January and July Climate Simulations over the Australian Region
Using a Limited-Area Model

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ABSTRACT

High-resolution climate simulations are presented for January and July over the Australian region using a limited-area model nested within a GCM. One new aspect of these simulations is that the model domain extends to tropical regions both north and south of the equator. Objective measures of skill are used to assess the quality of the model simulations, and the performance of the model is verified over various subregions of the model domain. Poleward of tropical regions, the nested model climatologies produced are generally superior to those produced by the GCM, and compare reasonably well to observations over the Australian continent at the regional scale; in particular, the simulations of precipitation and screen temperature are improved.

1. Introduction

The development of limited-area climate models (LAMs) is an active area of research; a recent review is that of Giorgi and Mearns (1991). The main advantage of these models is that they provide a high-resolution climate simulation over a limited domain while remaining much more economical to run than a global model of similar resolution. Compared to coarser global models, they allow a more accurate representation of orography, which is crucial for the simulation of regional precipitation. In this paper, a global model of relatively coarse resolution (spectral R21, or roughly 500 km) is used to provide the boundary conditions of a limited-area model, which is run at a resolution of 125 km.

The GCM provides the large-scale synoptic forcing to the LAM through its lateral boundaries. Because the LAM has a similar dynamical formulation and physical parameterizations to the GCM but a much higher horizontal resolution, it adds significant smaller-scale detail to the coarser simulation of the GCM. We will show in this paper that this extra detail represents a better simulation than that of the GCM in most regions of the LAM domain.

It might be expected that this technique would perform better in midlatitude regions than in the Tropics. In tropical latitudes, weather patterns are slower moving, and quasi-stationary systems may evolve within the nested model domain independently of the boundary forcing. Recent midlatitude modeling studies include those of Dickinson et al. (1989), who nested a 60-km version of the NCAR MM4 mesoscale model (Anthes et al. 1987) over the western United States within version CCM1 of the NCAR GCM (Williamson et al. 1987), with lateral boundary conditions provided every 12 h. They simulated five separate storms for a total duration of 20 days and obtained a significant improvement in predicted precipitation compared to that simulated by the GCM. Pitman et al. (1991) and Thomas et al. (1991) used versions of the same models to simulate six wintertime precipitation events for a total of 21 days over southeastern Australia.

Extensive model validation over Europe nesting within analyses was performed by Giorgi and Marinucci (1991); climate change scenarios over Europe were constructed from results produced using the same models (Marinucci and Giorgi 1992; Giorgi et al. 1992). Giorgi et al. (1993) have also performed some sensitivity experiments on the effect of various precipitation parameterizations over the western United States, running an enhanced version of MM4 nested within the European Centre for Medium-Range Weather Forecasts (ECMWF) analyses for periods of up to 2 years. This approach was also used by Liu et al. (1994), who used a modified version of MM4 to simulate June–August 1990, for a domain over east Asia. A longer simulation nesting within the GENESIS version of the NCAR GCM was performed by Giorgi et al. (1994). A rather different nesting approach was that of Kida et al. (1991), who have developed a spectral limited-area model nested inside a spectral global model. Limited-area climate modeling has also been performed over the Australian region by McGregor and

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Walsh (1991, 1993). They used the Division of Atmospheric Research Limited Area Model (DARLAM) at resolutions of 250 km and 125 km nested within a version of the Australian Bureau of Meteorology Research Centre GCM to model the climate of a domain encompassing Australia for perpetual January conditions. That work also demonstrated significant improvements in the pattern of precipitation of the nested model compared to the GCM. Another finding was that tropical orography located near the boundary of the nesting domain requires careful treatment in order to achieve successful simulations. Katzfey (1993) evaluated the ability of DARLAM, when forced at its boundaries by ECMWF analyses, to simulate the observed rainfall of three separate months (January 1986, 1987, and 1988) over a domain encompassing eastern Australia. He found that the model was able to reproduce reasonably well the observed patterns of precipitation, and also found that model biases of temperature and moisture were modest. The effects of the enhanced greenhouse effect on the climate of Tasmania have been modeled by McGregor and Walsh (1994), using DARLAM running at a resolution of 60 km nested inside another DARLAM simulation run at a resolution of 125 km.

