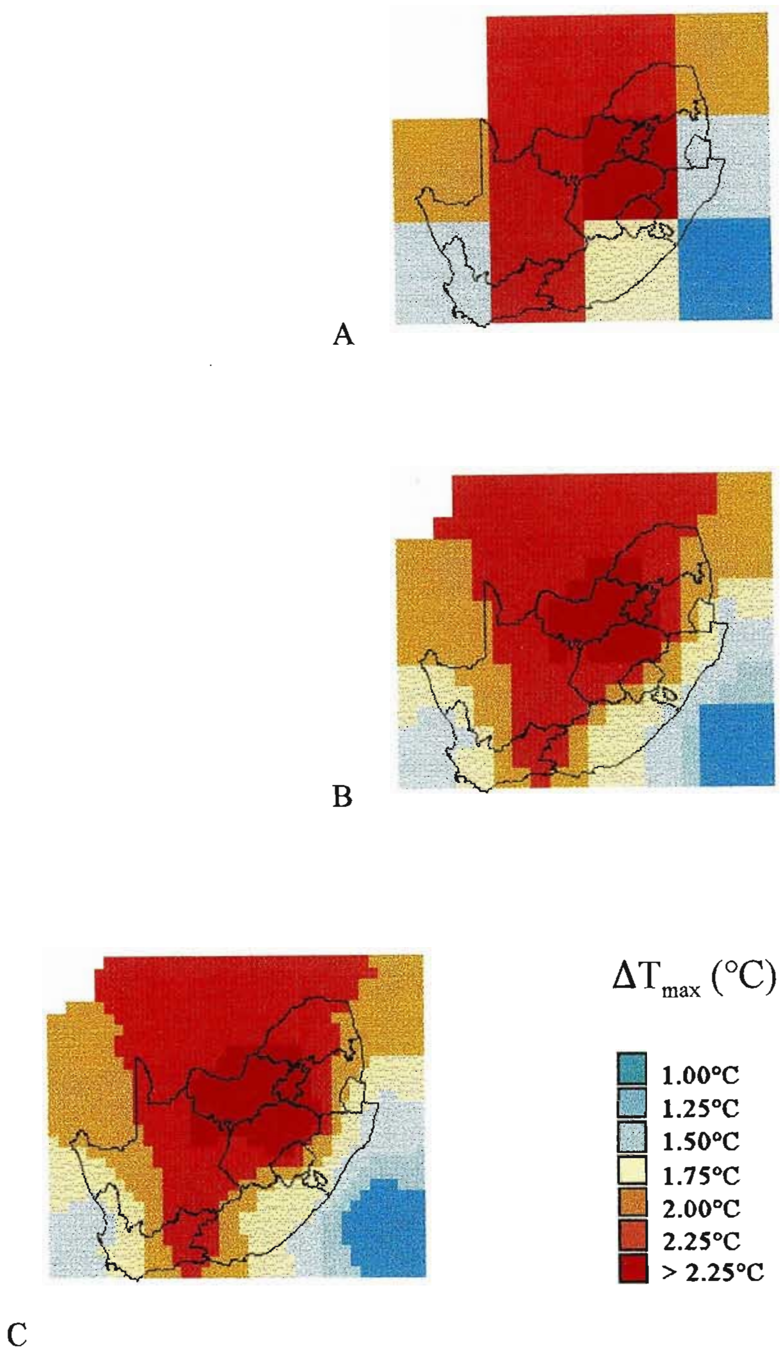

Figure 5.5 Inverse distance weighting (IDW) of changes in maximum temperature, output from SCENGEN as a 5° grid: An example for the month of May (A) 5° grid (B) 1° grid (C) 0.5° grid

with daily rainfall data from 1951-1993, to determine seasonal maize yield, and daily values of runoff production, recharge of soil water into the vadose zone, soil moisture status of the A- and B-horizons and net irrigation demand for present climatic conditions. These results were then summarised into monthly and annual totals. The Quaternary catchments climate data were then perturbed according to a set of scenarios, for changes in rainfall, minimum and maximum temperatures and, indirectly, reference evaporation obtained from SCENGEN and scaled down by means of the IDW technique (cf. Section 5.2). These changes were structured as "front-end" routines for the *ACRU* model (Kiker, 1996 *pers. comm.*):

i. Temperature: Changes in monthly means of daily minimum and maximum surface air temperatures for southern Africa were obtained using the SCENGEN programme. Seasonal and diurnal patterns described by the literature were broadly reflected in the information obtained for input into *ACRU* (cf. Chapter 3).

ii. Precipitation: Although GCMs provide highly variable and sometimes contradicting predictions of rainfall changes for southern Africa (cf. Chapter 3), it was decided to include the results of the UKTR transient model (Murphy and Mitchell, 1995) obtained from SCENGEN in this particular study. Percentage changes in monthly rainfall amounts were obtained from SCENGEN, and these were input in *ACRU* to perturb daily precipitation amounts accordingly.

iii. Potential Evaporation: The temperature, latitude and altitude based Linacre (1991) equation was used as a reference to calculate both the present and the future rates of potential evaporation (cf. Chapter 3) in the southern African region.

The atmospheric CO_2 levels associated with this scenario show an increase from the average value of 334 ppmv during the period 1961-1990, to approximately 560 ppmv which represents a doubling of CO_2 relative to the pre-Industrial level of 280 ppmv (Kunz, 1993). Accordingly, the maximum transpiration suppression option[5] in *ACRU* was invoked and the evaporation

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[5] *ACRU* was prompted to suppress maximum transpiration in C_3 plants by 22% and C_4 plants by 33% in response to elevated CO_2 levels.

routine in *ACRU* set to separate evaporation into that from the soil surface and transpiration from the plant for both the present and future climate simulations. The *ACRU* model was then used together with the perturbed climate database to determine possible future responses of maize yield, runoff production, recharge of soil water into the vadose zone, soil moisture status of the A- and B-horizons and net irrigation demand.

5.3.2 Methodology used for the sensitivity analyses

The following methodology was used to estimate the sensitivity of selected hydrological responses in southern Africa to a change in precipitation amount, with a constant change in temperature and CO_2:

Data from 1951-1993 were perturbed according to a set of scenarios for changes in rainfall and temperature and, indirectly, reference evaporation which was derived from temperature parameters. These changes were structured in "front-end" routines for the *ACRU* model (Kiker, 1996 *pers. comm.*). An effective doubling of CO_2 was simulated and transpiration suppression invoked through the evaporation routine in *ACRU*, which was again set to separate evaporation into that which evaporated from the soil surface and transpiration from the plant. For the sensitivity study, a uniform temperature increase of 2°C was applied across the southern African region. Precipitation, however, was initially increased by 10%, then decreased by 10% and finally maintained at 0%, i.e. no change in rainfall from the present to the future. The *ACRU* model was then used together with the perturbed climate to determine possible future responses of runoff production, stormflow response, recharge of soil water into the vadose zone and net irrigation demand. Model output for the three possible future precipitation regimes (+10%; 0%; -10%) were incorporated into an equation developed for estimating the sensitivity of the above hydrological responses to a change in rainfall (Schulze, 1996 *pers. comm.*). This equation is based on the equation developed by Wigley and Jones (1985) for estimating the sensitivity of mean annual runoff to changes in climate. The equation for the sensitivity analyses takes the form:

$$\text{Sensitivity Index} = \frac{[X_{+10} - X_{-10}]}{X_0} \Big/ \frac{[P_{+10} - P_{-10}]}{P_0}$$

$$= \frac{[X_{+10} - X_{-10}]}{X_0} \Big/ \frac{[\,110 - 90]}{100}$$

$$= \frac{[X_{+10} - X_{-10}]}{X_0} \Big/ 0.2$$

where, X = hydrological response unit e.g. runoff, quickflow

P = precipitation response unit

+10, -10, 0 = subscripts referring to possible future precipitation regimes

Model output resulting from the SCENGEN derived anticipated climate changes and the sensitivity analyses are discussed in Chapters 6 and 7.

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Chapter 6 describes how the models selected in this present chapter 5 were used to assess possible impacts of climate change on agriculture, namely on the potential effects on maize yield.

CHAPTER 6

POTENTIAL EFFECTS OF CLIMATE CHANGE ON AGRICULTURAL PRODUCTION

In Chapter 4 it was illustrated that plants respond directly to changes in atmospheric CO_2 levels and indirectly to changes in climatic variables, such as temperature and precipitation. A crop's response to climate change is a function of the interactions between the direct and indirect effects of CO_2 "fertilisation" on plants. If climate change is made up of a combination of CO_2 enrichment and changes in climatic variables, then plant growth rates and thus crop yields, as well as areas of optimum production, could be affected significantly in a future climate. This could have widespread economic implications for agriculture, in addition to potentially altering food security in the region (IPCC Agricultural Impacts,1995).

6.1 Crop Responses to Climate Change

6.1.1 Crop response to CO_2 enrichment

The magnitude of a crop's response to climate change is dependent on the concentration of atmospheric CO_2 and the photosynthetic pathway of the plant: C_3 or C_4. Chapter 4 illustrated that C_3 crops, such as wheat, rice and potatoes, may benefit more from the CO_2 "fertilisation effect" than C_4 crops, which include maize and sugarcane. This photosynthetic advantage over C_4 crops at higher CO_2 concentrations may result in more C_3 crops being grown in the future. However, Chapter 4 also indicated that transpiration suppression is more pronounced in C_4 crops than in C_3 crops, leading to increased water use efficiency and therefore improved tolerance to drier climatic conditions. Consequently, it can be counter argued that more C_4 crops may be grown in the future, should climate change lead to increased aridity. Weed-crop competition is also a factor shaping crop response to climate change, and was discussed in Chapter 4, together with the potential impacts of insects and pathogens on crop yields.

6.1.2 Crop response to increased temperatures

The response of crops to increasing temperatures is less certain than crop responses to CO_2 enrichment. It has been hypothesised that crop yields may increase in response to a warmer climate because of a longer frost-free growing season and the opportunity to employ farming strategies such as planting earlier or later than usual to minimise crop contact with peak periods of pests. However, increased temperatures may shorten crop life cycles through more rapid plant growth and development, thereby decreasing crop yields. Higher temperatures could increase the number of days when the temperature is above certain critical thresholds for crop growth and can lead to flower abortion and mutation of pollen. In addition to affecting the individual crop plant, temperature changes may also influence the geographic distribution of crop production areas. Cropping belts may shift and expand or contract, depending on the critical temperature thresholds of the crop. For example, deciduous crop production occurs in regions where the winter temperature is sufficiently low to allow appropriate periods of chilling. An increase in temperature will reduce the areas in which deciduous crops can be grown successfully.

6.1.3 Crop response to changes in water availability

Changes in water availability due to precipitation changes, will also greatly influence crop production in South Africa (Schulze, Kiker and Kunz,1993). Changes in rainfall patterns and intensities are important factors in determining soil moisture status and thus plant available water. Increases in climatic variability can lead to an increased demand for irrigation to maintain plant available water at optimal levels. Increased irrigation demand will result in increased competition for regional water supplies and promote conflict amongst water users (Whitmore,1991). The expected increase in plant water use efficiency (WUE) associated with CO_2 enrichment may counteract the impact of droughts, and thus irrigation demand, to a limited extent. However, the expected increase in leaf surface area associated with increased carbon fixation and plant growth implies that the beneficial effects of increased WUE are minimised.

6.1.4 Crop response to combined changes in CO_2, temperature and rainfall

A doubling of CO_2 levels enhances crop yield potential. However, when coupled with an increase in temperature, projected yields may decline, owing to increased soil water deficits and/or the shorter growing season of the crop. An increase in precipitation may offset the reductions in yield associated with warming, whilst a decrease in precipitation could accentuate them. The actual response of individual crops to climate change could be shaped by the photosynthetic pathway of the crop and its adaptability to changing conditions that will determine its competitive ability within an ecosystem.

6.2 Potential Impact of Climate Change on Maize Yield in southern Africa

The southern African subcontinent is largely semi-arid and sub-humid, with a diversity of soils and physiography. The broad range of climates within the region, which are characterised by high intra-seasonal and inter-annual variability of rainfall, makes it a high risk environment with regard to agricultural productivity (Schulze, Domleo, Furniss and Lecler,1995b). Despite this status, a high percentage of the land has traditionally been devoted to agricultural activities. However, rapid urbanisation and expansion of industry and mining has forced agriculture into areas considered to be climatically marginal and consequently sensitive to changes in climate (Human,1992). The fragile balance within these high risk environments may be threatened by the unknown regional impacts of climate change. Shifts in crop belts and crop yields; changes in sensitivity to crop failure, pests and pathogens will have significant effects on food production, food supply, hunger and nutrition within a region or nation and on international trade (Agricultural Impacts IPCC,1995).

It was with the above factors in mind, that the potential impact of climate change on maize yields in southern Africa was investigated. Maize is the staple grain crop of southern Africa (Schulze *et al.*,1995b). Changes in maize yield could thus have widespread ramifications for the majority of the population, particularly those that utilise it as a primary food source.

6.2.1 Methodology

The *ACRU* maize yield model uses daily temperature information (derived internally in the model by Fourier Analysis from monthly values) to "drive" the thermal time process through growing degree days. This transpiration and phenologically based submodel (cf. Table 6.1) has been developed and tested extensively under southern African conditions (Schulze *et al.*,1995b) and is thus considered appropriate for use in this particular study. A planting date of the 15 November was specified, to ensure that soil temperatures across the region would be sufficiently high to stimulate germination. A growing season of 150 days, which is a typical length for cultivars used in southern Africa, was also specified.

