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Regional Climate Modelling

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With 4 Figures

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Summary

Regional climate modelling is becoming increasingly popular. The most common technique employs high resolution limited-area models to economically produce detailed climatologies for selected regions. A short review is presented of the underlying principles, recent simulations, limitations of the method and future prospects.

1. Introduction

The resolution of current general circulation models (GCMs) is still not fine enough to resolve small-scale atmospheric circulations, for example those affected by orography or details of the land surface. As an alternative, it is possible to produce detailed climate simulations for selected regions by nesting a limited-area model (LAM) within a global GCM, or within observational analyses. Such nested models have come to be termed regional climate models (RCMs) although the term could also encompass variable-resolution global GCMs. For any global climate model it is clearly desirable that the GCM simulation should produce realistic intensities and frequencies for each type of major synoptic system. If an RCM is nested in such a GCM simulation, it is then possible to produce a realistic detailed climatology, at least for mid-latitude domains where the boundary forcing can determine the broad behaviour of the RCM systems (Vukicevic and Paegle, 1989). Prior reviews of the regional climate modelling technique including descriptions of earlier simulations have been provided by Giorgi and Mearns (1991), McGregor et al. (1993) and Giorgi (1995).

The earliest extended LAM integration experiments were for periods of several days (Dickinson et al., 1989). Subsequently, simulations of one month or longer have been performed. A list of these longer experiments is given in Section 2. The most common RCM simulations have been for January or July, nested within a GCM, for multiple individual months. Ideally the model should be run for some 10 or 20 individual months in this mode to provide a stable climatology. More recently, seasonally-varying simulations have been run for a number of years including a full annual cycle. RCMs run for periods of about 3 months have also been used for simulations of monsoon and climate variability.

Recently, several meteorological centres have been routinely running their limited-area weather prediction models for one-month simulations in order to determine model biases and reveal deficiencies in model parameterizations. This has been helpful for model development (D. Majewski, personal communication) and has led naturally to improvements in those centres' regional data assimilation systems. Because the same physical parameterizations are often used in both RCMs and GCMs, another important role of regional climate models is that of providing a framework for testing the high resolution performance of those parameterizations.

The next section briefly discusses some practicalities of regional climate modelling and gives an overview of the usage of such models. Section 3 describes results from long RCM simulations nested within GCMs. Section 4 presents aspects of regional climate modelling where difficulties may arise. Section 5 describes some applications of RCMs to the modelling of climate change.

2. Basic Methodology

2.1 Types of Simulation

Tables 1 and 2 provide lists of climate simulations performed by RCM or variable-resolution models, current until the end of 1995. The tables provide model resolution, the domain and duration of simulation. All the listed RCM simulations employ nested LAMs, with the exception of the variable resolution model of Déqué and Piedlievre (1995). A detailed evaluation of the individual simulations is not attempted in this paper.

Table 1. *List of Regional Climate Model Simulations Having a Duration of at Least 1 Month and Nested Within a GCM*

Researchers	Resolution	Duration	Region
a) Perpetual January 1 × CO_2 simulation			
McGregor Walsh (1993)	250 km	10 months	Australia
Hostetler Giorgi Bates Bartlein (1994)	60 km	3 months	USA
b) Individual January/July 1 × CO_2 simulations			
Giorgi (1990)	60 km	6×1 month	USA
Marinucci Giorgi (1992)	70 km	5×1 month	Europe
Marinucci et al. (1995)	20 km	5×1 month	Europe (Alps)
Podzun Cress Majewski Renner (1995)	0.5°	5×1 month	Europe
Lüthi Cress Davies Frei Schär (1996)	56 km	3×1 month	Europe
McGregor Walsh (1994)	125 km/60 km	10×1 month	Tasmania
Walsh McGregor (1995)	125 km	10×1 month	Australasia
c) Individual January/July 2×CO_2 simulations			
Giorgi Marinucci Visconti (1992)	70 km	5×1 month	Europe
McGregor Walsh (1994)	60 km	10×1 month	Tasmania
d) Seasonally-varying 2 × CO_2 simulations			
Giorgi Brodeur Bates (1994)	60 km	3.5 years	USA
Giorgi Marinucci (1996)	50 km	5 years	Europe
Jones Murphy Noguer (1995)	50 km	10 years	Europe
Jacob Podzun Claussen [3]	0.5°	4 years	Europe
Hirakuchi Giorgi (1995)	50 km	5 years	East Asia
McGregor Katzfey Nguyen [2]	125 km	10 years	Australasia
Déqué Piedlievre (1995)	T21–T200	10 years	Europe-AMIP
Walsh McGregor (1996b)	125 km	5×18 months	Australasia-AMIP
e) Seasonally-varying 2 × CO_2 simulations			
Giorgi Brodeur Bates (1994)	60 km	3.5 years	USA
Jones Murphy Noguer Keen (1996)	50 km	10 years	Europe
Hirakuchi Giorgi (1995)	50 km	5 years	East Asia
McGregor Katzfey Nguyen [2]	125 km	10 years	Australasia

[1] Int. Conference on Monsoon Variability and Prediction. Int. Centre for Theoretical Physics, Trieste, Italy, 9–13 May 1994.
[2] Third Int. Conference on Modelling of Global Climate Change and Variability, Hamburg, Germany, 4–8 September 1995.
[3] WMO Int. Workshop on Limited-area and Variable Resolution Models, Beijing, China, 23–27 October 1995.

