CHAPTER 2

PERSPECTIVE FOR NESTED CLIMATE MODELLING OVER SOUTHERN AFRICA

2.1 INTRODUCTION

The challenge of simulating regional climate is in essence one of representation of climate forcing on two different spatial scales. These scales are the large-scale (defined as the range of approximately 1000 km to global) and the mesoscale (defined as the range of a few kilometres to several hundred kilometres) (Giorgi and Mearns, 1991). For example, large-scale forcing induced by the Earth's orbital characteristics, radiation budget and the abundance of greenhouse gasses, modulates the atmospheric general circulation. This in turn determines the succession of weather events that characterise the climate regime of a given area. Mesoscale forcing such as forcing induced by complex topographical features and surface characteristics modifies the structure of weather events and initiates mesoscale atmospheric circulation systems. Embedded in the large-scale atmospheric systems, the mesoscale circulation systems contribute to modulate the regional distribution of climate variables (Giorgi and Mearns, 1991).

AGCMs are the primary tools available for atmospheric simulation (climate and shorter-term variability). Current AGCMs have reached a high level of sophistication and provide a full three-dimensional representation of the atmosphere. These models intend to solve the equations for conservation of momentum, mass and energy and include parameterisation schemes for the main physical processes in the atmosphere such as radiative transfer, cloud formation and precipitation and boundary layer and surface physics. The applications of AGCMs over southern Africa include simulations of present day climate (Joubert, 1997; Rautenbach and Engelbrecht, 2001), simulations of climate variability (Joubert, 1997; Engelbrecht and Rautenbach, 2001) and experiments describing possible links between droughts/floods over the sub-continent and global sea surface temperature (SST) variations (Mason et al., 1994; Jury and Pathack, 1996).

Although AGCMs adequately reflect the main characteristics of the general circulation over southern Africa (Joubert, 1997; Rautenbach and Engelbrecht, 2001; Engelbrecht and Rautenbach, 2001), their performance in reproducing regional climate detail is rather poor (Joubert et al., 1999; Engelbrecht and Rautenbach, 2000). A major problem in AGCMs when trying to simulate the regional climate has to do with horizontal resolution. AGCMs used for simulating present climate conditions over southern Africa have been run at resolutions of approximately 2.5° for both latitude and longitude (Joubert, 1997; Rautenbach and Engelbrecht, 2000; Engelbrecht and Rautenbach, 2001). This relatively course resolution is a result of the computational requirements set by the global climate modelling system which rapidly become prohibitive as the resolution increases (MgGregor et al., 1993b; Giorgi and Mearns, 1991). At these resolutions the effect of large-scale forcing on the general atmospheric circulation can be successfully captured. The impact of local forcing, which acts on scales as small as a few kilometres and strongly influence the detailed distribution of atmospheric variables over many parts of southern Africa, is however lost. For example, the small-scale atmospheric circulation induced by detailed topography can not be presented at typical AGCM resolutions (McGregor, 1997a). In addition there are important small-scale meteorological phenomena such as tropical cyclones that are not adequately parameterised as sub-grid scale processes at typical AGCM resolutions. These phenomena are vital in their own right and also significantly affect the mean climatology of a specific region (McGregor et al., 1993b).

As a computationally feasible alternative, it is possible to produce detailed climate simulations for restricted areas on the globe by nesting a high-resolution LAM within a global AGCM, or within an observational analysis. Such nested models (which are primitive equation models) are also known as RCMs, although the term could also encompass variable resolution global AGCMs (McGregor, 1997a). A selected domain is modelled in a stand-alone fashion with a high-resolution LAM, noting that for climate modelling purposes it is necessary to include a representative range of synoptic weather patterns in the simulations. One means of providing an appropriate range of synoptic situations is to first run a larger scale AGCM and to interpolate the output to LAM resolution at the boundaries of the nested model. These interpolated fields are then used to force the LAM at its lateral boundaries (McGregor et al., 1993b). The AGCM simulation should produce realistic intensities and frequencies of the various types of major synoptic systems. The LAM, with a horizontal grid resolution of approximately 100 km, may simulate some of the mesoscale features leading to a more accurate, detailed and realistic depiction of a region's climate. This is at least possible in mid-latitude domains where the boundary forcing usually determines the broader behaviour of LAM systems (Vucicevic and Paegle, 1989). The climatology of a LAM is determined by the succession of weather events simulated from the contribution of lateral boundary conditions and the internal characteristics of the model. This implies that nested climate modelling is in essence a boundary value problem.

Research groups are increasingly constructing LAMs for climate modelling applications. The main advantage of these models is that they provide a high-resolution climate simulation over a limited domain, whilst remaining much more economical to run than a global model of similar grid resolution. Although LAMs are restricted to a specific domain, they often employ more detailed physical parameterisation schemes than their global counterparts. They also allow for a more accurate representation of topography which is, for example, crucial for the simulation of regional precipitation. If the LAM has a dynamical formulation and physical parameterisation similar to that of the AGCM but a much higher resolution, it adds significant smaller-scale detail to the coarser simulation of the AGCM (Walsh and McGregor, 1995). In general the additional detail results in an improved simulation compared to that of the AGCM. Unlike interpolation methods and statistical techniques (downscaling), the nested AGCM-LAM methodology is a physically based procedure (McGregor et al., 1993b). Note again that the successful application of the nested modelling approach requires that the AGCM provides adequate broad-scale simulations.

While theoretical and scientific problems remain to be solved in the use of nested LAMs, the potential applications are numerous. It is anticipated that LAMs will be coupled on a more regular basis to other components of the earth-atmosphere system such as ocean, sea-ice, biosphere and hydrology models. Lynch et al. (1995) have performed Arctic experiments with an LAM coupled to a dynamic sea-ice model, while Leung et al. (1996) have coupled a LAM to a surface hydrology scheme. There is potential for greatly improved projections of the possible impact of climate change. These projections could take the form of improved estimates of rainfall changes in mountainous catchment areas and better estimates of soil moisture changes in agricultural regions (McGregor et al., 1993b). Further afield there is also a possibility that the impact of future climate change on the accumulation of snow over the Antarctic continent could be better predicted, which would lead to an improved estimate of possible changes in sea level (McGregor et al., 1993b). Provided that suitable sea-surface temperature forecasts are available, there is also a possibility that predictions of the regional effects of El Niño, namely droughts and floods, could be enhanced and made considerably more detailed (McGregor et al., 1993b).

In the next section examples of important mesoscale forcing over southern Africa are presented. Theoretical aspects concerning nested climate modelling are discussed in the remainder of the chapter, with the emphasis on the application of the nested AGCM-LAM methodology on the southern African sub-region.

2.2 MESOSCALE FORCING OVER SOUTHERN AFRICA

Mesoscale atmospheric forcing is primarily induced by complex distributions of surface characteristics such as topography, coastlines, inland water masses and vegetation characteristics. These vary on a scale of 10-100 km. Precipitation is also strongly affected topographically by means of condensation due to topographic upliftment and enhanced convection during summertime. An example that clearly illustrates the impact of topographic forcing on regional scale precipitation is the Klein area of South Africa. Figure 2.1 shows the observed average annual precipitation over this region. Dry conditions normally prevail over the Klein Karoo, which lies in the rain-shadow of the Lange and Outeniekwa Mountains. As a result of the mountains wetter conditions are recorded over and up-wind of the mountain ranges.