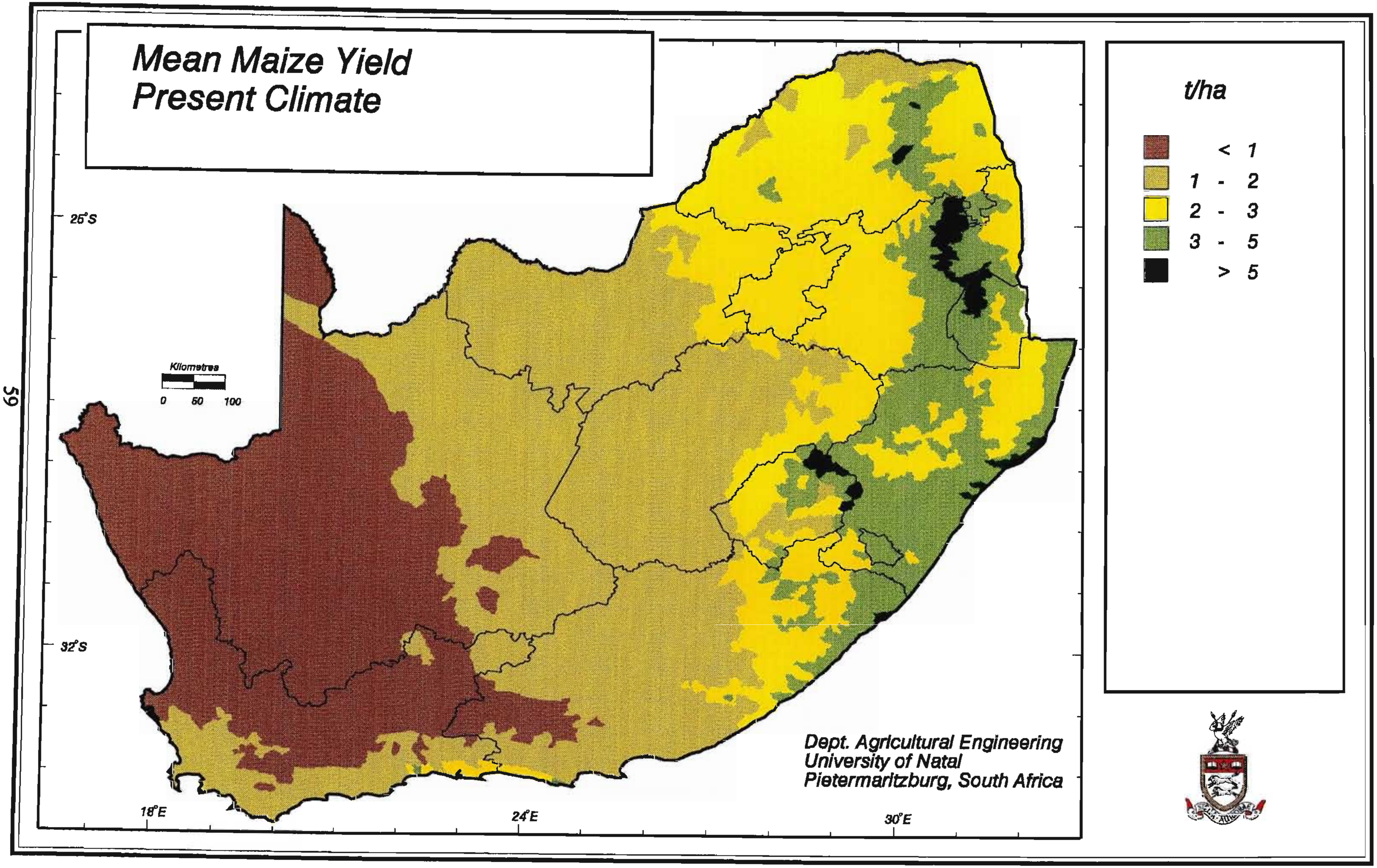
Table 6.1 Phenological states of maize related to accumulated growing degree days (T_t) after planting (Domleo,1990)

Phenological State	T_t
Plant Emergence	150
Onset of Flowering	700
End of Flowering	1150
Maturity of Cob	1700

6.2.2 Discussion and results

The results presented in the following figures represent seasonal maize yields obtained under conditions of sound management. Figure 6.1 shows mean simulated maize yields obtained in southern Africa under present climatic conditions. Areas with the highest potential maize production are found in the eastern and the north-eastern areas of the country. Simulated yields in these regions average 4-5 tons per hectare (t/ha). The more marginal production areas are found to the west of the high production areas and show yields of 2-3 t/ha. Those areas simulated to produce yields of less than 2 t/ha are considered unsuitable for commercial maize production. Areas suitable for maize production generally correspond to those areas with a mean annual rainfall greater than 500 mm (cf. Figure 6.2). The difference in simulated maize yields between the specified future climate and the present climate is shown in Figure 6.3.

Figure 6.1


Mean Maize Yield
Present Climate
t/ha
< 1
1 - 2
2 - 3
3 - 5
> 5
Kilometres
0
50
100
25°S
32°S
18°E
24°E
30°E
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There appears to be a yield increase in both the marginal and high production areas in the future. The marginal areas generally show potential yield increases of between 0.5-1.0 t/ha, whilst high production areas show potential yield increases > 1 t/ha. Yield increases occur despite the decreases in mean rainfall obtained from SCENGEN over much of the region (cf. Figure 6.4).

These results show that a decrease in rainfall amount simulated for the future climate, particularly in areas with a high mean annual rainfall, may not adversely affect potential maize yield, possibly due to the ability of C_4 crops such as maize to tolerate drier climatic conditions (cf. Chapter 4). This tolerance, coupled with CO_2 enrichment and warmer temperatures may be responsible for the increases in simulated maize yields obtained in this study, resulting in part from an increase in water use efficiency through transpiration suppression. Increased evaporative demand on evaporation from the soil surface as a result of increased temperature is thus largely counteracted by the CO_2 "fertilisation" effect (cf. Chapter 4).

*****

This chapter has emphasised the potential effects of climate change on agriculture which were initially mentioned in Chapter 4. Furthermore, the potential effects of a specified future scenario on maize yields in southern Africa were also discussed. The following chapter describes how the models selected in Chapter 5 were used to assess possible impacts of climate change on hydrological responses in southern Africa.

Figure 6.2

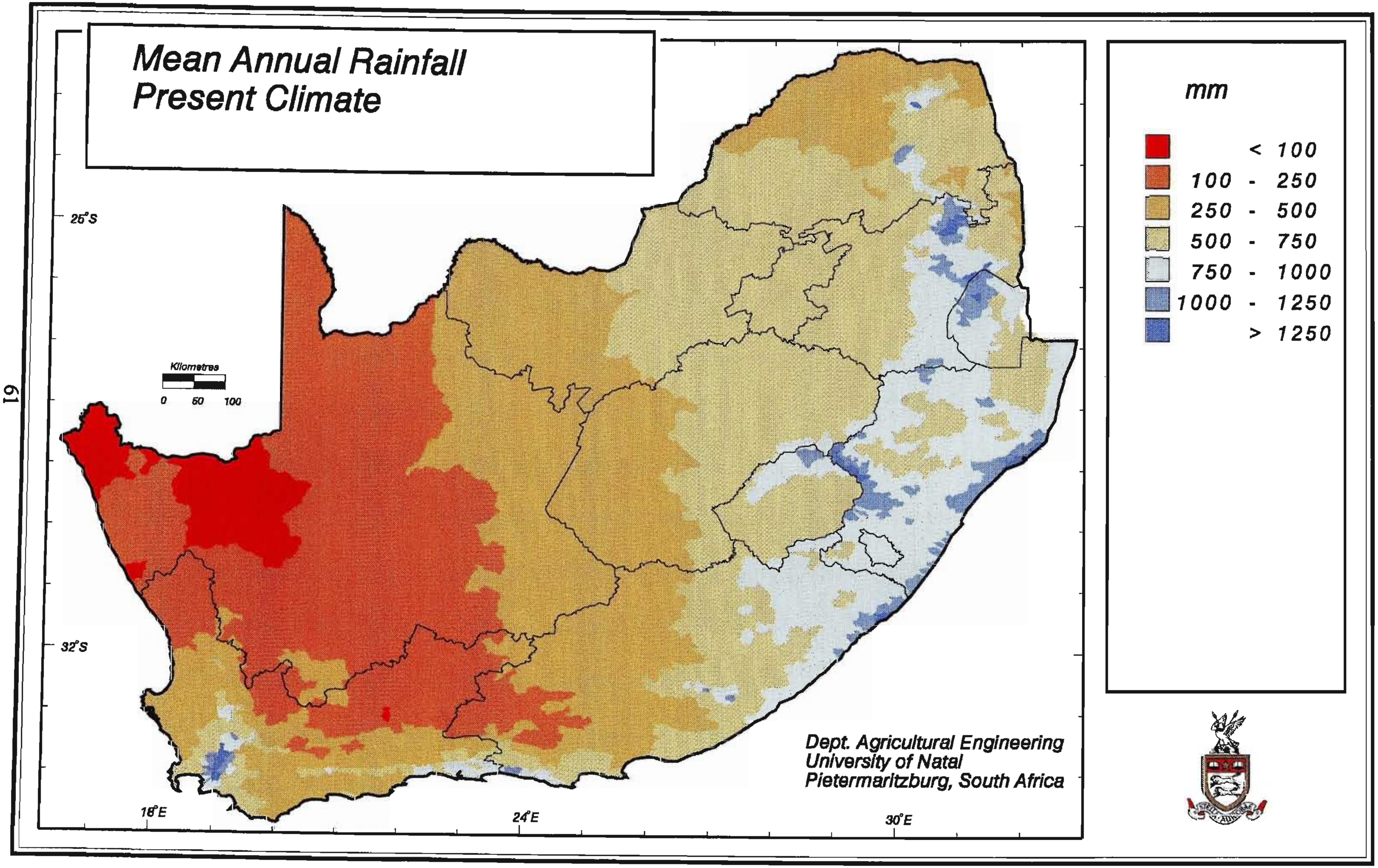
Mean Annual Rainfall
Present Climate
mm
< 100
100 - 250
250 - 500
500 - 750
750 - 1000
1000 - 1250
> 1250
Kilometres
0
50
100
25°S
32°S
18°E
24°E
30°E
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Figure 6.3

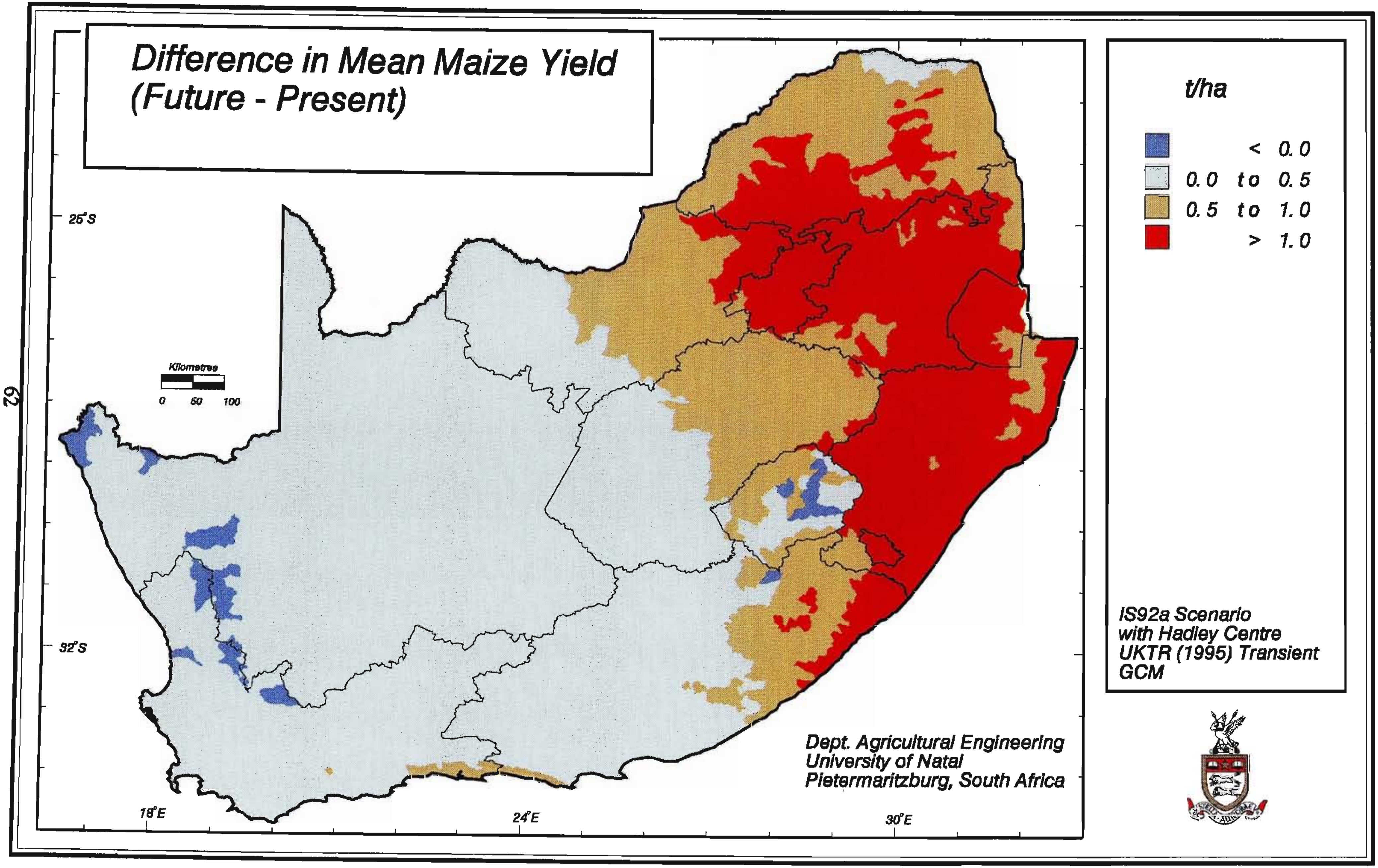
Difference in Mean Maize Yield (Future - Present)
t/ha
🟦 < 0.0
⬜ 0.0 to 0.5
🟫 0.5 to 1.0
🟥 > 1.0
Kilometres
0 50 100
25°S
32°S
18°E
24°E
30°E
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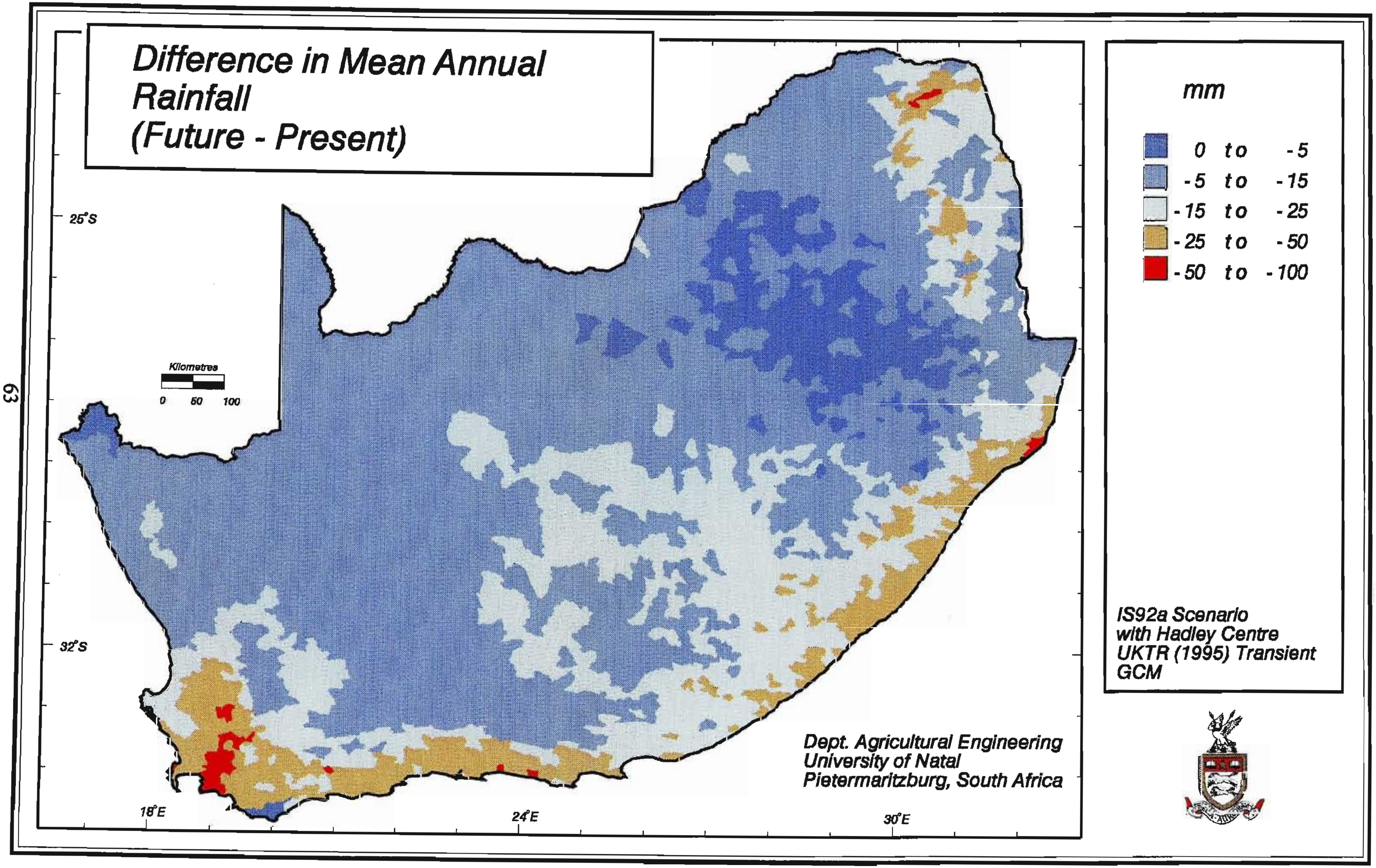
Figure 6.4


Difference in Mean Annual Rainfall (Future - Present)
mm
0 to -5
-5 to -15
-15 to -25
-25 to -50
-50 to -100
25°S
32°S
18°E
24°E
30°E
Kilometres
0
50
100
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CHAPTER 7

POTENTIAL EFFECTS OF CLIMATE CHANGE ON THE HYDROLOGICAL SYSTEM

Climate change has the potential to impact on the terrestrial hydrological system by affecting INPUTS to the system (rainfall, temperature, reference evaporation), SYSTEM PROCESSES (vegetation dynamics, soil infiltrability) and OUTPUTS to the system (runoff, sediment yield, recharge of soil water into the vadose zone). Furthermore, impacts on the hydrological system would alter the quality, quantity and distribution of southern Africa's water resources (Kunz and Schulze, 1993).

