CHAPTER 3

SIMULATING CLIMATE WITH THE LIMITED AREA MODEL DARLAM

3.1 INTRODUCTION

The nested model DARLAM has been developed to meet the requirements of both climate simulation experiments and shorter-term mesoscale studies (Walsh and McGregor, 1995). The LAM has evolved during the last decade from the 2-time level semi-Lagrangian model proposed by McGregor (1987). A full set of climate model parameterisations have since been added (McGregor et al., 1993b). DARLAM has been used over many locations with a variety of horizontal and vertical resolutions. The major applications focused on regional climate simulations nested within output fields saved 8-hourly or 12-hourly from the CSIRO9 AGCM.

Many simulations have been performed by nesting DARLAM either within the CSIRO9 AGCM or observational analyses. A one-way nesting technique was employed in all simulations. The earliest simulations were for perpetual January conditions. Subsequently, multiple January and July simulations have been performed followed more recently by full seasonally varying simulations of up to 20 years in duration. The latest regional climate simulations were nested for 140 years within the CSIRO9 AGCM transient simulation. In these simulations the atmospheric equations were integrated forward in time over nine levels in the vertical at both 125 km and 60 km horizontal grid resolutions (McGregor, 1999). The latest version of the model has 18 levels in the vertical with the lowest level at 40 m (McGregor, 1999).

Model simulations for both 1xCO_2 and 2xCO_2 conditions over the Australian and south-east Asian region have been performed at a grid resolution of 125 km. Selected doubly-nested simulations have then been performed at 50 km and 60 km resolution. In most of the experiments the focus was to determine the skill of the model with respect to the simulation of the seasonal cycle of surface air temperature and precipitation. Daily maxima and minima of model simulated surface air temperature have been studied and the simulated representation of the daily range examined.

Prior to the present study, DARLAM has also been successfully applied over New Zealand and South Africa. Good agreement was generally obtained between DARLAM simulations and observed climatologies. These studies revealed that an important aspect that still needs to be addressed is excessive precipitation simulated by DARLAM over regions of steep topography (McGregor, 1999; Joubert et al., 1999).

Tropical domains pose additional difficulties for the one-way nested modelling approach. These difficulties are related to the weaker boundary forcing in such domains and the greater necessity for compatible physical parameterisation schemes (see section 2.3.1). Most climate simulations performed with DARLAM over tropical regions produced acceptable climatologies with somewhat unrealistic annual variability in precipitation patterns (McGregor, 1999).

This chapter commences with a description of both the CSIRO9 AGCM and DARLAM. It is followed by a discussion of nested climate modelling experiments performed with DARLAM over various regions in the world. Emphasis is placed upon the two previous simulations performed over southern Africa. Finally, the crucial role of topography in the DARLAM simulations is discussed.

3.2 THE CSIRO9 AGCM (MARK II VERSION)

The CSIRO9 Mark II AGCM is a 9-level climate model with R21 spectral resolution that utilises an equally spaced east-west grid of 64 and a pole to equator grid of 28 unevenly spaced latitudes per hemisphere. A T63 version of the model is also available. The model utilises a sigma co-ordinate system (σ-system) in the vertical. The model integrates the flux formulation of the primitive equations (Gordon, 1981) forward in time. Unlike the advective formulation (Bourke, 1974) the flux formulation ensures that both energy and mass are conserved during the model integration. These conservation properties are vital when an AGCM is used for the multi-annual integration required for climate simulations. Gordon (1981, 1993) and Rautenbach (1999) provide details concerning the derivation of the model's dynamical equations.

The main prognostic variables are surface-pressure, surface-pressure weighted divergence, surface-pressure weighted vorticity, temperature and moisture. Apart from the moisture, which is a grid variable formulated in terms of a semi-Lagrangian moisture transport scheme (McGregor, 1993), the remaining variables are all spectrally analysed. The main prognostic variables are calculated at full σ-levels in the vertical, while the diagnostics of vertical velocity and geopotential height are derived at half levels.

Time integration is performed by using a semi-implicit Leapfrog scheme where linearised fast moving gravity wave generating terms are used to link the divergence, thermodynamic and surface-pressure equations (Hoskins and Simmons, 1975; Simmons and Hoskins, 1978; McGregor et al., 1993a). This implies that the time step is no longer restricted by gravity wave generating terms and that longer time steps can be used.