Table 2. *List of Regional Climate Model Simulations Having a Duration of at Least 1 Month and Nested Within Analyses*

Researchers	Resolution	Duration	Region
a) Individual January/July 1 × CO_2 simulations			
Giorgi Marinucci Bates (1993)	70 km	1 month	Europe
Giorgi Marinucci Bates DeCanio (1993)	70 km	1 month	Europe
Cress Majewski Podzun Renner (1995)	0.5°	1 month	Europe
Sasaki Kida Koide Chiba (1995)	127 km	1 month	East Asia
Lynch Chapman Walsh Weller (1995)	63 km	1 month	Arctic
Walsh McGregor (1996a)	125 km	7×1 month	Antarctica
b) Seasonally-varying 1 × CO_2 simulations			
Giorgi Bates Nieman (1993)	60 km	2 years	USA
Leung et al. (1996)	90 km/30 km	1 year	NW USA
Christensen Christensen Machenhauer [2]	56 km	20 months	Europe
c) Seasonal tropical simulations			
Semazzi Lin Lin Giorgi (1993)	80 km	3 months	Sahel SST anomalies
Liu Giorgi Washington (1994)	50 km	3 months	East Asia monsoon
Gong Li [3]	100 km	3 months	East Asia monsoon
Bhaskaran Jones Murphy Noguer (1996)	50 km	4 months	Indian monsoon
Kanamitsu Juang [1]	40 km	2.5 months	Indian monsoon
Vernekar Ji [2]	80 km	3 months	Indian monsoon
Lal Jacob Podzun Cubasch [3]	0.5°	6 months	Indian monsoon

[1] Int. Conference on Monsoon Variability and Prediction. Int. Centre for Theoretical Physics, Trieste, Italy, 9–13 May 1994.
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The tables include simulations for USA, Europe, Asia, India, Australasia, the Sahel, the Arctic and Antarctica. Table 1 lists simulations nested within a GCM in order to provide a climatology for present-day or enhanced-greenhouse conditions. Also in Table 1 there are two simulations of climate variability which use initial conditions and observed sea surface temperatures from the Atmospheric Model Intercomparison Project (AMIP) (Gates, 1992); no lateral boundary forcing is required for the global AMIP simulation of Déqué and Piedlievre (1995), whilst for the simulations of Walsh and McGregor (1996b) it is provided from a five-member ensemble of GCM simulations run for AMIP. Table 2 lists simulations nested within analyses, usually in order to provide basic verification of the particular RCM; it includes a group of simulations studying seasonal climate variability, in particular monsoonal activity.

There are several possibilities regarding duration of simulations. The simulation of McGregor and Walsh (1993) consisted of a 300-day perpetual January run nested within a perpetual January GCM. It is necessary to prescribe the deep soil temperatures for perpetual runs, which normally restricts their applicability to present-day conditions. 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 Bonneville and Lahontan 18000 years ago. A popular and more versatile approach is to run a sequence of individual simulations for a given month (typically January and July) from different years of the analysis or GCM.

Recently, multi-year seasonally varying runs have also been performed; these are the most satisfactory as they allow soil moisture and temperature to evolve realistically over longer time scales. The surface fluxes are interactively modelled for all the simulations shown in Table 1, with the exception of Sasaki et al. (1995) who prescribe a constant surface wetness and do not include radiative transfer processes.

2.2 Nesting Procedures

RCMs may be nested either in objective analyses provided by forecast centres, or in model output from global GCMs. Multiple nesting down to finer scales has also been performed, within a

GCM by McGregor and Walsh (1994), and within analyses by Leung et al. (1996). Typically the analyses or GCM output are available two or three times per day, and these are interpolated in time and space to the lateral boundary points as required during the simulation.

Most RCMs employ one-way nesting with full external forcing at the outermost boundary, and with the weighting of the external fields progressively reduced away from the boundary following Davies (1976); exponentially decreasing weights have been adopted by Giorgi et al. (1994) and Walsh and McGregor (1995). Giorgi et al. (1993a) found it beneficial to modify their lateral boundary scheme for water vapour to include a zero-gradient condition for outflow. Some alternative nesting procedures are described at the end of Section 4.

2.3 Initialization

Both GCMs and RCMs require a comprehensive set of physical parameterizations. With their finer horizontal resolution, RCMs require careful treatment of surface, soil and vegetation interactions. Variables such as surface temperature, subsoil temperature and moisture, and surface albedo may exhibit discontinuities at topographic interfaces, for example at land/sea boundaries, or boundaries of different vegetation or soil types. Special interpolation methods need to be employed to initialize these variables near such interfaces. As an example, the following simple method is used to interpolate the CSIRO GCM ocean surface temperature data to the Division of Atmospheric Research Limited Area Model (DARLAM) grid, independently of the land data. First, an intermediate interpolation and extrapolation of only the ocean surface temperature GCM data is performed to provide this field over the whole GCM grid. This intermediate field is then interpolated to the RCM grid, bypassing any problems with discontinuities. A similar procedure is used for other fields such as soil temperature and soil moisture.