Quantitative projections of the impacts of climate change on a particular system can be developed. However, they are limited by the modeller's knowledge of critical processes and climatic and non-climatic stresses that may affect the response of the system to climate change (IPCC,1995). Despite the uncertainty associated with quantitative projections, the need to assess the potential response of both ecological and social systems to climate change and the ability of these systems to adapt to change in a sustainable manner, requires the development of these projections (Parry, Carter and Hulme,1996). A "critical" climate change demarcates the boundary between a change which can be accommodated by the social or ecological system and one that cannot.

This chapter describes potential hydrological responses to climate change in southern Africa. Two approaches are adopted in this study. The first, and more conventional approach is to consider the question: "Given a **specified** climate change, what would its impact be on the hydrological system?" This approach was adopted when comparing the present and future response of runoff, recharge of soil water into the vadose zone, soil moisture distribution in the A- and B-horizons, net irrigation demand and maize yield (cf. Chapter 6), obtained using the SCENGEN methodology (cf. Chapter 5.3.1). The second approach to climate change impact studies is to consider the question: "How much of a climate change is required to perturb the hydrological system significantly?" This approach was adopted when analysing the sensitivity indices of runoff, recharge of soil water into the vadose zone, stormflow and net irrigation demand obtained using the methodology of the sensitivity analyses outlined in Chapter 5.3.2.

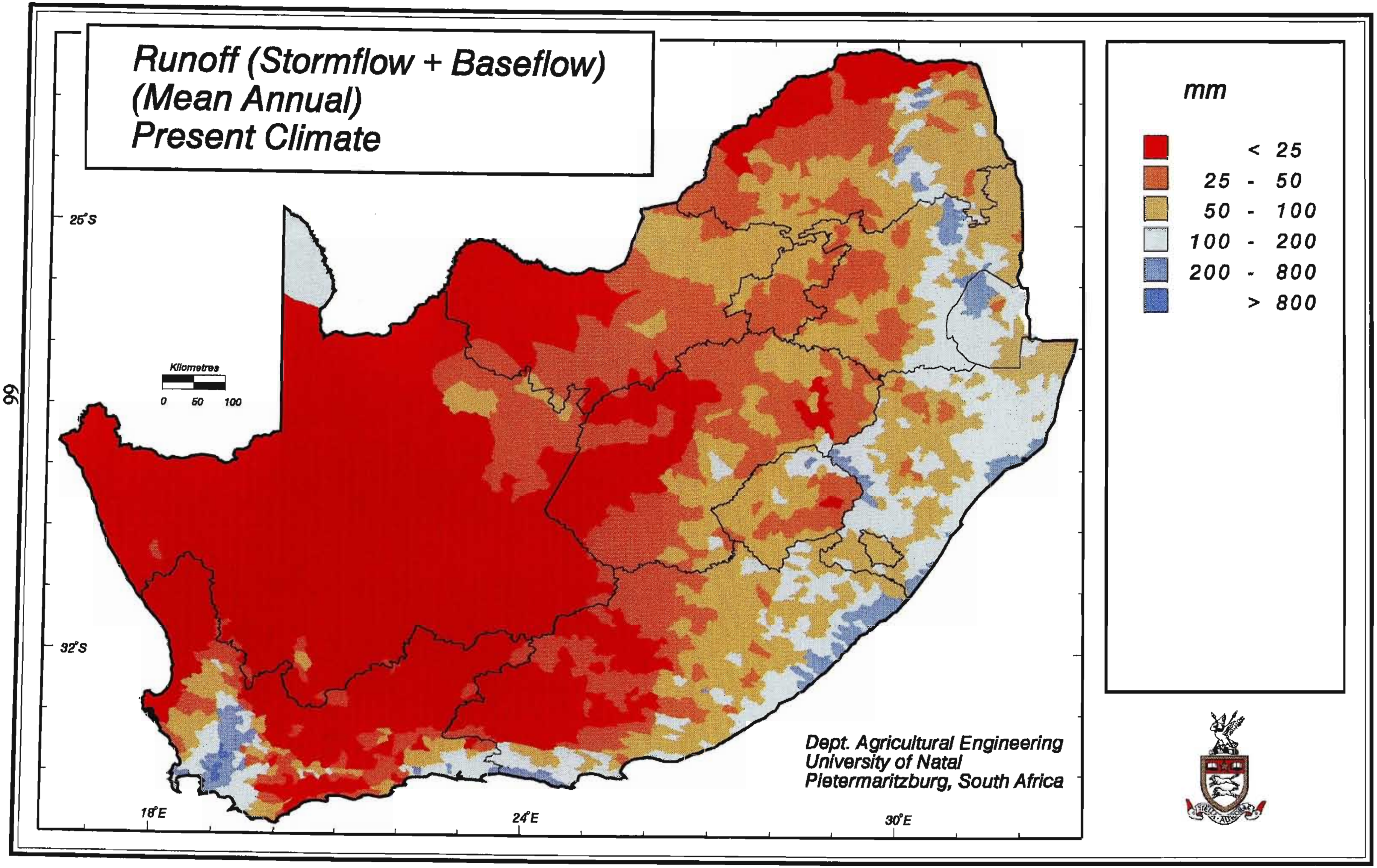
7.1 Impact of Climate Change on Hydrological Responses

7.1.1 Impact of a specific climate scenario change on runoff response

Simulated runoff, comprising stormflow plus baseflow, may be influenced by climatic factors such as rainfall, temperature and reference potential evaporation, which are, in turn, directly influenced by climate change. Climate change may also indirectly influence runoff by changing the soil-vegetation characteristics, of which the most important is the impact of increased atmospheric concentrations of CO_2 on plant transpiration and water use efficiency (cf. Chapter 4). Changes in runoff may have implications for hydrological engineering design and the ecology of streams and dams.

Southern Africa is characterised by very dry areas, where the mean annual runoff is < 25 mm, and very wet areas, where the mean annual runoff ranges from 200 mm to more than 800 mm (cf. Figure 7.1). This pattern of runoff relates to that of the mean annual rainfall of the present climate (cf. Figure 6.2). Figure 7.2 represents the change in mean annual runoff, i.e. the difference between the runoff of a future climate scenario obtained using the SCENGEN methodology (cf. Chapter 5.3.1), and that of the present. Figure 7.2 shows a simulated decrease in mean annual runoff over the south western parts of the country. This may be attributed to a large projected decrease in mean annual rainfall over that part of the region (cf. Figure 6.4), coupled with the expected increase in temperature and hence reference evaporation. Because this is primarily a winter rainfall area, changes in soil-vegetation characteristics will have a minimal effect on the runoff response due to low evaporative losses from transpiring vegetation. Increases in mean annual runoff, ranging primarily from 0-70 mm, are simulated for the rest of the southern African region. This is in contrast to the expected decreases in mean annual rainfall simulated for the region in Figure 6.4. Increases in runoff may be associated with increased plant water use efficiency owing to increased stomatal resistance,

Figure 7.1



Runoff (Stormflow + Baseflow)
(Mean Annual)
Present Climate

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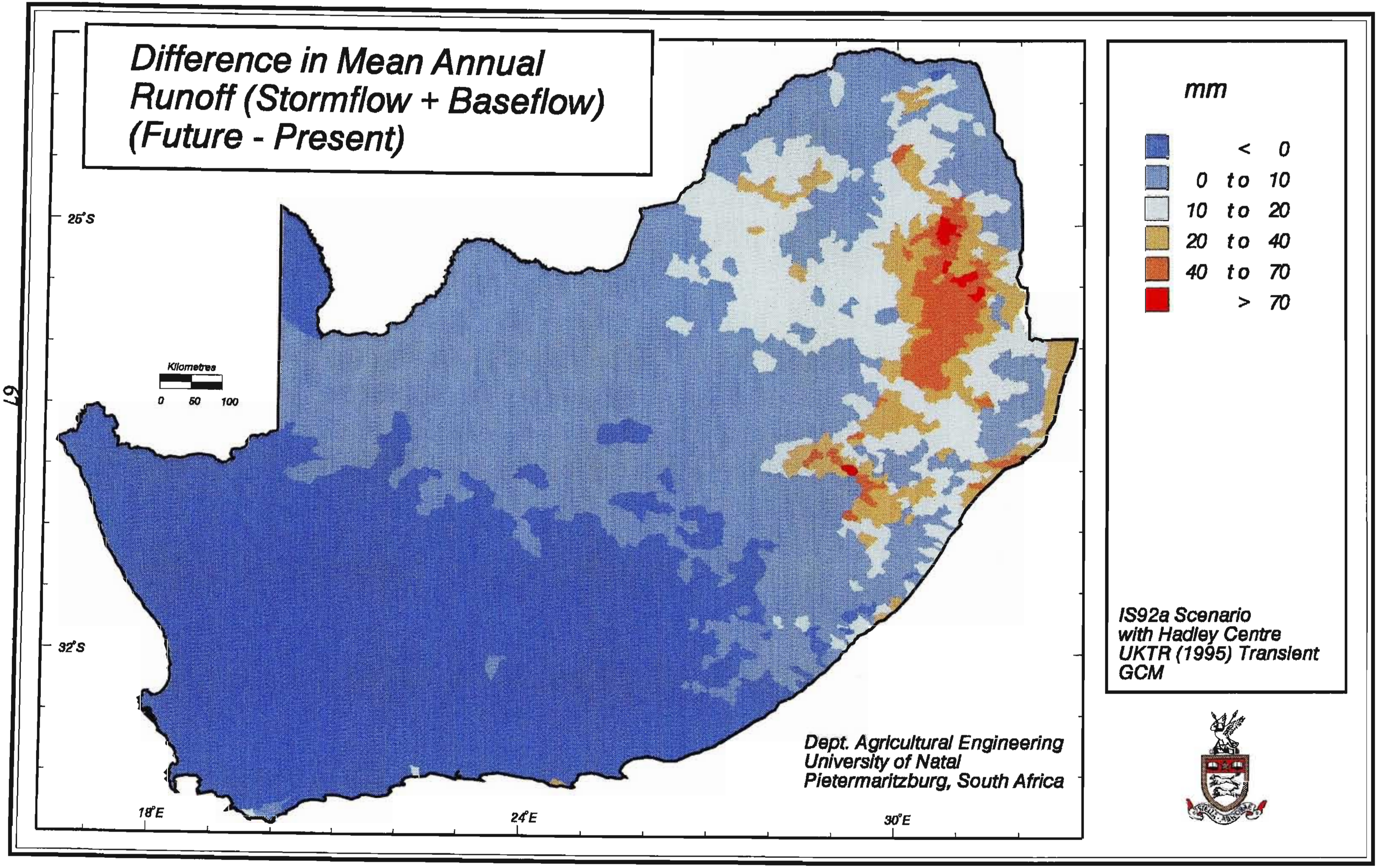
Figure 7.2



Difference in Mean Annual Runoff (Stormflow + Baseflow) (Future - Present)

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with Hadley Centre
UKTR (1995) Transient
GCM

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a consequence of increased atmospheric concentrations of CO_2. Furthermore, more rapid plant growth and an associated increase in canopy density may reduce soil evaporation. The combined effect of these factors is a potential increase in runoff per unit of rainfall in well vegetated areas (Schulze, 1991), which may counteract the essentially small percentage decreases in rainfall expected over the region in the future. The CO_2 "fertilisation" feedback routine included in the *ACRU* model appears to be responsible for the unexpected increase in runoff response simulated for the future (cf. Appendix 1).

7.1.2 A sensitivity study of runoff response to rainfall changes

Figure 7.3 shows the sensitivity of mean annual runoff in southern Africa following perturbation of the daily rainfall record by a percentage factor ranging from -10% to +10%, in increments of 10%. Areas with a sensitivity index (defined in Chapter 5) of 2-4 are not considered to be highly sensitive to a change in precipitation. Those areas with an index < 2 are considered to be the least sensitive to a change in precipitation, whilst those areas with an index > 4 are considered to be those areas most sensitive to a change in precipitation. Mean annual runoff along the eastern coast is not very sensitive to a change in precipitation. The generally humid and high rainfall climate exhibited along the coastline renders it less sensitive, relative to other areas. The areas most sensitive to a change in precipitation are in the winter rainfall region. The mean annual rainfall in these regions ranges from < 100 mm to approximately 500 mm. A small change in precipitation in these areas will thus have a large effect on the runoff response, particularly in winter, because rainfall becomes a dominating factor in runoff response during the season when evaporative losses to transpiration are low, and antecedent soil moisture conditions remain high.

