Assessment of the Regional Climate Model Version 3 over the Maritime Continent Using Different Cumulus Parameterization and Land Surface Schemes

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ABSTRACT
This paper describes an assessment of the Regional Climate Model, version 3 (RegCM3), coupled to two land surface schemes: the Biosphere–Atmosphere Transfer System, version 1e (BATS1e), and the Integrated Biosphere Simulator (IBIS). The model’s performance in simulating precipitation over the Maritime Continent was evaluated against the 3-hourly Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis 3B42 product. It is found that the model suffers from three major errors in reproducing the observed rainfall histogram: underestimation of the frequency of dry periods, overestimation of the frequency of low-intensity rainfall, and underestimation of the frequency of high-intensity rainfall. Additionally, the model does not accurately reproduce the observed timing of the diurnal rainfall peak, particularly over land. These four errors persisted regardless of the choice of lateral boundary conditions, convective parameterization scheme, or land surface scheme. The magnitude of the wet–dry bias in the simulated volumes of rainfall was, however, strongly dependent on the choice of the convection scheme and lateral boundary conditions. The Grell convection scheme with Fritsch–Chappell closure was the best performing of the convection schemes, having the smallest error magnitudes in both the rainfall histogram and average diurnal cycle, and also having good representation of the land surface energy and evapotranspiration components. The 40-yr ECMWF Re-Analysis (ERA-40) was found to produce better simulations of observed rainfall when used as lateral boundary conditions than did the NCEP–NCAR reanalysis. Discussion of the nature of the major model errors is provided, along with some suggestions for improvement.

1. Introduction
The Maritime Continent is a vitally important region for global rainfall and circulation processes, due to large inputs of heat and moisture into the upper troposphere from intense convection in the region. Therefore, accurate simulation of the climate of the Maritime Continent region is critical for simulations of both regional and global circulations under current and future climate conditions (Neale and Slingo 2003). But future changes to the climate of this region still carry a high degree of uncertainty, and those projections are also likely to vary significantly across the region due to its complex topography and oceanic influences (Christensen et al. 2007). We therefore have a pressing need to improve our climate simulation capability over this region and achieve better predictive ability with regard to the impacts from land use and global climate changes.

Various studies have shown that general circulation models (GCMs) lack sufficient accuracy in reproducing the observed climate over the Maritime Continent region, with land areas having either a wet bias (e.g., Dai and Trenberth 2004, coupled model in Martin
et al. 2006) or a dry bias (e.g., Yang and Slingo 2001, atmosphere-only model in Martin et al. 2006), with underestimation of rainfall over the oceans (e.g., Neale and Slingo 2003; Collier and Bowman 2004). It has been suggested that the source of these errors includes poor representation of the diurnal cycle of convection over land and the complex circulation patterns generated by land–sea contrasts (Martin et al. 2006). In part, this is because the coarse resolution of GCMs, on the order of 2° per grid cell, is not sufficient to physically represent the islands within the Maritime Continent; the islands only occupy one or part of a single grid cell (Neale and Slingo 2003). Work by Hahmann and Dickinson (2001) lends weight to that argument by showing that GCM simulation of precipitation over land in the tropics was sensitive to subgrid-scale surface heterogeneities.

Failure to accurately simulate rainfall processes has flow-on effects to the simulation of the land surface hydrology. Dai and Trenberth (2004) suggested that GCMs fail to capture nonlinear processes impacting the diurnal cycle of land surface hydrology, such as the partitioning of rainfall between evaporation and runoff. Indeed, simulation of the diurnal rainfall cycle is notoriously problematic for GCMs, with the most common error being the early occurrence of daily peak precipitation around midday in simulations, about 4–6 h ahead of observations (e.g., Yang and Slingo 2001; Collier and Bowman 2004; Dai and Trenberth 2004).

However, relatively few studies using regional climate models (RCMs) have been conducted over the Maritime Continent. Those studies have generally shown better performance than the GCMs but some errors remain, particularly with regard to simulation of the diurnal rainfall cycle. Francisco et al. (2006) applied the Regional Climate Model (maintained at the International Center for Theoretical Physics) to simulations of monsoonal rainfall over the Philippines. In general, the model could reproduce observed monsoonal rainfall patterns well, but its performance depended strongly on the choice of lateral boundary conditions and the ocean flux scheme (Francisco et al. 2006). Wang et al. (2007) used the Regional Climate Model (developed at the International Pacific Research Center) to simulate the diurnal cycle over the Maritime Continent. Those authors found that the model could reasonably reproduce the diurnal cycle, with afternoon rainfall maxima over land areas and nighttime maxima over ocean areas, but with a time shift that was about 2–4 h too early compared with satellite observations (Wang et al. 2007). Joseph et al. (2008) used the Coupled Ocean–Atmosphere Mesoscale Prediction System (COAMPS) to simulate rainfall and flow fields around the Malay Peninsula on 23 April 2002. The model reproduced observations reasonably well, but with a cold bias over land during the daytime and a rainfall peak about 1 h ahead of observations (Joseph et al. 2008). Qian (2008) used version 3 of the Regional Climate Model coupled to version 1e of the Biosphere–Atmosphere Transfer Scheme to simulate the diurnal rainfall cycle over Java, Indonesia. The model was able to reproduce the diurnal cycle reasonably well (Qian 2008), but the simulation was restricted to that single island with relatively low topography, and thus the results cannot be extended to the rest of the region.

