GLOBAL AND REGIONAL CLIMATE MODELING: APPLICATION TO SOUTHERN AFRICA

by

B.C. HEWITSON

Department of Environmental and Geographical Science
University of Cape Town
Cape Town

Report to the Water Research Commission on the Project

"Dynamical modeling to investigate regional climate response to global change forcing"

Head of Department: Professor R.F. Fuggle
Project Leader: Assoc. Prof. B.C. Hewitson

WRC Report No. 806/1/01
ISBN No. 1 86845 712 5

ACKNOWLEDGEMENTS

The research in this report emanated from a project funded by the Water Research Commission entitled :

"Dynamical modeling to investigate regional climate response to global change forcing"

The Steering Committee responsible for this project, consisted of the following persons :

Dr. GC Green	Water Research Commission (Chairman)
Mr. H Maaren	Water Research Commission
Dr. W Jordaan	South African Weather Bureau
Prof. P Tyson	University of Witwatersrand
Prof. RE Schulze	University of Natal
Dr. CJ de W Rautenbach	University of Pretoria
Proj. J van Heerden	University of Pretoria
Mr.s. A Riphagen	South African Weather Bureau
Mr. W Tennant	South African Weather Bureau
Prof. J Litjeharms	University of Cape Town

The financing of the project by the Water Research Commission and the contribution of the members of the Steering Committee is acknowledged gratefully.

This project was only possible with the co-operation of many individuals and institutions. The author therefore wishes to record sincere thanks to the following collaborators:

- Dr. Debbie Hudson
- Mr. Chris Jack
- Mr. Jeremy Main
- UK Meteorological Office support team
- NCAR MM5 support team
- Prof. W. Gutowski, Iowa State University

Dynamical modeling to investigate regional climate response to global change forcing

B.C. Hewitson
University of Cape Town

EXECUTIVE SUMMARY

The project on global and regional modeling seeks to develop capacity on dynamical modeling for the purpose of addressing the issues of climate change over southern Africa. This objective is in response to the recognition that global climate change holds serious consequences for South African society, perhaps more so than for many other nations due to the variable nature of the regional climate, the dependence by society on primary production, the scarcity of water, and the utilization of marginal lands for agriculture.

Compounding this situation is the limited capability for dynamical model investigations of climate processes, the small research community, and the almost total lack of high-end computing in South Africa to support research in this field. While there is a rich heritage for empirical research in South Africa, this approach is intrinsically constrained by the data of the past, and has difficulty in projecting future changes in the climate system. In order to undertake such research a tool based on the physical dynamics of the global system is required. This is computationally expensive, and hence has little support base in South Africa.

In contrast, many developed nations devote entire institutions to this task. However, the work undertaken overseas seldom addresses the regional questions for South Africa, and it is left up to the local scientists to tackle this problem. To this end the project seeks to:

- develop a viable base for regional climate change studies through process based modeling,
- adapt and evaluate nested modeling procedures for Southern Africa,
- develop the skills and expertise in regional climate modeling among scientists and students,
- generate process-based regional climate change scenarios to complement empirical techniques.

The primary results of this work are on two levels, that of capacity building, and that of model evaluation and development. In addition, the model has been tested in a sensitivity study. In reaching the primary objective of capacity building there has been the establishment of a computational system capable of supporting the climate modeling activities, and the installation, validation, and use of suitable global and regional climate models. The computational system has been developed around high-end computational servers as an alternative to costly supercomputers. The installed system delivers the performance of a low-end supercomputer, while costing approximately 1/10th of an equivalent supercomputer. Furthermore, the system is expandable and allows for extension as funding allows (demand, even now, greatly outstrips available performance). The system was jointly funded from multiple research sources, and directly support 5 WRC projects in the atmospheric/ocean studies.

The installed models directly related to this project include the UK Meteorological Office Unified model for global modeling, and the PennState/NCAR MM5 regional climate model for regional studies. Each of these models are considered world leaders, have a large user base in the international community, and have continued active development by the original developer teams. In addition to these models, which are used directly in this project, the computational system is used by the oceanographic community to operate their complementary ocean models.

In terms of building capacity among people, a core group of scientists and students has been created who have developed key expertise in running the models, and understanding the related operational difficulties. It must be noted that installing and running the model is only half the problem, and that understanding what the model can and cannot do, and how to correctly use the model is as important. To this end valuable collaboration has been developed with international scientists, particularly in the USA and in the UK. These links have led to further research activities, and greatly benefited the skill of the local researchers.

In terms of the development objectives of the project, the global UM model has been successfully ported to the local hardware, and a number of short duration global simulations undertaken with the model. These have been used in two ways, firstly to evaluate the model performance over southern Africa, and secondly to conduct a basic science experiment of the regional climate sensitivity to the doubling of atmospheric CO_2.

In the first study the global model is run with the standard forcing for present day conditions – namely the same orbital and solar constants, the observed distribution of vegetation and land masses, present day atmospheric chemistry, and with prescribed climatological sea surface temperatures. The model simulations, while not long enough to develop a climatology, are shown to simulate climate dynamics that fall within the observed variability of the climate system.

In the second global experiment, all parameters of the model are retained as before, with the exception of a doubling of the atmospheric CO_2 concentration. As such, this represents a simple sensitivity experiment to look at the first-order response of the climate system. The results indicate a response that is in full accord with the physical principles, and also in general agreement with the climate change results shown by other global simulations undertaken overseas. In light of the demonstrable performance, and the success obtained with the model by other international institutions, it appears that the model is suitable for southern African studies. Furthermore, as the model has a sophisticated interface facilitating easy use of the model by scientists with limited experience, the model is particularly appropriate for the southern Africa community.

The global models, however, do not capture the regional details. These global models are orientated toward capturing the coupled global system, including the complexities and feedbacks from such features as El Niño. Thus a regional model is required to obtain the required spatial scales for understanding climate impacts. The regional model is used over a limited domain (in this case, southern Africa), and has its boundaries forced by the more coarse resolution data derived from the global model – a so called nested simulation, where the regional model is "nested" in a larger domain. Here the model integrates the peripheral synoptic scale forcing and simulates the regional climate with cognizance of the regional forcing factors, for example complex topography.

Three regional experiments are presented in this report; a simulation of the Laingsburg flood event of 1987, and two nested runs where the model is nested within the global simulations of the present day, and the global simulation with doubled atmospheric CO_2. In the Laingsburg case the model responds well, simulating the complex event well, with the possible residual errors also attributable to the boundary data used, or the mismatch in characteristics between model data and observational station data.

The two remaining nested simulations focus on deriving regional detail from being driven with the coarse resolution global simulation data. When nested in the present day global simulation the regional model effectively captures the regional detail over the sub-continent, including the complexities of the topographical forcing. With the doubled CO_2 simulation, the model captures the regional detail of the climate response, and provides specific information not obtainable form the global simulation.

Overall the models suggest a future climate that is warmer (especially in summer) with the greatest warming located over the continent and the maximum towards the western half of southern Africa. In addition, there is an increase in atmospheric humidity, although the translation of this change in terms of rainfall is less clear. These results are completely in accord with global studies undertaken elsewhere in the international community, and are qualitatively in agreement with the regional projections of the IPCC third assessment report (IPCC, 2001).

The above results effectively demonstrate the success of the development of the modeling infrastructure. As a direct consequence of this work new funding and targeted research based on climate modeling has been initiated to address the critical climate issues for southern Africa: climate change, variability and extreme events, and seasonal forecasting. These activities have been developed as a team initiative based on the capacity developed through this project, and involve the greater proportion of the academic atmospheric science community in South Africa.

The primary recommendation to come from this is for continued support of capacity to maintain a critical mass, and functional hardware infrastructure. It is well recognized that dynamical modeling is by far the optimum means of investigating future developments of the climate system, and for understanding the processes governing the current variability. However, it is not a single-scientist task, and requires a team approach. While expensive research by South African standards, it is nonetheless critical that we follow this path, as witnessed by the substantially greater investment in this approach implemented in other nations.

Table of Contents

LIST OF FIGURES

1. Introduction

The potential of global climate change as a consequence of increased anthropogenic greenhouse gas emissions has long been recognized as a threat to society. As a result, extensive resources are being invested in climate change research by many nations in an effort to understand the potential regional manifestation and impacts of such change.

The Inter-governmental Panel on Climate Change (IPCC) is tasked with periodic assessment of the current state of climate change. In the second assessment report (IPCC, 1995), the principal conclusion was that there is substantial evidence that anthropogenic emissions are causing global changes (IPCC, 1995). In the third assessment report, currently in preparation, the conclusion is that the scientific community now has strengthened confidence in this statement (Mitchell, *pers comm*), while the balance of the draft report indicates a potential for significant impact on society.

A primary tool underlying the IPCC related research is that of dynamical models – computer representations of the underlying physics and dynamics of the coupled global system – used to derive projections of future climate states. This approach is seen as essential to developing understanding of climate change, since alternative empirical/analogue techniques are inherently constrained to the characteristics of past climate, and cannot incorporate processes that may lead to threshold or non-linear changes by the climate system. Although it is well recognized that the dynamical models are not perfect, it has been shown that the models are able to capture the climate system trends of the past century[1] (see Figure 1), and thus one may have reasonable confidence in their ability to project future climate.

1.1 Uncertainty

At present, the greatest uncertainty is related not to whether climate *will* change, but rather a) what path the future global emissions of greenhouse gases will follow, and b), given an emissions scenario, what the regional manifestation of the consequent climate change will be. The emissions scenarios are themselves the subject of a concerted research effort[2] that has, to date, concluded that there are four equally probable pathways in response to global economics and politics, as follows (taken from http://sres.ciesin.org/):

- The A1 storyline and scenario family describes a future world of very rapid economic growth, low population growth and rapid introduction of new and more efficient technology. Major underlying themes are economic and cultural convergence and

[1] See http://www.cru.uea.ac.uk/link/
[2] See http://sres.ciesin.org/

capacity building, with a substantial reduction in regional differences in per capita income. In this world, people pursue personal wealth rather than environmental quality.

- The A2 storyline and scenario family is a very heterogeneous world. The underlying theme is that of strengthening regional cultural identities, with an emphasis on family values and local traditions, high population growth, and less concern for rapid economic development.
- The B1 storyline and scenario family describes a convergent world with rapid change in economic structures, "dematerialization" and introduction of clean technologies. The emphasis is on global solutions to environmental and social sustainability, including concerted efforts for rapid technology development, dematerialization of the economy, and improving equity.
- The B2 storyline and scenario family is a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is again a heterogeneous world with less rapid, and more diverse technological change but a strong emphasis on community initiative and social innovation to find local, rather than global solutions.

The other side of uncertainty relates to the regional manifestation of global change, and is a critical component, as it is only when one understands the regional manifestation that society may develop appropriate adaptation and mitigation strategies. This area of research is also receiving much attention, as the *global* modeling tools used in climate change research perform best at the synoptic and larger scales of atmospheric processes. At the local scale the coarse spatial grid resolution of the global models (on the order of only 200-300 km) is unable to resolve the characteristics of the regional response. Moreover, when considering the important variable of precipitation, the global model performance at the regional scale is especially problematic.

There are two methodological approaches available to address this problem; firstly empirical techniques which derive regional scale information based on empirical relationships with the larger scale forcing from the global model. This can be very effective, and has been the focus of a separate WRC project (Hewitson, 1997). However, the technique has limitations in that it does not provide a clear interpretative framework for understanding the processes underlying the change. In addition, the technique is inherently constrained to the historical range of climate variability.

The alternative technique is again one of dynamical modeling, but in this case a regional model with a high spatial resolution over a limited domain is used. In this approach the regional model is nested in the global model; i.e. forced on the boundaries of the domain with the lower resolution data derived from the global simulation. This approach thus incorporates the forcing from non-local but important global features, such as El Niño, yet accommodates the local details (e.g. topography), and provides a high spatial resolution consistent with the global forcing. In addition, the regional model now provides a full 3-dimensional representation of the circulation dynamics, allowing investigation of the processes driving the climate change.

2. Constraints and objectives in nested modeling for South Africa.

2.1 Background and objectives

While the nested modeling approach in principle addresses the research needs for South Africa, it is nonetheless an expensive approach: expensive financially, computationally, and in developing personnel skills. The global and regional models are the result of years of development by teams of scientists, and thus out of the scope of the South African research community. Fortunately, selected models from international institutions are available to the wider scientific community. However, the skills and computational hardware to support the use of these tools are particularly lacking in southern Africa.

At present the only active climate modeling activities in the SADC region take place at the SA Weather Bureau (which is focused on short term forecasting and not climate change), and at the University of Pretoria where some global modeling has taken place. Apart from this, the modeling that has taken place with an Africa focus is generally undertaken at overseas institutions (e.g.: Sun et al., 1998a,b) Nonetheless, in recent years there have been few modeling studies undertaken at institutions in southern Africa. These, however, have been focused primarily on case studies of weather events (e.g.: Crimp and Mason, 1998, Crimp et al., 1998, Mason and Joubert, 1997). In part this has been due to limited modeling expertise in the South African community, but primarily due to a lack of suitable computational infrastructure.

Given the variability of the climate system over South Africa, and the particular vulnerability of society to the climate system due to the strong dependence by society on primary production, there is a critical need to develop capacity for modeling climate change. These needs are what this project principally addresses, namely to:

- develop a viable base for regional climate change studies through process based modeling,
- adapt and evaluate nested modeling procedures for Southern Africa,
- develop the skills and expertise in regional climate modeling among scientists and students,
- generate process-based regional climate change scenarios to complement empirical techniques.

Consequently, the bulk of this report is focused on development. A key principle underlying the work to reach these objectives, is to establish a sustainable framework including the support tools required for ongoing usage of the modeling tools. For example, while an individual may implement a model in order to address a particular research question, such an approach inevitably involves once-off software and procedures that are not documented, nor easily understood or adopted by other researchers, or by students.

2.2 Infrastructure

Dynamical modeling is an especially computationally demanding task, run for the most part on supercomputers at major climate research institutions[3]. Suitable hardware infrastructure capable of handling current generation global and regional models has until now not been available to the academic research community in southern Africa[4]. While supercomputers are prohibitively expensive, practical alternatives now exist in the form of high-end workstation servers. These can provide Giga-flop performance at the level of low-end supercomputers, and cost ~1/10th the cost of an equivalent "super-computer[5]".

The particular requirements for such a machine involve significantly more than simple processor clock speed, an often quoted benchmark. Rather the systems need to be integrated with substantial high-speed memory, fast communication between memory and CPU, and extensive fast disk storage arrays. The combined package is then capable of sustained Giga-flop throughput.

Even such a system is expensive by South African funding standards. For this project the joint resources of Water Research Commission projects, the National Research Foundation, ESKOM, and the University of Cape Town were used to jointly fund a high-end computational system based around the Silicon Graphics Origin 2000 core system. The system is dedicated to system modeling and supports ~15 scientists, and is composed of the following key components:

- Origin 2000 6-processor computational server (~2.5 Giga-flop performance)
- 1 Gigabyte memory
- ~300 Gigabyte RAID disk storage
- 100baseT networking

The balance of this report now focuses on the implementation of global and regional nested models, their characteristics, requirements, and performance over the southern Africa domain. It should be re-emphasized that the results reported here are not intended as definitive modeling studies – rather they are results from work focused on establishing

[3] See for example: http://www.ncar.ucar.edu
http://www.meto.gov.uk
http://www.csiro.au

[4] While low-end supercomputers exist at the SAWB, these are not available for extensive climate change modeling.

[5] For example, a CRAY J90, such as used by the SAWB.

a base for future modeling work, evaluating the models, and for refining the procedures and developing skills.

3. Global Modeling – The UK Meteorological Office Unified Model

The UK Meteorological Office (UKMO) Unified Model is one the leading global models currently available. This model has in recent years been extensively rewritten to take advantage of current computing hardware and incorporates a fully coupled dynamical ocean model. Packaged with a comprehensive user interface the model is accessible to students and scientists not especially computer literate. In addition the UKMO is committed to an ongoing development program for the model, and explicitly supports external licensed users. The model is termed the Unified Model (UM) as it targets multiple applications of earth system modeling, from short-term weather forecasting through to long-term climate simulations.

