LATE QUATERNARY ENVIRONMENTAL RECONSTRUCTION AND CLIMATE MODELLING IN THE WINTER RAINFALL REGION OF THE WESTERN CAPE, SOUTH AFRICA

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<u>ABSTRACT</u>

The southwestern Cape of South Africa is a floristically diverse region experiencing winter rainfall, and is important as it represents a significant southern hemisphere example of a Mediterranean climate regime. Acquiring palaeoenvironmental data from this region is imperative in understanding the climatic changes that have occurred during the Late Quaternary, with a view to improved palaeoclimatic modelling. The spatial distribution of studies for the Late Quaternary in the southwestern Cape is uneven and palaeoenvironmental reconstructions have been largely restricted to sites, which are easily accessible, and appropriate only for the methods being used (e.g. palynology for wetlands). Moreover, many of the palaeoenvironmental reconstructions implemented thus far fall outside the winter rainfall region *sensu stricto*. Hence spatial differentiation in climatic response may have remained obscured due to the 'selection' of sites used.

Reconstructions have been hampered by a paucity of evidence and may be over simplistic as a result. A regional differentiation seems to exist within the winter rainfall region as a whole, thus the region was divided into three sub-regions to aid in identifying this signal, in both the proxy palaeoenvironmental and the palaeoclimate model data.

Relationships arising from palaeoclimate model simulations of the region and palaeoenvironmental evidence reveal the potential for evaluation of the climate state over longer timescales. Such a method also aids in providing information on under-sampled regions and in identifying areas in need of sampling, hence facilitating a more complete regional synthesis of Late Quaternary palaeoenvironments in the southwestern Cape. As palaeoecological evidence has shown considerable changes in the winter rainfall region over the last 20-25ka, this is the primary time period under focus.

Climate model simulations attempt to facilitate the inference of regional climate and identification of relationships between the model and the palaeoevidence. Evaluation of palaeoclimate simulations further provides opportunities for model validation under conditions different from those used in the simulation of current climate, and constitutes an important means of improving levels of confidence in such models. Thus, by linking a synthesis of palaeoenvironmental evidence for the southwestern Cape to climate model simulations, one can establish the accuracy of the simulated climate, as well as sites in need of additional proxy data.

A comparison of GCM data from the Palaeoclimate Modelling Intercomparison Project (PMIP) shows how seven climate models compare with one another and to what extent the differences are critical for southern Africa. The models are evaluated in terms of their ability to reproduce features of the mean circulation over southern Africa, their systematic biases, and the consistency between models in simulating past climates. After grouping the models based on the commonality displayed, this information is then compared to the proxy data results to gain an overall understanding of how the winter rainfall region has changed over the past 25ka.

The climate model and proxy data comparison reveals that environmental conditions of the LGM were much cooler and drier than today in the south, compared to milder, more moist conditions in the western parts of the study area. The Holocene Altithermal at 6ka BP showed possible cyclical climatic changes in the southern parts compared to today, with warming occurring towards the western parts of the study area.

The approach of combining proxy palaeoenvironmental data and climate model data is new to South Africa, although extensively undertaken elsewhere, particularly in the Northern Hemisphere. It is seen to be a reliable way of gaining an overall synthesis of past environmental changes.

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This work is dedicated to those people who have impacted most on my life: my mum and dad who continually support me from afar; my Cape Town family who were always here to listen: Gran M-H, Fenja and Hugh; my best friend Melanie Skeggs, who was experiencing the same anxiety over her Botany masters; and most importantly my wonderful fiancé Graham Barrable, who I am lucky to have as a part of my life.

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CHAPTER ONE

MONITORING CLIMATE CHANGE

CHAPTER 1: MONITORING CLIMATE CHANGE

The primary aims of this thesis are to examine past climate change from proxy data evidence for the winter rainfall region of South Africa, and to compare the results to palaeoclimate model output. Since gaps and inconsistencies exist in the proxy data (Meadows and Baxter, 1999), it is necessary to attempt to gain an overall perspective of past climate change by including an additional source. In this regard, climate models are a favourable tool, as climate models generally contain a commonality between them, thus making them suitable for the examination of past climate change.

Climate change is a phenomenon that has intrigued the human mind for centuries. However only very recently, compared to the age of the Earth, mankind has discovered the possibility of predicting climatic change from known changes in the past. It is generally thought that if definitive climatic cycles can be identified from the past, then these cycles can be used to aid in predicting future climate change (Hobbs, *et al.*, 1998). Thus a method is needed to identify these past changes as accurately as possible. One of the most globally used methods is reconstruction of the past environmental changes from proxy data.

The potential value of proxy data records globally has been an issue for a while and this awareness of the value of proxy data records in South Africa is growing, but especially those records covering periods of rapid temperature increase. While some of the longer palaeoenvironmental records extend to around 130 000 years ago (start of the Upper Pleistocene) or even earlier, a useful dating framework is available from ^{14}C for no more than the last 40 000 years (Partridge, *et al.*, 1990). The main emphasis for this study has therefore been placed on this period, which includes two prominent episodes of warming: following the Last Glacial Maximum, and the Holocene Altithermal (see Chapter 2).

With a view to the evidence of changing temperatures, it is necessary to examine what the environmental evidence shows climatic conditions to be like in the past. This is approached by examining all forms of proxy data available (see Chapter 2) and by creating a regional synthesis for past changes. These changes are then compared to climate model output.

The climate model output is acquired from seven models from the PMIP (Paleoclimate Modelling Intercomparison Project)(see Chapter 3). Specific variables are examined for the study region and an indication of past atmospheric circulation and climate change established for the available data (present, 6ka and 21ka BP). Particular models are grouped to establish the best scenario for southern Africa, as some models are not ideal for the Southern Hemisphere, being designed primarily for use in the Northern Hemisphere (Partridge, 1993; Taylor *et al.*, 2000)

The model outputs showing the best case scenario for present day simulations are then compared to the proxy data findings to achieve a synthesis of past climate changes for the study region, that being the winter rainfall region (see section 1.5.) of the Western Cape Province, South Africa (see Chapter 4). The main restriction to Quaternary environmental reconstruction in the study region is the limited availability of proxy data for this period. However, a combined analysis of proxy data and palaeoclimate modeling may aid in a more complete overall synthesis of past climate change. Thus the main aims of this study are to combine the two methods of environmental reconstruction, i.e. proxy palaeoenvironmental data and palaeoclimate modelling, thereby obtaining a synthesis of environmental change in the winter rainfall region of the Western Cape, South Africa.

1.1. Past Climate Change

Climate is an important component of the Earth's environment and climatic fluctuations have a strong impact on many aspects of the earth system including, for example, sea level, water supplies, soil, vegetation, agriculture and energy use (IPCC, 2001). Periods of fluctuating warm and cold, drought and flood, famine and plenty have occurred repeatedly in the past and it is certain that they will occur in the future.

Climate change has been a consistent feature of earth history, with the Quaternary period being the focus for the most detailed reconstructions as to the nature of climate change. The Quaternary consists of approximately the last 2 million years, and is the most recent major period of the geological record (Fig. 1.1), extending up to and including the present day (Lowe and Walker, 1998). In the geological timescale, periods are divided into epochs, where the Quaternary Period consists of the Pleistocene Epoch, which ended around 10ka BP, and the Holocene Epoch, which is the present warm interval within which we live.

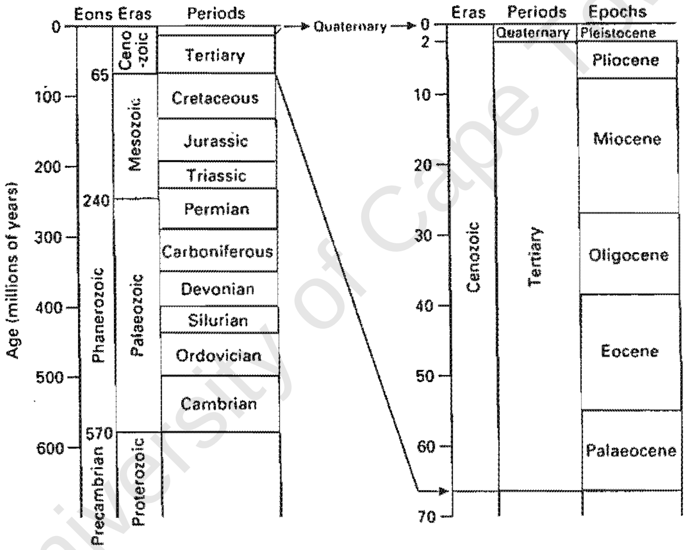

Figure 1.1: The Quaternary relative to the geological timescale (modified from Lowe and Walker, 1998).

The Quaternary has long been considered to be synonymous with the layman's perspective of the "Ice Age", as one of the most distinctive features of the Quaternary has been periodic glacier activity during cold stages, with the building up of major continental ice sheets and the expansion of mountain glaciers in many parts of the world (Duplessy, 1999). These cold stages have alternated with warmer periods (interglacials), when temperatures were occasionally higher than those of present day. The Last Glacial Maximum (LGM) was seen to be around 21ka BP (thousand years before present), and makes an interesting time frame to examine environmental changes that occurred (Goudie, 1994). This time frame is particularly interesting as it is the most recent global ice age that occurred in climatic history and also the most well documented period from palaeoclimatic history.

The surface of ice age Earth at the LGM, roughly 21ka BP, has been reconstructed by CLIMAP[1] (1976, 1981). During this period the Northern Hemisphere differed markedly from today with the presence of huge land-based ice sheets, as much as 3km thick, and by a significant increase in the extent of sea ice and marine-based ice sheets (Duplessy, 1999). The Southern Hemisphere did not experience the same degree of glaciation as evident in the Northern Hemisphere. Particularly in Africa south of the equator, the climate was never sufficiently severe to become more than periglacial during the LGM (Preston-Whyte and Tyson, 1993). In the Southern Hemisphere, the most striking contrast between the glacial period and the interglacials was the greater extent of sea ice in the Southern Ocean during the LGM (Hobbs, *et al.*, 1998). This caused global sea levels to be around 120m below present day levels (Goudie, 1994).

On the continents, the grasslands, steppes and deserts spread at the expense of forests, and the extent of snow-covered land was significantly greater during the LGM (Lowe and Walker, 1998). The global average sea surface temperature (SST) change associated with ice age cooling was close to 2°C lower, with the magnitude of the cooling depending strongly on the geographic location (Goudie, 1994). The patterns of SST resulted in a marked steepening of thermal gradients along frontal systems. As the cooling was much stronger over the continents than over the oceans, the estimate of

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[1] CLIMAP: Climate/ Long-Range Investigation, Mapping and Prediction

the global average surface air temperature cooling was about 4-5°C lower over the LGM (Lindesay, 1998).

Measurements of the composition of the air in bubbles trapped in polar ice have provided evidence for major changes in the CO_2 and CH_4 concentration, which were much lower during the LGM: Compared to Holocene CO_2 and CH_4 values of 280ppm and 700ppb, glacially determined values for the LGM were only 200ppm and 350ppb respectively (Barnola *et al.*, 1987; Chappellaz *et al.*, 1990). The 'missing' CO_2 was trapped in the ocean rather than the continent, as estimates of changes in terrestrial carbon storage suggest that the reduction of boreal and temperate forests resulted in a decrease of the amount of carbon in the terrestrial biosphere (Van Campo *et al.*, 1993).

Another form of evidence is the geological record, which exhibits major sedimentary changes, often occurring within a few centimetres (Meadows, 1992). These changes often reflect abrupt climatic variations. Like sedimentary changes, ice cores have also been shown to exhibit abrupt changes in only a few centimetres (Bryant, 1997). These abrupt changes have been particularly well illustrated in the record from the Vostok ice core in Antarctica, that of the Greenland GISP2 (Greenland Ice Sheet Project) (Fig. 1.2) and GRIP (Greenland Ice Core Project) ice cores and in the Makapansgat Valley stalagmite record, which was recovered from Cold Air Cave in the Northern Province of South Africa (Fig. 1.3) (Thompson, et al., 1998; Tyson and Preston-Whyte, 2000). These records are particularly important to palaeostudies in the Southern Hemisphere as the Makapansgat Valley record is the most complete record for southern Africa and links in with the globally recorded findings: Antarctica in the Southern Hemisphere and Greenland in the Northern Hemisphere (Holmgren, et al., 1999; Tyson and Preston-Whyte, 2000).

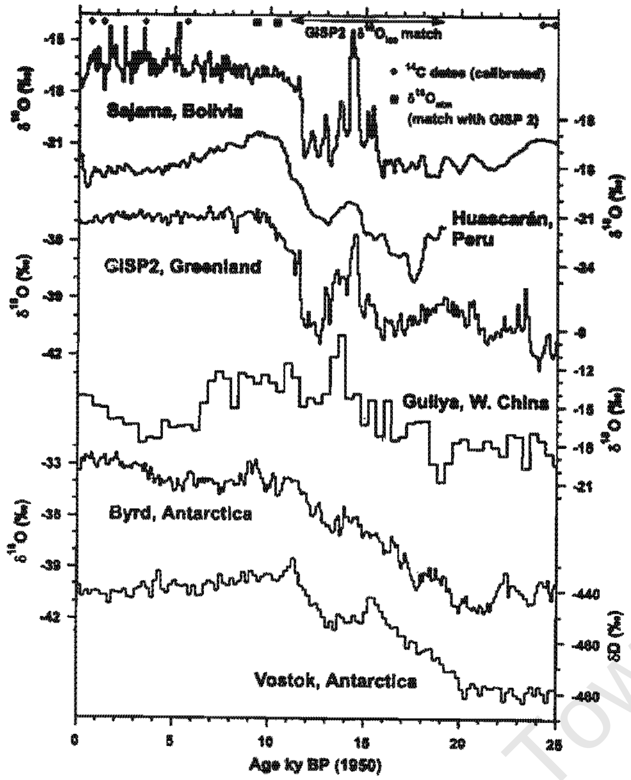

Figure 1.2: Records showing climatic changes from ice cores from the Tropics, Greenland, and Antarctica (Thompson, *et al.*, 1998). Taking particular note of the GISP2 and Vostok ice cores.

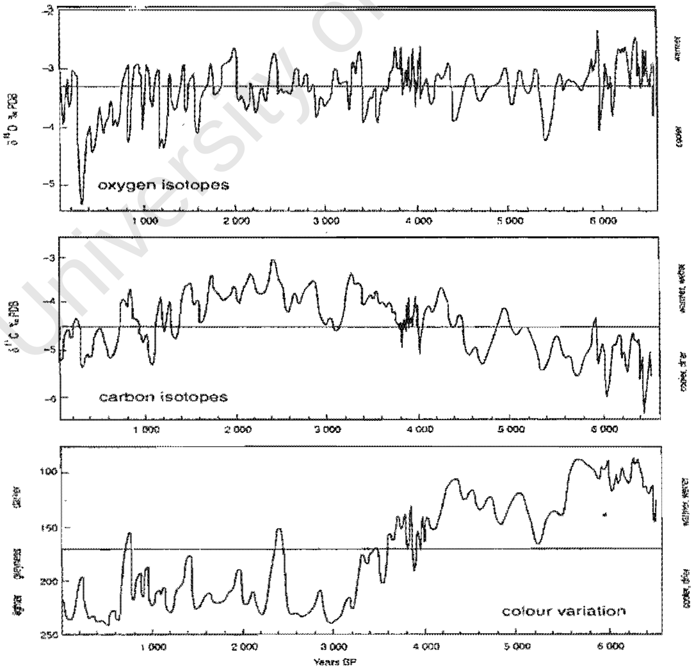

Figure 1.3: A 6600 year record of $\delta^{18}O$, $\delta^{13}C$ and colour density (grey-level) changes in a stalagmite taken from Cold Air Cave in the Makapansgat Valley south-west of Pietersburg in the Northern Province. Taken from Tyson and Preston-Whyte (2000).

Abrupt variations suggest that the climate system consistently and frequently changes between near-glacial and near-interglacial conditions in periods of less than a few decades (Duplessy, 1999). Reconstructing palaeo-environments with a view to identifying abrupt climatic changes requires a linkage of interactions between the various components of the climate system. From the abrupt climatic changes that palaeoenvironmental studies have depicted during the deglaciation, and to a smaller degree during interglaciations, a framework of active interactions between the various components of the environment can be revealed. With a view to this, a brief examination of Quaternary palaeoenvironmental studies for the southern African region is presented.

1.2. Quaternary Palaeoenvironmental Studies in South Africa

Palaeoenvironmental data are derived from a number of sources. They include, for example, environmental isotopes, pollen, charcoal, sediments, palaeosols and micromammalian remains. Often geomorphic features are in themselves good indicators of environmental change (Lowe and Walker, 1998). The potential exists for interpretations of different types of data to vary, making it important to keep in mind that the inferences made from the data are subject to various interpretive limitations.

Partridge *et al.* (1990) show that available sources of palaeoclimatic data for South Africa indicate that significant changes in both temperature and rainfall occurred in southern Africa during the late Pleistocene and Holocene. A synthesis by Meadows and Baxter (1999) of all available palaeoclimatic evidence from sites in the southwestern Cape showed the coincidence of warmer temperatures with drier conditions over the late Quaternary (and vice-versa) of the winter-rainfall region. This is in contrast to the rest of the country, which experiences summer rainfall (Meadows and Baxter, 1999) and frequently suggests contemporaneous cooler temperatures and greater aridity. These factors alone make the late Quaternary an interesting time period for a more thorough analysis, especially in the 'anomalous' winter rainfall region.

The climatic changes revealed by palaeoenvironmental data identify a framework of interactions between the various components of the environment as well as the climate system. Thus it is particularly beneficial to examine the climates of the late Quaternary, as they are fundamental to the reconstruction of past environmental changes.

1.3. Climate Modelling

Climate models were initially designed as an attempt to understand the processes that produce climate and to predict the effects of changes in those processes (Preston-Whyte and Tyson, 1993). Models are basically deductive and are formulated from the fundamental equations governing the physical processes under consideration, making them powerful in their representation of climate dynamics (Preston-Whyte and Tyson, 1993).

Climate models can be fully three-dimensional in character, and comprise a series of equations with prescribed initial boundary conditions and physical constraints. A climate model represents a controlled environment, within which the impact of anomalies on the climate system can be studied (Hudson, 1998). By comparing an anomaly simulation to a control simulation, the nature, degree and extent of climatic variability can be identified.

Weather forecasting and palaeoclimate simulations continue to provide important tests of the realism of components of climate models under different initial and external conditions (IPCC, 1996). Many of these models are being used to predict future climate change and, although there is broad agreement among the models, there are also many differences in the details of their predictions (Joussaume and Taylor, 2000). The main advantage is that climate models are continually improving in their ability to simulate the major features of contemporary climate (IPCC, 1996).

1.3.1. Climate modelling in South Africa

At this stage, no climate models have been developed specifically for the southern African climate, except where nested models are being adapted for the region (Hewitson and Crane, 1996). This is possibly due to the lack of expertise and resources available by comparison with the more developed countries in the Northern Hemisphere, but this is slowly changing[2]. Climate model runs from global climate models (GCM's) have, however, been used to simulate southern African climate changes (Joubert and Hewitson, 1997). In this sense climate modelling in southern Africa is an ongoing pursuit (Joubert, 1994; Jones, *et al.*, 1999), particularly in the context of present and future climate changes. The following are some examples of climate model studies that have been conducted in southern Africa:

Kiker (2000) has identified sectors and areas of highest vulnerability to climate change in South Africa, as potential changes in climate may have significant effects on various sectors of South African society. In this study three different GCMs were used to represent a possible evolution of the global climate system. Kiker's (2000) conclusions were that the performance of the models supports the view that they are capturing the primary dynamical response to the increased radiative forcing from changing concentrations of atmospheric gases. Thus the GCMs seem to be adequately skillful in capturing the fundamental dynamics of the atmosphere represented by the synoptic circulation over southern Africa (Kiker, 2000).

In another study, Hewitson (1999) used GCMs to derive regional precipitation scenarios over southern Africa. The study was initiated in response to scenarios of potential precipitation change being severely limited in spatial and temporal resolution at the time, making planning for the future difficult. Hewitson (1999) found that by using a downscaling procedure and subsequent climate projections, the result was a viable, justifiable and pragmatic solution for the immediate and near future climate change impact research needs.

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[2] http://www.egs.uct.ac.za/workshops/mm5/

Rind (1998) used a GCM to evaluate the effects of changing meridional temperature gradients and uniform warming on the general circulation of the atmosphere. From this study, Tyson (1999a) found the results to confirm key aspects of his conceptual general circulation model postulated previously (Tyson, 1986). He concluded that both the South Atlantic and South Indian anticyclones bordering South Africa are sensitive to changes in the meridional temperature gradient (Tyson, 1999a).

Hudson (1998) used an atmospheric GCM to study the interconnections between Antarctic sea-ice extent, Southern Hemisphere circulation and South African Rainfall. She derived regional-scale precipitation over South Africa from a GCM using empirical downscaling, and found that sea-ice perturbation causes a decrease in rainfall over the north-east coast, and an increase in rainfall over the interior parts of the country (Hudson, 1998). Precipitation was also seen to increase in winter over the west and south coasts. Hudson (1998) concluded that an Antarctic sea-ice anomaly has the potential to alter circulation patterns and precipitation over the southern Africa.

The examples given above all show how models have the capability to reproduce present and future climates. In order to determine whether models can simulate climatic conditions different from today, climate models can be run to simulate palaeoclimates, and palaeodata can be used to evaluate the results. Past climates in South Africa are not usually climatologically examined in much detail further back than the very recent past (maximum 200 years BP). This research aims to extend this period as far back as possible (roughly 25ka BP) and combines the two methods of environmental reconstruction from proxy palaeodata and climate modelling in the winter rainfall region of the Western Cape, South Africa.

1.3.2. The proxy data contribution to climate modelling

Environmental reconstruction from proxy data has been conducted in South Africa using many different methods, but results from palaeoclimatic modelling simulations have not yet been compared to proxy findings. Proxy data are important in this relation as they can be used in the verification of climate model simulations, especially on a regional scale.

Numerous studies of late Quaternary environmental change comparing proxy and model data have been undertaken in the Northern Hemisphere (e.g.: Bartlein *et al.* 1998; Prentice *et al.* 1998; Webb *et al.* 1998; Jackson *et al.* 2000), but similar methods of reconstructing the late Quaternary in southern Africa have not yet been attempted. The following are some examples of using proxy data and climate model data together in order to establish past climate changes:

Mitchell (1993) looked at using a three-dimensional GCM in equilibrium studies of past climates by fixing slowly changing parts of the climate system, such as sea surface temperatures. The results he presented from studies of the mid-Holocene, the Last Glacial Maximum (LGM) and the initiation of the last ice age are of interest. He concluded that, by comparing results from different models, it may be possible to distinguish those aspects of the simulated response which are robust, and therefore possibly more reliable, from those which are more likely dependent on the specific model formulation (Mitchell, 1993).

Late Quaternary climate change was examined in eastern North America by Webb III *et al.* (1998), where they looked at a comparison of pollen-derived estimates with climate model results. Their overall aim was to provide tests of the climate simulations for Version 1 of the National Center for Atmospheric Research (NCAR) Community Climate Model (CCM1) for 21,16,14,11 and 6 thousand years (ka). They concluded that there was an overestimation of summer temperatures in the southern parts of their region when compared to pollen data. Thus the pollen proxy data was helpful in verifying the accuracy of the model for that specific region.

Kohfeld and Harrison (2000) looked at evaluating the models using global palaeoenvironmental data sets. They found that models underestimate the magnitude of cooling and drying of much of the global land surface at the

LGM. They conclude that in order to yield the greatest scientific benefit, this type of research needs to be paralleled by continued advances in palaeodata analysis and synthesis, which in turn will help to define questions that call for new focused data collection efforts (Kohfeld and Harrison, 2000).

With respect to southern Africa in general, and its winter rainfall region in particular (see section 1.5.), it is important to compare proxy data findings with climate model output. Such an analysis should examine more than one model to gain an overall perspective on the model simulations available and to eliminate bias to one particular model output. There also needs to be a lot more work done to bridge the gaps in the proxy data set, as it is presently far from comprehensive, and progress in this direction will be all the more beneficial to the elucidation of palaeoclimates in the region.

1.4. Research Objectives

Both the analysis and running of numerical palaeoclimate experiments in the southern African sector is extremely underdeveloped. Most of the climate model analyses have been undertaken in the context of present and future climates (Joubert, 1994; Jones, *et al.*, 1999), with past climates not usually analysed further back than the very recent past of around the last 200 years. This study aims to combine the two methods of environmental reconstruction from proxy palaeoenvironmental data and climate modelling in the winter rainfall region of the Western Cape, South Africa. Focus will be placed on the last 25ka BP, i.e. beyond the recent past and into the late Quaternary to deal with a sufficiently wide scope of climate change conditions.

It is noted that there are problems with both proxy and model data. Model data as mentioned above, have not been sufficiently developed for southern African palaeoclimates, and due to the problems of resolution, the trend is to depict large-scale change as opposed to smaller features defined in the proxy data. Along the same lines, proxy data can be very site specific, missing the overall regional changes occurring. An example being that of pollen evidence from a vlei (bog) vs that from hyrax middens. The middens would show evidence closer to the time of deposition and more site specific than that of pollen grains deposited in the bottom of the vlei which could have been washed in. Another feature of the proxy data is that the signal showed often differs according to the type of material examined. For example mollusk evidence can differ to pollen evidence. Therefore this type of study needs to be approached with an open perspective in all directions.

Thus the objectives are to be achieved through a comprehensive synthesis of the proxy palaeoenvironmental evidence from numerous sites incorporated in the winter rainfall region of the Western Cape Province (Fig.1.4). Proxy palaeoenvironmental evidence is then used to retrodict what palaeoclimate models should reveal for the appropriate time period and these findings are then compared to the model data for the respective years BP.

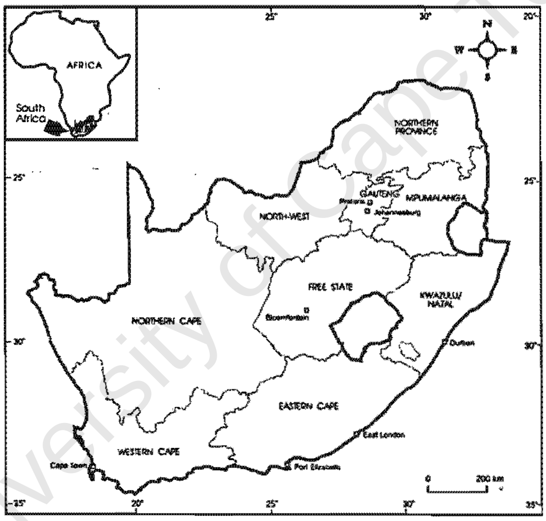

Figure 1.4: Location of the study region – Western Cape Province, South Africa.

Relationships arising from palaeoclimate model simulations of the region and palaeoenvironmental evidence reveal the potential for evaluation of the climate state over longer time periods. Such a method also aids in providing information on under-sampled regions and in identifying areas in need of sampling, hence facilitating a more complete regional synthesis of Late Quaternary palaeoenvironments in the southwestern Cape.

A literature review of all the possible palaeoenvironmental proxy data (refer to Chapter 2) pertaining to the western and southern parts of the Western Cape Province, reveals a distinct pattern of change in the spatial extent of the winter rainfall region during the late Quaternary period. This raises a number of fundamental questions that need to be addressed:

1) How has the winter rainfall region changed spatially since the last glacial maximum as reflected by proxy environmental evidence?
2) What do the climate models retrodict the past climates to be like?
3) Is there any correlation between environmental proxy data and climate model data for this region of the southwestern Cape?

The principle aim of this study is to reconstruct the late Quaternary environmental change in the southwestern Cape from a literature review of proxy data studies and climate model data, and to attempt to address the fundamental questions posed above. The investigation assumes a broad-based, multidisciplinary approach and draws on wide-ranging evidence from diverse sources such as sedimentology, palynology, archaeology, geomorphology, and palaeoecology, among others.

To complement the proxy data, climate model output for the late Quaternary is examined. The commonality generally displayed between climate models, makes them adequate tools in the examination of past climate change. This is particularly fundamental for the southwestern Cape as it is a geomorphologically diverse region making the linking of different types of proxy environmental evidence difficult. Thus a combined analysis of proxy data and palaeoclimate modeling would aid in a more complete overall synthesis of past climate change in the southwestern Cape. Research is focused on the winter rainfall region of the southwestern Cape, for the following reasons:

1) This particular area of the Western Cape is the only region south of the equator, on the African continent experiencing a Mediterranean-type climate.
2) The study area experiences winter rainfall, which is unique to the rest of the sub-continent, experiencing summer rainfall.

3) This region represents the equatorward boundary of direct influence of mid-latitude storms, making it a key feature in identifying climate change in the mid-latitudes.

1.5. Outline to the Remainder of the Thesis

The investigation proceeds by means of a comprehensive examination of the literature in Chapter 2, in order to compile as complete a synthesis as possible for the southwestern Cape covering the last 25ka. A detailed description follows this in Chapter 3, whereby climate model output from seven different models is used to reconstruct past climate changes for the region. Chapter 4 then presents a comparison of the palaeoenvironment compiled from the proxy data literature review and the model output, examining the similarities and dissimilarities between the data. Final conclusions and future recommendations are then made in Chapter 5, and thoughts are broached as to the feasibility of this type of study for future research.

CHAPTER TWO

PALAEOENVIRONMENTAL RECONSTRUCTIONS OF THE WESTERN CAPE QUATERNARY: PROXY EVIDENCE

CHAPTER 2: PALAEOENVIRONMENTAL RECONSTRUCTIONS OF THE WESTERN CAPE QUATERNARY: PROXY EVIDENCE

2.1. Introduction

The southwestern Cape represents a significant southern hemisphere example of a Mediterranean climate. The region is floristically and geomorphologically diverse, experiencing cold, wet winters and hot dry summers. Palaeoenvironmental data from this region are imperative in understanding the climatic changes that have occurred during the Late Quaternary, however reconstructions have largely been restricted to sites easily accessed and appropriate for the particular methods being used (e.g. palynology for wetlands). This 'selection' of sites may have resulted in spatial differentiation in the palaeoclimatic response to remain hidden. This chapter analyses the various forms of palaeoenvironmental data in reconstructing Late Quaternary environments in the Western Cape, with a view to compiling a synthesis to the best possible degree.

Relationships between palaeoenvironmental evidence and the inferred palaeoclimate reveal the potential for evaluation of the climate state over longer timescales. This method is important in providing a more concise regional synthesis of Late Quaternary environments in the southwestern Cape, whereby valuable information can be gained on under-sampled regions and identifying areas in need of further sampling. The sampled evidence to date has revealed that the most dramatic changes in the last 20-25ka over the winter rainfall region as a whole, making this the primary period under focus.

Current syntheses of proxy data available for the last 25ka show that significant gaps and inconsistencies exist (Meadows and Baxter, 1999). These gaps are partially due to the availability of sites, as the Western Cape Province is geomorphologically diverse and access to many possible study sites is almost impossible. However a pattern is emerging whereby the winter rainfall region appears to respond differently to climate changes that have occurred compared to other regions in southern Africa (Tyson and Preston-Whyte, 2000).

Considerable work has been done concerning environmental reconstruction from proxy data in southern Africa, particularly in relation to archaeology, as the subcontinent has been shown to play an important role in hominid evolution (see, for example, Vrba, 1985; Partridge, 1986; Bamford, 1999).

Evidence of late Quaternary environmental change is typically derived from a variety of sources, among these are studies of charcoal (Tusenius, 1986; February, 1992), pollen (Scholtz, 1986; Baxter, 1997; Meadows, *et al.*, 1996), micro-mammals (Avery, 1987; Thackeray, 1987; Avery, 1990) and Hyrax middens (Scott and Bousman, 1990; Scott, 1994a). Palynological evidence is of especial significance due to the presence of a relatively large number of wetlands in the region and therefore relatively well-preserved fossil pollen grains in particular localities. Taken together, these results aid in facilitating a synthesis of Late Quaternary environmental change in the Western Cape (Meadows and Baxter, 1999).

2.2. Introduction to the Study Area

The southwestern Cape is the only region of South Africa experiencing a winter rainfall peak, and is important as it represents the equatorward boundary of direct influence of mid-latitude storms, and is a particularly significant southern hemisphere example of a Mediterranean climate. The winter rainfall region is defined for this study as a region including areas where the mean monthly temperature for any month is >0°C and which receive >65% of their precipitation in the cold half of the year, i.e. April to September (Fig 2.1).

The winters in the southwestern Cape are generally moist, with the area having its rainfall restricted by the mountain ranges of the Cape fold belt (Preston-Whyte and Tyson, 1993). The summers are on the other hand arid, caused by the Benguela current, which creates strong upwelling on the west coast particularly during the summer months, thus intensifying summer aridity (Shillington, 1998). The dry, anticyclonic high-pressure systems, which are a prominent feature over southern Africa, migrate north in the winter months and allow the westerly winds into the southwestern Cape (Preston-Whyte and Tyson, 1993). This provides the winter rainfall and produces the Mediterranean-type climate.

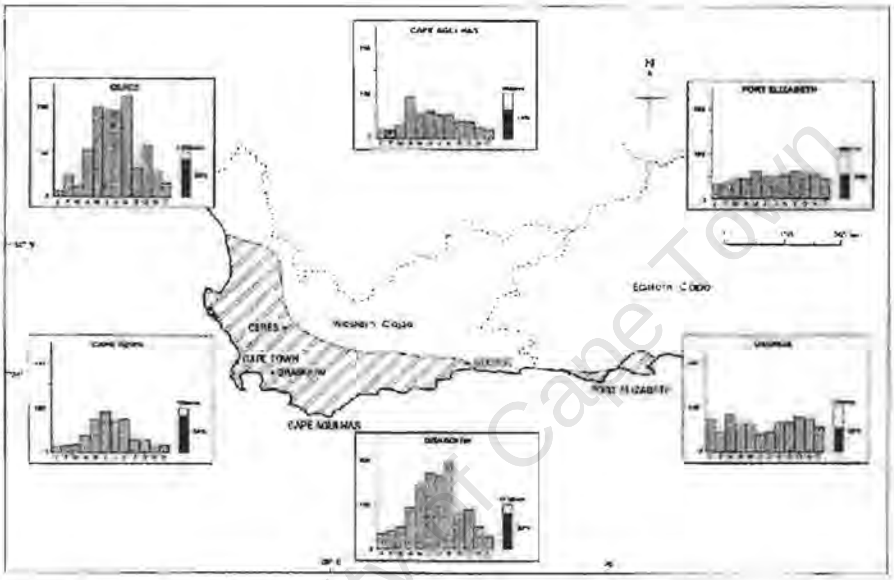

Figure 2.1: Climate diagrams for the southwestern Cape, showing mean annual rainfall distribution (Conacher and Sala, 1998).

This particular study area is important due to its situation at the southern tip of Africa. Any change in sea surface temperatures, ocean currents and Antarctic ice extents greatly affect the dynamics of the atmospheric circulation and hence rainfall systems in the region, with resultant climatic change. At the same time, should the atmospheric circulation patterns change, this would directly affect sea surface temperatures, ocean currents and Antarctic ice extents.

The study region is divided (Fig. 2.2) into a Western Sub-region, encompassing the west coast and adjacent inland areas; a Southern Sub-region, including the south coast and adjacent inland areas; and a Central Sub-region, which lies between the Western and Southern Sub-regions.

These divisions were chosen based on the relative amount of rainfall each area experiences. The Western sub-region is a definitive winter rainfall region, experiencing on average around 65% of rainfall in the winter months, with the summer months being particularly hot and dry.

The southern sub-region is characteristically a region experiencing more all-year rainfall than specifically summer or winter rainfall. There is no dry season as the mountains ensure a distribution of no less than 50mm falling within any one month, and generally temperatures are uniformly mild throughout the year (Geldenhuys, 1988). The Southern Sub-region is incorporated into this study as it still meets the required definition of a winter rainfall region. The Central Sub-region is the area between the southern and western divides. This region was chosen to examine the changes occurring between the particularly winter and particularly all-year rainfall regions.

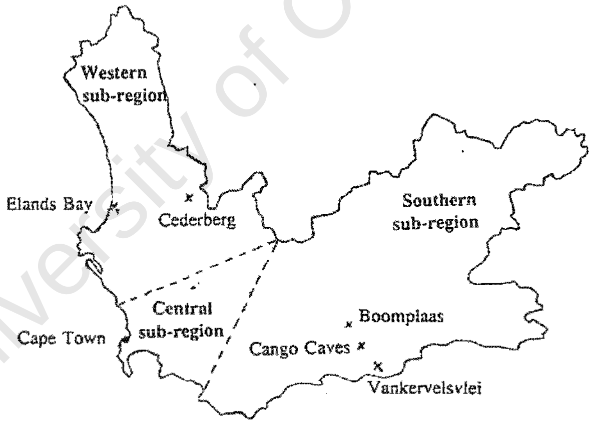

Figure 2.2: The Western Cape Province showing divisions of Western, Central and Southern Sub-Regions. (The places marked are some of the sites mentioned in the study).

Acquiring palaeoenvironmental data from this region is imperative in understanding the climatic changes that have occurred during the Late Quaternary. Considerable work has been done concerning environmental reconstruction from proxy data in southern Africa, particularly in relation to archaeology, as the subcontinent has been shown to play an important role in hominid evolution.

The proxy data collected for environmental reconstruction in the Western Cape Province is wide ranging, from charcoal and pollen studies to micro-mammal and Hyrax midden analysis. Of particular importance are the palynological findings, due to the presence of a relatively large number of wetlands and therefore well preserved pollen evidence. Together these results have facilitated a reasonable synthesis of Late Quaternary environmental change in the Western Cape (Meadows and Baxter, 1999).

2.3. Approach to the Study

The most precise and accurate environmental reconstructions emerge when a wide variety of palaeoecological and palaeoenvironmental techniques are applied to a particular problem or site (Meadows and Asmal, 1996). The aim of this study is to consider the various results from all proxy evidence and how they relate to one another in terms of environmental changes.

The specific objectives are to examine the proxy palaeoevidence for the time period of the last 25ka BP in the winter rainfall region, by dividing the region up into 3 sub-regions: Western, Central and Southern Sub-regions (Fig. 2.2). As a whole the entire region is in need of additional sampling in order to facilitate a more complex regional synthesis of Late Quaternary palaeoenvironments in the southwestern Cape. Palaeoecological evidence from various sources has shown marked climate changes in the winter rainfall region over approximately the last 25ka, therefore this has determined the primary time period under focus. However this study is restricted by the availability of proxy data for this period.