This current study builds on previous work by undertaking a more thorough evaluation of RCM performance in simulating the frequency and intensity of rainfall over the Maritime Continent. The study uses version 3 of the Regional Climate Model coupled to the Biosphere–Atmosphere Transfer Scheme (version 1e), which has previously shown good results in simulating the large-scale rainfall patterns caused by the monsoon systems over tropical West Africa, South America, and South Asia (Pal et al. 2007). It is therefore also expected to show good performance in simulating the large-scale dynamics over the Maritime Continent. While this model system has been used over Java by Qian (2008), and an earlier version was used over the Philippines by Francisco et al. (2006), a detailed investigation of the model’s performance over the Maritime Continent as a whole and with respect to diurnal precipitation, spatial variability in performance, and rainfall statistics has yet to be undertaken. In addition, the version 3 of the Regional Climate Model has recently been coupled to an alternate land surface scheme, the Integrated Biosphere Simulator (Winter et al. 2009), and the ability of this system to simulate the Maritime Continent’s rainfall has not yet been tested.

2. Methods

a. Model description

The Regional Climate Model (RegCM) was originally developed at the National Center for Atmospheric Research (NCAR) and is now maintained by the International Center for Theoretical Physics (ICTP). It is a three-dimensional, hydrostatic, compressible, primitive-equation, σ-coordinate regional climate model. RegCM version 3 (RegCM3) maintains much of the dynamical core of the fifth-generation Pennsylvania State University–NCAR Mesoscale Model (MM5; Grell et al. 1994) and employs NCAR’s Community Climate Model version 3 (CCM3) atmospheric radiative transfer scheme (described in Kiehl et al. 1996). Planetary boundary layer dynamics follow the nonlocal formulation of Holtslag et al. (1990; described in Giorgi et al. 1993a). Ocean
surface fluxes are handled by Zeng’s bulk aerodynamic ocean flux parameterization scheme (Zeng et al. 1998), where sea surface temperatures are prescribed. The Subgrid Explicit Moisture Scheme (SUBEX) is used to handle large-scale, resolvable, nonconvective clouds and precipitation (Pal et al. 2000). Finally, three different convective parameterization schemes are available for the representation of nonresolvable rainfall processes (Giorgi et al. 1993b): Kuo (Anthes 1977), Grell (Grell 1993) with Fritsch–Chappell (Fritsch and Chappell 1980) or Arakawa–Schubert (Grell et al. 1994) closures, and Emanuel (Emanuel 1991; Emanuel and Zivkovic-Rothman 1999). Further details of the developments and description of RegCM3 are available in Pal et al. (2007).

Land surface physics are modeled by the Biosphere–Atmosphere Transfer Scheme version 1e (BATS1e; described in Dickinson et al. 1993). BATS1e uses a one-layer canopy with two soil layers and one snow layer to perform eight major tasks, including the calculation of soil, snow, or sea ice temperature in response to net surface heating; calculation of soil moisture, evaporation, and surface and groundwater runoff; calculation of the plant water budget, including foliage and stem water storage, intercepted precipitation, and transpiration; and calculation of foliage temperature in response to energy-balance requirements and consequent fluxes from the foliage to canopy air (Dickinson et al. 1993). Additional modifications have been made to BATS1e to account for the subgrid variability of topography and land cover as described in Giorgi et al. (2003).

Winter et al. (2009) coupled RegCM3 to an additional land surface scheme: the Integrated Biosphere Simulator (IBIS; described in Foley et al. 1996). IBIS uses a hierarchical, modular structure to integrate a variety of terrestrial ecosystem phenomena. IBIS contains four modules, operating at different time steps, and includes a two-layer canopy with six soil layers and three snow layers. The four modules simulate processes associated with the land surface (surface energy, water, carbon dioxide, and momentum balance), vegetation phenology (winter-deciduous and drought-deciduous behavior of specific plant types in relation to seasonal climatic conditions), carbon balance (annual carbon balance as a function of gross photosynthesis, maintenance respiration, and growth respiration), and vegetation dynamics (time-dependent changes in vegetation cover resulting from changes in net primary productivity, carbon allocation, biomass growth, mortality, and biomass turnover for each plant functional type) (Foley et al. 1996).

b. Experimental design

Simulations were begun on 1 July 1997 and ended 31 December 2001. The first 6 months of output were ignored to allow for spinup. The resulting 4 yr of simulation (1998–2001) were used for evaluation of model performance and were chosen for maximal overlap between the datasets used for lateral boundary conditions and observational comparison, described below. The model domain (Fig. 1) was centered along the equator at 115°E, used a normal Mercator projection, and spanned 95 grid points meridionally and 200 grid points zonally, with a horizontal resolution of 30 km. The simulations used 18 vertical sigma levels, from the ground surface up to the 50-mb level. In all simulations presented, the land surface scheme was run every 120 s, twice the model time step. A small model time step was necessary because of the relatively high resolution used and to ensure convergence in areas with significant convective activity.

Sea surface temperatures (SSTs) were prescribed using the National Ocean and Atmospheric Administration (NOAA) optimally interpolated SST (OISST) dataset, which is available at 1° × 1° resolution and on
a weekly time scale (Reynolds et al. 2002). Topographic information for both RegCM3–BATS1e and RegCM3–IBIS was taken from the U.S. Geological Survey’s global 30-arc-second elevation dataset (GTOPO30), aggregated to 10 arc minutes (U.S. Geological Survey 1996).

For RegCM3–BATS1e, vegetation cover information was taken from the U.S. Geological Survey’s Global Land Cover Characterization (GLCC) database (U.S. Geological Survey 1997) at 10-min resolution. Soil properties were automatically assigned according to vegetation type.

For RegCM3–IBIS, vegetation biomes were based on the potential global vegetation dataset of Ramankutty (1999), modified to include two extra biomes for inland water and ocean as described in Winter et al. (2009). The vegetation biomes were used in conjunction with two additional datasets to populate each grid cell with plant functional types: the monthly mean climatology of temperature (New et al. 1999) and the minimum temperature ever recorded at a location minus the average temperature of the coldest month (Bartlein 2000). Soil properties, such as albedo and porosity, were determined based on the relative proportions of clay and sand in each grid cell. Sand and clay percentages were taken from the Global Soil Dataset, which has a spatial resolution of 5 min (Global Soil Data Task 2000). Soil moisture, soil temperature, and soil ice content were initialized in RegCM3–IBIS using the output from a global 0.5° × 0.5° resolution 20-yr offline simulation of IBIS as described in Winter et al. (2009). In all simulations presented, RegCM3–IBIS was run with static vegetation only.