Mesoscale forcing can also be of thermal origin, as induced by diverse radiative properties of land and ocean (water) masses. This results in the development land-sea breeze circulation, which significantly influences the local climate of southern African coastal regions. Along the north-west coast of Madagascar, land-sea breeze circulation systems are responsible for the dominant winds

(Jackson, 1954). The strongest sea breezes in southern Africa occur along the Namibian coastline where winds blow in the afternoons from the south or south-west after calm and overcast mornings (Jackson, 1954).

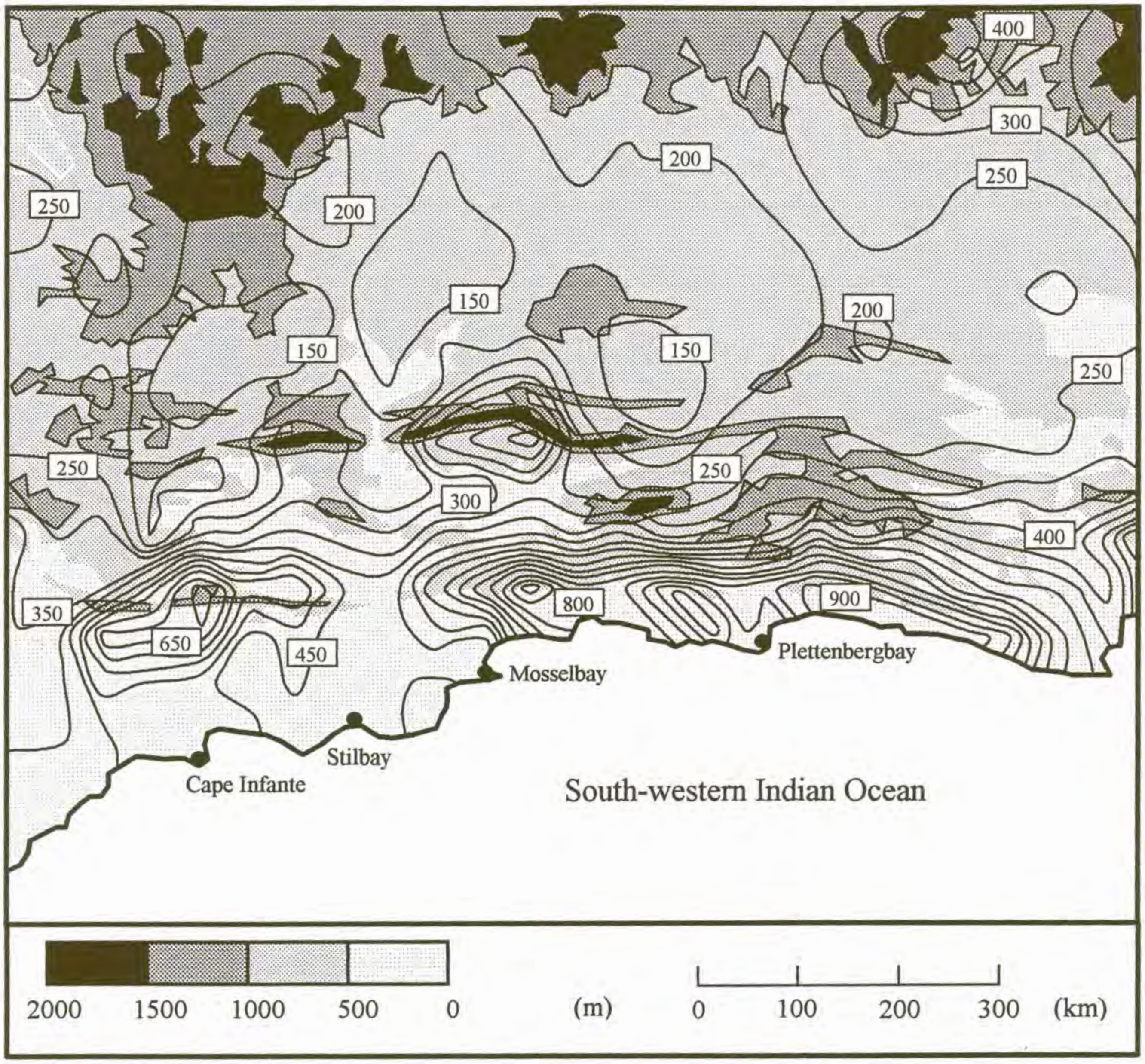

Figure 2.1 Topography (shaded with 500 meter intervals) over the Klein Karoo, Groot Karoo and south coast (20° to 25° east and 32° to 35° south) with isohyets indicating the average annual rainfall measured in millimetres. Note the increase in local rainfall totals against steep slopes of and over higher surface altitudes.

On a daily basis, during summertime, humid and relatively cool air moves over the Natal coast as a result of see breezes. From time to time these circulation patterns intrude as far as 60 km into the interior (Preston-Whyte, 1969). See breeze circulation is normally influenced by the gradient winds of larger scale (synoptic) pressure systems over the ocean (figure 2.2). The combined effect of meso and synoptic scale winds determines how far see breeze flow will intrude into the Natal interior (Preston-Whyte, 1969). The strong gradient in topography also results in the development of mountain-plain winds during the night and valley winds during the day. These circulation systems are present over the entire KwaZulu-Natal (from the Drakensberg to the coastline) (Tyson, 1966; 1968). Interaction between the gradient winds, land-sea breeze circulation and slope-induced circulation may result in complex mesoscale flow.

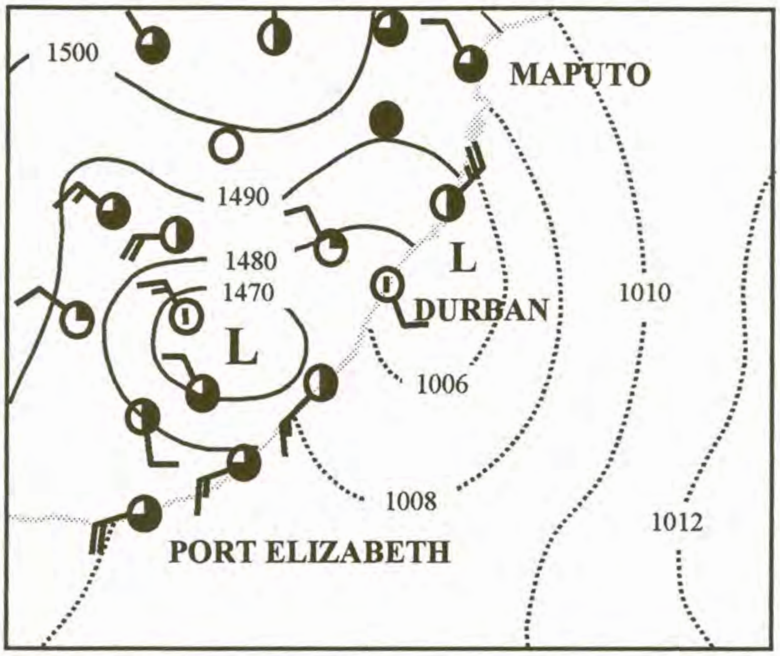

Figure 2.2 Gradient winds induced by a coastal low over the Indian Ocean may deepen the penetration of the sea breeze over the interior of KwaZulu-Natal. Geopotential heights (gpm) of the 850 hPa pressure level over the country (solid lines) and isobars of mean sea level pressure over the ocean (dotted lines) are shown for 14 January 1968 at 14:00 SAST.