Previous studies have shown that sea levels have fluctuated extensively during the late Quaternary. Around 21ka BP, sea levels were as much as 110m below present levels (Dingle and Rogers, 1972; Duplessy, 1999). This has major implications for the interpretation of the proxy data. The probable topography for the LGM has been determined using present day 5-inch topography and bathymetry, and lowering the sea level by 100m (Fig. 2.3). This provides a better perspective on the regional influencing factors at the time the proxy data were deposited at the site for that time period.

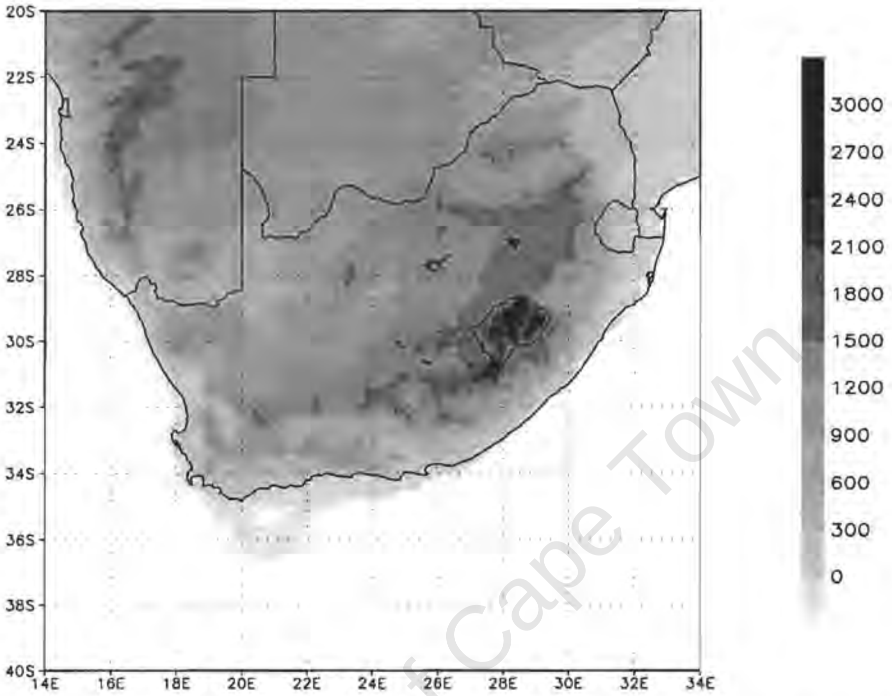

Figure 2.3: The shaded regions indicate what the topography at 21ka BP (heights in meters) would have been like, with the present day coastline and political boundaries outlined. Data are derived from present day topography and bathymetry.

Proxy data have been collected and collated based on a literature survey of palaeoecological work done in the southwestern Cape. This database has been expanded to include not only published works, by consulting experts and people working in the fields of Archaeology and related Quaternary studies, as well as resources at the South African Museum. The study area is roughly the present winter rainfall region, allowing for expansion and contraction of the winter rainfall region over the time period.

2.4. Sea Level and Surface Temperature Changes

The sedimentary evidence shows the expected fall in sea level to be as much as 120m below present levels around 17ka BP (Maud, 1990). Tankard (1976) claims that the recovery of sea level following the 17ka BP lowering was very rapid (167cm/100yrs) and by 9000 BP had reached only 25m below present levels (Fig 2.4.).

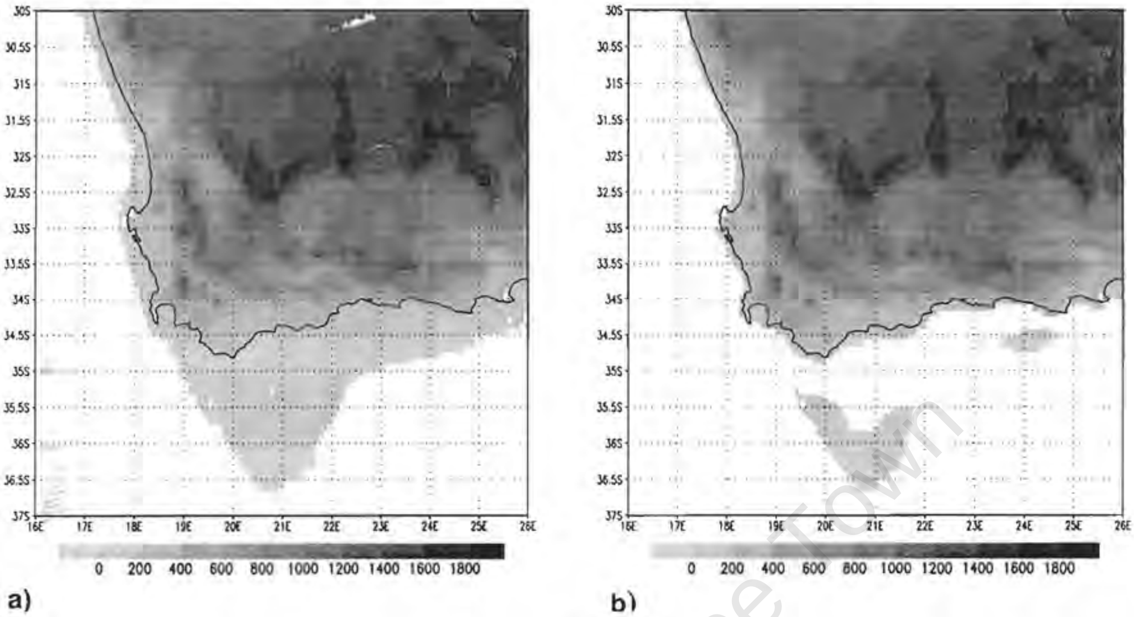

Figure 2.4: Various stages of the coastline over the last 25ka compared to present sea levels (outlined) for the study region, roughly during a) the LGM (*c.* -120m), and b) the early Holocene (*c.* –25m).

2.4.1 The Last Glacial Maximum

Nelson Bay Cave (see Fig 2.8 further on in the text), on the south coast approximately 40m above present sea level, provides good evidence for changes in sea level through the Late Quaternary. Lower sea levels in the southern Cape may have been in part responsible for the lower rainfall experienced at Nelson Bay Cave during the LGM, as it is today located at the coast (Deacon, *et al.*, 1984b). Shell fragments from Nelson's Bay Cave, dated around 18600 BP, reflect an advancing coastline after a low sea level (Inskeep, 1972). Whereas the cave was previously as much as 90km from the shore during the LGM, this sea level advance would have placed the cave near enough to the sea to allow occupants of the cave to carry shellfish to the cave (Inskeep, 1972). This is something that was impossible prior to this time as the cave setting was further inland during the LGM due to sea levels being as much as 130m lower than today (Inskeep, 1972).

Palaeosols from Elands Bay Cave suggest that the Benguela current was weaker 25–15ka BP with reduced upwelling (Butzer, 1984) thus implying a decrease in the southerly component winds (Shannon and Nelson, 1996). Decreased southerly winds would imply a decrease of polar air to the west coast and therefore cause increased sea surface temperatures along the western littoral. Increased sea surface temperatures would cause an increase in evaporation, thus promoting increased precipitation along the west coast for the LGM.

2.4.2 After the Last Glacial Maximum

Cartwright and Parkington (1997) identify a raised sea level, which possibly removed the strandveld from the area around Elands Bay Cave. This they found from a synthesis of studies on wood charcoal fragments in the cave. Klein (1991) reported an increase in available moisture around 13600 to 9600 BP from his examination of distal humeri of dune mole rats (*Bathyergus suillus*) at Elands Bay Cave. It is possible that this is due to a recovery in sea level after the LGM low, and the increase in available moisture could be related to the higher sea levels combined with increased upwelling nearer to the cave.

2.4.3 Early Holocene

Sea surface temperatures rose along the west coast from 10.5 to 13.5°C between 10000 and 8000 BP (Cohen, *et al.*, 1992). Along with this rise in temperature, sea levels themselves were also rising, with Baxter (1996) reflecting a rise of 12m up to present levels from 9000-7500 BP on the west coast. A further rise in sea level has been reflected subsequent to this, between 7000 to 4000 BP, where sea levels were 2-3m higher than today (Maud, 1990).

The establishment of sand dunes along the southern margin of Verlorenvlei (see Fig 2.6 further on in the text) occurred due to a rapid regression in sea level around 6500 BP (Baxter and Meadows, 1999). At this time the sea level was at least 3-4m lower than present levels (Baxter, 1996). After this, around

6000 BP, sea levels were back to within a metre of present sea levels, as seen from geomorphological evidence at De Kelders (see Fig 2.7 further on in the text) (Tankard, 1976).

2.4.4 Mid-Holocene

During the mid-Holocene, Rietvlei (just north of Cape Town) was a sheltered, open estuarine embayment, protected to the south by an outcrop of calcrete-capped late-Pleistocene marine deposits (Rogers, 1980). Evidence of the estuarine mollusc *Solen capensis* has been found for this period and since then is not present in the less saline Rietvlei today (Grindley *et al.*, 1988). ~~This is evidence of~~ a higher sea level stand for the mid-Holocene. Extensive oyster reefs built up in the Langebaan Lagoon area (see Fig 2.6 further on in the text) indicate more vigorous tidal circulation due to the higher mean sea level during the mid-Holocene (Robertshaw, 1978; Miller *et al.*, 1993).

Sea level seems to have dropped abruptly, rather then gradually after the high stand at 5180 BP (Reddering, 1988). This is seen at the Keurbooms estuary near Plettenberg Bay (see Fig 2.8 further on in the text), from the distinct double row of dunes that have formed. Reddering (1988) claims that had the sea levels decreased gradually from the mid-Holocene high, then the existing dune would have grown seaward by accretion, thus establishing a continuous and wider dune field. Since there is no evidence for this happening, the notion that sea levels decreased rapidly after the Holocene Altithermal is accepted. Relatively warm sea surface temperatures are noted along the Atlantic coast in the vicinity of Elands Bay around 4400 BP (Jerardino, 1995).

Around 4200 BP, sea levels rose to a maximum level perhaps 3m above present levels, as reflected in the high abundance of molluscs (*Solen capensis*) indicating estuarine conditions on the west coast (Jerardino, 1993). Particularly low average sea surface temperatures occurred around this time, recorded at Elands Bay on the west coast (Jerardino, 1995). Between 4000 and 3160 BP, the notion of a period of predominantly falling sea levels and high coastal sediment instability is suggested (Jerardino, 1993). These results come from unpublished data by Jerardino and Yates (cited in

Jerardino, 1993) and include evidence from Eland's Bay Cave; Spring Cave and Pancho's Kitchen Midden (some of which has subsequently been published by Jerardino (1998)).

2.4.5. The late Holocene

A late Holocene drop in sea level caused the barrier complex on the coast of Table Bay to develop, with the modern Milnerton Lagoon behind it linking Rietvlei to the present mouth (Grindley *et al.*, 1988). The present mouth of Rietvlei is much further south than the evidence showed for the mid-Holocene (Rogers, 1980).

A decrease in sea surface temperatures occurred at the start of the Late Holocene and seems to be contemporaneous with the worldwide Neoglacial advance of 3000-2000 BP as identified by Lamb (1982) and Tyson (1986). Jerardino (1993) also recognised this neoglacial expansion and identified areas in the Southern Hemisphere where sea levels dropped at least 2m. Illenberger and Verhagen (1990) have presented evidence for a minor sea level drop around 3000-2000 BP based on indirect evidence for sea level change from the Algoa dune fields. Figure 2.5 illustrates the effect of a 2m drop in sea level on the present coastline, taking particular note of the Southern Sub-region.

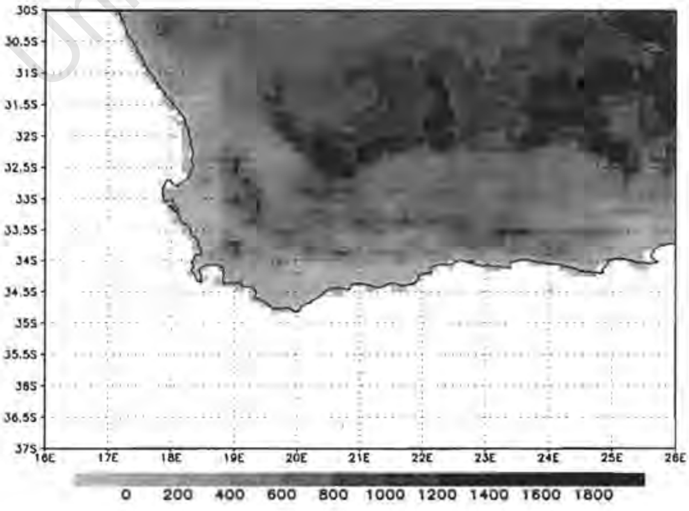

Figure 2.5: 2m drop in sea level showing the changes in coastline for the study area (present-day coastline outlined).

A lowering of average sea surface temperatures occurred from 3500 to 2300 BP along the southern Atlantic coast (Jerardino, 1993 and 1995). The absence of *Venerupis corrugata* shells from Tortoise Cave near Verlorenvlei, suggests a marked sea level drop roughly between 3000 and 2000 BP (Jerardino, 1993). Cohen *et al.* (1992) identified depressed sea-levels at Verlorenvlei and slightly cooler sea surface temperatures around 2500 BP, linking in with a slight increase in regional moisture availability at the time (Baxter, 1996).

A recovery in sea level to around the present mean with minor fluctuations began from around 2500 BP onwards. Jerardino (1993) notes sea level stabilization between 1800 and 760 BP. Much of the sandy coastline of the southwestern Cape was remodelled in the late Holocene and the present coastal configuration was only recently achieved (Miller, *et al.*, 1993; Baxter, 1996).

Declining sea surface temperatures in the Late Holocene are evident in mollusc shell isotope records from Nelson Bay Cave (Cohen and Tyson, 1995) and from sedimentological evidence of sea level fluctuations along the southern coast near Knysna (see Fig 2.8 further on in the text) (Marker, 1997). An increase in sea surface temperatures is later reflected from oxygen isotope records of *Patella granatina* for around 750 BP (Jerardino, 1995). This is then followed by a decrease in sea surface temperature, particularly evident again during the Little Ice Age, between 600 and 400 BP at Elands Bay Cave on the west coast (Jerardino, 1995).

2.5. Proxy Data Findings

Considerable complexity is evident in the natural environment of the contemporary southwestern Cape and any reliably accurate reconstruction of Quaternary palaeoenvironments must take this into account. Since it is clear that prevailing environmental conditions vary markedly with geographical locality, any identified palaeoenvironmental changes should be spatially variable. As environmental and biogeographical gradients in the study region are steep, there is no reason to expect environmental changes of the Quaternary to have been uniform throughout. It is with this in mind that the palaeoenvironmental evidence is examined, from the Last Glacial Maximum (LGM) up to the present, on a sub-regional basis. To begin with, sea level changes that have occurred over the last 25ka are examined since they too show evidence of fluctuations.

2.5.1. Western Sub-Region

A distinctive pattern of climate change during the last 20ka BP in the Western Cape is starting to emerge from palaeoenvironmental studies (Meadows and Baxter, 1998). Scott and Vogel (2000) indicate from $^{13}C/^{12}C$ ratios in fossil hyrax dung that the Cederberg has been a region, which has continually received winter rains over the last 20000 years. This evidence makes the Western Sub-region the primary focus for winter rainfall in the study. Figure 2.6 shows the Western Sub-region and some of the sites mentioned in the text to follow.

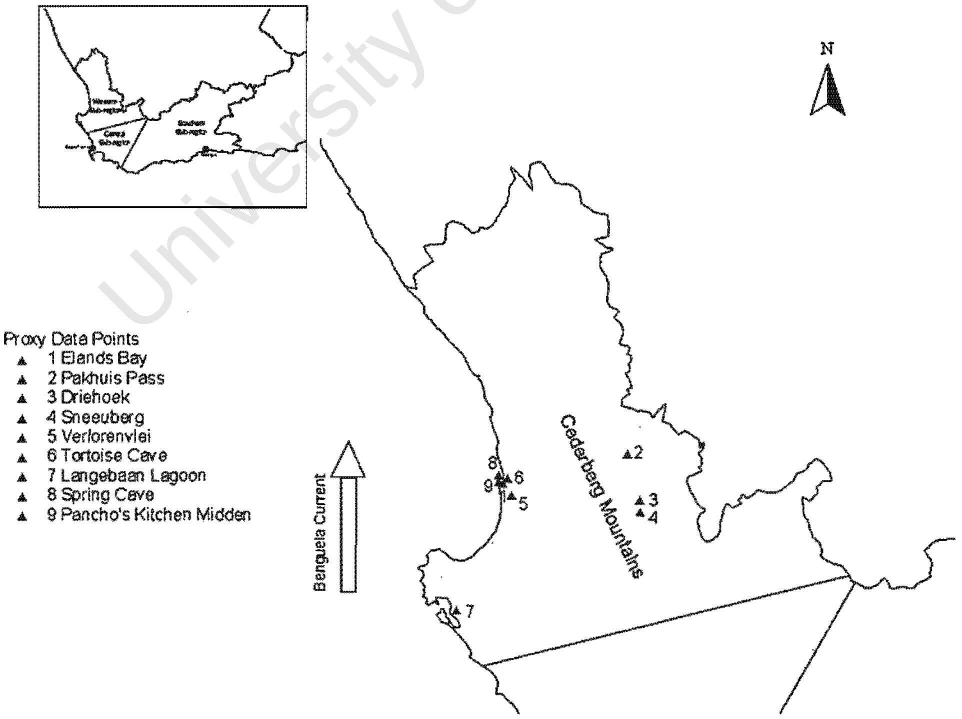

Figure 2.6: The Western Sub-region, showing the location of the proxy data sites.

2.5.1.1 Last Glacial Maximum

Proxy data studies show possibly more mesic conditions and lower temperatures for 21ka along the western region in the vicinity of Elands Bay (Baxter, 1996), particularly at the Elands Bay cave site where reduced evaporation and greater moisture availability are evident (Cowling *et al.*, 1999). The greater moisture availability in this cave is possibly related to the influence of the black southeaster carrying in moisture. The plants in the area would capture this moisture, as the lower sea level would cause them to be 100m higher in altitude and therefore able to capture the moisture carried in by the southeaster.

Pollen analysis of a Hyrax (small, rabbit sized herbivores belonging to the genus *Procavia*) midden from the Pakhuis Pass in the Cederberg, suggests that relatively cool but dry conditions prevailed around 22ka BP as seen from the evidence of depressed vegetation zones (Scott, 1994a). Pakhuis Pass is roughly 80km inland today and was approximately 120km inland 21ka BP, considering sea levels at that time. Pollen evidence from this midden suggests a significant change in the vegetation before the LGM. Parkington *et al.* (2000) suggest that the organic signal from the Cederberg may be insensitively located to detect major change, thus it would be reflecting the dry period before the LGM as opposed to the more moist conditions reflected elsewhere in the Western Sub-region.

A moist and cold LGM (25–16ka BP) is seen from sediments at Elands Bay and Diepkloof Caves, with the major soils indicating optimal vegetative cover and stable slopes, interpreted by Butzer (1979) as relating to the periods of *non*-glacial climate. Glacial-age environments were generally geomorphologically active, drier and to a large extent characterized by open vegetation (Butzer, 1984). Baxter (1996), however, shows the southwestern Cape to be markedly cooler and wetter than present during the LGM, thus an increase in temperatures could result in a decrease in rainfall (Meadows & Baxter, 1999). Deacon *et al.* (1984b) agree that the western Cape may have been wetter during the LGM.

Palaeosols in the west and southwestern Cape dating between 25–15ka BP are interpreted as indicating conditions at least as moist as during the mid-Holocene when geomorphic processes were highly active in the littoral zone in the Elands Bay area (Butzer, 1984). Butzer (1984) found the soils to represent increased surface stability and better groundcover, rather than a genuinely moist climate for the LGM. Particularly grazer-dominated larger mammal samples from Elands Bay show cooler temperatures with no evidence for changes in rainfall (Klein, 1980).

Pollen evidence from Eland's Bay Cave show that the area was subject to wetter and cooler climatic conditions at the time of the LGM (Meadows and Baxter, 1999). Parkington *et al.* (2000) indicate that they are not in a position to state environmental conditions with certainty, however they summarise the LGM in the western Cape as being "wetter, colder, cloudier and grassier than today" (pp546).

2.5.1.2 After the Last Glacial Maximum

For the Cederberg Mountains Meadows and Baxter (1999) suggest the beginning of cool and possibly moist conditions in the Cederberg around 15000-14500 years BP. They take their observations from pollen analysis of vlei sediments and, where Cyperaceae and Restionaceae pollen peak, local wetland elements are assumed to be more prominent at the time (Meadows and Baxter, 1999).

These moist conditions in the interior are reflected sedimentologically, with the initiation of organic-rich sediment near Driehoek (Fig 2.6) in the Cederberg around 14600 BP (Meadows, 1988a). Meadows and Sugden (1991) show vegetation conditions to be towards more restioid fynbos, implying moist conditions at Driehoek vlei at this time. Scott (1994b) shows an increase in woody elements from palynology of hyrax middens in the Pakhuis Pass (Fig 2.6) after 14ka BP, possibly as a response to a mild warming and slight increase in rainfall after the LGM.

positive or neg?

Further evidence for increased moisture after the LGM is found from measurements of distal humeri from the dune mole rat (*Bathyergus suillus*). Modern dune mole rats show a close relationship between adult size and rainfall (Klein and Cruz-Uribe, 1987). Evidence from Elands Bay Cave show terminal Pleistocene animals that were much larger than their Holocene counterparts, implying increased rainfall of more than 400mm (Parkington, *et al.*, 2000).

in the Pleistocene?

2.5.1.3 Early Holocene

From 12ka BP, dry conditions followed the moist conditions along the western parts, particularly in the Cederberg region and this continued into the early Holocene (Holmes, 1998). The Pleistocene/Holocene transition is placed around 10000 BP, as the start of the post-glacial epoch (Roberts, 1998). Pollen analysis of vlei sediments found the Early Holocene to be warmer and drier than the period following the LGM (Baxter 1996).

Evidence from the isotopic enrichment in the inner shell surface of mollusc shells from *Patella granatina* (Cohen *et al.*, 1992) have shown that a decrease in sea surface temperatures occurred around 11000–10000 BP. The timing and duration of this event coincides with the Younger Dryas as seen in the Northern Hemisphere (Bjorck, *et al.*, 1996; Blunier, *et al.*, 1997; Stocker, 1999). This type of temperature decrease may be linked to an increase in the frequency and/or intensity of upwelling events off the southwest coast (Cohen, *et al.*, 1992). Evidence for increased upwelling would then concur with the evidence found showing that the Western Sub-region was drier at this time, as increased upwelling would lead to aridification of the interior coastal belt (Hewitson, pers comm.).

Van Zinderen Bakker (1976) presents evidence for an important environmental change occurring in the coastal regions of Elands Bay around 12000-9000 BP. A shift from open grassland-type vegetation to more closed shrubby vegetation, as reflected in the fossil faunal evidence from Elands Bay Cave (Van Zinderen Bakker, 1976). This change is possibly linked to a warming and decreased precipitation from the more moist and cold environmental conditions of the Last Glacial Maximum (Van Zinderen Bakker, 1976). Geomorphological evidence from Elands Bay reflects the last major aeolian phase as having occurred around 12500-8000 BP (Butzer, 1979), coinciding with evidence supporting a drop in precipitation at this time.

With the rise in sea surface temperatures around 10-8ka BP (Cohen, *et al.*, 1992) possibly causing a climatic warming brought about by less intense atmospheric circulation in the southern Benguela Current region, a resulting decrease in upwelling is possible (Baxter and Meadows, 1999). This is supported by pollen data from Elands Bay Cave reflecting warmer temperatures for 10-8ka BP (Baxter, 1997). Meadows (1988a) shows the interior to be moister at around 9640 BP, from peat initiation and from pollen analysis (Meadows and Sugden, 1993) showing Proteoid fynbos with a restioid understory on Sneeuberg in the Cederberg. This warmer, moister climate is also reflected from Driehoek in the Cederberg, where Meadows and Sugden (1991) show vegetation to be of a more ericaceous, arboreal and proteoid nature around 10090 BP.

A distinct phase in the early Holocene resulted in a greater proportion of the runoff into the Pakhuis Basin remaining as standing water. From around 10000 – 8750 BP, there is evidence of the Pakhuis Basin existing as a lake or marsh, where today it is largely in-filled by unconsolidated sediment interpreted as Quaternary alluvium by Meadows and Holmes (1999). Neotectonic activity may have promoted lake formation, as other sites in the vicinity show evidence of lower precipitation within the catchment at about the same time (Meadows and Holmes, 1999).

The period 10000 – 9000 BP is characterised by a dramatic increase in the frequency of marine elements accumulating within the Verlorenvlei sediments, (Grindley, 1986). Palaeoenvironmental evidence shows that the vlei has fluctuated between being a marine and freshwater system (Baxter and Meadows, 1999). A wave cut shelf at about 1m to 1.5m above sea level exists around the shores of Verlorenvlei probably representing an early Holocene higher water level (Grindley, 1986). Jerardino (1993) finds evidence to support this from Tortoise Cave, an east-facing rock shelter 500m from the south bank of Verlorenvlei. At around 8000 BP evidence for increasing temperatures and large-scale sea level rise are noted for southern Africa (Yates *et al.*, 1986).

2.5.1.4 Mid-Holocene

Particle size analysis carried out at Verlorenvlei failed to reveal with any precision the environment of deposition of the sediments, although there is some evidence of a cyclic pattern of sedimentation and a series of upwardly fining deposits (Meadows and Asmal, 1996). What the sediments do show is that between 5500 – 5000 BP the vlei was experiencing estuarine conditions where the catchment was more arid than today and reduced vegetation cover favoured the deposition of sandy sediments derived from the lower catchment areas (Baxter, 1996). These estuarine conditions must have prevailed until at least 3800 BP (Meadows *et al.*, 1994).

Geochemical analysis at Verlorenvlei has revealed the existence of three distinct sedimentary units: One, deposited prior to 5000 BP classified as silica-rich; a second deposited between 5000 and 200 BP and is characterised by more argillaceous sediments, although there is a hiatus between 3800 and 300 BP; the third is dominated by sandy, siliceous sediments and was laid down in the post-colonial period (Meadows and Asmal, 1996). Sedimentation seems to commence around 5500 BP, with indications that the surrounding catchment was somewhat more arid than contemporary conditions.

Results from stable isotope analysis and the wood anatomy of archaeological charcoals provide a preliminary climatic record in the Elands Bay area, showing that apparently cooler and wetter conditions prevailed at about 4200 BP (February, 1990). These results come from a high percentage of woody plants, not found today in the study area, being recovered from charcoal samples contemporary with the cool and wet episodes mentioned above.

A geoarchaeological study in the Elands Bay area suggests substantial aeolian sand transport and dune formation between 4000 and 2400 BP (Miller *et al.*, 1993) supporting the idea of decreasing sea levels and partial desiccation. A corrected shell date of 3080 BP was obtained from a well-developed paleaosol buried in the dune formation, suggesting a possible wet episode in the area at the start of the Late Holocene (Miller *et al.*, 1993). A synthesis by Meadows (1992) shows the last 5000 years to be generally moister than before in many places, making the early and late Holocene remarkably different to one another.

2.5.1.5 Late Holocene

The Late Holocene (around 3000 BP) is seen from micromammalian samples to be wetter at Elands Bay (Deacon, *et al.*, 1984b). Cohen *et al.* (1992) show isotopic enrichment in the inner shells of mollusk *Patella granatina* to occur between 4000 and 2000 BP, reflecting a decrease in sea surface temperatures. A sea level drop of 2m is enough to initiate a slight drying of the interior, as direct moisture from the sea would not reach as far inland as before (Fig 2.5.). This drying is noted from the vegetation composition at Driehoek in the Cederberg around 3230 BP. Detailed pollen studies by Meadows and Sugden (1991) found the vegetation consisting of dry ericaceous fynbos, signifying dry environmental conditions at the time.

Geochemical analysis at Verlorenvlei revealed a depositional hiatus after 3800 BP, which is coincident with declining sea levels at the time (Miller, 1970). It is thought that moister climatic conditions post-5000 BP and prior to 200 BP favoured run-off in the upper reaches of the catchment and brought down greater quantities of the finer grained material from the upper catchment (Meadows and Asmal, 1996). This situation is consistent with increased river capacity due to higher rainfall conditions.

Sites at Muisbosskerm and Spring Cave (Fig 2.6) signal an increase in regional moisture availability around 2500 BP (Baxter, 1996). Further north of these sites, cooler wetter conditions might have prevailed until 2000 BP in the Namaqualand region, as suggested by the microfaunal evidence of Spoeg

River Cave (Avery, 1992). Spoeg River Cave is roughly 500km north of Cape Town (Fig 2.6.), along the west coast.

The Little Ice Age was a 500 year climatic event from around 700-200 BP (Tyson *et al.*, 2000). It was a cooling period, which reached its maximum around 400 BP (Grove, 1988). This has been reflected from isotopic enrichment seen in mollusc shells of *Patella granatina* between 750-400 BP (Cohen, *et al.*, 1992), as well as in tree-ring data of *Widdringtonia cedarbergensis* from the Cederberg (Dunwiddie and LaMarche, 1980), and in the Cango Cave speleothem oxygen isotope record from the southern Cape (Talma and Vogel, 1992).

Further late Holocene evidence comes from sediments at Verlorenvlei, which show sedimentation resuming from about 300 years ago, approximately around the time of European colonial occupation of the area; by this time the site was clearly dominated by open freshwater conditions. The replacement of marine influences with freshwater hydrology is documented in the pollen evidence and suggests significantly greater moisture availability in the catchment prior to the occupation of cattle in the area (Baxter, 1996). The subsequent increase in sedimentation probably resulted from overgrazing, reducing vegetation cover and leaving the sandy surface soil material exposed and thus prone to aeolian erosion by the predominant strong summer southeasterly winds (Sinclair *et al.*, 1986). These winds would then remove the exposed sand mainly to the south of Verlorenvlei so that the vlei acted as a sediment trap for the eroded materials (Baxter, 1996).

2.5.2. Central Sub-Region

An early synthesis of palaeoenvironmental evidence indicates increased upwelling off the southwest coast of Africa evident around 18ka BP, coinciding with decreased temperatures on the continent (Van Zinderen Bakker, 1982). The wind systems were possibly more vigorous with the influence of the westerlies extending equatorward during this time. The same synthesis reflected winter rain and a cooler climate south of 25°S, encouraging the spread of montane grassland (Van Zinderen Bakker, 1982). Figure 2.7 shows the location of proxy data sites mentioned in the following section.

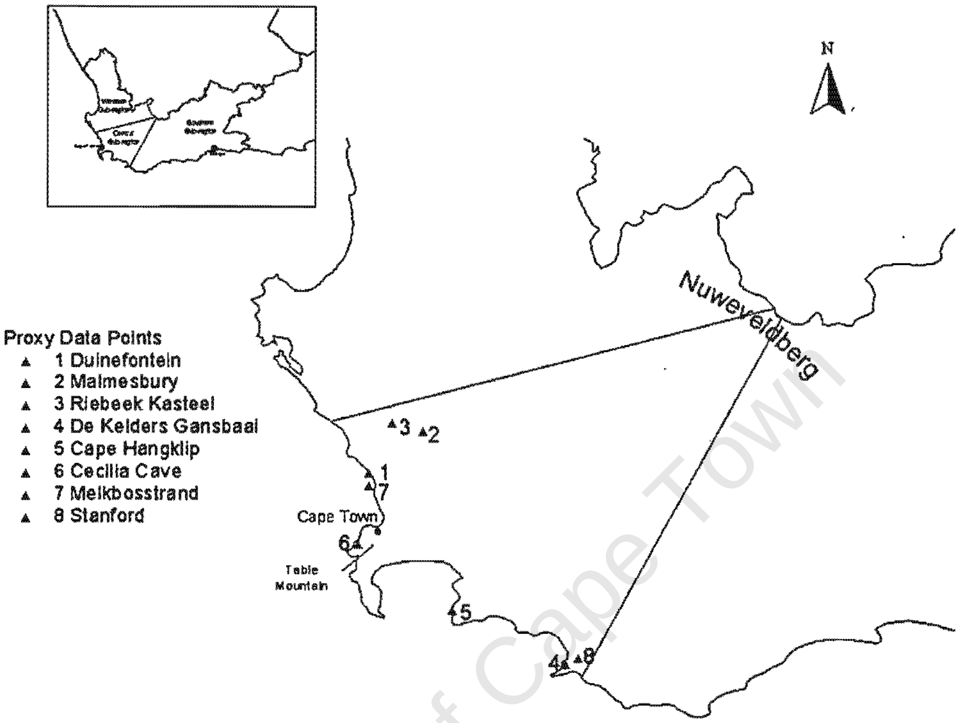

Figure 2.7: Proxy data sites in the Central Sub-region.

2.5.2.1 Last Glacial Maximum

A study of lizard distribution as palaeoenvironmental indicators (Mouton, 1986) was carried out in this region, south of $32.60^{O}S$ and west of $19.30^{O}E$. The results showed cold, cloudy conditions primarily over the Cape Peninsula roughly 20-18ka BP. Mouton (1986) proposes that this part of the southwestern Cape experienced more frequent winter rainfall, with the Cape coastal region experiencing extended periods of cloud cover and receiving the full impact of strong winds. Newell, *et al.* (1981) concurs with the idea of an increase in wind speed and quotes a figure of up to 17% increase from their synthesis of palaeoenvironmental data for the LGM, irrespective of season.

The vegetation during the LGM may have been significantly altered in relation to the fynbos recognised at present. Results from an archaeological study at

Duinefontein (Fig. 2.7) by Klein *et al.* (1999) imply that glacial climatic conditions would encourage grasses relative to the historically dominant small-leafed shrubs. Cowling and Holmes (1992) agree that grasses may have enjoyed a particular advantage on freshly exposed, unleached calcareous sands near coastal settings. This is evidence for climatically altered vegetation, from the small leafed, shrubby fynbos present today, to a semi-grassland terrain during the LGM.

Climate not only has a control over vegetation, but it also has a major control on geomorphic process and landform development (Meadows, 1988b). From the colour of sediments and inference of the presence of iron oxides, Drew (1999) shows tentative evidence for a wetter climate during the LGM at Riebeek Kasteel, northwest of Malmesbury in the Western Cape.

Around 21ka, the coastal caves at De Kelders suggest dry and cooler conditions than present based on micro-mammalian remains in sediments (Avery, 1982). Sedimentary evidence from De Kelders shows the sea level to have been low enough on the southern Cape coast for the development of a dune field between 21ka and 12ka BP (Tankard, 1976). Maud (1990) comments that extensive dune formation implies windier and less vegetated conditions than those of present conditions. These findings agree with Mouton (1986) showing stronger wind conditions around the LGM from evidence of lizard distributions.

2.5.2.2 After Last Glacial Maximum

The presence of reddish sediments at Riebeek Kasteel favoured the formation of haematite, tentatively dated after the LGM (Drew, 1999). These sediments show that conditions were drier and warmer than the LGM (Drew, 1999). This is in contrast with the rest of South Africa, where conditions were moister as seen from a synthesis of various palaeoenvironmental data sources (Partridge, *et al.*, 1990). The evidence of calcretes in the Central Sub-region, particularly evident at Duinefontein (Klein, 1976), suggests relatively dry conditions around 12ka BP (Butzer, 1984).

2.5.2.3 Early Holocene

Schalke (1973) identified peat initiation at Cape Hangklip, a coastal vlei, around 11000 BP, implying cooler, moister conditions from 11000-6000 BP. Pollen analysis was done at the site and the pollen species ratios seem to support these implications (Schalke, 1973).

Sediments from the rear of Cecilia Cave on the eastern flanks of Table Mountain have revealed a complex sequence of organic and other deposits. A radiocarbon date of 7880 BP fixed the chronology and pollen studies by Baxter (1989) link this period to environmental conditions perhaps drier and warmer than currently prevail. This more xeric phase is followed by a scenario of greater moisture availability around 5000 BP, the mid-Holocene (Baxter, 1989).

2.5.2.4 Mid-Holocene

The Central Sub-region of the southwestern Cape (Fig. 2.7) is characterised by humification and decalcification, increasing in prominence from the drier northwest (Melkbosstrand) to the wetter southeast (Stanford). This evidence suggests subhumid conditions for the mid-Holocene, possibly a little wetter than those prevailing today through the Central Sub-region (Deacon, *et al.*, 1984b).

2.5.2.5 Late Holocene

The second half of the Holocene was characterised by temperatures similar to present, but with a greater degree of available moisture. This has been seen from micro-mammalian samples from the Late Holocene, which show it to be wetter after 2000 BP at De Kelders (Deacon, *et al.*, 1984a). Baxter (1989) found the Late Holocene to have, tentatively, slightly cooler temperatures from around 3500 BP, as seen from deposits in Cecelia Cave.

Meadows (1988a) shows cool, moister conditions leading up to the Little Ice Age, with the initiation of peat at 760 BP in the Nuweveldberg, the most interior part of the Central Sub-region. Tyson and Lindesay (1992) see the Little Ice Age (around 700-150 BP) in the winter rainfall region as being a period of increased wetness. There is sufficient evidence to say that the winter rainfall region was somewhat expanded and experienced increased rainfall over the period of the Little Ice Age (Tyson and Lindesay, 1992). This increased rainfall would encompass the entire Central Sub-region, as it was an integral part of the winter rainfall region then.

2.5.3. Southern Sub-Region

The main sites studied in the Southern Sub-region are pollen and archaeological evidence from Boomplaas, Cango, and Nelson Bay Caves, as well as various other proxy data studies in the sub-region (Fig. 2.8.). Figure 2.8 shows three sites outside of the designated Western Cape Province, Lorie, Uitenhage, and Melkhoutboom Cave. These sites were included in the study as they fall into the defined present winter rainfall region, even though they are officially part of the Eastern Cape Province.