3.1 General model description

The UM is well described on the Web[6], but the salient features are reviewed here. The material in this section is drawn largely from the UM documentation.

The model contains representations of both the physical and dynamical processes that are occurring within the atmosphere, land surface, and oceans. Both global and regional configurations are available, although only the global implementation is applied here. The fully dynamical ocean sub-model may represent the ocean, or alternatively a simpler mixed layer ocean may be used, or even simply prescribed sea-surface conditions may be applied.

The atmosphere component incorporates the atmospheric dynamics and physical parameterizations of sub-grid scale processes such as cloud formation. A spherical coordinate system is used, discretized horizontally on a regular latitude-longitude grid. A variable resolution is available, and in this project a grid resolution of 3.25° longitude by 2.5° latitude is used. In the vertical, 18 levels are pre-defined with the top of the atmosphere set to the 10hPa.

3.2 Model dynamics

The model dynamics are represented by the equation set covering the equations of motion, the conservation of mass or continuity equation, an energy equation and an equation of state (wind components, temperature, pressure and density). Coriolis is included, while each tracer variable is represented by a transport equation (most notable is the transport equation for moisture). For large-scale flows, the hydrostatic approximation

[6] See http://www.meto.gov.uk

is used. The vertical coordinate system is a hybrid sigma system, and is thus terrain following. The convergence of the meridians of the latitude-longitude grid as the poles are approached is controlled by the use of Fourier filtering along latitude lines. The dynamics also includes horizontal diffusion to prevent the accumulation of energy at the smallest scales.

3.3 Model physical parameterizations

The physical parameterizations are a critical component of the model performance, and represent those processes not explicitly governed by the equation set in the model dynamics. The key categories of the parameterizations are:

a) Radiation

   The model radiation code handles short-wave incoming solar radiation, and the absorption or reflection by clouds and atmospheric gases, and the Earth's surface. The albedo of the Earth's surface is dependent upon the vegetation type and is specified as an ancillary file. Long-wave fluxes depend upon the amount and temperature of the emitting medium and its emissivity. As the effects of each radiatively active constituent of the atmosphere (water vapour, carbon dioxide and ozone, etc.) are quite different, long-wave radiation is considered in six wavebands whereas short-wave is considered in four. Clouds interact to a significant degree with both long and short-wave radiation and are treated as homogeneous plane-parallel slabs. In any grid-square a number of layers may form a convective tower, and have fractional cover, height, phase and water/ice content.

b) Surface and sub-surface processes

   Each land point has an assigned soil and vegetation type with associated characteristics used to calculate the heat, moisture and momentum fluxes. Soils are calculated in four separate levels, with the temperature varying according to the radiation balance at the soil surface. Snow cover will act as an insulator to the soil. The soil moisture content is altered according to evaporation and precipitation.

   The vegetation canopy can intercept precipitation while the canopy throughfall is absorbed by the soil unless the intensity is too great or the soil is already saturated in which case surface runoff occurs. Soil water is primarily lost though evaporation and transpiration through plants. Over the sea the roughness length is increased with increasing wind speed to represent the interaction with waves.

c) Large-scale cloud and precipitation

   Fractional cloud cover with separate values for cloud water and cloud ice mixing ratios are used, with precipitation occurring at a rate which increases with increasing cloud water mixing ratios. The precipitation algorithm includes a simulation of growth by accretion and coalescence as a consequence of precipitation from a layer above and also includes the Bergeron-Findeisen process. Evaporation and melting of precipitation is allowed to take place. Dynamical ascent is the most important process but cloud may also be formed by radiative cooling and turbulent transport.

A cloud model is used to represent cumulus and cumulonimbus convection, and includes the possibility of precipitation-induced downdraughts. In addition the dilution of the cloud by entrainment of environmental air is included. One cloud model is used to represent a number of convective plumes within the grid square, and precipitation is diagnosed within that square if: (i) cloud liquid/ice content exceeds a critical amount and (ii) the cloud depth exceeds a critical value.

d) Gravity Wave Drag
The Unified Model includes a parametrised gravity wave drag, whereby flow over mountains in stable conditions excites waves. Stress exerted is proportional to the sub-gridscale variance of topography and the wind speed, and the waves allowed to propagate vertically, reducing static stability by ascent and increasing wind-shear. When "breaking" of the wave is diagnosed a drag is exerted, representing the outbreak of turbulence with the onset of shear instability.

3.4 Model interface and computational performance

The UM has a sophisticated graphical interface coupled to a database server holding experiment configurations. In this manner past experiment configurations may be simply retrieved, viewed, and altered as need be and are accessible to multiple researchers, even via the internet from remote locations. This aspect is particularly beneficial for collaborative work with researchers based at other institutions.

The interface provides access to all parameters of the model allowing easy configuration of both the physics packages and parameterizations. In addition the interface is used to configure which fields and domain are to be saved from a simulation. Figure 2a, b, and c show sample windows from the interface.

Care needs to be taken with the configuration of the files to be saved. A standard 1-year simulation, saving enough information to drive a nested regional model, can easily generate up to 10Gigabyte of data. If only a sub-domain is selected for saving then this can also affect the simulation time due to the additional post-processing tasks performed.

4. Global experiments:

Two of the global experiments are reported here, each of 18 months in duration, with the objective of:

a) validating the model,
b) carrying out a sensitivity experiment to look at the first order response to a doubling of atmospheric CO_2, and
c) generating boundary fields for the regional simulations with the nested regional model.

The control run experiment (standard forcing) is used to evaluate the performance of the model. Specific focus is paid to the daily circulation fields since monthly or seasonal means elucidate little more than the most basic features, and may often obscure errors in the model. The doubled atmospheric CO_2 run investigates the first-order instantaneous response, and both the control and doubled CO_2 runs are subsequently used to drive the nested regional model.

It must be noted that the intent here is not to generate long term climate change simulations, as these are beyond the computational capacity of the existing system. Rather, such simulations are the purview of the larger international organizations, and future work will use restart conditions from key periods in the transient climate change simulations to initialize the global model for time-slice experiments. A time-slice experiment focuses on short periods (~ 10 years) which are re-run to generate the boundary conditions for a nested model (saving boundary conditions for an entire 150 year transient simulation is impractical).

4.1 Validation of daily circulation fields with Self Organizing Maps

Before considering the model performance, a means of evaluating the model needs to be first discussed. As noted earlier, evaluating model performance with mean fields is not always very effective. An alternative to mean field patterns is to evaluate the circulation in terms of daily circulation types, and their frequency of occurrence. An ideal tool for this is the Self Organizing Map (SOM), a tool that allows rapid visualization of the distribution of circulation types. A comprehensive overview of this technique may be found in Hewitson and Crane (2000), and only a basic explanation is provided here.

Consider for a moment the daily circulation patterns, and trying to spread all possible patterns out on a surface such that similar patterns are adjacent, while dissimilar patterns are separated according to the degree of dissimilarity. Such a procedure would effectively show the range of circulation types. If one associated each type with a frequency of occurrence, this would allow rapid visualization of the characteristics of a given season, and this objective is effectively accomplished by the SOM.

More formally, the SOM maps N-dimensional data fields (in this case circulation patterns) onto a two dimensional array of nodes. In this manner the SOM would map the circulation field of, say, time step 1 to a node x_i, y_j on the array of nodes. A circulation pattern of similar type from another time step would map to this same node, or a node very close to x_i, y_j. The mapping function of the SOM is learned in a training procedure, and once trained each node has associated with it a characteristic circulation pattern. Thus, by training a SOM with global reanalysis data ("observations"), one creates a mapping function that allows subsequent evaluation of the circulation patterns from the global model.

Figures 3, 4 and 5 show the distributions obtained from such a procedure. The three SOM mapping are for all months (figure 3), December/January/February (DJF – figure 4) and June/July/August (JJA – Figure 5). The SOMs are based on 12-hourly NCEP reanalysis data spanning 1958 to 1997 (2.5°grid resolution). The spatial domain covers the region from 50S to 20S, and 15E to 45E. In each of the figures the characteristic circulation patterns for each season are shown, as represented by each node in the SOM. As would be expected, the larger the SOM array, the greater the differentiation achieved between circulation modes. Conversely, the smaller the array, the greater the degree of generalization. The array sizes used here were selected subjectively to span the dominant modes found in the data, using a 5x7 array for the annual data (35 nodes or circulation modes) and a 4x5 array for the seasonal data (20 nodes or circulation modes).

Having established the characteristic patterns, the frequency of occurrence of each pattern within the data may be determined, and the two dimensional frequency across the SOM nodes plotted. The annual, DJF and JJA 40-year mean frequency patterns are shown in Figure 6. These mean patterns, however, belie the substantial inter-annual variability that exists within the climate system. For example, Figure 7, 8, and 9 show the variability of the frequency pattern that may be found in different years, and highlights the significant difference that may occur from one season to another.

4.2 Global model control and doubled CO_2 simulations

The control and doubled CO_2 experiments are undertaken with climatological mean sea surface temperatures, and use standard forcing parameters for present day conditions (atmospheric chemistry, solar forcing, vegetation distributions, etc.). The initialization fields are from an equilibrium state of the model, so no spin-up time for the model is required. The model was configured to save the Southern Hemisphere fields only, and includes all vertical levels. CPU clock time for the simulation on a single SGI Origin 2000 CPU is about 4 days / year, and scales linearly with the addition of further CPUs up until the potential maximum of 6 on the present (shared) system.

Figure 10 shows the mean sea level pressure patterns for DJF and JJA from the control simulation. As can be seen, on the face of it there is little to tell from the mean pattern as to the validity of the simulation output. Thus the data from the simulation are mapped onto the SOM node array with the mapping function determined in the earlier SOM development with the reanalysis data (see later).

The second of the global simulations presented evaluates the first order response to a doubling of CO_2. In this simulation the parameters of the model and the surface boundary conditions are left unchanged and the only difference is the doubling of the atmospheric CO_2. As the simulation is only 18 months long these results can **not** be taken as a climate change projection. Rather, the experiment (a) tests an aspect of the model sensitivity, and (b) highlights the first order response of the climate system without taking into account how feedback processes may moderate/exacerbate the response over time. The doubled CO_2 simulation is started from the same initial conditions as the control run, and run out for 18 months as before. Again, the Southern Hemisphere is saved for further application in the nested simulations.

Before looking at the changes in daily circulation, it is perhaps interesting to consider the changes in the mean large-scale fields, recognizing this is only one season's response. Figure 11 shows the mean temperature change for DJF and JJA between the two simulations. In this case the change is a maximum over the continent, and is in accordance with most climate change results based on long term simulations.

Given the short duration of the simulation, it is perhaps more informative to consider the response of the daily circulation fields, as evaluated with the SOMs by comparing the frequency of events with those found in individual years in the NCEP data. Figure 12 shows the SOM frequency maps for the control run, and the anomaly maps for the doubled CO_2 for DJF and JJA. Looking firstly at the control run, it can be seen that the DJF frequency pattern has similarities to the pattern found in 1995 (see figure 8, top panel). Similarly, for JJA, the model frequency pattern has similarities to 1988 (figure 9, central panel). Thus, although not evaluating of the long-term behavior of the model, the SOM analysis of the simulation does indicate that the model circulation characteristics fall within the span of seasonal characteristics found in the NCEP data.

Turning to the doubled CO_2 simulation, figure 12 shows the changes in daily circulation as a result of the perturbation. The principal changes in DJF appear to be a strengthened south Atlantic high positioned further south, partnered with a commensurate reduction in westerly wave troughs positioned to the southwest. For JJA, the patterns indicate a reduction in moderate strength extensions of the south Atlantic high pressure across the continent, and an increased incidence of strong westerly wave troughs to the south west of the continent.

5. Regional modeling: the PennState/NCAR MM5 climate model

The MM5[7] model was selected for it's recognition as one of the leading regional models, and the attributes that make it particularly versatile for the African context – most notably the suitability for use on small PC-based clusters. The model is widely used at many institutions for a wide variety of applications, including nested modeling for climate change. In this latter role it is only recently that a truly climate version of the model has been released with the inclusion of an interactive land surface scheme, although for a number of years individual users have developed their own coupling to interactive land-surface schemes.

The MM5 is designed as a community model, with a broad support base, and as a result has a wider range of physics options (this is both an advantage and disadvantage, as the choice of physics packages needs to be evaluated for a given domain). In addition the model has been ported to most UNIX-based hardware systems, and may thus be used on anything from a standard PC through to a supercomputer.

A major stumbling block for many models, both global and regional, is the data interface. The MM5 is no different in this regard. In response to this a significant effort by this project has been placed on the development of pre- and post-processing software to facilitate the ingestion of data and the post-analysis in other software packages. As a result the system as implemented at UCT has the ability to interface with multiple other data formats through the common format based around GrADS. This data format is simple, understood by the broader community, and often the format of choice for data distribution. The post-processing routines developed also allow the MM5 output to be easily transferred into GrADS format for analysis, as well as into Vis5d format for 3-dimensional visualization.

Details of the model characteristics, dynamics, and physics are very well documented and not presented in detail here. These are publically available on the web at http://www.mmm.ucar.edu/mm5/overview.html. In addition bi-annual training workshops are available[8], along with an active discussion list by users who are able to assist in problem solving. The salient features are described in Text boxes 1 and 2, and are largely taken from the overview presented on the web.

The southern Africa domain presents an especially challenging domain for regional modeling due to a number of complicating factors including:

- Very strong orographic forcing
- Strong linkage to SST
- Broad ranging vegetation and surface characteristics with strong spatial gradients

[7] See the MM5 home page at http://www.mmm.ucar.edu/mm5/mm5-home.html
[8] Two students from the project have successfully completed this training workshop.

- Strong influence of both Westerly and Easterly waves
- Strong convective activity over interior

5.1 MM5 test case – the Laingsburg flood

As an initial test of the model performance under these factors, a challenging task was set to simulate the Laingsburg flood event of 1981. This event involved a cut-off low with a intense precipitation resulting in numerous deaths and damage with substantial economic impacts. For the simulation, the model was initialized with data from the 16th January and run for 10 days through to the end of the 25th January. Boundary conditions were derived from the NCEP reanalysis data with a 6-hour time interval. The model time-step used was 90 seconds, with a 30km horizontal grid resolution, 25 vertical levels, and a 64x64 grid covering the southern portion of Africa between approximately 45°S and 20°S, and 15°E and 35°E. Data were saved on a 3-hour interval.

Keeping in mind that a regional model can only perform as well as the forcing boundary conditions, the results appear to be remarkably good, especially considering the challenging nature of the particular case being simulated. The MM5 captures the evolution of the cut-off low well, along with the local modification of surface features by the complex regional topography. For example, figure 13 shows the wind field at sigma level 0.52 (~ 500hPa) from the NCEP boundary fields, and the MM5 simulation (regridded to the NCEP grid for comparison), for 12Z on the 25th of January. The key difference of note here is that the MM5 has positioned the center of the low slightly to the north of where the NCEP data places it.

In terms of precipitation the MM5 appears reasonable, as shown in figure 14, where the MM5 precipitation is compared with regridded station observations derived from the CCWR database[9]. While discrepancies exist, it is difficult to say whether the MM5 is at fault, or the NCEP fields, or the gridded station data. In all likelihood all three have a role to play. Thus the comparison needs to be interpreted in light of the following points:

- The MM5 produces area averages across a grid cell. Thus for a 30km by 30km grid cell the MM5 precipitation represent the integrated value across the cell, and is thus naturally a different measure to a spot values as would be represented by a station observation.
- The cut of low was positioned further north in the MM5, and this would position the rainfall processes differently, and with topographical modulation alter the rainfall pattern.
- Regridding station data itself introduces error, as it makes assumptions about how the data changes across space, and is inherently biased away from difficult terrain through the location of stations.

[9] Computing Center for Water Research – http://www.ccwr.ac.za

5.2 Nested modeling with global model forcing.

As an example of nesting within a global model, a case study is presented here where the MM5 is nested within the UM control and doubled CO_2 simulations described earlier. The month of January is focused on, as the summer season is one of the key concerns for South Africa. The MM5 model is started 10 days prior to the start of the month in order to allow the boundary conditions to propagate through the domain.