Stormflow is defined as water generated at or near the surface of the catchment from a specific rainfall event. It is that contribution to runoff that excludes baseflow. The sensitivity of mean annual stormflow responses to climate change, shown in Figure 7.4, closely resembles that of mean annual runoff responses to climate change (cf. Figure 7.3). Stormflow responses are generally not very sensitive to changes in precipitation, except in the winter rainfall region where often consecutive days of frontal rain and high antecedent soil moisture content associated with that allows for a rapid surface and near surface response. In the summer rainfall

Figure 7.3

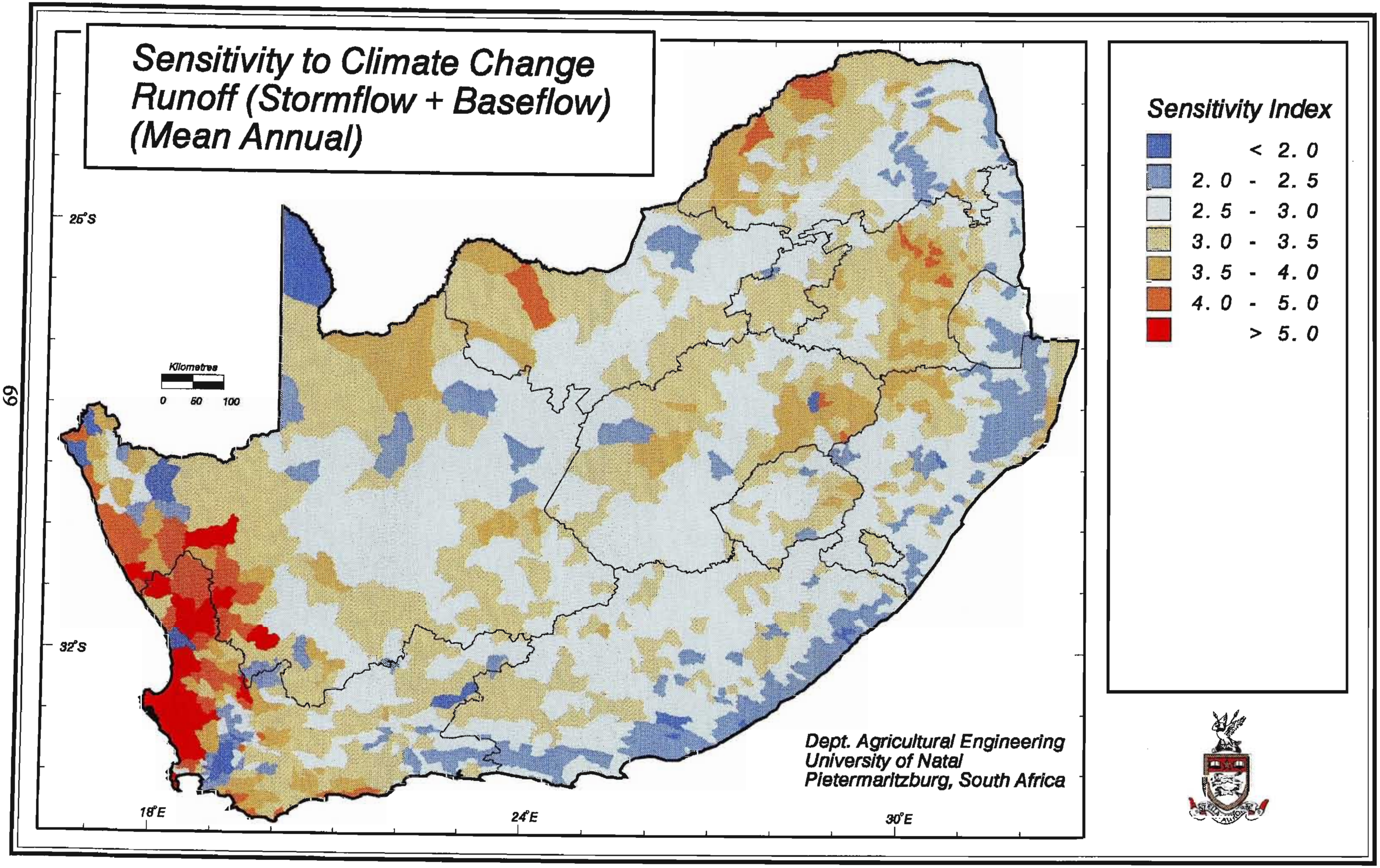
Sensitivity to Climate Change
Runoff (Stormflow + Baseflow)
(Mean Annual)
Sensitivity Index
< 2.0
2.0 - 2.5
2.5 - 3.0
3.0 - 3.5
3.5 - 4.0
4.0 - 5.0
> 5.0
25°S
32°S
18°E
24°E
30°E
Kilometres
0
50
100
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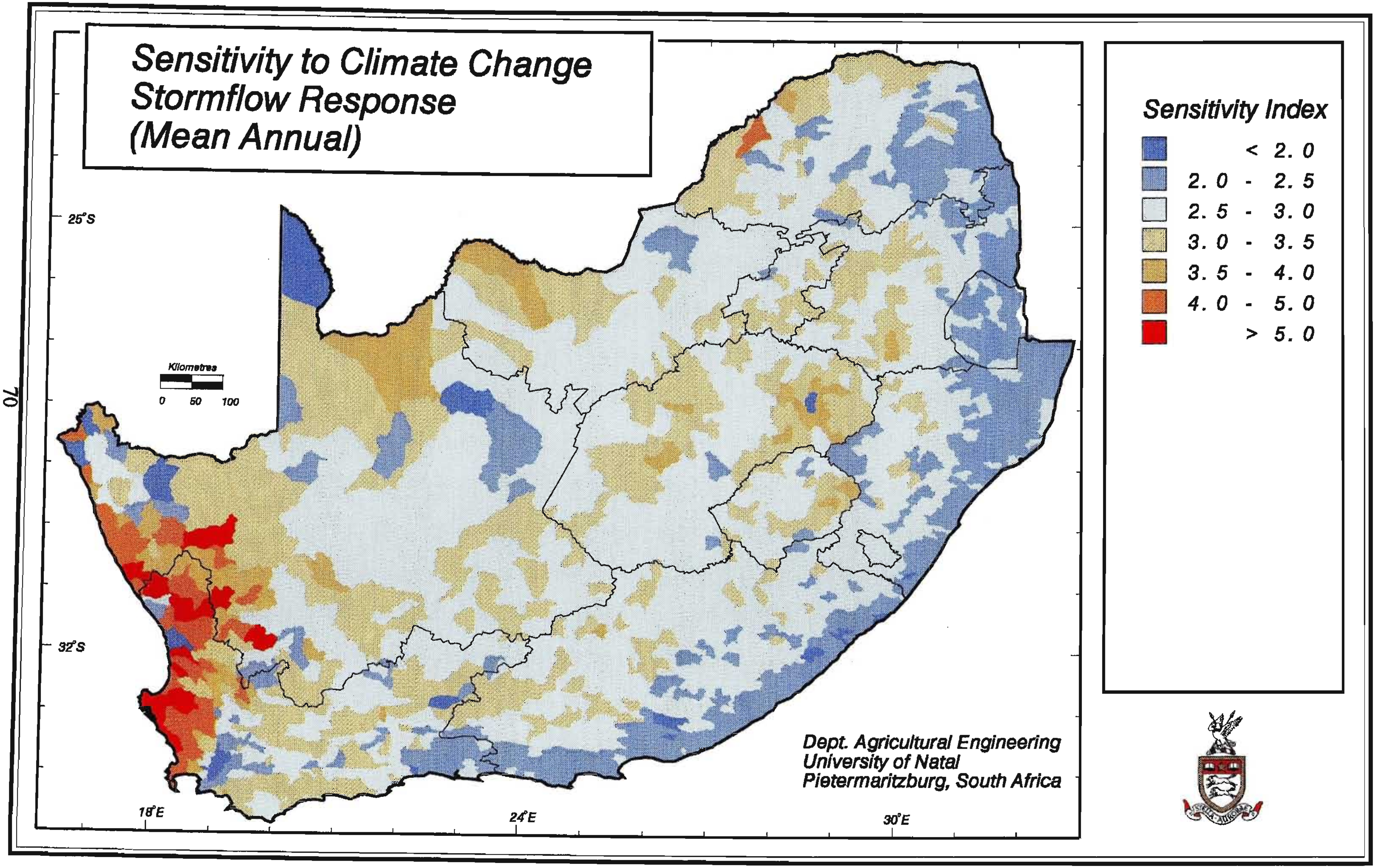
Figure 7.4


Sensitivity to Climate Change
Stormflow Response
(Mean Annual)
Sensitivity Index
< 2.0
2.0 - 2.5
2.5 - 3.0
3.0 - 3.5
3.5 - 4.0
4.0 - 5.0
> 5.0
Kilometres
0
50
100
25°S
32°S
18°E
24°E
30°E
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regions, less frequent convective storms associated with high evaporative losses between storms are major causes of a reduction in the sensitivity of stormflow to climate change.

7.2 Impact of Climate Change on Crop Water Demand by Irrigation

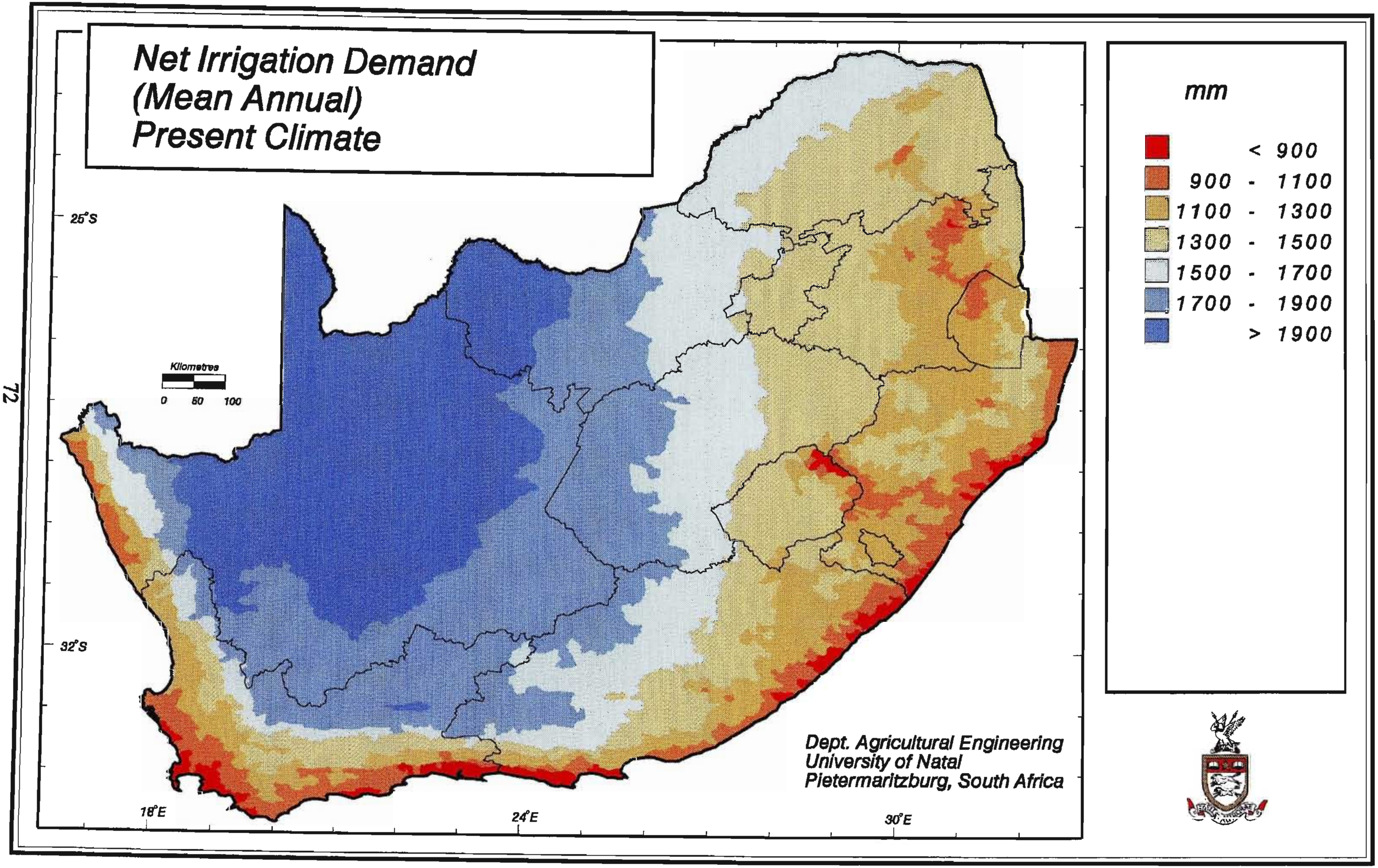
Climate change may result in changes in demand for water resources, possibly leading to conflict and competition for water resources between water users. This could be potentially problematic, particularly with regard to water demand for irrigation. Over 50% of southern Africa's stored water is utilised by irrigation (Schulze,1997). If climate change results in a general decrease in rainfall amounts, then the need for irrigation may nevertheless increase, despite expected improvements in plant water use efficiency resulting from increased transpiration suppression and reduced soil water evaporation, because of more rapid initial canopy growth (Schulze, 1991). The area under cultivation may also decrease. With the world population projected to double to approximately 10 billion in 2050, according to the IS92a scenario (Legget, Pepper and Swart,1992), problems of food security may become an important future consideration if climate change resulted in decreased rainfall amounts.

7.2.1 Impact of a specific climate scenario change on net irrigation demand

Present mean annual net irrigation demand, which is directly influenced by precipitation, is illustrated in Figure 7.5. In the *ACRU* simulations it was assumed that a summer crop, with growth characteristics of maize planted on November 15 and with a 140 day growing season, and a winter crop with growth characteristics of wheat planted in May 1 and with a 120 day growing season, were being cultivated on a 0.8 m deep sandy clay loam. These crops were subjected to demand irrigation, i.e. soils were replenished by a net irrigation application to their drained upper limit (i.e. field capacity) once soil moisture was depleted to 50% of the plant available water capacity. No restrictions on water availability were assumed.

Areas with a high net irrigation demand correspond to those areas with a low mean annual rainfall (cf. Figure 7.5 and Figure 6.2) and vice-versa. The humid eastern coast, with its high mean annual rainfall, has the lowest net irrigation demand, whilst the arid interior with

Figure 7.5


Net Irrigation Demand
(Mean Annual)
Present Climate
mm
< 900
900 - 1100
1100 - 1300
1300 - 1500
1500 - 1700
1700 - 1900
> 1900
Kilometres
0
50
100
25°S
32°S
18°E
24°E
30°E
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additionally a high rate of potential evaporation, has the highest net irrigation demand. In a future climate, net irrigation demand (cf. Figure 7.6) is expected to increase over the entire region, partially in response to the widespread decrease in rainfall projected in Figure 6.4, coupled with the warming expected as a consequence of the augmented greenhouse effect. The high rainfall areas in the east of the country and the winter rainfall region in the south west show the smallest increase in net irrigation demand. The projected decrease in mean annual rainfall in the eastern part of the country is very small, relative to the mean annual rainfall experienced in the area. Consequently, there is only a small increase in net irrigation demand. In contrast, the projected decrease in mean annual rainfall over the winter rainfall region is larger, relative to the mean annual rainfall of the region. However, the rainfall occurs in winter, when temperatures are cooler and evaporative demand is lower. This may account for the relatively small increase in net irrigation demand. Large increases in net irrigation demand are evident in the arid interior of the region and may be attributed to the projected decrease in rainfall and warming expected over the region. Furthermore, the transpiration suppression routine is not utilised when calculating net irrigation demand. Thus the feedback response associated with CO_2 "fertilisation" evident in the results obtained from the other hydrological response simulations, has no effect on net irrigation demand. Consequently, the results obtained for this particular hydrological response are in accordance with the literature.