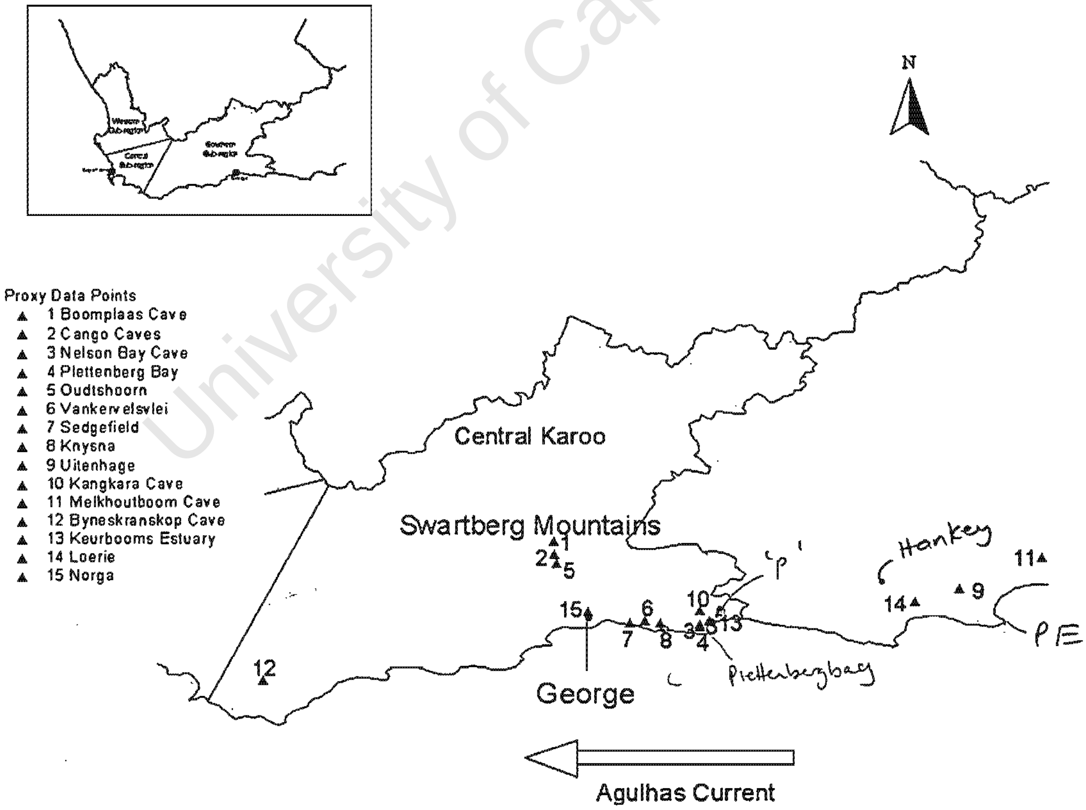

Figure 2.8: The Southern Sub-region, showing the location of sites included in the proxy data analysis.

2.5.3.1 *Last Glacial Maximum*

Well stratified sediments from Boomplaas cave have yielded charcoal and pollen samples which indicate the absence of tree taxa and record low diversity for the period 26-16ka BP. Scholtz (1986) comments that this period (26-16ka BP) was cold, but especially dry in the Southern Sub-region.

Geomorphological data from the Cango Valley for the LGM show significantly lower temperatures in comparison to today (Partridge, 1993). Speleothem data from the cave support this finding, showing temperatures decreasing by as much as 5°C at around 20ka BP (Partridge, 1993). Pollen and charcoal also indicate the LGM to be somewhat drier than present. Deacon *et al.* (1984a) found evidence from deposits in Boomplaas cave to reflect little significant changes in precipitation during the LGM.

Angular roof clasts at Boomplaas cave are thought to reflect cold periods for the LGM (Deacon, *et al.*, 1984a), although there is no evidence for intense frost shattering, as can be found in Europe during this time. Boomplaas has several horizons of coarse, subangular spall with a central date of about 22ka BP (Deacon, *et al.*, 1984a). Butzer (1973) has interpreted this as evidence for a mainly moist and cold LGM, however the evidence for a moist LGM in this area has subsequently been disputed by other evidence (Irving and Meadows, 1997; Maud, 1986; Avery, 1982). Cold conditions at Boomplaas are suggested by cleavage planes and conchoidal fractures on quartz grain surfaces studied with a scanning electron microscope by Deacon, *et al.* (1984a).

Sediments from wetlands have also provided palaeoenvironmental evidence for the Southern Sub-region. Pollen studies from Vankervelsvlei show a major depositional phase up to around 20ka BP followed by a period of low productivity (Irving and Meadows, 1997). Irving and Meadows (1997) suggested that less forest vegetation cover existed and a shift towards taxa associated with drier and cooler conditions. In the same area, Klein (1980) found evidence from micro-mammalian data for slightly increased rainfall around 22ka BP, before the LGM.

Examination of all the palaeoenvironmental data suggests that the inter-glacials were generally wetter than the glacial time spans for the Southern Sub-region. This is not surprising as the Agulhas Current, a major source of moisture today, was much further off the present southern shores (Huston, 1980) due to a much reduced sea level (Fig. 2.3). The cooler drier conditions of the LGM associated with reduced vegetation cover, were also linked to extensive erosion of elevated areas, and subsequently accompanied by widespread deposition of colluvium (Maud, 1986). This colluvium generally contains Middle Stone Age artefacts, and is found in the lower topographic situations in the coastal hinterland and interior of river basins (Maud, 1986).

Microfaunal evidence in the Southern Sub-region for 21ka BP indicates that there was a severe climate, cold and dry with very cold winters (Avery, 1982). Grazing macrofauna is dominant, indicating grassland (Klein, 1983) in an area, which is presently an intermontane region with vegetation being more like a forest than grassland. Cowling (1986) shows through a comparison of past vegetation history with present, that the LGM was drier than the Holocene in the Southern Cape. Deacon (1983) agrees that drier conditions prevailed in the southern Cape coastal region during the LGM than the Holocene.

Around 17ka BP in the Southern Sub-region, Deacon, *et al.* (1984a) noted an abrupt decline in the diversity of biological indicators. The southern coastal region in particular had very windy and cool conditions and was covered with open vegetation (Van Zinderen Bakker, 1982). As the lowest diversity of pollen, charcoal and small mammals is correlated with harshest climates, it is inferred that climates were both cold and dry during the LGM (Deacon, *et al.*, 1984a). This low diversity has been identified from O_2 isotope ratios from the nearby Cango Caves, where the findings from a stalagmite show a mean annual depression of as much as 5°C lower than present (Deacon *et al.*, 1984a).

Charcoal deposits from the Cango Valley show a virtual absence of woodland around 22–17ka BP, another pointer to the suggested harsh climatic conditions that prevailed around the LGM (Deacon *et al.*, 1984a). The Southern Cape was cooler and drier during the LGM, which is reflected by the majority of the interior of South Africa (Partridge, *et al.*, 1990). Results from Thackeray (1998) suggest that the coldest interval of the LGM was also dry in the vicinity of Nelson Bay Cave.

A firm estimate of the scale of temperature change has been calculated from the isotopic composition of groundwater from the Uitenhage aquifer. This included isotopes of O_2, N_2, and Ar and, although not directly within the Southern Sub-region, they showed as much as 5.5°C cooler temperatures than present for the LGM (Heaton, 1981; Vogel, 1983) – a finding which is consistent with evidence from the stalagmite from Cango Caves. During the LGM, vegetation in the Cango Valley was relatively open, containing semi-arid scrub and experiencing cold and dry climatic conditions.

Scholtz (1986) identified the absence of the olive tree (*Olea europaea*) from the Cango Valley between 26–16ka BP as evidence for dry and especially cold conditions. This was determined from charcoal assemblages found in sediments from Boomplaas Cave, and related to a range of wood morphological types. Nelson Bay Cave shows evidence of frost-weathering and roof-spalls dated between 19000-16500 BP, when Brain (1986) suggests a reduction of as much as 10°C in mean winter temperatures, however temperature decreases to this extent are no more than ‘circumspect’.

Deacon and Deacon (1986) note that human populations were more widespread during the present and Last Interglacial, than during the LGM. During the LGM they may have been fragmented and were possibly confined to particular refugia. This is seen with the onset of the LGM, which apparently correlate with a decrease in archaeological visibility, consistent with a decrease in human populations during the 'harsher' climatic conditions (Deacon and Deacon, 1986).

2.5.3.2 After the Last Glacial Maximum

Temperatures and rainfall increased and dense mesic vegetation became more extensive on valley floors in the Southern Sub-region after the LGM (Avery, 1984). Scholtz (1986) identified a sharp warming and increased precipitation, between 17–14ka BP, when the olive tree and other woody taxa reappear in the charcoal record.

In the southern Cape and interior, dry conditions experienced during the LGM were followed by a period of higher rainfall that lasted to some time after 12ka BP (Deacon, *et al.*, 1984b). Evidence for higher rainfall comes from Boomplaas cave, where the low carbonate, phosphate and pH measurements around 16ka BP are indicative of leaching, prior to the accumulation of material around 13ka BP.

Evidence for increased temperature and precipitation around 14ka BP is reflected in charcoals in the Cango Valley, which show a marked increase in taller woody taxa, indicative of more effective precipitation. At the same time, diversity and species composition of plant and small mammal species increased, indicating a warming of temperatures and an increase in precipitation (Deacon, *et al.*, 1984b).

A stalagmite collected 1km from the entrance to Cango Caves reflects a hiatus in growth between 14ka and 5ka BP. As the availability of drip water and the bicarbonate content of the ground waters can change with changing climate, the growth and hiatuses in the growth of speleothems or cementation of a deposit, may have palaeoclimatic significance (Deacon, *et al.*, 1984a). No cavestone would have formed under conditions of low precipitation when water did not percolate down into the cave. It is, nevertheless, difficult to ascertain the precise meaning of the hiatus, since controls of speleothem formation can be relatively subtle (Talma and Vogel, 1992). The changes are possibly linked to changes in the structure and composition of the vegetation as well as to the source of the groundwater feeding the fissures of the cavern system (Deacon, *et al.*, 1984a).

In Kangkara cave, south east of Cango Caves (Fig 2.8), a much shallower sequence of sediments reveals an angular spall horizon dated 12500 and 12330 BP; subjacent deposits are completely decalcified (Deacon, 1982). This is evidence of cool subhumid climates at this time (Butzer, 1984). These climates would be marginally warmer than the LGM, but cooler than today, with more available moisture.

Around 12000–10500 BP Butzer (1984) identified extensive decalcification of shell in the brown stony loam unit from Nelson Bay Cave. Further inland at around the same time, 12–10ka BP, a period of marked leaching and drip-line erosion is indicated in the interior cave of Boomplaas (Butzer, 1984). These are clear indicators of increased moisture availability and are possibly supported by evidence for increased peat accumulation around the same time in the southern Cape (Meadows, 1988a). Also around 12-10ka BP, Thackeray (1998) shows evidence for the expansion of C_4 grasses from ungulate bone samples at Nelson Bay Cave, implying warmer and wetter conditions.

2.5.3.3 Early Holocene

An important environmental change is evident between 12000-9000 BP in the southern coastal region, when the grassland was largely replaced by a denser, but dispersed vegetation (Klein, 1972b). Fossil faunas from Nelson Bay Cave and Melkhoutboom Cave (Fig. 2.8) have shown evidence for this shift, and it is thought to have been due to a slight temperature warming and an increase in precipitation, from the 'harsher' LGM conditions at the coastal areas (van Zinderen Bakker, 1976). Deacon (1979) identified a trend from the cold and dry LGM to more mesic conditions being completed around 9000-5000 BP for the early Holocene.

A shift to somewhat warmer and drier environments at Boomplaas is seen at around this time (10ka BP) from charcoals indicating an increase in composites and thicket taxa (Deacon, *et al.*, 1984b). The thicket taxa are then replaced by *Acacia karroo*, indicating yet drier environments.

Over the past 10000 years, soil formation has been a constructive process, with soils in the southern Cape having been developed on and from Cenozoic sediments aided by rich organic matter and high rainfall to the south of the coastal mountain ranges (Thwaites, 1984). The Early Holocene was relatively dry, except for modest pedogenesis around 8000–7000 BP (Butzer, 1984). The central interior of the Southern Sub-region and some coastal areas were wetter than at present, although some eastern and south-central areas were seen to be drier at around 7000 BP (Tyson, 1999b).

Pollen data from Groenvlei, at the coast near Knysna (Fig 2.6.), suggest that yellow-wood (*Podocarpus*) forests of the region were reduced between 8000-7000 BP (Martin, 1968). Generally, pollen data covering the period between 11000 and 6000 BP is characterised by a progressive warming in the southern Cape (Scott, 1990).

2.5.3.4 Mid-Holocene

Mid-Holocene changes in this sub-region seem to have been accompanied by a shift in rainfall seasonality (Partridge, 1993). Based on a synthesis of palaeoclimates in southern Africa, Tyson (1999b) shows that annual rainfall would have been higher during the mid-Holocene compared to present in many areas of the southern Cape. At Byneskranskop Cave this trend can be seen as early as 6200 BP (Avery, 1993), but overall in the Southern Sub-region the shift from a predominantly summer rainfall region to a year-round rainfall regime, began nearer to 5500 BP and is present only after about 5000 BP in the central Karoo (Bousman, *et al.*, 1988). Pollen from the southern Cape show an increase in forest elements between 7500–2600 BP. Deacon *et al.* (1984b) concurs and presents evidence for moister conditions between 5000–1300 BP based on an earlier synthesis of palaeoenvironmental change.

A progressive increase in ^{13}C is found in the Cango Caves speleothem after deposition recommenced at around 5000 BP (Partridge, 1993). This slow increase of ^{13}C does not correspond with the ^{18}O-derived temperature curve that Talma and Vogel (1992) attained from the Cango stalagmite, suggesting seasonality of rainfall, where initially rainfall reflected a winter-maximum and this slowly moved towards a more summer/all-year trend, which culminated as late as 2000 BP in some areas (Talma and Vogel, 1992). A return to drier and somewhat cooler conditions occurs after this, as is reflected in the decrease in forest pollen elements in the Cango Caves speleothem after 2600 BP (Partridge, 1993).

The last 5000 BP has seen the climate over southern Africa characterised by a number of extended warmer and wetter periods and cooler and drier counterparts; these may have occurred in a quasi-regular fashion (Bousman *et al.*, 1988; Tyson, 1999b). Proxy evidence for the mid-late Holocene mirrors this variability. Pollen findings near Knysna and microfauna of Byneskranskop Cave suggest slightly warmer and drier conditions about 6500–3500 BP, compared with the preceding and subsequent period (Avery, 1982). This evidence links up with the charcoal record from Boomplaas Cave, where Scholtz (1986) documents the dominance of *Acacia karroo* which implies that warm and relatively dry conditions in the Southern Sub-region existed for the last 3000 years. However evidence for moister conditions is indicated from cave flowstones, particular soil profiles, and valley-floor peats from around 4850–1300 BP (Butzer, 1984).

2.5.3.5 Late Holocene

Geomorphological evidence of the development of a sand berm near Knysna shows increased storminess with evidence to support lower winter temperatures and an extended winter for the Late Holocene (Marker, 1997). Peat initiation at Loerie (Fig 2.8), a small valley flood plain, around 4010 BP (Butzer and Helgren, 1972) and Norga (Fig 2.8), around 3500 BP, are also supportive of cool and moist conditions (Meadows, 1988a).

The major periods of naturalistic animal engravings from rock art seem to coincide with wetter and warmer climates about 3200-2500 BP and 2250-1800 BP (Butzer, *et al.*, 1979). This would support the palaeoenvironmental data examined already, showing cyclical changes of wet and dry periods during the mid-late Holocene. At Groenvlei, near Knysna, forest elements show a temporary decline under cooler conditions around 2000 BP (Scott, 1990). Rock engravings of a more geometric pattern are thought to be favoured when the climate is drier, as have been found after 1300 BP in the southern Cape (Butzer, *et al.*, 1979).

The Holocene climate appears to have fluctuated around the present-day mean with the warmest temperatures in the early-mid Holocene and somewhat cooler conditions within the last 2000 years (Deacon, *et al.*, 1984b; Maud, 1986). Leading up to the Little Ice Age, Norga peat deposits near George saw a change from extensive forest and wetland conditions, to a less mesic period during which forest and wetland development was retarded (Tyson and Lindesay, 1992). The Little Ice Age in the southern Cape is confirmed by isotope analysis of mollusc shells at Nelson Bay Cave (Cohen and Tyson, 1995), as well as by dated shifting distributions of Iron Age villages in southern Africa (Huffman, 1996). Tyson (1999a) notes that the Cango Cave record supports the notion of cooling during the Little Ice Age, roughly 300-400 BP. The Little Ice Age was not uniformly cool and conditions were far from stable (Ingram et al., 1981). Summers are seen to become drier in the summer rainfall region, and winters somewhat wetter, with the net annual rainfall decreasing (Tyson and Lindesay, 1992).

Deacon, *et al.* (1984a) have found close correlations between the evidence at Boomplaas and Cango Caves and that of the isotope record from Dome C in Antarctica, and state that there can be no doubt that they relate to the same southern hemisphere and worldwide phenomena.

2.5.4. Synthesis

The proxy palaeoenvironmental data are highly complex in both space and time and are in need of a more concise form of comparison between the regions. This next section presents a summarised account of the Late Quaternary for the winter rainfall region of the Western Cape, based on the previous discussion. A tabulated form of the findings appears at the end of the section (Table 2.1):

2.5.4.1 Western Sub-Region

The LGM is seen to be wetter and cooler than present. Palaeoenvironmental evidence points towards conditions being cooler as opposed to cold, as what is expected during the LGM. This then merges into drier and warmer conditions with the early Holocene being definitely dry and warm. Evidence from Verlorenvlei has shown the mid-Holocene to be dry and warm, as an extension of the early Holocene, leading into a sub-humid and wet climate over the Sub-region in the mid-late Holocene. The conditions suggest temperatures similar to present conditions, but with more available moisture. The Late Holocene reflects higher levels of available moisture than the mid-Holocene, leading into a drying period as we move towards present conditions.

2.5.4.2 Central Sub-Region

The LGM is seen to be dry and cool in the more eastern parts of the Central Sub-region, with cold and cloudy conditions with evidence for stronger winds bringing rain in the western parts. This then led to warming and an early Holocene, which is drier and warmer than the LGM. The mid-Holocene reflects sub-humid conditions showing evidence of a definite increase in precipitation. The Late Holocene then showed a continuation of this increase in precipitation, being characterised by more available moisture, prior to considerable drying through to today's conditions.

2.5.4.3 Southern Sub-Region

The Southern Sub-region depicted the LGM to be characteristically cold but dry. A move to more moist and warmer conditions followed the LGM, leading into a more warm and dry early Holocene. The early Holocene was not completely warm and dry, but changed later to more cool sub-humid conditions. This was followed by a warm mid-Holocene, showing a cyclical pattern between moist and very dry conditions, terminating in a drier phase. The Late Holocene reflects warm conditions, with a cyclical pattern of moist to relatively dry conditions, ending in a moist phase.

Table 2.1: A brief synopsis of precipitation and temperature changes for the past 25ka, as seen from proxy data evidence.

Time	Years BP	Western Sub-region	Central Sub-region	Southern Sub-region
LGM	25–17ka	Wetter Cooler	Dry Cool	Dry Cold
After LGM	16–11ka	Drier Warm	Drier Warm	More moist Warmer
Early Holocene	10–8ka	Dry Warm	Dry Warm	Dry Warm
Mid-Holocene	7–4ka	Dry to sub-humid Warm	Sub-humid to moist Warm	Moist to dry Warm to cool
Late Holocene	3ka to present	Wetter Warm	Wetter Warm	Moist to dry Warm

2.4. Discussion of Proxy Findings

The southwestern Cape, situated at a continental extremity and climatically and vegetationally differentiated from the rest of sub-Saharan Africa, is an area that merits special attention in South African Quaternary studies (Hendey, 1973). The palaeoenvironmental evidence examined thus far shows significant differences between the southern and western coastal sub-regions of the southwestern Cape during the last 25ka BP, although both fall within the present day winter rainfall region *sensu lato*. As far as the proxy data show, the differences are significant enough to treat the two sub-regions separately.

The western and southwestern Cape, where temperatures were lower during the LGM (Fig. 2.9), shows definite geomorphological evidence for moister climates, and it becomes apparent that the winter and summer rainfall regions were experiencing quite different shifts in precipitation patterns (Meadows, 1992). For example palaeosols in the western and southwestern Cape dating between 25–15ka BP are interpreted as indicating conditions at least as moist as during the mid-Holocene when geomorphic processes were highly active in the littoral zone (Butzer, 1984). This is in direct contrast to the Southern Cape, where conditions were cold and dry for the LGM (Partridge *et al.*, 1997).

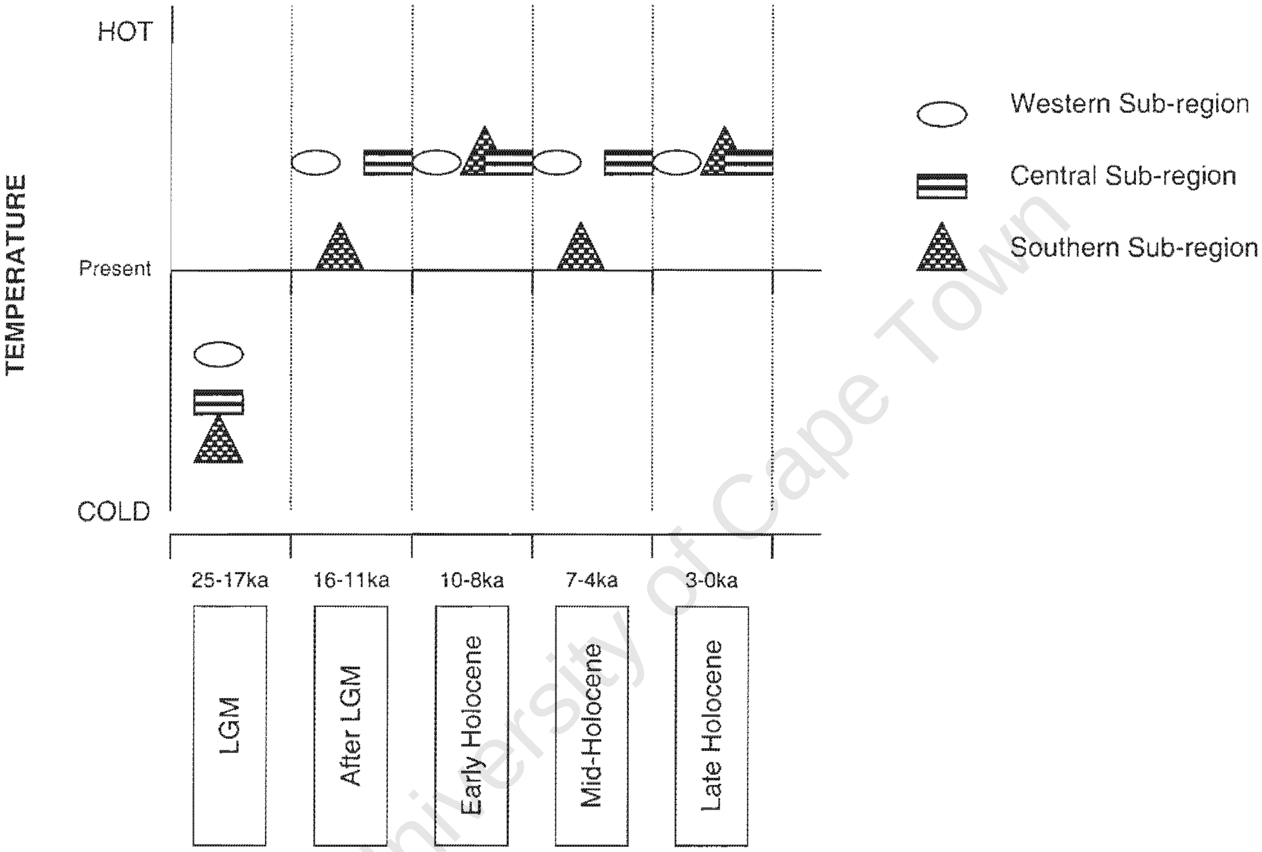

Figure 2.9: A summary of changing temperatures from proxy palaeoenvironmental evidence. A graphic representation comparing palaeo-temperature changes to present conditions between the Western, Central and Southern Sub-regions.

The temperature decrease for the LGM in the Western Sub-region is reflected in the pollen studies from both coastal and inland areas. The proxy data for the region also suggest evidence of a stronger South Atlantic High Pressure system at the time. Partridge *et al.* (1999) confirm that a significant latitudinal migration of major elements of atmospheric circulation occurred during the LGM. The drier conditions in the proxy data are possibly linked to stronger southeasterly winds (implying greater upwelling on the west coast) and/or increased subsidence and more southerly storm tracks. Another explanation is possibly related to the distance the site was from the coast, as sea levels have fluctuated extensively over the last 25ka. This means that the coastal site of Elands Bay would have been 30-40 km further inland some 21ka BP.

Figure 2.10: A summary of changing precipitation from proxy palaeoenvironmental evidence. A graphic representation comparing palaeo-precipitation changes to present conditions between the Western, Central and Southern Sub-regions.

The most interesting finding that this study clearly shows is the fluctuation of precipitation throughout the study region, spatially over time (Fig 2.10). This is seen from the likeness displayed when comparing the Western Sub-region (presently dominated by winter rainfall) with the Southern Sub-region (presently all-year rainfall). The fluctuations between these wet and dry conditions is clearly identified in the Central Sub-Region, which displays characteristics of both the Western and Southern Sub-regions at various times during the last 25ka (Fig. 2.10). Partridge *et al.* (1999) suggest that a shift to a greater proportion of winter rainfall is indicated for the LGM, linking with the summary in Figure 2.10 which shows greater rainfall for the Western Sub-region (presently experiencing winter rainfall) while the Central and Southern Sub-regions (presently all year rainfall), along with the interior summer rainfall region (Scott, 1993), remains dry.

In the Central Sub-region, the LGM is seen to be cold and dry in the east (similar to the Southern sub-region), but cold and wet in the northwest (like the Western sub-region). The Early Holocene is then seen to be dry and warm, like the Western Sub-region, while the Southern Sub-region shows cool and sub-humid conditions (Fig. 2.10). During the Mid-Holocene the central and Western Sub-regions share the same characteristics of being sub-humid and wetter, while the Southern Sub-region displays cyclical conditions of wet and dry during a warm phase. This is where the Central Sub-region seems to remain, as it displays wetter conditions and higher levels of available moisture, unlike the Southern Sub-region, which is remarkably cyclical up to present-day conditions.

A maximum Holocene warming between 8000 and 5000 BP is seen in both the summer and winter rainfall regions of southern Africa from biological evidence (Partridge *et al.*, 1990) and isotopic data from groundwater in the Uitenhage aquifer (Heaton et al., 1986). The groundwater indicates that temperatures exceeded the contemporary mean by about 2°C. This Holocene Altithermal is thought to peak between 7000 and 6500 BP, in agreement with hemispheric trends (Scott, 1993). Partridge *et al.* (1999) set the limits of warming for the Holocene Altithermal at around 1-2°C.

The winter rainfall region is differentiated from the summer rainfall region when considering precipitation for the Holocene Altithermal. Both the Pretoria Saltpan (Partridge *et al.*, 1993) and the Wonderkrater site (Scott, 1989) which fall well into the summer rainfall region in the Gauteng Province reveal conditions wetter than today, whereas all the evidence for the winter rainfall region show much drier conditions (Table 2.1).

The next step in this study is to examine synoptic climate model data on a regional scale for the past 20-25ka, and then to compare the model output to the proxy data found for the study region. The aim is then to identify areas in need of further study, as distinct gaps clearly exist in the proxy data for the Late Quaternary in South Africa.

CHAPTER THREE

PALAEOENVIRONMENTAL CHANGES AS DEPICTED FROM CLIMATE MODELS

CHAPTER 3: PALAEOENVIRONMENTAL CHANGES AS DEPICTED FROM CLIMATE MODELS

3.1. Introduction

An extension of knowledge of the climate's response to the long-term changes in external forcing, and in the configuration of the Earth's surface over geological timescales, provides a unique opportunity to increase our confidence in climate models (IPCC, 1996). Palaeoclimatic data records are expanding for the late Quaternary in southern Africa (Meadows and Baxter, 1999), but remain relatively scarce when compared to the Northern Hemisphere studies. This restricts the use of these reconstructions in model evaluation to a portrayal of general climatic regimes, rather than the detailed evaluation of models and processes afforded by modern observations (IPCC, 1996).

Climatic changes since the last glacial maximum are large and comparatively well documented, with proxy estimates of palaeoclimatic conditions being obtained from a variety of environmental records (see Chapter 2). Using such data as boundary conditions, atmospheric models have been used to simulate the climate of the last glacial maximum (Braconnot, 2000). One such example is PMIP (Palaeoclimate Modelling Intercomparison Project)[1].

PMIP was initiated in order to coordinate and encourage the systematic study of atmospheric general circulation models (GCMs) and to assess their ability to simulate large changes of climate, such as those that occurred in the distant past (Joussaume and Taylor, 2000). Project goals include identifying common responses of atmospheric GCMs to imposed palaeoclimate "boundary conditions"; understanding the differences in model responses; comparing model results with palaeoclimate data; and providing atmospheric

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[1] http://www-pcmdi.llnl.gov/pmip/index.html

GCM results to aid in the analysis and interpretation of palaeoclimate data (Joussaume and Taylor, 2000).

PMIP's main focus is on the mid-Holocene, around 6000 years BP, and the last glacial maximum, around 21000 years BP. This focus is due to the fact that global climatic conditions were remarkably different at these times compared to present and relatively large amounts of palaeoclimate data exists for these periods (IPCC, 1996). The major climatic "forcing" factors are also relatively well known for these time periods (Taylor, *et al.*, 2000). As an example of these climatic changes, proxy data for the west coast of South Africa show the mid-Holocene at 6000 BP, to have had drier to more sub-humid conditions than today, and the last glacial maximum around 21000 BP, to be cooler and wetter than today (see Chapter 2).

Some of the palaeoclimate features simulated by models in previous studies seem consistent with palaeoclimatic data, but others do not (Harrison, 2000). Correlations between model outputs and local palaeoclimatic records have not always been satisfactory (Partridge, 1993; Taylor, *et al.*, 2000). This is particularly true of the Southern Hemisphere, where data sets of adequate resolution are too few (except in some local areas) to permit proper comparison and calibration (Partridge, 1993). This is on a general scale, as some local areas have detailed calibration of past environmental change events. With this in mind we broach the following study.

3.2. Analytical Techniques

This section is divided into three, where the climate models used in the study are examined first, and then the variables analysed in the study are discussed. Lastly a general discussion of Global Climate Models (GCM's) is addressed.

3.2.1. Climate models

Seven models were selected from a suite of models used in the PMIP studies (Table 3.1). This subjective choice was made based on the availability of model data and their common usage for other applications (Kutzbach and Guetter, 1986; Pollard and Thompson, 1992). The models chosen are from globally recognised and established modelling groups, with proven success in palaeoenvironmental studies (Phillips, 1994; Gates, 1999).

The PMIP models used were all Atmospheric Global Climate Models (AGCM's)[2]. The boundary conditions for the PMIP models used included present insolation and sea surface temperatures (SST), with CO_2 levels at 280ppm for the control run (0ka BP). The 6ka BP simulation also used present SST and CO_2 of 280ppm, with a calculated insolation[3] for 6ka BP. The 21ka BP run used ice sheets from Peltier[3] and CO_2 at 200ppm, with insolation calculated for 21ka BP[3]. The landsurface changes observed were only for 21ka BP, where ice sheets and coastlines were changed (see Appendix H). A more detailed account of the seven models used can be found in Appendix C and H.

Table 3.1: Details of the seven models taken from the Palaeoclimate Modelling Intercomparison Project (PMIP) [4].

MODEL	DESCRIPTION (YEAR)	OWNERS	RESOLUTION
CCC2.0	CCCMA Version 2 (1992)	Canadian Centre for Climate Modelling and Analysis	T32 (3.75° x 3.75°) /L10
CCM1	NCAR CCM1 (1992)	IES-Center for Climatic Research	R15 (4.5° x 7.5°) /L12
GEN2	GENESIS2 (1995)	Pennsylvania State University	T31 (3.75° x 3.75°) /L18
GFDL	GFDL CDG (1997)	Geophysical Fluid Dynamics Laboratory	R30 (2.25° x 3.75°) /L20
MRI2	MRI GCM-IIb (1995)	Meteorological Research Institute	4°x5°/L15
UGAMP	UGAMP UGCM Version 2 (1994)	The UK Universities' Global Atmospheric Modelling Programme	T42 (2.8° x 2.8°) /L19
UKMO	UKMO HADAM2 (1997)	United Kingdom Meteorological Office	2.5°x3.75° /L19

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[2] http://www-pcmdi.llnl.gov/pmip/docs/introdoc.html
[3] http://www-pcmdi.llnl.gov/pmip/docs/condidoc.html
[4] http://www-pcmdi.llnl.gov/pmip/docs/PMIPmain.html

The time frames were restricted by the data available for 0ka (taken as a present day simulation), 6ka and 21ka BP for the southern African region within an atmospheric window extending from 15°-45°S and 0°-50°E. Reanalysis data from the National Centers for Environmental Prediction (NCEP) were used as a comparison of the accuracy of model representation of "observed" phenomena. NCEP data are generated from forecast charts which are public domain and created by a global medium range forecast model in the USA (Kalnay *et al.*, 1996).

It is necessary to note that GEN2 was incomplete in its data for 21ka as some grid cells showed data to be missing over the interior of southern Africa. This model was still used in the analysis as the missing data from the respective grid cells did not influence the area of interest.

3.2.2. Variables analysed

The variables examined include climatological annual means of sea-level pressure, wind speed, temperature and total precipitation. These variables have been chosen subjectively, based on the need to simulate general circulation patterns and to identify the models' success at simulating small-scale changes.

Table 3.2: The variables used to determine past environmental changes from the seven models.

VARIABLE	ABBREVIATION	UNITS	LEVEL
Mean sea-level pressure	Slp	hPa	-
Wind speed and direction	uv winds	m/s	Surface and 850 hPa
Temperature	Ta	°C	Surface and 850 hPa
Total precipitation	Ppt	mm/day	-

The examination of atmospheric circulation is of primary importance since it is the main control behind regional changes in wind speed/direction, temperature, precipitation and other climatic variables (IPCC, 1996). This circulation is primarily dependent on the distribution of high and low pressure cells around the earth. The horizontal distribution of pressure is particularly fundamental in meteorology, as it is directly involved with lateral movements of atmospheric air masses (Guyot, 1998), thus driving the circulation of the atmosphere. Pressure changes indicating general circulation patterns are accompanied by changes in the wind field, i.e. surface wind stress that drives the oceanic circulation patterns (IPCC, 1996).

Wind may be defined as a practically horizontal displacement of air (Guyot, 1998). Such a movement is caused by variations of pressure resulting from differential heating of the global surface or by dynamical factors in the atmosphere itself (Whittow, 1986). This movement, and the close links winds have to changes in sea-level pressure, make changes in winds one of the primary variables to consider after sea-level pressure, within the context of climate change.

Temperature and precipitation are also important variables for consideration as they are visible indicators of climatic change. Mean annual temperature has fluctuated over time, but particularly over the last 25ka as can be seen in Chapter 2. Mean annual precipitation has also fluctuated extensively in the past, showing alternating periods of wet and dry conditions as shown by environmental proxy data indicators (see Chapter 2).

Total cloud cover and specific humidity are extremely sensitive on a regional scale, and are good indicators of a models capability/ inability to simulate past climates. Specific humidity is defined as the "mass of water vapour as a proportion of the total mass of moist air of which it forms a part" (Preston-Whyte and Tyson, 1993, p357), and thus it is closely linked to percentages of cloud cover in the region.

3.2.3. Global Climate Models (GCM's)

One of a global climate model's (also known as a general circulation model; both terms are abbreviated as GCM) primary aims is to numerically simulate changes in climate as a result of slow changes in some boundary conditions or physical parameters (Peixoto and Oort, 1996). Changes in the solar constant and greenhouse gas concentrations are examples of the boundary conditions and physical parameters respectively, which can be altered in GCM's when simulating climate. GCM's numerically simulate the 'state' of the atmosphere, using a finite expression of the equations of motion. Simulations may extend for many years, such that an understanding of the means and variability of the climate can be achieved. The quality of a GCM is judged, amongst others, by the quality of the statistics of tropical or extra-tropical disturbances that it displays.

One of the goals of GCM's is to simulate climate over a global spatial coverage for many years at a time. The spatial resolution of GCM's is generally coarse (typically ~3°-5°), with relevance placed on clouds and radiation; the surface, including the land, ice, ocean, etc; ocean dynamics; and model stability (Peixoto and Oort, 1996), thus enabling GCM's to show synoptic features well.

A key problem in GCM modelling is long-term stability, and sensitivity to small changes in surface conditions or radiation input. The atmosphere may be 'almost transitive'. This means that it is neither invariant (i.e. intransitive where it alternates irregularly between prolonged periods in one or other of two different states - Linacre (1969)) nor transitive (McGuffie and Henderson-Sellers, 1997). An 'almost transitive' system can flip between alternative patterns. The flipping to and from Ice Age conditions is an example. An increase in solar radiation will lead to rising temperatures, the extent of which is dependent on the amount of ice on the surface; since ice cover will reflect much of the extra radiation away, causing increased heating, until eventually the heating is sufficient to melt the ice. Conversely, reduced radiation will lower temperatures more if the surface is free of ice, accelerating the formation of ice (McGuffie and Henderson-Sellers, 1997).

Sub-grid scale processes are those that have dimensions smaller than the model resolution. Certainly cloud microphysical processes are in this category. These processes therefore need to be 'parameterised' i.e. the aggregate effect of the clouds on the resolved scale is calculated. This is due to changes in the radiation fluxes or moisture and mass transport as examples. Parameterisations are empirical approximations based on large-scale resolved variables. Global models do not resolve cumulus clouds (even thunderstorms), so their presence and effects are parameterised: for instance, when the atmosphere is conditionally unstable and moisture convergence occurs on a gridscale, thunderstorms, which stabilise the atmosphere and generate rain, are assumed.

Parameterisations may have a theoretical justification, but they always need to be tested experimentally. All models parameterise atmospheric radiation, sub-gridscale motion, chemistry, and cloud physics. Clearly, some parameterisations are specific to GCM's. Parameterisation of GCM's for past changes are usually tuned to present day conditions, and this can affect the realism of the model output. Hence spatial patterns, more than magnitude of change, are important in analysing features from GCM output for past climate changes.