The CSIRO9 AGCM simulates a comprehensive range of physical processes including radiation and precipitation, which act as forcing of the dynamical equations. The model is intended for general climate simulation and thus represents full annual and diurnal cycles. The physical parameterisation schemes of the CSIRO9 AGCM include a modified version of the Arakawa (1972) cumulus convection scheme, the Deardorff (1977) soil moisture scheme and the GFDL diurnally-varying parameterisation for longwave and shortwave radiation (Fels and Schwarzkopf, 1975; Schwarzkopf and Fels, 1991). The model also includes a stability-dependent boundary layer based on Monin-Obukhov similarity theory (Louis, 1979). Soil temperatures are calculated using a three-layer model with a zero-flux condition at the bottom. A diagnostic cloud scheme is also included, as well as parameterisation of gravity wave drag (Chouinard et al., 1986).

3.3 DARLAM

DARLAM is a full primitive equations model that uses a Lambert conformal projection. In most experiments with DARLAM, simulations have been performed using the same 9-level vertical structure used for the CSIRO9 AGCM. In the present experiments (discussed in Chapter 5) the nested model uses 18 σ-levels in the vertical. Horizontal grid resolutions in previous experiments performed with DARLAM varied between 15 km and 125 km. In the present experiments a horizontal grid resolution of 60 km is used. The dynamical formulation and current parameterisation schemes of DARLAM are outlined in the following section (obtained from McGregor, 1999).

3.3.1 Dynamical formulation

- DARLAM is a 2-time-level, semi-implicit, hydrostatic primitive equations model.

- DARLAM uses semi-Lagrangian horizontal advection with bi-cubic spatial interpolaton (see Chapter 4 for more details).

- Departure points are derived using the procedure proposed by McGregor (1993). See Chapter 4 for more details.

- Vertical eigenvector decomposition is used, with an isothermal reference profile.

- Helmholtz equations are solved by successive over-relaxation.

- Total variation diminishing (TVD) vertical advection is applied (Thuburn, 1993).

- Winds are staggered on an Arakawa C-grid.

- Treatment of the pressure gradient term is similar to that given in Corby et al. (1972), in which avoids large truncation errors are avoided.

- DARLAM uses a Lambert conformal projection.

- A one-way nesting technique with exponentially decreasing weights is used (Davies (1976) style).

- Multiple nesting options are available.

- A shape-conserving interpolation option is available (Bermejo and Staniforth, 1992).

3.3.2 Physical parameterisation schemes

- DARLAM presently uses an Arakawa/Gordon mass-flux cumulus convection scheme.

- Evaporation of rainfall is included in simulations.

- Tiedtke shallow convection is used.

- GFDL parameterisation for long-wave and short-wave radiation is applied.

- Interactive diagnosed cloud distributions are included.

- Gravity wave drag options are available.

- Stability-dependant boundary layer and vertical mixing (Louis (1979) style) are included.

- The vegetation/canopy scheme includes:
  - six layers for soil temperatures
  - six layers for soil moisture (Richards' equation)

- Diurnally varying skin temperatures for SSTs are included.

- An option for cumulus mixing of trace gasses exists.

DARLAM incorporates a set of physical parameterisation schemes that are similar to those used in the CSIRO9 AGCM (described in section 3.2). The surface fluxes are calculated with a modified Louis (1979) parameterisation. The roughness length over land is 0.16m, while Charnock's (1955) formulation is used over the ocean with a parameter value of 0.018.

There are however some differences between the parameterisation schemes used in the two models. In some experiments with DARLAM (Walsh and McGregor, 1995, 1997a) a modified Kuo (1974) convection scheme was used in the nested model and gravity wave drag was excluded. Sensitivity experiments indicated that DARLAM results were not severely affected by differences in the convection parameterisation (note that the CSIRO9 AGCM uses a version of the Arakawa (1972) convection scheme). In previous simulations with DARLAM over South Africa, Joubert et al. (1998, 1999) used a modified version of the Arakawa (1972) convection scheme. Here it was mentioned that several other convection schemes have been tested in earlier unpublished sensitivity tests but that the Arakawa (1972) scheme outperformed the others in numerous single-month sensitivity tests. In these experiments enhanced surface drag parameterisation has been included near mountainous terrain to account for subrid-scale topographic drag. Further details of the parameterisation and vertical mixing schemes are outlined in McGregor et al. (1993a). Different methods for determining soil moisture (Kondo et al., 1990) is used in monthly climate simulations with the two models (see section 2.8). These methods are known as the α-method (DARLAM) and β-method (CSIRO9 AGCM).

Vegetation data includes soil and vegetation types as well as the associated physical characteristics. Albedo fields have been derived from data produced by the Simple Biosphere model (SiB) (Dorman and Sellers, 1989). These fields are used in the surface canopy scheme of Kowalczyk et al. (1994). The US Navy 5' topography fields were aggregated to model grid resolution to produce surface elevation fields.