In this experiment the MM5 has not been tuned at all and the MM5 physics options used are noted in text box 1. The same grid (30km) and domain size (64x64) is used as was in the Laingsburg experiment. The domain selected is chosen to be small to avoid the regional model developing it's own climatology in the center of the domain. This approach was adopted after discussion with a number of modelers internationally, and appears to be advocated by most of nested modeling community focused on climate modeling (as opposed to forecasting) (F. Giorgi, *pers com*).

5.3 UM fields versus MM5 results – control run

The nesting within a climate control run, as undertaken here, is markedly different from the previous section in which the MM5 model is driven by observational data. In the case of a control run the boundary data are derived from the UM simulation which, apart from the sea surface temperature fields, is a free-running simulation of the climate, and not of a particular period in the observational record. The MM5 results are thus not comparable with any particular observational data set other than at the qualitative level of mean patterns.

The initial evaluation of the MM5 results are presented as a comparison of the MM5 fields with the UM fields from the global control run. Figures 15, 16, and 17 show mean January fields from the UM fields, and the equivalent fields extracted from the MM5 simulation. In the figures it is important to note that the periphery of the domain represents the region where the boundary forcing is applied -- essentially the low-resolution boundary field from the UM interpolated onto the MM5 grid. Consequently, the periphery should not be interpreted as the MM5 response.

The monthly mean figures indicate that the MM5 introduces much of the regional detail clearly lacking in the UM fields. In particular, the MM5 captures the local modification of wind flow over the complex topography of the escarpment, and the acceleration of the wind field on the south-western coastal margin under the influence of the south Atlantic high pressure system. When considering the surface air temperature, the added regional detail from the MM5 is readily apparent, and clearly captures the topographical forcing.

Figures 18, 19, and 20 show the same comparisons as above, but in this case for a snapshot single time slice selected out of the month. In these examples it is even more apparent how the MM5 introduces the regional complexities in the flow fields and in surface temperatures for a given instant in time.

5.4 MM5 regional responses to the doubled CO_2 boundary fields

As with the global UM run, the MM5 results can be used to elucidate some of the regional characteristics of the UM response to a doubling of atmospheric CO_2. Figure 21, 22, and 23 shows the January mean results, where the MM5 resolution anomalies for selected fields at the surface and mid-troposphere indicate the regional details. Again, the MM5 captures well the regional modification of the response, adding significant spatial detail to the results. Since this is only one January, no detailed interpretation of the response pattern is advisable.

Notwithstanding the short duration of the simulations, as a sensitivity study some interesting attributes of the change are worth noting which are all in accordance with the anticipated changes under a future warmer world:

- In the mid-troposphere over the continent there is an anomalous anti-cyclonic flow. Similarly, at the surface there is an increased onshore flow from the Indian Ocean and onto the southwestern margins of the continent. Both are indicative of a strengthened Hadley circulation. For the central interior this has commensurate implications for stability, convective processes, and the strength of the elevated inversion over the sub-continent.
- The specific humidity at the surface is increased over the entire sub-continent, and even in the mid-troposphere there is an increase over much of the domain. This is in accordance with the increased temperatures and consequent evaporation from surfaces, and over the continent, perhaps enhanced by the strengthened flow in from the Indian Ocean. This increase, to some extent, may offset the stability issues related to the increased anti-cyclonic flow. However, this enters into the speculative realm[10].
- The temperature changes are greatest over the continent, especially in the western regions. This is in accordance with the changes in circulation identified, as well as reflecting the thermal responsiveness of the arid climate regions. Over the oceans and to a lesser extent the well-vegetated land surface regions, moisture plays a significant buffering effect on temperature response. This, coupled with the strengthened high-pressure systems, is the primary process driving the regional disparities in temperature response. At the surface there is a decrease over the ocean off the southwestern margins of the continent, perhaps related to the increased flow from more southerly regions.

---

[10] Of interest is that the empirical downscaling (Hewitson, 1999) over South Africa indicated a climate change tendency toward less frequent summer convective events, and an increased intensity when the events occur. Hewitson's study used different techniques and different global models, yet the result would fit well with the physical processes related to increased boundary layer moisture and increased stability seen here.

The above points, however, must be viewed in the light of the short duration of the simulation which is only one year long. Given the high degree of inter-annual variability in the climate system, extrapolation of these results to a general climate change scenario is dangerous. Nonetheless, as noted later, these results are in accordance with the broad expectations of the regional responses to climate change.

6. Summary

6.1 Lessons learned

The changing climate, and the particular vulnerability and dependence of South African society to the variable nature of the climate system make it imperative that suitable tools are available for process based research of the climate system. For the most part this implies the need for computationally intensive climate modeling. The primary constraint in this regard within southern Africa has been limited computing resources, and too few model-literate researchers.

In order to undertake a sustained investigation of the climate system based on modeling, a level of capacity needs to be achieved in terms of both scientists, and suitable software tools. These need to be readily accessible by scientists and students without requiring intensive time investments whenever new experiments are undertaken, or to learn the procedures in the first place. To this end this project has focused on the development of an infrastructure based on hardware and software in the mainstream of the global modeling community. In addition, a critical mass of model literate scientists and students has been developed, out of which national team initiatives have been spawned.

In undertaking this work within the constraints of Africa, and in context of the small South African atmospheric science community, the following points may be identified:

- The software should be based on well established models which have wide acceptance in the international community. Both the UM and MM5 have explicit mandates to supporting the wider community, and both are well regarded as leaders among the available models.
- Developed collaborative links with established modelers in the international community is essential. To this end, the links with the UKMO, and with Prof Gutowski at the Iowa State University have proved invaluable in developing skill within the research team. In undertaking modeling, there are a host of pitfalls that are not readily apparent, and while the principles may be readily learned, the pragmatics of the implementation are not so simple.
- A suitable level of competence in computer science issues is important, as much of the model software often requires specific adaptation to the available computing infrastructure.
- A team approach greatly assists in implementation. To this end the team developed at UCT is now in a position to undertake a far broader range of experiments that may

complement one another. The capability developed has already spawned two other research projects, both of which involve researchers from other institutions in South Africa, and benefit the creation of a national team approach.

6.2 Key accomplishments:

The results indicate a significant improvement in the ability to develop climate change scenarios at the regional scale for southern Africa. In the past there has existed a dependence on global low-resolution data from research institutions overseas, and empirical techniques to downscale this to regional information. The ability to undertake process based modeling nested in GCM simulations adds a valuable tool to developing regional climate change scenarios, as well as to investigate the physical processes underlying the projected changes.

While there will always be a degree of uncertainty pertaining to regional climate change scenarios, the more one can validate a procedure, and the more one can account for the primary processes underlying climate change, then the greater confidence one may have in the plausibility of a climate projection. In this regard, the work presented here forms an important building block toward this objective.

In terms of more specific details, capacity and technology transfer are summarized in text box 3, while the project has also provided the following:

- A computational hardware infrastructure capable of handling both global and regional modeling, along with the required peripheral storage and networking environment. The existing system is used by over 20 scientists and students for ocean and atmospheric research. Since the system was purchased under joint funding from a number of sources, at present at least 5 WRC project make use of the system, along with related research under various NRF funded scientists. In addition to local users, scientists at other institutions are also using the system through collaborative links. Overall the system usage is greater than 90% over the course of the year.
- A current generation global model, ported to the local hardware, installed, and with a user friendly interface facilitating access by students and other scientists. The model is actively supported by the UKMO, and regular upgrades and developments are available. Additionally, through the usage of this model new collaborations have begun with international partners, and exchanges between the institutions have, and still are taking place.
- A current generation regional climate model, ported to the local hardware. In addition, a suite of software for pre- and post-processing of the input and output data has been developed to facilitate the ease of use. The model has undergone testing, and now provides the starting point for at least 3 other research project beginning, or ongoing, at UCT.

- A team of model-literate scientists and students has been established, and valuable experience acquired. All of these are continuing in their modeling activities, either on existing projects, or initiating new research through collaboration with researchers overseas.
- The establishment of the above infra-structure and expertise has also led to a new initiative to hold a regional modeling training workshop in 2001 for young scientists from the SADC region. The proposal has been developed for international funding agencies, and the overseas collaborators have already agreed to participation and support. This activity would not be possible without the work of this project, and stands to be a catalyst to modeling activities addressing a far broader range of research questions.

6.3 Recommendations, and future directions.

As indicated above, this project has already spawned a number of other projects. Most notable has been the Innovation fund award from the Dept. Arts, Culture, Science, and Technology to address seasonal forecasting through modeling, and draws in scientists from 5 institutions in South Africa. Secondly is a continuation project from the Water Research Commission to investigate climate variability and extreme events, past, present and future. In the light of this, a number of recommendations may be made.

1) With the establishment of modeling infrastructure there is the ongoing concern for maintaining the performance of the computational hardware. With the ever-increasing sophistication of models, countered by the aging of computer equipment, there is a real need for funding upgrades and developments to the computers. This need, unfortunately, is problematic within the South African research community. Thus serious consideration needs to be given to the continued support of a facility to serve the national needs for atmospheric research.

   In contrast, most developed nations have national centres targeted on atmospheric/oceanic research, with committed support for the institution as a whole. This is not a viable model for South Africa at present, but nonetheless, it is valuable perspective to look beyond the project level of research, and consider the disciplinary level of support.

2) In terms of the most pressing science issues, the key concerns are being addressed by current projects (climate change, variability, seasonal forecasting, etc.). However, there is a significant shortage of scientists and students nationwide engaged in this work. In part this is a difficulty in attracting computer and mathematically literate students as such people are easily attracted in careers that offer substantially higher salaries. This problem is even more difficult when considering attracting students from previously disadvantaged communities. In seeking to address this, both the WRC and the UCT modeling research team have offered targeted bursary support

nationwide, with little success. As a result there is a need for proactive activities to draw in such students, as well as to provide support for the development of a critical mass of senior scientists.

3) Finally, the nature of modeling lends itself well to a team approach. As such, collaborative links between institutions locally and internationally can have a significant multiplier effect on the effectiveness of the work undertaken, as well as enhancing the depth of understanding.

Overall, the South Africa modeling community is well positioned to address the questions about the process-based dynamics governing the regional climate system. With the rich empirical heritage of the atmospheric science community, there is no difficulty in finding the issues to address. Rather, it becomes a case of how best to address these questions within the capabilities of the infrastructure.

7. References:

Crimp S., and Mason S., 1996: The extreme precipitation event of 11 to 16 February 1996 over South Africa, *Meteorol. Atmos. Phys.*, 70, 29-42.

Crimp S., Lutjeharms J., Mason S., 1998: Sensitivity of the tropical-temperate trough to sea surface temperature anomalies in the Agulhas retroflection region, *Water SA*, 24, 93-100.

IPCC 1995: *The Science of Climate Change: Contribution of Working Group I to the Second Assessment of the Intergovernmental Panel on Climate Change*, Eds: JT Houghton, LG Meira Filho, BA Callender, N Harris, A Kattenberg and K Maskell, Cambridge University Press, UK. pp 572

IPCC 2000: *The Science of Climate Change: Contribution of Working Group I to the Third Assessment of the Intergovernmental Panel on Climate Change*, draft document.

Hewitson BC., 1997: *A methodology for developing regional climate change scenarios from general circulation models*, WRC Report 594/1/97, Water Research Commission, Pretoria.

Hewitson BC., and Crane RG., 2000: Self Organizing Maps: Applications to Synoptic Climatology, In revision for *Climate Research*.

Mason S., Joubert A., 1997: Simulated changes in extreme rainfall over southern Africa, *Int. J. Climatology*, 17, 291-301.

Sun L., Semazzi F., Giorgi F., Ogallo L., 1999: Application of the NCAR regional climate model to eastern Africa. 1. Simulation of the short rains of 1988, *J. Geophys. Res.*, 104, 6529-6548.

Sun L., Semazzi F., Giorgi F., Ogallo L., 1999: Application of the NCAR regional climate model to eastern Africa. 2. Simulation of inter-annual variability of short rains, *J. Geophys. Res.*, 104, 6549-6562.

Text Box 1

Features of the MM5 Modeling System

- Globally re-locatable
- Three map projections:
  - Polar stereographic
  - Lambert conformal
  - Mercator
- Support different true latitudes
- Variable resolution terrain elevation, landuse, soil type, deep soil temperature, vegetation fraction, and land-water mask datasets are provided

---

- Flexible and multiple nesting capability
- Can be configured to run from global scale down to cloud scale in one model
- Can be run in both 2-way and 1-way nesting mode:
  - 2-way: multiple nests and moving nests
- 1-way: fine-mesh model driven by coarse-mesh model
- Nest domain can start and stop at any time.

- Real-data inputs
- Use routine observations -- Upperair and surface reports, including wind, temperature, relative humidity, sea-level pressure, and sea surface temperature.
- Couple with global models and other regional models
- Use other model's output either as first guess for objective analysis, or as lateral boundary conditions, e.g. NCEP and ECMWF global analysis, NCEP/NCAR and ECMWF reanalysis, NCEP ETA model.

- Non-hydrostatic and hydrostatic (V2 only) dynamic frameworks.

- Terrain-following vertical coordinates.

- Choices of advanced physical parameterization.

- Four-dimensional data assimilation system via nudging.

- The MM5 model runs on various computer platforms: Cray, SGI, IBM, DEC, Sun, HP, and PCs running Linux.

- Parallelization

  Parallelize on shared-memory machines:

  Cray (EL, J90, YMP), HP-SPP2000, SGI, SUN and DEC Alpha high performance workstations

  Parallelize on distributed-memory machines:

  IBM RISC 6000 cluster, IBM SP2, Cray T3E, SGI Origin 2000, HP-SPP2000, and Fujitsu VPP

- Well-documented, and user-support available.

TEXT BOX 2

MM5 Model Physics Options
(italicized option are the defaults used in the experiments discussed)

1) Precipitation physics

Cumulus parameterization schemes:
- Anthes-Kuo
- ***Grell***
- Kain-Fritsch
- Fritsch-Chappell
- Betts-Miller
- Arakawa-Schubert

Resolvable-scale microphysics schemes:
- Removal of supersaturation
- Hsie's warm rain scheme
- Dudhia's simple ice scheme
- ***Reisner's mixed-phase scheme***
- Reisner's mixed-phase scheme with graupel
- NASA/Goddard microphysics with hail/graupel
- Schultz mixed-phase scheme with graupel

2) Planetary boundary layer process parameterization
- Bulk formula
- ***Blackadar scheme***
- Burk-Thompson (Mellor-Yamada 1.5-order/level-2.5 scheme)
- Eta scheme (Janjic, 1990, 1994)
- MRF scheme (Hong and Pan 1996)
- Gayno-Seaman scheme (Gayno 1994)

3) Surface layer process parameterization
- ***fluxes of momentum, sensible and latent heat***
- ground temperature prediction using energy balance equation
- variable land use categories (defaults are 13, 16 and 24)
- 5-layer soil model
- OSU land-surface model (V3 only)

4) Atmospheric radiation schemes
- Simple cooling
- Dudhia's long- and short-wave radiation scheme
- ***NCAR/CCM2 radiation scheme***
- RRTM long-wave radiation scheme (Mlawer et al., 1997)

TEXT BOX 3

Summary of technology transfer and capacity building

Technology transfer:
As a direct result of the project two new research projects have bee initiated. The first is WRC funded and focuses on continued modeling work on climate change and variability, and is collaborative with the University of Pretoria. The second is funded by the Dept. Arts, Culture, Science and Technology, and focuses on seasonal forecasting. This latter project involves researchers at 5 institutions around South Africa and two institutions overseas, and is a direct outcome of the capacity developed in this project.

In addition, also as a direct result of this work, a capacity building workshop has been funded by international agencies to train black southern Africa young scientists (primarily from the SADC region) in climate modeling. This has the intention of creating a regional collaborative research team.