As computer processing has become less expensive, models have become refined to allow for increased spatial resolution, more accurate parameterisations, and more simulations. Atmospheric predictions have been at the forefront of computer development ever since John von Neumann used one of the world's first computers, the EDVAC, to run a weather simulation at Princeton University's Institute for Advanced Study, in 1945.

3.3. Technical Approach

The simulations of the present day climate state from the models were compared to NCEP reanalysis data to examine the differences shown between the models for present conditions. This was done in order to gauge the realism of the model representation of known climatic conditions. In order to examine the climatic changes that have occurred in the past, anomaly fields are considered. The anomaly fields are derived from the 0ka simulation and the past simulation, and show the changes that have occurred for each variable between the present (0ka) and the 6ka and 21ka BP periods respectively. This highlights how the different variables have changed between the various models for respective time periods when compared to present day simulations.

3.3.1. Observed Data Compared to Model 0ka

NCEP mean monthly data were used as "observed" and compared with the output of the model 0ka. NCEP annual data for 29 years (1970-1998) were averaged together to get an approximation of current climatic conditions. Southern African climatological features can be coarsely divided into three main processes (Fig. 3.1): 1) the continental thermal trough; 2) westerly flow south of the continent; and 3) the placement of the two high pressure systems off the coast.

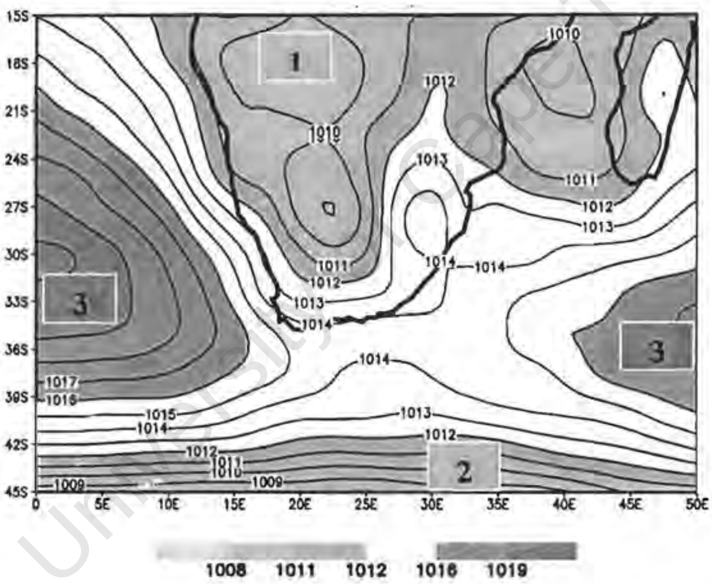

Figure 3.1: NCEP sea level pressure diagram showing situation of 1) the continental thermal trough; 2) westerly flow south of the continent; and 3) the two high pressure systems.

With these features in mind a discussion of how the model 0ka compared with the observed (NCEP) results follows. Anomalies are derived for the models by examining the differences between the model 0ka and NCEP for each variable. The full suite of anomalies for the different variables can be found in Appendix D. A summary of the findings with regard to each process is found in Table 3.3 as a quick reference to the next section.

Table 3.3: General findings for the model output from the seven PMIP models for 0ka vs NCEP data for the three main climatological regimes over southern Africa.

VARIABLES	1) THE CONTINENTAL THERMAL TROUGH	2) WESTERLY FLOW SOUTH OF THE CONTINENT	3) THE TWO HIGH PRESSURE SYSTEMS
Sea level pressure	Presence of trough noted with slight westerly displacement	Westerly flow displaced southward in many models	Depicted in all models, but generally stronger (2/7 are weaker)
Winds	Westerly displacement, shifts with circulation	Decreased westerly flow	Decreased anti-cyclonic high pressure flow
Temperature	All models show cooler than observed	Cooler temps, with well defined N-S temp gradient	Negative temperature bias
Precipitation	Wetter in East over escarpment, well defined E-W gradient	Wetter south of the sub-continent	

3.3.1.1. Continental thermal trough for 0ka BP

A westerly displacement of the continental thermal trough is noted in the sea level pressure fields, causing a weakening of pressure over the western interior and coastal regions. Figure 3.2 shows an example of this westerly displacement simulated from the UKMO model. This type of displacement is not uncommon and has been seen as a feature in GCM runs designed specifically for simulating present day conditions (Hewitson, pers comm.).

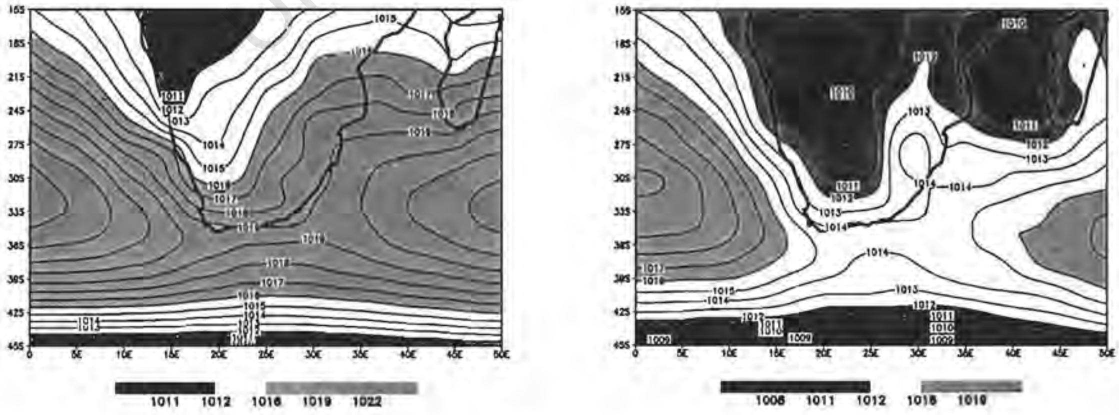

Figure 3.2: Present day simulated sea level pressure from the UKMO model (left) compared to NCEP (right). Note the westerly displacement of the continental trough.

The wind field shows similar spatial displacements and intensity as sea level pressure due to the overall circulation effects. Thus the southward flow associated with the thermal trough has shifted westwards. This implies a westward extension of convective rainfall over the interior. Due to decreased wind strengths into the interior from the east, associated with the more southerly displacement of westerly flow, the available moisture in the interior is now dependent on the circulation features slightly north of the domain (Fig. 3.3).

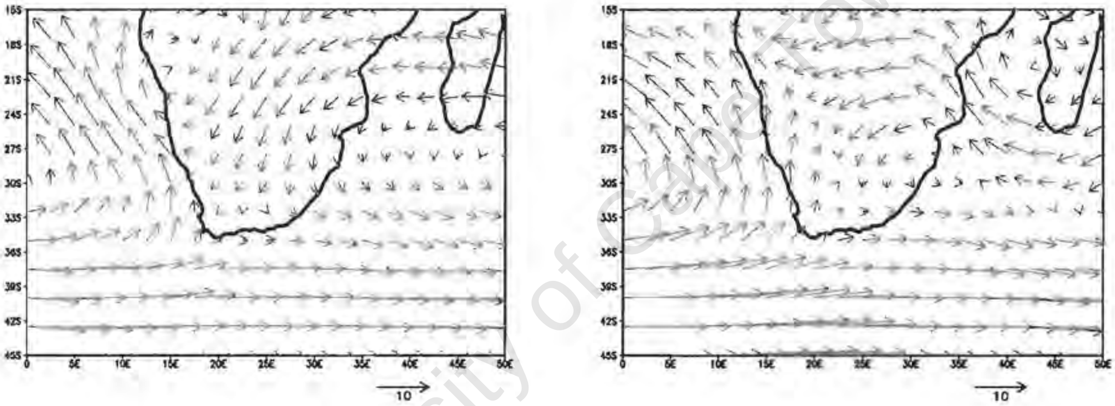

Figure 3.3: Present day simulated wind speed and direction from the MRI2 model (left) compared to NCEP (right). Note the model's dependence of moisture from the northern interior due to the decreased flow from the South Indian High Pressure system.

Temperatures over the interior are cooler in the model output than the observed NCEP data, showing a negative temperature bias (Fig. 3.4). This is linked to circulation changes showing a westward displacement and contraction of the warm regions. Low model resolution and land surface processes possibly contribute to these differences.

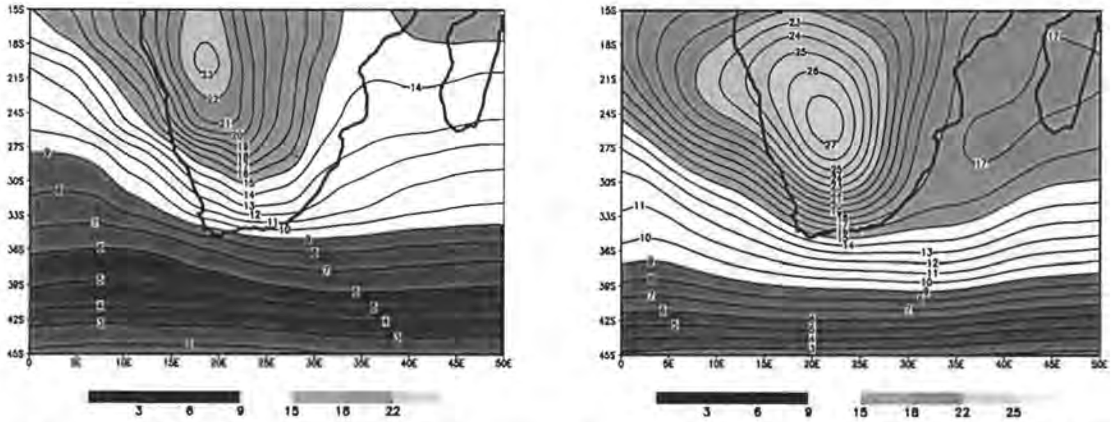

Figure 3.4: Present day simulated temperature at the 850hPa level from the CCC2.0 model (left) compared to NCEP (right). Note the negative temperature bias over the interior for the model simulation.

Precipitation data in models is problematic, however the spatial distribution is generally well positioned. All seven models identify the E-W precipitation gradient sufficiently, showing wetter conditions in the east, leading to drying as one moves to the west of the sub-continent. The models do however have a problem with orographic rainfall and underestimate it on the escarpment (Fig. 3.5). This is possibly due to the representation of topography in the models. The larger the resolution, the less chance there is of depicting the escarpment "step". All models identify more precipitation further north as one nears the tropics (Fig. 3.5).

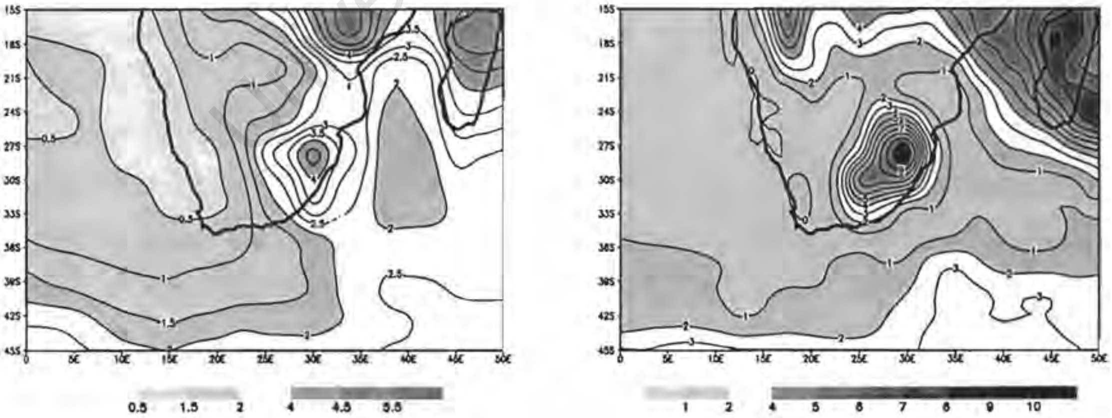

Figure 3.5: Present day simulated precipitation from the CCC2.0 model (left) compared to NCEP (right). The general pattern of change is correct, but note the under estimation of precipitation over the eastern escarpment. As in the other model simulations, the identification of tropical moisture further north is noted.

3.3.1.2. Westerly flow to the south of the continent for 0ka BP

The low pressure to the south of the sub-continent is reflected as being weaker in the model output as compared to NCEP data. This links in with the wind data showing decreasing westerly flow, possibly linked to the southward displacement of the mid-latitude low pressure belt, mentioned above. This could imply a displacement of the winter storms in a more southerly direction.

Precipitation patterns show that the rainfall is centered over the mid-latitudes, but as this belt is displaced slightly south in the models, this results in a slight under estimation of precipitation in this area to the south of the continent (Fig. 3.5). The models generally have problems representing rainfall, possibly due to the low model resolution, but as in this instance, spatial distribution is well positioned.

The latitudinal temperature gradient is well reflected in this area of westerly flow, but generally the models show slightly cooler temperatures for this region (Fig. 3.6). This outcome can partially be explained by the low resolution of the models and the surface processes in the area.

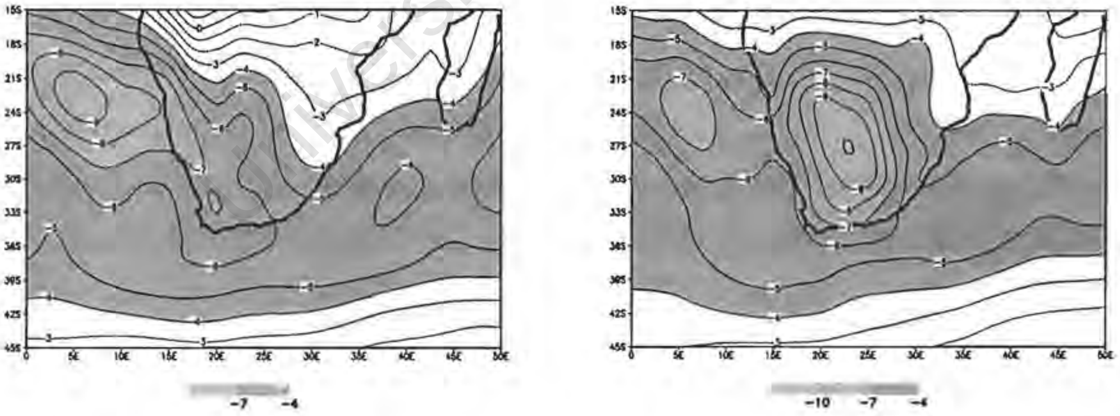

Figure 3.6: Temperature anomaly maps at 850hPa level from the UGAMP (left) and UKMO (right) models after being compared to NCEP. These show an example of the extent to which the models depict cooler temperatures overall for present day simulations.

3.3.1.3. The South Atlantic and South Indian high pressure systems for 0ka BP

Overall sea level pressure seems to be greater in the models than reflected from NCEP. This holds for five models out of seven, with CCM1 and GEN2 being the only two models which have weaker pressure.

The winds reflect a decreased pressure gradient due to the slight westward displacement of the general circulation. The displaced South Indian anti-cyclonic high pressure flow then leads to a decreased flow on the east coast. This is reflected by a decrease in wind strength to the interior of the sub-continent from the South Indian High Pressure system (Fig. 3.3). The decreased anti-cyclonic flow would imply a decrease in available moisture to the interior from the East and a decrease in upwelling along the west coast from the South Atlantic High Pressure system.

Temperature changes reflects a contraction and westward displacement of the warmest regions over the land, likely due to differences or an inadequate representation of the thermal processes and albedo's as mentioned above (Fig. 3.4). Precipitation patterns link to this by showing a westward displacement of precipitation fields inferred from the westerly displaced circulation patterns, mentioned previously. The model with the least agreement for temperature and precipitation is CCM1, which has a much lower resolution than the rest of the models (Table 3.1).

All the variables support a decreased strength in the southerly flow over the west coast, but this phenomenon can be explained by the general low resolution of the models compared to NCEP data, which has a higher variance and its source resolution is greater[5].

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[5] http://wesley.wwb.noaa.gov/reanalysis.html

3.3.2. Model anomaly results for 21ka and 6ka BP for the southern African region.

The anomaly maps for sea level pressure, vector winds, temperature and precipitation for 6ka and 21ka BP are considered in this section with a brief tabular summary of the described results in Appendix E. In brief, model variability is variable specific. For example, temperature at 21ka is the only variable that shows 100% agreement throughout the models, and they simulate a cooling period. This links in well with documented data worldwide, as the Last Glacial Maximum was known to occur at this time (Wright *et al.*, 1993; Gasse *et al.*, 1997; Wyputta and McAvaney, 2000). Thus the following analysis is based on the agreement of the majority of the models in the study.

3.3.2.1. Continental thermal trough for 21ka and 6ka BP

Sea level pressure is an important climate variable which has fluctuated along with climate changes in the past. For the last glacial maximum (21ka BP), the climate models form two distinct groups of change: those showing a slight weakening of pressure and those showing a distinct strengthening of pressure overall. As mentioned before, the patterns of change displayed by the models is more important than the overall degree of change when examining palaeo changes from different models. Thus the presence of the continental thermal trough is noted for 21ka BP as being displaced slightly to the west (Fig. 3.7).

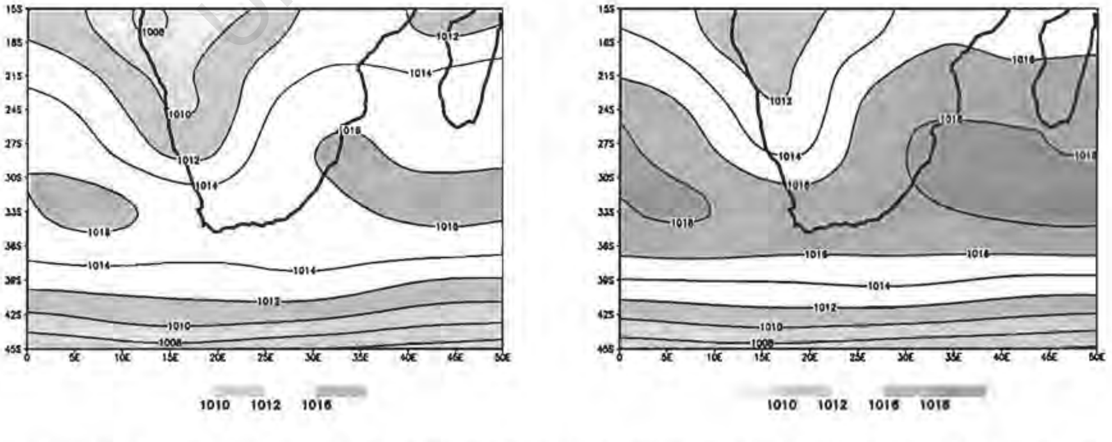

Figure 3.7: Sea level pressure simulations for 21ka (left) and 0ka (right) BP from the GEN2 model showing a slight westward displacement of the continental trough for 21ka BP compared to the present day simulation.

Temperatures for 21ka BP show a general cooling. This is in agreement with global declines in temperature for the Last Glacial Maximum (Duplessy, 1999; Jackson, *et al.*, 2000). All the models reflect overall cooling for 21ka BP, which is as expected as the entire globe was experiencing ice age conditions (see Chapter 1), known as the Last Glacial Maximum. Generally the interior experienced the greatest cooling compared to present, with some models predicting as much as a 6°C decrease. The thermal trough evident over the sub-continent was still present, but much cooler than those temperatures identified for the 0ka BP model simulations.

The only marked differences in temperature for 21ka BP are from UGAMP and UKMO, which not only indicate that there was very little change in temperature over the southern Cape coast, but they also clearly indicate an area of warming on the west coast (Fig. 3.8). This is possibly linked to the model land-sea mask reflecting temperatures that are not realistic for the model. The inaccuracy of the model at the surface due to land-sea mask interference, makes temperature at the 850hPa level a more reliable variable to analyse (this is discussed later in section 3.3.3 along with Table 3.4).

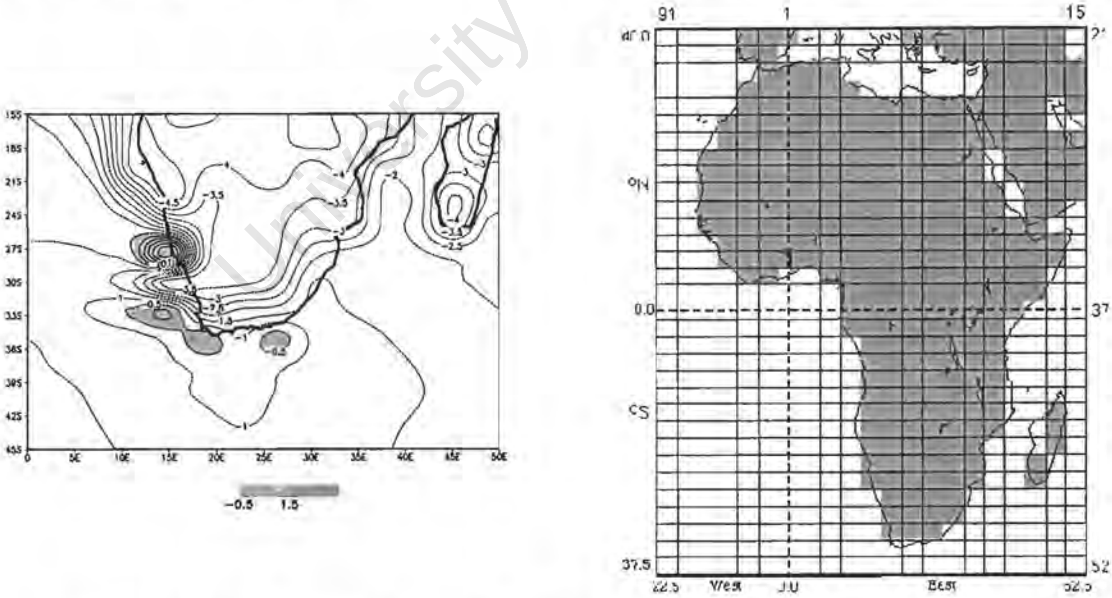

Figure 3.8: 21ka BP anomaly map of 2m surface temperatures for the UKMO model (left) shows two areas of warming: along the west coast near Luderitz and along the southern Cape coast. The map on the right shows the land-sea mask used for the model simulation.

The models show a 100% agreement for precipitation at 21ka BP, with increases and decreases in precipitation varying over the sub-continent. The increases in precipitation are mostly concentrated over the eastern half of the interior. There is a general agreement of a slight decrease to no change in precipitation over the south coast, with all the models reflecting a decrease in precipitation over the winter rainfall region.

For 6ka BP the continental low pressure trough is weaker than the present day simulation. This feature is more marked in CCC2.0; UGAMP and UKMO. The weaker continental thermal trough is displaced further north in GEN2, due to the extended high pressure from the South Indian anti-cyclone.

The temperature pattern for 6ka BP shows general agreement for cooling to little change over the oceans and coastal regions. The interior shows general conformity in the models as they all reflect the continental thermal trough. The temperature anomalies show a different picture. Over the sub-continent, CCC2.0 and GEN2 reflect varying degrees of cooling. GFDL, UGAMP, and UKMO also show this cooling, but with a slight interior warming taking place in the northern interior, and for UKMO along the south coast. MRI2 reflects an intense warming for this period, raising temperatures up as much as 3.9°C in places.

Precipitation for 6ka BP has a general consensus of increases in the east, compared to today, and a decrease or little change in the southwestern regions. Regions of highest precipitation in the models seem to be centred over Natal and the eastern coastal regions, where generally slightly wetter conditions are seen. Only two out of six models suggest drying to marginal change for this area (GFDL and UGAMP) when compared to present. There seems to be a general consensus in all the models (except MRI2) that there is a slight decrease to very little change in precipitation over the southwestern Cape for 6ka BP.

3.3.2.2. Westerly flow to the south of the continent for 21ka and 6ka BP

Overall there is almost total agreement, barring CCC2.0, concerning a decreased westerly flow to the south of the sub-continent for 21ka BP. This would mean a decrease in the frequency of winter storms to the sub-continent, and implies a decrease in moisture to the winter rainfall region.

Closely related to sea level pressure and circulation changes are the wind fields, which show some significant changes for 21ka BP. The winds for 21ka BP show a weaker westerly flow which implies a decrease in winter storms, coupled with a decrease in upwelling along the western littoral, could well cause increased moisture along the west coast.

For 6ka BP, the mid-latitude low pressure belt is slightly more intense. Thus the westerly flow to the south of the continent is reflected as being slightly more intense for 6ka BP than today (Fig. 3.9). This would cause enhanced moisture transport over the winter rainfall region at the south of the sub-continent than today.

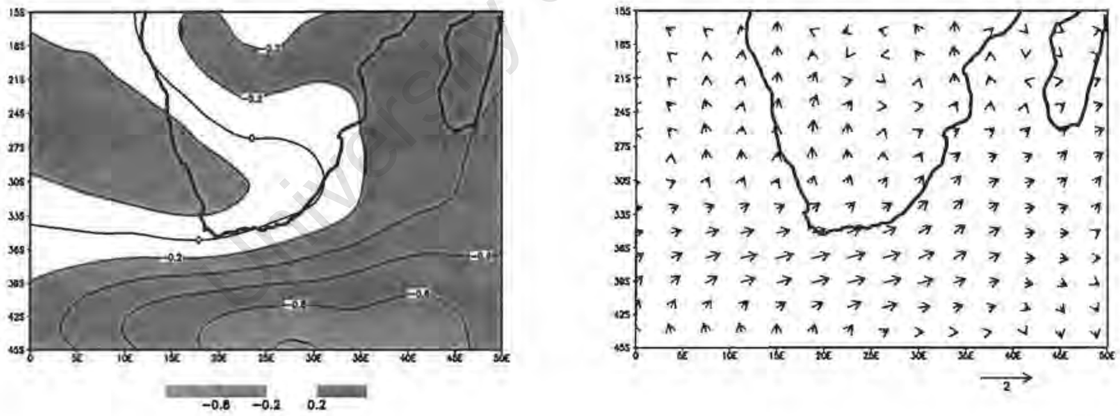

Figure 3.9: Anomaly map of sea level pressure (left) and winds (right) from the GFDL model, showing an increased intensity of westerly flow to the south of the sub-continent.

The wind patterns for 6ka BP show a distinct commonality between the majority of the models. All the models, barring MRI2, reflect an increase in the westerly winds to the south of the sub-continent (Fig. 3.9), linking in with the increased westerly flow mentioned above. This could possibly increase the frequency and/or intensity of winter storms to the sub-continent.

3.3.2.3. The South Atlantic and South Indian high pressure systems for 21ka and 6ka BP

The two sub-tropical high pressures are evident in all the models for 21ka and 6ka BP. At 21ka BP the on-shore easterly flow to the interior was weaker, thus supporting the notion that there was decreased available moisture to the interior. The South Atlantic High Pressure system seems to show increased flow thus affecting the west coast.

Closely linked to pressure patterns are those of winds. The winds originating from the anti-cyclonic flow of the sub-tropical cyclones are generally increased in strength, or show little change for 21ka BP. There is a notable decrease in the strength of on-shore easterly winds to the interior, linking in with the circulation patterns mentioned above. This is reflected in six out of seven of the models, making CCC2.0 the only model supporting the idea of increasing flow into the interior. A decrease in on-shore easterly flow supports the notion of decreased available moisture to the interior. Linked to the increase in wind strength caused by the South Atlantic High Pressure system mentioned earlier, a resulting increase in upwelling along the west coast would be evident for 21ka BP.

A large majority of the models show a commonality between them with a general strengthening of the sub-tropical high pressure systems for 6ka BP. Half the models (CCC2.0; UGAMP and UKMO) show the presence of an extension of the high pressure system to the south of the sub-continent. The extended high pressure would cause a decrease in the number of storms affecting the southern parts of the sub-continent, as well as decreasing the chances of precipitation in the interior. The extended high pressure could also contribute to the southward migration of the mid-latitude low pressure belt as mentioned above.

Generally little change is seen in the winds for the on-shore easterly flow, thus making the moisture flux to the interior much the same as conditions of today. However the models show conflicting results with respect to the South Atlantic High Pressure system (a strengthening or weakening), thus showing stronger (Fig. 3.10) or weaker (Fig. 3.11) winds respectively along the west coast.

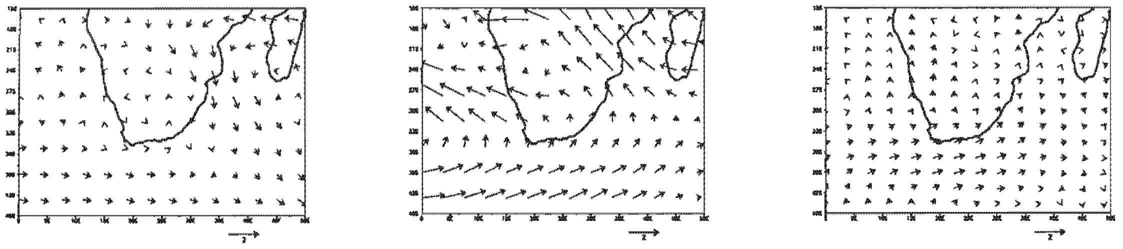

Figure 3.10: Anomaly maps of simulated wind speed (m.s^{-1}) and direction from CCC2.0 (left), GEN2 (centre), and GFDL (right) models for 6ka BP. Showing the increasing strength of the South Atlantic High Pressure System.

The South Atlantic High Pressure system for 6ka BP contributes to a two-way grouping of the models: CCC2.0, GEN2, and GFDL (Fig. 3.10) show the high pressure system to be increasing in strength, resulting in increased anti-cyclonic flow and thus increasing wind strength and the intensity of upwelling events along the west coast. The second group MRI2, UGAMP, and UKMO (Fig. 3.11) reflect a weakening of the South Atlantic High Pressure system, thus supporting the notion of weaker winds having a negative effect on upwelling along the coast.

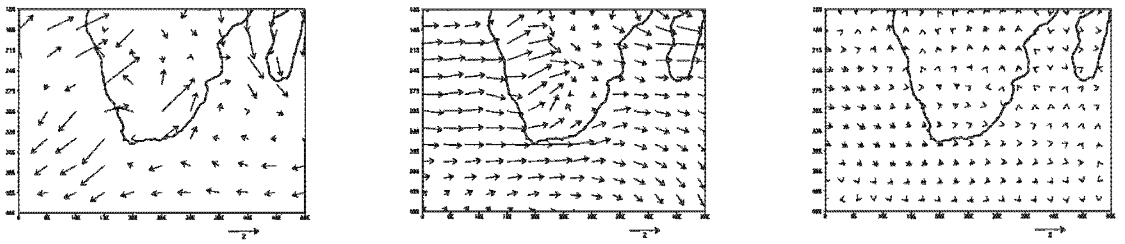

Figure 3.11: Anomaly maps of simulated wind speed (m.s^{-1}) and direction from MRI2 (left), UKMO (centre) and UGAMP (right) models for 6ka BP. Showing the decreasing strength of the South Atlantic High Pressure System.

The temperature pattern for 6ka BP shows general agreement for cooling to little change over the oceans and coastal regions, however the models differ as far as the interior is concerned. Due to the model output being so variable at this scale, it is important to examine the sub-regional scale within the southern African domain. This is dealt with in the next section, Section 3.3.3.

3.3.3. Three specific sub-regions within the southern African domain

It is important to examine the sub-regional scale within the southern African domain, attributable to the model output being so variable. Three sub-regions were subjectively chosen, having identical climates within the sub-region, but with varying climates between the three sub-regions. They were located in southern Africa in: 1) an area over the Gauteng Province (25°-28.5°S 25°-30°E) experiencing a mild climate with summer rainfall conditions; 2) the southern Cape coastal belt (32.5°-35°S 18°-27°E) experiencing all-year rainfall; and 3) the interior of Namibia (20°-27°S 15°-20°E) being a semi-desert component with very little summer rainfall (Fig. 3.12).

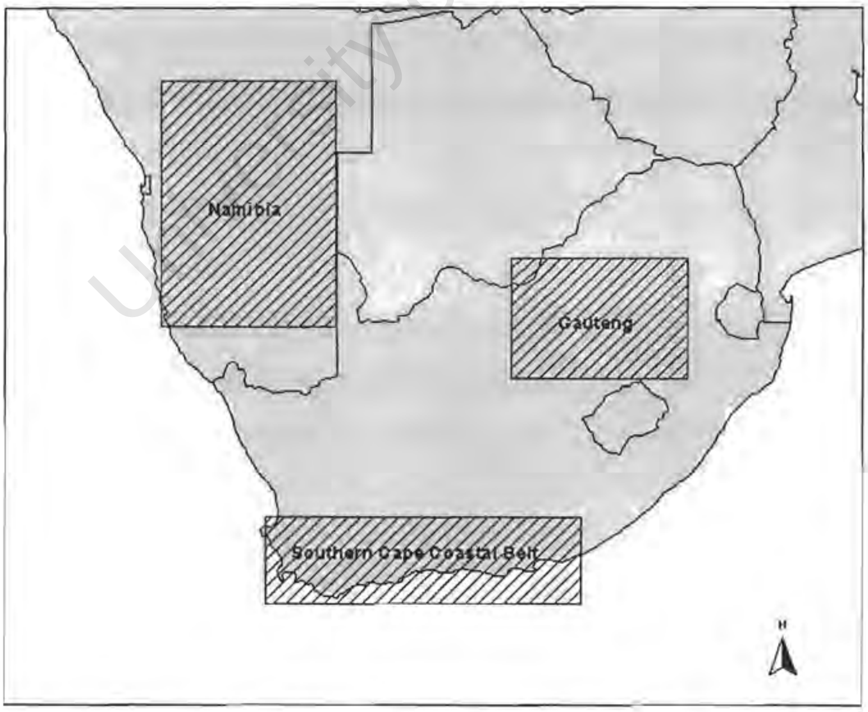

Figure 3.12: Positions of the sub-regions, Gauteng with a mild climate, the southern Cape coastal belt experiencing all year rainfall, and Namibia, a semi-desert climate.

Anomaly maps are appropriate for showing broad scale changes, however model scatter is not identified well from general anomaly maps. Thus the models were regridded to a 2.5° by 2.5° resolution to create a common grid and for comparative purposes with NCEP data. It is important to note that regridding doesn't increase accuracy by any means, and the data are regridded merely to aid in comparison. The means of the variables sea level pressure; u and v winds; temperature and precipitation over the three sub-regions were then determined from the regridded data and compared to one another. It was necessary to group by variable as the models displayed differing results per variable.

At this stage it is necessary to re-examine the differing model resolutions. The finer the resolution, the better the model output. Table 3.3 indicates the models in order of finest resolution at the top, to coarsest resolution on the bottom. Model resolution is particularly important as one can disregard important features when a model resolution is too big. For example as noted above, the larger the resolution, the less chance there is of depicting the escarpment "step". This has implications for precipitation, among other variables, whereby values can be grossly under estimated.

Table 3.3: Model resolution, from the finest at the top to the coarsest.

Model	Resolution
GFDL	2.25° x 3.75°
UKMO	2.25° x 3.75°
UGAMP	2.8° x 2.8°
GEN2	3.75° x 3.75°
CCC2.0	3.75° x 3.75°
MRI2	4° x 5°
CCM1	4.5° x 7.5°

Keeping model resolution in mind, the model mean of the whole region was then determined for each variable and the averages for the three sub-regions were then subtracted from the model mean. This process removes the systematic bias from the models and enables a more appropriate inter-model comparison. With each model represented by the set of regional anomalies, the model results are clustered first using Single Linkage clustering to identify outliers, and then with Ward's Method to identify cohesive groups. Single linkage is particularly good at detecting outliers, whereas Ward's Method is variance related, thus making it insensitive to outliers. Ward's method is the most frequently used hierarchical clustering technique for climatic classification (Kalkstein, *et al.*, 1987).

Comparing the models' response per variable with each separate timeslice created the clusters. The clusters were grouped with data from the three sub-regions of interest. The Single Linkage and Ward's Method clustering produced the following results (Table 3.4):

Table 3.4: The results from the cluster analysis, where Single linkage clustering identifies outliers and Ward's Method identifies cohesive groups.

Variable	Time (BP)	Model Outliers	Cohesive Model Groups	
			1	2
Sea level pressure	0ka	MRI2;CCM1	GEN2;GFDL;UKMO	MRI2;UGAMP;CCC2.0
	21ka	MRI2	GEN2;GFDL;UKMO; CCM1	MRI2;UGAMP;CCC2.0
	6ka	MRI2	GEN2;GFDL;UKMO	MRI2;UGAMP;CCC2.0
U Winds	0ka	UGAMP;CCC2.0;CCM1	GFDL;UKMO	CCM1;GEN2;MRI2
	21ka	CCC2.0	GEN2;GFDL;UKMO	MRI2;UGAMP;CCC2.0
	6ka	UGAMP	GEN2;GFDL;UKMO	MRI2;CCC2.0
V Winds	0ka	UGAMP;CCM1	GEN2;GFDL;UKMO	MRI2;CCC2.0
	21ka	CCM1;UGAMP	GEN2;GFDL;CCC2.0; UKMO	CCM1;UGAMP
	6ka	UGAMP	GEN2;GFDL;UKMO	CCC2.0;MRI2
Temperature (* Table 3.4)	0ka	CCM1;MRI2	GEN2;UKMO;GFDL; CCC2.0	MRI2;UGAMP
	21ka	UGAMP;CCM1	CCC2.0;MRI2;GFDL; UKMO	CCM1;GEN2
	6ka	UGAMP	UGAMP;UKMO;CCC2.0	MRI2;GEN2;GFDL
Precipitation	0ka	UGAMP;UKMO	GEN2;GFDL;UKMO; CCM1;CCC2.0	MRI2;UGAMP
	21ka	UKMO	GEN2;GFDL;CCM1; CCC2.0	MRI2;UGAMP
	6ka	MRI2;UGAMP	GEN2;GFDL;UKMO; CCC2.0	MRI2;UGAMP

Ward's Method defined two main groups of models. GEN2, GFDL and UKMO were more commonly grouped together throughout the clustering, with MRI2 and UGAMP being the other models grouping together. Figure 3.13 shows an example of this clustering, with the other cluster trees listed in Appendix F.