For most simulations, the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) dataset, available from September 1957 to August 2002 (Uppala et al. 2005), was used to force the boundaries. For comparison purposes, two simulations with RegCM3–BATS1e were also forced with lateral boundary conditions taken from the National Centers for Environmental Prediction (NCEP)–NCAR Reanalysis 2 product (hereafter referred to as NNRP2) dataset (Kanamitsu et al. 2002). The exponential relaxation technique of Davies and Turner (1977) was used with both datasets.

To evaluate the sensitivity of the model to the choice of convective parameterization scheme, simulations were run using three of the options available with RegCM3: the Grell scheme using both the Arakawa–Schubert and Fritsch–Chappell closures methods and the Emanuel scheme. Over the tropics, the Kuo scheme has consistently shown poor simulation of rainfall and is not considered to be an appropriate scheme for use in this region (e.g., Jenkins 1997, Slingo et al. 1994), so it was not included in this study. The Grell scheme with the Fritsch–Chappell closure and the Emanuel scheme were also used to test the influence of the lateral boundary conditions and land surface scheme. The default parameter values were used in all convection schemes.

A total of seven simulations are presented in this study. Table 1 summarizes the different characteristics of these simulations and lists the names used to reference each simulation throughout the text.

c. A note on the choice of lateral boundary conditions and convection scheme

Climate model performance is generally highly sensitive to the choice of lateral boundary conditions and convective parameterization scheme. In this study, preference is given equally to the Grell convection scheme with the Fritsch–Chappell closure and to the Emanuel convection scheme, while the ERA-40 lateral boundary conditions are favored over the NNRP2. Here, we provide brief explanations for these choices.

Previous evaluations of the ERA-40, NNRP1 (the first NCEP–NCAR reanalysis), and NNRP2 products have identified their relative strengths and weaknesses. Representation of the intertropical convergence zone (ITCZ) is much stronger and closer to observations in ERA-40 than NNRP1, as evidenced by the locations and magnitudes of rainfall (Janowiak et al. 1998; Trenberth and Guillemot 1998), atmospheric water vapor (Trenberth and Guillemot 1998), and diabatic heating and cooling (Chan and Nigam 2009). ERA-40 also shows a stronger Walker circulation over the Pacific basin than does NNRP1 (Chan and Nigam 2009). Both NNRP1 and NNRP2 have poor representations of the interannual variability in water vapor, and the representation of the El Niño–Southern Oscillation pattern is better in ERA-40 than in NNRP1 or NNRP2 (Sudradjat et al. 2005).

The amplitude of diabatic heating in ERA-40 is too high, indicating overrepresentation of convection, and precipitation from ERA-40 is higher than satellite observations (Chan and Nigam 2009). However, the variability and spatial patterns of water vapor in ERA-40 are

<table>
<thead>
<tr>
<th>Simulation name</th>
<th>Convection scheme</th>
<th>Boundary conditions</th>
<th>Land surface scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFC</td>
<td>Grell with FC</td>
<td>ERA-40</td>
<td>BATS1e</td>
</tr>
<tr>
<td>EMAN</td>
<td>Emanuel</td>
<td>ERA-40</td>
<td>BATS1e</td>
</tr>
<tr>
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<td>Grell with AS</td>
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<td>BATS1e</td>
</tr>
<tr>
<td>GFCNCEP</td>
<td>Grell with FC</td>
<td>NNRP2</td>
<td>BATS1e</td>
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<td>EMANIBIS</td>
<td>Emanuel</td>
<td>ERA-40</td>
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similar to the observations (Sudradjat et al. 2005). NNRP1 has large and significant dry biases in the tropics, particularly over the oceanic tropical convergence zones (Trenberth and Guillemot 1998) and over the Maritime Continent (Newman et al. 2000). The dry bias in NNRP1 appears to be stronger than the wet bias in ERA-40 (Chan and Nigam 2009; Newman et al. 2000). This dry bias in NNRP1 does not seem to have been fixed in NNRP2, since Sudradjat et al. (2005) showed that NNRP2 still contains a dry bias in atmospheric water vapor over the Maritime Continent and the western Pacific warm pool. Therefore, while both reanalysis products contain deficiencies, it is considered that the ERA-40 product contains better representation of the dynamics over the tropics and the Maritime Continent than does NNRP2.

Previous studies have demonstrated that the convective parameterization schemes have different strengths and weaknesses. The Kuo parameterization is a bulk scheme in which rainfall is calculated as a fraction of the moisture convergence within each vertical column. Convective activity as simulated by the Kuo scheme is initiated when the moisture convergence exceeds a given threshold value and the vertical sounding is convectively unstable. As mentioned above, this type of convection scheme is not considered appropriate for simulating tropical convection and thus has not been investigated here.

The Grell and Emanuel schemes are both mass flux schemes that implement convective adjustment in accordance with the quasi-equilibrium assumption, in which convective clouds act to stabilize the environment as fast as large-scale processes destabilize it. The Grell scheme treats clouds as two steady-state circulation events: an updraft and a downdraft. No mixing occurs between the cloud and the environment except at the top and bottom of the circulations, with no entrainment or detrainment along the edges of the cloud. In contrast, the Emanuel scheme assumes that mixing within clouds is highly episodic and inhomogeneous and considers convective fluxes based on an idealized model of subcloud-scale updrafts and downdrafts.