Another consideration during intialization is the need to vertically interpolate the GCM atmospheric fields (especially temperature) to the pressure levels of the RCM, and to hydrostatically adjust the surface pressure to the height of the RCM orography. This vertical compensation is also required near the boundary rows whilst nesting, if the GCM and RCM orography differ.

2.4 Choice of Domain Size

Experiments have been performed over Europe to study the effect of domain size. Jones et al. (1995) concluded that the RCM domain should be sufficiently small that the synoptic circulation does not depart far from that of the driving GCM. However the domain should also be sufficiently large to allow development in the RCM of features having a finer scale than those skilfully resolved by the GCM. Similar conclusions were reached by Podzun et al. (1995).

3. Simulations of Present Day Climate

A number of simulations of present-day climate have been performed using RCMs nested within GCMs. Giorgi (1990) nested the NCAR MM4 model at 60 km resolution within R15 and T42 versions of the NCAR CCM1 GCM for 6 Januarys over the western United States. He verified that the large-scale average circulations of the RCM were similar to those of the driving GCMs, but that the RCM produced better regional detail of precipitation and temperature distribution. The frequencies of RCM daily precipitation also compared well with observations.

The same models were used by Marinucci and Giorgi (1992) over Europe for 5 months for each of January, April, July and October. As in the United States case, similar advantages were found for the RCM, particularly in the colder seasons. A cold bias of a few degrees in the surface temperatures and an underprediction of precipitation were attributed to deficiencies of the GCM simulation. Several 30-day simulations nested in ECMWF analyses were performed by Giorgi et al. (1993a, 1993b) in order to refine their physical parameterizations and treatment of lateral boundaries. A version of the model with 20 km grid was subsequently nested in a T106 ECHAM3 GCM by Marinucci et al. (1995) to produce January and July simulations of the western Alpine region; temperature and precipitation errors were of the same order, or smaller, than those of the coarser simulation.

Podzun et al. (1995) also simulated European climate using the Europa-Modell of the

Deutscher Wetterdienst nested within the ECHAM GCM for 5 Januarys and 5 Julys. A variety of physical parameterizations was employed and two alternative domain sizes. Again they found the RCM successfully simulated regional structures, such as precipitation maxima at coasts and mountains and sharp temperature gradients at the coast. The RCM area mean of precipitation was underestimated, similarly to the driving GCM. The same model has been used by Lüthi et al. (1996) in a study of January and July interannual variability.

Walsh and McGregor (1995) used DARLAM nested at 125 km resolution within the CSIRO Mark 1 GCM for 10 Januarys and Julys for a domain which included Australia, New Zealand and much of southeast Asia. The mean sea level pressures of the RCM showed some improvements over the Australian continent compared to the GCM. Improved patterns for temperature and especially precipitation were also evident over the continent, although the magnitudes of precipitation were only improved marginally. In the tropics the RCM precipitation was mostly inferior to that of the GCM except near land masses, where the RCM was better able to represent orographic precipitation.

The first seasonally-varying climate simulation was performed by Giorgi et al. (1994) over the continental US using the RegCM2 version of the NCAR model nested for $3\frac{1}{2}$ years within the NCAR GENESIS GCM. Overall the RCM reproduced spatial and regional patterns of precipitation better than the GCM. The RCM added much realistic detail to the simulated surface climatology, especially during the cold season. Giorgi and Marinucci (1996) repeated their European simulations with this more recent model for 5 years at 50 km resolution. Biases in surface air temperature were much improved. There was still an underprediction of precipitation, attributed to use of an explicit moisture scheme.

Jones et al. (1995) nested the United Kingdom Meteorological Office Unified Model over Europe at 50 km resolution in their GCM for 10 years. High spatial correlations were found for both RCM precipitation and screen temperatures.