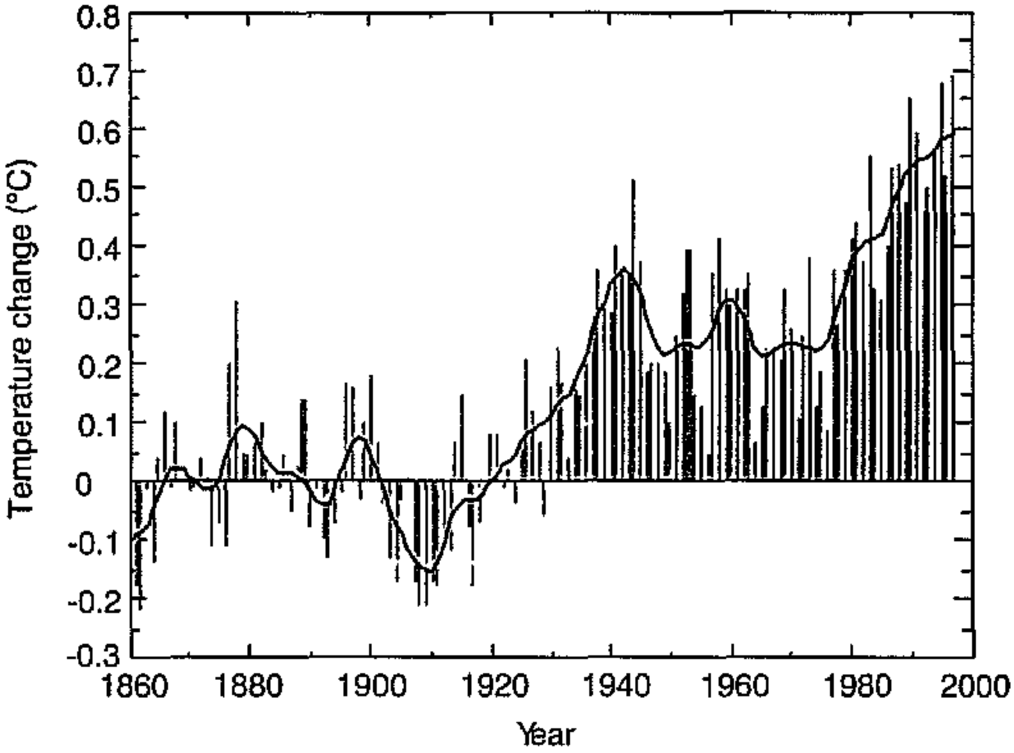
Physical Capacity:

The infrastructure developed through this project has been co-funded by UCT, the NRF, and other WRC projects to create a computing system capable of handling the models, and also supporting other climate related research. The infrastructure consists of:

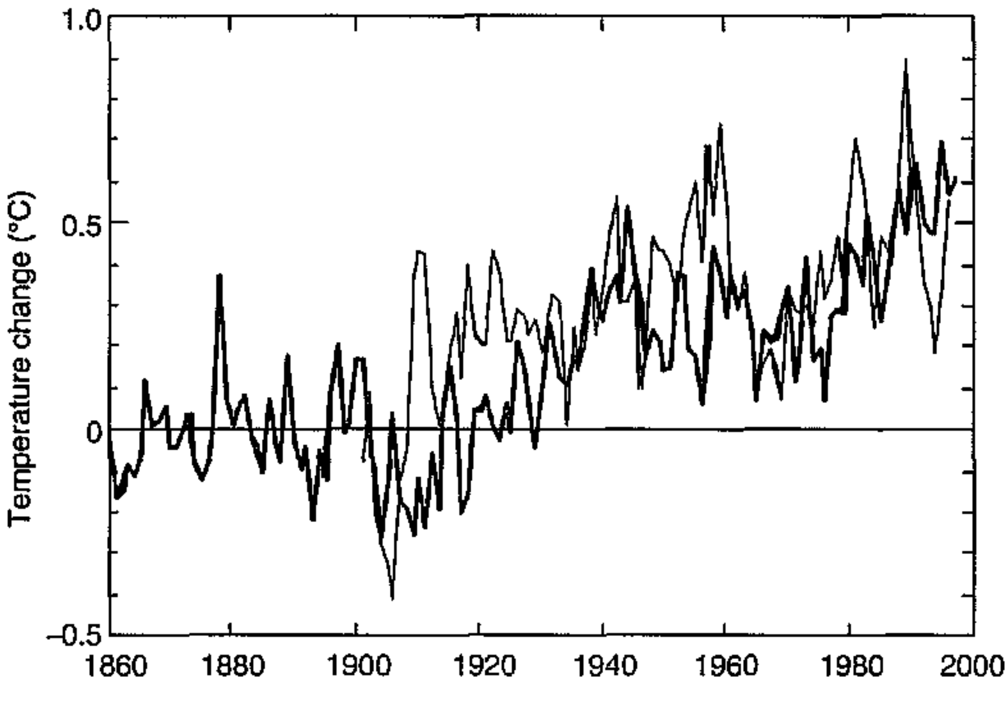
- Origin 2000 computational server
  - 6 x RS10000 processors
  - 1 GigByte memory
  - 30 GigByte disk space
- Raid storage system (150 GigByte)
- Tape storage system (50GigByte AIT high speed system)

Human capacity (participants/contributors to project):

Name	*Institution*	*Gender*
Chris Jack	UCT	Male
Chris Lennard	UCT	Male
Jeremy Main	UCT	Male
Debbie Hudson	UCT	Female
William Gutowski	Univ. Iowa, USA	Male
Anette van der Waal	UK Meteorological Office	Female



(a)



(b)

Figure 1: Mean global temperature change (a), and comparison with model simulations (b) (thick line – observed, thin line – model). (http://www.cru.uea.ac.uk/link/)