Davis et al. (2009) showed that the Grell scheme with both the Arakawa–Schubert (AS) and Fritsch–Chappell (FC) closure methods underestimated convective rainfall over tropical land areas, while over the ocean the Grell scheme with the FC closure overestimated the convective rainfall while the Grell approach with the AS closure underestimated the result. The Emanuel scheme was found to overestimate total rainfall over both land and ocean, but provided the most realistic partitioning of convective and stratiform rainfall, as well as better spatial distribution of convective rainfall (Davis et al. 2009). Pal et al. (2007) showed that simulations using the Emanuel scheme over the West African monsoon region overestimated precipitation over the wettest areas, while Jenkins (1997) showed that the Grell scheme over West Africa underestimated summer season precipitation. Over South America, the Grell scheme has been shown to underestimate the magnitude of both precipitation and temperature, while the Emanuel scheme performs reasonably well in simulating the distribution of precipitation over the continent and its adjacent oceans (Pal et al. 2007). Over Korea and East Asia, work by Im et al. (2008) and Singh et al. (2006) showed that the Emanuel scheme was better able to simulate the monsoon circulations and the timing and amplitude of rainfall compared to the Grell scheme. However, the Emanuel scheme consistently overestimated rainfall volumes, while the Grell scheme tended to overestimate winter season precipitation and underestimate summer season precipitation (Im et al. 2008). Therefore, neither the Grell nor Emanuel scheme consistently provides better simulation over the tropics.

d. Comparison datasets

To assess the performance of RegCM3–BATS1e and RegCM3–IBIS, model precipitation output was compared to data from the Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA) 3B42 product (described in Huffman et al. 2007), referenced in this paper simply as TRMM. The TRMM product is available from January 1998 to the present day, and was considered the most appropriate dataset for use in this study because it is available across the Maritime Continent at 3-hourly temporal and 0.25° × 0.25° spatial resolutions, making it one of the highest-resolution datasets available over this region.

Huffman et al. (2007) showed that TRMM produced good matching in the rainfall histogram compared to radar observations at Kwajalein, in the Marshall Islands. When comparing time series of precipitation estimates from TRMM to observations obtained from buoys in the western Pacific Ocean, Huffman et al. (2007) also noted that the two datasets agreed on the occurrence of most precipitation events, despite some differences in sampling.

To further ensure that TRMM would be suitable for use in this study, its precipitation estimates were compared to those from the meteorological station at Changi Airport, on the island of Singapore. Hourly rainfall observations were obtained for the period 0000 local time (LT) 1 January 1998 to 2400 LT 31 December 2001. The hourly data were aggregated into 3-hourly time periods to match the temporal resolution of TRMM. Figure 2 shows the histogram using the 3-hourly aggregated Changi station data and the TRMM land grid point closest to the island of Singapore, averaged for the
period 1998–2001. The lowest rainfall intensity bin of less than 0.0417 mm h$^{-1}$ represents zero rainfall, since TRMM does not provide rainfall at intensities less than 1 mm day$^{-1}$. Figure 2 shows that there is very good agreement in the histograms between the two datasets, and importantly the match at both ends of the histogram is very close.

Figure 3 shows the diurnal rainfall cycle using the same two datasets, averaged over the period 1998–2001. The time stamp for the aggregated Changi station data is offset from the TRMM time stamp by 0.5 h. This is because the time stamp for the center of the given 3-hourly averaging window used for the TRMM product is on the hour, while for the Changi dataset the center of the given hourly data window is on the half hour. Again there is good agreement between the two datasets in terms of the general shape and magnitude of the curve. Figure 3 shows that the daily peak in TRMM lags slightly behind the Changi station data. However, with the 3-h data interval of TRMM, it is impossible to say exactly how large the lag is between the datasets. TRMM does contain a wet bias, with an average total daily rainfall of 7.4 mm day$^{-1}$ compared to 6.8 mm day$^{-1}$ from the Changi data. Also the peak daily rainfall rate in TRMM, occurring around 1600 LT, is approximately 0.2 mm h$^{-1}$ higher than the Changi station data. Despite this bias, it is considered that the TRMM dataset compares well enough to the Changi station data to be suitable for this study.
3. Simulation results

The two simulations chosen as the comparative basis for all other simulations are the Grell scheme with Fritsch–Chappell closure (GFC) and the Emanuel scheme (EMAN) used with the ERA-40 boundary conditions and the BATS1e land surface scheme. Analysis of these two simulations will be presented first.

a. GFC and EMAN

Figure 4 presents the rainfall histogram for TRMM compared to the GFC and EMAN simulations. The histogram has been constructed by splitting the domain with a land–ocean mask (excluding the boundary edges) to elucidate differences in model performance over different surface types. The lowest rainfall intensity bin, equivalent to less than 1 mm day$^{-1}$, is used to represent dry periods, as explained previously.

Figure 4 shows that both simulations contain significant errors in the rainfall histogram, particularly with respect to the simulated frequency of dry periods and low-intensity rainfall (the first and second rainfall bins, respectively). The first rainfall bin shows the proportion of time that the observations–simulations record no rainfall, so the proportion of time with nonzero rainfall can be found by taking the difference between 100% and the value in the first rainfall bin (this will be equal to the sum of the remaining rainfall bins).

The magnitude of error is larger in EMAN than in GFC. Over land, EMAN simulates nonzero rainfall nearly 3 times as frequently as TRMM (nonzero rainfall occurs 51% of the time in EMAN but only 17% of the time in TRMM), while GFC simulates nonnegligible rainfall nearly twice as frequently as TRMM (nonzero rainfall occurs 30% of the time in GFC). Figure 4 also shows that both GFC and EMAN simulate low-intensity rainfall, less than 0.25 mm h$^{-1}$, over land about 10 times more frequently than is recorded in TRMM. Over ocean, the errors in the frequencies of dry periods and low-intensity rainfall are even worse than over land in both simulations.