This paper describes the results of climatological simulations over the Australian region with DARLAM, which is one-way nested within selected months of a long seasonally varying simulation of the CSIRO nine-level general circulation model (CSIRO9 GCM, McGregor et al. 1993a). Ten separate 30-day simulations have been performed for both January and July; the averages of these 10 Januarys and Julys constitute the model climatology for those months. The 30-day simulations incorporated both diurnal and seasonally varying radiation, but were initialized separately with output fields taken from the GCM; no vertical-mode initialization was performed, however. There was a short spinup period of about 2 days before the DARLAM moisture cycle reached equilibrium. This was found to have a negligible effect on the DARLAM climatologies. One major difference in our simulations from previous work is the inclusion in our model domain of extensive tropical regions both north and south of the equator; the size of our domain is also considerably larger than that used in any of the above experiments. The results presented here include the first simulation using a LAM of July climatology in this region, either in tropical latitudes or in the midlatitudes. In addition, the use of 10 realizations of each month to form a model climatology, which is more than have been employed in some previous studies, may provide a more robust comparison to climatological observations.

2. Model description

The nested model DARLAM has been developed for both mesoscale studies and for climate change experiments. The model is a two-time-level, semi-implicit, hydrostatic primitive equations model; it uses an Arakawa staggered C-grid and semi-Lagrangian horizontal advection with bicubic spatial interpolation. An earlier version was described by McGregor (1987). In the present experiments the model uses one-way nesting with lateral boundary conditions specified from a version of the CSIRO9 GCM, which has evolved from the flux-conserving GCM of Gordon (1981). DARLAM uses a Lambert conformal projection, and in the present experiments has the same vertical level assignments as the GCM. An example of a 77 × 77 domain with 125-km grid spacing is shown in Fig. 1 (also indicated on Fig. 1 are locations mentioned in the text).

The physical parameterizations of the CSIRO9 GCM include a modified version of the Arakawa (1972) cumulus convection scheme, the Deardorff (1977) soil moisture scheme, and the diurnally varying GFDL parameterization 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. Soil temperatures were calculated using three conducting layers with a zero flux condition at the bottom. A diagnostic cloud scheme is also included, as well as a parameterization of gravity wave drag (Chouinard et al. 1986). In these simulations, DARLAM incorporates similar physical parameterizations but uses a modified Kuo (1974) cumulus scheme and does not include gravity wave drag. Sensitivity experiments suggest that the DARLAM results were not

![Figure 1](image-url)
greatly affected by this difference in convective parameterization. The models use differing treatments for evaluation of available soil moisture, the "α-method" for the GCM and the "β-method" for DARLAM, following the terminology of Kondo et al. (1990). The impact of these differences in soil moisture parameterizations appears to be small for simulations of about 30 days or less in length. At each time step, the outermost five boundary rows of DARLAM are relaxed toward the interpolated values provided every 8 h by the GCM, using the nesting procedure of Davies (1976). In the case of surface pressure and temperature, the boundary fields are altered to compensate for any differences in height of the interpolated orography of the GCM compared to DARLAM. Sea surface temperatures were taken from the climatology of Bottomley et al. (1990).

The model was run on a CRAY Y/MP computer; timings for a single day for these experiments were 30 s per model day for the GCM, and 130 s per model day for the nested model at 125-km resolution.

3. Statistical methodology

The results discussed here involve the comparison of two different model simulations to observations. Thus it is important to have statistically rigorous means of evaluating whether for a particular field the limited-area model DARLAM is superior to the GCM. The problem of the statistical evaluation of model output has been examined by numerous authors (Santer and Wigley 1990; Wigley and Santer 1990; Portman et al. 1992; Katz 1992), and many different techniques have been suggested for this purpose. In this paper, we will use two standard statistical measures to assess the quality of our model simulations. These are the pattern correlation technique and the rms error.