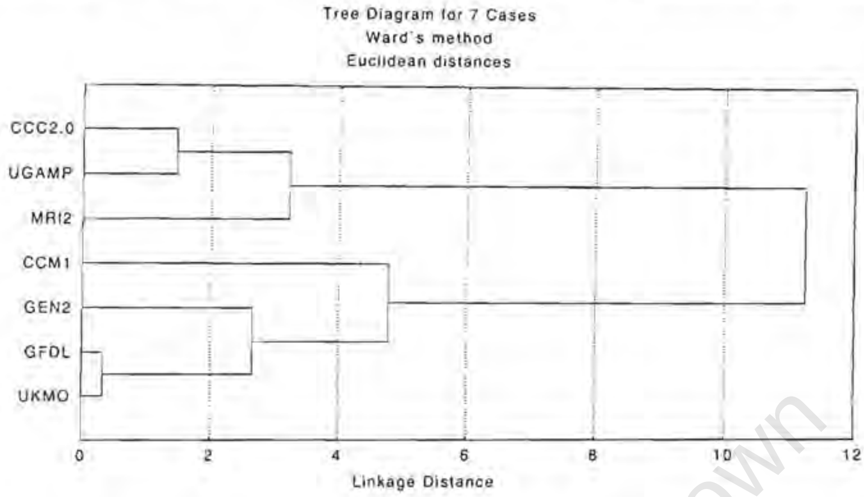

Figure 3.13: An example of Ward's Method clustering for sea level pressure at 0ka BP showing the models most commonly grouped together: UGAMP/MRI2 in this case with CCC2.0, and GEN2/GFDL/UKMO.

Single linkage clustering showed the outliers to vary per time period and variable (Table 3.4). GEN2 and GFDL were the only models not shown as outliers for any of the timeslices. UGAMP and CCM1 were the most common outliers to be found (Table 3.4). Figure 3.14 shows an example of Single Linkage clustering with the remainder of the Single linkage clusters listed in Appendix G.

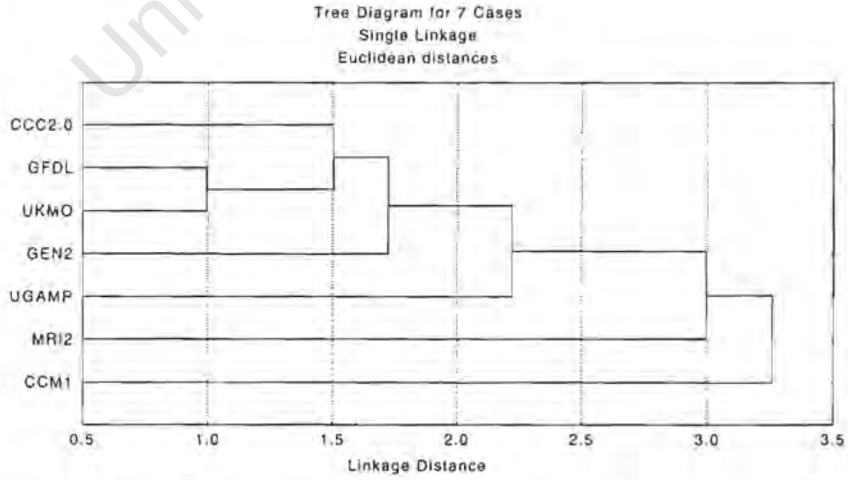

Figure 3.14: An example of Single Linkage clustering for temperature at 0ka BP showing MRI2 and CCM1 to be the outliers when the tree is cut at 2.5 linkage distance.

Both Ward's Method and Single linkage showed differing results between their clustering when clustered by the individual variables of 2m surface temperature and temperature at the 850hPa level (Table 3.5). It was subjectively decided that temperature at the 850hPa level would be used for this analysis, as it is more robust at showing synoptic scale climate changes than surface temperature. The fact that the two temperature clusters are different is probably due to how the models reflect surface processes, thus influencing the outcome of the 2m surface temperature. From this point on temperature will always refer to temperature at the 850hPa level for these reasons, unless otherwise stated.

Table 3.5: The results from the cluster analysis for temperature differ between 2m surface temperature and 850hPa temperature. The differences are displayed here.

Time (BP)	Model Outliers	Cohesive Model Groups		Model Outliers	Cohesive Model Groups	
		1	2		1	2
	2m Surface Temperature			*Temperature at 850hPa*		
0ka	CCC2.0	GEN2;UKMO; CCM1;CCC2.0	MRI2;UGAMP; GFDL	CCM1; MRI2	GEN2;UKMO; GFDL;CCC2.0	MRI2;UGAMP
21ka	UGAMP	GEN2;UKMO; CCM1;CCC2.0	MRI2;UGAMP; GFDL	UGAMP; CCM1	CCC2.0;MRI2; GFDL; UKMO	CCM1;GEN2
6ka	GFDL	GEN2;UKMO; CCC2.0	MRI2;UGAMP; GFDL	UGAMP	UGAMP;UKMO CCC2.0	MRI2;GEN2; GFDL

The models from the two cohesive groups were then averaged together and it was found that models reflect different groups of similar results for different variables. Typically the models fall into two main groups: most noted together were GEN2, GFDL and UKMO, with the second group being MRI2 and UGAMP. The models constantly identified as outliers for almost every variable were UGAMP and CCM1 (Table 3.4). The variables are then discussed for the cohesive groups in the next section and it is these data that are compared to the proxy data findings for the study region (Chapter 4).

3.3.4. Overall, which models are consistent?

The GEN2/GFDL/UKMO and MRI2/UGAMP main groups identified were then reanalysed using the group averages of the variables for 21ka and 6ka BP. The following sub-sections are a discussion of the results found from averaging the grouped models. Firstly the 0ka BP averages are compared to NCEP and then the 21ka and 6ka BP grouped averages are compared to their present day simulations (0ka BP). This grouped model output is the data that will ultimately be used to compare to the proxy data findings (Chapter 2) in Chapter 4. The following is what was found:

3.3.4.1. Grouped model output for 0ka BP compared to NCEP

Overall the sea level pressure for the GEN2/GFDL/UKMO group showed stronger high pressures and a weaker continental low pressure when compared to NCEP, with an extended high pressure system to the south of the sub-continent (Fig. 3.15). The westerly wave is weaker, possibly showing a southerly displacement due to the extended high pressure south of the sub-continent. The continental low pressure trough is also weaker and distinctly displaced to the west (Fig. 3.15). Although recognising the lower resolution of the GCM data, this can also partially explain the weaker low pressure trough over the interior.

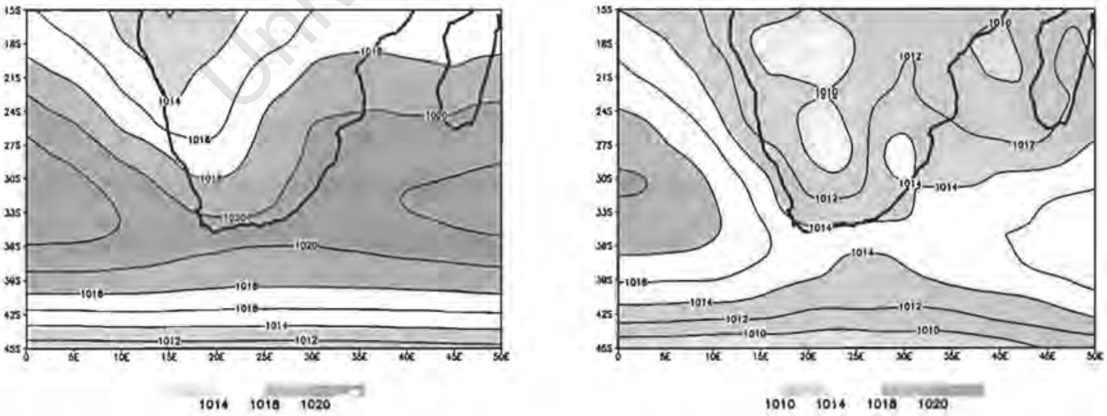

Figure 3.15: The GEN2;GFDL;UKMO grouped model simulation (left) of sea level pressure for 0ka, compared to NCEP (right). The features to note are the extended high pressure to the south and the westerly displaced continental low pressure trough over the sub-continent.

The winds from the GEN2/GFDL/UKMO group of models shows decreased onshore easterly flow into the interior when compared to NCEP, as well as decreased anti-cyclonic flow from the South Atlantic High Pressure system. This would negatively affect the moisture availability to the interior and upwelling along the west coast respectively. A decrease in upwelling can result in less aridity along the western coastal regions. These findings are small when compared to the precipitation anomaly for the model group compared to NCEP (Figure 3.16). What needs to be noted is that the models generally underestimate precipitation over the escarpment due to their characteristically low resolution, and so this is a feature of models in general and not necessarily this model group in particular (see Fig. 3.16 for an example).

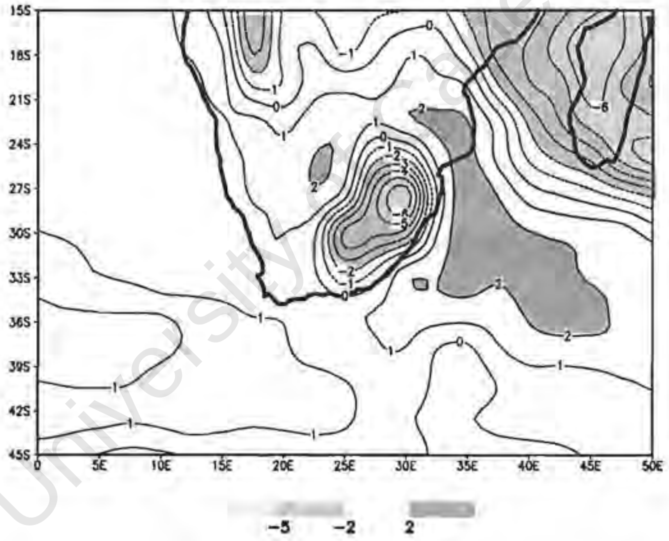

Figure 3.16: The GEN2;GFDL;UKMO grouped model anomaly of precipitation for 0ka compared to NCEP. The features to note are the accuracy of the simulation over the west and south coasts, and the oceans.

GEN2/GFDL/UKMO simulate cooler temperatures for 0ka BP than NCEP. However as mentioned before, the magnitude of change is less important than the pattern of change, and as can be seen in Fig. 3.17, the general pattern of change is correctly simulated.

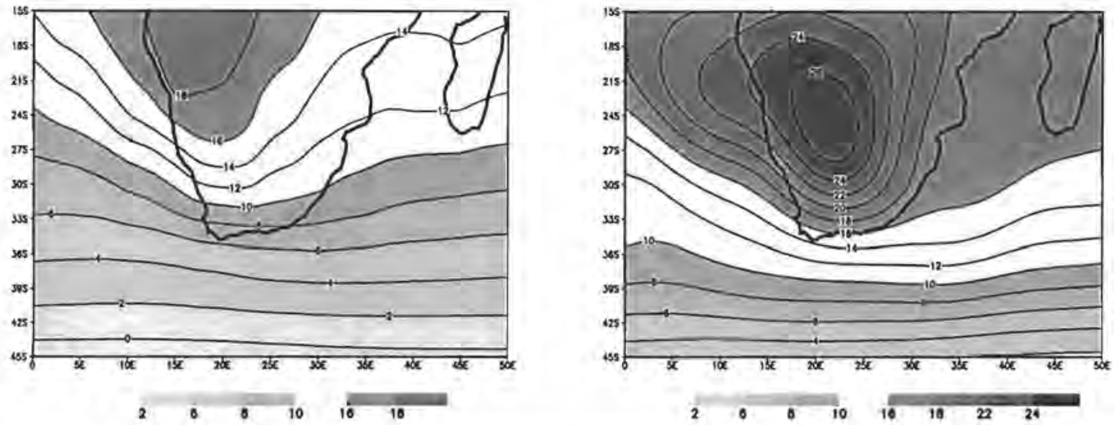

Figure 3.17: The GEN2;GFDL;UKMO grouped model simulation (left) of temperature for 0ka compared to NCEP (right). The features to note are the accuracy of the simulation in depicting the thermal trough over the interior as well as the latitudinal gradient of temperature change.

MRI2/UGAMP model simulation for 0ka BP compared to NCEP data shows a significant deepening of the continental low pressure trough. This is reflected by the winds where greater on-shore easterly flow is evident in the model (Fig. 3.18). Both sub-tropical high pressures also show significant strengthening, with evidence of a probable extended high pressure to the south of the sub-continent (Fig. 3.19). The mid latitude low pressure belt seems to be displaced to the south, due to the extended high pressure. The MRI2/UGAMP model simulation shows decreased westerly flow to the south of the sub-continent, again linked to the extended high (Fig. 3.18 & Fig. 3.19).

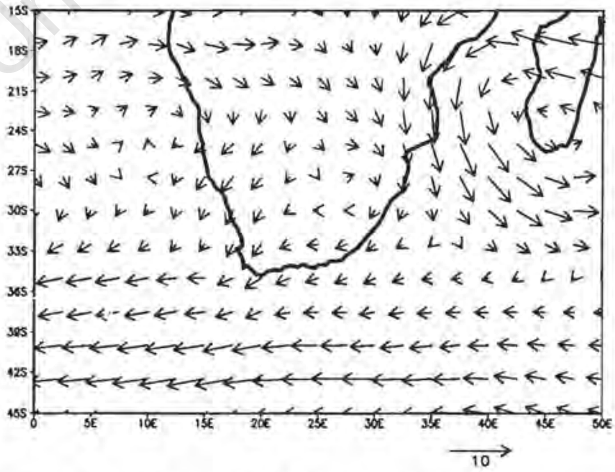

Figure 3.18: The MRI2/UGAMP grouped model anomaly of wind speed and direction for 0ka compared to NCEP. Note the increased onshore easterly flow and the decreased westerly flow south of the sub-continent.

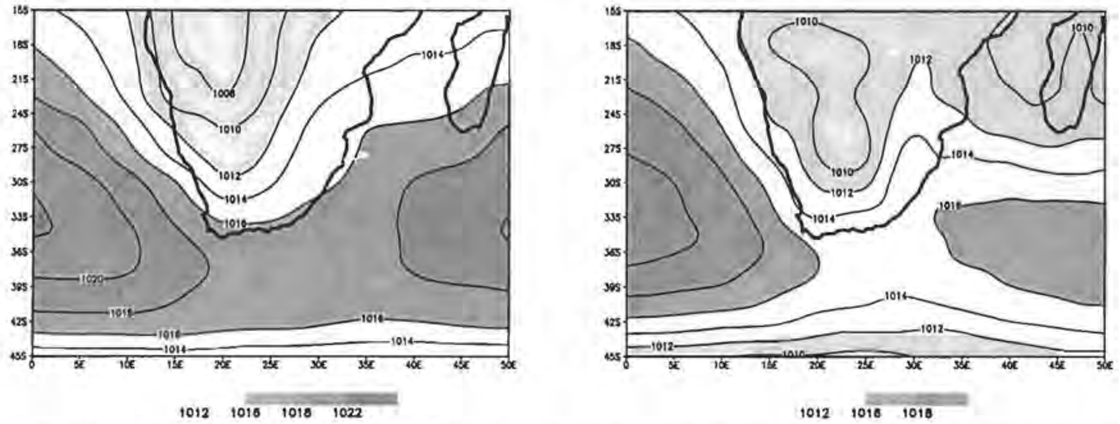

Figure 3.19: The MRI2/UGAMP grouped model simulation (left) of sea level pressure for 0ka compared to NCEP (right). The features to note are the strengthened continental low pressure and sub-tropical high pressures, as well as the extended high.

MRI2/UGAMP simulates a clear latitudinal gradient of temperature, clearly depicted in NCEP data, but with much reduced interior temperatures (Fig. 3.20). This causes the anomaly to show overall cooler interior and west coast temperatures (Fig. 3.20). Precipitation for 0ka BP is well simulated in MRI2/UGAMP when compared to NCEP. There is a clear E-W gradient, with only a slight under estimation over the escarpment and over estimation over the western parts of the sub-continent (Fig. 3.21).

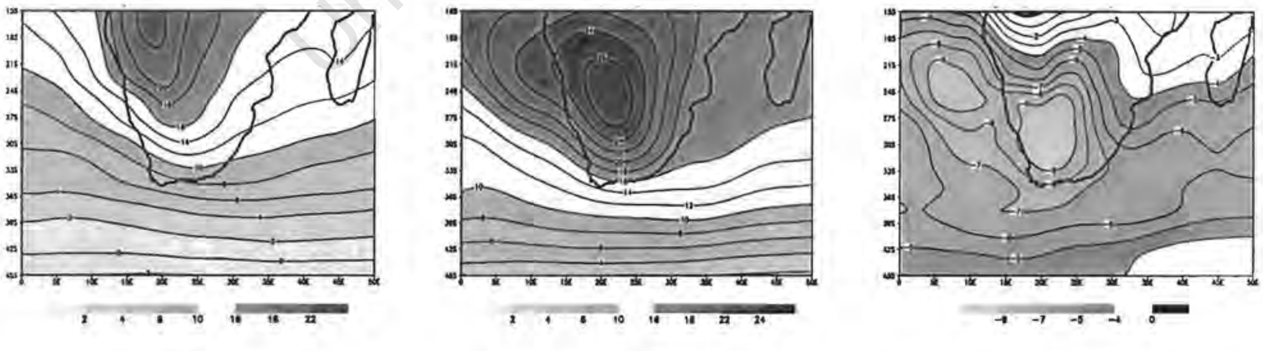

Figure 3.20: The MRI2/UGAMP grouped model simulation of temperature for 0ka (left) compared to NCEP (center), with the anomaly on the far right. The features to note are the accuracy of the simulation in depicting the latitudinal gradient of temperature change, but the gross under estimation of temperature over the sub-continent.

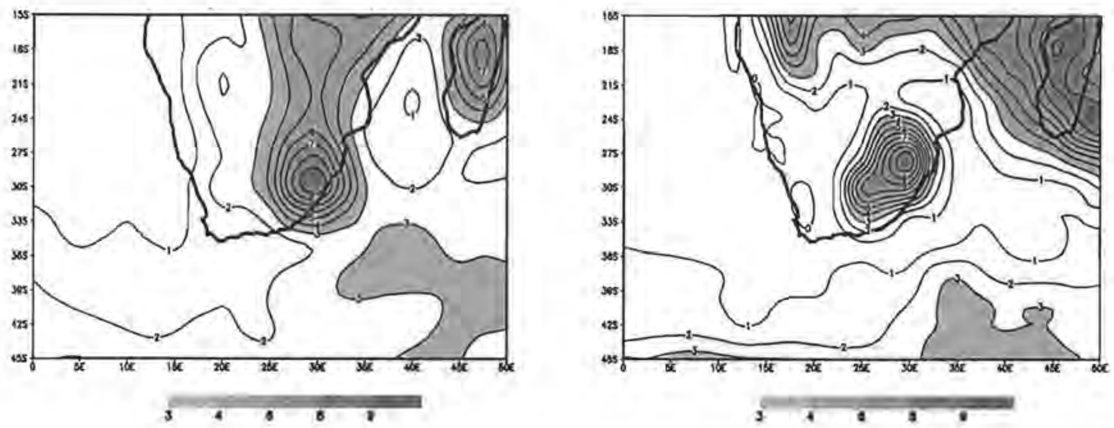

Figure 3.21: The MRI2/UGAMP grouped model simulation of precipitation for 0ka compared to NCEP. The features to note are the accuracy of the simulation in depicting the E-W gradient of change, with a slight over estimation of precipitation over the western interior.

3.3.4.2. Grouped model output for 21ka BP

GEN2/GFDL/UKMO showed the sea level pressure to be greater overall, but the patterns of change showed a possible displacement of the mid-latitude low pressure to the south, as the pressure to the south of the country was much displaced. This displacement is reflected by the flow pattern of the winds (Figure 3.22), which clearly reflect a weakened latitudinal gradient of pressure change to the south of the country for 21ka BP.

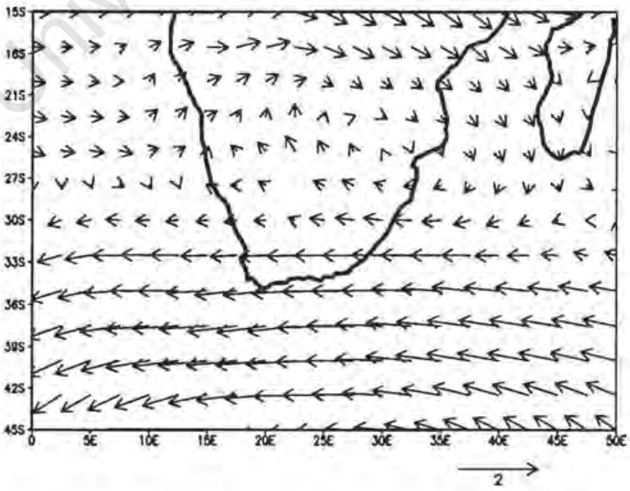

Figure 3.22: The GEN2/GFDL/UKMO grouped model anomaly of the winds for 21ka compared to 0ka BP. The weakening of the westerly flow resulting in the deepened latitudinal gradient to the south of the country is clearly displayed.

The temperature anomaly of GEN2/GFDL/UKMO shows conditions to be overall cooler for 21ka BP (Fig. 3.23). Greater cooling seemed to occur in the interior with milder conditions on the southwestern coast. Precipitation seems to link in with the areas of change of temperature. The precipitation anomaly shows wetter conditions with the cooling in the interior, and dry conditions in the southwestern regions, where little change of temperatures were noted (Fig. 3.24).

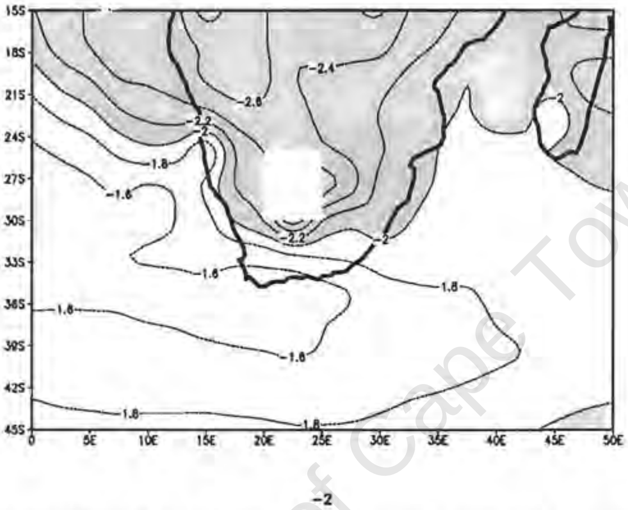

Figure 3.23: The GEN2/GFDL/UKMO grouped model anomaly of temperature for 21ka compared to 0ka BP. Temperatures seem to be much cooler in the interior (up to 2.8°C), whereas the southwestern coastal regions experience reduced changes in comparison, of only 1.6°C cooler.

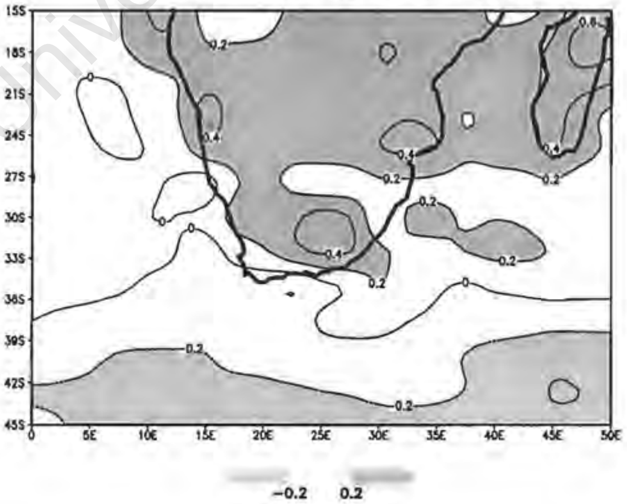

Figure 3.24: The GEN2/GFDL/UKMO grouped model anomaly of precipitation for 21ka compared to 0ka BP. The interior experiences wetter conditions for 21ka BP, whereas the southwestern coastal region has drying conditions to little change at all.

MRI2/UGAMP also reflected the higher overall pressure for 21ka BP, but showed conditions of a developing extension of the high pressure and a slight southerly displacement of the mid-latitude low pressure belt (Fig. 3.25). This southerly displacement is possibly caused by the extended high pressure system mentioned before. The continental trough displays much less of a westerly displacement than seen in the GEN2/GFDL/UKMO group.

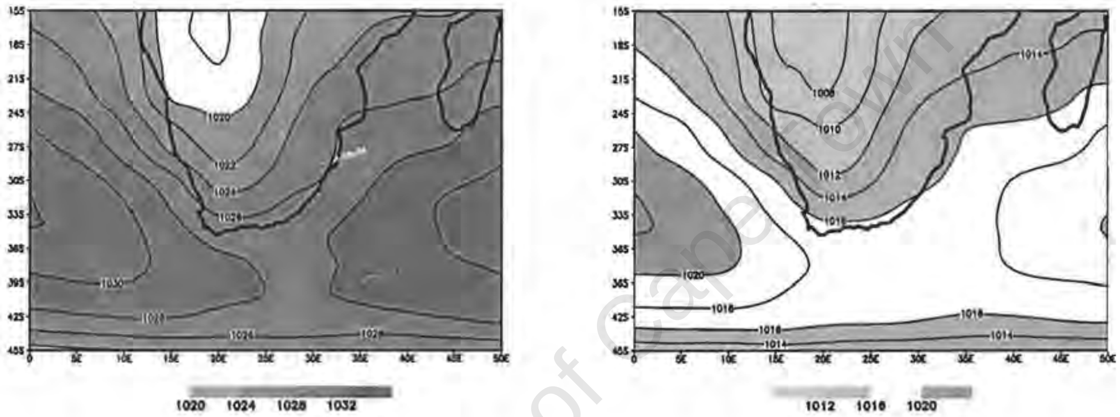

Figure 3.25: The MRI2/UGAMP grouped model simulation of sea level pressure for 21ka (left) compared to 0ka BP (right). Apart from the overall increase in pressure for 21ka BP, there is clear evidence of a developing extended high pressure possibly forcing the southward migration of the mid-latitude low pressure belt.

The winds for MRI2/UGAMP reflect the circulation changes with the anomaly map showing much reduced westerly flow south of the sub-continent (Fig. 3.26). The decreased anti-cyclonic flow from the South Atlantic High Pressure system is also evident, supporting the notion of decreased upwelling for the last glacial maximum (21ka BP). At the same time there is much reduced onshore easterly flow to the interior, causing less available moisture for 21ka BP.

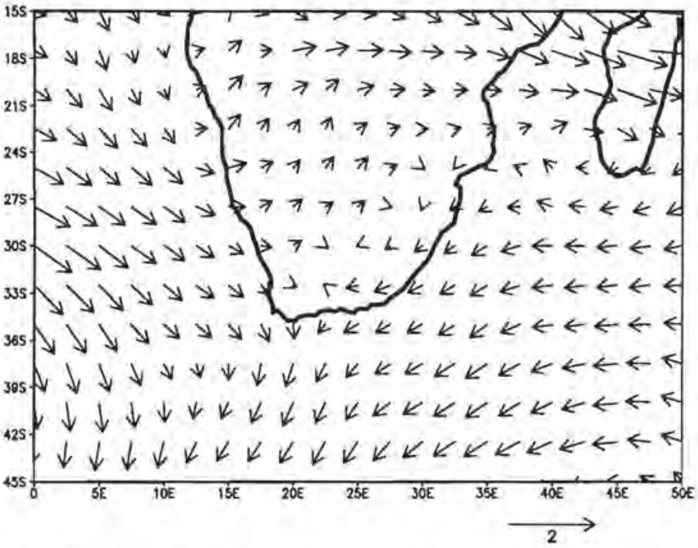

Figure 3.26: The MRI2/UGAMP grouped model anomaly of the wind speed and direction for 21ka compared to 0ka BP. The anomaly particularly outlines the decreased anti-cyclonic flow of the two sub-tropical high pressures.

MRI2/UGAMP show slightly cooler temperature for 21ka BP. The degree of cooling ranges from 1.4°-2.2°C with very little change in the temperature gradients from the 0ka simulation. The largest change in temperature occurs in the more northerly parts of the southern African region (Fig. 3.27).

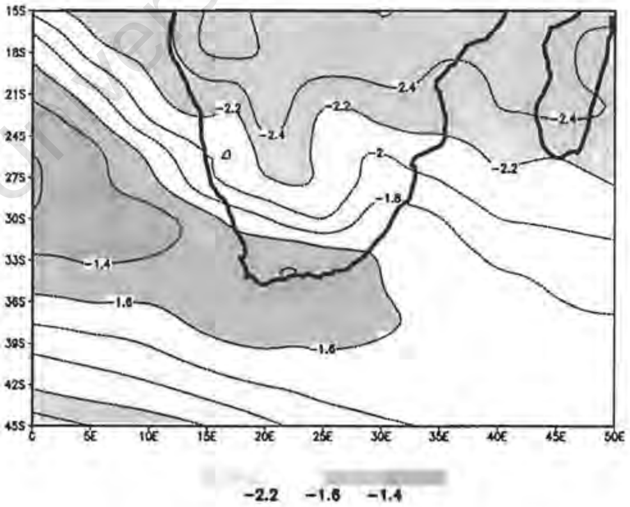

Figure 3.27: The MRI2/UGAMP grouped model anomaly map of temperature for 21ka compared to 0ka BP. The simulation shows particularly cooler temperatures in the more northerly regions, with less marked changes over the southern parts.

Precipitation from the MRI2/UGAMP simulation for 21ka shows a very patchy pattern indeed. Figure 3.28 shows that there was little change at all along the western coastal regions, with a slight decrease in precipitation along the southern coast. The eastern half of the sub-continent experiences mainly drier conditions over the high lying regions. The places experiencing wetter conditions for 21ka BP seem to be the interior of the sub-continent and towards the tropics (Fig. 3.28).

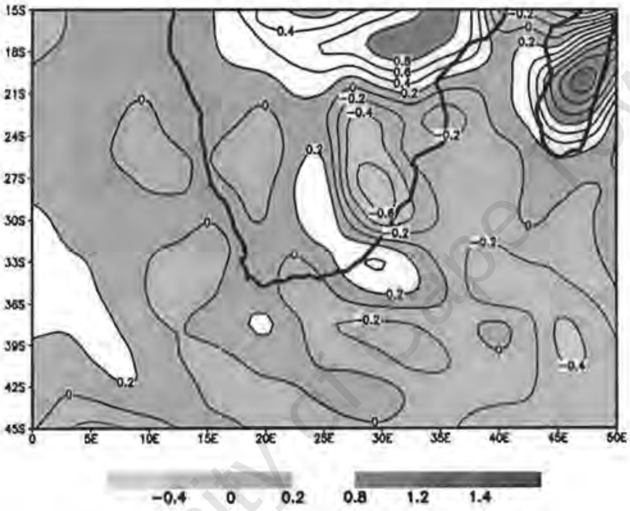

Figure 3.28: The MRI2/UGAMP grouped model anomaly of precipitation for 21ka compared to 0ka BP. The anomaly shows the patchiness of change in rainfall for the last glacial maximum.

3.3.4.3. Grouped model output for 6ka BP

Sea level pressure for 6ka BP as simulated from the GEN2/GFDL/UKMO model group retrodict increased southwesterly flow along an increased pressure gradient (Fig. 3.29). This increased flow would bring cool air to the sub-continent as the source of the flow is from the cool polar regions in the south. The anomaly map shows evidence for a strengthened South Atlantic High Pressure and a slightly weakened South Indian High Pressure for 6ka BP (Fig. 3.29).

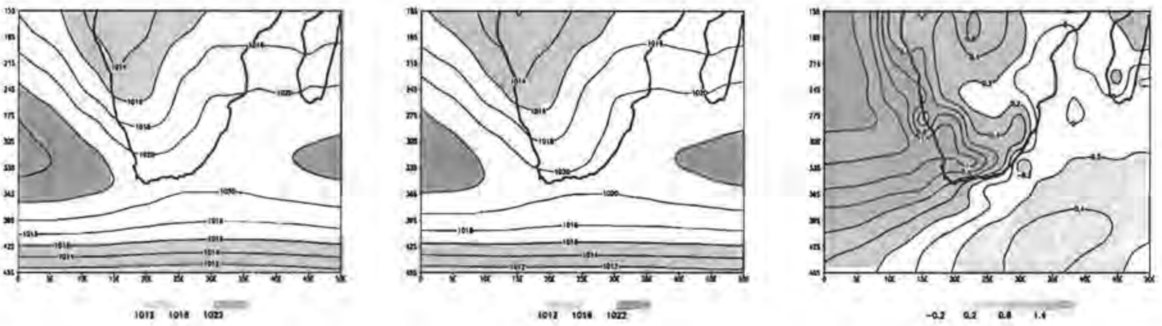

Figure 3.29: The GEN2/GFDL/UKMO grouped model 6ka (left), 0ka (centre) BP and anomaly map (right) of sea level pressure. The increased southwesterly flow along an increased gradient is noted from the anomaly.

The increased southwesterly flow is supported by the winds anomaly map of 6ka BP, whereby it clearly illustrates a positive flow and therefore a general strengthening of flow in this direction (Fig. 3.30).

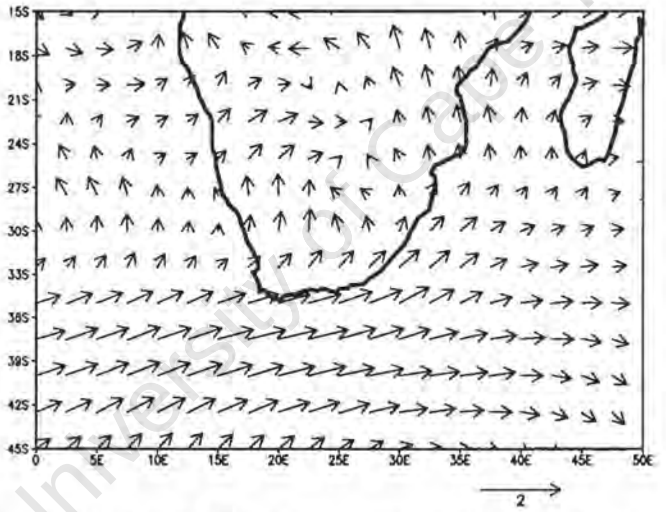

Figure 3.30: The GEN2/GFDL/UKMO grouped model anomaly of wind speed and direction for 6ka compared to 0ka BP. The anomaly shows the increased southwesterly flow from the polar regions.

Temperatures for 6ka BP show conditions to be warmer over the northern interior and cooler over the rest of the subcontinent (Fig. 3.31). The continental thermal trough is displaced slightly west in the simulation, causing warmer temperatures on the northwestern coast. The cooler conditions are particularly evident over the southern parts of the sub-continent. This is possibly linked to the increased southwesterly flow of cool air from the Polar Regions mentioned before.

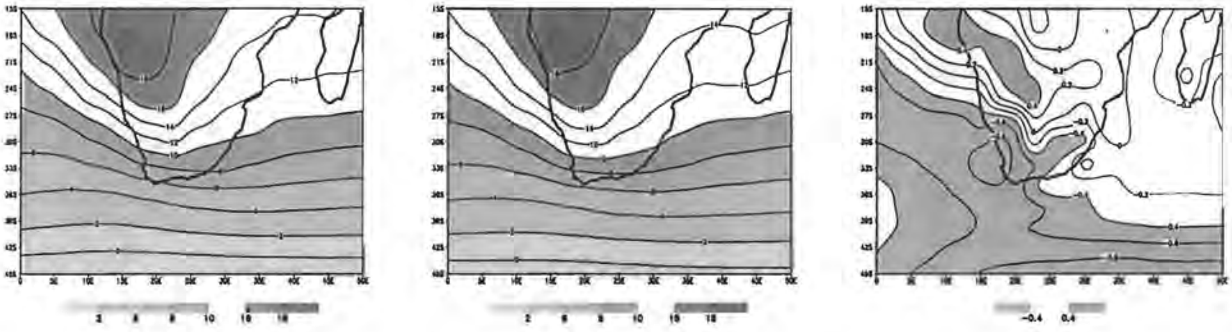

Figure 3.31: The GEN2/GFDL/UKMO grouped model 6ka, 0ka BP and anomaly maps of temperature. The westerly displacement of the continental trough and the cooling in the south are important features to note.

Precipitation shows conditions to be dry over the Atlantic Ocean and the majority of the interior from the west (Fig. 3.32). The southeastern parts of the Indian Ocean on the other hand seem to contain greater moisture for 6ka than present conditions. Noted is the increased precipitation over the eastern escarpment, which is possibly misrepresented due to the models inability to handle orographic rainfall. This is common of most models, as mentioned previously, and needs to be taken into account.

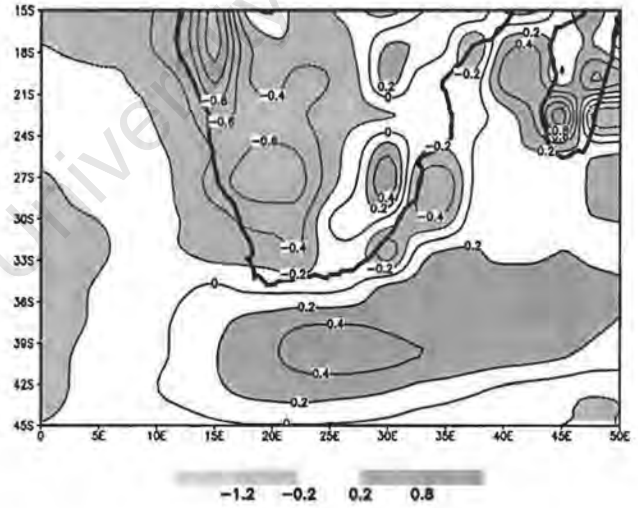

Figure 3.32: The GEN2/GFDL/UKMO grouped model anomaly of precipitation for 6ka compared to 0ka BP. The anomalous drying over the western regions, and wetter conditions over the escarpment are of particular note.

MRI2/UGAMP on the other hand, show an almost equal increase in pressure overall, with evidence for a possible weak extending high to the south of the sub-continent at 6ka BP (Fig. 3.33). The South Atlantic and South Indian High Pressures are both increased in this model group for 6ka BP.