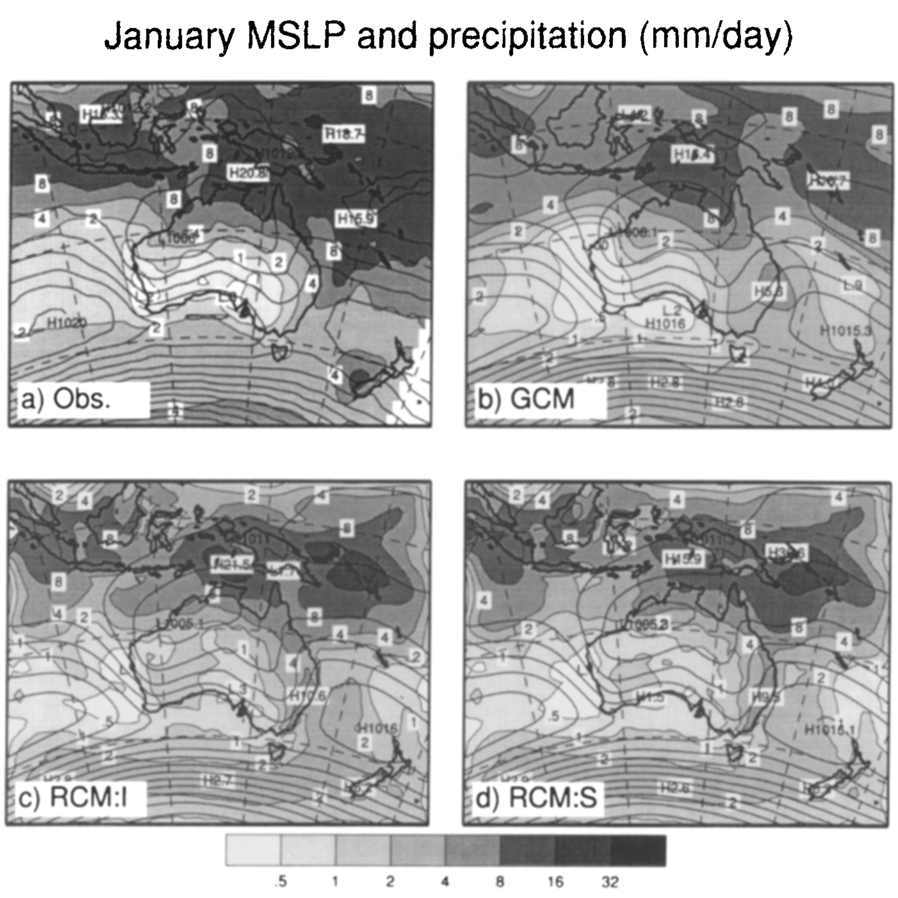

Fig. 1. Precipitation for January from a) observations, b) GCM, c) 10 individual months of the RCM, d) 10-year seasonally-varying RCM. Units are mm d^{-1}. Also shown are the mean sea level pressures (contour interval 2 hPa)