3.4 THE NESTING TECHNIQUE

In experiments performed with DARLAM (see section 3.5 for more details) a one-way nesting technique was followed, with boundary conditions specified from the CSIRO9 AGCM or observational analyses. At each time-step the outermost boundary rows of DARLAM are relaxed towards the interpolated values supplied every 8 or 12 hours by the CSIRO9 AGCM. A modified Davies (1976) scheme with exponentially decreasing weights as proposed by Giorgi et al. (1994) was used. At each time step, the contribution of the forcing boundary conditions decreases exponentially to below five percent at five grid-points inside the outer boundary. For MSLP and temperature the boundary fields are altered to compensate for any differences that might arise in elevation fields as a result of diverse model topographic features (DARLAM vs CSIRO9 AGCM).

3.5 PREVIOUS EXPERIMENTS PERFORMED WITH DARLAM

3.5.1 INTERNATIONAL EXPERIMENTS

CSIRO scientists (McGregor, Katzfey and Walsh) have performed most limited-area climate modelling experiments with DARLAM over the Australian region. At higher latitudes the nested climatologies produced are generally superior to those produced by the forcing AGCMs and compare reasonably well to regional observations over the Australian continent (Walsh and McGregor, 1995).

The first experiment performed with DARLAM was for perpetual January conditions (McGregor and Walsh, 1991, 1993). In an effort to simulate the climate of a domain encompassing Australia for perpetual January conditions DARLAM has been nested at grid resolutions of 250 and 125 km within a version of the Australian Bureau of Meteorology Research Centre's AGCM. The experiments indicated significant improvements in LAM precipitation patterns over that of the AGCM. Another finding was that tropical region topography near the boundary of the domain requires careful treatment (McGregor and Walsh, 1991, 1993).

A 60 km resolution DARLAM simulation has been nested within another DARLAM simulation at a resolution of 125 km to investigate the impacts of the enhanced greenhouse effect on the climate of Tasmania (McGregor and Walsh; 1994). This doubly-nested simulation within the CSIRO9 AGCM generated significantly improved regional climate detail for Tasmania.

These experiments were followed by high-resolution climate simulations for January and July over the Australian region (Walsh and McGregor,1995). They one-way nested DARLAM at a resolution of 125 km within the CSIRO9 AGCM. One new aspect of these simulations was that the model domain extended to tropical regions both north and south of the equator. The size of the domain was also considerably larger than those used in previous experiments. Ten separate 30-day simulations have been performed for January as well as July. Ensemble averages of the ten January and July simulations have been used as the model climatology. The 30-day simulations incorporated both diurnally and seasonally varying radiation but were initialised separately from CSIRO9 AGCM output fields. No vertical mode initialisation was performed. A short spin-up period of approximately two days allowed for the DARLAM moisture cycle to reach equilibrium. DARLAM results indicated improvements in simulations away from the model boundaries. DARLAM simulations were also closer to reality over sub-tropical and mid-latitude regions. The improvement appeared to be the greatest in mid-latitudes over land.

The latter DARLAM simulations showed a general improvement in the simulation of precipitation when compared to the AGCM. This result, along with improved results obtained for screen temperatures, may be attributed to more detail in the DARLAM topography (Walsh and McGregor, 1995). Biases relative to observations in the DARLAM simulations pointed out that the general overestimation of rainfall is a problem that occurs in regions of steep topography. Over the ocean the simulation of precipitation by the CSIRO9 AGCM and DARLAM was of comparable quality (Walsh and McGregor, 1995).

A follow up ensemble of 10-year runs was carried out in both seasonal and multi-month mode (see section 2.8). These runs showed that the multi-month approach reproduces climatologies almost as well as the seasonally varying runs, provided that care is taken with the initialisation of soil variables (McGregor, 1997a).

DARLAM has been used by Renwick et al. (1997) for 50 km doubly-nested simulations over New-Zealand. The study showed significant improvements in precipitation patterns near topography or coastal features. There is, however, a tendency for excessive precipitation on the highest peaks. Extreme precipitation over New Zealand was modelled at 15 km resolution by Katzfey (1995).

Finally, the nested model has been applied over Antartica (Walsh and McGregor, 1996) and for studying inter-annual variability (Walsh and McGregor, 1997a). It has also been used to simulate the transport of greenhouse gasses and the characteristics of their sources and sinks (McGregor, 1997a).

