# CHAPTER 1

# INTRODUCTION

## 1.1 BACKGROUND

Enhanced levels of greenhouse gasses of direct or indirect anthropogenic origin might substantially change the climate of planet Earth. Changes in global climate have the potential to severely affect the climate of different regions of the world. Shifting climatic zones, higher sea levels and more frequent storms, droughts, floods and heat waves could generate a range of social, economical and political disruptions (Rowlands, 1998). Understandably, there is an increasing demand by the scientific community, policy makers, and the public for realistic future scenarios of the possible impact of climate change. There is also a need to understand the complex behaviour of the present climate and general circulation of the atmosphere. Shorter-term climate variability, such as the occurrence of floods and droughts, might severely affect the environment. These aspects have rendered the issue of regional climate simulation critically important.

Atmospheric general circulation models (AGCMs) are the primary tools available for climate simulation. Current AGCMs have reached a high level of sophistication, and provide a full three-dimensional representation of the atmosphere. Mathematical equations for the conservation of momentum, mass and energy are numerically solved in these models. Also included are parameterisation schemes for the main physical atmospheric processes such as radiative transfer, cloud formation with precipitation, boundary layer and surface physics. On different levels in the vertical AGCMs are integrated forward in time over the entire globe and are often coupled with other models resembling the earth-atmosphere system to form coupled atmosphere-ocean-sea-ice-snow-cover models.

Coupled models are essential to generate relatively stable projections of paleo, present or future global climate. Here, a model needs to run for long simulation periods to allow for the various components in the atmospheric system to reach equilibrium. Limitations of present day computer resources are of such a nature that a relatively coarse horizontal resolution is used in AGCM runs (nothing finer than 1° longitude and latitude). Another limitation in high-resolution AGCM development is that the physical parameterisation schemes used in the models have specifically been developed and tuned for coarser horizontal resolutions. These schemes may not be suitable for higher resolution models.

Despite the limitations on resolution, AGCM simulations adequately capture the main features of the atmospheric general circulation since large scale forcing such as the Earth's orbital characteristics, radiation budget and global greenhouse gas abundance are included in the code formulation. Large scale forcing modulates the succession of weather events that characterise the climate regime of a given area. Capturing of the large-scale forcing by an AGCM will therefore ensure that the climate is adequately simulated.

However, important smaller-scale (also known as regional or mesoscale) meteorological forcing and circulation systems are not resolved (or adequately parameterised) at typical AGCM resolutions. Mesoscale forcing, such as those induced by complex topographical features and surface characteristics, may modify the structure of weather events. This often initiates additional mesoscale circulation systems that are not detected in larger-scale AGCM results. Embedded in the large-scale atmospheric systems, these smaller circulation systems contribute to regulate the regional (local) distribution of atmospheric variables within a given region.

The main challenge in regional climate modelling is to include forcing on the mesoscale and to capture the associated mesoscale circulation systems and their modifying effect on the regional atmospheric circulation. There are three main approaches to the simulation of regional climate change (Giorgi and Mearns, 1991):

1) *Purely empirical approaches* in which forcing is not explicitly accounted for, but regional climate scenarios are constructed from instrumental data records or paleoclimatic analogues.

2) *Semi-empirical approaches* in which AGCMs are used to describe the atmospheric response to large-scale forcing of relevance to climate change, but empirical techniques account for the impact of mesoscale forcing.

3) *Modelling approaches* in which mesoscale forcing is described by increasing model resolution only over areas of interest.

Their own empiricism and the availability of data sets of adequate quality, limit the empirical and semi-empirical approaches. During the last decade a nested limited-area model (LAM)–AGCM methodology for regional atmospheric simulation has become popular. The technique is physically rather than empirically based and has a wide range of applications.

More recently, a variable resolution (stretched grid) AGCM methodology for regional climate simulation has been developed, with encouraging preliminary results. In this study, however, the focus will be on the nested LAM-AGCM methodology.