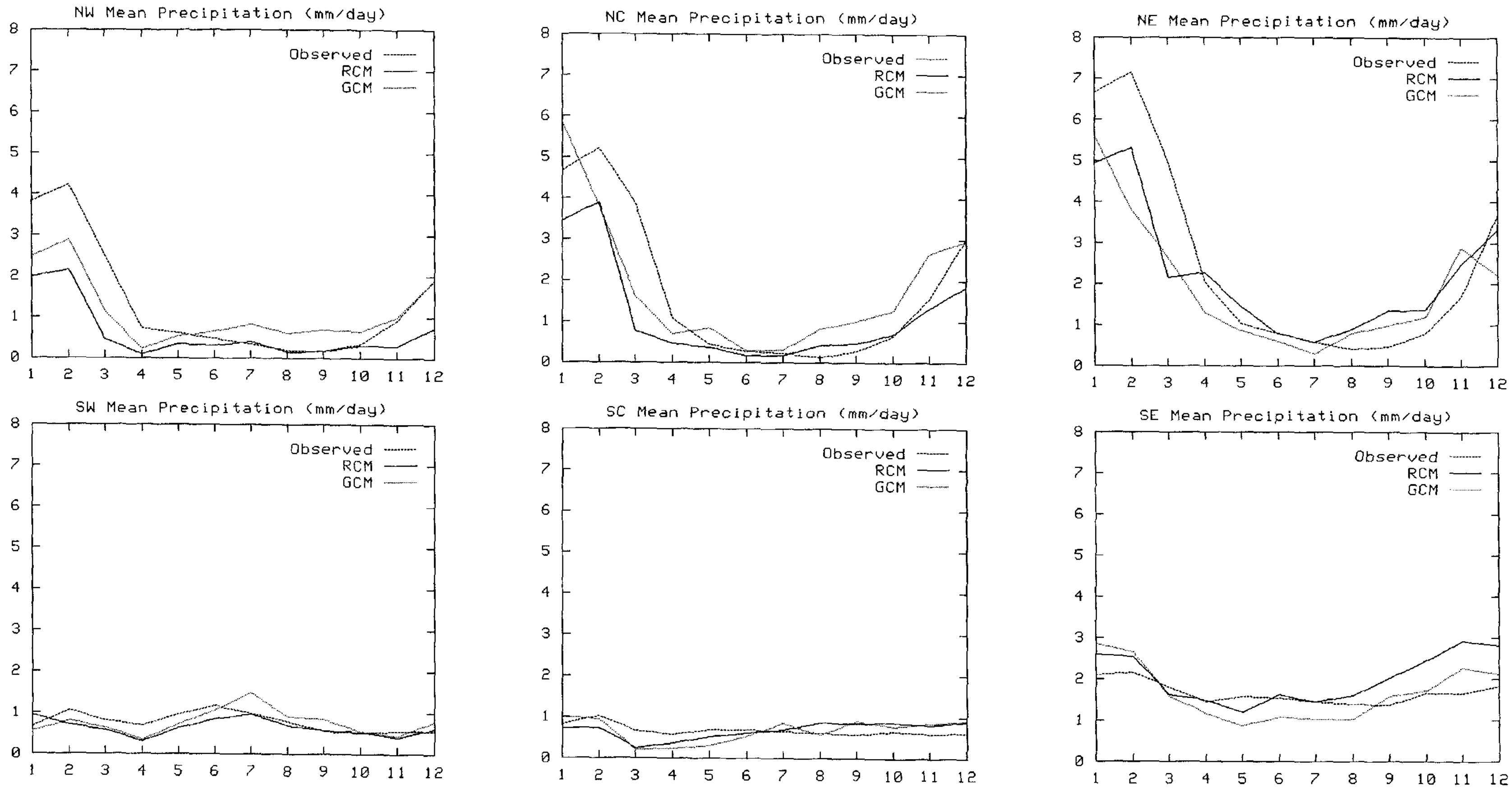

Fig. 2. Average monthly precipitation of 6 Australian sub-regions for January through December under $1 \times CO_2$ conditions from a) observations (dashed), b) GCM (dots) and c) RCM (solid)

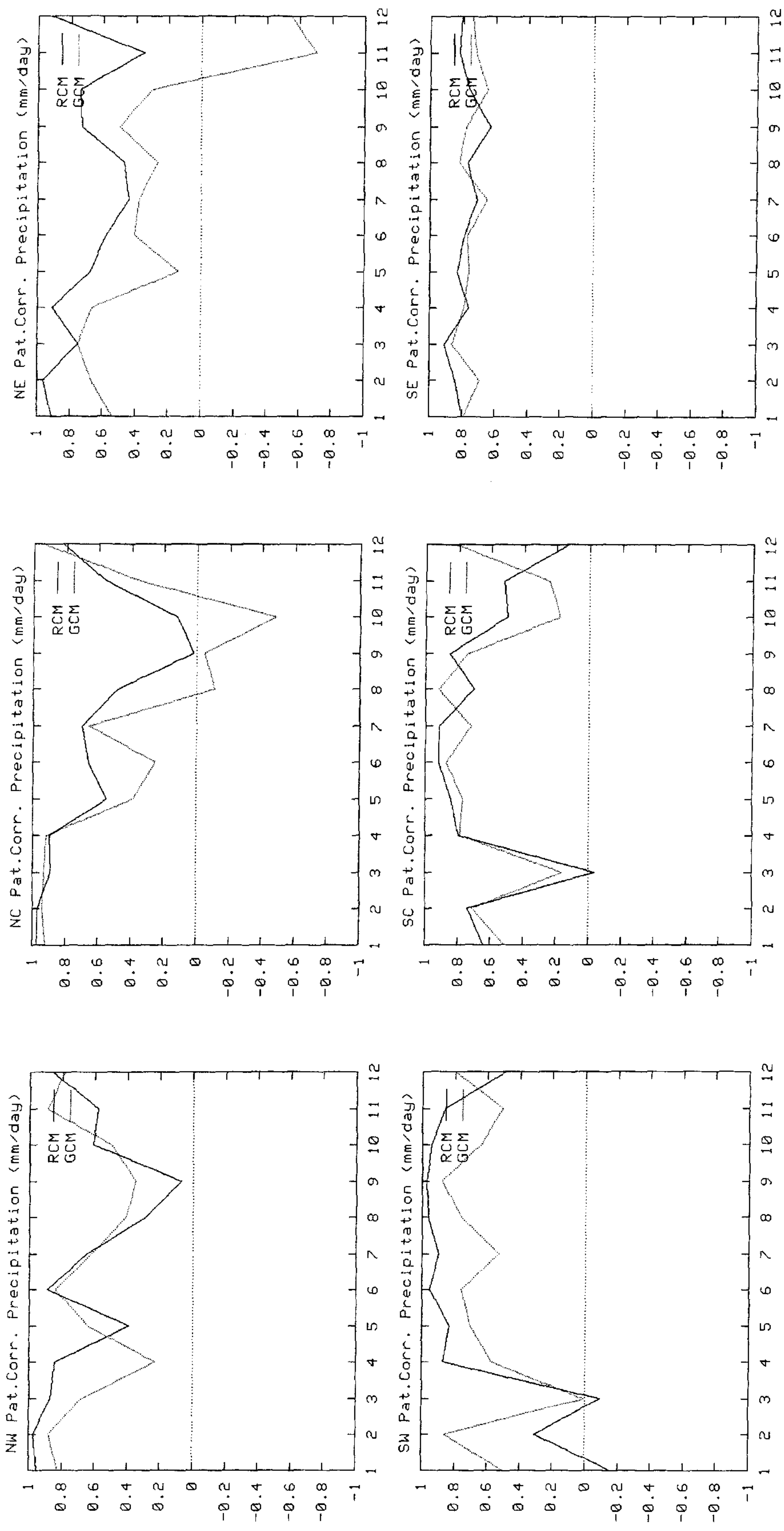

Fig. 3. Pattern correlations for monthly precipitation of Australian subregions under 1 × CO_2 conditions from a) GCM (dots) and b) RCM (solid)

Unlike Marinucci and Giorgi (1992), Giorgi and Marinucci (1996), and Podzun et al. (1995), they found a bias towards excessive domain-averaged precipitation.