The model errors in the low-intensity end of the rainfall histogram could be physically understood as the model simulating frequent drizzle, while the observational data suggest less frequent bursts of rainfall. Figure 5 illustrates this difference: it shows the time series of rainfall over the location of Singapore for the first 2 months of the analysis period, January–February 1998. The simulated rainfall time series for EMAN (not shown here) is qualitatively similar to that of GFC, but with more pronounced errors. While there are differences between TRMM and Changi in the magnitude and exact timing of rainfall, the datasets agree on the general spacing and order of magnitude of rainfall events. In contrast, GFC simulates much higher frequency of rainfall with relatively low intensities.

In the medium rainfall intensity range of 0.25–2 mm h$^{-1}$, Fig. 4 shows that both GFC and EMAN simulate rainfall over both land and ocean with higher frequency than does TRMM, though the errors are
smaller for GFC than for EMAN. For rainfall of intensity 2–5 mm h\(^{-1}\), GFC simulates rainfall with similar frequency to TRMM. EMAN simulates similar frequency of rainfall to TRMM over ocean, but overestimates rainfall frequency at this intensity over land. For high-intensity rainfall of greater than 5 mm h\(^{-1}\), Fig. 4 shows that GFC simulates rainfall with less frequency than TRMM over both land and ocean. EMAN simulates rainfall of high intensity at about the same frequency as TRMM over land, but with less frequency than TRMM over ocean.

Figures 6–8 illustrate the spatial difference in rainfall over land and ocean through their representations of the average diurnal cycle, with each 3-hourly averaging window over 24 h represented by one panel in each figure. Figure 6 shows the average diurnal cycle for 1998–2001 from TRMM. The diurnal movement of rainfall between land and ocean is very clear. Rainfall over land begins in the late afternoon (around 1600 LT mid-domain), builds into the evening (until about 2200 LT mid-domain), and dissipates by early morning (around 0400 LT mid-domain). Over ocean the rainfall begins late at night (around 2200 LT mid-domain), builds in the morning (until about 0400 LT mid-domain), and dissipates by early afternoon (around 1300 LT mid-domain).

Figures 7 and 8 show the average diurnal cycles of rainfall from GFC and EMAN, respectively. In both simulations, the model capably simulates a diurnal signal of rainfall over land, with rainfall building in the late morning and prolonged rainfall over some mountainous areas in the evening. However, there are several errors to note in both simulations. In GFC, the magnitude of the rainfall peak over land is not as great as in TRMM, while the magnitude of rainfall over ocean is skewed relative to TRMM: the enclosed ocean in the center of the domain shows a negligible diurnal signal and very little total rainfall, but the open-ocean areas in the corners of the domain receive more rainfall than most of the land areas. In EMAN, the rainfall over land is significantly greater than in TRMM, although the simulated oceanic rainfall is generally better in EMAN than in GFC. In both simulations, the diurnal rainfall peak arrives about 6 h too early compared to TRMM.

Table 2 presents the average total rainfall, separately for land and ocean, for TRMM and the model simulations. In GFC there is a dry bias over land and a wet bias over ocean. Figure 7 shows that this bias occurs over the more open ocean areas toward the edges of the domain. EMAN presents a very significant wet bias over land, with nearly twice the amount of rainfall as TRMM, and also contains a wet bias over ocean.

Figure 9 shows the average diurnal cycle of rainfall separately for land and ocean for each of the convection schemes used in this study. Over land, the daily peak rainfall rate occurs around 1900 LT in TRMM but around midday in GFC and EMAN, as was suggested in Figs. 6–8. Over ocean, both GFC and EMAN simulate the average diurnal cycle of rainfall reasonably well compared to TRMM. The peak rainfall rate in both simulations occurs at approximately the same time as TRMM, in the early morning. The diurnal amplitude of rainfall over ocean is also well represented in the simulations.

b. Convection scheme comparison

Figure 9 also shows the simulated diurnal cycle of rainfall from the GAS simulation. The rainfall histogram for this simulation contained values midway between the EMAN and GFC histograms, and so for brevity it is not shown here. Table 2 presents the average daily rainfall over land and ocean for each simulation.
Fig. 6. Diurnal cycle of rainfall from TRMM. The local time for the center of the domain is given at the bottom of each panel. Each panel represents the average rainfall rate (mm h$^{-1}$) over a 3-h period centered at the given time, averaged over the period 1998–2001.
Fig. 7. As in Fig. 6, but for the GFC simulation.
FIG. 8. As in Fig. 6, but for the EMAN simulation.
The results show that the GAS simulation presents a dry bias over both land and ocean, and the bias is worse over land than that presented by GFC. The timing of the diurnal cycle in GAS compares well to observations, although the amplitude of the cycle is much smaller in GAS than in TRMM.

### Table 2

<table>
<thead>
<tr>
<th>Product/simulation</th>
<th>Land avg</th>
<th>Ocean avg</th>
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<tbody>
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<td>TRMM</td>
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<td>7.0</td>
</tr>
<tr>
<td>GFC</td>
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<td>EMAN</td>
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</table>

The results show that the GAS simulation presents a dry bias over both land and ocean, and the bias is worse over land than that presented by GFC. The timing of the diurnal cycle in GAS compares well to observations, although the amplitude of the cycle is much smaller in GAS than in TRMM.

c. **Lateral boundary conditions comparison**

Simulations using both the Grell approach with the Fritsch–Chappell closure and the Emanuel scheme were run using NNRP2 instead of ERA-40 data, to test the model’s sensitivity to lateral boundary conditions. These simulations are termed GFCNCEP and EMANNCEP; descriptions are given in Table 1. Figure 9 shows the average diurnal rainfall cycle for the GFCNCEP and EMANNCEP simulations compared to TRMM and the GFC and EMAN simulations. Average daily rainfall values over land and ocean are presented in Table 2.