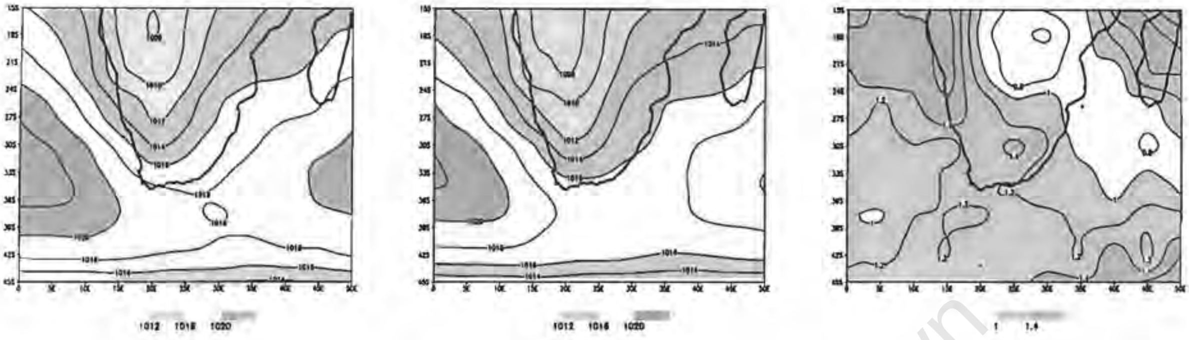

Figure 3.33: The MRI2/UGAMP grouped model 6ka (left), 0ka (centre) BP and anomaly map (right) of sea level pressure. Take particular note of the 'almost' extended high to the south of the sub-continent.

Temperature changes from the MRI2/UGAMP group show overall increases for 6ka BP (Fig. 3.34). Of particular note is the intensely warmer conditions over the northern interior, but with a lower degree of change over the southwestern parts. The latitudinal thermal gradient is well represented from this model group.

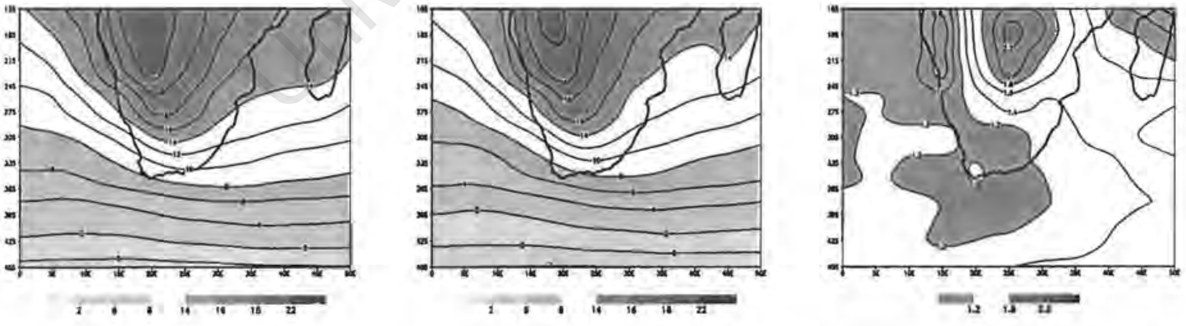

Figure 3.34: The MRI2/UGAMP grouped model 6ka (left), 0ka (centre) BP and anomaly (right) maps of temperature. There is an overall increase, with the most intense increases being in the northern interior.

Precipitation is less well defined, but broadly shows increases in the eastern parts and little change to decreases in the western parts (Fig. 3.35). The entire Natal coast in the east shows increased rainfall for 6ka BP compared to the simulation for 0ka BP. The drying in the northern interior is possibly linked to the intensely greater temperatures than compared to elsewhere, but this same explanation does not stand for the drying areas over the ocean.

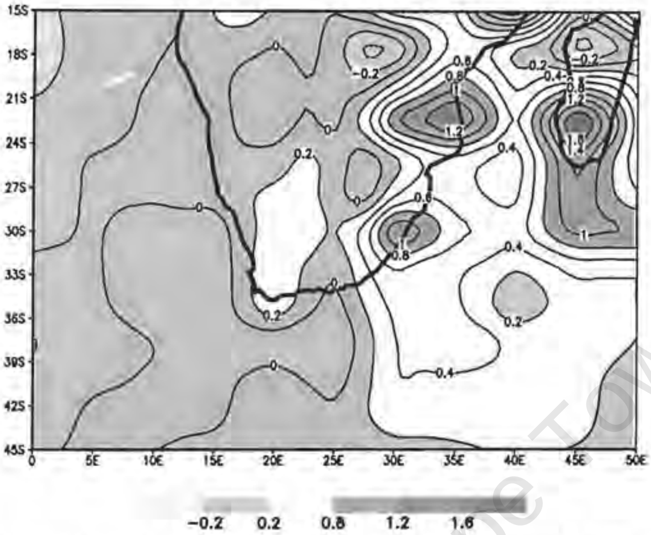

Figure 3.35: The MRI2/UGAMP grouped model anomaly map of precipitation for 6ka BP compared to 0ka BP. There is a general increase in the eastern parts, with drying to little change for the northern and northwestern parts.

3.3.4.4. GEN2/GFDL/UKMO grouped simulation compared to MRI2/UGAMP grouped simulation

GEN2/GFDL/UKMO anomalies with MRI2/UGAMP showed that the grouped models displayed differing results. For 0ka BP, sea level pressure anomalies for GEN2/GFDL/UKMO showed more intense sub-tropical high pressures than MRI2/UGAMP, with increased latitudinal pressure gradient and an extended high to the south of the sub-continent (Fig. 3.36). The wind field anomaly reflects reduced flow of the South Atlantic High Pressure and less on-shore flow from the South Indian High Pressure system where the pressure gradient is reduced due to the weaker continental low trough in GEN2/GFDL/UKMO model simulation. The extended high pressure caused the continental low to be weaker, thus the main differences for 0ka BP are over the interior and to the south of the sub-continent where the westerlies flow.

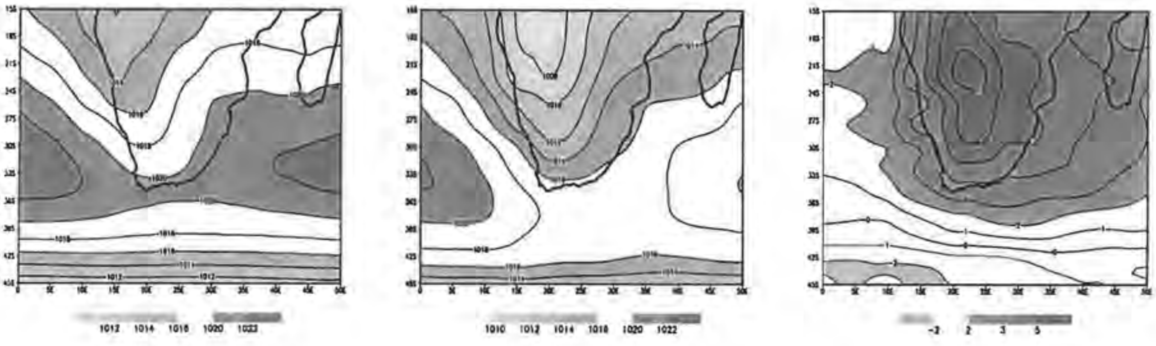

Figure 3.36: Sea level pressures for GEN2/GFDL/UKMO (left) and MRI2/UGAMP (centre) grouped model simulations for 0ka BP, with the anomaly map of GEN2/GFDL/UKMO minus MRI2/UGAMP (right). Note the extending high pressure in GEN2/GFDL/UKMO and the intense interior low pressure in MRI2/UGAMP.

Precipitation differences between the two model groups for 0ka BP show MRI2/UGAMP depicting much more precipitation over the eastern areas, inline with the escarpment (Fig. 3.37). Other than this there is very little difference to note between the two groups. Temperature on the other hand shows a deeper continental thermal trough, thus causing GEN2/GFDL/UKMO to show overall cooler temperatures over the sub-continent than MRI2/UGAMP for 0ka BP (Fig. 3.38).

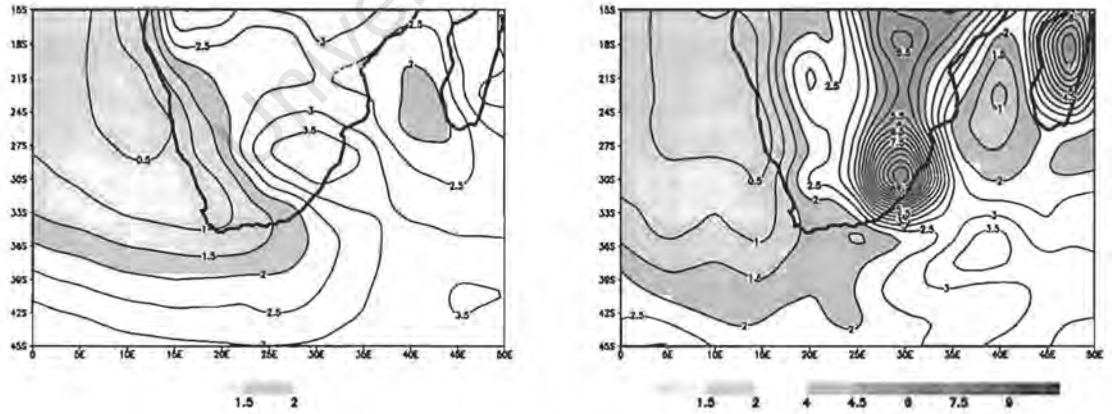

Figure 3.37: Precipitation simulations for GEN2/GFDL/UKMO (left) and MRI2/UGAMP (right) grouped model simulations for 0ka BP. The increased precipitation over the eastern escarpment is evident in the MRI2/UGAMP simulation, with both simulations showing evidence of the E-W precipitation gradient.

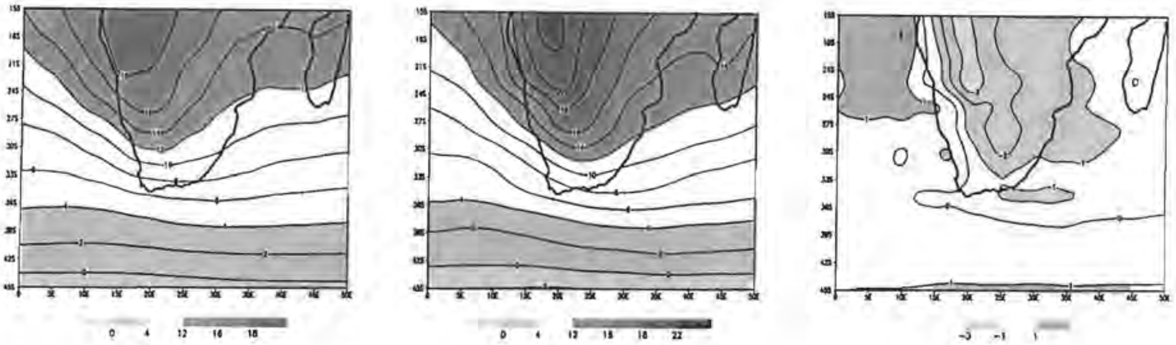

Figure 3.38: Temperature simulations for GEN2/GFDL/UKMO (left) and MRI2/UGAMP (centre) grouped model simulations for 0ka BP. Take particular note of the deeper interior thermal trough of MRI2/UGAMP as reflected in the anomaly of GEN2/GFDL/UKMO minus MRI2/UGAMP (right).

For 21ka BP, MRI2/UGAMP show more intense sub-tropical high pressures, and a continental low pressure trough which is more central to the sub-continent. MRI2/UGAMP show the westerly flow to be displaced much further south than GEN2/GFDL/UKMO, thus causing notable differences in the pressure anomaly maps for this area (Fig. 3.39). The winds depict these differences, with stronger westerly flow to the south of the sub-continent seen from GEN2/GFDL/UKMO, and much reduced anticyclonic flow from the sub-tropical high pressures. Of particular note is the decreased flow along the west coast from GEN2/GFDL/UKMO whereby they would retrodict less upwelling for 21ka BP than MRI2/UGAMP (Fig. 3.40).

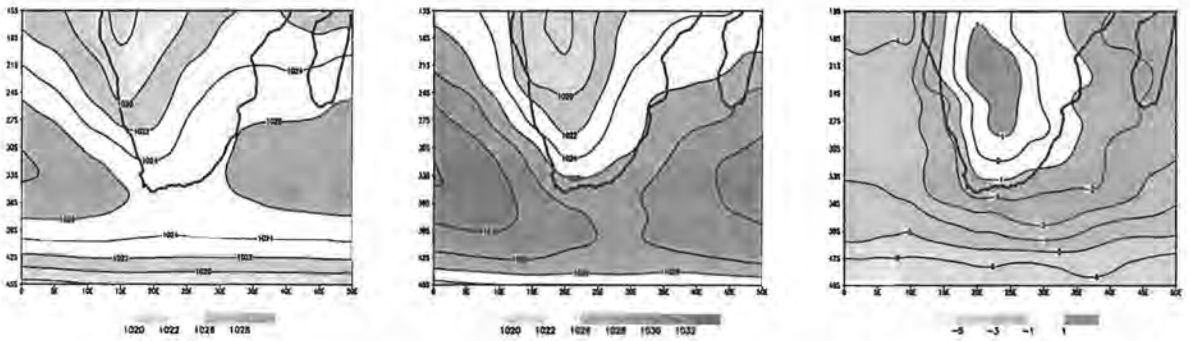

Figure 3.39: GEN2/GFDL/UKMO (left) and MRI2/UGAMP (centre) grouped model simulations for sea level pressure at 21ka BP. The increased pressure of the extended high in the south from the MRI2/UGAMP simulation and the pressure differences over the interior are noted in the anomaly of GEN2/GFDL/UKMO minus MRI2/UGAMP (right).

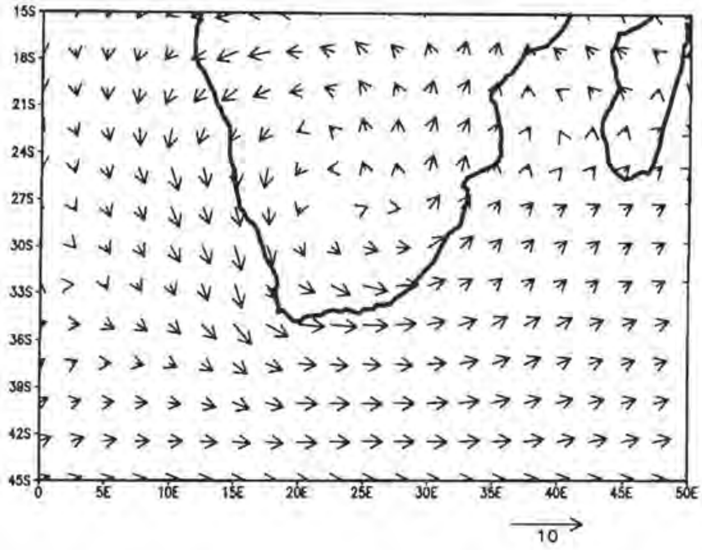

Figure 3.40: Anomaly of the GEN2/GFDL/UKMO minus MRI2/UGAMP grouped model simulation for wind speed and direction at 21ka BP. The anomaly shows decreased wind speed along the south and west coasts for the GEN2/GFDL/UKMO simulation.

The precipitation and temperature differences for 21ka BP are much the same as for 0ka BP (Fig. 3.41). GEN2/GFDL/UKMO depict less precipitation to the eastern parts of the sub-continent than MRI2/UGAMP. Other than that there are very little significant differences between the two model groups for 21ka BP precipitation. 21ka BP temperature shows the latitudinal gradient well for both groups, with MRI2/UGAMP having a stronger thermal trough over the interior making GEN2/GFDL/UKMO simulate cooler temperatures for the interior than MRI2/UGAMP for 21ka BP.

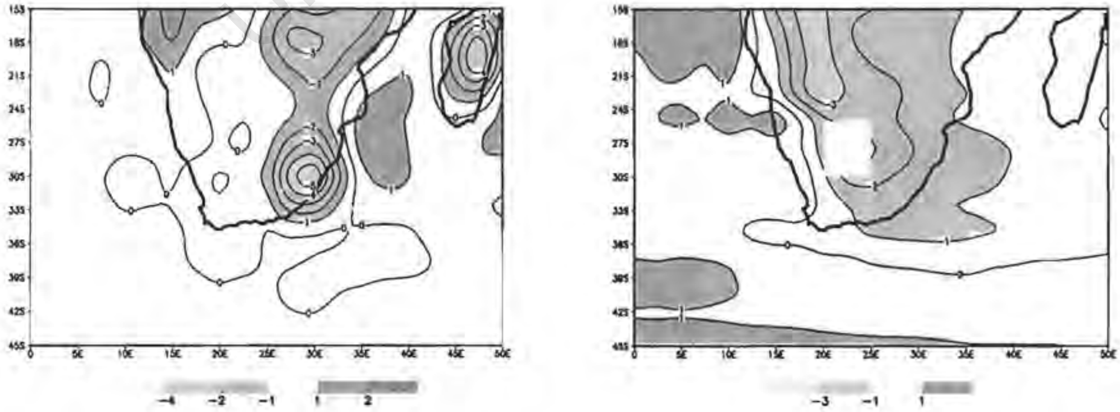

Figure 3.41: Anomalies of precipitation (left) and temperature (right) for the GEN2/GFDL/UKMO minus MRI2/UGAMP grouped model simulation at 21ka BP. The anomalies are much the same as the 0ka BP anomalies of the same variables.

The differences between the sea level pressure and wind fields are much the same for 6ka BP as for 0ka BP for the two model groups. The main points to note is evidence for a stronger extended high pressure over the southern parts of the sub-continent and the stronger latitudinal gradient the south of this feature in GEN2/GFDL/UKMO (Fig. 3.42). This causes the westerly flow to the south of the sub-continent to be stronger in the GEN2/GFDL/UKMO simulation. As the continental low pressure is also reduced in the 6ka BP GEN2/GFDL/UKMO simulation, the anticyclonic flow is reduced along the west coast. MRI2/UGAMP displays a stronger interior low pressure trough, with a partial retraction of the sub-tropical highs. Thus the on-shore easterly flow is greater in the 6ka BP MRI2/UGAMP simulation than the GEN2/GFDL/UKMO simulation.

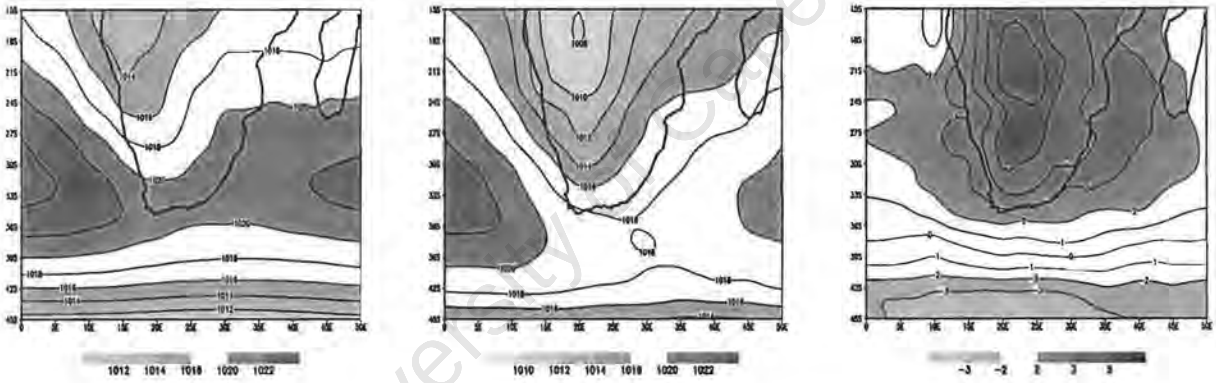

Figure 3.42: Sea level pressure of the GEN2/GFDL/UKMO (left) and MRI2/UGAMP (centre) grouped model simulations with the anomaly map (right) at 6ka BP. The anomaly is much the same as the 0ka BP anomaly of GEN2/GFDL/UKMO minus MRI2/UGAMP, noting the extended high pressure in both groups.

Precipitation and temperature anomalies show the same differences as for 0ka BP, with increased precipitation along the escarpment and a more intense thermal trough over the interior in the MRI2/UGAMP simulation (Fig. 3.43). The E-W precipitation gradient and the latitudinal thermal gradient are well depicted in both model groups.

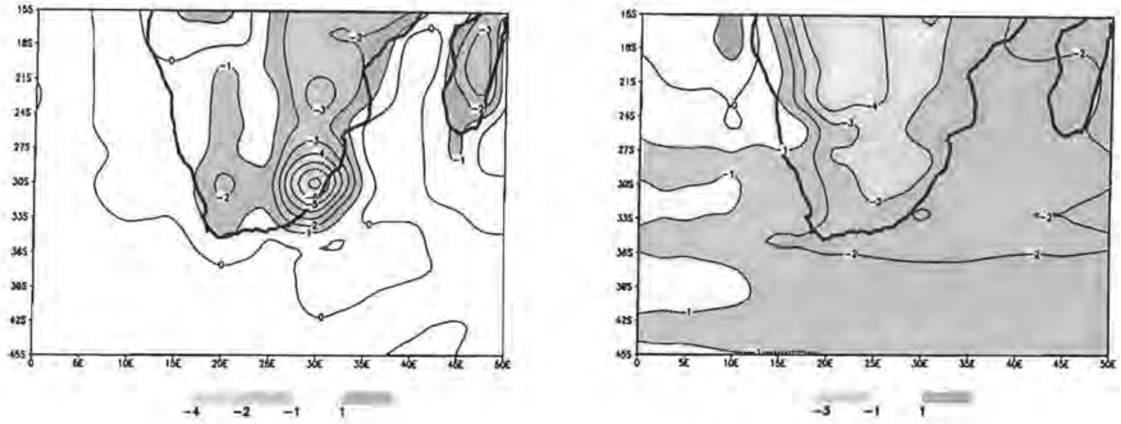

Figure 3.43: Precipitation (left) and temperature (right) anomalies of the GEN2/GFDL/UKMO minus MRI2/UGAMP grouped model simulations at 6ka BP. The anomalies are much the same as the 0ka BP anomaly, noting the lower precipitation and cooler temperatures from the negative values shown by the GEN2/GFDL/UKMO minus MRI2/UGAMP anomaly.

3.4. Conclusion

This Chapter has examined climate modelling and its application for palaeoclimates in the Southern Hemisphere, but more specifically to southern Africa. After due consideration of seven different global climate models, it was comprehensively decided upon to group the models with similar output and examine the results.

After performing Ward's Method and Single Linkage clustering on the seven different models, two main groups were identified. They were GEN2/GFDL/UKMO and MRI2/UGAMP. After a comparison of these groups, GEN2/GFDL/UKMO was chosen as the group to be used in Chapter 4 as the model group for comparison with the proxy data, for further analysis of palaeoclimate studies in southern Africa. This conclusion was reached on the following accounts:

1. As the two groups shared basic similarities, it was decided that the group that contained the greater number of models would be more robust in its application to palaeoclimate studies, in this case. This is due to the consensus of response in model groups, and as

GEN2/GFDL/UKMO grouped three out of the seven possible models, this was the group chosen.

2. Further examination of the outliers produced from the Single Linkage clustering procedure, showed that both UGAMP and MRI2 came up as outliers when looking at the four main variables (sea level pressure; wind speed and direction; temperature and precipitation) over the three time periods (0ka; 21ka and 6ka BP). It was also noted that GEN2 and GFDL did not once come up as outliers in this study.

Chapter 4 then proceeds from here using the climate model output from the GEN2/GFDL/UKMO grouped simulation to compare to the proxy palaeoenvironmental data findings in the southwestern Cape from Chapter 2. This analysis aims towards validating palaeoclimate models and possibly identifying gaps in the proxy palaeoenvironmental data.

CHAPTER FOUR

COMBINING PROXY DATA AND CLIMATE MODELLING: TOWARDS AN OVERALL SYNTHESIS

Chapter 4: COMBINING PROXY DATA AND CLIMATE MODELLING: TOWARDS AN OVERALL SYNTHESIS

4.1. Introduction

Due to the number of gaps and inconsistencies that exist in the palaeoenvironmental proxy data (Chapter 2), it is helpful to examine another source of information to support the climatic changes indicated by the proxy data. In this study seven global climate models (GCM's) were evaluated (Chapter 3) to identify changes in the climate for the periods of 21ka and 6ka BP. From a close examination of the output from the models, one main group has been chosen for comparison with the proxy data, comprising the GEN2/GFDL/UKMO model simulations.

The spatial resolution of palaeo- GCM's is generally coarse, at typically ~3°-5°. Palaeoclimate models generally display coarser resolution in their model output than GCM's designed for present and future climate studies. This is for a number of reasons: Firstly for simplicity. Generally palaeoclimate models are run globally examining large-scale features. The boundary conditions for the simulation (land surface cover, sea surface temperatures, etc…) are only broadly specified due to uncertainties in the understanding of these fields in palaeo-conditions. As such, a finer resolution simulation would only complicate the output and would not be required for depicting large-scale features.

A second motivation for coarse resolution is to complete the palaeoclimate simulations at a faster rate. The coarser the resolution the faster the model runs can be simulated, and therefore lower the computational requirement (Collins, pers. comm.). As palaeoclimate simulations are long, computing time needs to be considered; therefore resolution is compromised to facilitate reduced processing time.

Thirdly, palaeoclimate models are generally based on older versions of more recent model developments, and have not progressed at the same rate as the GCM's used for present and future analysis (Collins, pers. comm.). GCM simulations are constantly being improved upon, and this includes refining the model resolution. However, in light of the current uncertainty in boundary fields for palaeostudies, significant increases in model resolution are perhaps not the highest priority.

Coarse resolution models generally tend to underestimate variables. A prime example is estimating precipitation over mountainous areas. The eastern escarpment in Natal is an example in this study, where precipitation has been grossly underestimated for the present day simulation compared to NCEP data (Chapter 3). Another factor is that they cannot simulate sub-grid scale processes. That is, the GCM's cannot simulate those processes that have dimensions smaller than the model resolution, thereby not capturing the finer localised changes. Thus, the models reflect large areal averages.

4.1.1. Comparing proxy data and GCM simulations

In this chapter a comparison is made between the climate model output of the GEN2/GFDL/UKMO selected group (Chapter 3) with the proxy palaeo-environmental evidence (Chapter 2). The results are discussed over the area of interest, where the three main Sub-regions referred to are the Western, Central and Southern Sub-regions (as defined in Chapter 1). The results look specifically at the last glacial maximum, around 21ka BP, and the Holocene Altithermal, around 6ka BP, as this coincides with the period for which palaeoclimate model data are available. The chapter concludes with a discussion of the findings comparing these different types of data.

4.1.2. Results of the Last Glacial Maximum (21ka BP)

The last glacial maximum was a major global cooling period around 21ka BP. This has been identified in the proxy palaeoenvironmental data for the southwestern Cape where temperatures point towards cooler conditions when compared to today, although not as dramatic as the cooling experienced globally. The model output similarly reflects "milder" cooling of the Western and Central Sub-regions, leading to colder conditions over the interior parts of the Southern Sub-region, as is seen in the anomaly map of temperature for 21ka BP (Fig 4.1). It is important at this point to remember that the grouped model means and anomalies for 21ka BP show a blank over the interior of the sub-continent due to one of the GCM's showing undefined values for this region, in order to keep the model group mean spatially consistent.

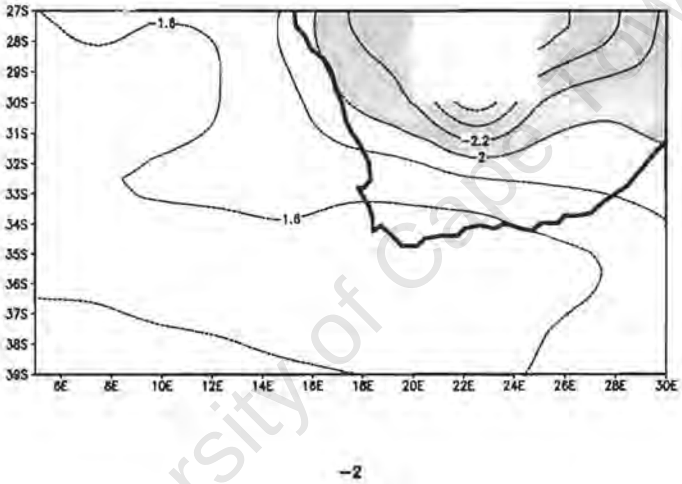

Figure 4.1: 21ka simulated mean temperature anomaly from the GEN2/GFDL/UKMO model group (The anomaly is with respect to the model group mean for present day conditions). The model output depicts cooling for the last glacial maximum, with milder conditions along the southwestern coast.

Temperatures from the model output in the study region were around 1.6°C to 1.8°C cooler than present, whereas the interior and northern parts drop as much as 2.6°C to 2.8°C. The grouped model simulation for temperature shows little change within the Central Sub-region itself (Fig. 4.1). The Southern Sub-region, like everywhere else shows cooling for the last glacial maximum, but there is a clear indication in this region of a latitudinal gradient of change, with cool conditions in the south, leading to colder conditions further north. This concurs with the proxy data evidence in the interior of the Southern Sub-region, particularly from the Cango and Boomplaas cave sites, which depict much colder conditions for 21ka BP compared to those of the Western and Central Sub-regions.

The palaeoenvironmental proxy data reflect the last glacial maximum as being wetter by today's standards in the Western Sub-Region, with the Central and Southern Sub-regions showing clear drying conditions (Fig. 4.2). The grouped model output place the Western Sub-region over a shifting interface, whereby the model output show little change at all, with a possibility of wetter conditions in the north and drier conditions in the south of the sub-region.

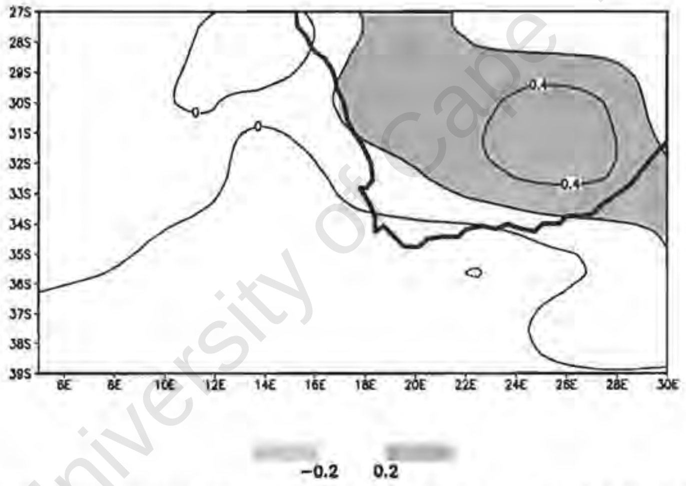

Figure 4.2: 21ka simulated mean precipitation anomaly from the GEN2/GFDL/UKMO model group (the anomaly is with respect to the model group mean for present day conditions). The model output depicts wetter conditions in the northeast, with drying progressing in a southwesterly direction.

Climate model output at this coarse resolution represents large areal spatial averages. As such, specific point-by-point comparison with proxy data is not valid, as discussed earlier. Thus the transition area with wetter conditions further north could well represent the slightly wetter conditions retrodicted by the proxy data to have occurred over the Western Sub-region during the LGM.

The Central and Southern Sub-regions on the other hand are clearly defined by the model output as being drier during the LGM (Fig. 4.2). This corresponds well with the proxy data whereby conditions were noted as being particularly dry in these parts (Fig. 2.10). Proxy palaeoenvironmental data for the Southern Sub-region show characteristically cold but particularly dry conditions for the last glacial maximum. An examination of the GEN2/GFDL/UKMO grouped model data show that this region was not unlike the Western Sub-region as it also falls into a transition zone, but distinctly shows drying along the coast in the Southern Sub-region. The drying along the coast links in with the decrease in the westerly flow depicted from the wind simulation for 21ka BP (Fig. 4.3), possibly decreasing the number of winter storms to this part of the sub-continent, and therefore causing drier conditions to prevail.

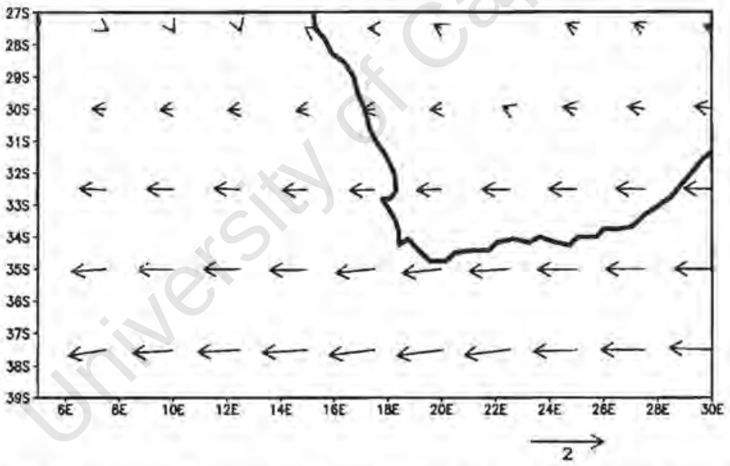

Figure 4.3: 21ka BP simulated anomaly (model 21ka-0ka BP) of wind speed and direction from the GEN2/GFDL/UKMO model group. Shows the weaker westerly flow reflecting the deepened pressure gradient and the decreased southerly component winds on the west coast.

The winds for 21ka BP over these parts show a weaker westerly flow, reflecting a weakened north-south pressure gradient with a weakened low pressure belt to the south of the sub-continent. The weaker westerly flow of the wind fields implies decreased winter storms to the sub-continent (Fig. 4.3), which could be the cause of the drying identified over the Southern and Central Sub-regions respectively.

Proxy data were identified that do not support these findings. Notably, Mouton (1986) infers stronger winds with more frequent winter rains, particularly in the Central Sub-region during the LGM. However the proxy palaeoenvironmental interpretation is based on palaeo-reptilian evidence primarily from the Cape Peninsula area. As the climate model resolution is so coarse, it is not possible to identify with such specifics whether these features were present or not. What is clear is that these data were very site specific, and even today the day-to-day weather conditions vary greatly over the Cape Peninsula, making it unsuitable to use as an overall representation of the entire Central Sub-region.

According to the palaeoenvironmental proxy data, the last glacial maximum then merged into warmer conditions for the early Holocene. The proxy data reflect a drying period for the Western Sub-region, with increases in moisture availability for the Central and Southern Sub-regions, where a distinctly dry LGM was experienced. Unfortunately the model data for conditions after the last glacial maximum leading into the early Holocene are not available. However after the proxy data reflected drier-warmer conditions, this lead into a mid-Holocene Altithermal of more humid conditions around 6ka BP.

4.1.3. Results of the Holocene Altithermal (6ka BP)

The 6ka BP time period reflects what is known as the Holocene Altithermal, which is recognised as a period of global warming. Proxy palaeoenvironmental data depict conditions on the west coast, particularly at Verlorenvlei (Fig. 2.4), as definitive dry and warm conditions, leading into a sub-humid and wet climate over the mid-late Holocene.

The Central Sub-region reflected sub-humid conditions with much greater precipitation when compared to the Early Holocene, which was warm and dry from proxy palaeoenvironmental data. Even compared to present day conditions, this period was seen as having much more available moisture along with warmer conditions. Proxy data from the Southern Sub-region noted warmer temperatures and more precipitation than the LGM, but conditions much the same as those experienced today for this 6ka BP period.

Temperatures reflected by the grouped model output show conditions to be much cooler than speculated by the proxy palaeoenvironmental data for 6ka BP, especially along the western coastal reaches (Fig. 4.4). Conditions in the models for 6ka BP are seen to be particularly cooler when compared to present day temperatures for all the Sub-regions, but as much as 1.4°C warmer than the LGM in places.

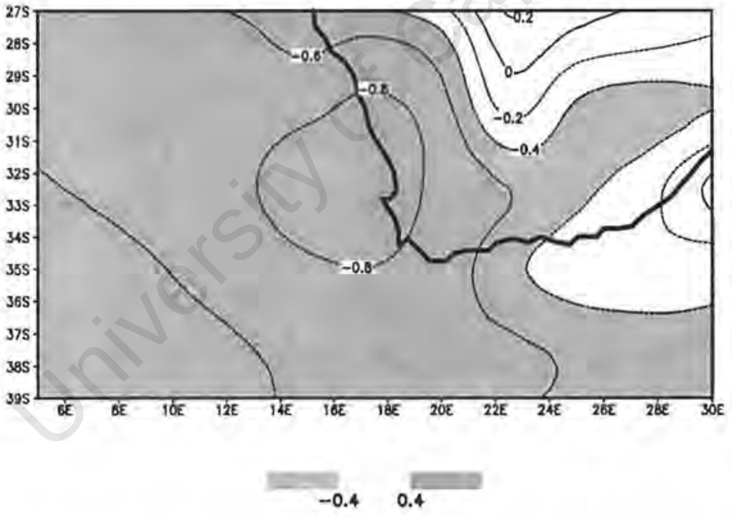

Figure 4.4: 6ka simulated mean temperature anomaly from the GEN2/GFDL/UKMO model group (the anomaly is with respect to the model group mean for present day conditions). The model output depicts cooling in the southwest and warming over the northern interior.

Proxy palaeoenvironmental data reflect temperatures for 6ka BP, particularly in the Central and Southern Sub-regions, with a cyclical nature of change, from warm to cool when compared to today's conditions. The model simulation shows overall cool temperatures in the region for 6ka BP, where the southern parts are relatively warmer than the western reaches (Fig. 4.4). However it must be remembered that the models show means where the simulation was run for only 10 years, and so do not represent long term variability.

Looking at the Southern Sub-region on its own, a particular anomaly temperature gradient exists whereby temperature changes are larger in the western parts and smaller to the east (Fig. 4.4). This is evident for the coast as well as the interior of the Southern Sub-region.

It is necessary to remember at this point that the spatial pattern of change is more robust than the individual grid cell values (Table 3.3). Also, climate models of this coarse resolution may depict spatial displacement, particularly when the region of focus is small when compared to the resolution of the models.

With this in mind, the GEN2/GFDL/UKMO model simulation for 6ka BP temperature shows cooler conditions over the Central Sub-region (Fig. 4.4). Although not as cold as the Western Sub-region and considerably warmer than at the last glacial maximum, conditions were cooler than present day conditions in this region. This is in contrast with the proxy data, which reveal warm conditions for this time period.

The model output for precipitation clearly depicts drying over the entire Western Sub-region and much of the interior (Fig. 4.5). A precipitation gradient seems to exist over the study area whereby conditions are drier in the northern parts, decreasing to little change in the southern parts. This pattern holds for the interior as well as the coastal regions. The proxy data reflect these changes in the Western Sub-region whereby conditions are particularly drier by comparison to both the Central and Southern Sub-regions.