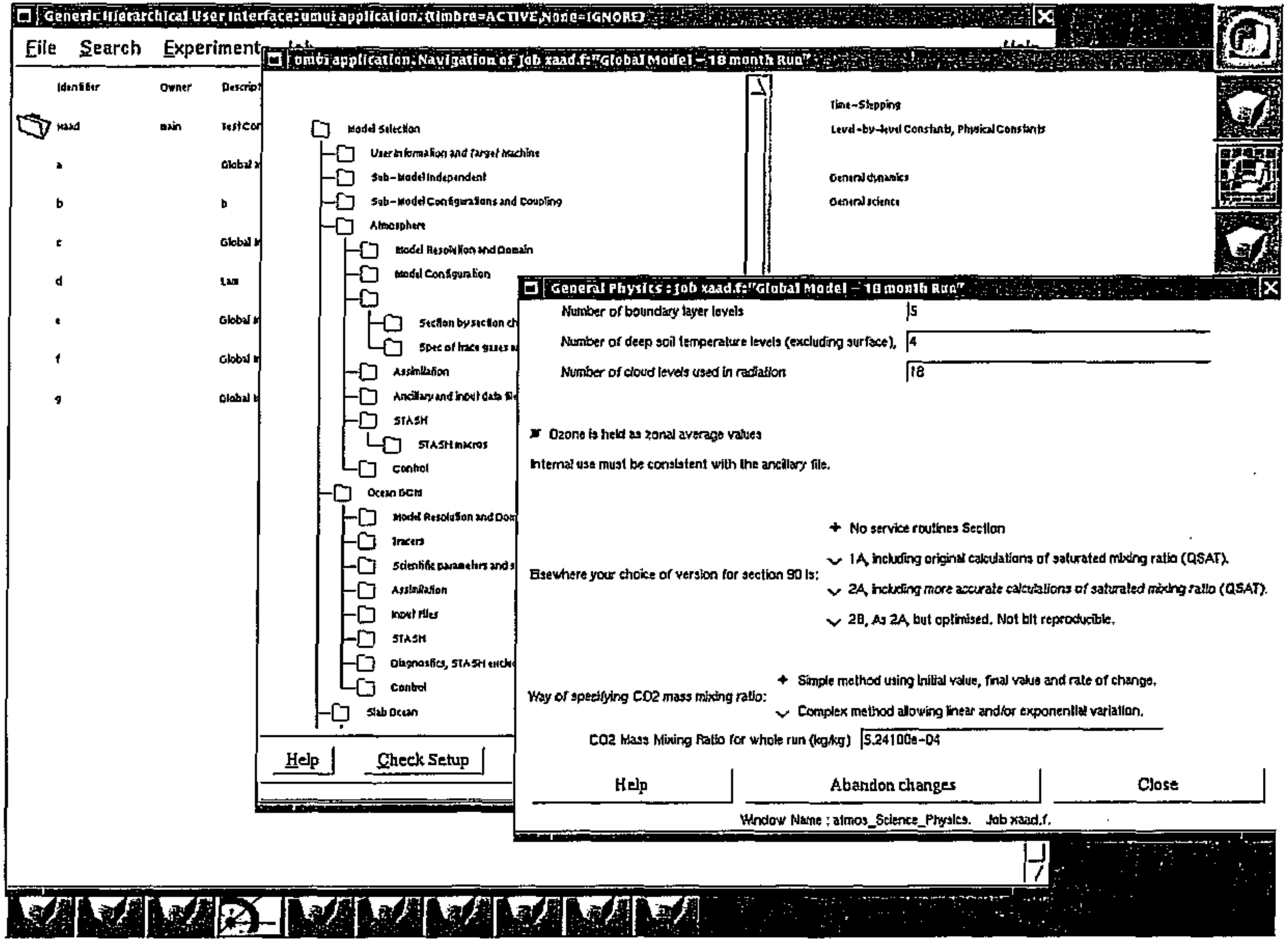


Figure 2: Example interface page to the UM model

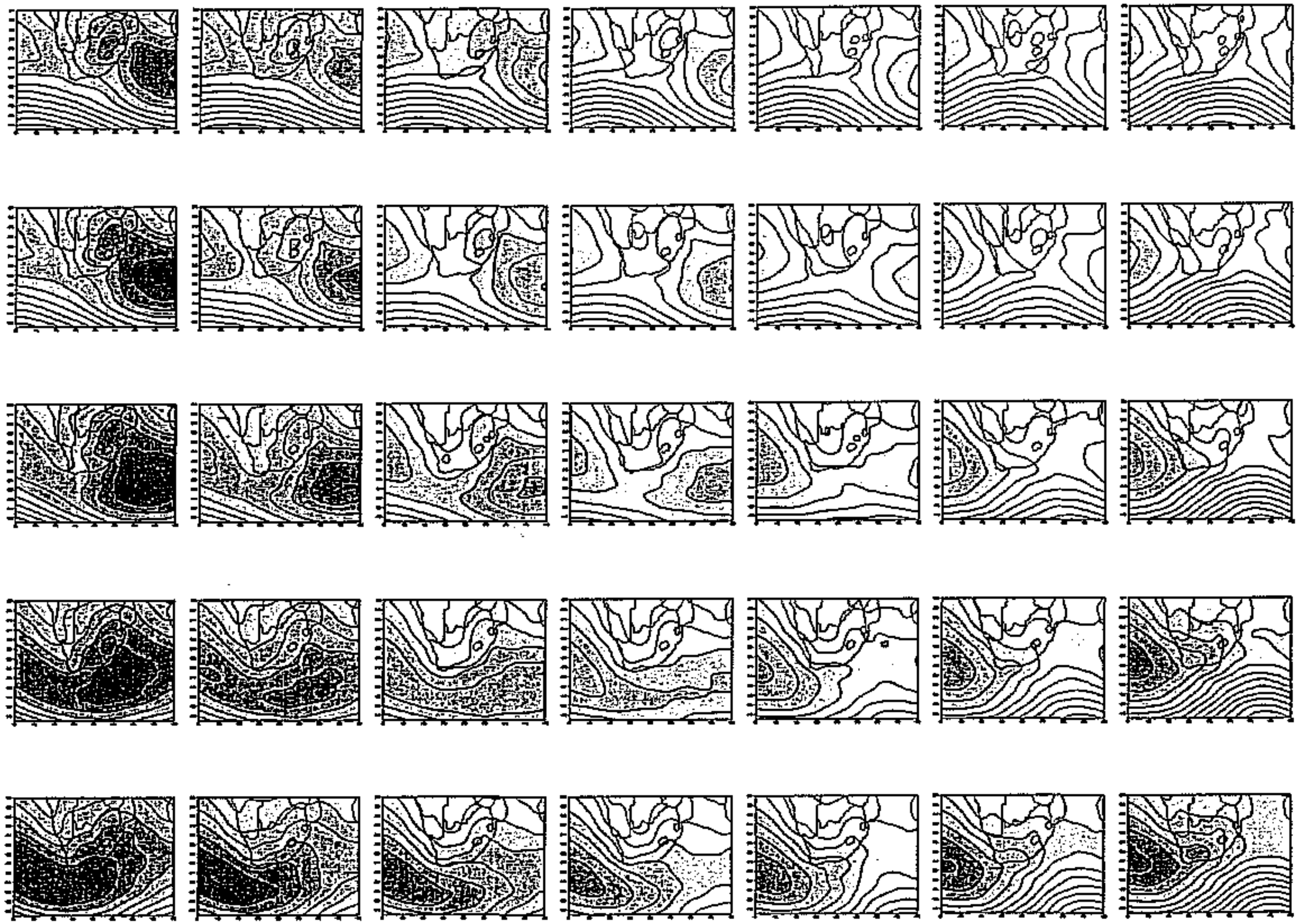


Figure 3: SOM modes for all months

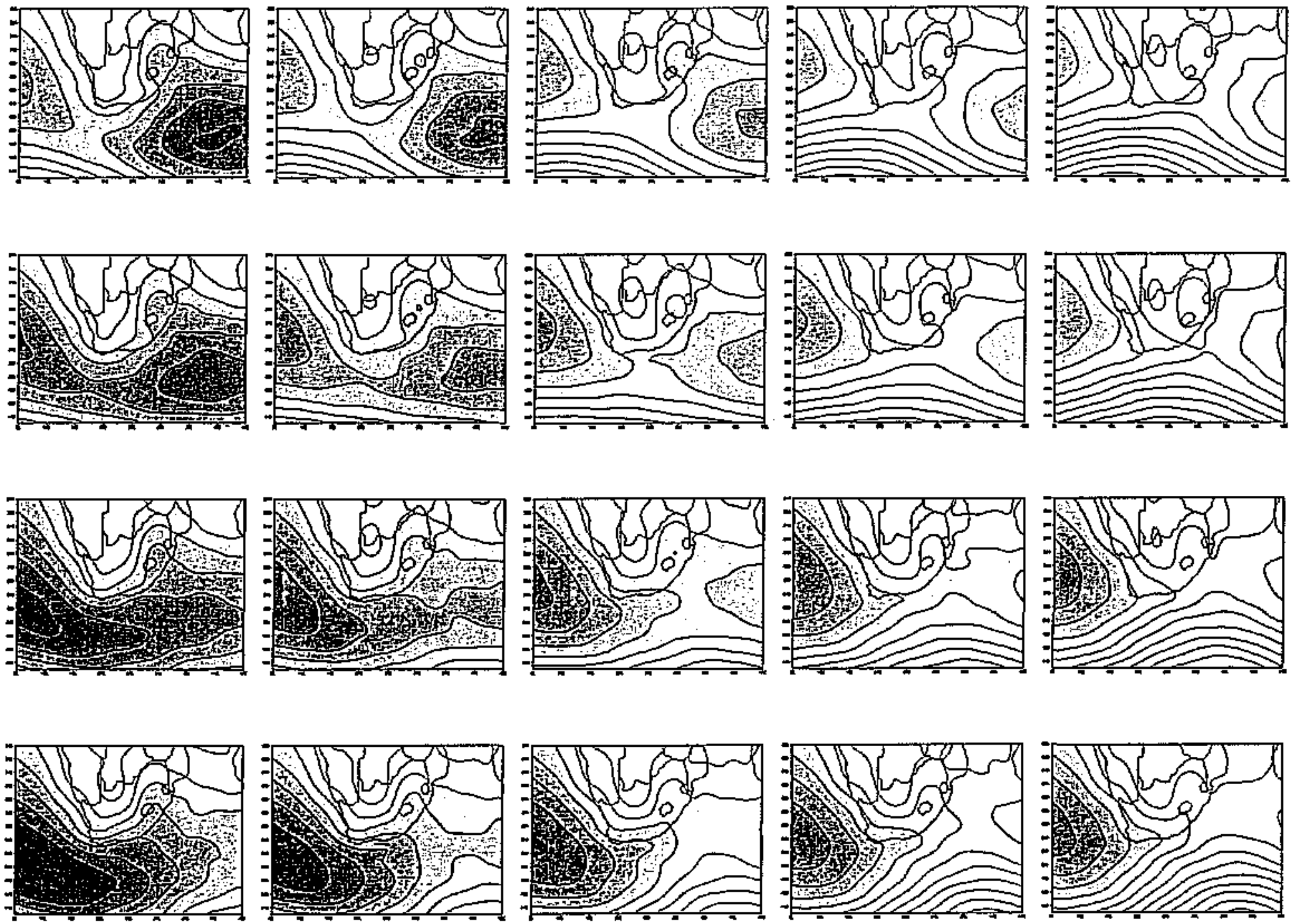


Figure 4: SOM modes for DJF

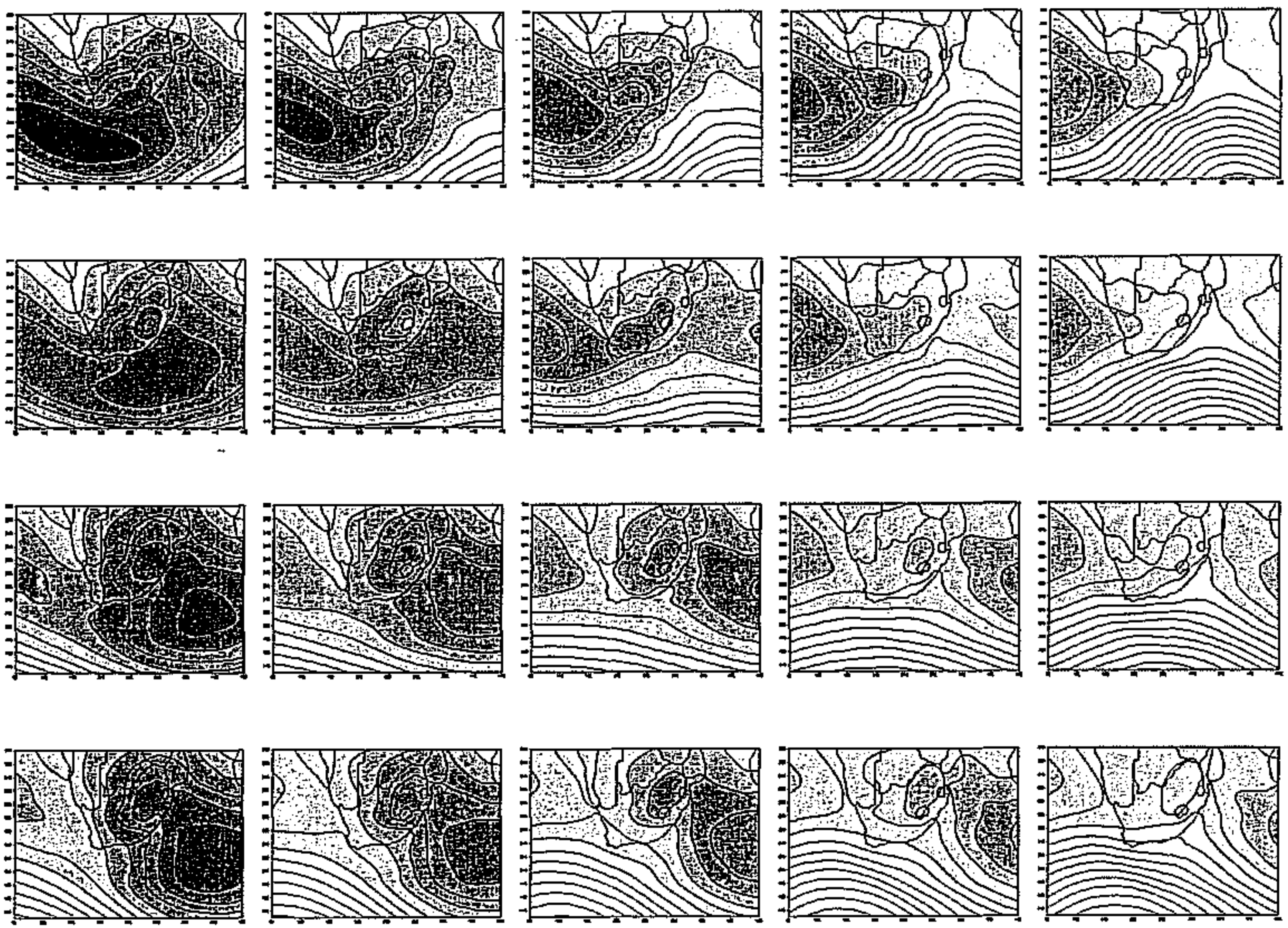


Figure 5: SOM modes for JJA

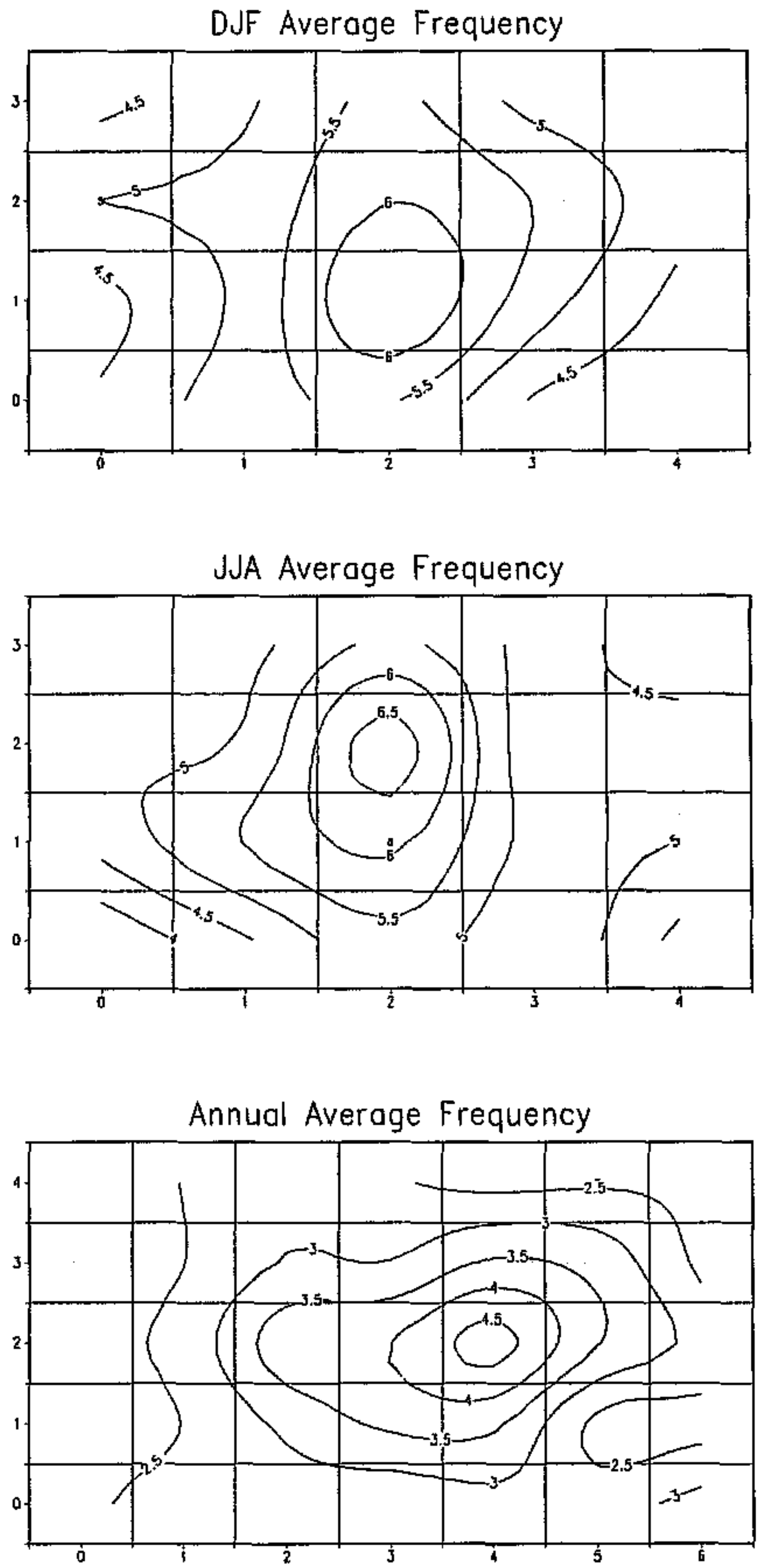


Figure 6: Frequency (%) of modes found in annual, DJF, and JJA SOM mappings (NCEP). Each grid cell in the figure relates to the synoptic pattern in the corresponding position on the SOM map in Figure 3.

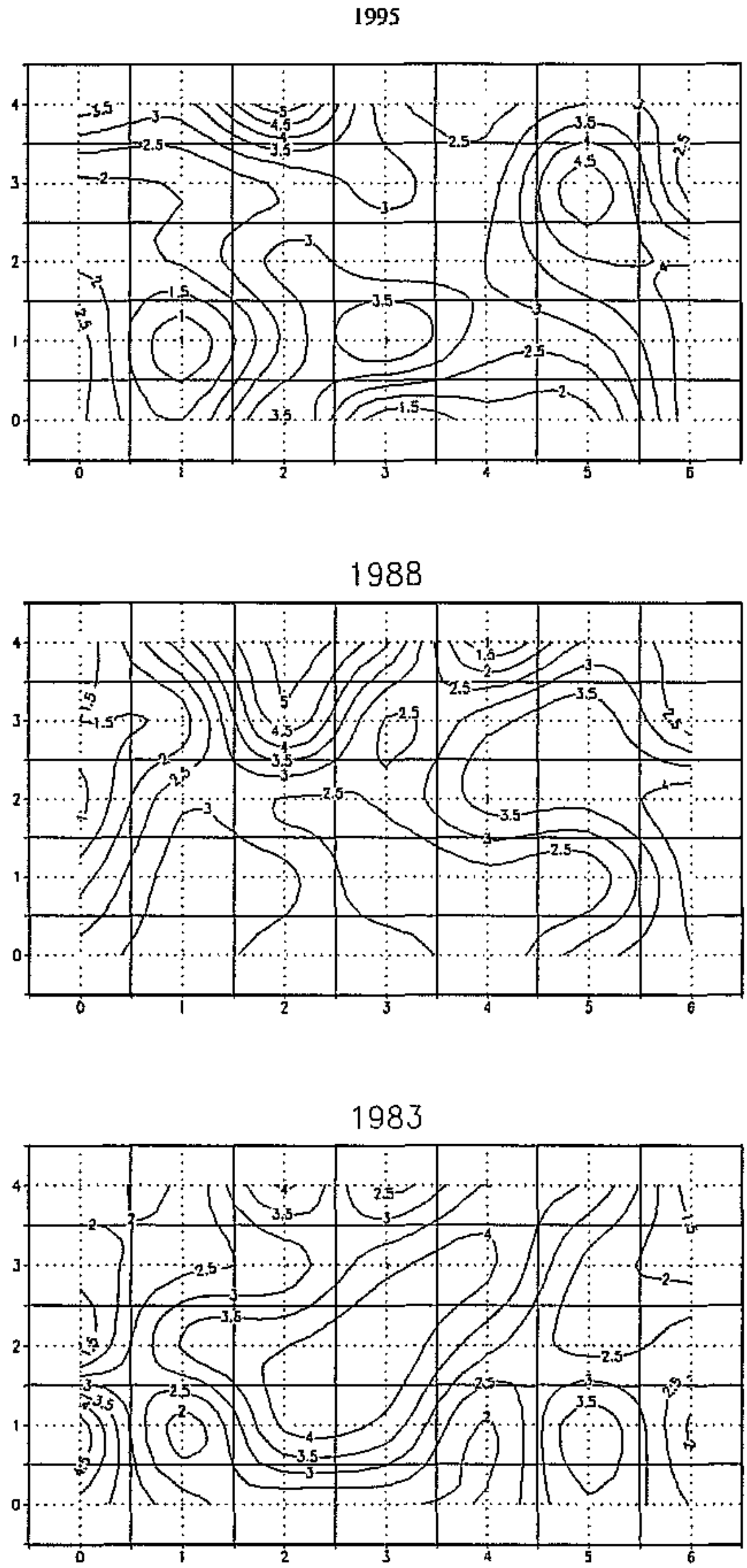


Figure 7: SOM frequencies (%) for all months of selected years (NCEP). Each grid cell in the figure relates to the synoptic pattern in the corresponding position on the SOM map in Figure 4.

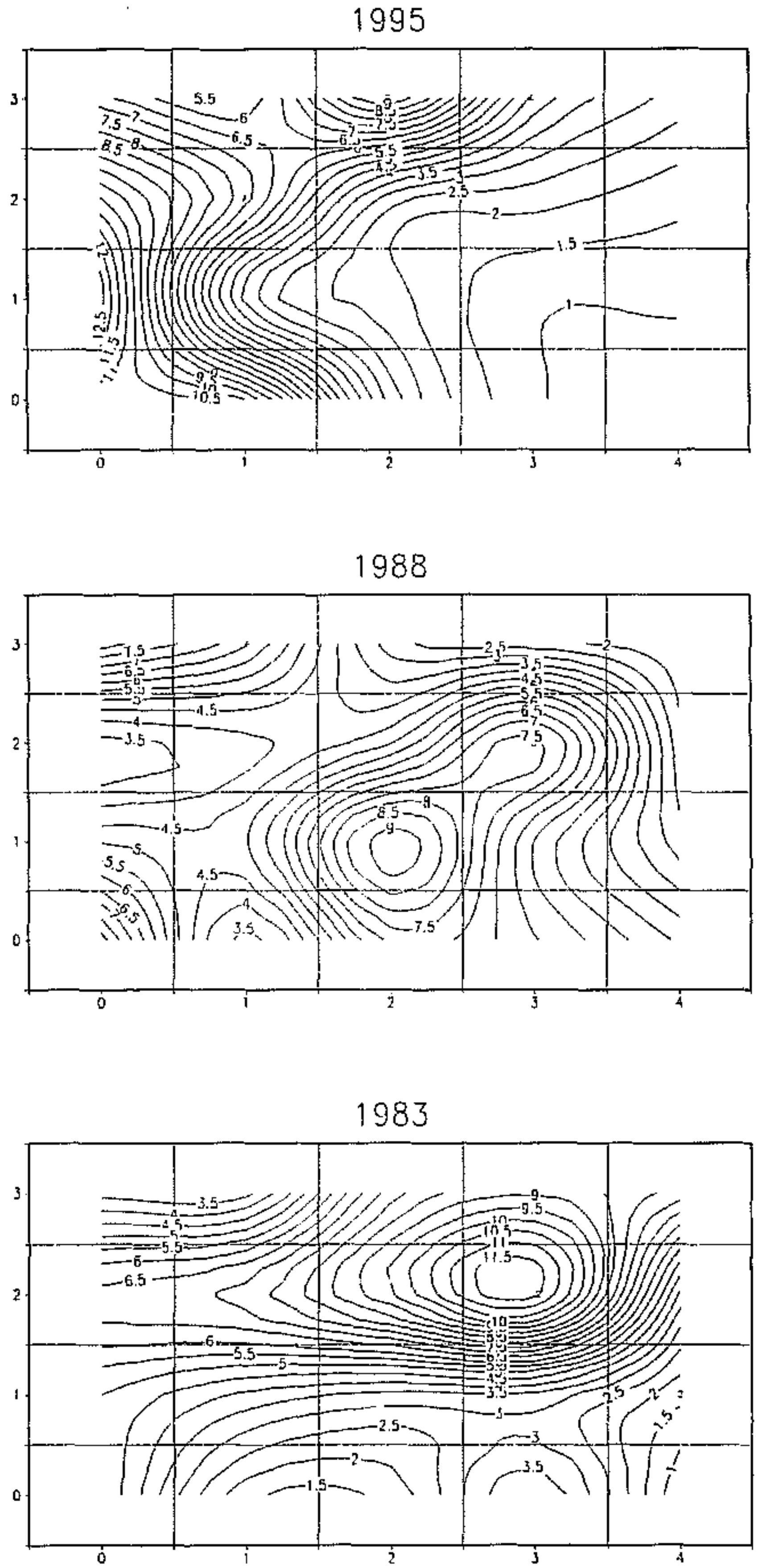


Figure 8: SOM frequencies (%) for DJF of selected years (NCEP). Each grid cell in the figure relates to the synoptic pattern in the corresponding position on the SOM map in Fig 5.