Figure 9 shows that both GFCNCEP and EMANNCEP simulate a diurnal rainfall cycle over land and ocean with generally the same shape and timing as their respective comparison simulations, GFC and EMAN. Both GFCNCEP and EMANNCEP contain the same timing error of an early daily rainfall peak over land. However, the magnitude of rainfall is significantly impacted by the choice of boundary conditions. Using NNRP2 instead of
ERA-40 reduced the rainfall in GFC by 40% over land, worsening the dry bias that this scheme presents over land. The rainfall in EMAN was reduced by nearly 50% over land, virtually eliminating the wet bias that this scheme presents over land and producing a rainfall volume that matches TRMM. Over ocean, the impacts of using NNRP2 were even greater, reducing the rainfall simulated by both GFC and EMAN by at least 70% and producing significant dry biases. The rainfall histogram as simulated by GFCNCEP and EMANNCEP (not shown for brevity) showed some improvement compared to GFC and EMAN, but still contained significant error in the simulation of dry periods and low-intensity rainfall, and significantly worsened the error in terms of the underestimation of high-intensity rainfall.

d. Land surface scheme comparison

Finally, simulations using IBIS were run as an alternative to BATS1e, to test the sensitivity of the model performance to the underlying land surface scheme. These simulations are termed GFCIBIS and EMANIBIS; descriptions are given in Table 1.

Figure 10 shows the rainfall histogram just for the land grid cells. There are some small differences between the simulations using BATS1e and IBIS that vary depending on the convection scheme. With GFCIBIS, the errors in the frequency of dry periods and low-intensity rainfall are slightly less than in GFC: the frequency of dry periods increases from 70% in GFC to 72% in GFCIBIS compared to 82% in TRMM, while the frequency of low-intensity rainfall decreases from 12% in GFC to 11% in GFCIBIS compared to 3% in TRMM. Thus, the histogram for GFCIBIS is a closer match to TRMM than for GFC. In contrast, EMANIBIS produces worse error than EMAN: the frequency of dry periods decreases from 49% in EMAN to 45% in EMANIBIS, and the frequency of low-intensity rainfall increases from 17% in EMAN to 19% in EMANIBIS. However, the differences between GFC and GFCIBIS or between EMAN and EMANIBIS are smaller than the differences between TRMM and any of the individual simulations.

Figure 11 shows the average diurnal rainfall cycle for the GFCIBIS and EMANIBIS simulations compared to TRMM and to the GFC and EMAN simulations. Average daily rainfall values over land and ocean are presented in Table 2.

Over land, Fig. 11 shows that the timing of the diurnal rainfall cycle in GFCIBIS is significantly changed relative to GFC, with the daily rainfall peak occurring in the late evening with a closer match to TRMM. The total rainfall over land in GFCIBIS is also improved compared to GFC, with a very close match to TRMM. However, the diurnal amplitude of the rainfall cycle is poor in GFCIBIS with a value of only 0.125 mm h\(^{-1}\) compared to 0.5 mm h\(^{-1}\) in TRMM. The general shape and timing of the diurnal rainfall cycle is unchanged between EMAN and EMANIBIS, leaving the errors with an early and overestimated daily rainfall peak, although EMANIBIS produces a smaller daily rainfall peak than EMAN, which reduces the wet bias.
Over ocean, the shape and timing of the diurnal rainfall cycle are relatively unchanged between GFC and GFCIBIS and EMAN and EMANIBIS. For both convection schemes, IBIS results in less rainfall than BATS1e, producing a small dry bias in GFCIBIS and leaving a small wet bias in EMANIBIS.

To further investigate the differences between the BATS1e and IBIS simulations, the components of the surface energy flux were determined; average daily values are presented in Table 3. Net radiation is defined as the sum of the surface absorbed (incoming minus reflected) shortwave and longwave radiation. Residual ground heat is calculated as the residual of the net radiation minus the sum of the turbulent heat fluxes (latent plus sensible).

The net radiation at the land surface is higher in GFC than in GFCIBIS. The majority of the radiation is removed from the land surface via latent heat flux in both GFC and GFCIBIS, though GFC has a higher value of latent heat flux to compensate for a higher net radiation, while the sensible heat flux values are almost the same between the two simulations.

The net radiation at the land surface is almost the same in EMAN and EMANIBIS, but the breakdown of

![Figure 11](image_url)

**TABLE 3.** Simulated average daily land surface energy fluxes and evapotranspiration components over the period 1998–2001.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>$R_N$</th>
<th>LH</th>
<th>SH</th>
<th>ET</th>
<th>$T$</th>
<th>GE</th>
<th>$I$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFC</td>
<td>154</td>
<td>117</td>
<td>37</td>
<td>4.0</td>
<td>2.0</td>
<td>0.7</td>
<td>1.3</td>
</tr>
<tr>
<td>EMAN</td>
<td>149</td>
<td>153</td>
<td>-2</td>
<td>5.3</td>
<td>1.2</td>
<td>0.7</td>
<td>3.4</td>
</tr>
<tr>
<td>GFCIBIS</td>
<td>143</td>
<td>104</td>
<td>36</td>
<td>3.6</td>
<td>2.1</td>
<td>0.4</td>
<td>1.0</td>
</tr>
<tr>
<td>EMANIBIS</td>
<td>143</td>
<td>134</td>
<td>6</td>
<td>4.6</td>
<td>1.6</td>
<td>0.6</td>
<td>2.4</td>
</tr>
</tbody>
</table>

$R_N$ = net radiation absorbed at the surface (W m$^{-2}$).
LH = latent heat flux away from the surface (W m$^{-2}$).
SH = sensible heat flux away from the surface (W m$^{-2}$).
ET = total evapotranspiration (mm day$^{-1}$).
$T$ = transpiration (mm day$^{-1}$).
GE = ground evaporation (mm day$^{-1}$).
$I$ = interception loss (mm day$^{-1}$).
net radiation is significantly different between the two simulations. In EMAN, almost all the radiation at the land surface is removed via latent heat flux, with the latent heat flux being so strong as to create a negative net sensible heat flux (i.e., a net flux from air to ground instead of from ground to air). In contrast in EMANIBIS, while the majority of the net radiation is still removed by latent heat flux, some radiation is also removed from the surface via sensible heat flux.