## 1.2 NESTED CLIMATE MODELLING

Detailed climate simulations for restricted areas of the globe by a high-resolution LAM provide a computationally feasible alternative to relatively course resolution AGCM simulations. Here the LAM (a primitive equation model) is nested within a global AGCM, or within a global observational analysis. This implies that the AGCM (or observed analysis) provides the LAM with information at the lateral boundaries of its domain during the integration. Therefore, nested climate modelling is in essence a boundary value problem. LAMs operating in this framework are known as nested climate models (NCMs) or regional climate models (RCMs).

AGCM simulations should produce realistic intensities and frequencies of the major synoptic systems during a climate simulation. The LAM, with a horizontal grid resolution finer than 100 km (100 km x 100 km), may capture some of the mesoscale forcing and circulation features. Generally it is found that the higher grid resolution of the nested simulations results in a more accurate, detailed and realistic depiction of the climate over a selected region. Nested climate modelling is becoming increasingly popular to produce more detailed atmospheric circulation patterns for selected regions.

## 1.3 REGIONAL CLIMATE MODELLING AT THE CSIRO

For some years the CSIRO (Commonwealth Scientific and Industrial Research Organisation) in Australia has been involved in an active programme aiming to simulate regional climate using the Division of Atmospheric Research Limited Area Model (DARLAM). DARLAM has been nested within the coarser resolution CSIRO9 (9 levels in the vertical) R21 (rhomboidal truncation at wave number 21) spectral AGCM, or alternatively, within observational analysis. DARLAM is a two-time-level, semi-Lagrangian LAM with physics similar to that of the AGCM (McGregor et al., 1993a; McGregor, 1997a). Generally the higher horizontal resolution of the DARLAM simulations provides significantly improved climate simulations (compared to the AGCM) near distinctive topographical features, in particular for precipitation and near-surface atmospheric variables.

The earliest DARLAM simulations were performed with perpetual January conditions. Subsequently, multiple January and July simulations have been performed followed by full seasonal cycle simulations up to 20 years in duration. During these simulations DARLAM was nested in the CSIRO slab-ocean (fixed observed ocean climatology as lower boundary input) AGCM. Most of the simulations over Australia with both 1 x $CO_2$ and 2 x $CO_2$ conditions have been performed at a grid resolution of 125 km. In addition, selected doubly-nested simulations have been performed at 50 km and 60 km grid resolutions.

Previously DARLAM has successfully been applied over New Zealand and South Africa. Output results compared well with the associated observed patterns. However, an important aspect that still needs to be improved is the fact that DARLAM tends to simulate excessive precipitation over regions with steep terrain.

New developments at the CSIRO involve the use of variable resolution AGCMs in order to simulate regional climate. For this purpose a new two-time-level AGCM has been designed on a conformal-cubic grid (Rancic et al., 1996). The model utilises a semi-Lagrangian advection scheme. A major advantage of this approach is that the model can be used in stand-alone mode without the limitations imposed by a nesting procedure. Encouraging preliminary results have been obtained.

## 1.4 ATMOSPHERIC MODELLING AT UP

Atmospheric modelling at the University of Pretoria (UP) was initiated in the early 1990's when the CSIRO4 (4-levels in the vertical) AGCM was obtained through a licence agreement between the University of Pretoria and the CSIRO. The model was installed on a local super computer (CONVEX C-120). A number of model simulations were performed, which included a 20-year control run, as well as selected experiments outlining the interaction between the ocean surface and atmosphere over the Indian and Pacific Oceans (Van Heerden et al., 1995).