Interaction between meso and synoptic scale circulation systems significantly influences the climate of certain parts of southern Africa. An example is the occurrence of heavy local storms over the escarpment of Mpumalanga and the Northern Province in South Africa. These storms are often the product of atmospheric motion on three different scales as indicated in figure 2.3 (Garstang et al., 1987):

- On the synoptic scale a westward moving trough is produced on or above the 850 hPa pressure level, which induces westerly to north-westerly flow over the north-eastern escarpment.

- On the mesoscale a lid inversion develops over the escarpment through either advection or by subsidence of Highveld air. This is normally associated with a low-level easterly flow.

- Local effects amplify both the 850 mb westerly flow over the escarpment and the surface easterly flow of moist Lowveld air.

The surface easterly flow that undercuts the 850 mb westerly flow is probably a product of both the synoptic and mesoscales of motion, with the latter in the form of escarpment heating (Garstang et al., 1987). If the intrusion of moist Lowveld air along the escarpment takes place early and far enough to the west, heavy convective storms occur at the places where no damping inversion has developed through either advection or subsidence.

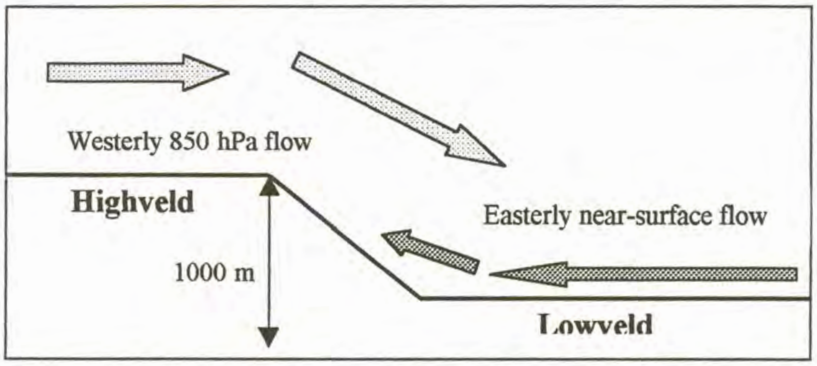

Figure 2.3 Circulation characteristics favourable for the development of heavy convective storms over the eastern escarpment of South Africa (After Garstang et al., 1987).

These examples emphasise the need for high-resolution information in order to characterise the climate of areas in southern Africa where mesoscale atmospheric circulation is important. AGCMs with horizontal grid resolutions in the order of 100 to 500 km are capable of providing information regarding the response of large-scale atmospheric circulation over southern Africa as a result of large-scale forcing. From the discussion in this section however, it is clear that AGCMs are not suitable to simulate detailed atmospheric circulation that results from mesoscale boundary forcing.

2.3 NESTING TECHNIQUES

2.3.1 ONE-WAY NESTING

Nested modelling requires that boundary information to propagate freely into the nested domain and that the nested model does not suffer excessive reflection of its generated flows. The most popular nesting strategy adopted so far is the technique of one-way nesting (figure 2.4). Here the flow of information occurs only from the AGCM towards the LAM. Most NCMs developed to date employ the so-called "relaxation" method to generate meteorological lateral boundary conditions (LBC). The purpose is to force nested model solutions toward the large-scale circulation fields over a lateral boundary zone.

A commonly used scheme is that of Davies (1976). In this scheme several (typically five) boundary rows provide a buffer zone at each time step with full incorporation of the outer solution at the outermost rows, tapering off over the inner rows to the inner solution of the LAM. Different functions can be used as the weighting function. Davies (1976) has carried out one-dimensional wave equation calculations to obtain weights for the tapering, which minimise reflections. Giorgi et al. (1994) and Walsh and McGregor (1995) have adopted exponentially decreasing weights. The functions are chosen to minimise noise in areas adjacent to the buffer zone (Giorgi et al., 1993c). This approach has proven to be effective to ensure a smooth transition between driving condition-dominated and NCM-dominated regimes and to reduce noise (Giorgi and Mearns, 1999). A slightly different one-way nesting scheme (used in the National Centre for Atmospheric Research (NCAR) MM4 model) is that of Perkey and Kreitzberg (1976). This scheme has 4 buffer rows over which tendencies of the variables are weighted.

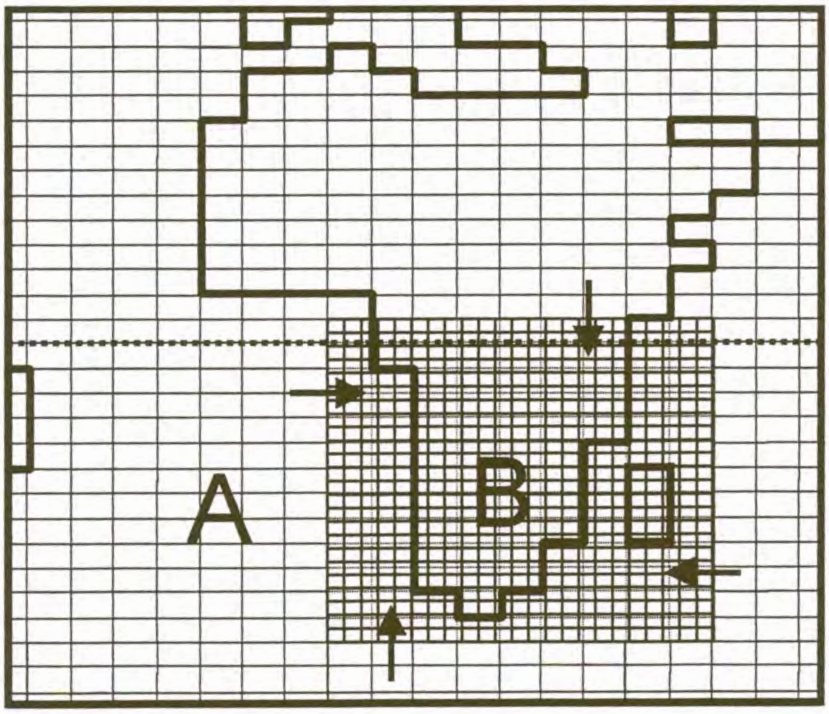

Figure 2.4 One-way nesting over a southern African domain. Information is allowed to flow from the relatively coarse resolution AGCM to the higher resolution nested model. Flow in the opposite direction is not allowed.

The size of the buffer zone varies depending on the model domain. A configuration of buffer zones with only a few boundary points and a linear weighting function tends to produce an unrealistic sharp transition from model solution to driving boundary values (Giorgi et al. 1993c). This results in noise generation near the boundaries that can be substantially reduced by using broader buffer zones and an exponentially varying function allowing for a smoother transition from model solution to driving fields (Giorgi et al., 1993c). For typical continental scale domains most current regional models use buffer zones of 10 grid point width or more. This is usually sufficient to provide a smooth lateral forcing (Giorgi and Mearns, 1999).

Giorgi et al. (1993c) proposed a modification to the standard relaxation technique where a wider buffer zone is adopted in the upper troposphere compared to that of the middle and lower troposphere. The rationale behind this approach is that the large-scale wave patterns and circulation fields in a nested LAM are essentially determined by the driving LBC. Therefore, a relatively wider zone aloft increases the consistency between the nested model and the driving large-scale circulation pattern, in both magnitude and phase. However, the high-resolution forcing resolved by a nested LAM originates primarily at the surface due to topography and coastlines. For this reason the LAM should develop its own internal mesoscale circulation in the middle and lower troposphere, which is achieved by reducing the size of the buffer zone and thus the direct boundary forcing (Giorgi and Mearns, 1999).