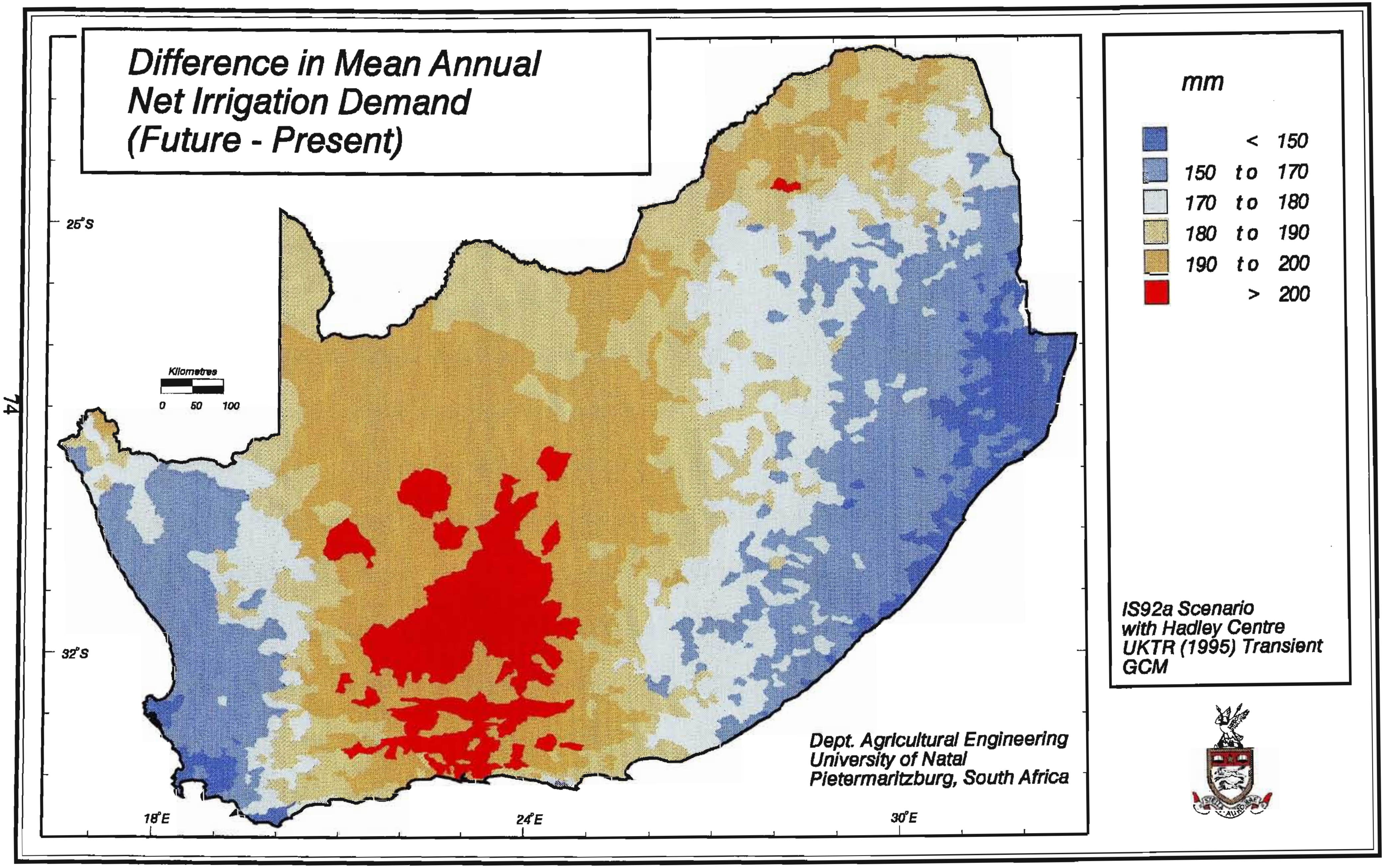
7.2.2 A sensitivity study of net irrigation demand

Mean annual net irrigation demand is not very sensitive to a change in precipitation (cf. Figure 7.7). In the drier areas of the region, net irrigation demand is so high, even under present conditions, that a change in precipitation has little effect. In the wetter, north eastern areas of the country, where net irrigation demand is relatively low, a change in rainfall alters net irrigation demand to a greater extent. However, generally, net irrigation demand is insensitive to a 10% change in precipitation.

7.2.3 Impact of a specific climate scenario change on soil moisture content

Soil moisture content in the A- and B-horizon influences a range of hydrological responses. Generally, soil moisture content in the A-horizon may influence the rate of evaporation from

Figure 7.6


Difference in Mean Annual Net Irrigation Demand (Future - Present)
mm
< 150
150 to 170
170 to 180
180 to 190
190 to 200
> 200
25°S
32°S
18°E
24°E
30°E
Kilometres
0 50 100
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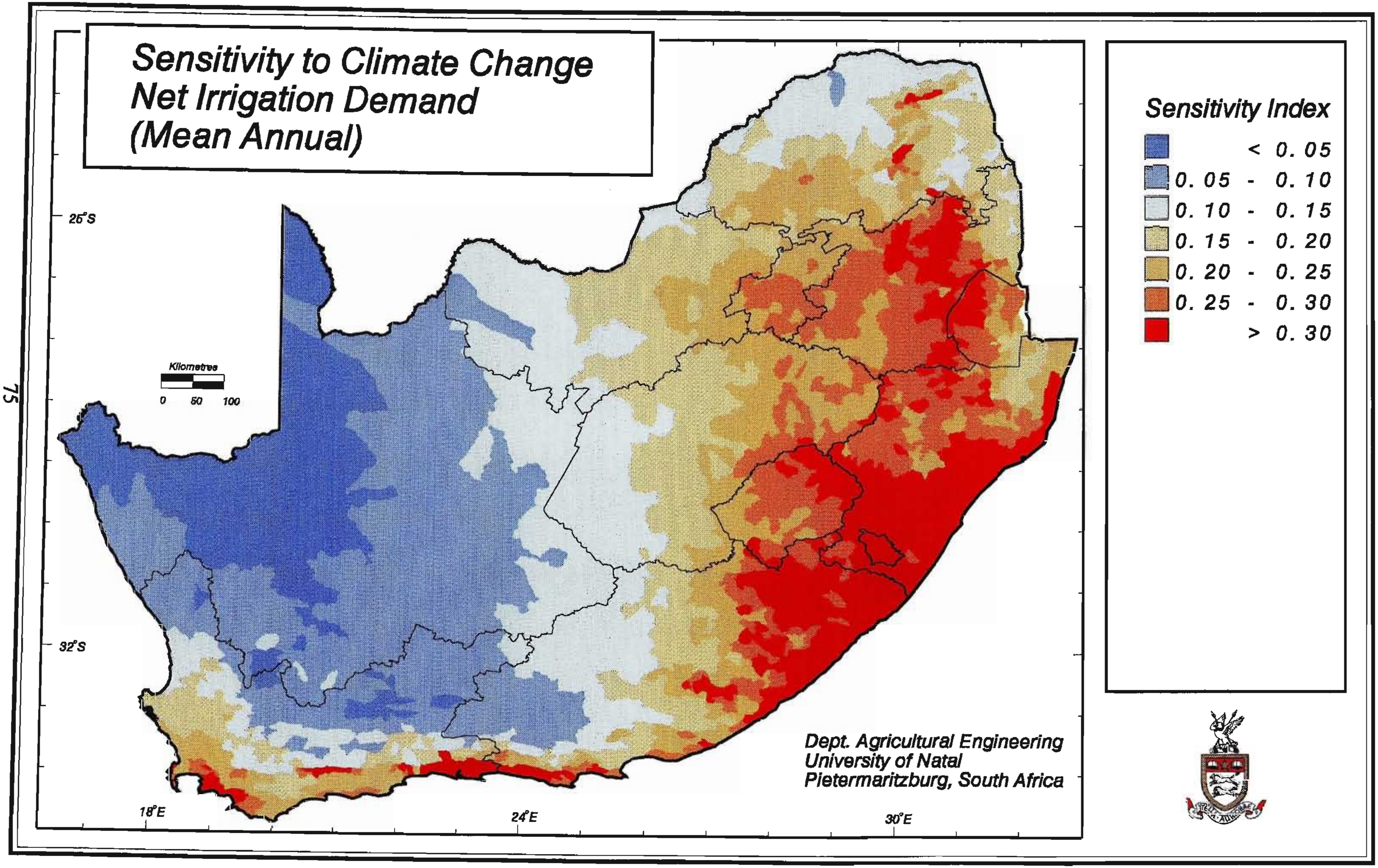
Pietermaritzburg, South Africa
STELLA AURORAE

Figure 7.7


Sensitivity to Climate Change
Net Irrigation Demand
(Mean Annual)
Sensitivity Index
< 0.05
0.05 - 0.10
0.10 - 0.15
0.15 - 0.20
0.20 - 0.25
0.25 - 0.30
> 0.30
Kilometres
0
50
100
26°S
32°S
18°E
24°E
30°E
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the soil surface, stormflow generation and the amount of saturated drainage from the A-horizon to the B-horizon, whereas soil moisture content in the B-horizon plays a role in plant transpiration and the amount and rate of saturated drainage from the B-horizon to the intermediate or groundwater store, i.e. recharge through the soil profile into the vadose zone (Schulze,1995a). Consequently, climate change effects on soil moisture content may be significant.

Soil moisture content is dependent on the thickness of the respective soil horizon, its texture (and hence the permanent wilting point , drained upper limit and porosity) and, of course, the interplay of the local climatic regime and vegetative cover. The annual mean of daily values of soil moisture in the A-horizon under present climatic conditions is illustrated in Figure 7.8. The arid and semi-arid areas of the interior have an average annual soil moisture content < 25 mm, in contrast to the higher rainfall areas to the north east of the region, which have an average annual soil moisture content ranging from 45 mm to > 60 mm. Figure 7.9 shows the simulated changes in the annual of daily mean soil moisture content in the A-horizon. Decreases in the annual of daily mean soil moisture content shown for the south western parts of southern Africa could be attributed to a large projected decrease in mean annual rainfall over that part of the region (cf. Figure 6.4), coupled with the expected increase in temperature and hence reference evaporation. Furthermore, because this is primarily a winter rainfall region, changes in soil-vegetation characteristics will have a negligible effect on the soil moisture content of the topsoil due to low evaporative losses from transpiring vegetation. The simulated decrease in soil moisture content of the topsoil in the south west of the country is reflected in the decrease in simulated runoff response obtained for this area (cf. Figure 7.2). Increases in the annual of daily mean soil moisture content in the topsoil, ranging from 0-2 mm, are simulated for the rest of the southern African region. The increases in runoff shown in Figure 7.2 are a result of the increases in the amount of soil moisture in the topsoil, evident in Figure 7.9. Increases in soil moisture content may be associated with increased plant water use efficiency owing to increased stomatal resistance, which is incorporated into the *ACRU* model as a transpiration suppression routine. The CO_2 "fertilisation" feedback appears to be responsible for the unexpected increase in the annual of daily mean soil moisture content of the A-horizon simulated for the future.

Figure 7.8

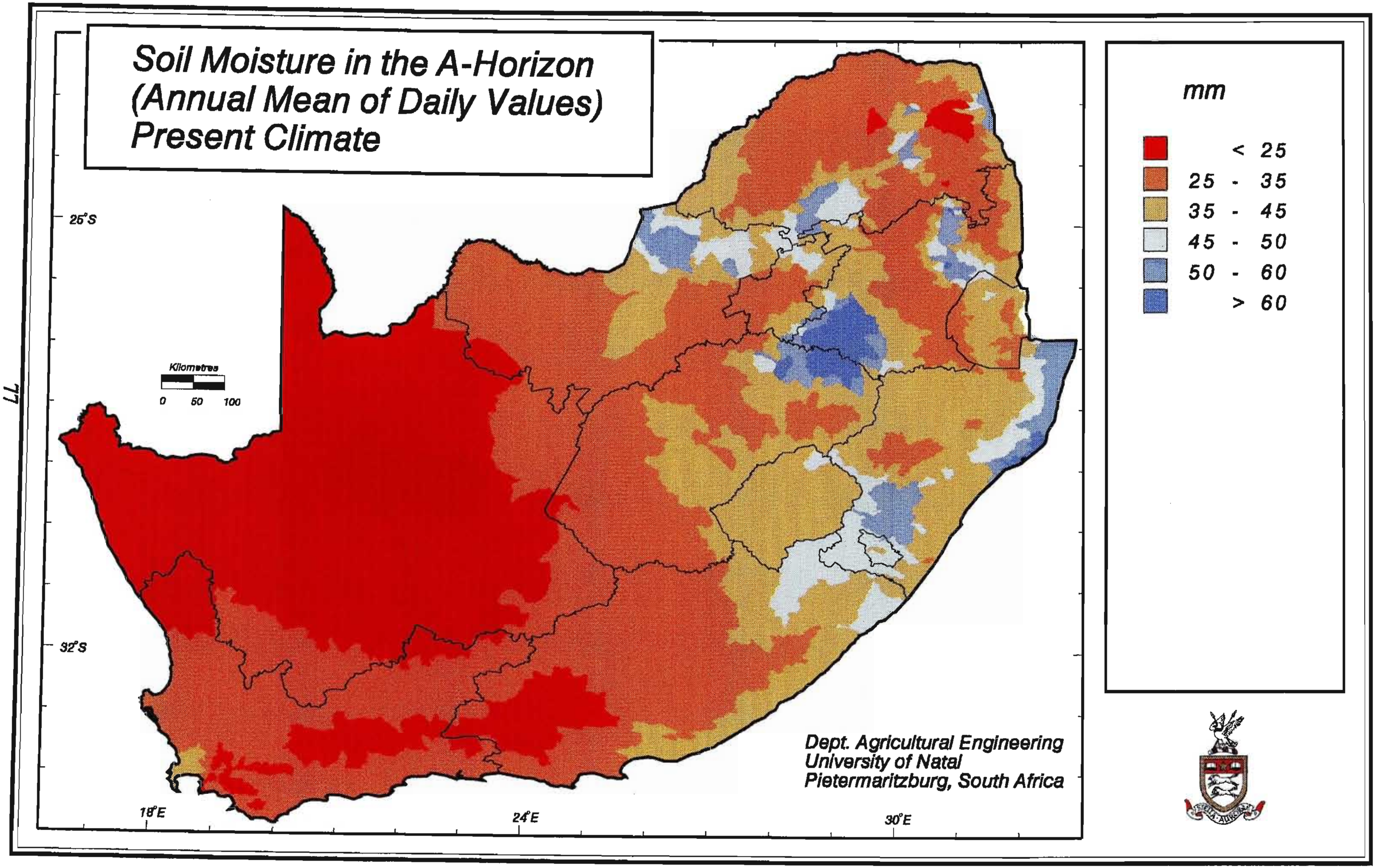
Soil Moisture in the A-Horizon
(Annual Mean of Daily Values)
Present Climate
mm
< 25
25 - 35
35 - 45
45 - 50
50 - 60
> 60
Kilometres
0
50
100
25°S
32°S
18°E
24°E
30°E
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Figure 7.9