Recently, 10-year seasonally-varying simulations have been completed for the Australasian region using DARLAM nested within the CSIRO Mark 2 GCM, for both $1 \times CO_2$ and $2 \times CO_2$ conditions. The domain employs a grid length of 125 km and includes tropical regions. Figure 1 shows the observed climatological precipitation for January and corresponding simulations from the CSIRO Mark 2 GCM, as well as two different RCM simulations for $1 \times CO_2$ conditions. The two RCM runs were identical, except one was run in individual-month mode and the other in seasonally-varying mode. All three simulations reproduce the dry interior of the continent. Both RCM simulations capture the detail of the northern Australian monsoonal precipitation pattern better than the GCM, and also the tighter gradient along the east coast due to orographic enhancement. Assurance for the use of RCMs in the economical individual-month mode is provided by the similarity of the two RCM simulations. Improvements made to both the GCM and RCM have led to better tropical precipitation patterns than obtained in the earlier Walsh and McGregor (1995) simulations. Note that the mean sea level pressure (MSLP) patterns of the simulations are all similar and capture the main features of the observed climatology.

The seasonality of the observed and simulated precipitation is shown in Fig. 2 for 6 subregions of the Australian continent; the subregions have the same layout as the figure panels, with dividing lines given by the tropic of Capricorn and meridians at 130E and 140E. For the northern subregions both the GCM and RCM display the correct seasonality, including the large effects of the Australian monsoon. The RCM correctly has peak rainfall in February although the magnitude should be greater. Overall the southern subregions are simulated well, although both models tend to be a little too dry in the first half of the year and too wet in the second half. The pattern correlations (their definition is given by McGregor and Walsh, 1994) for the same subregions are shown in Fig. 3 and are generally larger for the RCM, particularly in the northern and eastern regions, reflecting the improved resolution of the coastline and orography respectively.

4. Limitations of Regional Climate Models

4.1 Orographic Effects

Steep orography can lead to excessive accumulated orographic precipitation (for example Giorgi et al., 1994; McGregor and Walsh, 1994; Jones et al., 1995). This problem is more evident at higher resolution, but is probably not specific to regional climate models. The cause is not fully understood, but for DARLAM the excess precipitation is at resolved scales and therefore is probably related to the model's mountain wave response. Horel et al. (1994) attribute their excessive simulated 5-day rainfall over the Andes to dynamical effects of the Kuo cumulus parameterization scheme. Various models use one or more of the following methods to ameliorate the problem: filter the orography; time-average the latent heating (e.g., Giorgi, 1991); or use different precipitation triggers from the GCM. Some models (Giorgi et al., 1993a; Walsh and McGregor, 1995) also reduce the horizontal diffusion near orography, in order to reduce spurious vertical redistribution of moisture related to the use of terrain-following coordinates. Leung et al. (1996) report benefits from using a new subgrid parameterization for orographic precipitation.

4.2 Tropics

Although there have been several seasonal simulations of monsoons using RCMs nested within analyses, few longer climate simulations for the tropics have been completed using RCMs nested within a GCM. The tropics have particular problems concerning the role of gravity-inertia waves in dispersing heat from rainfall, thereby generating and maintaining tropical divergent circulations (see for example Paegle et al., 1983). Artificial constraints on these waves at the lateral boundaries of LAMs make it unlikely that such models can generate better broad-scale tropical circulations than the nesting GCM. A related feature of the tropics is that the weather patterns move more slowly than in the mid-latitudes and provide less of a "flushing" mechanism within the RCM. It is possible for systems to develop in large nested domains somewhat independently of the GCM forcing; this may also occur within very large mid-latitude domains.

A further problem for the tropics is that simulated precipitation patterns and the corresponding heating rates are very sensitive to the choice of cumulus parameterization scheme (e.g., Krishnamurti et al., 1980; Horel et al., 1994). This is illustrated in Fig. 4 by means of 1-month January simulations using DARLAM. In Fig. 4a, a modified Arakawa (1972) mass-flux cumulus scheme is used, as used for the long GCM and RCM simulations of Fig. 1. The precipitation pattern resembles the observed high rainfall of the Australian monsoon. In Fig. 4b a Kuo (1974) cumulus scheme is used, in contrast based on closure by moisture convergence; the Australian monsoon rainfall pattern is deficient for this run. It can be seen from the MSLP patterns of Figs. 1 and 4 that the Kuo cumulus scheme has caused a deterioration in the circulation patterns over northern and eastern Australia. This experiment also indicates that the RCM and GCM should use similar cumulus parameterization schemes in the tropics.

Other 1-month tests with DARLAM have found that tropical nested simulations are sensitive to the numerical formulation of vertical advection (Walsh and McGregor, 1995) and to the choice of radiation scheme. Regarding the radiation scheme, if the RCM scheme develops a cool bias in the tropics compared to the GCM or analyses, spurious boundary inflow or outflow can be generated, resembling a large scale sea-breeze.

4.3 *Conservation Properties*

GCMs can invoke and satisfy global conservation rules. Similar simple conservation rules are not available for limited domains. However, conservation is not as important an issue for RCMs because the continual boundary forcing is designed to keep the large-scale circulation features similar to those of the GCM. It is still necessary to check that long-term biases are not accumulating in the interior of the domain; as mentioned above this is more likely in the tropics, especially if the RCM and GCM use incompatible physical parameterizations.