The pattern correlation ρ of two spatial fields is simply the correlation of a series of data points xi from one field with corresponding values oj from the other field:

$$\rho = \frac{\Sigma (x_i - \bar{x})(o_j - \bar{o})}{[\Sigma (x_i - \bar{x})^2][\Sigma (o_j - \bar{o})^2]^{1/2}},$$

where $\bar{x}$ is the mean of $x_i$ and $\bar{o}$ is the mean of the observations $o_j$. In the following analysis of the results, pattern correlations are performed between model fields $x_i$ and observations $o_j$, both interpolated to the DARLAM grid; the summations are performed over all grid points. A bilinear interpolation technique was used, which is adequate given the smooth nature of the monthly averaged fields. For screen temperature fields, the zonal mean of the observations was subtracted from each variable before the correlation was performed, in order to remove the high spatial autocorrelation in this field. The mean rms error r is defined as

$$r = \left[\frac{\Sigma (o_j - x_i)^2}{N}\right]^{1/2},$$

where $N$ is the number of points over which the sum is taken.

The assessment of the quality of the model simulations naturally depends upon the reliability of the observational data to which they are compared. The long-term record of Schutz and Gates (1971, 1972) was used for mean sea level pressure (mslp). For surface air temperature, the dataset of Legates and Willmott (1990b) was used. This dataset has a reasonable coverage over Australia and the Philippines from station observations, but coverage is less adequate over some interior regions of Indonesia and New Guinea. Over the oceans, the quality of this dataset appears reasonable, but there may be some question about the accuracy of the data in oceanic regions remote both from land and from the main shipping lanes, in particular, the region south of 45°S. Surface air temperatures over the oceanic regions examined in this study should on average resemble the sea surface temperatures (Peixoto and Oort 1992). The precipitation observations are those of Legates and Willmott (1990a). There is a reasonable station coverage over Australia, New Guinea, and the Philippines, and a less dense but still reasonable station network over Indonesia. Over the oceans, the quality of the precipitation data is more debatable. Because of the almost total lack of reliable observations over the oceans, a great deal of estimation and regression was applied by the above authors to synoptic observations in order to obtain precipitation estimates. While some oceanic islands have good quality precipitation records, many of the island stations are in locations where precipitation is orographically enhanced, and thus the precipitation is greater than that of the surrounding oceanic regions. Accordingly, the precipitation observations over the ocean should only be taken as approximations to the correct values.

4. Results

Previous experiments on a smaller Australian domain by McGregor and Walsh (1993) showed that the simulation of climate by a limited-area model is significantly improved by a better representation of orography. The GCM orography (Fig. 2a) is rather smooth; for example, in the narrow highland region of New Guinea, in reality there are large areas higher than 2000 m with peaks exceeding 4000 m, which in the GCM orography are smoothed out over the entire island. Similarly, over Australia there is only a suggestion of the Eastern Highlands (see Fig. 1), which are just inland along much of the east coast and are generally higher than 500 m. The DARLAM orography (Fig. 2b) was taken from averages over 125-km grid squares of the U.S. Navy 5' orography. The orography over New Guinea in this case is much narrower and more realistic. In addition, there is a more realistic representation of the Australian Eastern Highlands. Islands such as Luzon in the Philippines, which are essentially without
orography in the GCM, have some orography in the DARLAM representation.

a. January mean sea level pressure and screen temperature

Figure 3 shows the comparison between observations (Schutz and Gates 1971), the CSIRO9 simulation, and the DARLAM simulation for January mslp. The observations (Fig. 3a) show that the mslp pattern over the Australian continent is dominated by a few main features. There is a heat low over the northwest of the continent; south of the continent the gradient is tighter as the pressure falls toward the circumpolar trough. To the southeast and southwest are subtropical high pressure regions. Immediately north of Australia is a region of weak pressure gradient, while north of the Philippines the pressure increases as the winter monsoon high over Asia is approached. The CSIRO9 model (Fig. 3b) simulates these features reasonably well, although the heat low as simulated in the GCM is too intense by 1 to 2 hPa, the circumpolar trough is too shallow by several hPa, and the high pressure region over south Asia is too strong, also by several hPa. The DARLAM simulation (Fig. 3c) in common with the CSIRO9 simulation has a heat low that is slightly too deep, although the pattern over the southeast of the continent appears improved since the anomalies from the Schutz and Gates observations (not shown) are smaller. In other regions the simulation appears similar to that of CSIRO9. Note also that sampling errors over this region for a 10-yr average versus a long-term climatology are of the order of 1 hPa (P. Whetton, personal communication). Pattern correlations and rms errors (not shown) suggest that the two models have mslp simulations of roughly equal quality for this month.