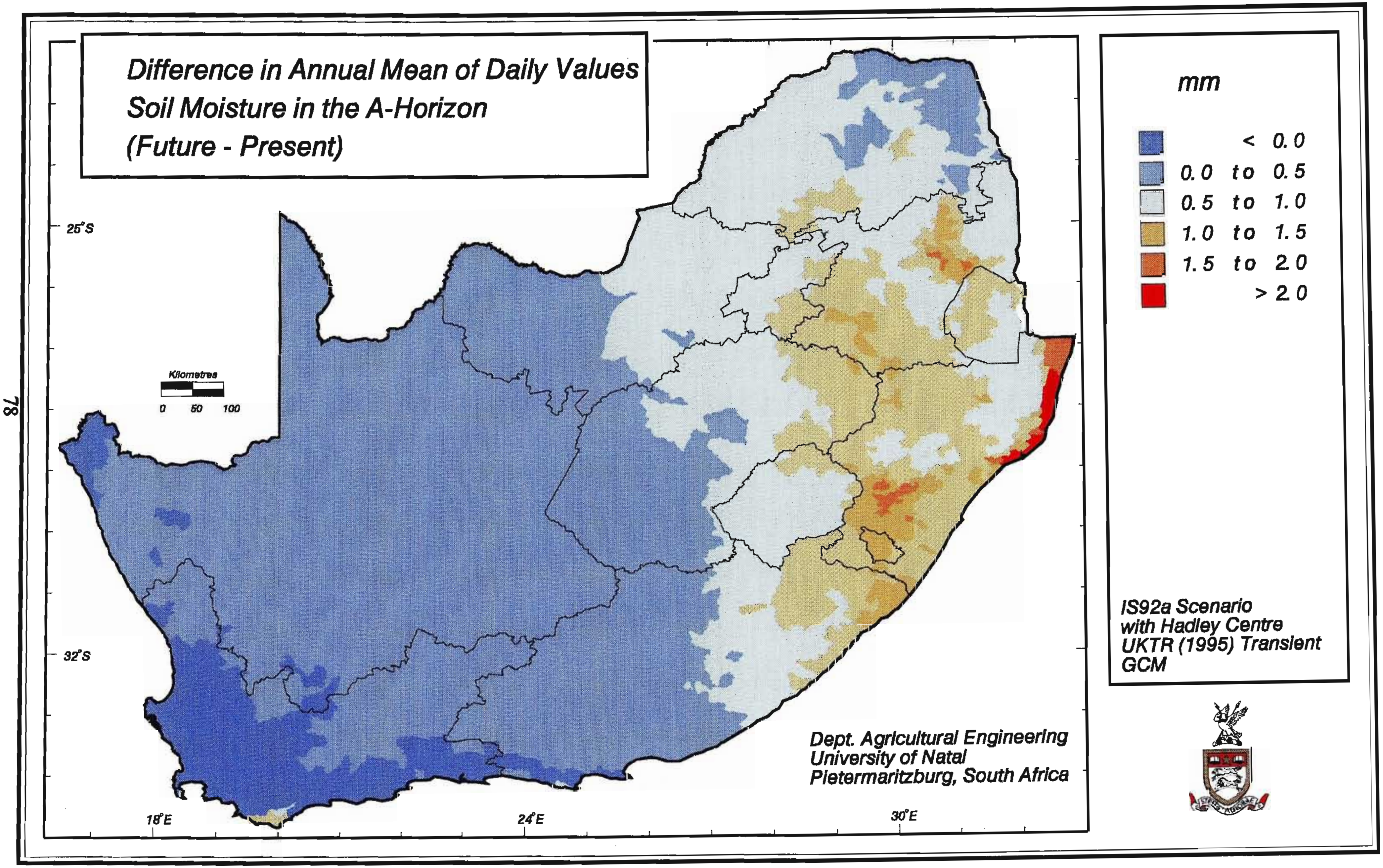
Difference in Annual Mean of Daily Values
Soil Moisture in the A-Horizon
(Future - Present)
mm
< 0.0
0.0 to 0.5
0.5 to 1.0
1.0 to 1.5
1.5 to 2.0
> 2.0
Kilometres
0
50
100
25°S
32°S
18°E
24°E
30°E
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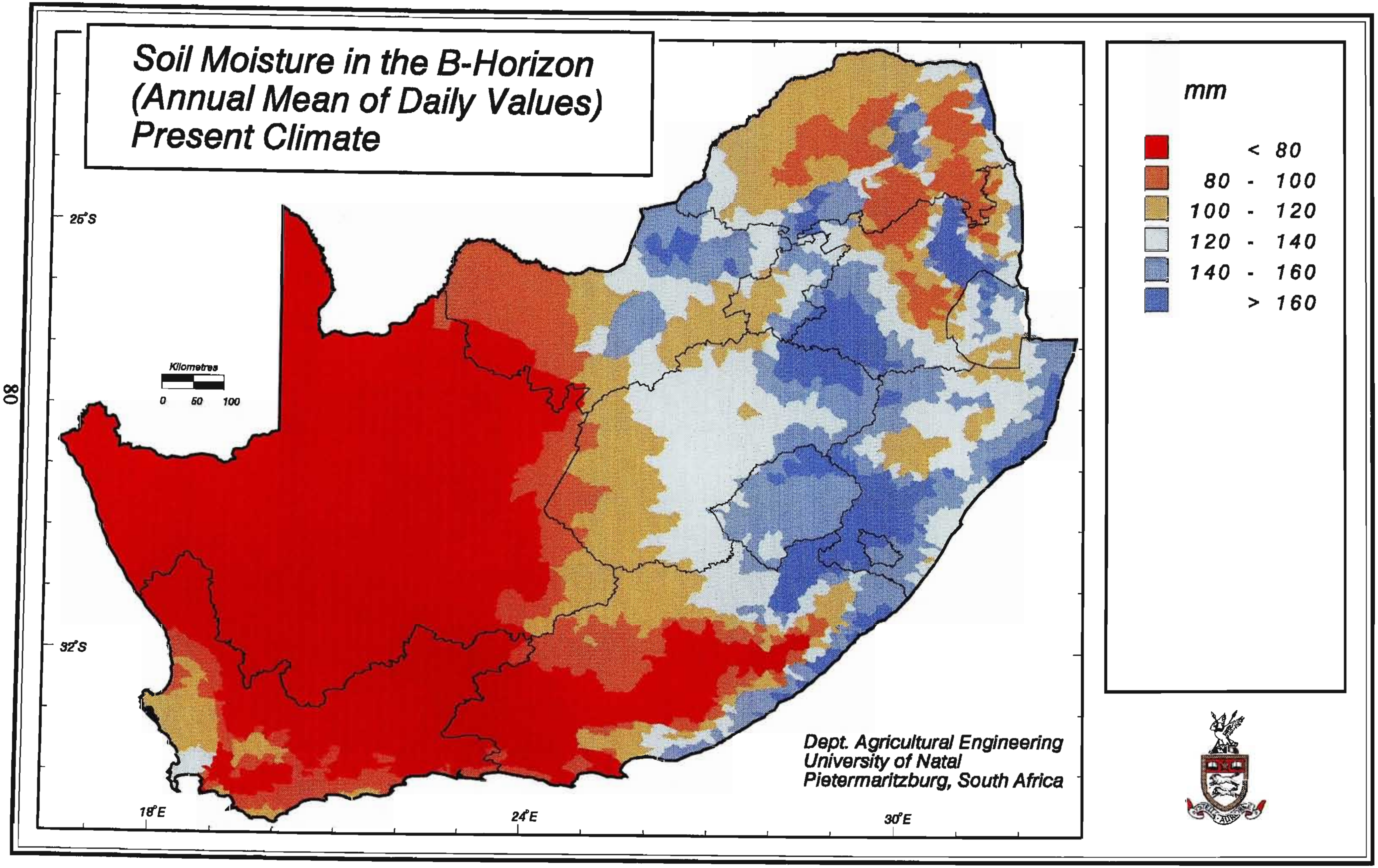
Figure 7.10 shows the annual of daily mean soil moisture content in the B-horizon under present climatic conditions. In this study, the soil moisture content of the B-horizon (ranging primarily from 800-2200 mm) is greater than that of the A-horizon (ranging primarily from 300-700 mm) because the active root extraction of the vegetative cover, viz. veld in good hydrological condition, is concentrated in the A-horizon, and also because the B-horizon is generally thicker than the topsoil horizon. Both soil surface evaporation and plant transpiration draw water from the A-horizon, whereas the B-horizon loses soil water only by the relatively lower extraction by deeper roots, by very slow capillary action (into the A-horizon) or by saturated drainage (into the vadose zone). The annual of daily mean soil moisture content in the B-horizon under present conditions (cf. Figure 7.10) has a similar distribution to that of the A-horizon (cf. Figure 7.8). Similarly, the simulated changes in the annual of daily mean soil moisture content in the B-horizon (cf. Figure 7.11) also resemble the changes illustrated in Figure 7.9. Decreases in soil moisture content in parts of the western Cape may be attributed to decreased saturated drainage from the A-horizon to the B-horizon following reduction in projected rainfall with climate change. Soil characteristics of the catchment such as porosity, texture and the depth of the A- and B-horizon could also account for the decreases shown in Figure 7.11. Increases in the annual of daily mean soil moisture content of the subsoil generally correspond to those parts of the southern African region that experience a simulated increase in soil moisture content of the topsoil (cf. Figure 7.9). Consequently, increased saturated drainage from the topsoil to the subsoil could account for the simulated increases in the annual of daily mean soil moisture content of the B-horizon.

7.3 Climate Change Effects on Underground Water Supplies

Water supply from precipitation, streamflow or groundwater will be impacted by climate change. Therefore, climate change may also affect regions that are solely or highly dependent on unregulated river systems or groundwater for water supply. Groundwater supplies have to be replenished i.e. recharged, periodically. Recharge rates may decrease or increase depending on the climate change scenario considered. In this study, saturated drainage from the bottom of the B-horizon into the vadose, i.e. intermediate zone, was simulated with the *ACRU* model as an index of recharge through the soil profile, eventually into the groundwater store.

Figure 7.10



Soil Moisture in the B-Horizon (Annual Mean of Daily Values) Present Climate

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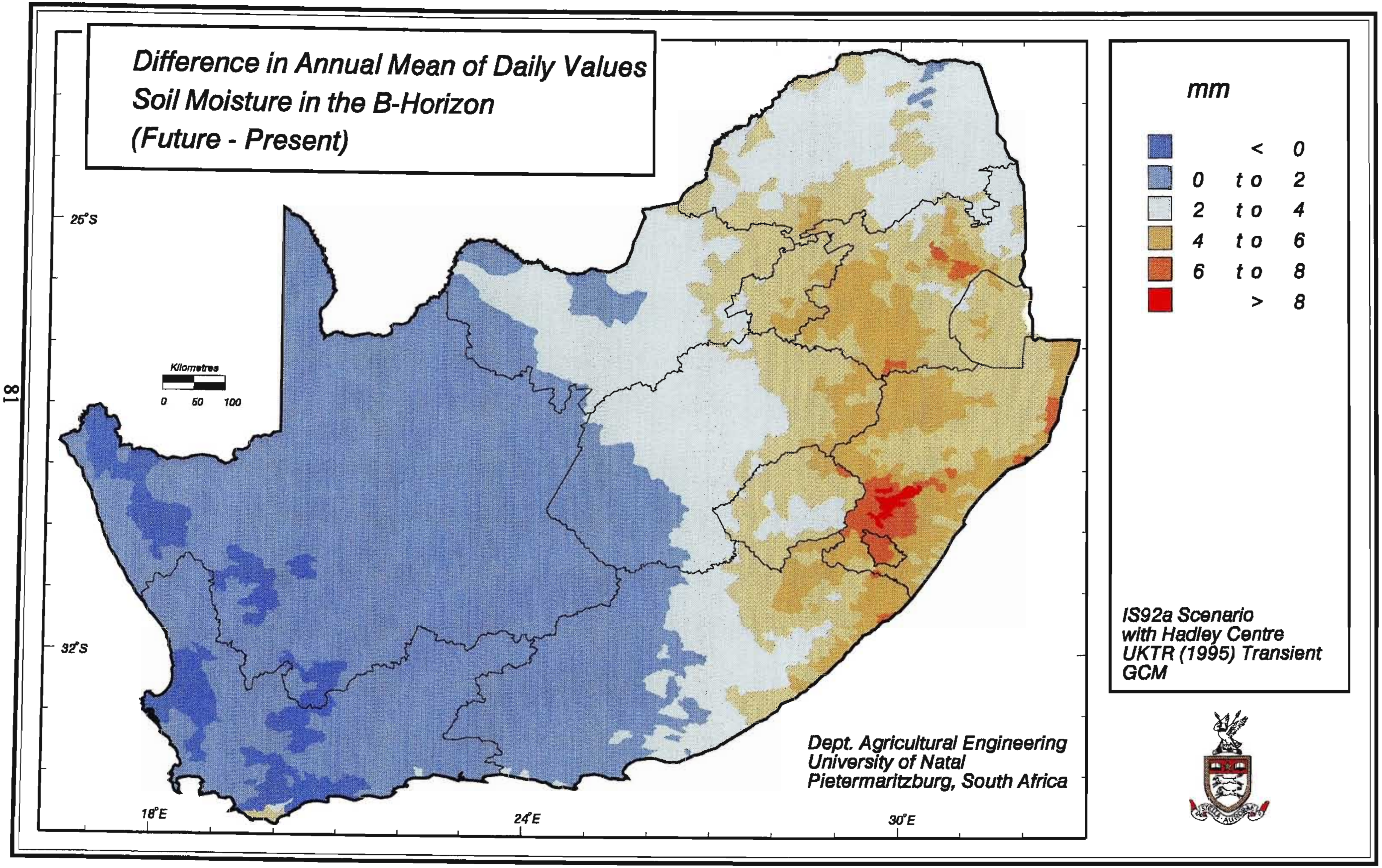
Figure 7.11


Difference in Annual Mean of Daily Values
Soil Moisture in the B-Horizon
(Future - Present)
25°S
32°S
18°E
24°E
30°E
Kilometres
0
50
100
mm
< 0
0 to 2
2 to 4
4 to 6
6 to 8
> 8
IS92a Scenario
with Hadley Centre
UKTR (1995) Transient
GCM
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7.3.1 Impact of a specific climate scenario change on recharge into the vadose zone

Areas with a high soil moisture content in the B-horizon (cf. Figure 7.10) generally exhibit high rates of recharge into the vadose zone (cf. Figure 7.12). Low rates of recharge are evident in the arid and semi-arid interior of the region. Simulated increases in recharge in the eastern parts of the southern African region (cf. Figure 7.13), ranging from 0-50 mm, could be attributed to the increased movement of water from the A-horizon to the B-horizon, and thence to the vadose zone. Decreases in recharge simulated for the south western parts of the region may be attributed to simulated decreases in soil moisture content in the A- and B-horizons, with a concomitant decrease in soil water drainage through the horizons to the vadose zone. Furthermore, those areas exhibiting < 2 mm increase in the annual of the daily mean soil moisture content of the B-horizon generally also show a decrease in recharge into the vadose zone through the soil profile. This could be a consequence of the simulated decrease in rainfall, coupled with an increase in temperature and hence evaporative demand, which may reduce the already negligible rates of recharge in those areas.