Since the large majority of surface absorbed radiation is removed via latent heat flux in all four of these simulations, it is possible that overestimation of evapotranspiration (ET) contributes to the observed errors in simulated rainfall. This potential source of error was further investigated by looking at each simulated component of ET: transpiration from foliage, evaporation from ground surfaces (either beneath canopy or from patches of bare ground), and interception loss (evaporation directly from wetted vegetation surfaces). Average daily values of each ET component from GFC, EMAN, GFCIBIS, and EMANIBIS are presented in Table 3.

In both GFC and GFCIBIS, the largest contributor to the total ET is transpiration, with interception loss constituting a smaller fraction in both simulations. It is interesting that the interception loss decreases from GFC to GFCIBIS even though the total rainfall over land increases. This is likely due to the shift in timing of the rainfall cycle, shown in Fig. 11. The increase in evening rainfall, and the concomitant decrease in midday rainfall, leads to a decrease in the amount of water available for direct evaporation from the wet canopy when the available radiation is highest. Ground evaporation is the smallest component of ET, representing only a small fraction of the total ET in both simulations.

The ET component breakdown results are quite different for the Emanuel scheme simulations. The total ET is higher in both EMAN and EMANIBIS, and the largest contributor to the total ET is interception loss. The partitioning between interception loss and transpiration is therefore reversed between the GFC and EMAN simulations. This result can be understood in terms of the much higher volumes of rainfall simulated by both Emanuel scheme simulations and the peak rainfall occurring at midday in both of these simulations, concomitant with the peak radiation and therefore leading to high evaporation rates from the wetted canopy. Ground evaporation is again the smallest component of ET in both EMAN and EMANIBIS.

To compare these results to observations, Table 4 presents measured values of ET from field studies conducted at various locations across the Maritime Continent. These studies suggest that the average observed ET is approximately 3.5 mm day$^{-1}$. Hence, the simulated total ET is too high in all simulations presented here except GFCIBIS.

Table 4 also presents field-measured values of interception loss and transpiration from the Maritime Continent region. The average observed value of interception loss is approximately 1.2 mm day$^{-1}$, while for transpiration the average observed value is about 3 mm day$^{-1}$. Hence, the interception loss simulated by GFC and GFCIBIS is close to the observations, but the interception loss simulated by EMAN and EMANIBIS is too high. The simulated transpiration rates are about 0.5–1 mm day$^{-1}$ too low in GFC and GFCIBIS and 1–1.5 mm day$^{-1}$ too low in EMAN and EMANIBIS.

4. Discussion

The simulations presented here have demonstrated three significant errors in the rainfall histogram as simulated by both the RegCM3–BATS1e and RegCM3–IBIS model systems: 1) underestimation of dry periods,
2) overestimation of low-intensity rainfall, and 3) underestimation of high-intensity rainfall. These errors indicate that the model simulates near-constant drizzle, particularly over the ocean, while observations show less-frequent, intense bursts of rainfall. It is noted that the magnitude of the error in reproducing the observed frequency of high-intensity rainfall is relatively small, certainly smaller than the error in reproducing the observed frequency of low-intensity rainfall. However, since high-intensity rainfall has such a significant impact on surface hydrology, and therefore its accurate simulation is crucial for studies of land-use change, it is considered that the histogram errors documented here are all significant.

These errors persist, to a greater or lesser degree, regardless of the choice of convective parameterization scheme, land surface scheme, or lateral boundary conditions. The Grell convection scheme with the Fritsch–Chappell closure approach used in conjunction with the IBIS land surface scheme presented the smallest magnitude of error in the rainfall histogram compared to the other simulations presented here, but still contained substantial error. In results not shown here, the histogram errors also persisted when the horizontal resolution was increased to 15-km grid cell size, the model domain was increased to twice the extent of the current domain in each direction, and 29 vertical layers were used instead of 18, indicating that the errors are not merely artifacts of the model setup.

This study has also documented error in the volume of rainfall simulated over both land and ocean. The presence of either a wet or dry bias and the magnitude of this bias were shown to be highly dependent on user choices. In particular, changing the convection scheme and/or lateral boundary conditions can significantly impact the results. The Grell convection scheme with the Fritsch–Chappell closure approach generally showed the smallest magnitude bias of the convection schemes tested here. Despite the Emanuel scheme’s more sophisticated treatment of mixing and entrainment processes, which might lead one to expect better results over regions with significant convection, this scheme did not show good performance over the Maritime Continent, with very large error in the rainfall histogram and a significant wet bias over land.

Both the Grell and Emanuel schemes suffered from error in the timing of the diurnal rainfall cycle, with a daily peak that was 6–9 h too early compared to TRMM. It is noted that the diurnal cycle in TRMM presented a lag relative to the Changi station data, and therefore it is possible that the actual daily rainfall peak occurs earlier over the Maritime Continent in general than is indicated by TRMM. However, it can still be said that the simulated diurnal cycle is too early.

The errors documented here are not unique to RegCM3. For example, Dai and Trenberth (2004) showed that the NCAR Community Climate System Model GCM simulated precipitation greater than 1 mm day$^{-1}$ occurring at least 80% of the time over the Maritime Continent, with greater frequency of lower-intensity rainfall compared to the observations. Wang et al. (2007) documented simulation errors in the phase of the diurnal cycle of rainfall over this region. Therefore, the results presented here indicate that GCMs and RCMs experience the same difficulties in simulating the climate of the Maritime Continent, and it is not simply a matter of resolution or a specific user choice that is at fault. Rather, there is a more fundamental issue at the root of these simulation errors in large-scale models.