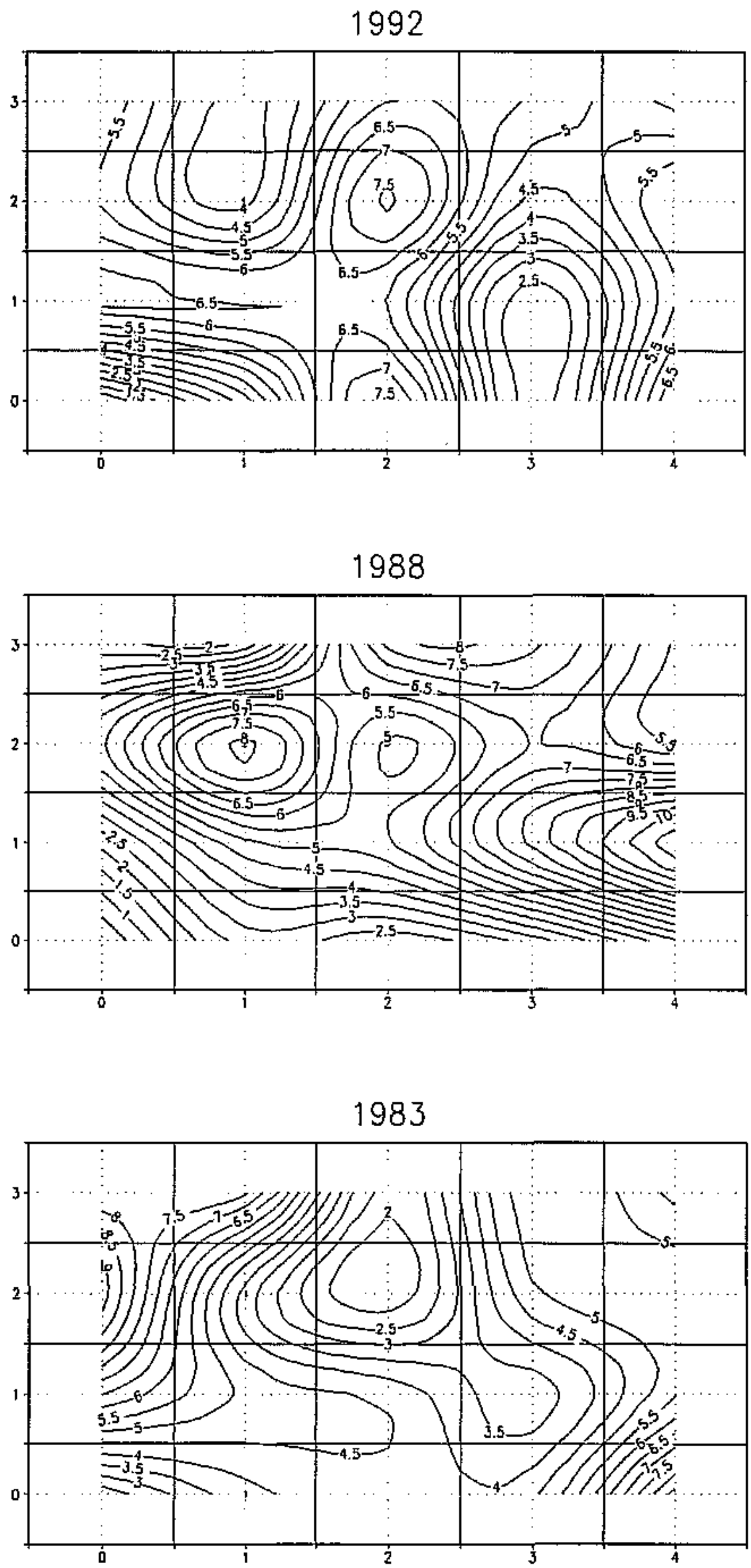
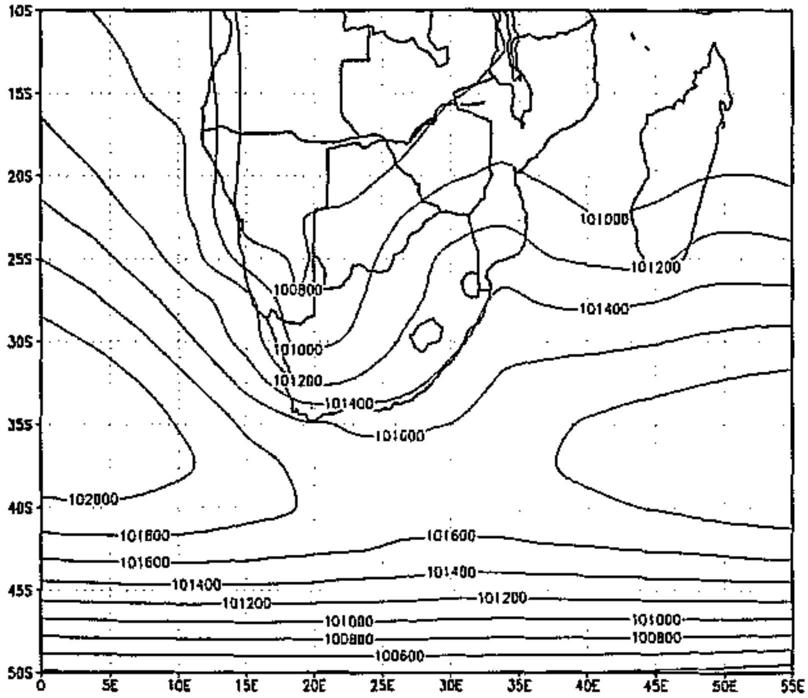
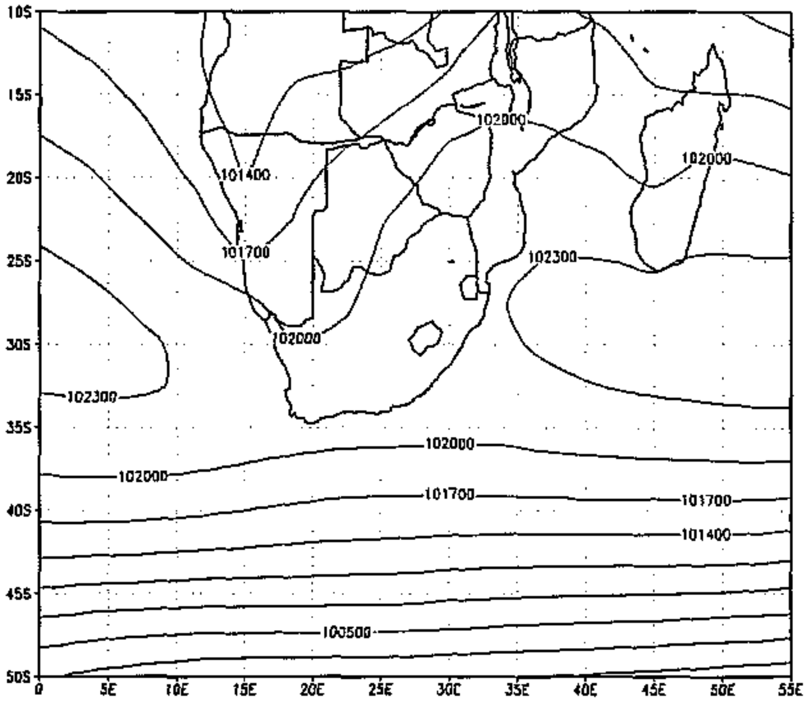


Figure 9: SOM frequencies (%) for JJA of selected years (NCEP)

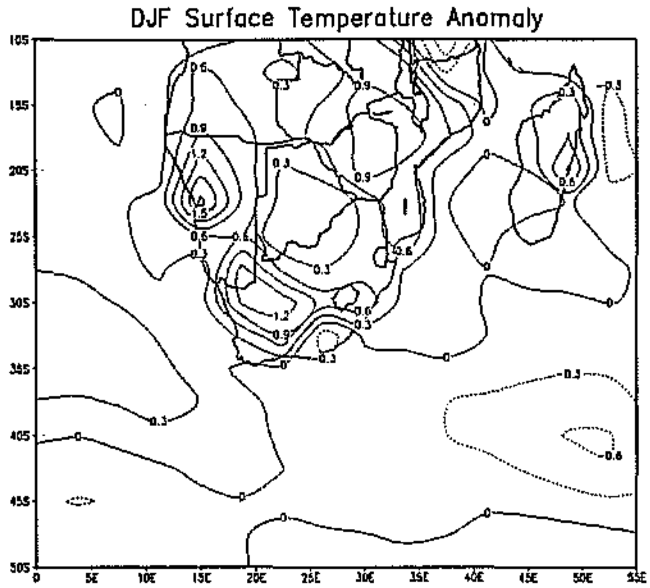


(a)



(b)

Figure 10: Mean sea level pressure (Pascals) patterns (Pa) for DJF (a) and JJA (b) from the control run of the UM model.



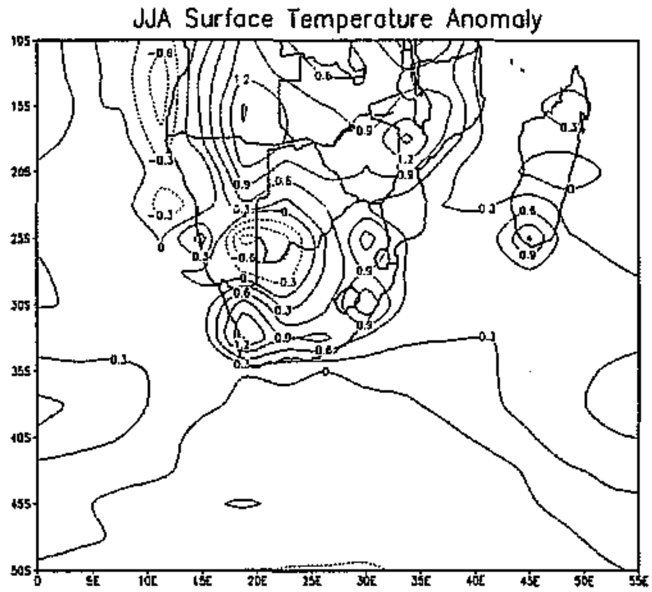


Figure 11: Temperature anomaly (°C) resulting from a doubling of atmospheric CO_2

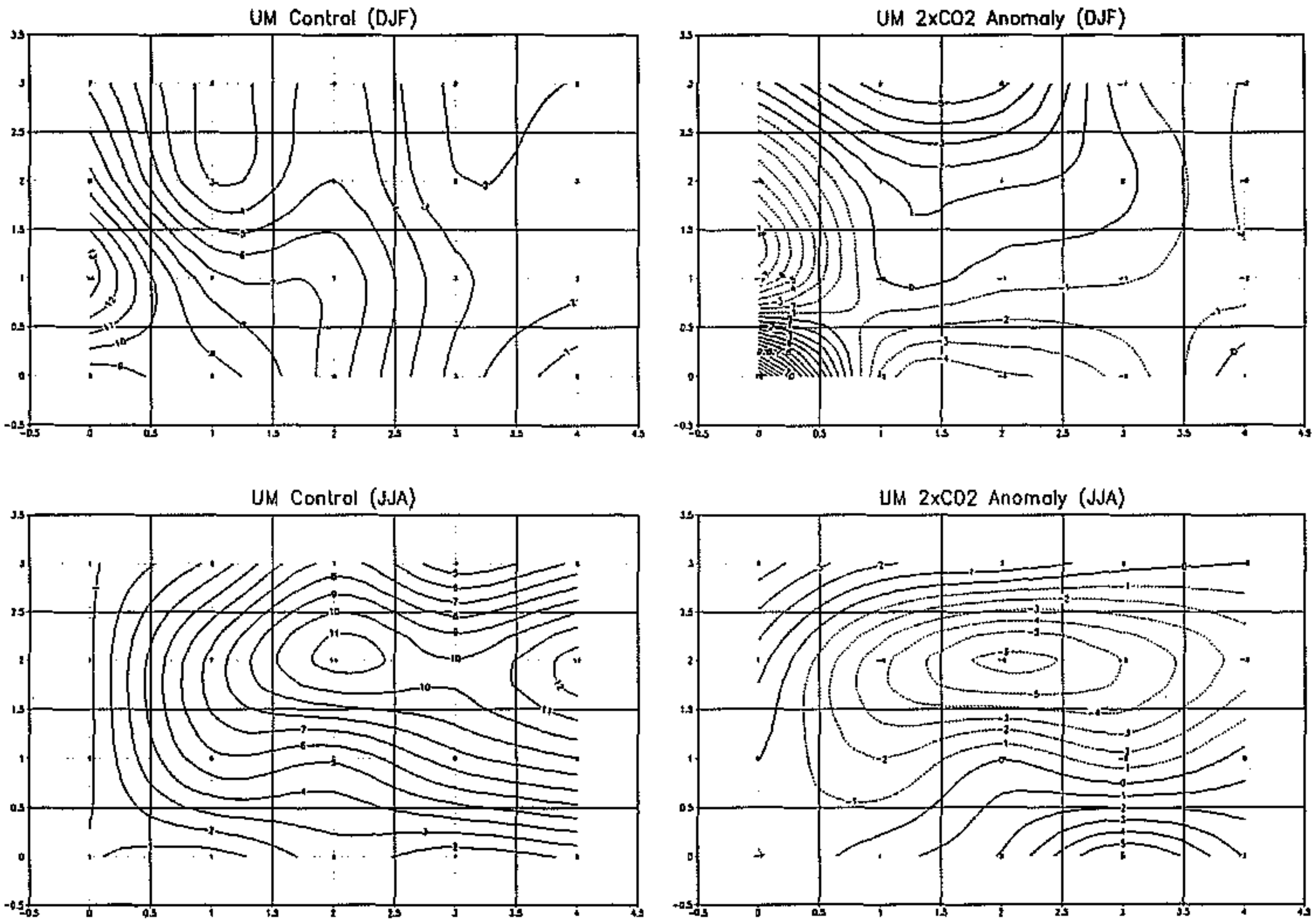
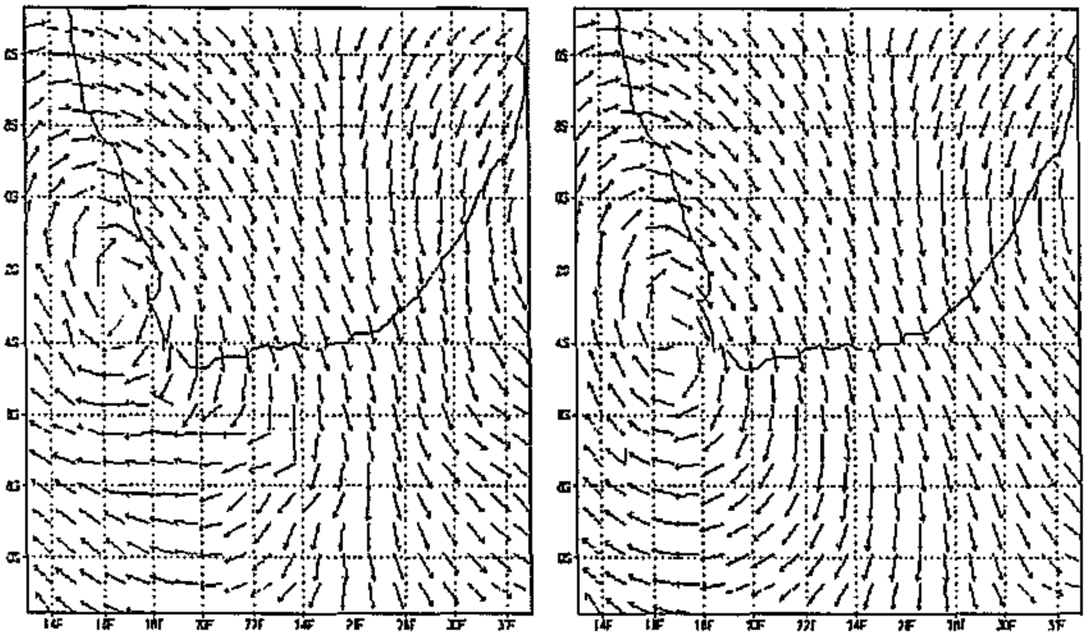
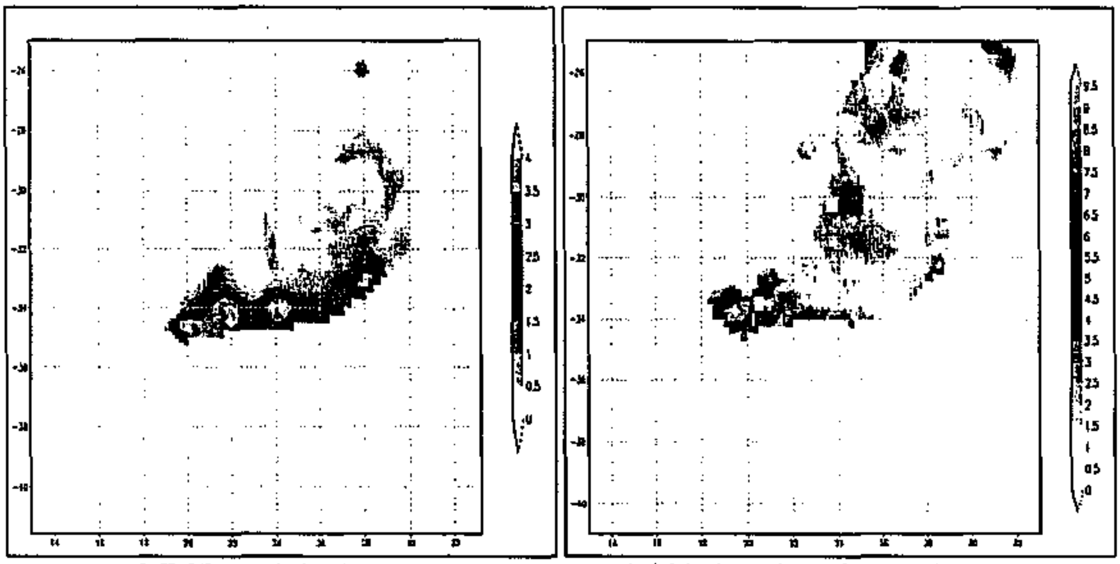