In 1995, with the assistance of CSIRO researchers, Dr. CJdeW Rautenbach (staff member in Meteorology at UP) installed the CSIRO9 Mark II AGCM with R21 spectral resolution on a CRAY-EL94 super computer located at the South African Weather Bureau (SAWB). A number of unpublished experiments were performed in order to investigate global ocean-atmosphere interaction. The model's ability to simulate present day climate over southern Africa was also emphasised (Rautenbach and Engelbrecht, 2001). During the last three years the AGCM became a useful tool to produce experimental seasonal forecasts of rainfall over the southern African region. In his PhD-thesis Dr. Rautenbach, with the assistance of Dr. HB Gordon from the CSIRO, introduced a hybrid (sigma/pressure) vertical co-ordinate to the dynamics of the CSIRO9 Mark II AGCM (Rautenbach, 1999). In this study it was indicated that the hybrid vertical co-ordinate system contributes to improved climate simulations in the upper levels of the atmosphere.

During 1997 Dr. Rautenbach and CSIRO researchers installed the CSIRO9 (Mark II) AGCM with a T63 (triangular truncation at wave number 63) spectral resolution on the CRAY-EL94 super computer located at the SAWB. The model has been used in a study to investigate the influence of extra-tropical Sea Surface Temperature (SST) fluctuations on the rainfall over South Africa (Rautenbach, 1998; Engelbrecht and Rautenbach, 2001).

Regional climate modelling has numerous applications in the southern African region (Engelbrecht and Rautenbach, 2000). Seen against this background an agreement was reached in 1999 between UP and the CSIRO to install DARLAM on a suitable computer at UP. With this prospect in mind the author visited the CSIRO (Atmospheric Research) during January 2000. During the visit the flow structure of DARLAM was studied in detail. With hard work and additional assistance from CSIRO scientists (Drs. JL McGregor and JJ Katzfey) via the Internet, DARLAM was eventually installed on a powerful workstation at UP. The first LAM simulations locally performed with DARLAM are described in Chapter 5.

## 1.5 OBJECTIVES OF THE RESEARCH

The research detailed in this thesis has three main objectives:

### 1.5.1 *To investigate the potential applications and theoretical limitations of the nested climate modelling methodology in the southern African region.*

This was attained through a thorough literature study of the nested climate modelling approach as well as the theoretical aspects of the technique. The investigation focused on how the unique land/sea/atmosphere features of southern Africa might influence the applicability of various theoretical aspects to the region.

### 1.5.2 *To study the structure and formulation of DARLAM, in particular the semi-Lagrangian scheme utilised to simulate advection.*

The properties of the semi-Lagrangian scheme used in DARLAM were analysed according to the work of Dr. JL McGregor who first proposed the scheme. Numerical approximations by the semi-Lagrangian scheme to the solution of the linear advection equation are examined and compared to approximations by well-known finite difference schemes. Numerical experiments were performed to investigate the properties of the semi-Lagrangian scheme in non-linear velocity fields.

### 1.5.3 *To implement DARLAM over an extended southern African domain, and to perform and verify preliminary atmospheric simulations over the region.*

In order to do this it was essential to become familiar with the flow structure and code of DARLAM. The interpolation algorithms, required to provide the nested model with initial and boundary conditions as supplied by the CSIRO9 (Mark II) AGCM, were obtained and studied. The DARLAM code was successfully installed on a powerful workstation with a Linux operating system. Multiple January and July atmospheric simulations, nested within a long seasonal cycle simulation with the AGCM, were performed over an extended southern African domain. The entire Southern African Developing Countries (SADC) region has been included in the domain. This achievement opens doors for further collaboration with our neighbouring countries.

## 1.6 ORGANISATION OF THE REPORT

In Chapter 2 the modifying effect of mesoscale forcing on the climate of southern Africa is discussed and the need for high-resolution climate simulations over the region is highlighted. The concept of nested climate modelling is defined and the philosophy behind the methodology is explained. This is followed by a detailed discussion of the theoretical aspects of nested climate modelling such as nesting strategies, domain size and lateral boundaries, model resolution, spin-up time and initialisation. Emphasis is placed upon the applicability of each aspect in the southern African region. The chapter concludes with a discussion of some of the unresolved theoretical issues in the field of nested climate modelling. Perspective is provided concerning the potential applications and theoretical limitations of the nested climate modelling methodology over southern Africa.