Overall the simple standard relaxation technique, if carefully designed, has proven to be adequate for most LAM applications and is therefore widely used. The main problem encountered with this technique is the occurrence of spurious precipitation near the downwind domain boundaries (Giorgi and Mearns, 1999). In a three-dimensional atmospheric model, the disturbances have complicated structures and travel from many directions. This implies that full attenuation of the reflections is not achieved. The residual reflections are primarily manifested near the horizontal boundaries in the divergence field, which may lead to some noise in the vertical velocity and related precipitation patterns (McGregor et al., 1993b). Although precipitation patterns may appear somewhat noisy near the boundaries, it should be noted that this noise does not normaly lead to contamination of the interior fields. This is because the AGCM moisture and temperature fields strongly override the modifications made to the heating and drying of the LAM in this boundary zone (McGregor et al., 1993b). At the surface however, the water budget and surface energy may be negatively affected (Giorgi and Mearns, 1999). Problems related to sharp transitions at the lateral boundaries can be improved by using multiple nesting or variable resolution configurations (Giorgi and Mearns, 1999, also see section 2.11).

The possible interpolation errors and the generation of noise implies that the abrupt change in model and driving data resolution at the lateral boundaries should be minimised. One way to decrease the driving model's resolution mismatch is to use a multiple nested mesh (Giorgi and Mearns, 1999). Multiple nesting can be done using either one-way or two-way (see section 2.3.3) nesting. An alternate technique is to use the variable resolution approach proposed by Qian et al. (1999). In this approach the grid resolution of the LAM should match that of the driving model in the lateral boundary zone but should gradually increase towards the interior of the domain, where a uniform fine resolution grid is placed. In both the multiple nested and variable resolution approaches the mismatch between the large-scale driving fields and LAM simulated fields are minimised. The model's computational efficiency could improve significantly since fewer grid points may be used in the buffer zone (Giorgi and Mearns, 1999).

A LAM may be nested in either objective analysis provided by forecast centres or in output provided by global AGCMs. Multiple nesting down to finer scales has also been performed, within an AGCM by McGregor and Walsh (1994) and within observed analysis by Leung et al. (1996).

An important issue concerning LBC provision is the interval of updates of the large-scale fields. Nested model LBC are needed at each time step and are usually linearly interpolated (in time) from two adjacent large-scale field updates (Giorgi and Mearns, 1999). Typically the analysis or AGCM output is available every 3 to 12 hours and these are interpolated in time and space to lateral boundary points as required during the simulation. At each time step the outermost boundary points of the nested LAM are relaxed toward the interpolated values. In general it is preferable not to select update intervals greater than 12 hours as this might cause the model to misrepresent systems rapidly moving across the lateral boundaries (Giorgi and Mearns, 1999).

For summertime simulations over southern Africa it would be preferable that the LBC updates occur at least every 6 hours to represent the diurnal cycle. This is necessary because differential heating associated with the diurnal cycle may cause local overturning of mesoscale circulation overland (Giorgi and Mearns, 1999). Experiments by Dickenson et al. (1989) showed that during winter, when the diurnal cycle is not pronounced, the model sensitivity to LBC update intervals from 3 to 12 hours is small. Likely, the importance of the frequency of LBC updates depends on domain and season, so it is always advisable to assess the model sensitivity to the update frequency and to use the highest frequency available (Giorgi and Mearns, 1999).

When applying one-way nested models to regional climate simulation, it is assumed that the development of systems within the model domain is constrained by the forcing from the AGCM provided boundary conditions. The boundary conditions provide means of removing flow inconsistencies, at least in regions where weather systems regularly sweep through the domain (Errico and Baumhefner, 1987). It might be expected that the one-way nesting technique would perform better in mid-latitude regions than in the tropics. In equatorial or tropical latitudes, where weather patterns move more slowly than in mid-latitude regions, it may happen that quasi-stationary systems develop within the nested domain. These have a life somewhat independent of the AGCM forcing (Walsh and McGregor, 1995). Thus, the one-way nesting approach has some theoretical limitations especially in the tropics where the "stationary problem" restricts the applicability of the technique. Nevertheless, Walsh and McGregor (1995) performed successful climate simulations over the Australian region. Included in their LAM domain were extended tropical regions both north and south of the equator.

2.3.2 SPECTRAL NESTING

A different one-way nesting technique has been proposed by Kida et al. (1991) and Juang and Kanamitsu (1994). It was previously believed that difficulty in prescribing the lateral boundaries would make spectral techniques inappropriate for nested limited-area modelling. Despite this Tatsumi (1986) developed a spectral LAM. His spectral model uses a Fourier expansion in the horizontal, with the lowest order coefficients provided from the large-scale fields. This results in a unique nesting technique.

The outer model (eg. AGCM) provides an average forcing over the whole domain, rather than just over the boundaries (McGregor et al., 1993b). The regional model solves the high wave-number component. This strategy ensures full consistency between the nested model and large-scale driving fields and presents a different philosophy concerning the role of the nested LAM (McGregor, 1997a). Spectral nesting avoids any necessity to match the LAM and AGCM topography and parameterisations (McGregor, 1997a; also see section 2.5). The technique has the disadvantage of preventing the formation of surface-forced secondary systems in the regional model that are not present in the driving fields (Giorgi and Mearns, 1999). It has yet to be demonstrated whether the extra constraints of the technique lead to a generally better or worse simulated climatology (McGregor, 1997a).

More recently Sasaki et al. (1995) modified the spectral nesting technique to allow full spectral nesting above 500 hPa only, and conventional LBC nesting at lower levels. This approach was followed in order to provide improved results with respect to the full spectral nesting, primarily because of the difficulty to nest the water vapour fields in the lower troposphere by means of spectral nesting (Giorgi and Mearns, 1999). This modified spectral method is conceptually similar to the modified conventional method of Giorgi et al. (1993c) and both methods appear to converge toward a criterion of stronger forcing in the upper, and weaker forcing in the middle and lower-tropospheric layers (Giorgi and Mearns, 1999).

2.3.3 TWO-WAY NESTING

In the one-way nesting approach the circulation produced by the nested LAM does not feed back into the global model. Ideally, there should be a two-way flow of information, which implies that flow inside and outside the LAM domain should interact in a single dynamic system. The latter approach is very attractive for specific locations and some difficulties experienced in the tropics with the one-way nesting approach are avoided (McGregor, 1997a). Improved simulations should be expected from the two-way nested technique (McGregor, 1997a).

Two-way interacting nested climate modelling experiments between AGCMs and LAMs have however not been attempted to date. One reason for this is the technical difficulty involved in fully coupling two complex model systems when the inner and outer models have different formulations, e.g. grid versus spectral. It is even more difficult when the outer model is a climate model as arbitrary modification of the outer model solution can act as an artificial source or sink of energy that can upset its conservation properties (McGregor et al., 1993b). Two-way nesting also presents the need to perform separate climate runs for each geographic configuration, which implies a lack of flexibility especially for long simulations. The model may also need to be re-tuned before every new configuration (McGregor, 1997a).

One way to facilitate coupling of global and LAM is to modify the spatial grid resolution of the LAM from a fine resolution over the area of interest to a coarser resolution over the rest of the globe. By matching grid resolutions from the two models at the lateral boundary area where the exchange of information takes place, inconsistencies associated with sharp contrasts in model resolution are minimised (Qian et al., 1999).