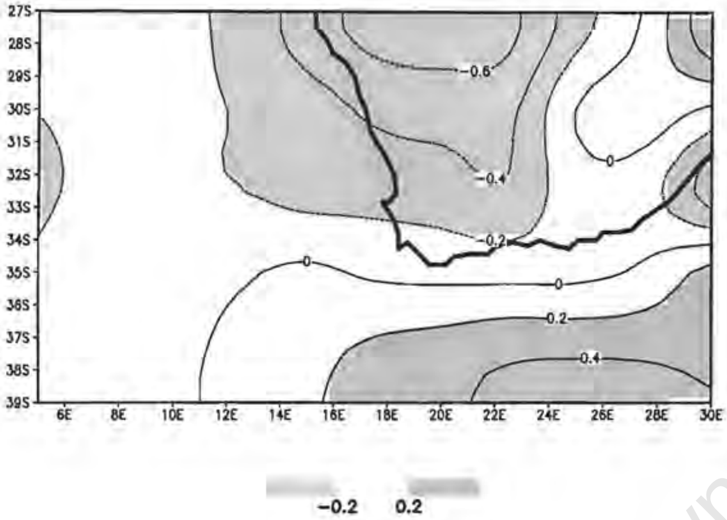

Figure 4.5: 6ka BP simulated mean precipitation anomaly with respect to present day from the GEN2/GFDL/UKMO model group. Drying is noted in the west, with increases in precipitation over the eastern escarpment. Little change is seen along the southern coast.

Notable from the proxy data is that the Southern Sub-region depicts little change from present day conditions, with the Central Sub-region being only slightly wetter than present for around 6ka BP. This is reflected in the model output where both the Central and Southern Sub-regions fall into areas of little change in precipitation for 6ka BP (Fig. 4.5). Precipitation changes are marginal during the mid-Holocene Altithermal compared to today from the model simulation, particularly as the Central and Southern Sub-regions are in a transition zone between being wetter in the south and drier to the north.

Modelled precipitation data for the mid-Holocene Altithermal is difficult to compare the proxy data findings to due to the cyclical nature of the precipitation indicated by the proxy palaeoenvironmental data. There is strong evidence from the proxy palaeoenvironmental data (Chapter 2) to suggest that precipitation varied from moist to very dry conditions throughout the mid-Holocene. The GEN2/GFDL/UKMO model group simulates little change in precipitation for the southern coastal regions, with slightly drier conditions in the interior, thus causing the Central and Southern Sub-regions to fall into the transition zone between wet and dry conditions. However, as noted earlier, due to the duration of the simulation, cyclical variability may not be captured.

Leading on into the late Holocene, proxy palaeoenvironmental data suggest that conditions became more sub-humid with a wetter climate. These wetter conditions then lead into a drying period in the Western and Central Sub-regions, as we near the conditions present today. The Southern Sub-region displayed a different signal with precipitation being distinctly cyclical between moist and relatively dry conditions during the late Holocene, ending in a moist phase before conditions of today. Temperature changes after the Holocene Altithermal are thought to have remained warm, with little change in the Western and Central Sub-regions, and slight fluctuations in the Southern Sub-region, leading up to today's conditions.

4.2. Discussion

It is difficult to reconstruct composite climate patterns on the basis of proxy evidence only. However, using climate model simulations allows one to infer a broader regional climate, as well as identify relationships between the model and the palaeoevidence found.

The palaeo-anomalies of the variables examined infer a regional climate and are seen to reflect proxy data rather well. From these findings we can cautiously say that they reflect proxy data spatially, but regionally the resolution is poor. A good example of this is the precipitation over the Central Sub-region, which can not identify the greater available moisture as depicted from the proxy palaeoenvironmental data for 6ka BP. Instead slight drying conditions were identified. Thus the main focus from the model data is an interpretation of the major climate systems that are shown and their influences over the region. One also needs to keep in mind that the model grid cells are large and therefore the spatial location of climate boundaries will not be accurately reflected, especially between mountain and coastal regions, which are close together. The Central Sub-region is one of extensive mountain ranges, particularly near to the coast, so this distortion of signal would be particularly appropriate here.

The southern region proxy palaeoenvironmental data all correspond to the model data, except for temperature. The Cango Caves record a lowering of as much as 5°C at around 20ka BP, but the model shows little or no corresponding change. This difference is possibly linked to localised conditions within the valley where the caves are located or possibly a chronological inconsistency. The region also showed drier conditions where the model was unchanged, and it is thought that at 21ka BP this region reflected more the characteristics of a winter rainfall region, unlike conditions today where it is more that of all year rainfall. Partridge *et al.* (1990) state that the drop in productivity in the Southern Sub-region is seen as a function of temperature difference and less so the result of extreme aridity as accepted for the rest of the subcontinent. This is reflected in the grouped model data where temperatures decline but precipitation remains much the same.

Accepting that the models broadly confirm the proxy data, that is on a more synoptic scale, an overall assessment of the 21ka and 6ka BP climate follows:

4.2.1. Climate at 21ka BP

The model group shows sea level pressure to have strengthened overall, with a decrease in intensity of the interior low pressure trough (Fig. 4.6). This would cause an increase in the effect the anticyclonic circulation has on the sub-continent. The proxy data shows some agreement with this, indicating that the anticyclonic circulation was significantly greater during the last glacial maximum than at present (Partridge *et al.*, 1999).

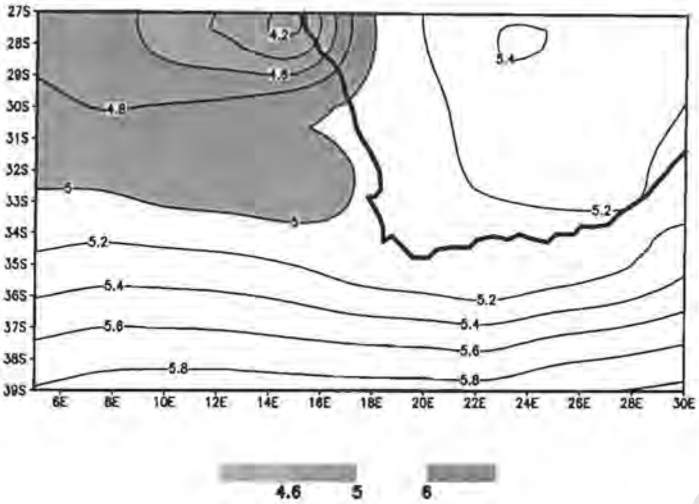

Figure 4.6: 21ka simulated mean sea level pressure anomaly from the GEN2/GFDL/UKMO model group (the anomaly is with respect to the model group mean for present day conditions). The model output depicts a decrease in the interior low pressure trough and an increase in anticyclonic high pressure circulation.

Temperatures are overall cooler for the LGM from the model simulation, but with slightly milder conditions in the southwestern parts (Fig. 4.1). These conditions are also reflected in the proxy data, whereby the three Sub-regions show related variations, with the Western Sub-region depicting the milder conditions, and the Southern Sub-region showing colder conditions. The Central Sub-region falls well between these two Sub-regions in the proxy data, still indicating cooling, but not as much as the Southern Sub-region and to a greater extent than the Western Sub-region (Fig. 2.9).

Precipitation in the model simulation shows dry conditions in the southwestern areas and wetter conditions in the interior (Fig. 4.2). This links in with the proxy data as the Western Sub-region shows wetter conditions during the LGM, with the Central and Southern Sub-regions indicating drying (Fig. 2.10). An interesting feature is that the model group simulation seems to depict wetter conditions with warming for the Western Sub-region and drier conditions with cooling in the Southern Sub-region for the LGM. This is clearly noted in the proxy data (Fig. 2.9 and Fig. 2.10) and specifically concluded by Meadows and Baxter (1999) that an increase in temperatures could result in a decrease in rainfall in the Western Cape.

4.2.2. Climate at 6ka BP

The model group simulation shows the South Atlantic High Pressure to have strengthened, while the South Indian High Pressure system weakened for 6ka BP (Fig. 4.7). These pressure changes caused increased southwesterly flow to the sub-continent from the Polar Regions. This could result in cold air penetrating the sub-continent from the Polar Regions.

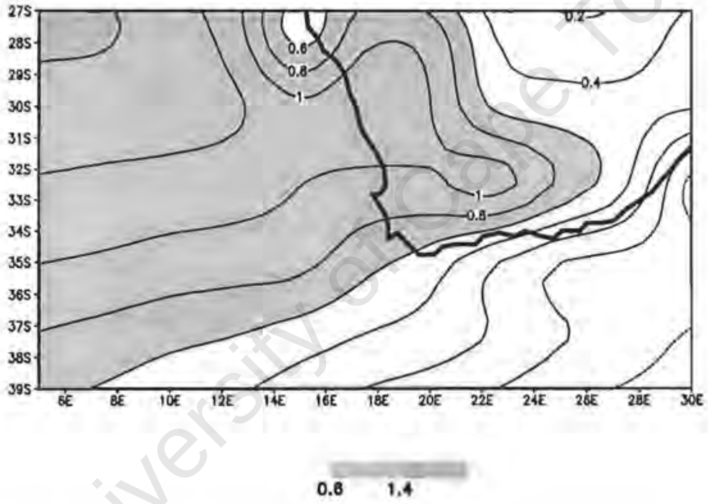

Figure 4.7: 6ka simulated mean sea level pressure anomaly from the GEN2/GFDL/UKMO model group (the anomaly is with respect to the model group mean for present day conditions). The model output depicts an increased southwesterly flow.

The temperatures in the model depict this input of cold air by reflecting a slight cooling in the southwestern parts, leading to slightly warmer conditions in the northern interior (Fig. 4.4). The thermal trough is displaced to the west in the model output. Temperatures for 6ka BP from the proxy data indicate little change in the Southern Sub-region compared to today, and warming in the Western and Central Sub-regions. Specifically the model simulation for temperature does not agree with the proxy data, however the degree to which the warming/cooling is reflected is so small that it is possible that the model is missing the optimal peak conditions of the Holocene Altithermal. This notion is discussed at the end of this section.

Modelled precipitation shows drying in the western parts with wetter conditions over the eastern escarpment (Fig. 4.5). Precipitation for 6ka BP in the model simulation reflects little change over the southern coastal regions. The proxy data shows similar conditions to the model output for the Holocene Altithermal at 6ka BP, where proxy data from the Western Sub-region detects the slightly drier conditions in the model. The Central and Southern Sub-regions reflect little change to a possibility of slightly wetter conditions from the proxy data, with the model data showing the region as one of little change to possibly drier conditions. It is important to note here that the Southern Sub-region in particular reflected cyclical changes in both temperature and precipitation throughout the mid-late Holocene. As the model output reflects purely a "snap shot" at 6ka BP in the mid-Holocene, the cyclical conditions are not detected.

The Holocene Altithermal has proved to be more difficult to compare the model and proxy data directly. This is possibly due to the variability throughout this particular time period. Scott (1993) and Partridge *et al.* (1999) discuss optimum conditions for the LGM and the Holocene Altithermal in the proxy data, concluding that extreme conditions did not occur everywhere at the same time. From this it is possible to assume that conditions reflected in the simulated temperature output could be showing post- or pre-Holocene Altithermal conditions.

4.3. In Conclusion

By forming relationships between climate models and proxy palaeoenvironmental evidence, there is potential to provide information on under-sampled regions, and identify areas in need of sampling to complete a regional synthesis of the Western Cape. This chapter has examined the average output of three global climate models, which have shown similar characteristics from statistical clustering methods. The results have their shortcomings, which will be discussed in the concluding chapter, but on the whole the model output compared well with the proxy palaeoenvironmental data.

CHAPTER FIVE

CONCLUSIONS

CHAPTER 5: CONCLUSIONS

5.1. Overview

The primary aim of this study has been to evaluate late Quaternary environmental changes in the southwestern Cape from proxy palaeoenvironmental data studies and palaeoclimate model data. The investigation assumed a broad-based, multidisciplinary approach, drawing on wide-ranging evidence from diverse sources such as sedimentology, palynology, archaeology, geomorphology, and palaeoecology, among others (Chapter 2).

Palaeoclimate model output for the late Quaternary has been examined in order to complement the proxy data. The palaeoclimate simulations display a general commonality in their simulations (Chapter 3), and simulate present day conditions adequately, hence supporting their use for palaeoenvironmental studies. This is particularly valuable for the southwestern Cape due to the diversity of the region making it difficult to link the different types of proxy palaeoenvironmental evidence. It is concluded that a more complete overall synthesis of past climatic changes in the southwestern Cape may benefit from a combined analysis of proxy data and palaeoclimate modeling (Chapter 4).

The study has been conducted with a view to broadly understanding the following ideas: Firstly, spatial variability in the winter rainfall region is well documented. Thus evidence has been found to identify the extent of this fluctuation in the Western Cape. The next idea was to investigate what climate models broadly simulate climate in the Western Cape region to be over the last 25ka, and thirdly, how these simulations link to the proxy data, specifically in the winter rainfall region of the Western Cape.

5.2. Summary and Synthesis of Results

Relationships arising from palaeoclimate model simulations of the region and palaeoenvironmental evidence reveal the potential for evaluation of the climate state over longer time periods. This methodology was used with the hope of gaining information on under-sampled regions and identifying areas in need of sampling, thus a more complete regional synthesis of Late Quaternary palaeoenvironments in the southwestern Cape is facilitated.

Palaeoenvironmental Proxy Data Distribution:

The literature review of all the possible palaeoenvironmental proxy data (refer to Chapter 2), pertaining to the western and southern parts of the Western Cape Province, has revealed a distinct pattern of change in the spatial extent of the winter rainfall region during the late Quaternary period.

Of particular note concerning the proxy palaeoenvironmental data is the lack of variety of sampling sites within the region. Where previous studies showed evidence of palaeoenvironmental change, further studies were conducted in close proximity to the original site. The west coast is a good example, where many studies have been conducted in the Eland's Bay area, namely Verlorenvlei; Grootdrift; Tortoise Cave; Spring Cave; Pancho's Kitchen Midden, to name a few. These studies were conducted in order to verify the data recorded at other sites in the area, but there remains a great need for sites to be identified in other areas in order to establish a more complete spatial synthesis of changing palaeoenvironmental conditions through the region. Coming back to the example, particularly few studies have been conducted north of the Elands Bay area, within the Western Cape (see Chapter 2, Fig. 2.4), thus spatial gaps exist in the proxy palaeoenvironmental data. However, with the inclusion of the palaeoclimate modeling, a synthesis of past environmental changes begins to emerge.

GCM Evaluation:

The GEN2/GFDL/UKMO grouped model simulations of present day conditions compare comparatively well to the NCEP data (Chapter 3). The GCM sea level pressure show similar features to NCEP data, with the main difference being a weaker interior thermal trough. The winds reflect a decrease in onshore easterly flow to the interior, therefore causing lower precipitation over the eastern escarpment. These features were identified in the majority of the climate models, which tended to underestimate location specific variables, such as precipitation over the escarpment, due to the low resolution. With regard to present day temperatures, the grouped model simulation showed similar spatial patterns, but with a negative temperature bias. Therefore the general features of today's climate were adequately simulated, and where differences occurred, these may be attributed in part to the characteristically low resolution of palaeoclimate model simulations (Chapter 4).

The Palaeoclimate Simulation:

With regard to palaeoclimate periods, the proxy data and the climate model data both identify the environmental differences in the spatial aspect, occurring in the winter rainfall region of the southwestern Cape for 21ka and 6ka BP. The Central Sub-region forms part of a climatic boundary between the Western and Southern Sub-regions. Analyses of the temperature (Fig. 2.9) and precipitation (Fig. 2.10) changes, which have occurred throughout the study region, reflect the position of the Central Sub-region as a boundary between the Southern and Western Sub-regions.

The LGM at 21ka BP is noted as being much cooler than today, with slightly milder conditions in the Western Sub-region compared to the Central and Southern Sub-regions. The Central and Southern Sub-regions are noted as being dry at this time, with the Western Sub-region reflecting wetter conditions for 21ka BP.

The Holocene Altithermal at 6ka BP is noted as being warmer by today's standards in the Western and Central Sub-regions, with little change in temperature in the Southern Sub-region when compared to today. Precipitation conditions reflect only mild fluctuations all the regions, with a tendency for drying in the Western Sub-region. The precipitation simulation differs from the proxy data output, thus resulting in an analysis of the feasibility of such a comparison.

Palaeoenvironmental Proxy and GCM Data Comparison:

The most significant result from the proxy-model data comparison is the lack of ability of the models to simulate conditions for 6ka BP. The proxy data detect clear cyclical changes in the Southern and, to an extent, Central Sub-regions. This is likely due to the model simulations not being of sufficient duration to capture long term variability.

Evaluation of palaeoclimate simulations further provides opportunities for model validation under conditions different from those used in the simulation of current climate. This constitutes an important means of improving levels of confidence in palaeoclimate models. By linking the synthesis of proxy data from the southwestern Cape (Chapter 2) to palaeoclimate model results for the time periods available (Chapter 3), the representativeness of the proxy data is related to the model simulation (Chapter 4). Overall, this study is deemed beneficial as the regional climate can be inferred from grouped model simulations of palaeoclimate data, thus determining the feasibility of linking this information to proxy data findings.

The main problems encountered in the study are linked to model resolution, with orographic influences on the variables causing the most contradictions in the results, as well as distinct gaps in the proxy data, causing the overall picture to possibly be biased towards one particular study signal. From these points, we consider the constraints and caveats to the study in more detail.

5.3. Constraints and Caveats

There are a number of constraints that are presented by the nature of the data. First, and most notably, is the lack of available palaeoclimate model data over the full period of the last 25ka BP. Compiling a regional proxy data synthesis with the GCM's for the last 25ka BP is only possible for two time slices, namely 21ka and 6ka BP, for which GCM data were available.

Conversely, the proxy data reflect a slow continuous change in the environment, and are therefore not easily compared to single points in time without some subjectivity.

Secondly is the issue of model resolution. Climate models used for the simulation of present and future climates are generally of a much finer resolution than those used in palaeoclimate studies. This is primarily due to computational constraints. In addition, the model data output available for this study were annual means, and as the analysis was comparing the changes in a marked seasonal climate region (winter rainfall), it would have been beneficial to have seasonal changes in the model output.

Generally climate models have difficulty representing orographically induced features (for example precipitation over the Natal escarpment) as well as with resolving boundary zones. Boundary zones are particularly important in this study, as the Sub-regions of interest are small relative to the resolution skill of the models. As much of the southwestern Cape consists of the Cape Fold Mountains and long thin stretches of coastline, detailed spatial features of climatic changes become more difficult to depict accurately.

The proxy data impose different constraints. A large portion of the proxy data for the study region has not been published, making inclusion of it in this study difficult unless supported by other palaeoenvironmental evidence. In this regard, a particularly important study is that conducted on the bank of dunes near Cape Agulhas, on the boarder between the Central and Southern Sub-regions. Work on these dunes was presented at a conference before this study began and as yet there has been no journal publication and the data could not be added to the synthesis. This is an important transition zone between the Central and Southern Sub-regions, and evidence for environmental change in this region could well have added to a clearer understanding of the fluctuations of the winter rainfall region.

Lastly, there is the question of data published based on less accurate or precise dating techniques. For example, many authors note that for a given period the temperatures were cooler than present day, but these are largely subjective interpretation with regard to the degree that cooling has taken place in the specified region, and the specific time period (Butzer, 1979&1984; Deacon *et al.*, 1984b; Klein, 1980; Parkington *et al.*, 2000; Scott, 1994a). Some estimates of the degree of cooling have been later refuted by subjective interpretation of other authors (for example Butzer, 1979 and Baxter, 1996). Thus, there is a need for more accurate or consistent dating of proxy palaeoenvironmental data.

Therefore, considering the relative constraints of the proxy and GCM data, there is still a lot of work that can and needs to be done in the Western Cape to compile a more complete and accurate regional synthesis of the fluctuations of the winter rainfall region during the late Quaternary.

5.4. Recommendations for Future Research

It is only by testing present climate variability against the past that a sound basis for understanding possible future conditions will be provided (Tyson, 1999b). In South Africa much excellent work has been done on the documenting and understanding of climatic and environmental change.

Leading on from the previous section, the following research avenues are suggested. Firstly, to compare in greater detail the accurately dated sites with those that have had dates suggested or inferred from the data. From this study there is evidence to support the notion that the lack of accurately dated material in the winter rainfall region constrains a more comprehensive synthesis. However, the LGM is a difficult area to improve upon with inaccuracies possibly remaining until more improved dating methods are applied, as Partridge *et al.* (1999) identify that dating control is based largely on radiocarbon ages, which are insufficiently precise to permit a high level of accuracy.

In general, changes in the climates of the winter and summer rainfall regions of South Africa are 180° out of phase (Lindesay, 1986; Muller and Tyson, 1988; Tyson, 1986). Further studies have shown that the winter rainfall region has fluctuated spatially in the past (Chapter 2). It is therefore interesting to examine the winter rainfall region and its current behaviour in more detail, with a view to comparing the present extent to the past and establishing a better understanding for future climatic changes.

A further topic of study briefly mentioned in Section 2.4 of Chapter 2, is the examination of sea level fluctuations for the late Quaternary. Not only have sea levels fluctuated dramatically in the past, but also extensive evidence exists for such changes currently. Sea level research can also be used as a critical component in the establishment and verification of a range of ocean-atmosphere models (Stanley, 1995). Palaeoceanographic information of this nature is also useful in resolving the underlying mechanisms of sea level change and climate, such that future trends may be more readily predicted (Baxter and Meadows, 1999).

Finally as indicated by this study, combining information of different types from varying different sources is beneficial to compiling a synthesis of palaeoenvironmental change. This approach is new to South Africa, although it has been used extensively in many countries in the northern hemisphere. It has been seen to be a reliable way of gaining an overall synthesis of past environmental and climatic changes and this study supports this notion. It is suggested that further studies, such as presented here, be conducted in the future. In this manner, an updated and more complete synthesis of palaeoenvironmental changes from the latest proxy data findings, combined with the latest climate model projections, can be achieved.

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APPENDICES

Appendix A Model Acronyms

Model	***Model Designation***	***PMIP Group***	***Location***
CCC2.0	CCCMA Version 2 (T32 L10) 1992	Canadian Centre for Climate Modelling and Analysis	Toronto, Canada
CCM1	NCAR CCM1 (R15 L12) 1992	IES-Center for Climatic Research	Madison, Wisconsin, USA
CCM3	NCAR CCM3 (T42 L18) 1992	IES-Center for Climatic Research	Madison, Wisconsin, USA
GEN2	GENESIS2 (T31 L18) 1995	Pennsylvania State University	Boulder, Colorado, USA
GFDL	GFDL CDG (R30 L20) 1997	Geophysical Fluid Dynamics Laboratory	Princeton, New Jersey, USA
MRI2	MRI GCM-IIb (4x5 L15) 1995	Meteorological Research Institute	Tsukuba, Japan
UGAMP	UGAMP UGCM Version 2 (T42 L19) 1994	The UK Universities' Global Atmospheric Modelling Programme	Reading, England
UKMO	UKMO HADAM2 (2.5x3.75 L19) 1997	United Kingdom Meteorological Office	Bracknell, England

Appendix B Acronyms:

BP	Before Present, ie before 1950, the base date for radiocarbon
CCC2.0	Canadian Centre for Climate Modelling, version 2.0
CCM1	Community Climate Model, version 1
CLIMAP	Climate/ Long-Range Investigation, Mapping and Prediction
GCM	General Circulation Model
GEN2	GENESIS model, version 2
GENESIS	Global ENvironmental and Ecological Simulation of Interactive Systems
GFDL	Geophysical Fluid Dynamics Laboratory model
ka	Thousand years
LGM	Last Glacial Maximum
MRI2	Meteorological Research Institute model, version 2
NCAR	National Center for Atmospheric Research
SSTs	Sea Surface Temperatures
UGAMP	UK Universities' Global Atmospheric Modelling Programme model
UKMO	United Kingdom Meteorological Office model

Appendix C   Resolution/model details:

Acronym	***Representation***	***Resolution***	***Degrees lon x lat***
CCC2.0	Spectral	T32	3.75 x 3.75
CCM1	Spectral	R15	4.5x7.5
CCM3	Spectral	T42	2.8 x 2.8
GEN2	Spectral	T31	3.75 x 3.75
GFDL	Spectral	R30	2.25 x 3.75
MRI2	Finite difference	4x5°	4 x 5
UGAMP	Spectral	T42	2.8 x 2.8
UKMO	Finite difference	2.5x3.75°	2.5 x 3.75

Where the resolution shows R = rhomboidal and T = triangular.

Appendix D   Graphic representation of 0ka BP model comparison with NCEP data, showing anomalies on the right hand side, for

Figure D.1: 0ka sea level pressure

Figure D.2: 0ka u and v winds

Figure D.3: 0ka Temperature

Figure D.4: 0ka Precipitation

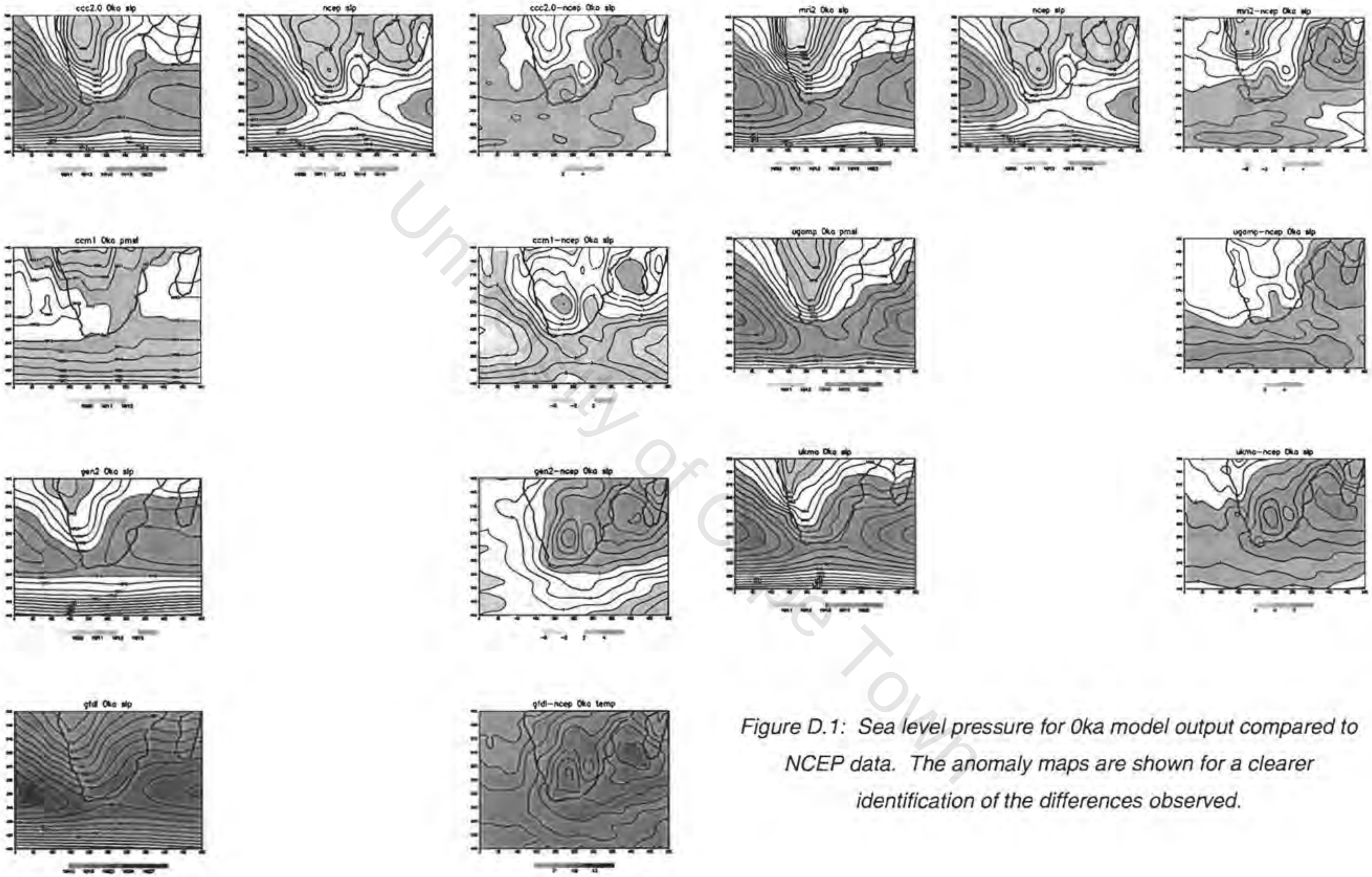
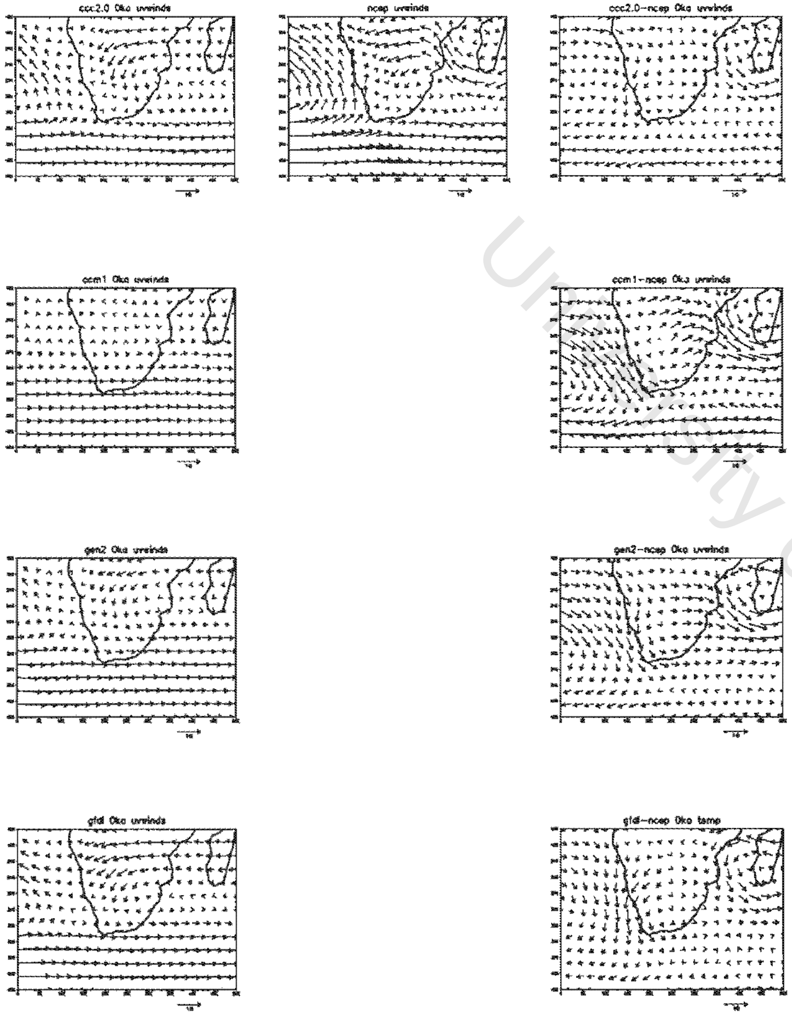


Figure D.1: Sea level pressure for 0ka model output compared to NCEP data. The anomaly maps are shown for a clearer identification of the differences observed.



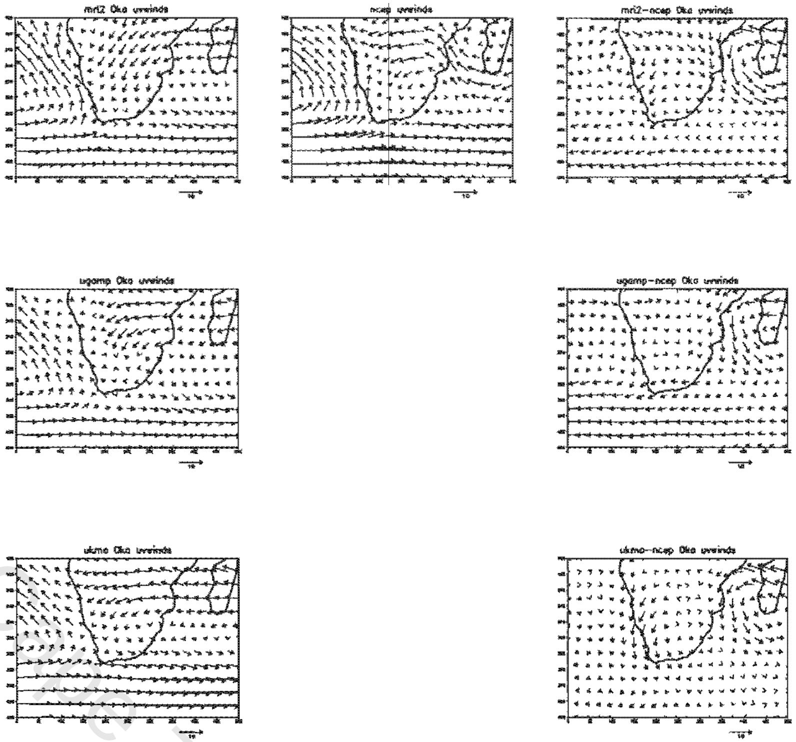


Figure D.2: *Wind data for 0ka model output compared to NCEP data as observed. The anomaly maps are shown for a clearer identification of the differences observed.*

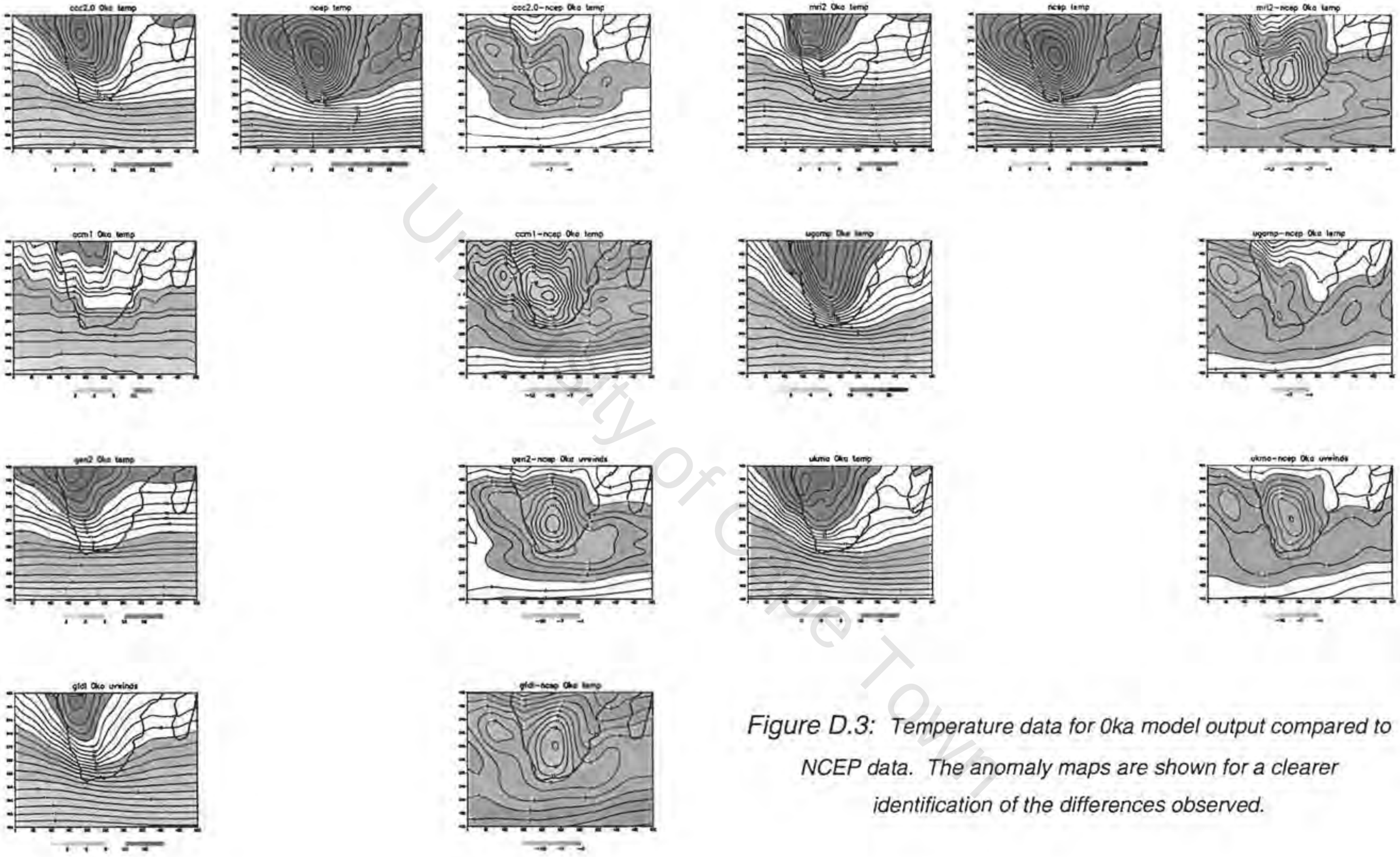


Figure D.3: *Temperature data for 0ka model output compared to NCEP data. The anomaly maps are shown for a clearer identification of the differences observed.*

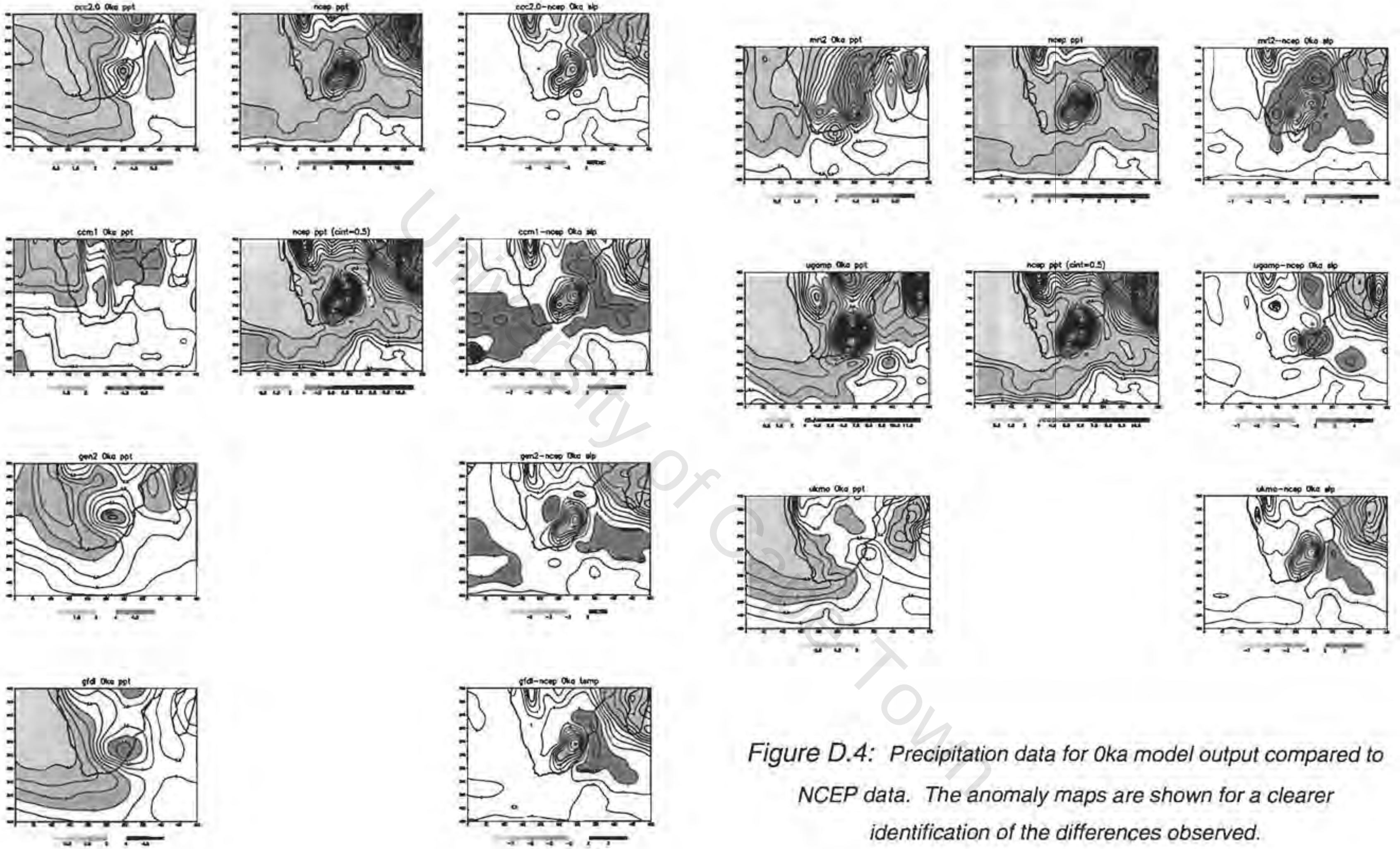


Figure D.4: *Precipitation data for 0ka model output compared to NCEP data. The anomaly maps are shown for a clearer identification of the differences observed.*

Appendix E Anomaly results per model:

The following results are listed in the tables:

Table E.1: Changes in sea-level pressure per model for 6ka and 21ka.
Table E.2: Changes in precipitation per model for 6ka and 21ka.
Table E.3: Changes in temperature per model for 6ka and 21ka.
Table E.4: Climatic changes from the clustered models (GEN2; GFDL; UKMO) for 6ka and 21ka.