Figure 12: SOM frequencies (%) (DJF & JJA) for the UM control run (comparable to individual years in NCEP data -- see earlier), and frequency anomalies as a function of doubled CO_2.



MM5 (regridded) NCEP Reanalysis

Figure 13: Comparison of MM5 and NCEP data for 25 January, 1981



MM5 precipitation Gridded station observations

Figure 14: Comparison of MM5 and observed precipitation showing the concentration of precipitation along the south and east coast of the continent.

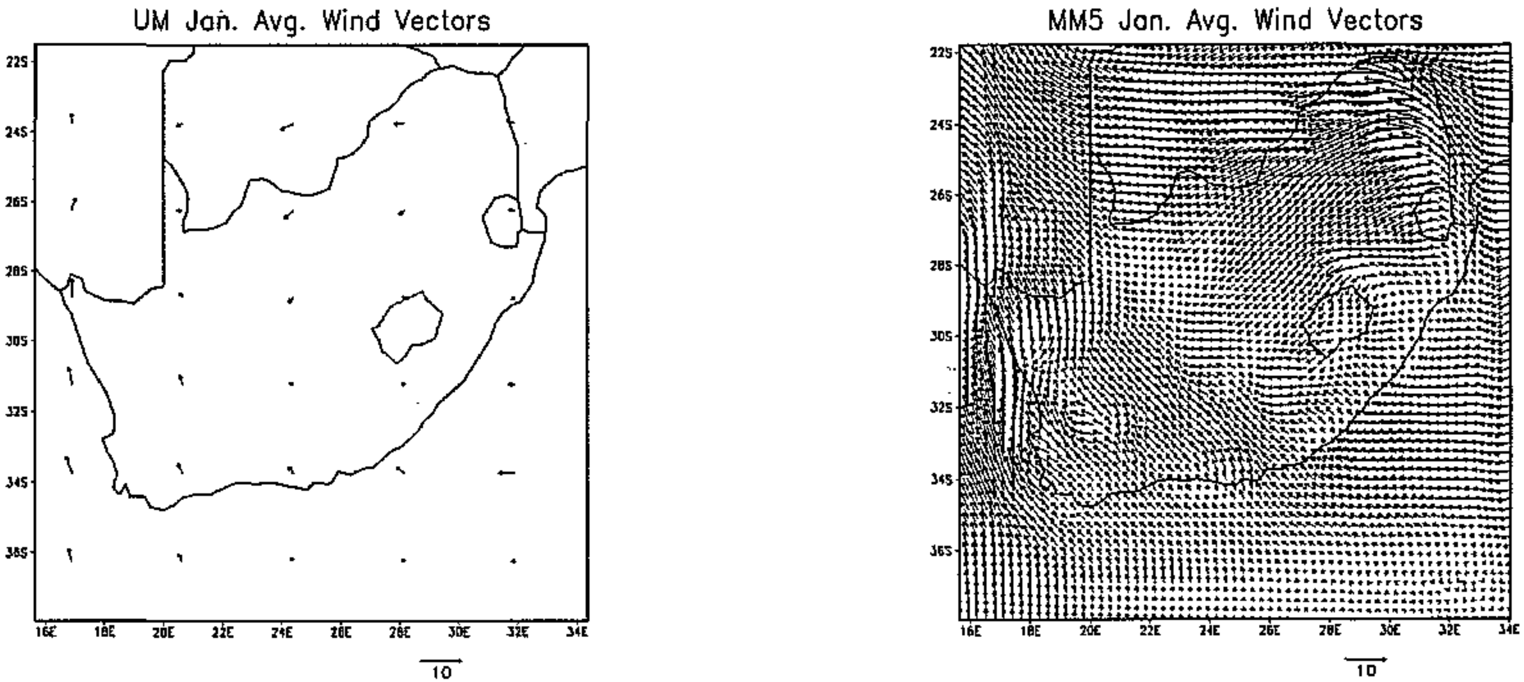


Figure 15: Comparison of monthly mean surface winds between the UM and MM5 derived from the control run.

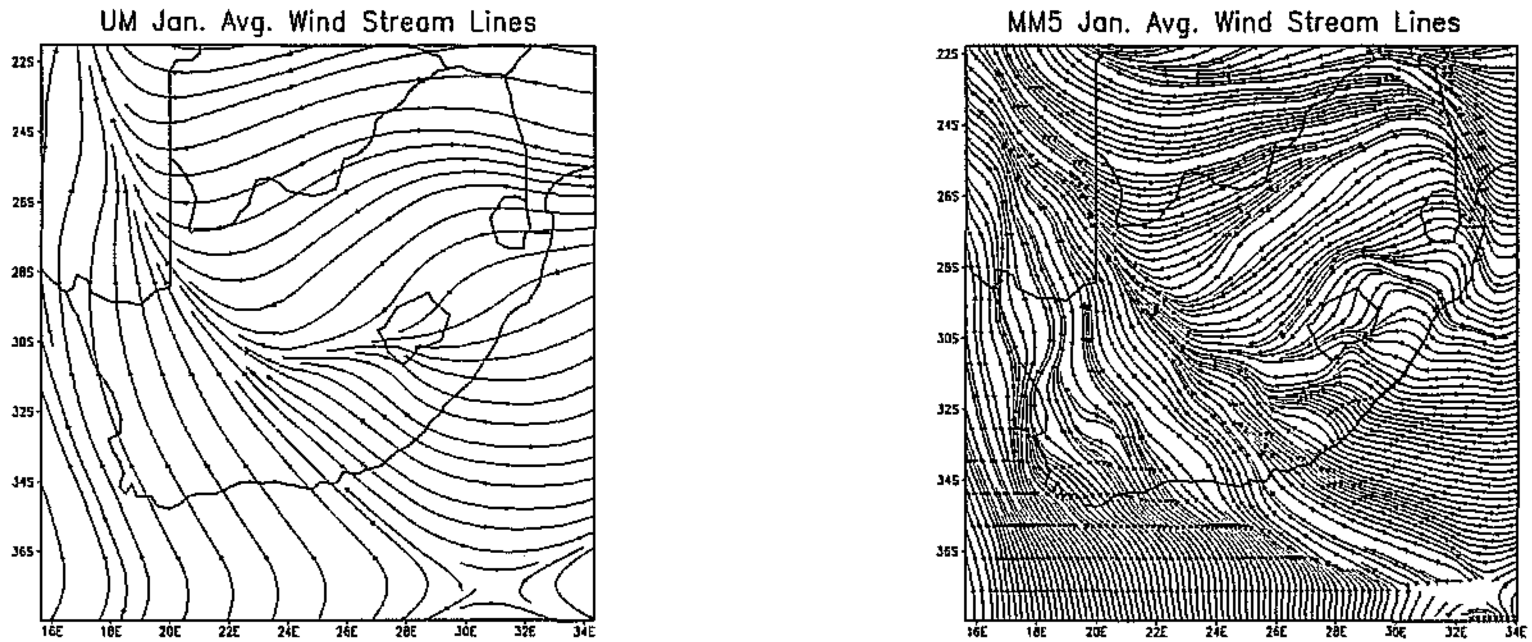


Figure 16: Comparison of monthly mean surface streamlines between the UM and MM5 derived from the control run.

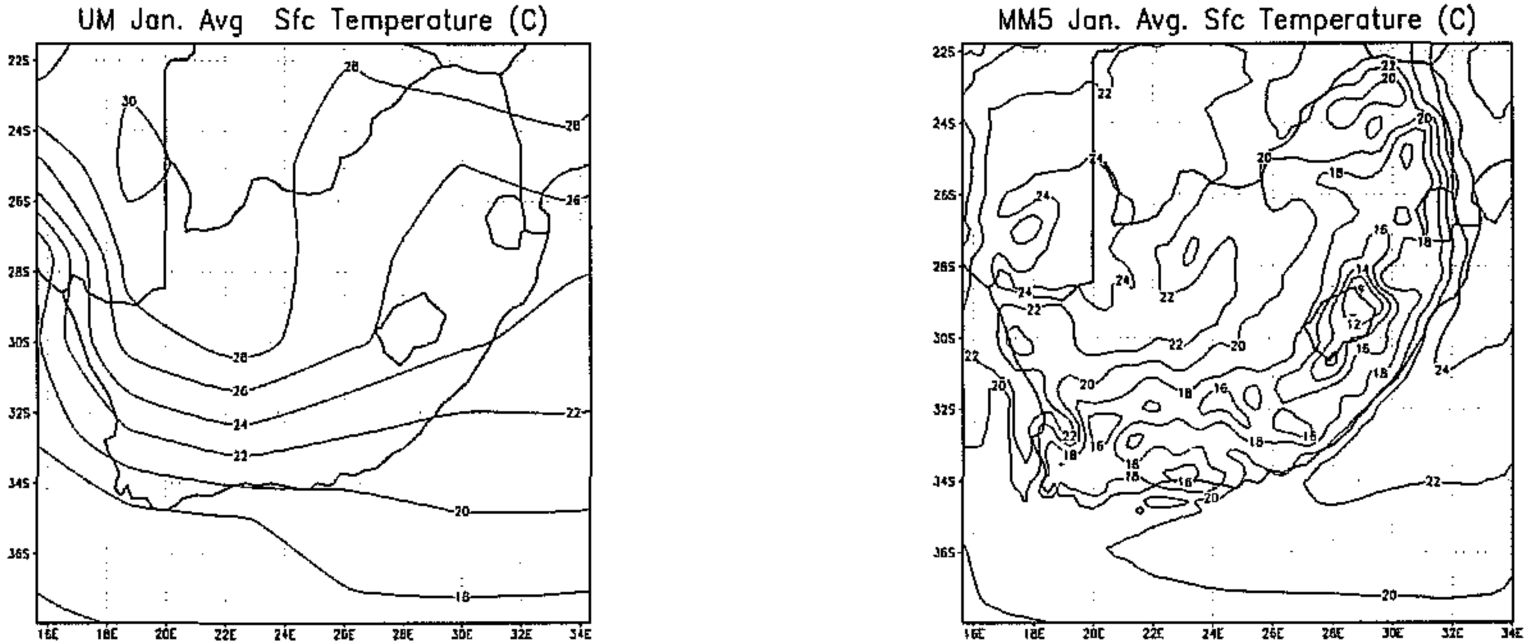


Figure 17: Comparison of monthly mean surface temperatures between the UM and MM5 derived from the control run.

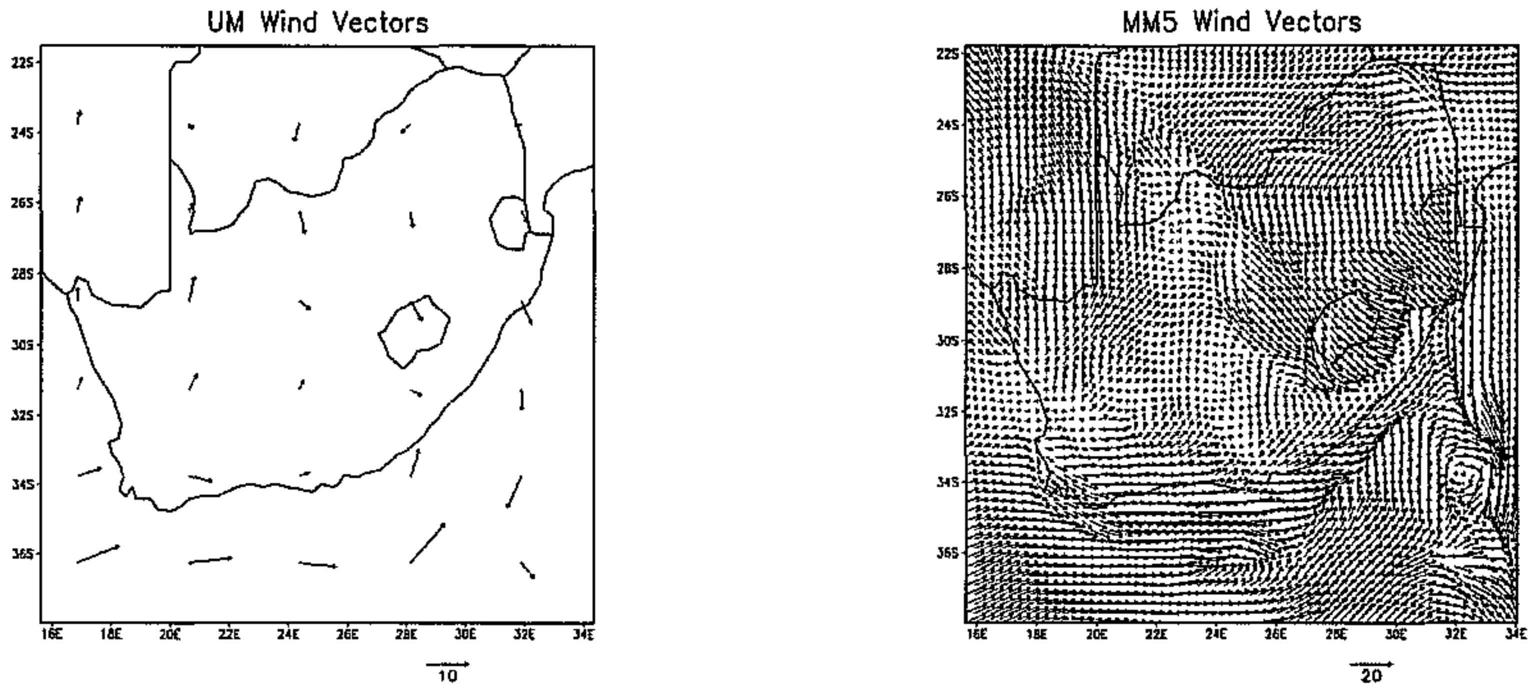


Figure 18: Comparison of surface wind vectors between the UM and MM5 for an instantaneous time slice.