3.5.2 EXPERIMENTS PERFORMED OVER SOUTHERN AFRICA

To date, only two NCM experiments have been performed over southern Africa. Joubert et al. (1998) used DARLAM to simulate January climate over the region. January was used to represent mid-summer (austral summer) conditions, given that most of the region experiences a pronounced summer rainfall maximum (Tyson, 1986). Using a one-way nesting procedure, lateral boundary and initial conditions were supplied by the CSIRO9 AGCM. The experiment consisted of twenty January ensemble members nested individually at 125 km resolution within the CSIRO9 AGCM.

The model simulation showed that DARLAM results are generally better than those of the CSIRO9 AGCM. The MSLP distribution simulated by DARLAM is more accurate over land masses than in the AGCM simulation. Throughout the troposphere DARLAM winds prove to be better than CSIRO9 AGCM wind simulations. Analysis of lower level wind patterns revealed that the CSIRO9 AGCM does not capture the observed low-level convergence in the vicinity of Mozambique. DARLAM noticeably improves on the latter flow deficiency, probably because of its more adequate representation of the topography of Madagascar (Joubert et al., 1998). It therefore seems essential that when designing LAM experiments over Southern Africa, Madagascar should be included in the model domain. Furthermore, it may prove worthwhile to choose the eastern boundary of the model domain as far away from Madagascar as possible.

Joubert et al. (1998) found that DARLAM captures the spatial pattern of observed rainfall and inter-annual rainfall variability over the region as a whole more accurately than the AGCM. Over most parts of the subcontinent, inter-annual variability in the DARLAM simulation is not significantly different from observations. Over the steep escarpment along the south-eastern coastline of South Africa, DARLAM simulates more rainfall than the AGCM and significantly more rainfall than observed. Inter-annual variability of rainfall over this region however, was not significantly different from the associated observed inter-annual variability. Over Madagascar, DARLAM simulates more rainfall than the AGCM, but less than observed. Here the simulated inter-annual variability is also significantly less than observed.

Joubert et al. (1998) concluded that DARLAM provides a more accurate and detailed simulation of the January climate over Southern Africa than the CSIRO AGCM. This is largely due to the fact that regional topographical features which influence the southern African climate are more clearly resolved by the 125 km LAM resolution (Joubert et al., 1998).

In the second nested climate modelling experiment over southern Africa Joubert et al. (1999) used DARLAM to simulate the full seasonal cycle in a 10-year simulation using present-day atmospheric CO_2 concentrations. The model's ability to simulate daily rainfall statistics during January was assessed. The NCM was one-way nested within the CSIRO9 AGCM. Again it was found that DARLAM simulates too much rain and too many rain days over the eastern parts of South Africa. The probability of occurrence of rainfall events of a given magnitude (expressed as the frequency of occurrence / total number of rain events*100) is largely similar to observations. However, the fact that the model simulates up to three times the observed number of rain days in January resulted in an overestimation of total rainfall. (Joubert et al., 1999).

Above average model simulated rainfall over the escarpment is associated with anticyclone ridging to the south of the subcontinent, which extends through the troposphere to the 500hPa level (Joubert et al.,1999). It is worth noting that observed extreme rainfall events are often associated with a similar circulation pattern, suggesting that DARLAM reliably reproduces the circulation responses associated with above-average rainfall (Joubert et al., 1999). In the DARLAM simulations, stronger than normal (compared to the nested model's climate) anticyclonic circulation is associated with above average moisture content, particularly in the zone of convergence on the leading edge of the ridging anticyclone (Joubert et al., 1999). In the immediate vicinity of the escarpment, simulations of anomalous onshore or upslope flow results in simulated upward motion indicating that the correct set of conditions for rainfall is produced (Joubert et al., 1999). While these results indicate sound physical reasons for rainfall to occur they do not explain why the daily rainfall statistics (both number of rain days and observed rainfall) are so much higher than observed (Joubert et al., 1999). One possible cause for this overestimation relates to a known problem concerning the representation of flow around steep orographic barriers (discussed in section 3.6). Despite problems experienced by Joubert et al. (1999) in the rainfall simulation, it was concluded that DARLAM results show a marked improvement in the simulation of southern African climate detail relative to the CSIRO9 AGCM.

3.6 THE ROLE OF TOPOGRAPHY IN DARLAM SIMULATIONS

Steep topography may lead to excessive accumulated topographic precipitation (Giorgi et al., 1994; McGregor and Walsh, 1994; Jones et al., 1995). This problem is more evident at higher model resolution but is probably not specific to LAMs (McGregor, 1997a). The reason for this is still not fully understood but for DARLAM the excess precipitation occurs at resolved scales and therefore is probably related to the model's mountain wave response (McGregor, 1997a). Horel et al. (1994) however, attribute excessive simulated 5-day rainfall over the Andes to dynamical effects of the Kuo cumulus parameterisation scheme.