Figure 4 gives some details of the comparison for screen height (1.8 m) temperature. The screen height temperature has been calculate in both the GCM and DARLAM using stability-dependent Monin–Obukhov theory. The observations (Fig. 4a) are interpolated to the DARLAM grid. They show that high temperatures in excess of 30°C are observed in the northern interior of Australia, with a steep gradient along the south coast. The topographic effects of the Eastern Highlands and coast are seen in that isotherms in this region are deflected northward. Over the oceans north of Australia, temperatures are greater than 27°C in equatorial regions, and decrease to the west and north. Some topographic effects can be seen over New Guinea and the islands of western Indonesia and Micronesia.

In general, the simulations of the two models have certain similarities, but there are also some major differences. DARLAM (Fig. 4c) has a better delineation of the land/sea boundary, as screen temperatures in the GCM (Fig. 4b) tend to follow the smooth orography of the global model, an effect that is especially noticeable in the GCM near and over New Guinea. Over Australia, changes in screen temperature biases
between the two models (not shown) are largely related to changes in model orography, although changes in rainfall patterns also have an effect on simulated screen temperatures through changes in surface evaporation. DARLAM temperatures are also mostly closer to observations over northern Australia and the southeast coastal zone, and along the southern coast of the continent. DARLAM is, however, worse by a degree or two in the eastern interior. Analysis of the DARLAM simulations shows that higher rainfall in this region is caused by the steep LAM orography (compared to that of the GCM), with associated uplift of the prevailing southwesterly wind.

In the statistical analysis of our results, we have divided the DARLAM domain into several latitude bands, based upon the observed variation of climatological regimes with latitude. Results are discussed for three such bands: tropical (23.45°S to 23.45°N), subtropical (40°S to 25°S), and midlatitude (45°S to 35°S). The tropical band is bordered by the Tropics of Cancer and Capricorn, the subtropical band is delineated by the region of the influence of the subtropical high in January (Fairbridge 1967), and the midlatitude...
domain is bounded on the equatorward side by the surface subtropical high in January and on the poleward side by 45°S, south of which the observations may be unreliable, as mentioned above. Figure 5 shows pattern correlations and rms errors for January screen temperature. The statistics are shown separately for points over both land and sea in each latitude band. Other authors have noted the unrealistic effects that may occur at the boundaries of LAMs (e.g., Giorgi 1990); we have therefore calculated statistics over interior portions of the domain that are less likely to be affected by these problems. The analysis for both statistical measures has been performed over points at least 10 grid intervals inside the DARLAM boundary.

Figure 5 shows that over land in the midlatitudes, the DARLAM pattern correlation is higher than that of the GCM, while the rms error is smaller. This is probably caused by the superior resolution of orography in DARLAM. In the subtropics over land, pattern correlations remain better in DARLAM, although the improvement compared to the GCM simulation is not as pronounced as in the midlatitudes. Rms errors in this region are similar in the two models.
In tropical land regions, the DARLAM pattern correlation is slightly better than that of the GCM, but the rms error is slightly worse. The performance of DARLAM appears inferior to the GCM over some regions of higher orography: for instance, the interiors of Kalimantan, New Guinea, and the Philippines. It is, however, apparent that the Legates and Willmott (1990b) data is not fully capturing the topographic variation of temperature in these regions. Their observations over land are based upon station data; in Kalimantan, there are two stations in the dataset, both of them at low elevations. Thus, the observations on the island show very little variation with topographic height; given that in reality the interior of Kalimantan has peaks rising to over 2000 m, and in DARLAM the orography of this island has a peak value of over 700 m, this apparent discrepancy is probably a result of poor station coverage in these regions. This is an example of valley bias in the observations. Similarly, over the mountainous regions of eastern New Guinea, the observations have closed contours near a couple of highland stations, but do not appear to be following the substantial orography of this island. Over Australia, the station distribution included in the observations is better than that over the islands farther to the north. In contrast to the results for the tropical region as a whole, we found that over tropical regions of Australia (south of 11°S), the pattern correlations and rms errors (not shown) indicate that DARLAM is definitely superior to the GCM.