Table E.1: Changes in sea-level pressure per model for 6ka and 21ka.

Model	location	6ka-0ka	21ka-0ka
CCC2.0	Interior	Marginal increases	Greater intensification
	S Atlantic	Marginal increases	Weakening of pressure
	S Indian	Greater intensification	Weakening of pressure
	S Ocean	Little change	Overall weakening, with a strengthening in the east
CCM1	Interior	-	Weakening to the west, little change in the east
	S Atlantic	-	Slight weakening
	S Indian	-	Slight strengthening
	S Ocean	-	Slight strengthening in the west leading to a weakening in the east
GEN2	Interior	Increased W-E gradient, showing a general strengthening	General decrease
	S Atlantic	Significant strengthening	General decrease
	S Indian	Significant weakening	General decrease
	S Ocean	Pronounced W-E gradient from stronger to weaker	General decrease, intensified north-south gradient
GFDL	Interior	Slight decrease to little change	Significant increase
	S Atlantic	Little change	Significant increase
	S Indian	Slight decrease	Significant increase
	S Ocean	Slight decrease, overall little change	More significant increase, showing intensified N-S gradient
MRI2	Interior	Overall slight increase	Overall significant increase
	S Atlantic	Overall slight increase	Overall significant increase

	S Indian	Overall slight increase	Overall significant increase
	S Ocean	Overall slight increase	Overall significant increase
UGAMP	Interior	Slight decrease	Significant overall increase
	S Atlantic	Slight decrease	Significant overall increase
	S Indian	Slight decrease	Significant overall increase
	S Ocean	Slight decrease	Significant overall increase
UKMO	Interior	Increasing with a decreasing seen in the center and on the W coast	Significant overall increase
	S Atlantic	Slight increasing	Significant overall increase
	S Indian	Slight increasing	Significant overall increase
	S Ocean	Slight decreasing	Significant overall increase, with strengthened N-S gradient

Table E.3: Changes in precipitation per model for 6ka and 21ka.

model	Location	6ka-0ka	21ka-0ka
CCC2.0	Interior	Wetter in E, no change elsewhere	Wetter overall, with greater intensity in E (same on W coast)
	S Atlantic	None	None
	S Indian	Slightly wetter to no change	Slight drying (Madagascar) to no change
	S Ocean	None	Slightly wetter to no change
CCM1	Interior	-	Drier in S&W parts, wetter in N
	S Atlantic	-	Slight drying
	S Indian	-	Slight drying
	S Ocean	-	Drier
GEN2	Interior	Wetter in SE, but drier elsewhere	Overall wetter, concentrated in SE and NW
	S Atlantic	Drier	Slight drying
	S Indian	Overall wetter, particularly off SE coast	Slight drying to no change
	S Ocean	Wetter with defined wet cell off SE coast	Slight drying
GFDL	Interior	Slight drying to no change (none in study region)	Slight variability to no change (none in study region)
	S Atlantic	None	None

	S Indian	None	Slight drying in S, wetter in N
	S Ocean	Slightly wetter to no change	Slight drying to no change
MRI2	Interior	Wetter, concentrated in the E	Wetter in center, no change in W, drier in E
	S Atlantic	Slight drying to no change	None
	S Indian	Significantly wetter	Slight drying to no change
	S Ocean	Variable to no change	Slight drying to no change
UGAMP	Interior	Overall drier	Variable overall, concentrated drying in E, no change in W
	S Atlantic	None	Variable to none
	S Indian	Variable to no change	Variable
	S Ocean	Slightly wetter to no change	Variable
UKMO	Interior	Wetter in E& central, drier in W&S	Wetter
	S Atlantic	None	None
	S Indian	Drier to no change	Wetter
	S Ocean	Variable to none	Variable to no change

Table E.4: Changes in temperature per model for 6ka and 21ka.

model	Location	6ka-0ka	21ka-0ka
CCC2.0	Interior	Overall cooling, stronger in the central S & SW	Strong cooling, concentrated in center
	S Atlantic	Slight cooling	Cooler
	S Indian	Slight cooling	Cooler
	S Ocean	Slight cooling	Cooler, to lesser extent SW of continent
CCM1	Interior	-	Overall cooler, with strong N-S gradient
	S Atlantic	-	Overall cooler, with strong N-S gradient
	S Indian	-	Overall cooler, with strong N-S gradient
	S Ocean	-	Overall cooler, with strong N-S gradient
GEN2	Interior	Overall cooler	Overall cooler
	S Atlantic	Cooling, stronger in S	Overall cooler
	S Indian	Slight cooling as move S	Overall cooler

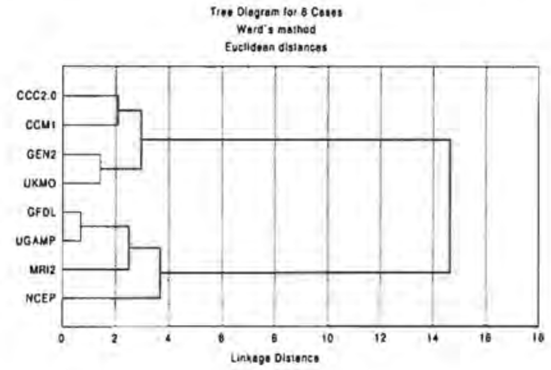
	S Ocean	Cooler, showing N-S gradient	Overall cooler
GFDL	Interior	Warmer in N, to cooling in S	Overall cooling, greater in center
	S Atlantic	Cooling	Cooling
	S Indian	Cooling	Cooling
	S Ocean	Cooling	Cooling
MRI2	Interior	Strong warming, particularly in N center	Overall cooling, particularly in NW
	S Atlantic	Strong warming	Cooling
	S Indian	Strong warming	Cooling
	S Ocean	Strong warming	Cooling
UGAMP	Interior	Warming in N, decrease in S	Overall cooling, weaker in NW & south coast
	S Atlantic	Warming in N, decrease in S	Cooling, concentrated in center
	S Indian	Slight cooling to no change	Slight cooling from S-N
	S Ocean	Slight cooling	Cooling, slight N-S gradient
UKMO	Interior	General warming, with cooling in S&W regions	Overall cooling, weakening along S coast
	S Atlantic	Cooling to slight change	Cooling, but colder in N
	S Indian	Warming along Natal coast, with slight cooling to no change	Cooling, from S to N
	S Ocean	Cooling to no change	Cooling

Table E.5: Climatic changes from the clustered model group GEN2; GFDL; UKMO for 6ka and 21ka.

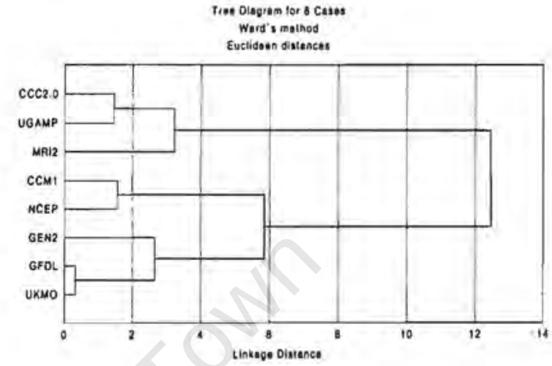
VARIABLE	**6ka-0ka**	**21ka-0ka**
Sea-level pressure	Increased SW-ly flow along an increased pressure gradient. Strengthened S Atlantic HP, weakened SE Indian HP	Weakened LP S of country. Greater HP overall. Increased N-S gradient
Winds	Increased SW-ly flow. +ve therefore general strengthening of flow	Weaker westerly flow S of country. This reflects deepened N-S gradient.
Precipitation	Dry over Atlantic & W interior. Wetter S of continent. Little change for S coast	Wetter over interior, dry S of continent and SW coast.
Temperature	Warmer over N interior. Cooler over rest, with increased cooling on W coast	Overall cooler, greater cooling in the N interior, milder on SW coast

Appendix F   Ward's linkage cluster trees

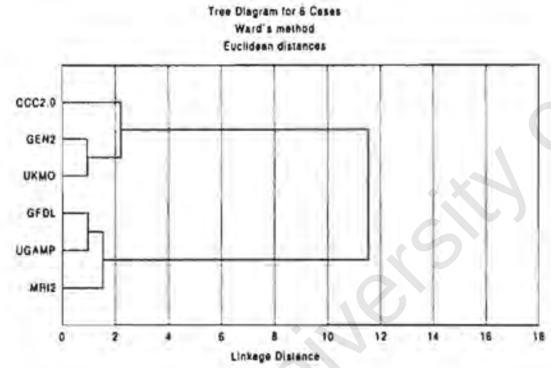
Tas (x_i-x) Surface air temperature
0calca



pmsl (x_i-x) Sea Level Pressure
0calca



6fixca



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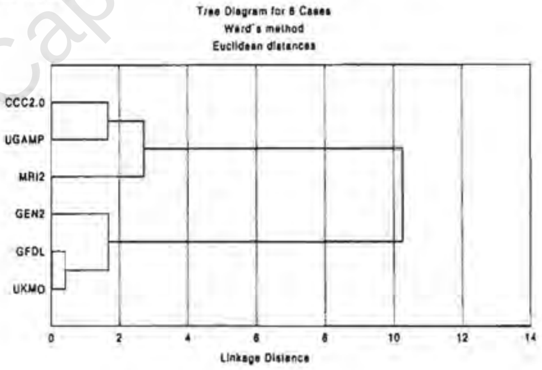
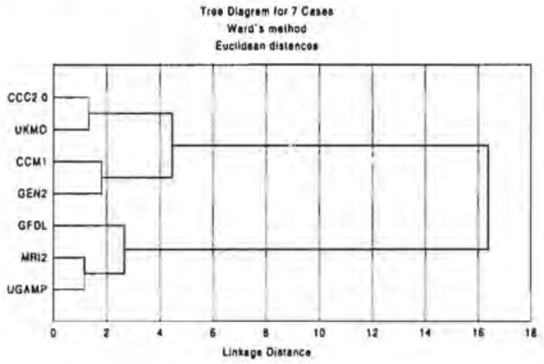
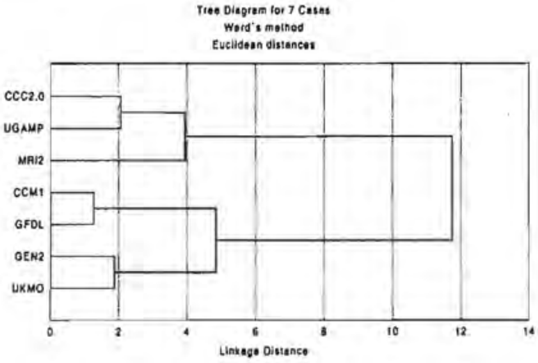


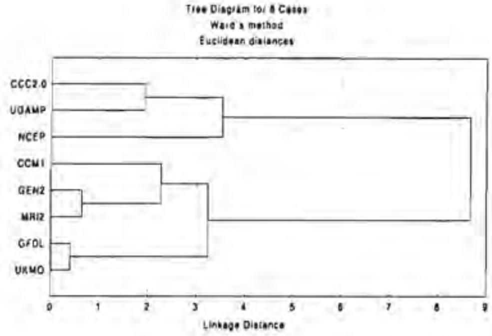
21calca



21calca



u winds (x_i-x) at 850hPa level
0calca



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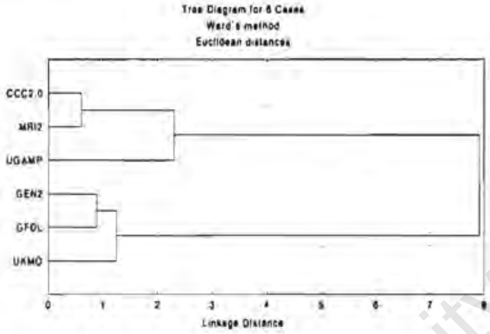
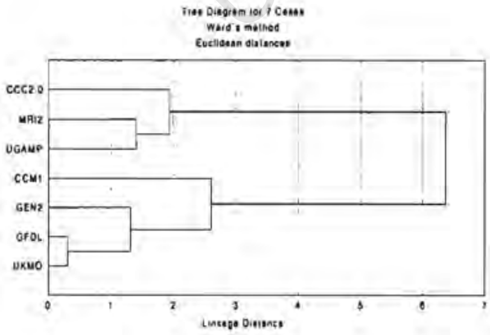
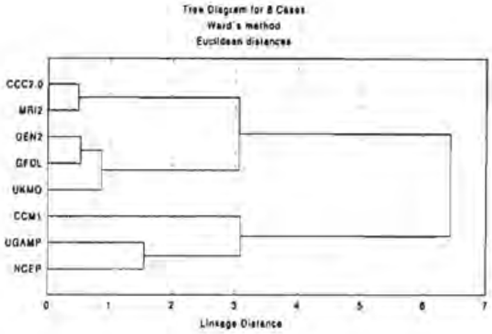


21calca



v winds (x_i-x) at 850hPa level
0calca



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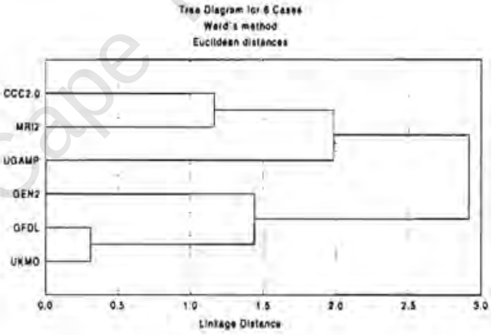

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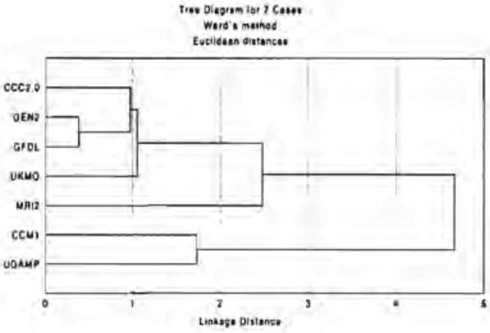
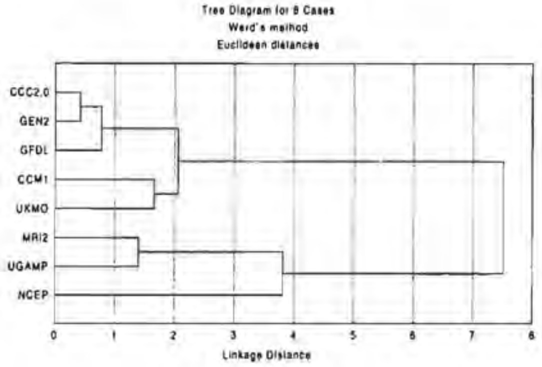


pr (x_i-x) Total precipitation

0calca



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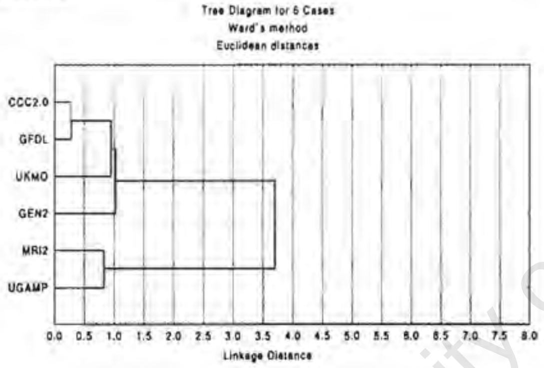
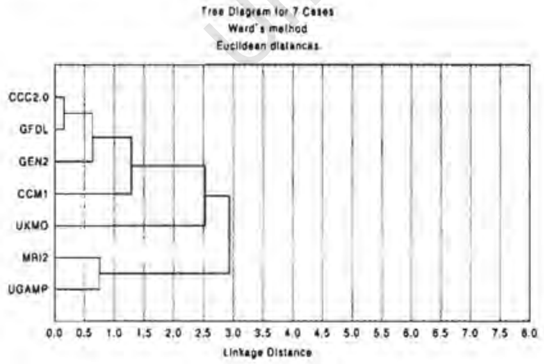
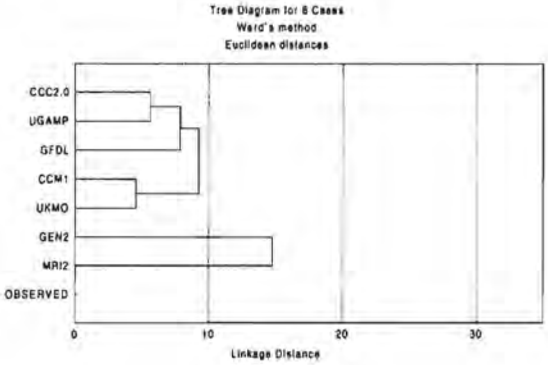


21calca



clt (x_i-x) Total cloud cover

0calca



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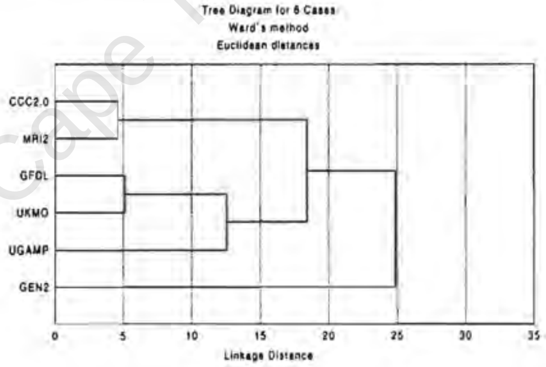

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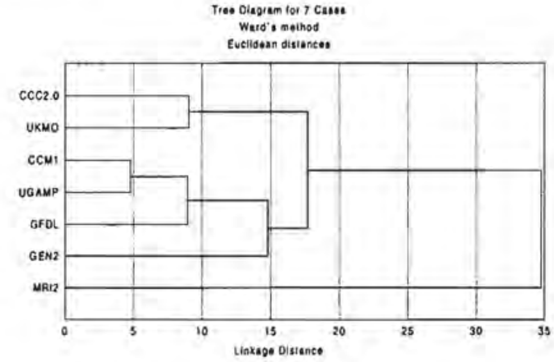
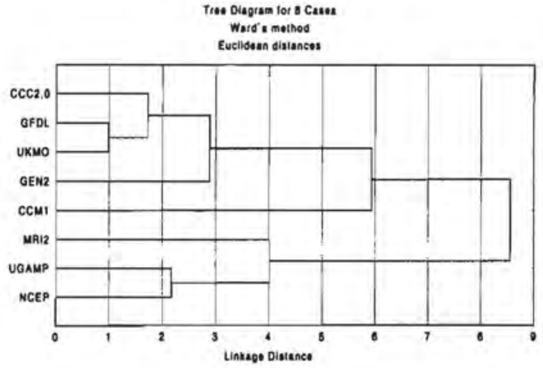


ta (x_i-x) Temperature at 850hPa
(z=2)
0calca



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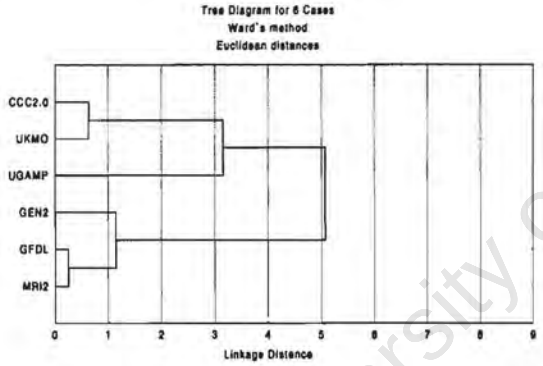

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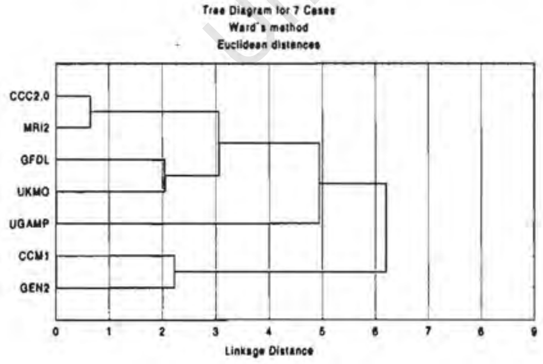
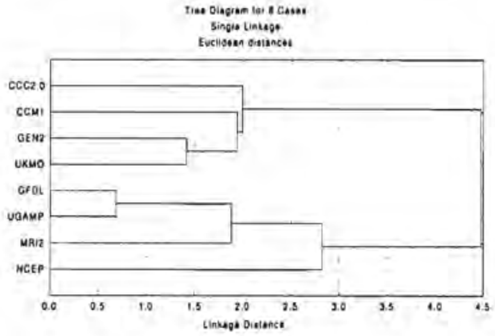


Appendix G Single linkage cluster trees

Tas (x_i-x) Surface air temperature

0calca



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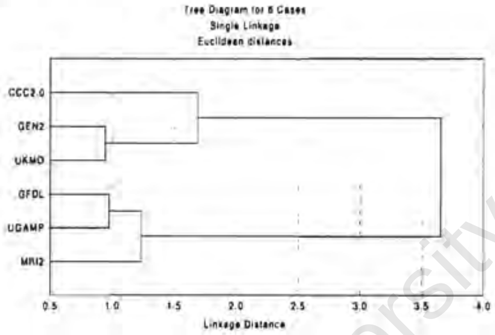
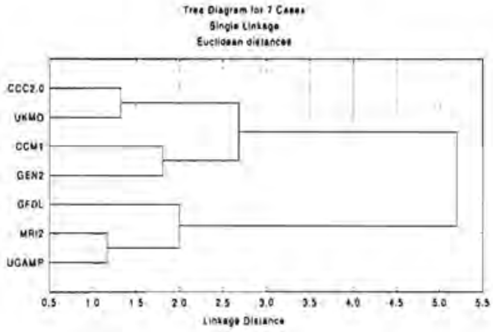
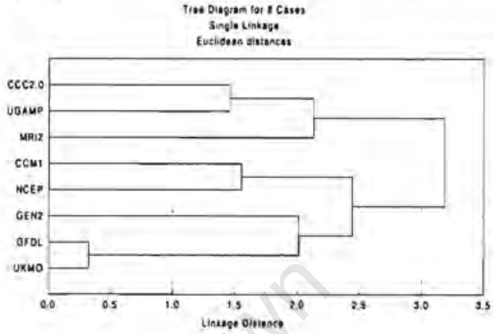


21calca



pmsl (x_i-x) Sea Level Pressure

0calca



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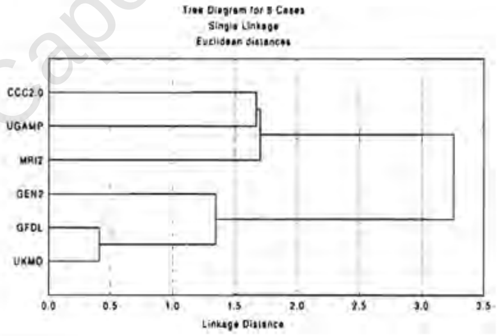

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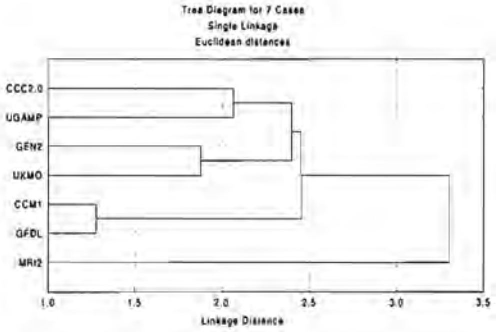
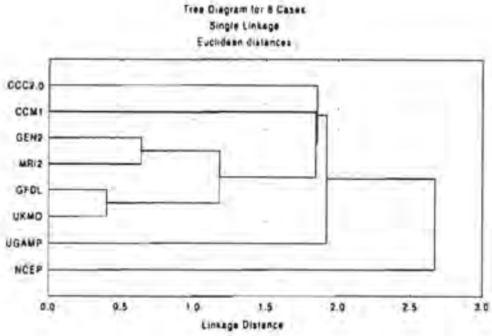


u winds (x_i-x) at 850hPa level

0calca



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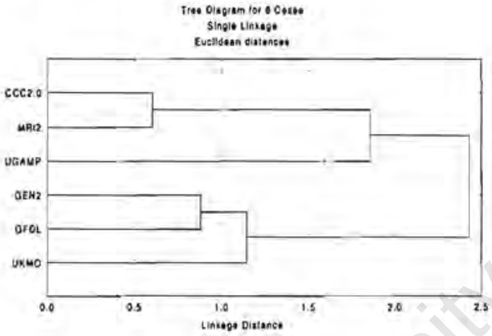

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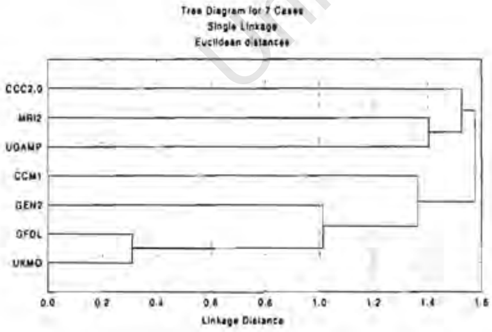
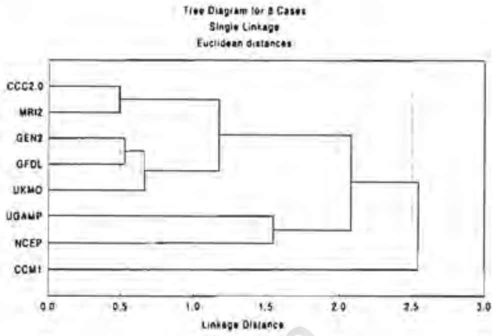


v winds (x_i-x) at 850hPa level

0calca



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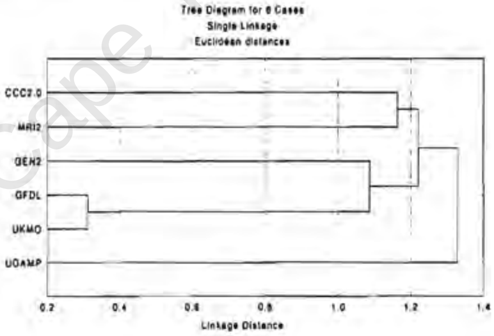

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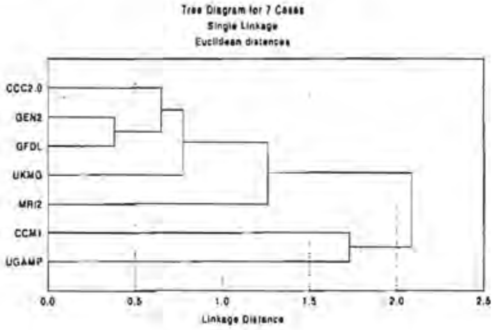
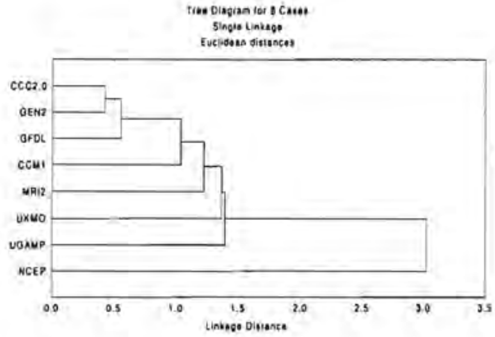


pr (x_i-x) Total precipitation

0calca



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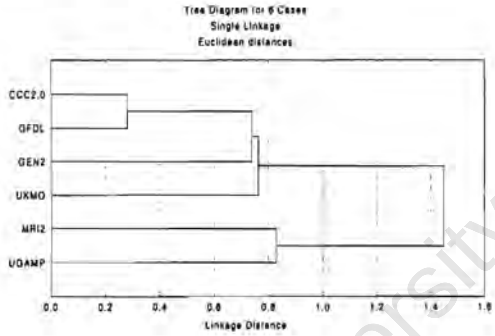

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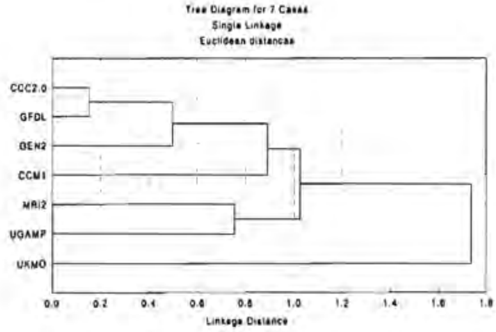
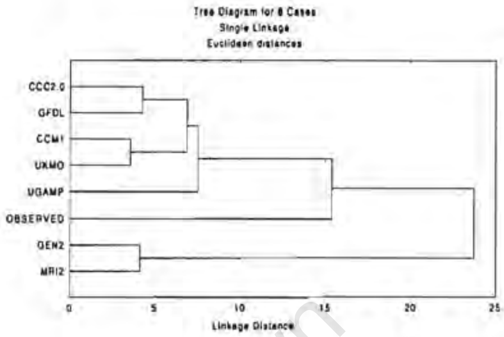
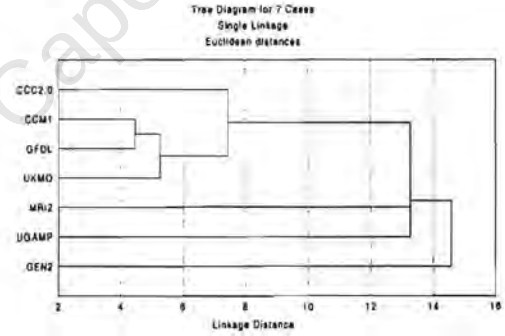


clt (x_i-x) Total cloud cover

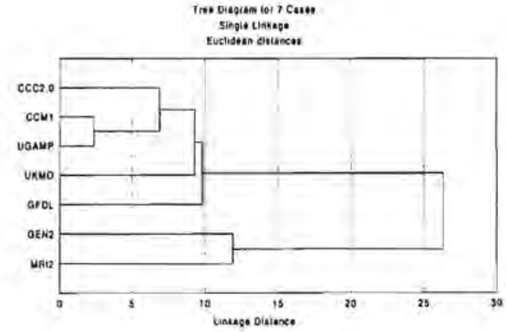
0calca



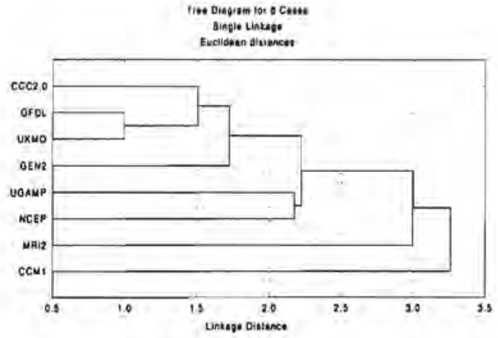
6fixca



21calca



ta (x_i-x) Temperature at 850hPa
(z=2)
0calca



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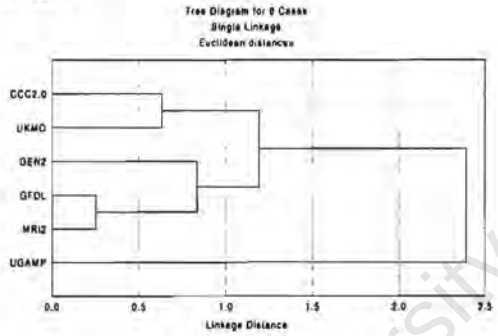

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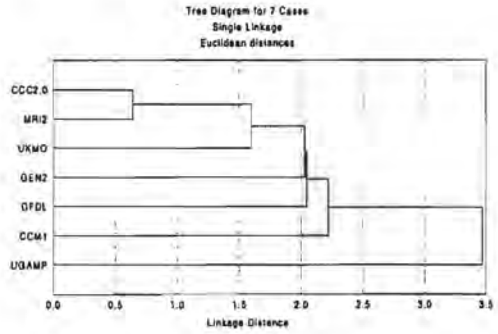

Appendix H PMIP Models

Concise details of the PMIP models used in the study as well as some forcing factors are included in this appendix. The list of tables explains the data to follow:

Table H.1: The CO2 concentration values, the different cycles included and the value of the solar constant.
Table H.2: The orography used.
Table H.3: Sea Surface Temperatures and Sea Ice.

Table H.1: The table lists the values for CO2 concentration, the different cycles included and the value of the solar constant.

Models	**CO_2 (ppm)**			**Cycles**	**Solar constant (W/m^2)**
	0ka	**6ka**	**21ka**		
CCC2.0	280	--	200	Seasonal/ diurnal	1365
CCM1	330	--	191	Seasonal	1365
GEN2	345	--	246.4	Seasonal/ diurnal	1365
GFDL	300	--	214.3	Seasonal	1365
MRI2	345	--	200	Seasonal/ diurnal	1365
UGAMP	345	--	200	Seasonal/ diurnal	1365
UKMO	323	--	229	Seasonal/ diurnal	1365

Table H.2: The table lists the prescribed orography for control, 6ka and 21ka (both the ice sheet extent and the surface elevation change compared to the present day are used).

Models	**0ka**	**6ka**	**21ka**
CCC2.0	GatNel	GatNel	[PMIP]
CCM1	GatNel	--	Peltier(21k)
GEN2	US Navy ?FNOC?	US Navy ?FNOC?	[PMIP]
GFDL	[AMIP]	[AMIP]	[PMIP]
MRI2	[AMIP]	[AMIP]	[PMIP]
UGAMP	[AMIP]	[AMIP]	[PMIP]
UKMO	[AMIP]	[AMIP]	[PMIP]

GatNel = Gates and Nelson (1975)

Peltier(21k) = Peltier's Last Glacial Maximum data (1994)[1]

[AMIP] = US Navy 10'x10' dataset (Joseph, 1980)

[PMIP] = Peltier (21k) - Peltier(0k) + orog(used for control run)[1]

US Navy ?FNOC? = Kineman, 1985

*) There are two methods used to compute the zonal equator-to-pole (meridional) oceanic heat transport (OHT) in the PMIP simulations (Table H.3):

- Method a) Inferring the OHT and associated transport from a present day experiment with prescribed SSTs.
- Method b) Inferring OHT from observed estimates (difference between satellite radiation measurements and calculated atmospheric transports).

Table H.3: The Sea Surface Temperatures (SST) and Sea Ice used in the models.

Models	**SST**		**SEA ICE**	
	0 & 21ka	**6ka**	**0 & 21ka**	**6ka**
CCC2.0	Method a	AlMob	CLIMAP(21k)	AlMob
CCM1	Method b	-	CLIMAP(21k)	-
GEN2	Method b	Shea	CLIMAP(21k)	Shea
GFDL	Method a	[AMIP]	CLIMAP(21k)	[AMIP]
MRI2	Method a	[AMIP]	CLIMAP(21k)	[AMIP]
UGAMP	Method a	AlMob	CLIMAP(21k)	AlMob
UKMO	Method a	MOHSST3	CLIMAP(21k)	MOHSST3

[AMIP] = For Sea Surface Temperature : Reynold's data (1979-1988) - 10 years mean[1].

For Sea-ice : US Navy and National Oceanic and Atmospheric Administration Ice Joint Center data for 79-88[1].

AlMob = Alexander and Mobley (1976)

Shea = Shea et al. (1992)

MOHSST3 = Meteorological Office Observational Climatology (1951-1980)[1]

CLIMAP(21k) = CLIMAP Last Glacial Maximum data (1981) [1]

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[1] http://www-pcmdi.llnl.gov/pmip/docs/modsstseaice.html