4.4 *Other Nesting Aspects*

Nested RCMs can produce spurious precipitation near the boundaries. This is essentially an artifact of the intermittent supply of boundary data from the GCM; at the boundaries atmospheric moisture reduction (from activation of the RCM precipitation parameterization) does not survive from one timestep to the next, producing an apparent extra moisture source. The problem is only cosmetic, because although the moisture reduction does not survive in the RCM fields because of the nesting procedures, neither does the corresponding convective heating.

With the usual one-way nesting method, there is a possibility that the nested RCM may develop

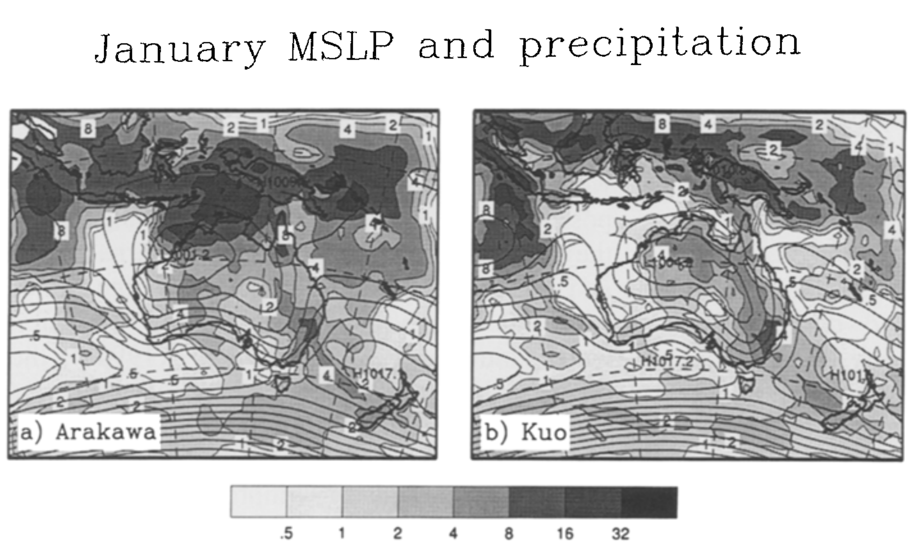

Fig. 4. Precipitation from a 1-month RCM January simulation using a) a modified Arakawa convection scheme and b) a Kuo convection scheme. Also shown are the mean sea level pressures (contour interval 2 hPa)

different synoptic systems from the nesting GCM. It may sometimes be advantageous for the extra topographic forcing of the RCM to provide this extra detail, but if this happens it would be preferable for the modified synoptic behaviour to feed back to influence the GCM. This may be achieved by 2-way nested models or models with composite or variable-resolution grids; an example of the latter is given by the simulations of Déqué and Piedlievre (1995). A disadvantage of such models is the expense of performing separate simulations for each region of interest and a possible need to re-tune the physical parameterizations for each chosen domain configuration. Another interesting technique, not included in the tables, is the time-slice method (Cubasch et al., 1995). First a standard long run was performed of the coarse T21 ECHAM GCM. For a selected 30-year period, the sea surface temperatures and sea-ice information from this run were interpolated to drive a higher resolution T42 GCM, previously initialized from the T21 GCM. The resolution of the T42 GCM (about 2.8°) is still coarse compared to the RCM runs in the table. The time-slice method is attractive, but is significantly more expensive computationally than the nested RCM method.

A quite different one-way nesting strategy has been proposed (Kida et al., 1991; Juang and Kanamitsu, 1994), where the large-scale GCM fields are effectively imposed each time step over the whole domain. This strategy ensures that the RCM provides an embellishment of the GCM simulation, and presents a different philosophy of the role of a nested RCM. This strategy will avoid any necessity to match the RCM and GCM topography and parameterizations. It has yet to be demonstrated whether the extra constraints of the technique lead to a generally better climatology.

5. Simulations of Climate Change

Giorgi et al. (1992) performed simulations for Europe under present-day and doubled-CO_2 conditions for January, April, July and October. The broad patterns of warming from the GCM and RCM were similar, but regional differences of up to 2 °C were produced. Averaged over land points, the GCM and RCM both produced an average increase of 12% in precipitation but there were significant differences both locally and regionally averaged.

McGregor and Walsh (1994) performed 60 km resolution simulations for a small Tasmanian domain, doubly-nesting within a 125 km RCM and the CSIRO GCM. The double-nesting method was found to be superior to nesting the small domain directly within the GCM. The spatially averaged precipitation response of the 60 km runs resembled the coarser runs, but the detailed response was quite different. For present-day conditions the 60 km RCM patterns much more realistically captured the effects of orography. For doubled-CO_2 conditions the models agreed in producing reduced precipitation in January and increased precipitation in July, but the RCM provided considerable enhancement over the mountainous regions. The average precipitation intensity was also examined; the RCM indicated a reduction for January, but an increase for July. As is typical of GCMs run for climate change experiments, there was greater surface warming near the south pole than at midlatitudes, leading to an average slackening of the southern ocean MSL pressure gradients and a corresponding average slackening of low-level winds. For July, only the 60 km simulation was able to resolve a local tightening of the gradient near Bass strait and indicate an increase in strength of the "roaring forties" winds.