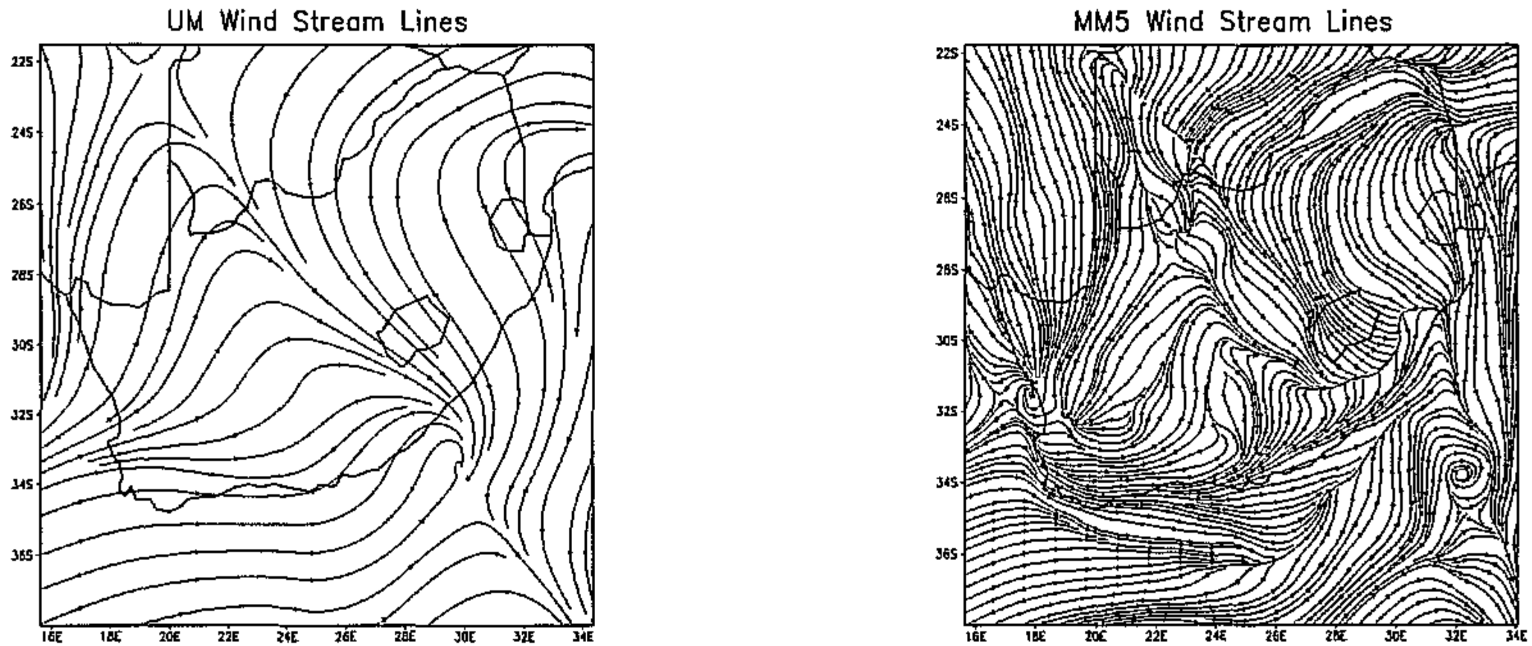


Figure 19: Comparison of surface streamlines between the UM and MM5 for an instantaneous time slice.

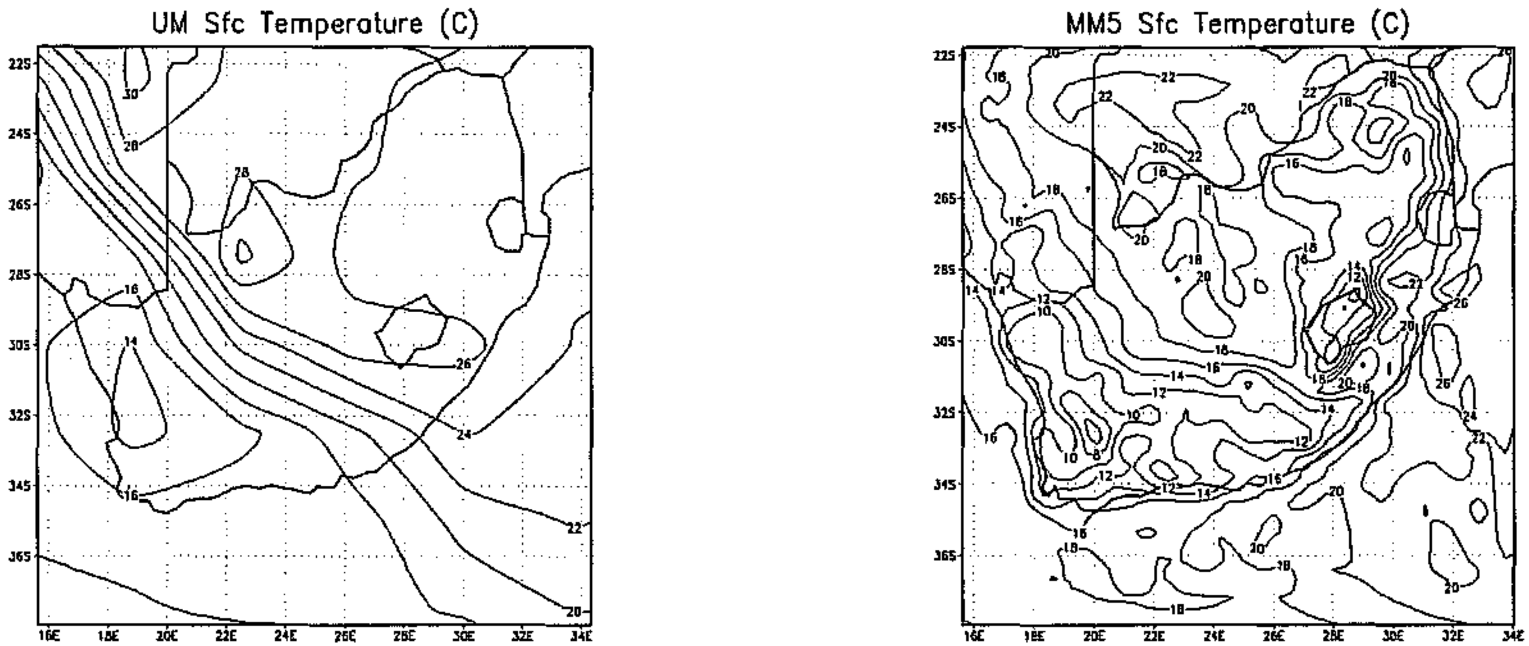
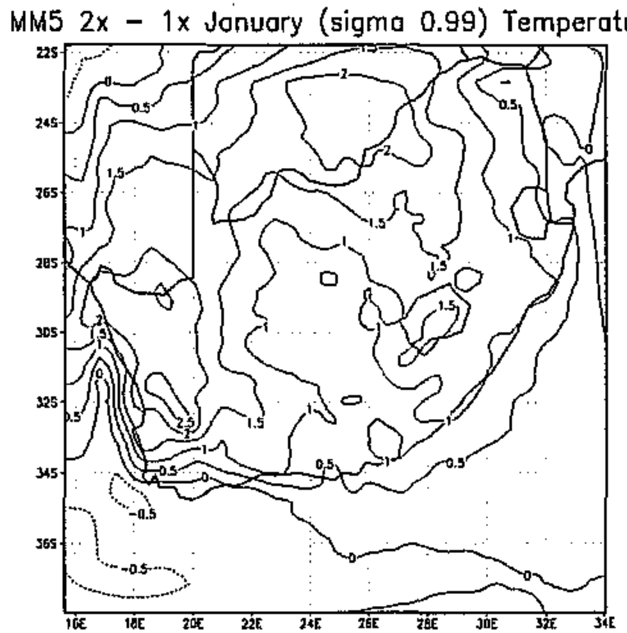


Figure 20: Comparison of surface temperatures between the UM and MM5 for an instantaneous time slice.



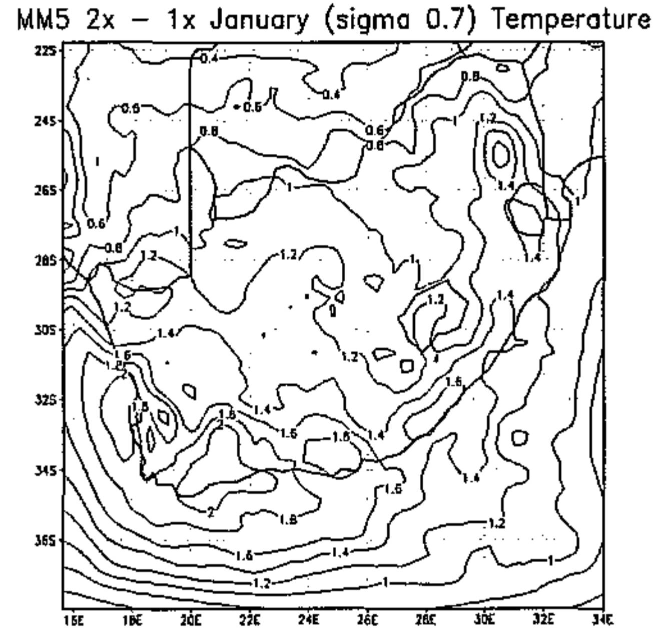


Figure 21: Boundary layer (sigma 0.99) and mid-tropospheric (sigma 0.7) mean January anomaly fields from the MM5 for temperature (°) between the future climate simulation and control run.

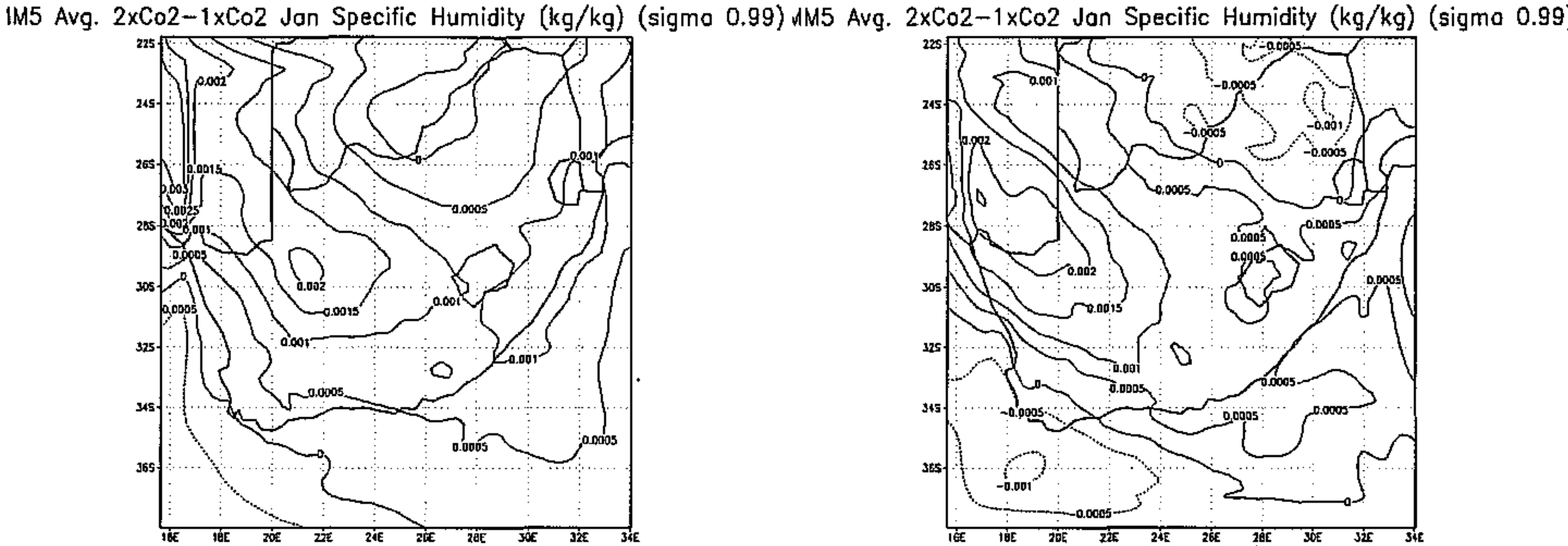


Figure 22: Boundary layer (sigma 0.99) and mid-tropospheric (sigma 0.7) man January anomaly fields from the MM5 for specific humidity (kg/kg) between the future climate simulation and control run.

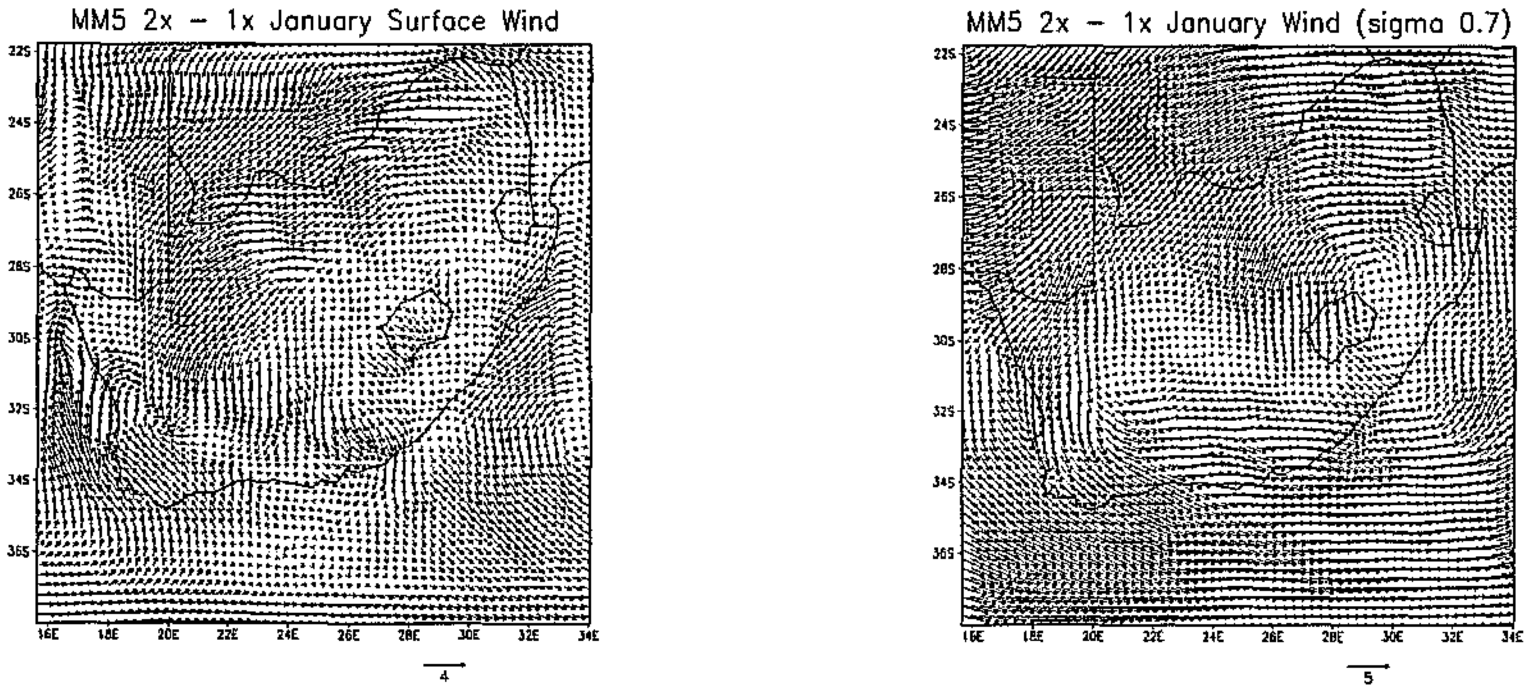


Figure 23: Boundary layer (sigma 0.99) and mid-tropospheric (sigma 0.7) mean January anomaly fields from the MM5 for wind (m/s) between the future climate simulation and control run.