7.3.2 A sensitivity study of recharge into the vadose zone

Mean annual recharge through the soil profile into the vadose zone is extremely sensitive to changes in precipitation. This is illustrated in Figure 7.14, where a large portion of the southern African region displays a sensitivity index > 5. In absolute values recharge rates are very low, consequently a change in precipitation has a large relative effect on recharge. Those areas less sensitive to a precipitation change include the more arid and semi-arid areas of the interior. Recharge in these areas is negligible and thus remains unaffected by a change in already low amounts of precipitation.

7.4 Discussion

A comparative analysis of the sensitivity of selected hydrological responses to climate change (cf. Figures 7.3, 7.4, 7.7 and 7.14) yield the following results, in ascending order of sensitivity:

Figure 7.12

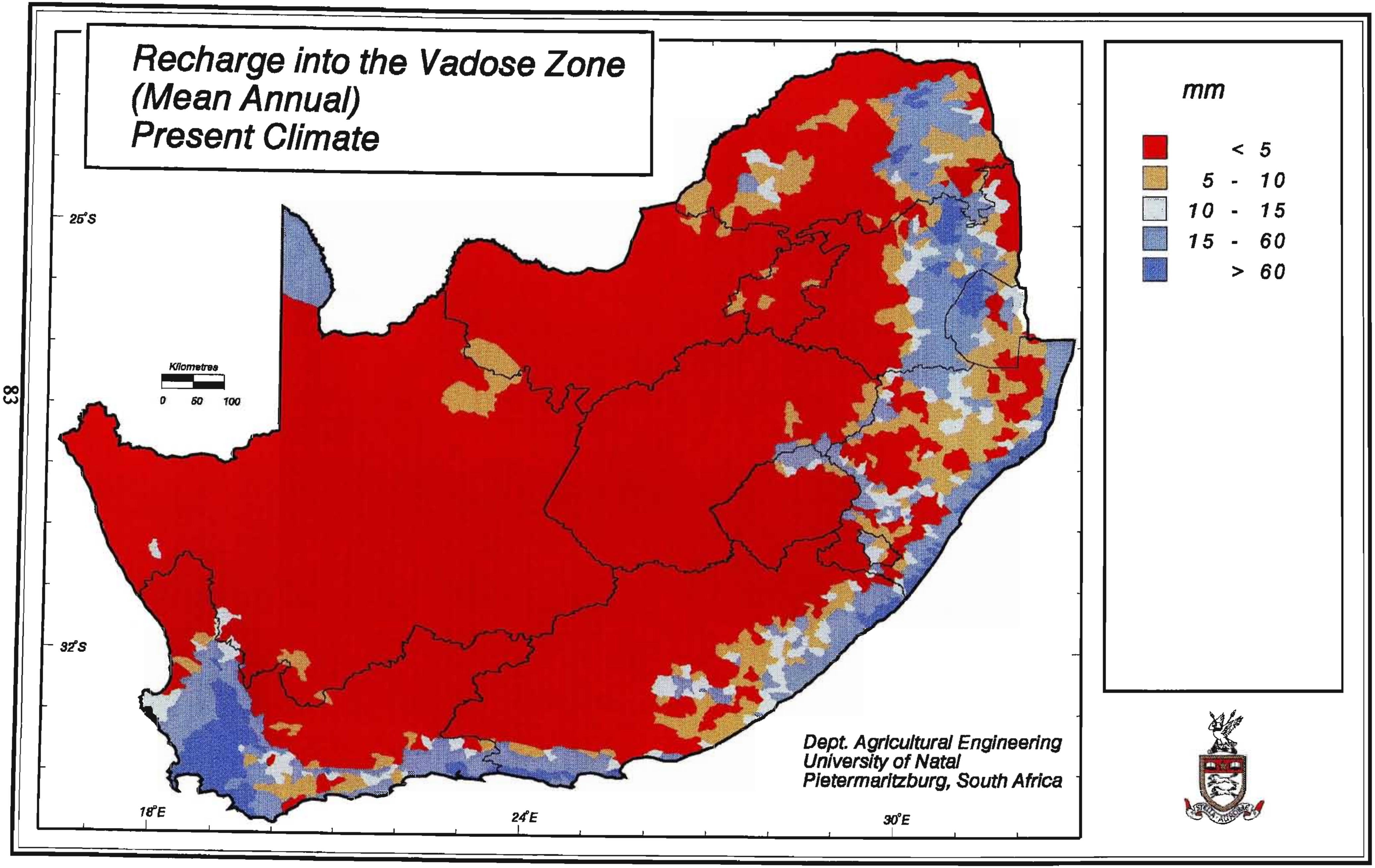
Recharge into the Vadose Zone
(Mean Annual)
Present Climate
mm
< 5
5 - 10
10 - 15
15 - 60
> 60
Kilometres
0 50 100
25°S
32°S
18°E
24°E
30°E
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Figure 7.13

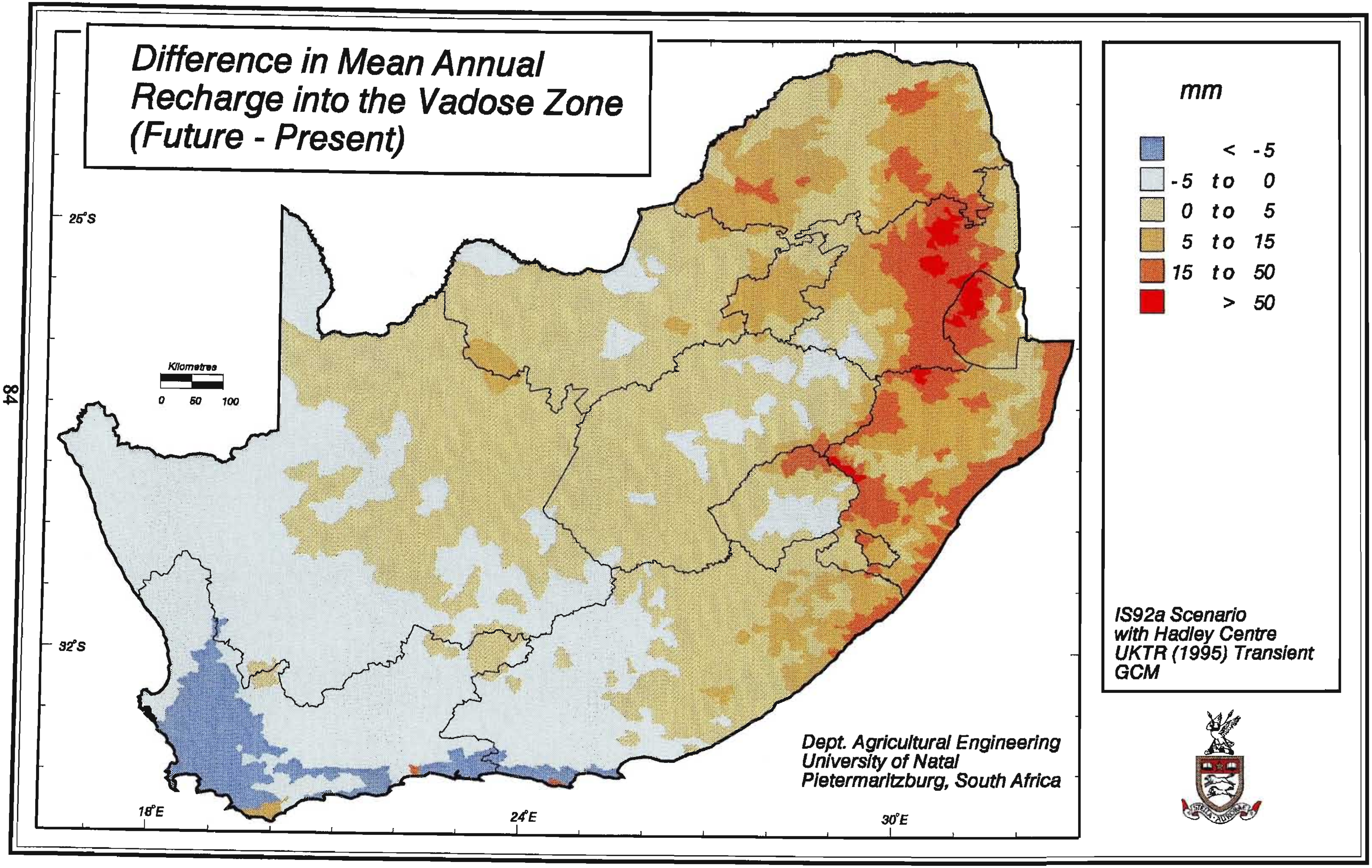
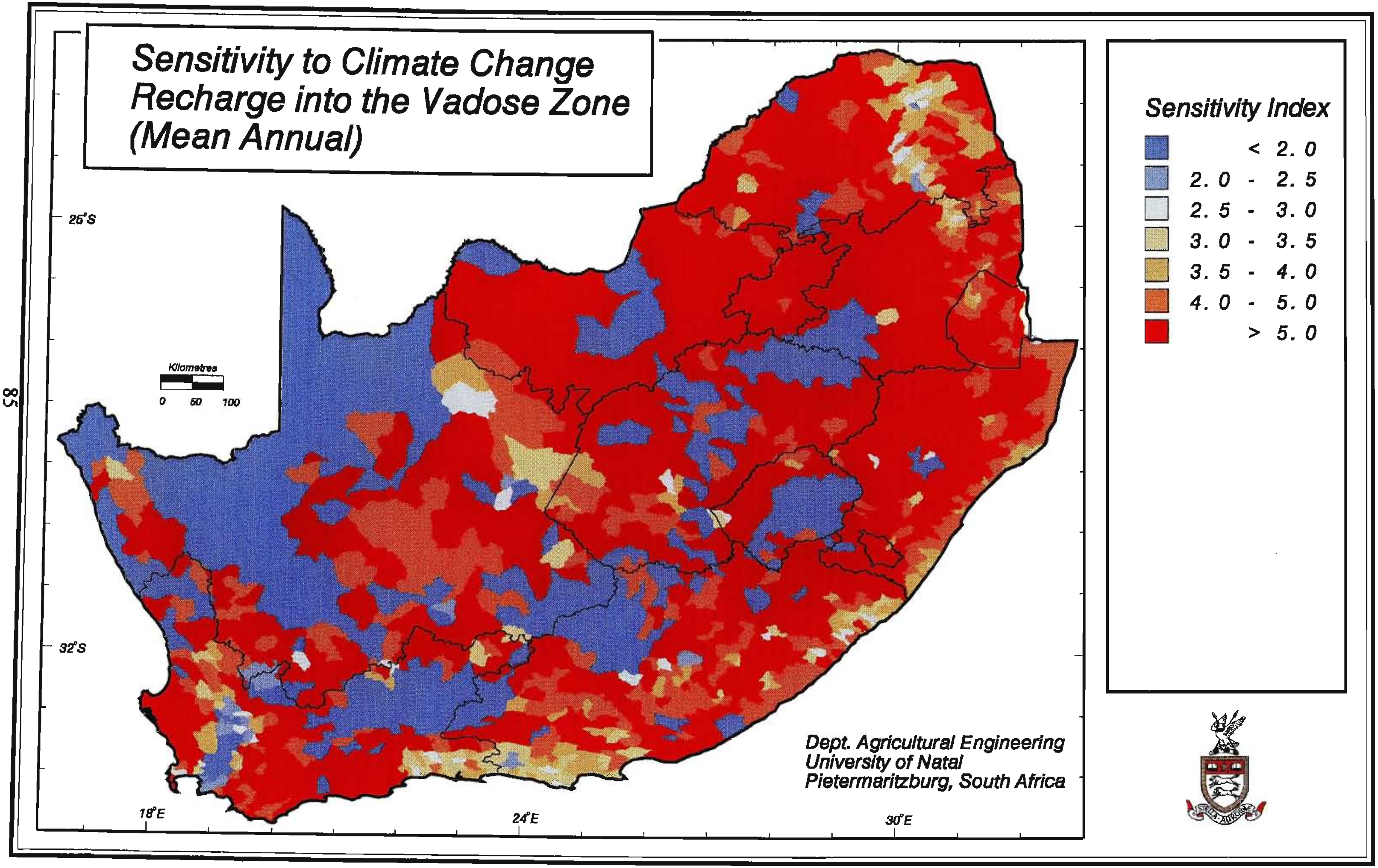

Difference in Mean Annual Recharge into the Vadose Zone (Future - Present)
mm
< -5
-5 to 0
0 to 5
5 to 15
15 to 50
> 50
Kilometres
0
50
100
25°S
32°S
18°E
24°E
30°E
IS92a Scenario with Hadley Centre UKTR (1995) Transient GCM
Dept. Agricultural Engineering
University of Natal
Pietermaritzburg, South Africa
STELLA AURORAE

Figure 7.14



Sensitivity to Climate Change
Recharge into the Vadose Zone
(Mean Annual)

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net irrigation demand < stormflow response < runoff < recharge into vadose zone

The extreme level of sensitivity of recharge to a change in precipitation suggests that the "critical" level or threshold of this hydrological response occurs around a 10% change in precipitation. The other hydrological responses considered in the sensitivity analyses appear not to have reached their "critical" levels with a 10% perturbation of precipitation.

The conventional climate change impacts study indicates that the widespread decreases in rainfall projected for the southern African region, using the results of the UKTR transient model in the SCENGEN programme, may not adversely affect the hydrological system if maximum transpiration of vegetation is suppressed following an effective doubling of CO_2. Simulated increases in runoff, soil moisture content in the A- and B-horizon and recharge into the vadose zone over much of the southern African region indicates a future climate that may be favourable to both the social and ecological systems in southern Africa. However, it is recommended that the suppression of maximum transpiration rates incorporated as a routine into the *ACRU* model be revised, and the more recent literature findings of Goudriaan and Unsworth (1990), amongst others, be considered as an alternative source of information to that of Idso and Brazel (1984).

CHAPTER 8

DISCUSSION AND CONCLUSIONS

Anthropogenically induced perturbation of the natural "greenhouse effect" will, most likely, alter the earth's climate. Consequently, climate change impact assessments are important tools for developing an understanding of the interactions of climate, environment and society. Furthermore, impact assessments provide managers, decision makers and policy makers with the scientific information necessary for the evaluation of potential socio-economic consequences of climate change, and also aid development and implementation of suitable response strategies.

Its remains uncertain as yet as to whether any observed trend in climate variables such as temperature or rainfall patterns is a definite greenhouse effect signal, or merely the "noise" of normal climate variability. However, the general consensus in the scientific community is that global warming is a real threat (IPCC,1995) requiring immediate action if the potential impacts of climate change are to be understood fully and mitigation strategies implemented to avoid a significant threat to social and ecological systems.