2.4 DOMAIN SIZE, RESOLUTION AND LATERAL BOUNDARIES

Experiments have been performed over Europe to study the effect of domain size on LAM simulations. Jones et al. (1995) concluded that the LAM domain should be sufficiently small in order to prevent simulated atmospheric circulation of the nested model departing from that of the driving AGCM on the synoptic scale. The domain also needs to be large enough, however, to prevent the coarse scale lateral boundary conditions from dominating the solution over the area of interest. More detailed simulations of atmospheric features representing a finer scale than those skilfully resolved by the AGCM should be achieved by the LAM (Giorgi and Mearns, 1991; Jones et al., 1995; Podzun et al., 1995). The horizontal resolution of the nested model therefore has to be fine enough to capture forcing and atmospheric circulation on the mesoscale.

The selection of domain size and horizontal resolution is generally determined by a compromise between meteorological and computational considerations. An increase in model domain size and a refinement in resolution are achieved at the cost of increased computation time. Stability considerations yield that the model time step has to decrease with the grid point spacing. As stronger vertical velocities are produced with a refinement in horizontal grid resolution, it is recommended that the vertical resolution is increased to maintain stability (Giorgi and Mearns, 1999). This implies that the relationship between computation time and model resolution is stronger than linear.

The model domain should encompass, to the extent feasible, all regions of forcing and atmospheric circulation that directly influence the climate and climate variability over the area of interest. For example, a domain over southern Africa should include the Agulhas retroflection region in the south-western Indian Ocean (Engelbrecht and Rautenbach, 2001) and Madagascar to the east (Joubert, 1998). Such a domain also needs to extend far enough over the Atlantic Ocean to adequately capture the development and propagation of mid-latitude cyclones (frontal troughs) and far enough to the north to capture tropical features such as the semi-stationary tropical surface trough.

It is also recommended that the model resolution should be fine enough to capture the forcing and atmospheric circulation of interest. For example, a study focussing on the eastern part of South Africa needs to employ a resolution capable of capturing the eastern escarpment at the atmospheric circulation scale of interest. A study focussing on equatorial Africa needs to employ a resolution capable of capturing mesoscale forcing and circulation induced by Lake Victoria. Studies focussing on agriculture in the Vaal River catchment area in South Africa may require information from the scale of a few tens of kilometres, while studies concerning the advection of trace gasses over the SADC region may require information at sub-continental scale. Thus, the model resolution must be of such a nature that useful information for specific applications is produced.

Another factor that influences the selection of model resolution is the suitability of physical parameterisation schemes and approximations of dynamical processes in the atmosphere. The validity of the hydrostatic assumption decreases significantly for horizontal scales smaller than approximately 10 kilometres. The same principle applies for the assumption of scale separation inherent in most cumulus parameterisation schemes (Giorgi and Mearns, 1999). In addition to this, different cumulus parameterisation schemes are often developed for specific spatial scales. Examples include the scheme of Anthes (1977), that has been developed for scales between 60 and 120 km, as well as that of Fritsch and Chappel (1980) who focus on scales of a few tens of kilometres.

Some care is also needed when locating the boundary zone. It is recommended that the occurrence of land-sea interfaces in the boundary zone is minimised to avoid problems of matching coastal outlines and attendant sensitivity of surface physical routines (McGregor et al., 1993b). In general it is preferable to place the lateral boundaries over the ocean rather than over land to avoid possible effects of unrealistic surface energy budget calculations near the boundaries (Giorgi and Mearns, 1999). Another reason for placing the boundaries over the ocean is the increased possibility of the formation of spurious precipitation near the lateral boundaries if placed over land and steep topography (Giorgi and Mearns, 1999).

It is also particularly advisable to avoid placing the domain boundaries over areas of complex topography. The mismatch between the coarse resolution (AGCM) driving data and fine resolution model topography may not only produce significant noise but often requires an extrapolation of variables below the surface level of the driving fields (Giorgi and Mearns, 1999). McGregor et al. (1993b) suggested the use of the smoothed AGCM terrain in the boundary zone of the LAM to avoid problems arising from vertical interpolation. In the nested model DARLAM, boundary fields are altered to compensate for any differences in altitude between the AGCM and LAM that may occur in the interpolated topography (McGregor, 1997a).

Finally, it is useful to select a domain where the area under investigation is located as far as possible from the lateral boundary zone. This prevents boundary region noise generated from excessively contaminating the solution over the area of interest. It also minimises the influence of the coarse resolution lateral forcing on the internal model physics of the LAM (Giorgi and Mearns, 1999).

2.5 PARAMETERISATION SCHEMES

Both AGCMs and LAMs require a comprehensive set of physical parameterisation schemes for processes that occur on sub-grid scales. Examples of physical processes include radiation, cloud formation, latent heating (especially in cumulus convection), vertical transfer in the lower boundary layer (the lowest 1 km of the atmosphere) and atmosphere-surface interactions (including ocean-atmosphere and ocean-biosphere interaction). Some of these processes are described in McGregor et al. (1993a). With finer resolutions, LAMs require particularly careful treatment of surface, soil and vegetation interactions (McGregor, 1997a). Wherever possible the parameterisation schemes are based on observations.

Parameterisation of cumulus convection and cloud estimation proved to be the most difficult since the parameterisation formulation strongly depends upon grid spacing. Cumulus convection parameterisation also needs to handle a wide range of conditions. For example, in the tropics there is abundant moisture and weak winds, whereas convection associated with mid-latitude systems typically occurs in a drier environment with stronger winds. The simulated precipitation patterns and the corresponding heating rates in the tropics are extremely sensitive according to the selection of a cumulus parameterisation scheme (Krishnamurti et al., 1980; Horel et al., 1994). Other tests indicated that tropical nested simulations are sensitive to the numerical formulation of vertical advection (Walsh and McGregor, 1995) as well as to the radiation scheme decided upon. If the LAM develops a cool bias in the tropics compared to the AGCM or observed analysis, spurious boundary inflow or outflow may be generated resembling a large-scale sea breeze (McGregor, 1997a). Therefore, the generality and suitability of a specific parameterisation scheme has to be investigated before it is used by means of sensitivity experiments in regional model simulations (McGregor et al., 1993b). These issues are important for LAM experiments over the SADC region, which includes extended areas located in both the tropics and mid-latitudes. Although a parameterisation scheme formulation is supposed to cope with a wide range of environmental conditions, it is advisable to apply diverse parameterisation schemes over regions with diverse weather phenomena (McGregor et al., 1993b).

McGregor (1997a) states that in general, physical parameterisation schemes in a LAM should be compatible to those in the driving AGCM. In particular, experiments with DARLAM indicated that the LAM and AGCM should use similar cumulus parameterisation schemes over the tropics (McGregor, 1997a). This ensures that maximum compatibility between the models is achieved (Giorgi and Mearns, 1999). LAM simulations may be used to investigate and test the high-resolution performance of parameterisation schemes of AGCMs (McGregor, 1997a). An important disadvantage when using the same parameterisation schemes in LAMs and AGCMs, is that physical schemes developed for course resolution AGCMs may not always be adequate for application in the finer resolution LAMs. Parameterisation schemes show significant sensitivity to horizontal resolution and thus can result in different behaviours in the nested and driving models (Giorgi and Mearns, 1999).