Over the ocean, pattern correlations are similar for the two models in the midlatitudes and subtropics, while rms errors in these regions are better in DARLAM. In both models, there are large negative biases over the ocean south of 45°S (not shown). One point to note is that the observations south of about 45°S over the ocean appear unusual, with large zonal temperature
gradients in a region with no land. In this location in January, the observed air–sea temperature difference is less than one degree (Peixoto and Oort 1992), and two well-known sea surface temperature (SST) datasets show no substantial zonal variation in this region (Bottomley et al. 1990; Shea et al. 1990). The observations in this area used by Legates and Willmot (1990b) to compile their dataset were taken from the Comprehensive Ocean–Atmosphere Data Set (COADS) (Woodruff et al. 1987) and from station observations. Both are lacking in this region, casting some doubt on the accuracy of their dataset in this location. Elsewhere over the oceans, DARLAM has generally smaller biases than the GCM. Small differences between the two simulations over the oceans are related to changes in orography (close to the coast) and changes in circulation patterns.

b. January precipitation

The precipitation observations (Fig. 6a) are interpolated to the DARLAM grid. They show that large amounts of precipitation occur north of Australia, with the exception of a region east of Sulawesi. A rainfall maximum occurs east of Mindanao, while a dry tongue is observed east of the Philippines over northern Micronesia. Over Australia, the north and east of the continent are wet, while the south and west are drier. The GCM simulation (Fig. 6b) has a reasonable pattern over the Australian continent, although it fails to capture the observed east coast gradient of precipitation, and it is too moist in the interior. The quality of the GCM simulation of precipitation over the Pacific is variable. In general, the GCM overestimates precipitation in the northern tropical oceans, but underestimates it south of the equator. Rainfall is underestimated to the north and east of Australia, while the dry tongue east of the Philippines is not well resolved. The observed rainfall maximum east of Mindanao is misplaced in the GCM.

DARLAM (Fig. 6c) also tends to overestimate rainfall in the northern latitudes and underestimate it in the southern part of the domain. DARLAM is rather better than the GCM over the high rainfall region of the Australian continent, especially in the northeast. The LAM captures the coastal gradient of the isohyets quite well.

Immediately north and east of Australia the DARLAM simulation is generally superior to the GCM, while over New Guinea itself CSIRO9 is largely superior. The higher-resolution orography of New Guinea in DARLAM is forcing a different circulation from that seen in the GCM (Figs. 2b and 2e), with precipitation to the south and east of the island greatly increased. Conversely, DARLAM precipitation is beneficially decreased east of Sulawesi compared to the GCM, which suggests a dynamical link in DARLAM between increases in precipitation near New Guinea and decreases near Sulawesi associated with a change in regions of preferred ascending motion. Farther north, like the GCM, DARLAM has difficulty resolving the dry tongue east of the Philippines. In addition, the DARLAM precipitation is considerably underestimated in the region near Java, while it is overestimated over the South China Sea. Part of this problem may be caused by the proximity of these tropical regions to the boundary of the nested model, and the large changes in orography imposed over Indochina in DARLAM compared to that in the GCM. In the tropical regions north of the equator, overall the simulation appears better in CSIRO9. There are also noticeable regions of anomalous precipitation near the boundaries of DARLAM, as seen in Fig. 6c; the significance of these will be discussed later in this section.

We note that in comparing simulations of precipitation it is desirable to use a quantity having an approximately normal distribution, in order to avoid biases in the analysis toward high or low rainfall values. For transforming the highly skewed spatial distribution of precipitation to a more normal distribution, Stidd (1953) proposed the use of the cube root of precipitation, which we denote by $P^{1/3}$.