In order to study the potential impacts of climate change in southern Africa, it was necessary to obtain reasonable climate change scenarios (cf. Chapter 3). These predictions of climate changes are products of the limitations and assumptions inherent in the models used in the predictions. Consequently, scenarios of climate change serve as indicators of the region's possible future physical and economic vulnerabilities, rather than as a definitive predictive tool for future agricultural or hydrological regimes.

Following the determination of potential scenarios for climate change, the sensitivity of processes within the natural system to climate change need to be identified. Plant response to climate change is dependent on plant type, viz. C_3 or C_4 plants. Accordingly, the maximum transpiration rates of plants was adjusted within the *ACRU* model for an effective doubling of CO_2 levels. However, the results obtained from the scenario study indicate that the transpiration suppression feedback routine needs to be reassessed.

The methods used to assess some of the potential impacts of climate change on agricultural production and hydrological responses in southern Africa are described in Chapter 5. The *ACRU* model and SCENGEN were linked to the Quaternary catchments database, which in turn was integrated with a GIS to allow for the interpretation of model output. *ACRU* and SCENGEN were used in Chapter 6 to assess potential impacts of climate change on agricultural production, using maize yield as a case study. The simulated increase in maize yields in the commercial maize producing areas of southern Africa indicate that maize production is relatively tolerant to a change in climate. In Chapter 7, a quantitative assessment of the sensitivity of hydrological responses to a change in precipitation was made, using the *ACRU* model. Sensitivity indices, which were computed for each Quaternary catchment, may be used to alert policy makers to potentially vulnerable areas in the region. The sensitivity analyses indicated that recharge of soil water into the vadose zone was particularly vulnerable to a change in precipitation, followed by runoff, stormflow response, and finally net irrigation demand, which was the least sensitive. An assessment of the potential impacts of a specified climate change scenario on selected hydrological outputs was also made in Chapter 7, using *ACRU* and the scenario developed with SCENGEN. Hydrological responses to the specified climate change varied across the region. However, general increases in runoff, soil moisture content of the A- and B-horizon, recharge into the vadose zone and net irrigation demand were simulated for most of the southern African region. Results were often a function of soil-vegetation-atmosphere dynamics, which is influenced by the CO_2 "fertilisation" effect predicted to occur with climate change.

The results produced in this study may be used to broaden the base of scientific knowledge describing interactions of climate with the environment and society. Furthermore, adaptive responses and policies may be designed, based on this scientific knowledge, and aimed at helping humanity to adapt to a potential change in climate, whilst also attempting to reduce the degree of anthropogenic interference with the climate system. It must be stressed that, although predictions regarding the magnitude and direction of global climate change remain controversial, the potential impacts of climate change on the agrohydrological system may be profound. Accordingly, it is necessary that scientists and engineers provide the necessary tools for policy makers to develop strategies facilitating the adaptation of ecological and social systems to possible future climate change.

CHAPTER 9

SUMMARY

The natural "greenhouse effect" is responsible for regulating the earth's surface temperature by means of "greenhouse gases" in the atmosphere, which block outgoing infrared radiation from the earth's surface while allowing for the penetration of incoming solar radiation through the atmosphere. Anthropogenic increases in greenhouse gas emissions may result in additional absorption and re-radiation of infrared radiation resulting in increases in global air temperature and changes in the precipitation regime. These changes in climatic variables could have significant implications for agricultural production and hydrological responses worldwide.

Regional changes in climate differ from global projections, primarily due to regional climatic influences. Accordingly, regional scenarios of climate change were developed for southern Africa, for use in impact assessment studies. Atmospheric CO_2 concentrations may increase from the 1990 level of 334 ppmv to approximately 560 ppmv by 2050. This represents an effective doubling of CO_2 relative to its pre-Industrial level of 280 ppmv, and is predicted to result in a temperature increase of between 1.5-2.5°C, obtained using transient models, or 3-4°C, obtained using equilibrium models. Specific seasonal and diurnal trends in temperature change were also predicted. Rainfall seasonality was predicted to remain relatively stable. There was very little agreement between models with regard to changes in rainfall amount. However, both equilibrium and transient models predicted rainfall decreases over much of the southern African subcontinent, although the extent of these decreases remains an issue of debate.

Since plants are exposed to the natural environment, they are sensitive to climate change. Increasing atmospheric CO_2 concentrations may result in increased plant photosynthetic rates, reduced transpiration per unit leaf area and increased plant water use efficiency. A temperature increase may result in faster photosynthetic rates, decreased water use efficiency , potentially shorter crop growth cycles and longer growing seasons. Little agreement exists in the literature regarding the combined effects of climate change on plant response. The lack of consensus is primarily attributed to the complexities of the biological system and the associated feedforwards and feedbacks inherent in the system that are not yet understood fully.

In order to simulate possible impacts of climate change in southern Africa, the *ACRU* agrohydrological model and SCENGEN were chosen. *ACRU* is a physical conceptual, multi-purpose modelling system revolving around a daily time-step, multi-layer soil water budget. SCENGEN is a computer programme designed to facilitate the generation of global and regional scenarios of climate change, using the experimental results of selected general circulation models (GCMs).

Southern Africa has been divided into 1946 relatively homogenous hydrological response zones known as Quaternary catchments. These have been captured into a Geographic Information System (GIS). The GIS was then linked to vegetation, soils and climate information bases developed for each of the 1946 zones (Meier and Schulze,1995), which are required as input by the *ACRU* model. A series of "front-end" routines, containing temperature and precipitation changes, were written for use in *ACRU*. These routines were used to perturb the Quaternary catchments database linked to *ACRU* to simulate a change in climate. *ACRU* and the scenario developed using SCENGEN were used together with the regional system infrastructure to assess possible impacts of climate change on agricultural production and hydrological responses in southern Africa.

ACRU and the SCENGEN scenario developed using the UKTR model and the IS92a emissions scenario, were used to assess potential impacts of climate change on simulated maize yields in southern Africa. Results indicated that simulated maize yields may increase in a warmer, CO_2-enriched environment. The effects of climate change on hydrological responses was also analysed using *ACRU* and the SCENGEN scenario. Hydrological responses to the specified climate change varied across the region. Generally, however, increases in runoff, soil moisture content of the A- and B-horizon, recharge into the vadose zone and net irrigation demand were simulated for most of the southern African region. These results are a function of soil-vegetation-atmosphere dynamics, incorporated into the *ACRU* model as a maximum transpiration suppression routine.

This study also evaluated the sensitivity of selected hydrological responses to a change in hydrological input, namely precipitation. Sensitivity indices, which were defined for each Quaternary catchment, indicate that recharge into the vadose zone is particularly vulnerable to a change in precipitation, followed by runoff, stormflow response, and finally net irrigation demand, which is the least sensitive.

Climate change impact assessments are important for developing an understanding of the interactions of climate with the ecological and social systems. Furthermore, impact assessments provide managers, decision makers and policy makers with the scientific information necessary for the evaluation of potential socio-economic consequences of climate change, and also aid development and implementation of suitable response strategies.

CHAPTER 10

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APPENDIX

The maximum transpiration routine in the *ACRU* model could be responsible for the increases in runoff, soil moisture content in the A- and B-horizon and recharge into the vadose zone simulated for southern Africa, despite the simulated decreases in rainfall obtained from SCENGEN (cf. Figure 1). Figures 3-5 compare the effects of climate change, including CO_2 "fertilisation" (incorporated into *ACRU* as a maximum transpiration routine), to climate change where CO_2 effects are absent, on selected hydrological responses and climatic variables.

Rainfall

Three sites were chosen to verify the results obtained in this study (cf. Chapter 7), viz. Cape Town, which falls within a winter rainfall area; Pietermaritzburg, which falls within a summer rainfall area with a high mean annual rainfall, and Pietersburg, which is found in a summer rainfall area with a lower mean annual rainfall.

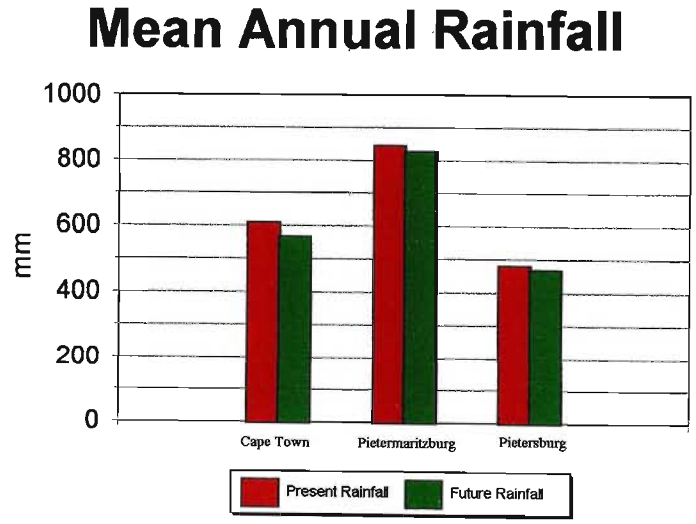

Figure 1 **Mean annual rainfall for the three sites obtained using the SCENGEN rainfall changes**

Evaporation

Warming in the southern African region, simulated using maximum and minimum temperature changes from SCENGEN, results in a simulated increase in potential evaporation (cf. Figure 2).

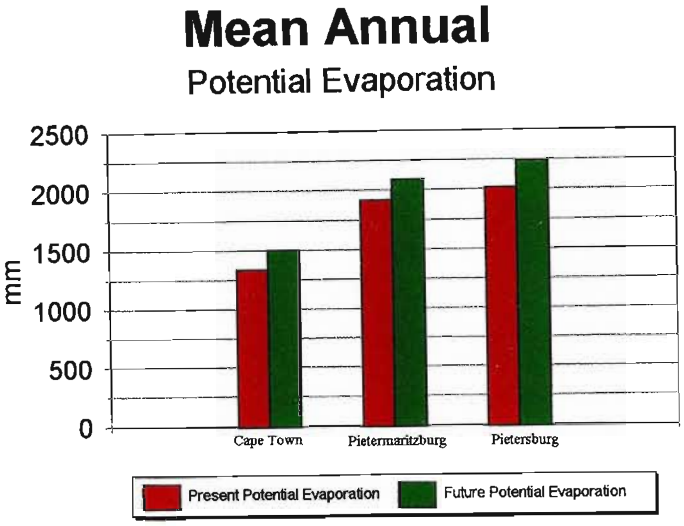

Figure 2 **Mean annual potential evaporation for the three sites obtained using the SCENGEN temperature changes**

Hydrological Responses

Figures 3-5 illustrate the effect of the maximum transpiration suppression routine in *ACRU* on selected hydrological responses. The feedback response associated with this routine is evident when comparing climate change responses without CO_2 effects, to climate change responses with CO_2 effects included. In all cases, the initial response of the selected sites to climate change without CO_2 effects is a reduction in hydrological output, relative to the present climate. With the exception of Cape Town, inclusion of the maximum transpiration suppression routine in the climate change simulation results in an increase in hydrological output relative to the present climate. The decrease in hydrological output obtained for Cape Town is attributed to soil-vegetation characteristics having a minimal effect on the runoff response in winter rainfall areas, due to low evaporative losses from transpiring vegetation.

Consequently, the hypothesis that the maximum transpiration suppression routine in *ACRU* is responsible for the unexpected increases in hydrological responses obtained in this study is proved to be correct.

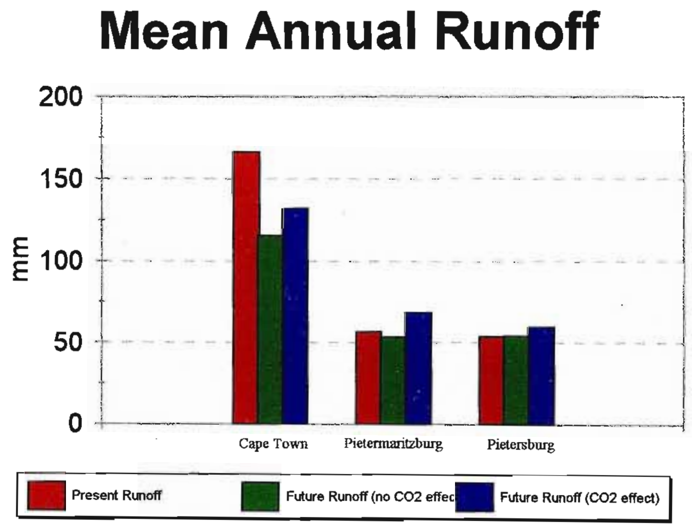

Figure 3 **Mean annual runoff for the three sites obtained using the SCENGEN changes**

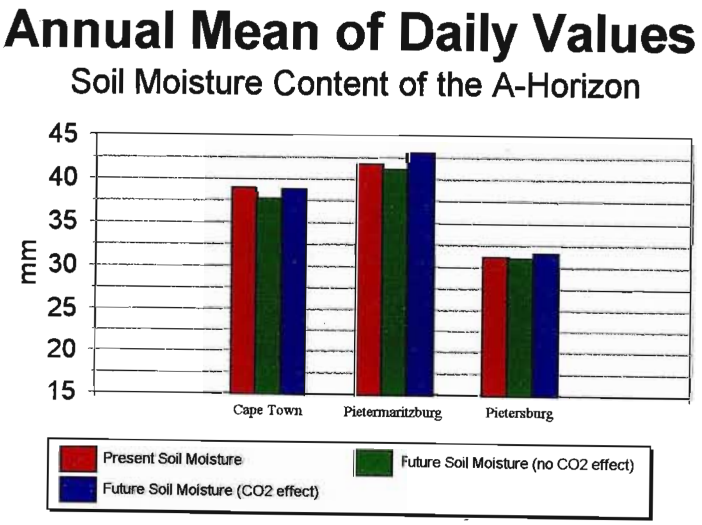

Figure 4 **Annual mean of daily values for soil moisture content of the A-horizon for the three sites obtained using the SCENGEN changes**

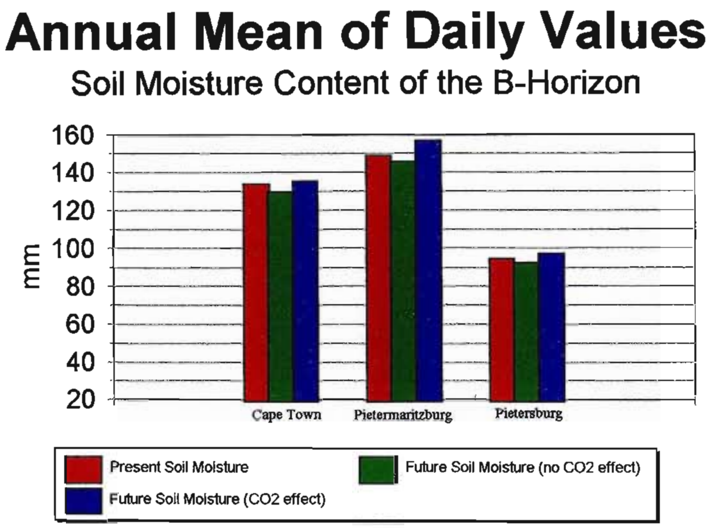

Figure 5 Annual mean of daily values for soil moisture content of the B-horizon for the three sites obtained using the SCENGEN changes