An alternative approach is to use different physical parameterisation schemes in the nested and driving models, where the schemes for each model are specifically developed and optimised for the respective model resolutions. A disadvantage of this approach is that it is often difficult to interpret differences in results since these are affected by not only diverse resolution forcing but also by differences in the physics schemes used (Giorgi and Mearns, 1999). Another potential disadvantage is that the parameterisation schemes may cause different forcing leading to spurious circulation in the interior of the domain (Giorgi and Mearns, 1999).

Giorgi and Mearns (1999) indicated that a LAM “sees” two important aspects namely initial and lateral boundary fields. The use of similar or different physics when driving LAMs can both lead to good quality simulations in the presence of good quality driving fields. LAM simulations are continuously improving as better parameterisation schemes are developed and as model resolution is further refined (McGregor, 1997a).

2.6 ATMOSPHERIC MODEL FORMULATIONS

The following discussion is based on that of McGregor et al. (1993b). As far as atmospheric science is concerned, there has been considerable development in numerical techniques during the past few decades. This includes the implementation of both spectral and grid-point representations, implicit and explicit time differencing schemes as well as the more recent semi-Lagrangian schemes. Atmospheric models may be integrated for several days to generate medium-range weather predictions or for extended periods for climate simulations. Models used for both applications are similar, although for climate simulations there is a strong emphasis on the overall conservation of physical quantities to reproduce the long-term behaviour of the atmospheric circulation. Several aspects concerning the dynamical and numerical formulation in AGCMs and LAMs are discussed in the following sections.

2.6.1 SPECTRAL MODELS

Most present day AGCMs are formulated in terms of an expansion in spherical harmonics. Examples include the spectral models of the Australian Bureau of Meteorology Research Centre (BMRC), the Canadian Climate Centre, the CSIRO in Australia, the European Centre for Medium-range Weather Forecasting (ECMWF), the Geophysical Fluid Dynamics Laboratory (GFDL) and NCAR. As an alternative finite difference methods on a grid, as employed in the United Kingdom Meteorological Office and Goddard Institute for Space Studies models, are also used in the so called "grid models". Spectral models can be designed to have highly self-consistent numerical formulation and accurate advection properties. Disadvantages include a tendency to smear out sharp gradients that may, in particular, affect moisture as well as the spectral smoothing of topography near coastlines. This complicates the specification of appropriate sea-surface temperatures.

It was previously considered that difficulties in prescribing the lateral boundaries would make spectral techniques inappropriate for limited-area modelling. However, a spectral LAM has been developed recently by Tatsumi (1986) (See section 2.3.2 for more details).

2.6.2 THE HYDROSTATIC APPROXIMATION

All climate models and most weather prediction models employ the hydrostatic approximation. The hydrostatic approximation embedded in the equations of motion assumes that vertical acceleration in the atmosphere is negligible compared to the other terms in the vertical momentum equation. The assumption allows for sound waves to be filtered out from the solutions, implying that relative large time steps may be achieved during model integrations. The vertical equation of motion reduces to an expression giving the height of a column of air as an integral of temperature with respect to the logarithm of pressure (hypsometric equation). The hydrostatic approximation is found to be valid for grid resolutions courser than 10 to 20 km (McGregor et al.,1993b; Giorgi and Mearns, 1999). For smaller grid lengths, inaccuracies may arise over steep terrain or during deep convection. The approximation's validity is consistent with the intuitive expectation that sound waves are considered as unimportant for the scale of atmospheric circulation considered in climate modelling.

2.6.3 CONSERVATION PROPERTIES

With the exception of the CSIRO model, all the spectral and grid point AGCMs listed in section 2.6.1 are formulated using the advective formulation of the equations of motion. The advective formulation attempts to achieve accurate horizontal transport and is written in terms of the basic wind components, temperature, surface-pressure and mixing ratio of water vapour. As an alternative the equations of motion may also be written in flux form (CSIRO model) using the original variables weighted by mass. In this form it is fairly straightforward for a grid point AGCM to guarantee conservation of mass and energy. It is more difficult to prove conservation of mass and energy in spectral models and many of these models just rely on the inherent accuracy of the spectral technique. LAMs may use either the advective or flux formulation. However, for a limited domain, conservation behaviour is dominated by fluxes across the lateral boundaries, which are supplied periodically by the outer AGCM (see section 2.3). Because of the sampling and interpolation considerations at the lateral boundaries, the conservation properties of the original equations provide little guidance for selecting the appropriate formulation for a LAM. The continual boundary forcing is, however, designed to keep the large-scale circulation features in the LAM similar to those of the driving AGCM. For this reason, conservation is not such an important issue in LAMs (McGregor, 1997a).

2.6.4 STAGGERED GRIDS

The majority of modern grid-point models employ grids in which the wind components are staggered horizontally with respect to the other variables. This staggering improves the accuracy of the pressure gradient terms in the momentum equations and leads to improved dispersion characteristics for gravity wave response (Schoenstadt, 1980). It also avoids spurious noise caused by solution decoupling over the grid (McGregor and Leslie, 1977). The Australian Bureau of Meteorology (McGregor et al., 1978; Leslie et al., 1985) and the CSIRO (McGregor, 1987) use LAMs with grids where the wind components are staggered half a grid length in their respective direction of motion. Purser and Leslie (1988) have found that non-staggered grids may be successfully used provided that high-order horizontal differencing and judicious filtering are employed.

2.6.5 HORIZONTAL ADVECTION

The selection of horizontal advection (i.e. transport) scheme can affect the degree of noise of the solution and the model's ability to maintain sharp gradients. Many grid-point models have used centred finite differencing of second or fourth order, or Lax-Wendroff schemes (Gadd, 1978b; Haltiner and Williams, 1980). In the last 15 years semi-Lagrangian techniques have been adopted for both LAMs and global weather prediction models, including the ECMWF model (Ritchie, 1991). The technique is based on finding an upwind departure point for each grid point (McDonald and Bates, 1987; McGregor, 1993), after which higher-order interpolation is used to obtain appropriate model variables at the departure point. The advection of water vapour improved significantly when using the semi-Lagrangian technique. Another important feature of semi-Lagrangian schemes is that significantly larger time steps can be achieved relative to other schemes. These aspects are discussed in more detail in Chapter 4.

2.6.6 TIME DIFFERENCING

Although the hydrostatic approximation removes fast travelling sound waves, the equations of motion still permit horizontally propagating gravity waves with phase speeds up to 300 ms^{-1}. Explicit models such as the NCAR MM4 model (Anthes et al., 1987) are constrained by these large phase speeds and require a very small time step to meet numerical stability criteria. With the split-explicit method, the gravity wave generating terms are split apart and solved with a small sub-time step embedded in each main time step (Gadd, 1978a). However, the most common treatment is to group the linear components of the terms contributing to gravity waves, and solve those implicitly. Robert et al. (1972) describes this technique in more detail. The semi-implicit method leads to a Helmholtz equation. This equation may be solved by using either iterative or direct methods, or analytically in the case of a spectral model, where it enables the use of a larger time step to be used.

2.7 SPIN-UP TIME AND INITIALISATION

Initial conditions for a LAM are supplied by observation analysis, or by forcing from an AGCM. Variables such as temperature, sub-soil temperature and moisture, and surface albedo may exhibit discontinuities at topographic interfaces, for example land-sea boundaries, or boundaries of different vegetation or soil types. Special interpolation methods need to be employed to initialise these variables near these interfaces (McGregor, 1997a).