Figure 7 shows pattern correlations and rms errors for $P^{1/3}$. For consistency with the analysis of the screen temperature results, we have excluded regions south of 45°S from the statistical calculations. In the midlatitudes, the GCM simulates a better pattern than DARLAM over sea points, while the rms errors are similar in the two models. Over land DARLAM has a better pattern than the GCM, although rms errors are higher in DARLAM. Closer examination suggests that this is because DARLAM is overestimating rainfall on the peaks of the Eastern Highlands of Australia. This has been previously shown to be a feature of lengthy limited-area model simulations (Giorgi et al. 1990; McGregor and Walsh 1994). We have examined the Legates and Willmot (1990a) rainfall figures over the Eastern Highlands and find them to be somewhat lower than those of Suppiah (1992, personal communication), who analyzed and interpolated over 900 Australian rainfall stations to create a dataset with a resolution of 0.0625°. This is also true over Tasmania, where the results of McGregor and Walsh (1994), using another high-resolution rainfall dataset, suggest that the Legates and Willmot (1990a) observations underestimate rainfall in the west of the island.

In the subtropics, DARLAM is superior to the GCM except in the rms errors over land, likely for the reasons discussed in the previous paragraph. In tropical land regions, pattern correlations and rms errors for DARLAM and the GCM are similar, although over northern Australia, as discussed earlier, DARLAM is much better than the GCM. Over tropical ocean areas, there is, however, a marked deterioration in the DARLAM simulation. As mentioned in the introduction, one might expect a priori that LAM simulations in tropical regions
using current techniques could suffer in comparison to simulations at higher latitudes.

Pattern correlations and rms errors for $P^{1/3}$ are also shown for land points in Fig. 7 using the Suppiah dataset as the baseline observations. The results are similar to those calculated from the Legates and Willmot data, with a couple of exceptions. The comparison in the Tropics using the Suppiah data is much more flattering to DARLAM than that using the Legates and Willmot data. There are some large differences between the two datasets in the Tropics, particularly in regions close to the coast or that have significant orog-
raphy. We consider the Suppiah dataset to be the more accurate because of its higher resolution in most regions. Another point to note is that the rms errors in the Suppiah comparison are generally lower for both models. This is consistent with both models exhibiting skill in most regions. We suggest that the Legates and Willmot data suffer from a low elevation bias in the precipitation field in some regions of Australia, as it evidently does over Kalimantan for screen temperature.

c. July mean sea level pressure and screen temperature

Figure 8 shows the comparison between the observations and the two models for July mslp. The observations (Schutz and Gates 1972; Fig. 8a) are dominated by the extended subtropical high over southern Australia, and the intense circumpolar trough to the south of the continent. Both models overestimate the strength of the subtropical high over southern Australia, DARLAM (Fig. 8c) more so than the GCM (Fig. 8b). In both models, pressure is too high over the northern part of the DARLAM domain by a couple of hPa, and both models underestimate the strength of the circumpolar trough. In addition, the observed large-scale wave pattern in the trough, with minimum pressures along a longitude line through the southwest of Australia, is inadequately simulated in both models, but is better in DARLAM. Pattern correlations with the observations are similar in both models, but the GCM has a slightly lower rms error than DARLAM for July (not shown).

The comparison between DARLAM and the GCM for screen temperature is qualitatively similar to that for January, so the results will be only briefly summarized. The same problems with the observations south of 45°S noted for January are also present in July. The most important differences between the GCM and DARLAM occur over tropical areas and over Australia. The anomalies over the tropical oceans are attributable to the mechanisms discussed for the January case. The differences over Australia and other land areas such as New Guinea may be mostly ascribed, as in January, to changes in the specification of orography.

The pattern correlations and rms errors are shown in Fig. 9. We define two of the geographical regions differently for July, based upon the observed northward shift in the climatological features of the general circulation. Midlatitude regions for this month range from 45°S to 30°S, while subtropical areas extend from 35°S to 20°S. The statistics give similar results qualitatively to those seen for January (Fig. 5). The main exception
for this month is that the GCM has much higher rms errors and lower pattern correlations in the midlatitudes than does DARLAM. This is caused by some large errors in the GCM near the coastline.