The nested model DARLAM is the only state of the art LAM developed in the Southern Hemisphere. Chapter 3 provides a general discussion of the most important features of DARLAM. The chapter includes a discussion of the strategy adopted to nest DARLAM within the CSIRO9 (Mark II) AGCM. The formulation of the AGCM itself is described briefly, followed by a description of the surface characteristics, dynamical formulation and parameterisation schemes of DARLAM. Previous experiments conducted with DARLAM over Australia, New Zealand and Asia are examined. Two experiments performed at a relatively coarse resolution over southern Africa with an earlier version of DARLAM are put in the spotlight. Regional climate modelling groups world wide are experiencing difficulties with the simulation of rainfall in regions of steep topography. DARLAM is no exception and therefore Chapter 3 concludes with a discussion of the impact of topography on DARLAM simulations.

DARLAM makes use of a unique semi-Lagrangian advection scheme. Various forms of the advection equation, that describes transport by the wind of a dependant variable, are considered in Chapter 4. In general, it is regarded as impossible (or at least very cumbersome) to obtain the exact solution of the non-linear advection equation. For this reason, numerous numerical methods have been developed to approximate the true solution of the advection equation. This chapter is primarily concerned with the multiply-upstream semi-Lagrangian method of approximating the true solution of the advection equation. The semi-Lagrangian scheme used in DARLAM in particular is put under the magnifying glass. The scheme is compared to well-known finite difference schemes, namely the Leapfrog scheme and Lax-Wendroff schemes, in order to evaluate their relative merits with regard to stability and accuracy. The investigation commences with a comparison between the different numerical solutions of the linear advection equation to its exact solution (which is known). Von Neuman's method is used to determine the stability properties of the various schemes. This is followed by an examination of the ability of the various schemes to represent the phase properties of the exact solution. Two-dimensional numerical tests are performed to investigate the behaviour of the schemes in events where the velocity field is non-linear. These tests include Crowley's test for uniform solid body rotation as well as Smolarkiwiecz's test for strong deformational flow. It is shown that the semi-Lagrangian scheme used in DARLAM is superior to the finite difference schemes with respect to phase, stability and conservation properties.

January and July climate simulations over an extended southern African domain (complete SADC region) have been performed using DARLAM. The model was one-way nested within output fields for selected months from a long seasonal cycle simulation with the CSIRO9 Mark II AGCM. Nine separate simulations (ensemble members) have been generated for both January (austral summer) and July (austral winter). Results from these simulations constitute the model climatology for the two months. Chapter 5 commences with a discussion concerning the design of the nested climate modelling experiment over southern Africa. The selection of observational data fields used for qualitative model verification is motivated. The chapter concludes with a discussion of DARLAM output results (mean sea-level pressure, winds, temperature and rainfall). The results are compared to the associated AGCM simulations and to observations. It is indicated that the DARLAM results are significantly better than those obtained from the AGCM. This is particularly true for near-surface variables close to topographic features. It is also shown that DARLAM severely overestimates rainfall over South Africa, particularly over regions of steep topography.

Some conclusions are made in Chapter 6 with respect to the applicability of the nested climate modelling methodology over southern Africa. The advantages of using a semi-Lagrangian limited-area model are highlighted. Potential applications of DARLAM over southern Africa are outlined and a view of the future role of nested climate modelling over southern Africa is presented.

Appendix A contains the VISUAL BASIC code developed to perform Crowley's Cone test with the semi-Lagrangian D3 scheme. Output is in MATLAB format for displaying purposes.

Appendix B contains the FORTRAN code developed to perform Smolarkiewicz's test of strong deformational flow with the semi-Lagrangian D3 scheme. Results can be displayed using PGPLOT software.