These errors are likely to stem from the same problem: convective rainfall is initiated in the model too frequently. There are two steps to activating the convective adjustment in the model: establishing threshold criteria for triggering convection, and creating sufficient environmental conditions to meet those criteria. Consequently, it is considered that there are two avenues of research to pursue to identify the genesis of the errors documented in this study. The first is simulation of the planetary boundary layer and the processes that drive the diurnal rise and fall of the boundary layer height, diurnal variations in boundary layer moist static energy, and the location of the lifted condensation level with respect to the level of free convection (given that colocation of the two levels is required for active convection). It is feasible that these processes are not being accurately simulated in the model, leading to errors in the environmental conditions that are necessary to trigger convective rainfall.

The second suggested avenue of pursuit is in the nature of the threshold criteria for triggering convection. Presently, the convection schemes in RegCM3 (and many other RCMs) contain threshold criteria that are essentially uniform in time and space and are meant to represent the mean behavior of an ensemble of convective cells. These schemes were originally made for use in a model with a coarse resolution, such that a single grid cell could be expected to contain an ensemble of individual convective cells. However, a single grid cell in an RCM simulation might only hold one or a few convective cells. Therefore, the effect of using a uniform threshold criterion is essentially to impose the mean behavior of many convective cells onto every convective cell within an RCM domain. We consider that both spatial and temporal variabilities in convection need to be incorporated into the RegCM3 model system to improve the model performance in the metrics used in this study. This problem has been identified and discussed by
Neelin et al. (2008), among others, and the current literature indicates ongoing work to incorporate stochasticity into the triggering of convective activity as one method of introducing the necessary variability.

There may also be other methods for altering the criteria for the onset of convection. For example, Chow et al. (2006) found that the Emanuel convection scheme produced too much rainfall over East Asia, particularly over the South China Sea region, during the Asian summer monsoon. The model performance was improved by applying convection suppression criteria in the form of a relative vorticity threshold, whereby the convection was shut down when the low-level flow was anticyclonic and stronger than a given threshold value (Chow et al. 2006). Peng et al. (2004) used the Emanuel scheme within the Navy Operational Global Atmospheric Prediction System (NOGAPS). Those authors found errors in the underprediction of high-intensity rainfall and too much light-intensity rainfall, with a systematic wet bias. Improvements in the performance of NOGAPS were achieved when the treatment of the mixing cloud mass flux was altered such that the flux depends on the undiluted air parcel buoyancy itself, rather than the buoyancy gradient (Peng et al. 2004). Improvements in simulated precipitation were also made when the updraft source level was changed, from the level of maximum moist static energy to the level that results in the greatest virtual temperature difference between the parcel and environmental air at the corresponding lifting condensation level, which maximizes the parcel buoyancy (Peng et al. 2004).

This study agrees with previous work that the ERA-40 dataset is much wetter over the Maritime Continent than NNRP2. Over land, NNRP2 may lead to reasonable simulations of the diurnal rainfall cycle over some locations and with certain model configurations. For example, Qian (2008) showed that RegCM3–BATS1e using the Emanuel scheme with the NNRP2 lateral boundary conditions showed good performance in simulating the diurnal rainfall cycle over the island of Java. However, the general wet bias in the Emanuel scheme and dry bias in NNRP2 means that the two used in combination could produce the correct volume of rainfall for the wrong reasons. This study shows that NNRP2 produces a general dry bias over ocean areas, and with any convection scheme except Emanuel it also produces a dry bias over land areas. Therefore, it is considered that the NNRP2 dataset is too dry for this region and less suitable for use as lateral boundary conditions than is the ERA-40 dataset.

This study indicates that the primary driver for the observed errors in the model is within the atmospheric part of the model system and not the land surface scheme, since the errors in the rainfall histogram were similar when using either BATS1e or IBIS. Also, it is noted that when simulated rainfall volumes are closer to observations (such as when comparing the Grell scheme results to the Emanuel scheme), the simulated surface fluxes and ET components are also closer to the observations. Since the partitioning between transpiration and interception loss is highly dependent on the fractional canopy area that is wet versus dry, which in turn depends on how frequently the canopy intercepts rainfall, it is easy to understand that this partitioning matches more closely the observations when the simulated rainfall volumes are more realistic. The better performance of the simulations using IBIS compared to BATS1e suggests that there is some influence of the land surface scheme on the simulated rainfall, but this effect is comparatively small.

5. Summary

This study has identified major errors in the simulated rainfall histogram that have not previously been documented in the RegCM3 model system: an underestimation of the frequency of dry periods, an overestimation of the frequency of low-intensity rainfall, and an underestimation of high-intensity rainfall. These errors exist over both land and ocean surfaces but are more severe over ocean surfaces. Additionally, this study has presented errors in the simulated phase of the diurnal rainfall cycle over the Maritime Continent that are consistent with previous work, with the early occurrence of the daily rainfall peak over land. These errors persisted to varying degrees with changing convective parameterization schemes, lateral boundary conditions, and land surface scheme. Therefore, they are thought to be the result of a fundamental issue in the nature of the convective initiation in climate models.

The volume of rainfall simulated by the RegCM3 model system was shown to be very sensitive to the choice of convective parameterization scheme and lateral boundary conditions. In general, it is considered that the Grell convection scheme with Fritsch–Chappell closure is best suited for use over the Maritime Continent, since it presents the smallest overall bias in the volume of simulated rainfall and the smallest error in the rainfall histogram. Boundary conditions using ERA-40 were much wetter than with NNRP2 and led to simulation results that were closer to the observations, in agreement with previous work and further demonstrating that NNRP2 is less suitable for use in the Maritime Continent region.

The results from this study also show that the diurnal rainfall cycle is sensitive to the choice of land surface scheme, although to a lesser extent than the convection
scheme choice. Simulations using IBIS generally had better representations than BATS1e of rainfall, surface energy fluxes, and ET components. However, the results indicate that the main driver for the rainfall errors lies within the atmospheric part of the model.

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