A second unsolved (but closely related) problem in nested climate modelling is the fact that LAMs tend to simulate too many rain days (compared to observations) as well as lower than observed rainfall intensities (rain per rain day) in regions of steep topography. This result has been noticed using different climate models (Jenkins and Barron, 1997; Walsh and McGregor, 1995; McGregor and Walsh, 1994; Giorgi et al., 1994).

The steep eastern escarpment of southern Africa contributes to the problem of excessive simulations of rainfall over regions of steep topography by LAMs. Evidence provided by Joubert et al. (1998) suggests that DARLAM simulates too much moisture over the eastern escarpment of South Africa. Over steep topography such as the eastern escarpment of South Africa and eastern Madagascar DARLAM simulates in excess of twice as much daily rainfall as is observed. The lower-tropospheric flow over the escarpment during rain events is upslope (perpendicular to the obstacle) as surface moisture is advected onshore around a ridging anticyclone (Joubert et al., 1998). It is speculated that DARLAM's semi-implicit, semi-Lagrangian scheme over-estimates vertical velocities over steep topographic gradients due to the semi-Lagrangian mountain resonance effect (Joubert et al., 1999). In essence, the very steep topography of south-eastern Southern Africa is difficult to reproduce in semi-Lagrangian regional model formulations (Joubert et al., 1998, 1999). This may be a reason for rainfall over-estimation along the southern escarpment. These results also indicate that improvements in the simulation of regional rainfall totals will only follow from further development of the regional model itself (Joubert et al., 1999).

McGregor (1997a) points out that various models use one or more of the following methods to ameliorate the problem. These methods include a filter of the topography, time averaging of latent heat (Giorgi, 1991) and the use of different precipitation triggers from the AGCM. Some models (Giorgi et al., 1993a, Walsh and McGregor, 1995) also reduce the horizontal diffusion near topography in order to reduce spurious vertical redistribution of moisture related to the use of terrain-following co-ordinates. Leung et al. (1996) report benefits from using a new subgrid parameterisation for topographic parameterisation.

The mountain wave response problem in DARLAM is probably related to the semi-Lagrangian technique used in the model to discretirise the total derivatives in the governing equations. Semi-Lagrangian treatment of advection improves model efficiency by permitting larger time steps than those allowed by Eulerian schemes (see Chapter 4). In order to remain stable, Eulerian time schemes must satisfy the Courant-Friedrichs-Lewy (CFL) criterion that restricts the size of the time step allowed to use for a given spatial resolution and advecting wind. However, it has been known for some time that there is a problem incorporating stationary orographic forcing into models using semi-Lagrangian techniques.

Coiffier et al. (1987) showed that semi-Lagrangian methods lead to wrong stationary solutions for Courant numbers greater than unity in the context of a three-time level linear baroclinic model and therefore suggested that the time-step advantage of semi-Lagrangian schemes vanishes in the presence of topography. In their review paper, Staniforth and Côté (1991) identified the need for further research on the incorporation of stationary forcing in semi-Lagrangian models in a way that does not limit the Courant number. This approach was reiterated by Tanguay et al. (1992). Kaas (1987) proposed solving this problem by spatially averaging the forcing along a directory and Tanguay et al (1992) have examined the effects of the solution proposed by Kaas (1987) in controlled experiments. They demonstrated that spatial averaging considerably reduces the level of spurious noise in the vicinity of the North American Rockies for integrations of both global spectral and regional finite difference models. The analysis however, indicates that although spatial averaging alleviates the problem, it is not eliminated.

Rivest and Staniforth (1994) examined the problem in the context of the shallow-water equations. Using a simple one-dimensional model, the source of the problem has clearly been shown to be spurious numerical resonance induced by the semi-Lagrangian semi-implicit discretization in the presence of topographic forcing. They found that simply off centring the semi-implicit scheme eliminates the spurious resonance. This can be achieved with a second order accurate (in time) scheme without loss of accuracy. Only 48-hour forecasts obtained from a global shallow-water model were evaluated however, and issues pertinent to longer time integrations such as mass conservation were not addressed in the study. The solution advocated by Rivest and Staniforth (1994) was subsequently included in the thermodynamic and momentum equations of some versions of the DARLAM code. The effectiveness of the solution over the steep south-eastern escarpment of South Africa remains to be illustrated.