Another consideration during initialisation is the vertical interpolation of AGCM atmospheric fields (especially temperature) to pressure levels as defined for the LAM, and to adjust the surface pressure to the new altitudes resulting from the more detailed finer resolution of the LAM's topography. Vertical compensation is also required near the boundary rows whilst nesting, if the topography of the AGCM and LAM differ (McGregor, 1997a).

Atmospheric spin-up time can be defined as the time taken by the LBC to pervade the nested model domain and generate a dynamical equilibrium between the LBC information and the internal model physics and dynamics. The spin-up time varies depending on the domain size, season and circulation intensity, but is typically in the order of a few days (Errico and Baumhefner, 1987; Anthes et al., 1989). In a LAM simulation the deviation of the model solution from the larger scale driving fields will tend to increase for the first few days of spin-up, where after it will oscillates around an asymptotic stage (Giorgi and Mearns, 1999). When the asymptotic stage (which depends on domain, season and location) is reached, the model simulates weather events that either enter the domain from the lateral boundaries or are generated in the interior of the domain with a relatively constant level of skill (Giorgi and Mearns, 1999).

A factor that contributes to complications of the spin-up procedure and model climatology is soil moisture and soil temperature initialisation. Soil water content and temperature affect weather and climate, especially during the summer, since it modulates surface and latent heat fluxes (Giorgi and Mearns, 1999). The temperature and water content of a surface soil layer of say, 10cm depth, equilibrate with the overlying climate relatively quickly (in the order of a few weeks). For a root zone of 1m depth, the equilibrium may be in the order of several seasons, while for deeper soil, it may be in the order of several years (Giorgi and Mearns, 1999). This problem is further complicated by the fact that reliable information for soil moisture and temperature initialisation is not available. Thus, if a nested model includes a soil module of several meters in depth, strict equilibrium occurs only after years of simulation. However, since the most hydrological active region is the rooting zone (order of 1m or less), for most practical purposes the soil spin-up can be considered as of the order of a few seasons to a year. This estimate depends on the sensitivity of individual models to soil moisture conditions (Giorgi and Mearns, 1999).

2.8 MODEL INTEGRATION PERIODS

As indicated, the atmospheric circulation properties of a LAM are dictated by the succession of weather events as simulated from the contribution of LBC and internal model physics after an atmospheric spin-up of several days. In LAM simulations the first days of spin-up are usually neglected in the analysis of results (Giorgi and Mearns, 1999).

A major aspect when performing climate simulation experiments has to do with the length of integration period required for producing a stable climatology. For example, observed average rainfall at a fixed location over a period of 10-years will, in the absence of climate change, only differ slightly from the average rainfall over a 20-year period. An average from a 1-year period will, however, differ significantly from a 10-year average, especially if a flood or a drought occured in the 1-year epoch. Climate models exhibit analogous patterns of internal variability (McGregor et al., 1993b). They are also sensitive to the prescribed SSTs, and would exhibit increased variability in the event where El Niño events are captured in model simulations. In order to obtain a stable average climate from a model, it is recommended that a simulation of at least 10-years is performed (Miyakoda et al., 1972). However, Walsh and McGregor (1995) point out that some differences between long-term monthly averages could still be expected due to sampling errors that is caused by the fact that climatological averages are produced by averaging relative small groups (for example 10-years) of ensemble members.

A popular strategy to produce a model simulated climatology for a specific month is to nest separate simulations for that month rather than to perform seasonal cycle runs. Here, a model simulation is constructed by running multiple 30-day simulations of a particular month for successive years and then averaging the results to obtain a climatology for that month. Model simulations of at least 10 to 20 individual months in this mode is required in order to provide a stable climatology (McGregor, 1997a). This methodology has been followed in several studies using the NCAR MM4 mesoscale model and DARLAM. The LAMs may also be nested within observed analysis, (Giorgi and Morinucci, 1991; Giorgi et al., 1993a, b; Walsh and McGregor, 1996) or within AGCM simulations (Giorgi, 1990; McGregor and Walsh, 1994; Marinucci et al., 1995; Walsh and McGregor, 1995). See McGregor (1997a) and Chapter 3 for more examples.

A less versatile approach with respect to the duration of the simulations is to perform a perpetual run for a particular month, say January, nested within a perpetual January GCM (McGregor and Walsh, 1993). It is, however, necessary to prescribe the deep soil moisture temperatures for perpetual runs, which normally restricts their applicability to present day conditions (McGregor, 1997a). However, Hostetler et al. (1994) were able to use 90-day perpetual January and

July simulations to study the role of lake-atmosphere feedbacks in sustaining paleolakes 18 000 years ago.

More recently, with the improvement in computer capacity, multi-year seasonal cycle simulations have been performed (McGregor, 1997a; Chapter 3). These seasonal-varying simulations are slightly more accurate than those run in individual-month mode. The reason for this is that these runs allow for soil moisture and temperature to evolve realistically over longer time scales (McGregor, 1997a). In this manner most problems associated with atmospheric spin-up time are avoided. The model is also allowed to develop its own internal atmospheric circulation (Giorgi and Mearns, 1999). In addition, along term simulation allows for an improved equilibrium between the model climate and surface hydrological cycle as well as a improved detection of systematic deficiencies in the internal model physics (Giorgi and Mearns, 1999).

Another possible way to produce simulated climatologies for the entire annual cycle is to force both the AGCM and LAM with observed climatological SSTs (model SST climatology). Multiple seasonal cycle simulations might be obtained when starting each simulation with slightly different initial conditions. This procedure is followed because of the non-linear nature of the atmospheric equations and internal chaos. A multiple-member ensemble mean of output variables constitutes the model climate. About five realisations of each model are necessary in order to reduce the effect of internal variability. This approach was used by Engelbrecht and Rautenbach (2001) to obtain a model climatology from the T63 version of the CSIRO9 Mark II AGCM. It may also be required that a short spin-up period of approximately a month precedes the model simulation. This will allow for physical processes, like the moisture cycle, to reach equilibrium (McGregor, 1997a).

2.9 VERIFICATION OF NESTED MODELS

According to McGregor et al. (1993b), the ultimate verification of a nested climate model is to compare a sufficiently long simulation with the current climate. This should include climate verification of aspects such as storm statistics and frontal intensities. Simulations of the order of a month or longer pose additional requirements to the models if compared to the more conventional short-term simulations. This is because most parameterisation schemes have a long time scale (such as the effect of radiation on the flow). These simulations may be verified against the observed mean climatology for the period under consideration. It is vital to make sure that long-term biases are not accumulating in the interior of the domain. This is more likely to happen in the tropics. For control experiments, one has to keep in mind that the veracity of nested LAM simulations greatly depends upon the veracity of the broad-scale aspects of the AGCM simulation (McGregor, 1997a).

A measure of the minimum error one might expect from the LAM may be obtained from nesting the model within observed analyses. This mode of verification may also provide a way to verify LAM parameterisation schemes (McGregor et al, 1993). Recently, many meteorological centres have routinely run their limited-area weather prediction models for one-month simulations in order to determine model biases and reveal deficiencies in model parameterisation schemes. This contributes to model development (D. Majewski; personal communication to J.L. McGregor) and led to improvements in the various regional data assimilation systems (McGregor, 1997a).

Since a major objective of nested LAM runs is to simulate mesoscale features that affect a specific region, it needs to be verified that the LAM realistically simulates those features. (McGregor et al., 1993b). For example, the ability of a LAM to reproduce weather systems can be verified by performing case studies of significant meteorological events and to compare the results with observations. Boundary conditions for the LAM may be specified from operational grid-point analyses (also regarded as observations), and the LAM simulation compared to the subsequent analyses and observations.