In their seasonally-varying $3\frac{1}{2}$ year simulations for the continental United States, Giorgi et al. (1994) found generally similar temperature changes for the GCM and RCM both locally and through the seasonal cycle. Basic precipitation changes were related to changes in the position and intensity of the midlatitude jet stream in the GCM. Consequently, the large-scale patterns of precipitation change were found to be similar for the two models. However there were large seasonal and regional differences, possibly related to the different representation of the Rocky Mountains barrier. The diurnal range and variance of daily temperature time series from this simulation and its control simulation were examined by Mearns et al. (1995a); the companion study of Mearns et al. (1995b) analysed the daily variability of precipitation. They pointed out the desirability of 10 to 20 year simulations in order to improve the statistical robustness of analyses of variability.

Hirakuchi and Giorgi (1995) have carried out 5-year seasonally-varying simulations for East Asia. The seasonal temperature cycle was reproduced but with a somewhat larger amplitude in both the GCM and RCM. The average precipitation over Japan was of the correct magnitude, but the precipitation over the other regions of the domain was excessive; this was ascribed to deficiencies in the GCM monsoonal circulations. The subsequent doubled CO_2 simulation indicated temperature increases of 4–11 °C; RCM precipitation changes were 10–30%, being rather larger than the changes in the GCM.

6. Concluding Comments

Increasingly, research groups are constructing RCMs for climate modelling applications. Successful one-way nesting experiments have been performed for periods of one month up to ten years. Doubly-nested experiments have also been performed. RCMs have become popular, not only for producing detailed simulations of climate and its variability, but also as a tool for the improvement of LAMs and their parameterizations.

Consistent success has been demonstrated for RCMs in mid-latitudes in simulating improved climatological patterns of precipitation and screen temperature, related particularly to orographic and coastal effects. These models can now reproduce seasonal temperature and precipitation behaviour on a regional scale. As expected, the seasonally-varying simulations are slightly more accurate than those run in individual-month mode; this is to be expected from their more realistic evolution of soil moisture and temperature.

RCMs have also been used for climate change experiments. For most simulations the broad climate changes produced by the RCM are similar to those of the GCM, but there are significant differences in detail, particularly for precipitation. As for the control experiments, the veracity of the nested RCM simulations depends greatly upon the veracity of the broad-scale aspects of the GCM simulation.

The one-way nesting approach has some theoretical limitations, especially in the tropics. The tropics are also relatively sensitive to the treatment of physical processes. Experiments indicate that physical parameterizations should be chosen in the tropics to be compatible with those of the driving GCM.

RCM simulations are continuing to improve as better parameterizations are implemented and as model resolution is further refined. A problem that has not been completely solved is the current tendency for high resolution climate models to produce excessive precipitation in regions of steep orography. As further improvements are made to the climatology of GCMs, benefits will also follow in the driven RCMs. Better simulations should also be derived from the further application of variable-resolution GCMs and two-way nested RCMs. So far there has been one published application of a variable-resolution GCM. This approach is very attractive for specific locations, and can avoid some difficulties experienced in the tropics with the one-way nesting approach. There is, however, a lack of flexibility from the need to perform separate long climate runs for each geographic configuration; the model may also need to be re-tuned for each new configuration. Similar benefits and limitations apply to two-way nested RCMs. The time-slice technique has also been successfully used for GCM simulations, although the resolution is still fairly coarse. Recently a variable-resolution GCM has been run for 8 years in time-slice mode (M. Déqué, personal communication), and this appears to be an attractive technique.

Just as middle atmospheric chemistry and trace gas transport schemes are being included in GCMs (for example Rasch et al., 1995), the advection of trace gases can also be usefully undertaken in RCMs. Simple representations of the surface sources and sinks of CO_2, SO_2 and radon have now been incorporated into the DARLAM RCM and month-long simulations have been performed. The simulated concentrations are being compared with observations at the Cape Grim baseline monitoring station in Tasmania, the eventual aim of the project being to improve the estimates of trace gas emissions over Australia. It is to be expected that RCMs will be increasingly coupled to other components of the climate system, such as ocean, sea-ice, biosphere and hydrology models. Already Lynch et al. (1995) have performed Arctic experiments with an RCM coupled to a dynamic sea-ice model, while Leung et al. (1996) have coupled an RCM to a surface hydrology scheme.

It would have been interesting to provide tables of results to illustrate variability among the models and indicate common strenths and weaknesses. A region where different RCMs have been used for long simulations is Europe. However, their is still the significant difficulty that the runs have been nested within different GCMs, which have their own positive and negative features. This difficulty will be addressed by the Program to Intercompare Regional Climate Simulations (Takle, 1995). This experiment will compare RCM performance from a number of models for two contrasting 60-day periods over the continental United States. It should provide valuable insights to further improve the RCM modelling technique.

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