d. July precipitation

Figure 10 shows the comparison for July precipitation. In the observations (Fig. 10a), a large band of heavy rainfall occurs southeast of the Philippines. Other large values are observed over the Philippines, east of New Guinea, and over parts of Indonesia and Indochina. Rainfall maxima are seen over New Zealand, Tasmania, and southwest Australia, while the interior of Australia remains dry. The GCM (Fig. 10b) seriously underestimates rainfall in the northern tropical regions of the domain; it is far too dry near Guam, and fails to simulate the rainfall maxima over the Philippines. Conversely, precipitation is overestimated in the GCM over large sections of the Southern Hemisphere west and south of Australia, and east of New Guinea. DARLAM (Fig. 10c) also does not simulate enough rain in the northern Tropics, and also seriously underestimates precipitation near Guam. It does, how-
ever, simulate the observed precipitation maxima over the large islands of Luzon and Mindanao in the Philippines. This result is again probably related to the much better representation of the orography of these islands in DARLAM. The circulation around New Guinea is substantially modified in DARLAM compared to the GCM, and precipitation southeast of the island is overestimated as a result. Both models fail to simulate the observed maximum east of Sulawesi. In addition, DARLAM also overestimates precipitation south and west of Australia.

Over the Australian continent, the GCM has rather too much rainfall over the interior, with a patchy and variable pattern compared to the observations. This is apparently caused by inhomogeneities in the horizontal moisture transport field in the GCM, which are in turn a function of low horizontal resolution and low horizontal diffusivity of moisture. The simulation of DARLAM is likewise too moist in the interior of Australia, although the better resolution of the orography of the east coast gives an improved representation of the 2 mm day$^{-1}$ contour in this region; however, DARLAM produces too much rain over the northeast of the continent. This may be a result of the changed circulation induced in DARLAM by the orography of New Guinea.

DARLAM appears to perform best in midlatitude regions of high orography near the land/sea interface: for example, over much of Tasmania, the southeast and southwest of Australia, and parts of the Eastern Highlands. The results of Fig. 11 show that in both the mid-latitudes and subtropics, DARLAM simulates a better precipitation pattern than the GCM, but rms errors are comparable. Over land points, DARLAM has a much superior pattern to the GCM, and also a better rms error. This result is probably again attributable to the improved orography in DARLAM, which is particularly important in the southern half of Australia in July, as this is a region largely of winter rainfall maximum. Although DARLAM still has a tendency to overestimate precipitation over regions of high orography, the improvement of the precipitation simulation in DAR-
LAM is so pronounced that in these latitudes the rms errors in DARLAM are still smaller than those of the GCM. Over the ocean, we see the reverse of the situation in January, with DARLAM having superior pattern correlations but inferior rms errors. This result, taken in conjunction with that for January, implies that the quality of the precipitation simulation of the two models is comparable over the oceans of the midlatitudes.

In tropical latitudes, DARLAM is mostly worse than the GCM. An exception is over tropical land points, where DARLAM appears to be performing slightly bet-
Fig. 11. Pattern correlations and rms errors of $P^{10}$ as in Fig. 7 but for July.

ter than the GCM. The comparison using the Suppiah dataset gives similar results in this month.

e. Spurious precipitation at DARLAM boundaries

As presently implemented, DARLAM suffers from spurious regions of precipitation in the areas close to the boundary. To investigate the effect of these regions on the simulation in the interior of the domain, we have compared the time evolution of precipitation to that of the moisture flux. The average precipitation rate is

$$\bar{P} = \frac{\iiint PdA d\sigma}{\iiint dA},$$  (3)

and the average moisture convergence (advected through the lateral boundaries) is

$$\bar{Q} = -\frac{\iiint \nabla \cdot (p, qv) dA d\sigma}{\iiint dA},$$  (4)

where $p$ is the surface pressure, $q$ is the specific humidity, $v$ is the velocity, $\sigma = p/p_a$, where $p$ is the pressure at a model level, and the area integrals are performed over all grid points lying at least 10 grid intervals inside the boundary. Both precipitation and the boundary moisture flux have also been averaged over the ten 30-day simulations that are used to calculate the model climatologies, and units have been converted to mm day$^{-1}$. Average evaporation has also been calculated similarly to precipitation in order to examine the conservation properties of the moisture budget of DARLAM.