Verification of LAM simulations can be problematic since a LAM might generate output on a higher spatial resolution than available from the upper atmosphere observational network. At the same time the model may not have enough resolution to simulate the surface observed fields (30 to 150 km nested model grid box averages versus denser point observation fields). One approach is to verify model simulations against the track and intensity of weather phenomena and observed accumulated precipitation, at least over land (McGregor et al., 1993b). Occasionally there are special observation programmes that provide higher spatial and temporal data to initialise models and to verify the simulations. McGregor et al. (1993b) provide some examples. In South Africa, a high-resolution rain gauge and radar rainfall observation network over the Vaaldam catchment area may prove to be ideal for LAM rainfall verification.

2.10 OTHER APPLICATIONS FOR NESTED MODELLING

LAMs have recently been employed for climate modelling. Here, simulations that extend over long periods are required. During the last twenty-five years LAMs have widely been used to make significant improvements in short-range weather forecasting, while case and mechanistic studies utilising LAMs furthered the understanding of mesoscale weather phenomena. Keyser and Uccellini (1987) discuss the use of regional models as an aid to explain and understand mesoscale weather events. They note that these models have become sufficiently accurate and have enough temporal and spatial resolution to provide a better understanding of atmospheric dynamics than possible with observed analyses.

In recent years LAMs have been used to investigate Australian weather systems such as east coast lows, tropical southerly busters affecting Sydney, the pollution-inducing Melbourne eddy and dispersion of pollutants (McGregor et al., 1993b). In South Africa recent applications of LAMs include investigations of air mass transport and associated moisture sources during cyclone Demoina (Crimp et al, 2000) as well as an investigations concerning the extreme precipitation events during 11 to 16 February 1996 (Crimp and Mason, 2000). The latter investigation utilised the Colorado State University Regional Atmospheric Modelling System (RAMS). The sensitivity of a tropical-temperate troughs to sea-surface temperature anomalies in the Agulhas retroflection region has also been investigated, again using RAMS, by Crimp et al. (1998).

The generality and suitability of the parameterisation experiments for different weather phenomena may be investigated by sensitivity experiments in LAM simulations. Furthermore, since the same physical parameterisation schemes are often used in both LAMs and AGCMs, LAMs may be used to provide a framework for testing the high-resolution performance of these parameterisations (McGregor, 1997a).

The relative importance of a given process in a weather event can also be investigated using a LAM, where the process can be altered or even eliminated. A comparison of the full model simulation with the altered simulation can give an indication of the importance of such a process. It must be kept in mind however, that non-linear interactions and feedbacks between various physical processes may prevent a clear determination of the importance of a process. The development of a weather system depends on the interaction of many of the various processes and not on a simple addition of the effect of a specific process (McGregor et al., 1993b).

Detailed simulations produced by LAMs make it possible to construct geographically detailed scenarios of climate change (Walsh and McGregor, 1995). For most simulations performed to date (some of these are discussed in Chapter 3) the overall climate change scenarios produced by the LAMs are similar to those provided by the AGCMs. There are, however, significant differences in finer detail, particularly for precipitation (McGregor, 1997a). The impact of a changing climate on local weather systems can also be examined through sensitivity experiments with a LAM. For example, it is likely that SSTs will increase with an increase in atmospheric CO_2 concentrations (Houghton et al., 1990). Typical weather systems may be simulated by LAMs with an enhanced SST to determine the possible effect of ocean heating (McGregor et al., 1993b).

2.11 ALTERNATIVES TO NESTED CLIMATE MODELLING

A new approach that may prove to be a suitable alternative to two-way nesting is that of running a global model with highly variable resolution (Courtier and Geleyn, 1988). The model horizontal grid point spacing is gradually refined toward the area of interest. This approach is very appropriate for specific locations on the planet. Difficulties experienced in the tropics with the one-way nesting approach can be avoided (McGregor, 1997a). Déqué and Piedelievre (1995) have successfully developed a variable resolution spectral model and grid point variable resolution global climate models are under development at the CSIRO (McGregor, 1996, 1997b).

Variable resolution global models may also have some disadvantages. The relative course resolution far from the area of interest may negatively influence the simulation and parameterisation schemes may not be adequate for use on a wide range of spatial scales (Giorgi and Mearns, 1999). Another disadvantage is that the time step needs to be shorter in a variable resolution domain than required without the local mesh refinement (Giorgi and Mearns, 1999). As in the two-way nesting technique, there is a lack of flexibility since the model has to be modified and independently run for each new geographic configuration (McGregor, 1997a).

2.12 UNCERTAINTIES AND A VIEW OF THE FUTURE

Despite the considerable potential of nested climate modelling there remain several unresolved issues which indicate that we are dealing with a relative new science. Presently all LAMs experience difficulties in regions of high and steep topography where long-term average precipitation is often over-estimated. At present the reasons for this overestimation are uncertain but possibilities include precipitation errors associated with the calculation of pressure gradients in terrain-following co-ordinates. This problem is discussed in more detail in Chapter 3. As previously discussed, there are uncertainties regarding the applicability of LAMs in tropical regions, where there is minimal synoptic forcing supplied by the appropriate AGCM to the LAM.

Results from NCAR depict substantial sensitivity to the initial specification of soil moisture (Giorgi and Marinucci, 1991), although this behaviour may be related to the exclusion of an adequate parameterisation for non-precipitating cumulus clouds. Data for initialisation of soil moisture remains sparse. It is known that present AGCM simulations of soil moisture are inadequate (Vinnikov and Yeserkepova, 1991), either as a result of deficiencies in the representation of hydrological processes or errors in the atmospheric fields. Improvements are anticipated when using LAMs because of their potential to achieve more accurate and detailed precipitation simulations (McGregor et al., 1993b).

Successful LAM simulation experiments have been performed by various groups for periods ranging from 1 month to several years (see Chapter 3). Consistent success has been demonstrated for NCMs in mid-latitudes where improved climatological patterns of precipitation and screen temperature (which is particularly related to topographic and coastal effects) have been simulated. Significant improvements are also detected in the details provided in nested LAM climatologies when compared to those of the associated AGCMs, especially for coastal and mountainous regions. Nested climate modelling has become popular, not only for producing detailed simulations of climate and climate variability but also as a tool for the improvement of LAMs and their internal parameterisation schemes (McGregor, 1997a).

With the inclusion of trace gas transport schemes and middle atmospheric chemistry in AGCMs (Rasch et al., 1985) the advection of trace gasses can also be incorporated in LAM experiments. Simple parameterisation of the surface sources and sinks of CO_2, SO_2 and radon have been incorporated in DARLAM (McGregor, 1997a).

There are several ways for future development in this challenging research field. According to McGregor (1993), improved physical parameterisation schemes for physical processes, cloud simulation and radiation properties are required, both for LAMs and AGCMs. Some of these improvements will follow from analysis of the new global data sets being acquired from remote sensing. Simulation of present-day climate will also be enhanced by the availability of improved SSTs, surface albedo, surface roughness and vegetation characteristics. NCM simulations will continue to improve with further refinement of model resolution. As further improvements are made to the climatology of AGCMs, benefits will also follow in the driven LAMs. Increased computer power and capacity, which may probably include massive parallel computers, will make longer model simulations with finer grid resolutions a reality. In the near future it may even be possible to perform two-way nested or variable resolution climate simulations over the entire globe.