The results for January (Fig. 12a) show that the GCM has an almost constant precipitation rate with time, while DARLAM experiences a spinup period of a couple of days, after which the precipitation rate slowly declines. Mean values are slightly higher in DARLAM than in the GCM. In both DARLAM and the GCM, $\bar{Q}$ is roughly 20% of the total precipitation rate. For July (Fig. 12b), both DARLAM and the GCM, after an initial spinup period, have roughly constant mean precipitation rates, with mean values slightly higher in the GCM than in DARLAM. The figures show that total evaporation is quite similar in the two models for each of January and July. The moisture budget in the interior of DARLAM is seen to be roughly in balance. In both models, DARLAM has
slightly less moisture convergence than the GCM, which is further consistent with the existence in DARLAM of anomalous regions of precipitation near the boundaries. Because the differences in $\bar{Q}$ between the two models are small, on average about 0.5 mm day$^{-1}$, the resulting impact on DARLAM simulations in the interior of the domain should be slight when compared to mean precipitations of about 5 mm day$^{-1}$ in January and about 3.5 mm day$^{-1}$ in July. Thus, we conclude that the influence on the interior of the DARLAM domain of the noticeable regions of anomalous boundary precipitation is small when compared to changes in circulation patterns and orography between the two models.

5. Conclusions

January and July climate simulations have been presented for the Australian region using a LAM nested within a GCM. The performance of the simulations has been evaluated over various latitude bands of the DARLAM domain using two statistical techniques: pattern correlations and rms errors. These techniques show that the DARLAM simulation is improved away from the boundaries of the domain, and is generally best in mid-latitude regions.

Comparisons between the two models have focused on their respective simulations of screen temperature and precipitation. For screen temperature, in general DARLAM gives better results than the GCM (particularly for pattern correlations) with a couple of exceptions, notably a region in the southwest of Australia and over the large islands of Indonesia. The former is a deficiency in DARLAM, while the latter may be a deficiency in the observations. In terms of the ability of DARLAM to simulate screen temperature in different latitudes, DARLAM performs best overall when compared to the GCM in the midlatitudes over land. Also, rms errors were particularly improved during January over tropical ocean areas.

For precipitation, pattern correlations are more improved than rms errors by the use of DARLAM. This result, along with that shown for the screen temperatures, can be explained in terms of the higher-resolution orography of DARLAM better representing the pattern of the actual orography than that of the GCM. The rms error of precipitation over land is sometimes larger in DARLAM than in the GCM, with the biases relative to the observations indicating that overestimation of precipitation in the LAM results is a problem over areas of high or steep orography. Over the oceans, the simulation of precipitation in the two models is of comparable quality, although there is considerable variation with latitude. The precipitation simulation of DARLAM compared to that of the GCM is best in the mid-
latitudes and subtropics; DARLAM is mostly inferior in the Tropics to the global model, except near land masses where DARLAM is better able to represent orographic precipitation.

The different statistical methods give generally similar results for the two models. The pattern correlation method is reasonable for assessing the quality of the simulation of screen temperature but only if the zonal mean of the observations is removed first. The rms error provides a good overall comparison between DARLAM and the GCM performance in each latitude band for a particular month. Because the spatial variability of precipitation in particular is different in each latitude band and month, intercomparisons between latitude bands and seasons of this statistic are subject to some interpretation. More work needs to be performed on these and similar measures of the skill of climate simulations.

One point to note again is that some differences from long-term averages are expected in the model climatologies presented here (especially of precipitation) due to sampling errors caused by the fact that climatological averages are produced from only 10 months of model output. Despite this shortcoming and the other problems discussed above, the nested model results demonstrate a general improvement over the R21 resolution global model simulations for regions of significant orography close to the land/sea interface. There is a considerable savings in computer resources using DARLAM, given that running the CSIRO9 GCM globally at a resolution of about 125 km would require about 1900 s day$^{-1}$ versus 130 s day$^{-1}$ for the nested model at the same resolution for the Australian domain. DARLAM is also being used at higher resolutions for various case studies (Katzfey 1994) and to develop new parameterizations. The model will be used for the construction of further geographically detailed scenarios of climate change.

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